Decentralized and Centralized Options Trading: A Risk Premia Perspective*

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Abstract

On-Chain options refer to option contracts, that are traded directly on a Decentralized Exchange on the Ethereum blockchain. We explain the functioning of this new market form, so-called automated market making for options trading, and report a novel set of stylized facts. We provide a comprehensive analysis of On-Chain options and compare their attributes to their Off-Chain counterparts on centralized exchanges. We identify an On-Chain risk premium stemming from the positive disparity in implied volatility between On-Chain and Off-Chain options, attributing it to factors like the complex On-Chain fee structure, trading volume, and net demand pressure.

Keywords: Decentralized Exchanges, Decentralized Finance, Blockchain, European Options, Implied Volatility, Liquidity Provision.

JEL Classification Codes: G10, G13, G14, G20

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Abstract

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1 Introduction

Over the last decade, most crypto investors focused on spot trading. With growing interest, options contracts on cryptocurrencies (crypto options) have surfaced. In July 2023, crypto options trading experienced a significant surge, reaching \$3.12 trillion, accounting for 69% of the total crypto volumes.[1] Up to recently, crypto options could be traded solely (*Off-Chain*) on centralized exchanges via the limit order book mechanism. Starting from late 2022, by embracing the advantages of blockchain technology, in decentralized finance (DeFi), crypto options can now also be traded (*On-Chain*) on decentralized exchanges (*DEXs*). Hence, *On-Chain options* are blockchain-based smart contracts that are self-executing and operate without intermediaries.

One of the striking features of a DEX for crypto options (options DEX) is that, instead of a centralized limit order book, it pioneers a novel form of liquidity provision, via an evolved automated market-making (AMM) mechanism for options (which we call *options AMM*). The main aim of an options AMM is to find the price of an option (i.e., its implied volatility (IV)) that balances supply and demand. In such markets, *liquidity providers (LPs)* do not explicitly set prices, but rather passively supply liquidity (underwrite options) by depositing tokens (stablecoins) into a *liquidity pool*. As a reward, the LP receives a share of the trading fees and the option price paid by liquidity takers (traders) generated from trading activity. In addition, LPs might generate a profit or loss depending on the trajectory of their underwritten position. The price impact for traders is calculated mechanically. When traders open a long position, they pay the option price (as calculated by the options AMM) to the liquidity pool. If the option expires in the money the trader's payoff is paid from the reserves in the respective liquidity pool (and therefore ultimately by the LPs). When traders short an option they deposit the quoted asset (or a base asset) as collateral. If a trader's collateral drops below the minimum requirement, liquidation is triggered by the protocol.

Our main contributions in this article are as follows: i) We explain the functioning of this new market form for options trading and report stylized facts associated with it, ii) empirically, using on-chain and off-chain data, we document a difference in the options' IV between an AMM and a limit order market, iii) we offer various explanations for this discovered difference

[1]Source: `https://economictimes.indiatimes.com/markets/cryptocurrency/crypto-derivatives-volumes-surge-to-3-12-trillion-in-july-cryptocompare/articleshow/103602746.cms?from=mdr`

such as the multi-layered On-Chain fee mechanism and the net demand pressure.

Our main analysis for the description of the AMM focuses on the Lyra protocol (Dawson et al. (2021b)), which is a self-custodial, high-performance crypto trading platform for options implemented as a system of smart contracts on a layer 2 scaling solution for Ethereum, such as Arbitrum and Optimism.[2] In contrast to AMMs for token trading (Lehar and Parlour (2023), Park (2023), Capponi and Jia (2024)) where there is only one price for each token quoted in another token, the options AMM consists of several components to equate demand and supply over the full option surface, i.e., strike and maturity. The options AMM does that by adjusting the options price (i.e., its IV) selectively depending on the demand for the respective strike and the maturity. The AMM is thereby able to mimic the well-known characteristics of the volatility surface such as the smile and the smirk. The AMM then calculates the option price as the Black and Scholes (1973) price utilizing the respective adjusted IV. In addition to the option price, the AMM also calculates a trading fee associated with the trade which results from the pool's internal risk management, i.e., hedging the pool's delta and vega exposure: For example, to reduce the delta risk, the AMM will automatically trade the underlying on a spot exchange, while to reduce the vega risk, the AMM will lower the fee if the trader's position is reducing the overall vega exposure of the pool. Hence, per construction, the AMMs minimize the inventory risk which leads to a direct first-order effect on option prices (Muravyev (2015)). The fees are redistributed to the protocol, the pools themselves, and hence ultimately to LPs.

The empirical analysis starts with the discussion of summary statistics on Lyra (pool composition, distributed fees, trading volume, and the traded options type) and profit and loss for LPs and traders. In the next part of our empirical analysis, we compare the fee structure of the two markets. In general, On-Chain trading for BTC options proves more cost-effective than Off-Chain, with average On-Chain trading fees at 18.20 USD compared to 26.24 USD Off-Chain. This trend is consistent when considering fees per unit (calculated as total fees per trade divided by trade size). For ETH options, the difference in trading fees is less significant, with comparable average fees of 12.97 USD (On-Chain) and 11.83 USD (Off-Chain). Important to mention, that Off-Chain only the bid-ask spread and some linear fees depending on the underlying price are charged by the market-maker. In contrast, the fee structure On-Chain is way

[2]See `https://www.lyra.finance/`. An overview of other existing DEXs for options trading and their TVL is given in Table A.1.

more complicated and consists of the pool's vega fees, the pool's delta fees, collateralization fees, option price fees, hedging fees, and a variance fee. A comprehensive breakdown of this fee structure will be provided in the main section of the paper.

In the major part of our empirical analysis, we focus on the option's IV which is a critical component in determining option prices and reflects the market's expectations regarding the future price volatility of the underlying assets. Therefore we analyze a large number of trades and quotes for European options On-Chain and Off-Chain. While the Off-Chain data is proprietary and only available through the respective exchange, the On-Chain data can be sourced directly from the respective blockchain.

Investigating a large cross-section of out-of-the-money (OTM) options for different underlyings (BTC and ETH), maturities, and strikes, we document that the IV for On-Chain options is on average 4% larger than for their centralized counterparts traded Off-Chain. This gap can increase substantially for longer-dated options. For example, the On-Chain IV for 30-day options on ETH is on average almost 20% larger than for the same options Off-Chain. Our analysis reveals that the difference in IV is increasing in the maturity of the options and for options closer to being at the money (ATM). The results are robust including fixed effects for time and the option's contract. To harvest the discovered "On-Chain risk premium," we construct a factor by selling options On-Chain exhibiting relatively higher implied volatility and simultaneously buying options Off-Chain with comparatively lower implied volatility. Given that the exact same option is sold and bought, the payoffs at maturity effectively cancel each other out. The factor displays a strong performance over our sample period. In line with the literature on "limits of arbitrage" (Shleifer and Vishny (1997), Gromb and Vayanos (2010)) incorporating transaction costs significantly reduces the profitability and leads in some cases to negative performances,

In the next phase of our analysis, we delve into the origin of this phenomenon by examining and comparing the dynamics of On-Chain and Off-Chain IVs. We consider various potential explanations, including the sensitivity of IVs to underlying shocks, transaction fees imposed by AMMs, and the influence of trading volume and (net) buying pressure which is measured by the difference between the number of contracts bought and sold.

To gain insight into the sensitivities of the respective IVs to sudden changes in the underlying assets, we analyze the IVs (On-Chain vs. Off-Chain) during the days with the largest drawdown for the respective underlying assets. A pronounced surge in IV is observable whenever the underlying asset undergoes a substantial drawdown, indicative of a leverage effect. Notably, this effect is magnified in the case of options traded On-Chain compared to their Off-Chain counterparts.

To shed light on how the multi-layered fee structure inherent in a DEX affects the resulting traded IV, we utilize a Vector Autoregression (VAR) model to mimic the operational dynamics of the DEX. We estimate the VAR model including the respective IV, Spot Price fee, Vega fee, Variance fee, Option Price fee, Pool's Delta and Vega, Underlying Return, and traded Volume. We repeat the estimation for the Off-Chain options considering the bid-ask spread as the only fee component. In summarizing our key findings, On-Chain, an increase in the Vega fee and Option Price fee leads to successive elevations in IV, whereas for Off-Chain, the bid-ask spread decreases the traded IV. Another finding lies in the impact of trading volume on the traded IV (Epps and Epps (1976), Tauchen and Pitts (1983), and Bollen and Whaley (2004)). On-Chain, a positive shock to the trading volume transmits into a persistent increase in the traded IV, whereas Off-Chain the effect is of lower magnitude and only visible for the traded IV of put options.

The results of the VAR model motivate a deeper investigation of measures related to the trading volume on the dynamics of the IV. (Retail) Demand pressure can have important effects on IV. We, therefore, follow Bollen and Whaley (2004) and construct the net buying pressure for traded options On-Chain and Off-Chain. Volume and net buying pressure do not always correlate strongly. On days with significant information flow, high trading volume may occur, yet the number of buy orders could match sell orders, resulting in zero net buying pressure. Our findings for Ethereum options suggest that net buying pressure effectively accounts for changes in On-Chain IVs across all moneyness levels of call options and for deep OTM put options. Conversely, Off-Chain, net buying pressure can only explain the dynamics of at-the-money (ATM) call options and deep OTM put options.

We conduct a series of robustness tests. While our main analysis focuses purely on Lyra V2 on Arbitrum we also present results for Lyra V2 on Optimism and for Lyra V1 on Optimism. In addition, we also investigate the difference in IV comparing other decentralized (Aevo) and centralized (Okex, and Bitcom) option trading exchanges. In summary, our robust findings confirm consistent results and observations across all exchanges.

2 Literature Review

The literature on DeFi is growing and divides itself into various parts: One strand of the literature is represented by the literature on *tokens*, such as platform adaption, token valuation (pricing), and token financing (Prat et al. (2019), Gryglewicz et al. (2021), Goldstein et al. (2023) and Sockin and Xiong (2023)). In addition, liquidity provision for options encourages the early adoption of productive platforms (Cong et al. (2021), and Cong et al. (2022)). We contribute to this literature by investigating the main quantities of one particular application of such a platform, that is, the decentralized trading of options.

For token trading, there are clear distinctions between decentralized and centralized exchanges (Härdle et al. (2020), Harvey et al. (2021), Makarov and Schoar (2022), and Aquilina et al. (2023)), in terms of market quality (Barbon and Ranaldo (2021)) and arbitrage rents and order-processing mechanisms (Capponi and Jia (2024), Lehar and Parlour (2023), and Park (2023)). Krishnamachari et al. (2021) and Xu et al. (2023) provide a thorough review of the different AMM protocols and their functioning. We contribute to this literature by analyzing some of the aforementioned aspects of options trading on decentralized exchanges.

Implied volatility varies across strike prices and the volatility moneyness smile (smirk) has been attributed to an aversion to price jumps (Dennis and Mayhew (2002), Pan (2002), Xing et al. (2010), and Yan (2011)). As a result, demand pressure can have effects on option prices and implied volatility (Bollen and Whaley (2004), Gârleanu et al. (2009), and Alexander et al. (2023)). Eaton et al. (2023) focuses on option prices and retail trading. The pricing of bitcoin options is discussed in Cao and Celik (2021). Another strand of literature focuses on microstructure in options, by examining asymmetries in price impacts and the significance of hedging costs (Boyle and Vorst (1992) and Engle and Neri (2010)) Additionally, the liquidity suppliers are subject to inventory risk (Muravyev (2015)), and quote revisions in options markets (Jameson and Wilhelm (1992) and Chan et al. (2002)), which impacts the option prices. Furthermore, the literature identifies an inverse relationship between bid-ask spreads and market maker hedging efficiency (Cho and Engle (1999)) and demonstrates the limited impact of information asymmetry on market liquidity (Vijh (1990)). To our knowledge, there is no academic literature about On-Chain options and their comparison to classic Off-Chain options. This paper will fill the gap in the literature.

3 Functioning of DeFi Options Exchanges

Before discussing the innovation in a DEX for option trading a short overview of the functioning of classic centralized exchanges is provided.

3.1 Centralized Exchanges

In a traditional options exchange, a broker-dealer order system is used, where a brokerage firm acts as both a broker and a dealer. The firm facilitates to buy and sell orders as a broker and executes trades for its account as a dealer. The exchange matches orders with counterparties, and the options clearinghouse oversees the final settlement. The largest exchange for trading (centralized) cryptocurrency options is Deribit, on which options are quoted directly in the respective currency (for example BTC or ETH) and not in USD.[3] Deribit utilizes a maker-taker fee model. The fee for trading BTC or ETH options for both the maker and taker is 0.03% of the underlying BTC (ETH) per options contract. In addition, a 0.015% fee for delivery (settlement) is charged.[4]

3.2 Decentralized Option Exchanges – Lyra

Lyra (Dawson et al. (2021b)) operates as an open protocol for European options trading on the Ethereum blockchain, i.e., Layer 2 solutions such as Arbitrum and Optimism.[5] It is decentralized, which means that all transactions are recorded on the Ethereum blockchain for transparency and audibility. It introduces a unique pricing model that takes into account real-time supply and demand dynamics to ensure precise and efficient pricing for traders. Users of Lyra can engage in options trading for various cryptocurrencies, including ETH and BTC.[6] Liquidity providers can also provide liquidity to the protocol, which simplifies position opening and closing while allowing them to earn rewards.

[3] The valuation of Deribit is approximately USD 400m (09/2022) with a revenue of USD 3m in 2023. Source: `https://app.dealroom.co/companies/deribit`

[4] https://www.deribit.com/kb/fees

[5] Layer 2 solutions are secondary protocols built on existing blockchains, aiming to boost scalability and transaction efficiency by processing many transactions Off-Chain, mitigating congestion and high fees on the main blockchain.

[6] One Optimism one can also trade options on OP (Optimism), LINK (Chainlink), ARB (Arbitrum), and XRP (Ripple).

3.2.1 Options Automated Market Maker (AMM)

An options market maker's main aim is to find an IV value that balances supply and demand. This equilibrium lets the automated market maker (AMM) profit from transaction fees, without incurring any risk, by buying and selling options equally. This market-derived IV is then used to calculate the Black and Scholes (1973) price (W). As usual, the model takes five key parameters: $\tau = T - t$ (time to expiry), r (risk-free rate), S_t (underlying price at time t), K (strike price), and the annualized IV.

Initialization: Upon listing an option, an initial baseline volatility value, along with ratios of listed strike volatilities, are initialized based on current market data from the nearest ATM strike on Deribit.

Standard Size: It is reasonable to assume that the price impact of a trade is proportional to its size. The AMM captures this effect through the notion of a standard size (SS) which allows it to contextualize each trade and alter its pricing parameters in proportion to a trade's size. The higher the standard size, the lower the slippage for traders.[7]

Volatility Impact: For every SS that the AMM buys or sells in a given expiry, the baseline IV will increase or decrease respectively for that expiry by 1 percentage point:

$$IV_{new} = \begin{cases} IV_{old} + 1\% & \text{pool sells 1 SS} \\ IV_{old} - 1\% & \text{pool buys 1 SS} \end{cases} \tag{3.1}$$

Skew Impact: The Black-Scholes model fails to incorporate the volatility smile commonly observed in options markets. The AMM incorporates skew into its pricing using the skew ratio $SR_{i,j}$ which is the ratio of $IV_{i,j}$ of a given strike (K_i) and expiry (T_j) to the baseline IV for the same expiry IV_j

$$SR_{i,j} = \frac{IV_{i,j}}{IV_j}. \tag{3.2}$$

Hence if the baseline IV_j changes so does the whole surface (for a fixed expiry) change ($IV_{i,j} = SR_{i,j} IV_j$). As for the volatility, for each SS bought (sold) the skew ratio increases (decreases)

[7]The standard size for sETH is 25.0 and for sBTC it is 0.32. In addition, the standard size is continuous, so 1/10th of a standard size moves the volatility by 0.1%.

by a constant c_r

$$(SR_{i,j})_{new} = \begin{cases} (SR_{i,j})_{old} + c_r & \text{pool sells 1 SS} \\ (SR_{i,j})_{old} - c_r & \text{pool buys 1 SS} \end{cases} \tag{3.3}$$

The final price of the option is then calculated as the Black and Scholes (1973) price for the $IV_{i,j}$ plus some fee (f) which results from the pool's internal risk management which is explained next.

3.2.2 Pool Risk Management – Delta and Vega Risks

Lyra accepts stablecoin collateral and provides options in rounds, where each round spans 28 days, and options can be traded with four discrete expiries (7, 14, 21, and 28 days from the round's start). The liquidity will be split into two sub-pools: i) Collateral pool (collateralized options and pays/receives premiums), and ii) Delta pool: which Hedges the delta exposure of the AMM by trading the underlying asset.

The net delta and vega positions define the risk profile, allowing for hedging actions to be undertaken when exposure is unacceptably high. To reduce the risk, the AMM incentivizes to open positions so that the risk of the AMM is reduced. Hence the AMM would charge a larger (lower) fee (in addition to the price W) if the trader's position is increasing (decreasing) the overall risk of the AMM. The exact functioning of how the risk is managed and the fees charged are outlined in the following.

Delta risk defines the exposure of an options position to a move in the underlying asset. The delta ($\delta_{i,j}$) of an option is calculated using Black and Scholes (1973). The delta exposure ($E_{i,j}$) is then calculated as the net position ($\rho_{i,j}$) times the delta ($\delta_{i,j}$). The net delta of the pool (Δ) is then simply the sum over all delta exposures (for each strike and maturity). The AMM will hedge a given net delta position by buying, selling, or short-selling the underlying asset on a spot exchange.

Vega risk defines the exposure of an option to move in the IV. For example, if an option has a vega of 0.25 and the IV increases by 15%, the vega in dollar terms would be $0.25 \times 0.15 = 0.0375$\$. For the options AMM the vega is directly connected to the *impermanent loss*.[8] For example, if the AMM sells a call with a vega of 0.0375\$ at 150 vol and buys it back for 165 it

[8]The impermanent loss for an options AMM is explained in Section 3.2.3 in more detail.

realizes a loss of 0.0375\$ $\times$ (165 − 150) = 0.5625\$. This effect is amplified at the pool level via the pool's net position.

The vega ($vega_{i,j}$) for an individual position is calculated using the Black and Scholes (1973) formula. The vega exposure ($E_{i,j}$) is then calculated as the net position ($\rho_{i,j}$) times the delta ($vega_{i,j}$) times a normalization factor $N_j = \frac{30}{T_j - t}$, where the latter incorporates the time-dependent risk profile of vega. The net standard vega of the pool (Ψ) is calculated as the sum over all vega exposures ($E_{i,j}$) (for each strike and maturity). The normalized vol ($NormVol$) in (dollar terms) is defined as the net standard vega of the AMM multiplied by the IV value of a trade ($IV_{i,j}$)

$$NormVol_{i,j} = \Psi IV_{i,j}. \tag{3.4}$$

Building on that, the vega utilization (VU_t) is defined as the 20% change in NormVol as a percentage of the size of the collateral pool (C_{total})

$$VU_t = \frac{0.2 \times |\text{NormVol}|}{C_{\text{total}}}. \tag{3.5}$$

The vega utilization at time t quantifies in dollar terms the risk of changes in IV to the options AMM.

The options AMM mitigates the delta and vega risk (quantified as vega utilization) by including their exposure into the fee imposed on the trades. This fee f (at time t) is defined as follows:

$$f_t = A \times W + B \times H \times VU_t + C \times S_t \tag{3.6}$$

where A, B, and C are coefficients and the parameter H is equal to 0 if the trade brings the absolute value of the options AMM's net standard vega (Ψ) closer to 0, and 1 otherwise. C represents the percentage fee associated with collateralizing and delta hedging on a spot exchange. Hence the fee consists of a flat fee depending on the option price ($W_{i,j}$), a dynamic vega fee, and a flat fee for exchange costs. Therefore, the AMMs inventory risk has a direct first-order effect on option prices (Muravyev (2015)).

3.2.3 Liquidity Provision for Options

LPs deposit stablecoins as collateral (sUSD or USDC) for underwriting calls and puts. Even though the liquidity provision is in stablecoins the LP is exposed to impermanent loss which emerges through the change in the option price and not through the underlying token as for LPs when providing liquidity for token trading (see Milionis et al. (2023), and Li et al. (2023)). The impermanent loss occurs when the prices, i.e., its IV of the options in the liquidity pool change. Because liquidity was provided at a specific IV, if the IV of the options increases or decreases significantly, the AMM will adjust the IV in the pool to reflect the new prices. Hence the impermanent loss is the adverse selection faced by LPs. If for example, in periods of market turmoil, the "true" implied volatility increases, arbitrageurs will enter the liquidity pool and buy the options until the AMM adjusts the IV in the pool to match the "true" IV again. The arbitrageur then sells the options at the increased IV back to the AMM or to the external market. The impermanent loss for LPs on Lyra is analyzed in great detail in Dawson et al. (2021a).

The LPs can deposit or withdraw funds only after they signal their intention three days in advance. The net asset value of a pool (which determines the LP's share of the pool) is computed using the geometric time-weighted volatility (GWAV) approach.[9] For withdrawal there is a fee of 0.3%.

3.2.4 Trading Options

When traders short a call they deposit the base asset (sETH, sBTC, or sUSD). However, when shorting puts, the risk profile has to be inversely proportional to the pay-off, and hence only the quoted asset can be deposited. Traders are restricted from opening positions in options with less than 12 hours to expiry and outside the specified delta range, as determined by the asset's preset limits, enhancing risk management and market stability. The deltas of the individual options are limited to absolute deltas between 10 and 90 (hence extreme deep ITM and OTM options are excluded).

When a user opens a short position, the option price the trader should receive is kept as collateral on the short position. If a trader's collateral drops below the minimum requirement,

[9]For details see Appendix B.1.

liquidation can be triggered by keepers, which are individuals who activate the liquidation process for underfunded positions.[10] During liquidation, the user is compelled to repurchase their option in a manner that generally benefits the options AMM. Subsequently, a flat percentage is deducted from the user's remaining liquidity, with this penalty being distributed among the liquidator, the repurchase AMM, and the security module.

4 Data and Methodology

We obtain Off-Chain option data through amberdata[11], encompassing option trades at a tick level and hourly quotes. The dataset spans multiple centralized exchanges (CEXs) and includes Bitcoin (BTC) and Ethereum (ETH) as underlying assets. The On-Chain data is obtained directly from the respective DEX using the methodology provided by The Graph. The Graph is a protocol that helps in accessing information on the Ethereum blockchain by allowing users to use a query language called GraphQL. For Lyra, we source trades at a tick level and hourly quotes. In the next step, we calculate the relevant fields for our analysis such as the IV and the options Greeks. We follow this procedure for Lyra Version 1, Version 2, and Arbitrum and Optimism respectively.

The On-Chain and Off-Chain options (trades and quotes) are matched based on their underlying asset, time to expiry, strike price, type, and observation time.[12] The fact that quotes are recorded on the hour On-Chain and Off-Chain allows us to match them perfectly. For trades (recorded on a tick level), we restrict the difference in the observation time between the On-Chain and the respective Off-Chain options not to be larger than one hour. By doing so we ensure that the On-Chain option and the Off-Chain option truly represent the same contract.

5 Empirical Analysis

In the main part of this analysis, we purely focus on Lyra V2 deployed on Arbitrum, for the reason that data availability and trading activity are higher as compared to Optimism. The results for Lyra V1 and Lyra V2 on Optimism can be found in the robustness section. Our

[10] The liquidation engine is explained in greater detail in Appendix B.2.

[11] `https://www.amberdata.io/`

[12] Options can be identified over time by their option-id, for example, "UNDERLYING-STRIKE-EXPIRY-TYPE" (e.g. "BTC-25000-060523-C").

examination focuses on ATM and OTM options with a maturity between 7 and 30 days.

5.1 Lyra – Summary Statistics

Our analysis starts with a basic overview of Lyra. Figure 5.1 presents key quantities for Lyra pools over time. As visible from Panel (a) most traded options are on ETH (on average 75.68%). The fees the pool generates over time are displayed on Panel (b): For ETH (BTC) on average 1996.19 USD (585.24 USD) per day. The fees the pool generates are distributed to the LPs. The average number of option traders is 62 (Panel (c)). Panel (d) displays the daily pool volume which is 1528985.80 USD (477946.61 USD) for ETH (BTC). Lastly, from Panel (e) one can infer the type of options that are traded (as the mean over the sample period): long calls (34%), long puts (25%), short calls (25%), and short puts (16%). As visible, the pool's composition is time-varying, which underlines the importance of the inventory risk for the AMM and ultimately the liquidity provider. In addition, the fact that long calls are traded the most leaves room for the hypothesis that demand pressure propagates to the option price and the IV after all.

Next, we briefly investigate the profit and loss for traders and LPs on Lyra. As visible from Figure 5.2 Panel (a) traders lose more than they earn ($-261,977$ USD in total). When providing liquidity (Panel (b)) the overall return over the sample is 3.18% for ETH and -2.69% for BTC.

5.2 On-Chain and Off-Chain – Strikes

Figure 5.3 illustrates the availability of strikes On-Chain and Off-Chain for each underlying asset over time. A noticeable discrepancy is evident: In the case of BTC, Off-Chain trading sees an average of 36 strikes traded (with 51 strikes quoted), whereas On-Chain trading registers only around 5 strikes traded (with 16 quoted). Similarly, for ETH, Off-Chain trading averages 26 strikes traded (with 37 quoted), while On-Chain trading shows only about 8 strikes traded (with 19 quoted).

5.3 On-Chain and Off-Chain — Transaction Fees

Figure 5.4 and Figure 5.5 depict the trading fees for a liquidity taker On-Chain and Off-Chain for BTC and ETH, respectively. The Lyra fees are defined as in equation (3.6) whilst

Figure 5.1: Lyra Stats - Pool Overviews. The figure shows key quantities for Lyra pools over time: Pool Composition (Panel (a)), the daily occurring total Pool Fees (Panel (b)), New and Existing Traders (Panel (c)), daily Pool Volume (Panel (d)), and the Pool Trades (Panel(e)). The options underlying assets are Bitcoin (BTC) and Ethereum (ETH). The data is obtained from Lyra deployed on Arbitrum. The data is winzorized at the 1% quantile. The sample period ranges from 01-2023 to 11-2023.

the Deribit fees, as introduced in Section 3.1, are computed as,

$$f_t = S_t \times x_t \times 0.03\%, \tag{5.1}$$

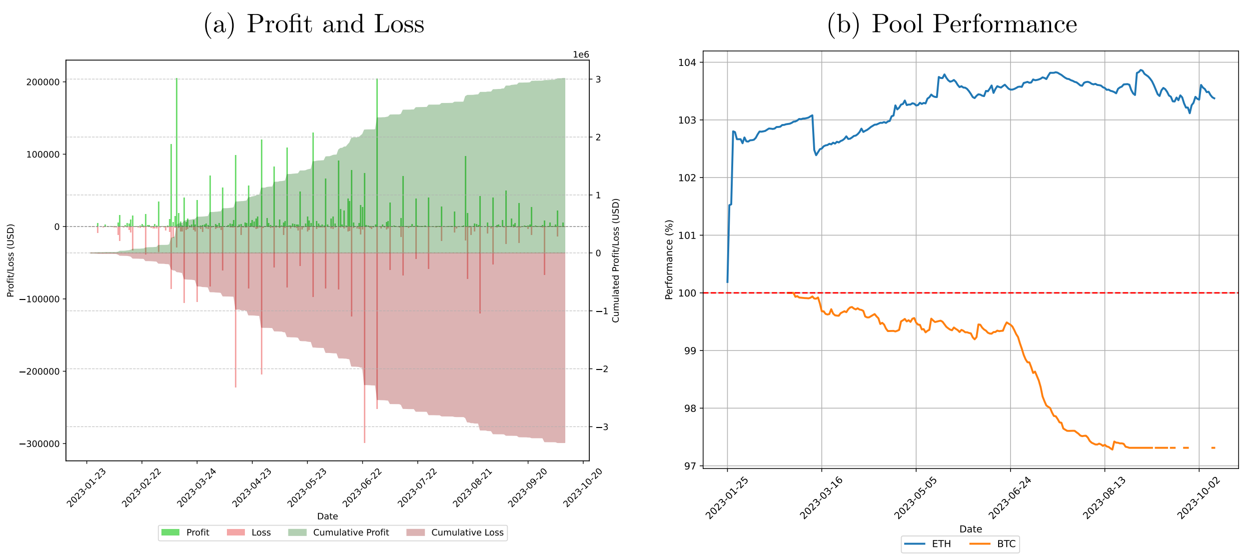


Figure 5.2: Lyra Stats – Pool Performance. The figure shows the Trader's Profit and Loss (Panel (a)) and the LPs Pool Performance (Panel (b)) over time. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH). The data is obtained from Lyra deployed on Arbitrum. The sample period ranges from 01-2023 to 11-2023.

where S_t is the underlying price and x_t is the trade size. Overall, for BTC, trading On-Chain is cheaper than Off-Chain: the trading fees On-Chain are on average 18.20 USD, while Off-Chain they are 26.24 USD. The results are consistent considering the trading fees per unit, Panel (c) and Panel (d), which we calculate as the total fees per trade divided by the trade size. For ETH the difference in trading fees is less pronounced: The average fees are comparable: 12.97 USD (On-Chain) vs. 11.83 USD (Off-Chain). Interestingly, the trade per unit is lower Off-Chain than On-Chain.

Figure 5.6 displays the individual components of the respective On-Chain trading fees. The largest fraction of the fees is made up of the spot price fee (58.79% for BTC and 61.05% for ETH), followed by the variance fee (22.38% for BTC and 20.97% for ETH), the option price fee (15.40% for BTC and 13.61% for ETH) and the vega fee (3.35% for BTC and 4.37% for ETH). In addition, as visible from the plots the magnitude of the total fees is comoving with the trading volume. This is due to the On-Chain fee mechanism as defined in equation (3.6).

5.4 On-Chain and Off-Chain — IVs

Next, we analyze the difference between the On-Chain and Off-Chain implied volatilities. Table 5.1 and Table 5.2 present the summary statistics On-Chain and Off-Chain for trades and quotes for BTC and ETH. Unconditionally, the option prices and IVs are larger On-Chain,

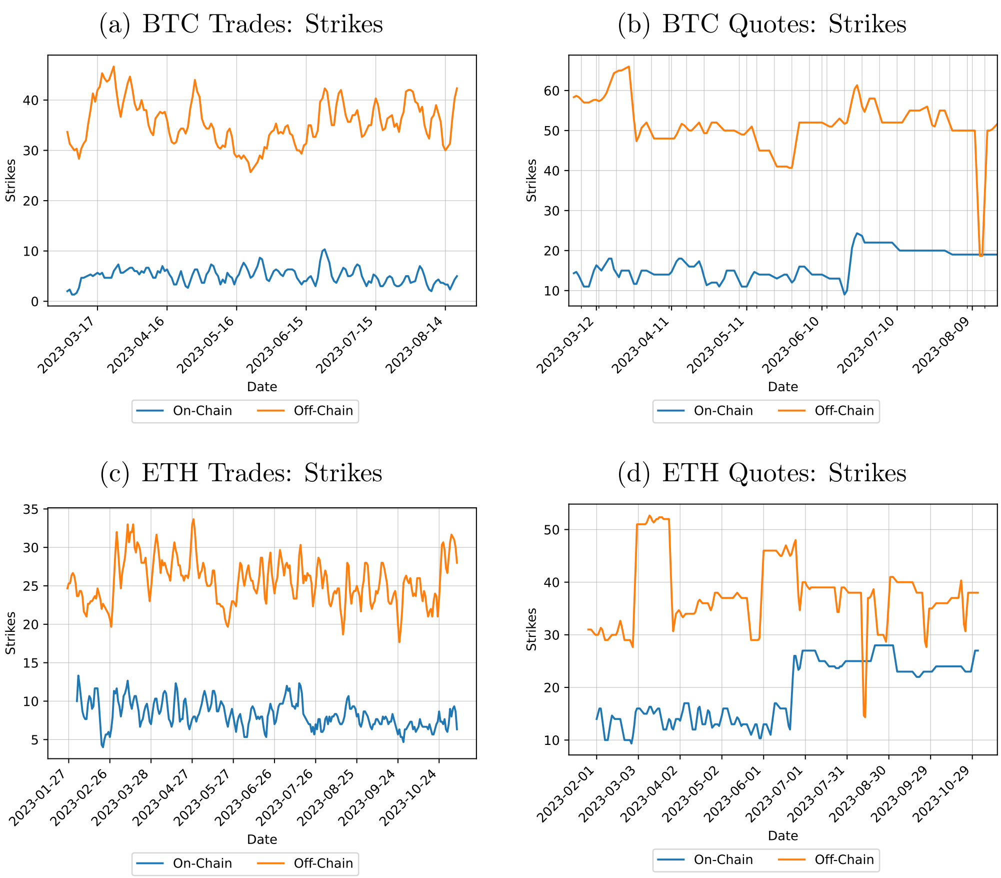


Figure 5.3: On-Chain and Off-Chain – Available Strikes Over Time. The figure shows the total number of quoted and traded strikes from call and put options, On-Chain, and Off-Chain, averaged for each day. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. Only options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level while the quotes are given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

while the trade size is larger Off-Chain. In particular, the one-side t-test indicates that at a 1% significance level, the IV On-Chain is on average larger than the one Off-Chain.

To better understand the emergence of the difference in IV, the On-Chain and Off-Chain IVs from trades and quotes for each underlying and averaged for different strikes are shown in Figure 5.7. As visible, the On-Chain and Off-Chain IVs display a strong comovement and similarity in levels. Nevertheless, the IVs start to diverge for low and high strike prices.

Figure 5.8 displays the average IVs averaged over maturities instead of strikes. As before, the On-Chain and Off-Chain IVs display a strong comovement even though the gap between the IVs is widening for longer maturity options.

Figure 5.9 (for BTC) and 5.10 (for ETH) resembles Figure 5.7 but for call and put options separately and investigating only 7 and 30 days to maturity. As visible, from Figure 5.9 and

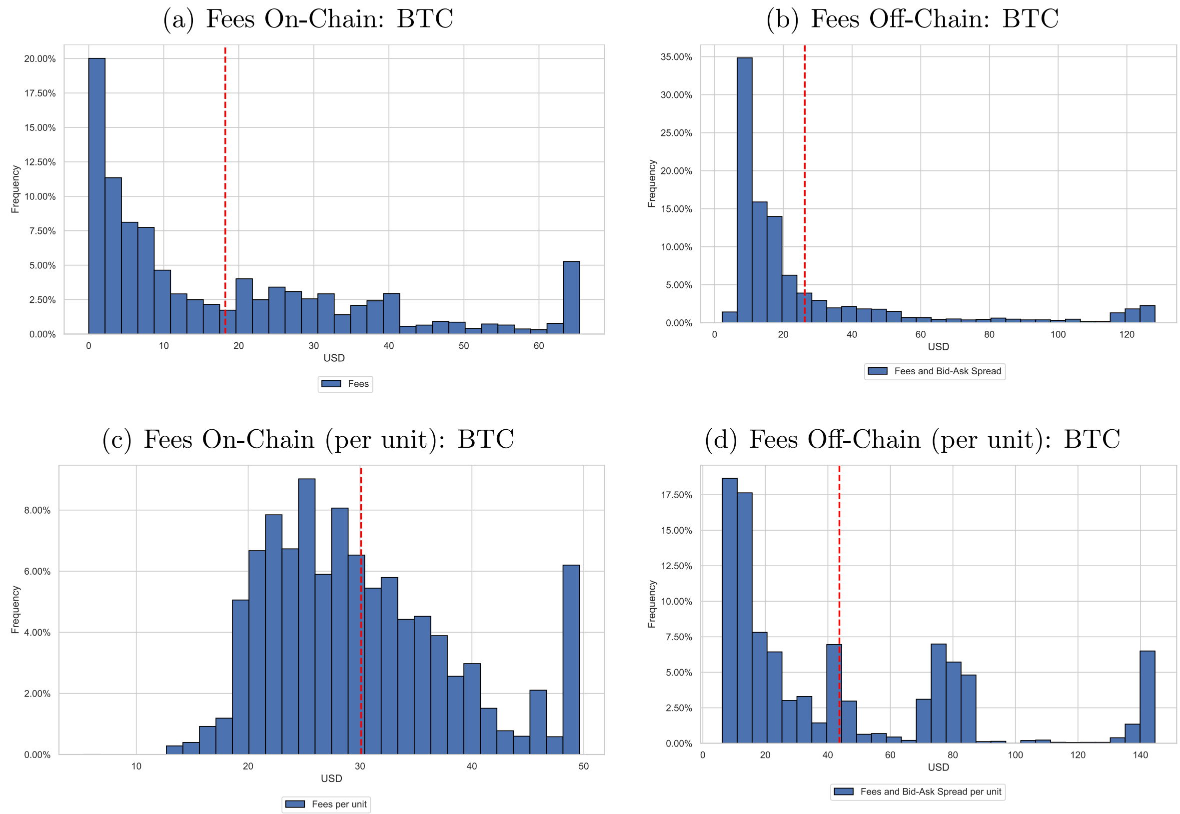


Figure 5.4: Transaction Fees – On-Chain vs. Off-Chain – BTC. The figure shows the histogram of total trading fees (Panel (a) and Panel (b)), and trading fee per unit (Panel (c) and Panel (d)), On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The fees On-Chain are calculated according to equation (3.6) and Off-Chain as described in Section 3.1. The options underlying asset is Bitcoin (BTC). The dashed red line denotes the unconditional average. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 5% quantile. The sample period ranges from 02-2023 to 11-2023.

Figure 5.10 Panel (c) the gap between On-Chain and Off-Chain is the widest for far OTM calls with a total difference of 0.2. For monthly put options on ETH, Figure 5.10 Panel (d) displays a consistent positive gap between the On-Chain and Off-Chain IV. The pattern is less clear for put options on BTC, where the difference in IV (On-Chain IV - Off-Chain IV) is negative (positive) for low (high) strikes.

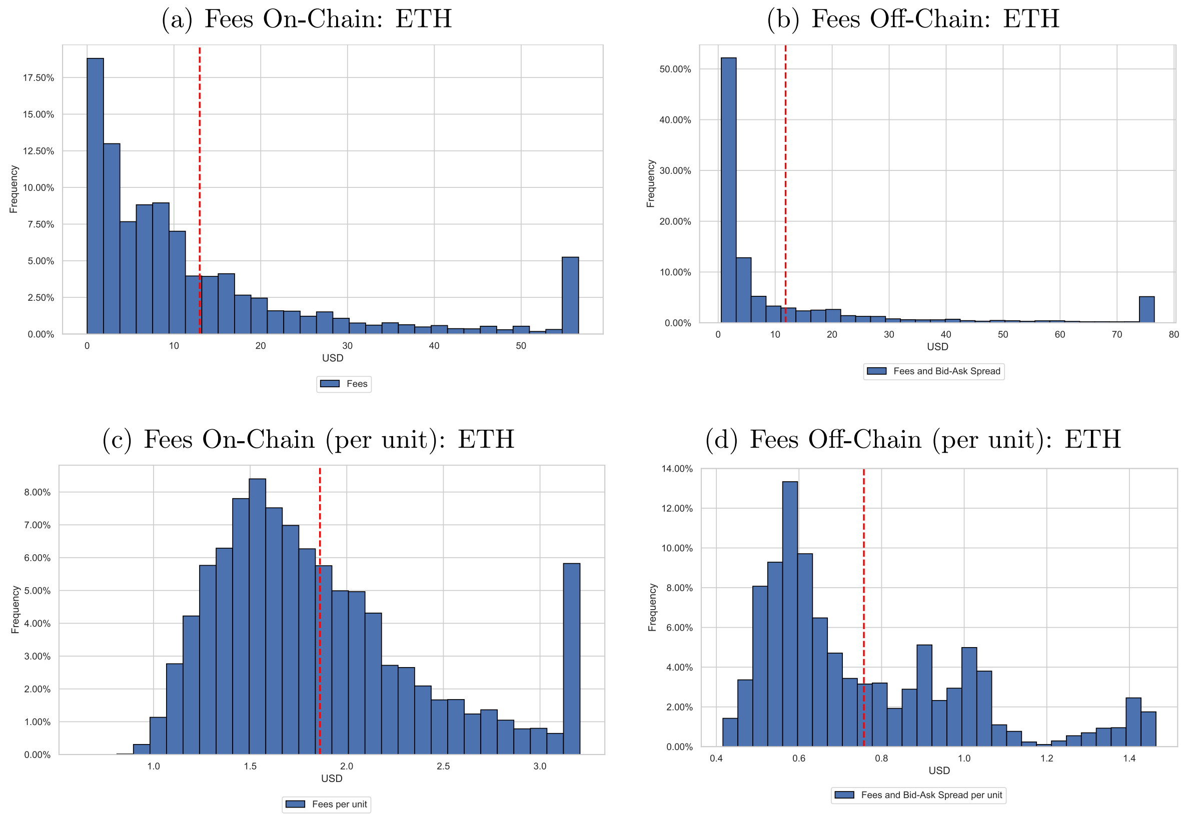


Figure 5.5: Transaction Fees – On-Chain vs. Off-Chain – ETH. The figure shows the histogram of total trading fees (Panel (a) and Panel (b))), and trading fee per unit (Panel (c) and Panel (d))), On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The fees On-Chain are calculated according to equation (3.6) and Off-Chain as described in Section 3.1. The options underlying asset is Ethereum (ETH). The dashed red line denotes the unconditional average. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 5% quantile. The sample period ranges from 02-2023 to 11-2023.

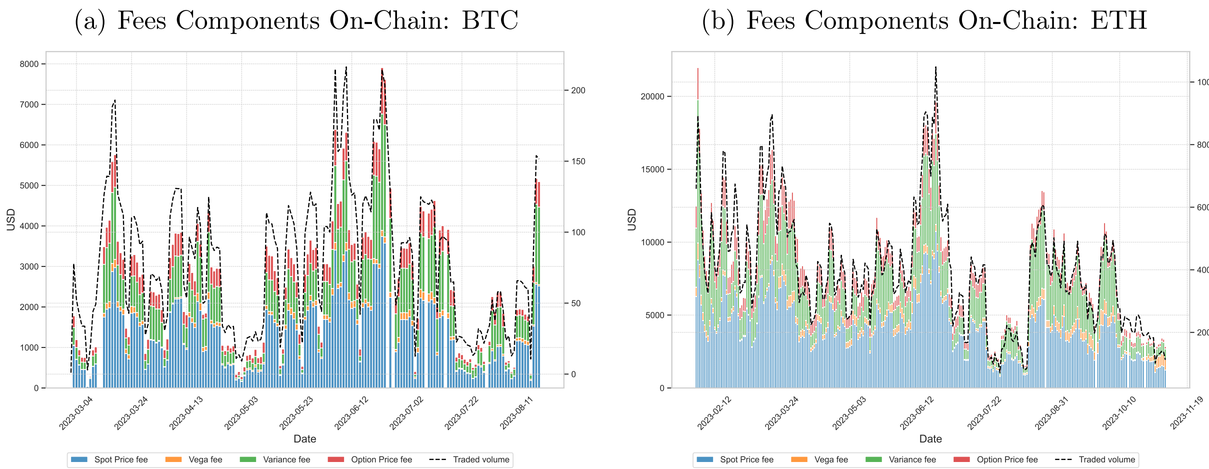


Figure 5.6: Fee Components – On-Chain. The figure displays the fee components and volume (dashed line) for Bitcoin (BTC) (Panel (a)) and Ethereum (ETC) (Panel (b)) in USD. The On-Chain data is obtained from Lyra deployed on Arbitrum. The components of the fees are mentioned in equation (3.6). Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 5% quantile. The sample period ranges from 02-2023 to 11-2023.

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	25032	25032	143333	143333
Instruments	257	257	560	560
Min Date	2023-03-02	2023-03-02	2023-02-01	2023-02-01
Max Date	2023-08-19	2023-08-19	2023-11-06	2023-11-06
Min Strike	18000	18000	1200	1200
Max Strike	40000	40000	2600	2600
IV mean	0.48	0.46	0.50	0.48
IV std	0.10	0.10	0.13	0.13
Price mean	418.99	405.22	28.13	25.44
Price std	255.21	236.45	18.01	15.23
Size mean	0.63	3.37	8.54	34.18
Size std	0.76	16.18	16.61	210.61

Table 5.1: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	65721	65721	123730	123730
Instruments	362	362	657	656
Min Date	2023-03-01	2023-03-01	2023-02-01	2023-02-01
Max Date	2023-08-19	2023-08-19	2023-11-02	2023-11-02
Min Strike	18000	18000	1200	1200
Max Strike	40000	40000	2600	2600
IV mean	0.51	0.49	0.49	0.48
IV std	0.11	0.10	0.14	0.13
Price mean	436.98	395.96	25.91	23.73
Price std	340.73	301.28	21.04	18.63

Table 5.2: Summary Statistics – Quotes. The table displays the summary statistics of the quoted options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. Only OTM options with maturity between 6 and 30 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

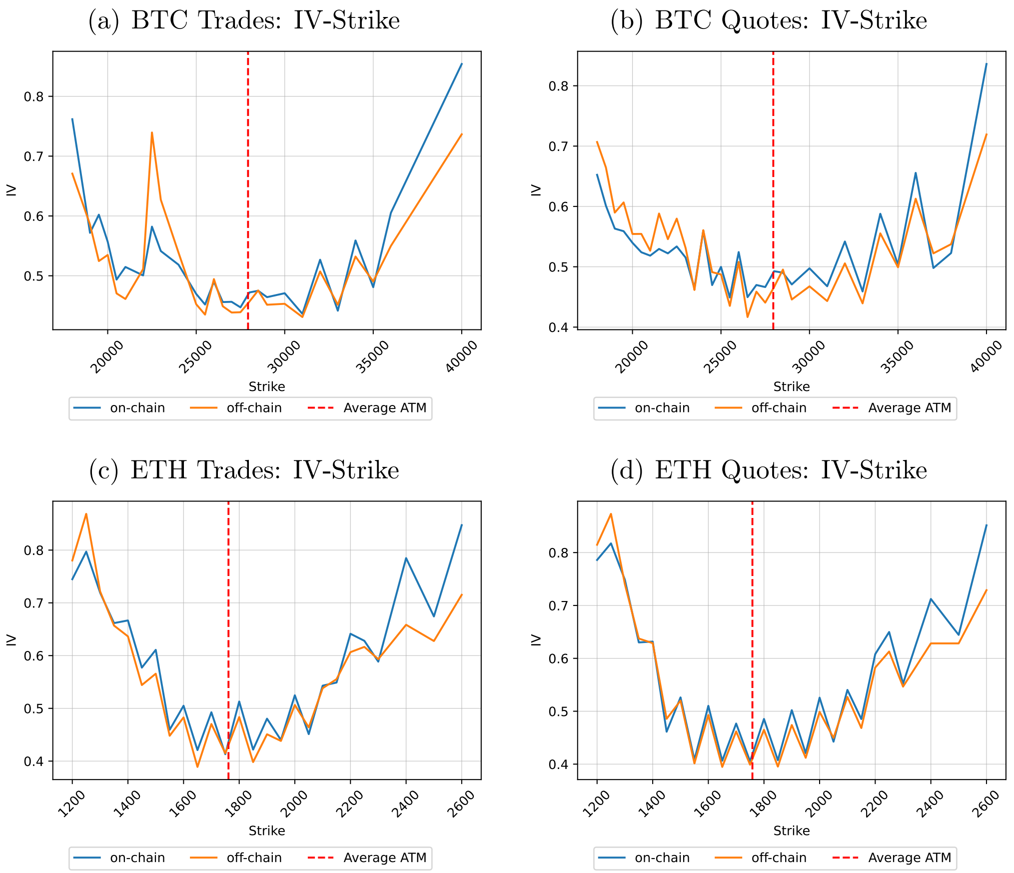


Figure 5.7: Implied Volatility and Strike Price. The figure shows the traded and quoted IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the strike price in USD. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level while the quotes are given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

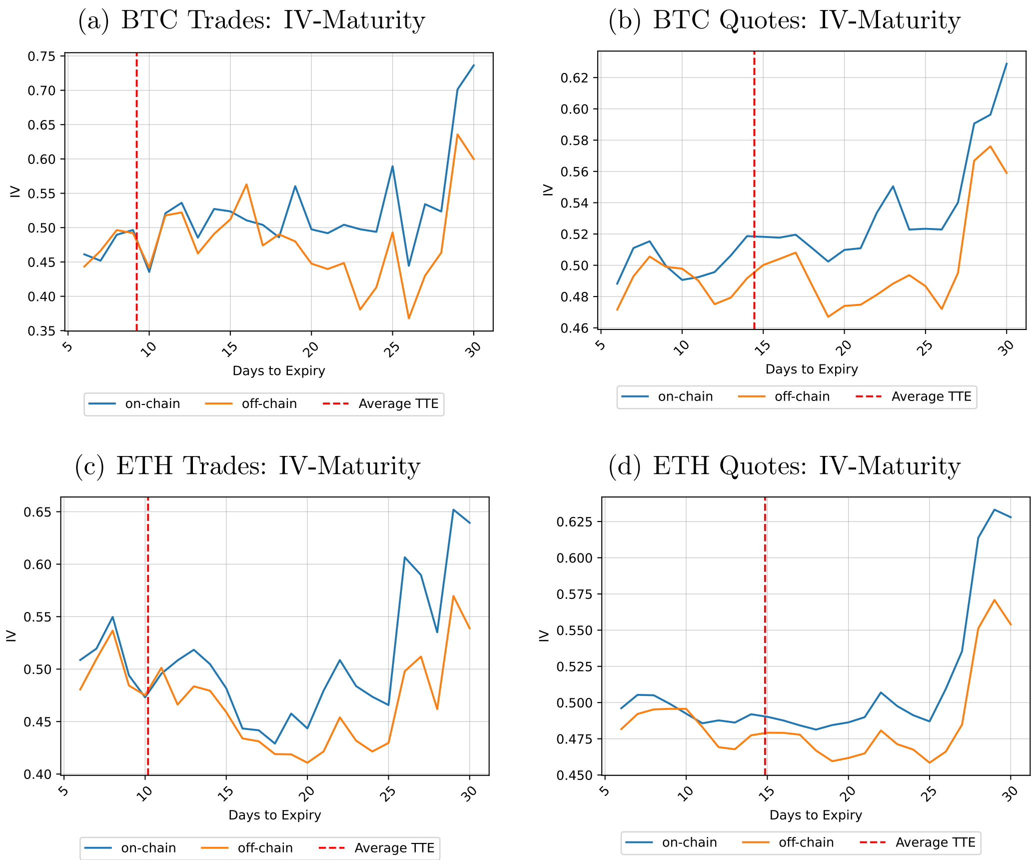


Figure 5.8: Implied Volatility and Maturity. The figure shows the traded and quoted IV from call and put options, On-Chain, and Off-Chain, averaged for different maturities. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the maturity in days. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level while the quotes are given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

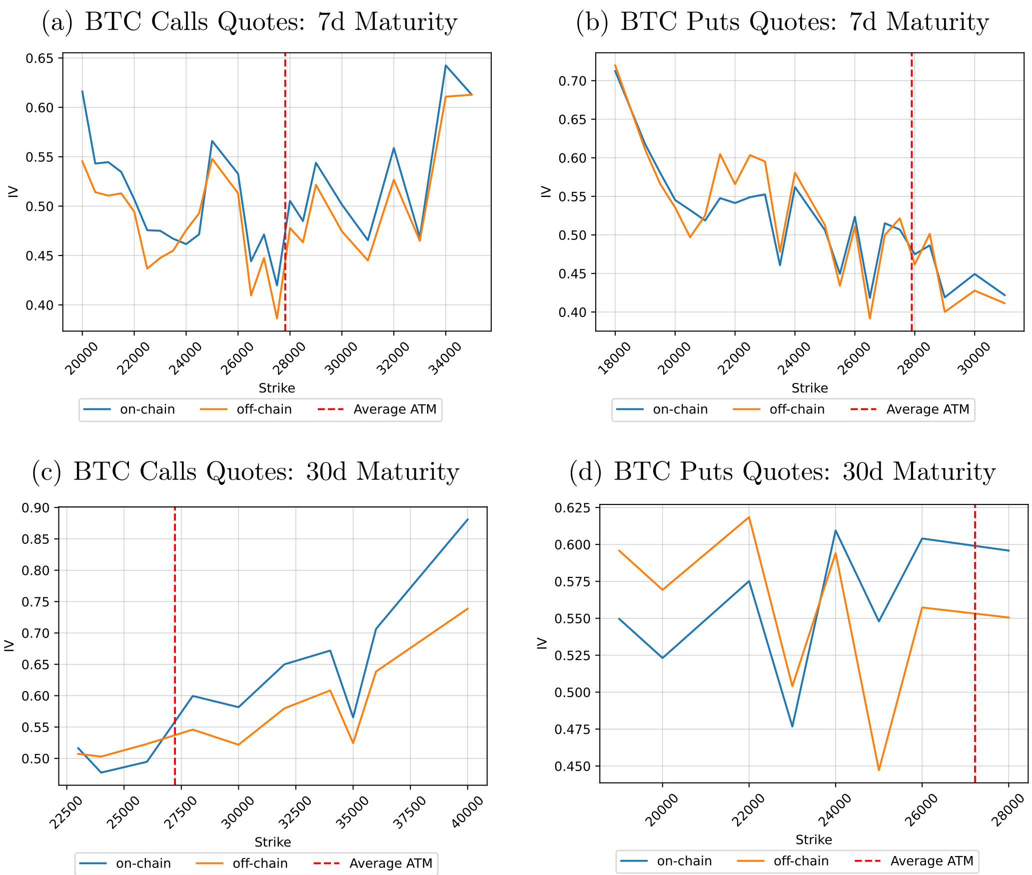


Figure 5.9: Implied Volatility for BTC and Strike Price – Call and Puts. The figure shows the quoted IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The underlying asset is Bitcoin (BTC). The x-axis represents the strike price in USD. In panels (a) and (b) only OTM options with maturity between 6 and 8 days are selected, while in panels (c) and (d) only OTM options with a maturity of 28-32 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

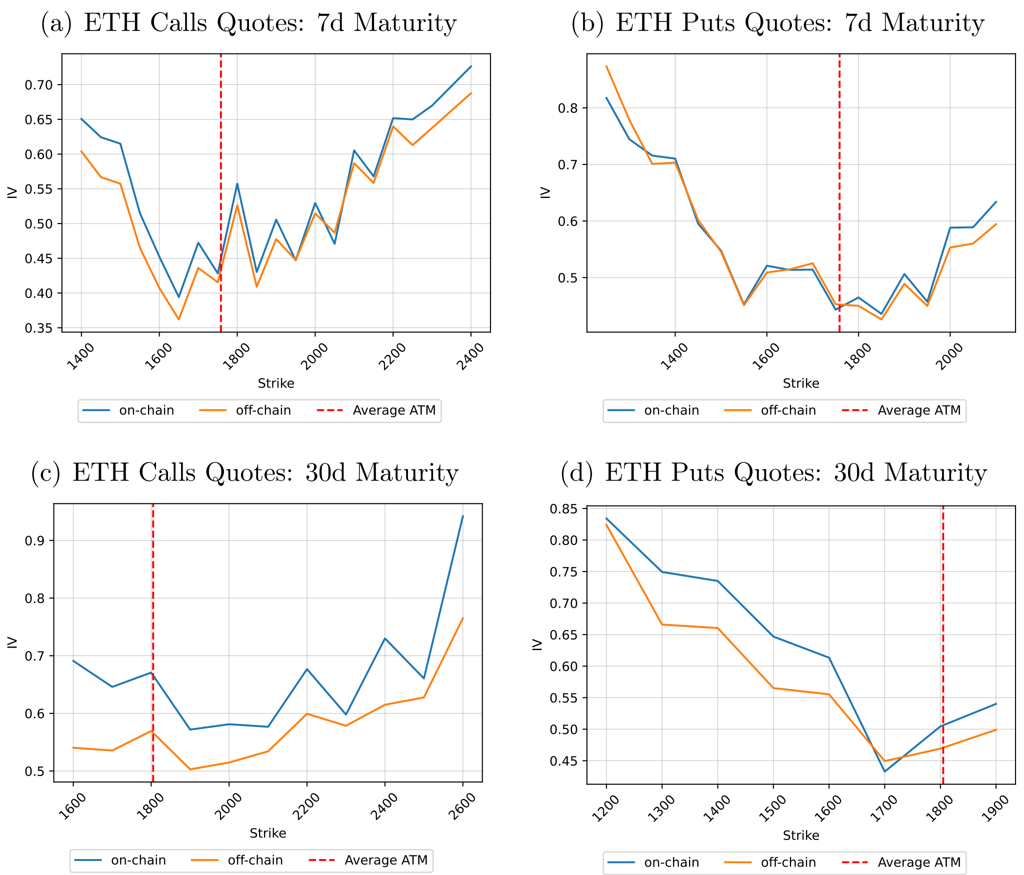


Figure 5.10: Implied Volatility for ETH and Strike Price – Call and Puts. The figure shows the quoted IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The x-axis represents the strike price in USD. In panels (a) and (b) only OTM options with maturity between 6 and 8 days are selected, while in panels (c) and (d) only OTM options with a maturity of 28-32 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

5.5 Regression Analysis – On-Chain and Off-Chain — IVs

In the next part of our empirical analysis, we extend the visual evidence given by the figures to a regression framework. The goal is to explain the difference between On-Chain and Off-Chain IVs (Diff IV) based on the On-Chain options' key characteristics (option type, maturity, and moneyness) and the Greeks which are relevant for the On-Chain option pricing, that is the (absolute) Delta and Vega (see Section 3.2.2). The absolute Delta for OTM options ranges from 0 to 0.5, and hence an increase in Delta indicates that the option is getting closer to ATM. The Vega measures the option's sensitivity to volatility and is always positive. Since the AMM manages the pricing of the option via the pool Delta and Vega risk, we especially focus on the Delta and Vega coefficients and their influence on the difference in IVs.

We run the panel regression specifications as outlined by equations (5.2)-(5.3). The difference in IV can be observed for each matched option-id over time. The first specification (5.2) regresses the differences in IVs simply on the options' key characteristics, where *Call* equals one if the option is a call option (and zero otherwise), *Maturity* denotes the maturity of the option in years, and *Mness* computed as S/K for calls and K/S for puts ranges from 0 (far OTM) to 1 (ATM). The second specification regresses the differences in IVs on the options Greeks associated with the AMMs risk management engine (Delta and Vega). In addition, in both specifications, we include fixed effects for either the option-id (α_i) and over time (α_t).

$$\text{Diff IV}_{i,t} = \beta_0 + \beta_1 \text{Call}_i + \beta_2 \text{Maturity}_{i,t} + \beta_3 \text{Mness}_{i,t} + \alpha_i + \alpha_t + \epsilon, \tag{5.2}$$

$$\text{Diff IV}_{i,t} = \beta_0 + \beta_1 \text{Abs. Delta}_{i,t} + \beta_2 \text{Vega}_{i,t} + \alpha_i + \alpha_t + \epsilon. \tag{5.3}$$

Firstly, Tables 5.3 and 5.4 present the results of the regression analysis for BTC and ETH trades, respectively. These results show that the gap in IV tends to increase for longer-dated options, options closer to at-the-money (ATM), and in the case of ETH also for call options. Furthermore, an increase in absolute delta towards ATM and higher Vega widen the IV gap. For ETH the findings remain consistent even with the inclusion of fixed effects. Following this, Tables 5.5 and Tables 5.6 provide the results of the same regression analysis but for quotes instead of trades. The results largely mirror those observed for trades, although there are some notable differences, specifically, the significance of the Call and Absolute Delta coefficients does not diminish for BTC trades.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.40036	-0.27263	-0.28877	-0.05484	-0.01928	-0.03797
	(0.00000)	(0.00000)	(0.00003)	(0.00000)	(0.00003)	(0.00000)
Call	-0.00040		0.00486			
	(0.68057)		(0.19116)			
Maturity	0.00363	0.00248	0.00384			
	(0.00000)	(0.00000)	(0.00000)			
Mness	0.39392	0.28497	0.28382			
	(0.00000)	(0.00000)	(0.00005)			
Abs. Delta				0.03363	0.03160	-0.03175
				(0.00000)	(0.16491)	(0.15229)
Vega				0.00004	0.00002	0.00005
				(0.00000)	(0.00000)	(0.00000)
R-squared	0.0906	0.0910	0.2963	0.1133	0.0987	0.3435
Adj. R-squared	0.0905			0.1132		
Observations	25847	1371	1371	25847	1371	1371
Entities		258			258	
Time Periods			934			934
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table 5.3: Regression Results – IV – Trades On-Chain vs. Off-Chain – BTC – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The trades On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Bitcoin (BTC). The trade data is sampled on a tick level and resampled to hourly frequency. The sample period ranges from 02-2023 to 11-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.35380	-0.39901	-0.28825	-0.04622	-0.02598	-0.02531
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.01167		0.00537			
	(0.00000)		(0.00000)			
Maturity	0.00194	0.00245	0.00254			
	(0.00000)	(0.00000)	(0.00000)			
Mness	0.36788	0.42196	0.30035			
	(0.00000)	(0.00000)	(0.00000)			
Abs. Delta				0.13586	0.08844	0.03204
				(0.00000)	(0.00000)	(0.00000)
Vega				0.00031	0.00029	0.00045
				(0.00000)	(0.00000)	(0.00000)
R-squared	0.0843	0.1536	0.2586	0.1910	0.1789	0.3294
Adj. R-squared	0.0843			0.1910		
Observations	146438	6767	6767	146438	6767	6767
Entities		561			561	
Time Periods			3233			3233
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table 5.4: Regression Results – IV – On-Chain vs. Off-Chain – ETH – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The trades On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Ethereum (ETH). The trade data is sampled on a tick level and resampled to hourly frequency. The sample period ranges from 02-2023 to 11-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.19556	-0.27883	-0.25675	-0.03349	-0.03446	-0.02655
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.02028		0.01664			
	(0.00000)		(0.00000)			
Maturity	0.00225	0.00248	0.00225			
	(0.00000)	(0.00000)	(0.00000)			
Mness	0.18576	0.28450	0.25417			
	(0.00000)	(0.00000)	(0.00000)			
Abs. Delta				0.01692	0.14538	0.03970
				(0.00000)	(0.00000)	(0.00000)
Vega				0.00003	0.00001	0.00002
				(0.00000)	(0.00000)	(0.00000)
R-squared	0.1002	0.0935	0.1831	0.1736	0.1572	0.2491
Adj. R-squared	0.1001			0.1736		
Observations	65721	65721	65721	65721	65721	65721
Entities		362			362	
Time Periods			4110			4110
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table 5.5: Regression Results – IV – On-Chain vs. Off-Chain – BTC – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Bitcoin (BTC). The quote data is given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.19505	-0.38408	-0.33238	-0.03511	-0.04028	-0.03738
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.02158		0.02022			
	(0.00000)		(0.00000)			
Maturity	0.00198	0.00241	0.00253			
	(0.00000)	(0.00000)	(0.00000)			
Mness	0.18368	0.39388	0.32433			
	(0.00000)	(0.00000)	(0.00000)			
Abs. Delta				0.09295	0.17181	0.07640
				(0.00000)	(0.00000)	(0.00000)
Vega				0.00029	0.00016	0.00035
				(0.00000)	(0.00000)	(0.00000)
R-squared	0.1039	0.1146	0.2595	0.1997	0.1933	0.3340
Adj. R-squared	0.1039			0.1997		
Observations	123730	123730	123730	123730	123730	123730
Entities		657			657	
Time Periods			6592			6592
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table 5.6: Regression Results – IV – On-Chain vs. Off-Chain – ETH – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The On-Chain data is obtained from Lyra deployed on Arbitrum, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Ethereum (ETH). The quote data is given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

5.6 Risk Factor – On-Chain and Off-Chain — IVs

In the next section, we capitalize on disparities in IV On-Chain and Off-Chain. By selling options On-Chain with relatively higher IV and buying options Off-Chain with comparatively lower IV, we seek to exploit this pricing differential. Since we buy and sell the exact same option, the pay-offs at the maturity offset each other. We construct the strategy on a weekly frequency at 10 am. We implement this strategy for various maturities (7 and 15 days), for puts and calls separately, and for different moneyness levels (ranging from 0.9 to 1).

In the first attempt, we consider quotes to construct our factor and we neglect the influence of transaction costs. The P&L of the strategy (in ETH) is shown in Figure 5.11 for calls and in Figure 5.12 for puts. Based on the regression findings outlined in Section 5.5, which demonstrate a greater discrepancy in IV for options nearing ATM, the factor tends to yield higher returns for moneyness levels closer to 1 (ATM).

(a) Factor: 7d Maturity (b) Factor: 15d Maturity

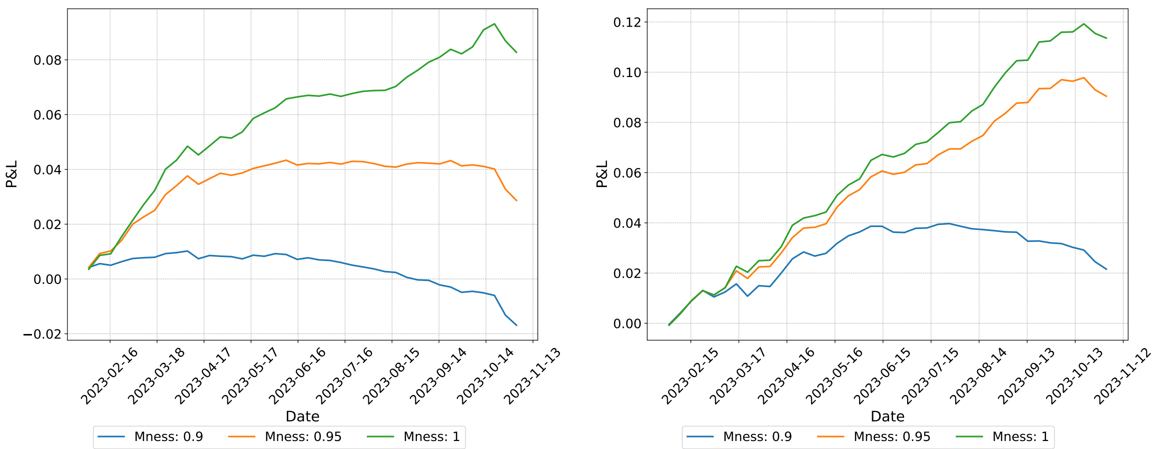


Figure 5.11: Factor – Calls – ETH – Quotes. The figure displays the P&L (in ETH) of the factor that aims to profit from the convergence of IV between the two exchanges over time, i.e., selling the On-Chain call options and buying the Off-Chain call options for a given maturity, and moneyness. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The y-axis represents the cumulative P&L in ETH. The factor is constructed on a weekly frequency at 10 am. The sample period ranges from 02-2023 to 11-2023.

Transaction costs directly impact the profitability of any trading strategy and can erode profits if not properly considered. Therefore, in the next step, we assess the performance of the factors including transaction costs. We estimate an average fee from the trade data which we apply for the construction of our factor based on the quotes data. By doing so we incorporate the multi-layered fee structure On-Chain. We estimate the average transaction fees for sell

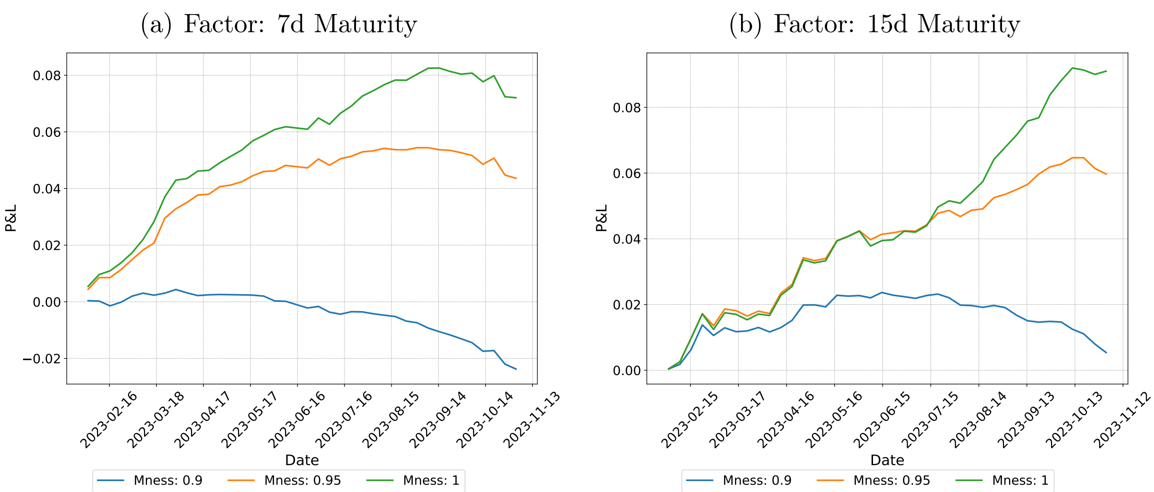


Figure 5.12: Factor – Puts – ETH – Quotes. The figure displays the P&L (in ETH) of the factor that aims to profit from the convergence of IV between the two exchanges over time, i.e., selling the On-Chain put options and buying the Off-Chain put options for a given maturity, and moneyness. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The y-axis represents the cumulative P&L in ETH. The factor is constructed on a weekly frequency at 10 am. The sample period ranges from 02-2023 to 11-2023.

trades as 0.001130 ETH for the 7-day maturity call, 0.001043 ETH for the 15-day maturity call, 0.001177 ETH for the 7-day maturity put, and 0.000991 ETH for the 15-day maturity put. When buying Off-Chain, we purchase at the respective ask quote instead of the mark price as before, including a fee of 0.0003 ETH. Therefore when constructing the factor one receives the premium net of fees from the sell On-Chain and one pays the premium including fees from the buy Off-Chain. The P&L (net of fees) of the strategy (in ETH) is shown in Figure 5.13 for calls and in Figure 5.14 for puts. As visible, the strategies suffer dramatically from the transaction costs and are less profitable. For the low maturity factor (Panel (a)) the P&L stagnates over time. The factor tracking the factor with options maturity of 15 days is still profitable but only for the highest moneyness range (ATM). To some extent, our results confirm the "limit to arbitrage" hypothesis (Shleifer and Vishny (1997)).[13]

[13] In Figure D.10 and Figure D.11 we report the P&L of the factor constructed using trade data and transaction fees incurred. The performance is in between the factor constructed from quotes without and with transaction fees.

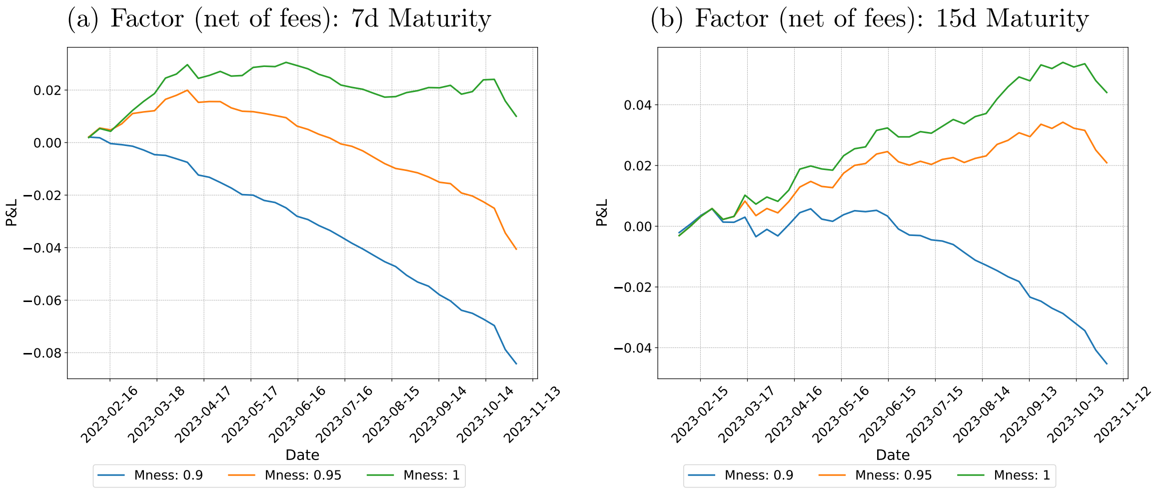


Figure 5.13: Factor – Calls – ETH – Quotes with Fees. The figure displays the P&L (in ETH) of the factor that aims to profit from the convergence of IV between the two exchanges over time, i.e., selling the On-Chain call options and buying the Off-Chain call options for a given maturity, and moneyness. The fees are estimated On-Chain as the average fees from the respective trades (sell trades for call options), and Off-Chain as 0.0003 ETH. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The y-axis represents the cumulative P&L in ETH. The factor is constructed on a weekly frequency at 10 am. The sample period ranges from 02-2023 to 11-2023.

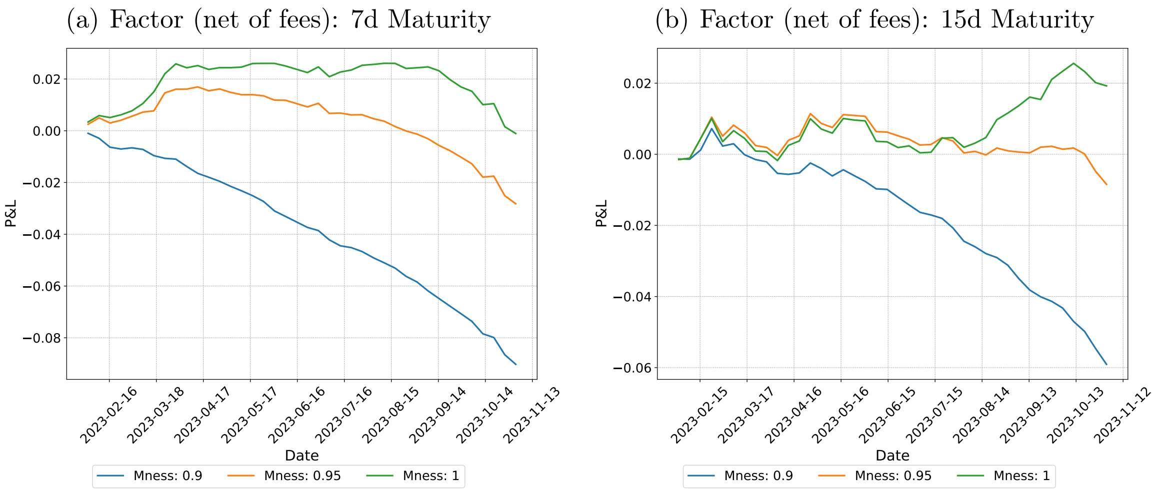


Figure 5.14: Factor – Puts – ETH – Quotes with Fees. The figure displays the P&L (in ETH) of the factor that aims to profit from the convergence of IV between the two exchanges over time, i.e., selling the On-Chain put options and buying the Off-Chain put options for a given maturity, and moneyness. The fees are estimated On-Chain as the average fees from the respective trades (sell trades for put options), and Off-Chain as 0.0003 ETH. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The y-axis represents the cumulative P&L in ETH. The factor is constructed on a weekly frequency at 10 am. The sample period ranges from 02-2023 to 11-2023.

5.7 Determinants of Decentralized Option Exchanges

In the next step, we investigate the difference in IV (On-Chain vs. Off-Chain) for the four worst days of the respective underlying. For each day we then select the option with the largest positive difference in IV. The results are presented in Figure 5.15 and Figure 5.16, where the panels are ascending in the drawdown (starting from the worst day). The respective option-id is reported in the title of the respective panel. Our analysis focuses on call options.

For BTC the worst day (the returns are reported in the brackets) in our sample was (a) 2023-03-09 (-0.068), followed by (b) 2023-06-05 (-0.058), (c) 2023-05-01 (-0.05), and (d) 2023-03-03 (-0.048). As visible there is a strong increase in IV whenever the underlying experiences a large drawdown (leverage effect). The effect is amplified for options traded On-Chain w.r.t to Off-Chain. For example in Panel (d), the call option (BTC-24000-17032023-call) with a strike price of 24000 and maturity of 14 days displays a jump in IV from around 0.5 to 0.70 (On-Chain). We repeat the analysis for ETH, for which the worst day in our sample was (a) 2023-08-17 (-0.12), followed by (b) 2023-03-09 (-0.076), (c) 2023-02-09 (-0.071), and (d) 2023-04-19 (-0.058). The results are presented in Figure 5.16 and are qualitatively similar. For dates with a lower drawdown in the underlying (Panel (d)) the Off-Chain IV does not even respond.

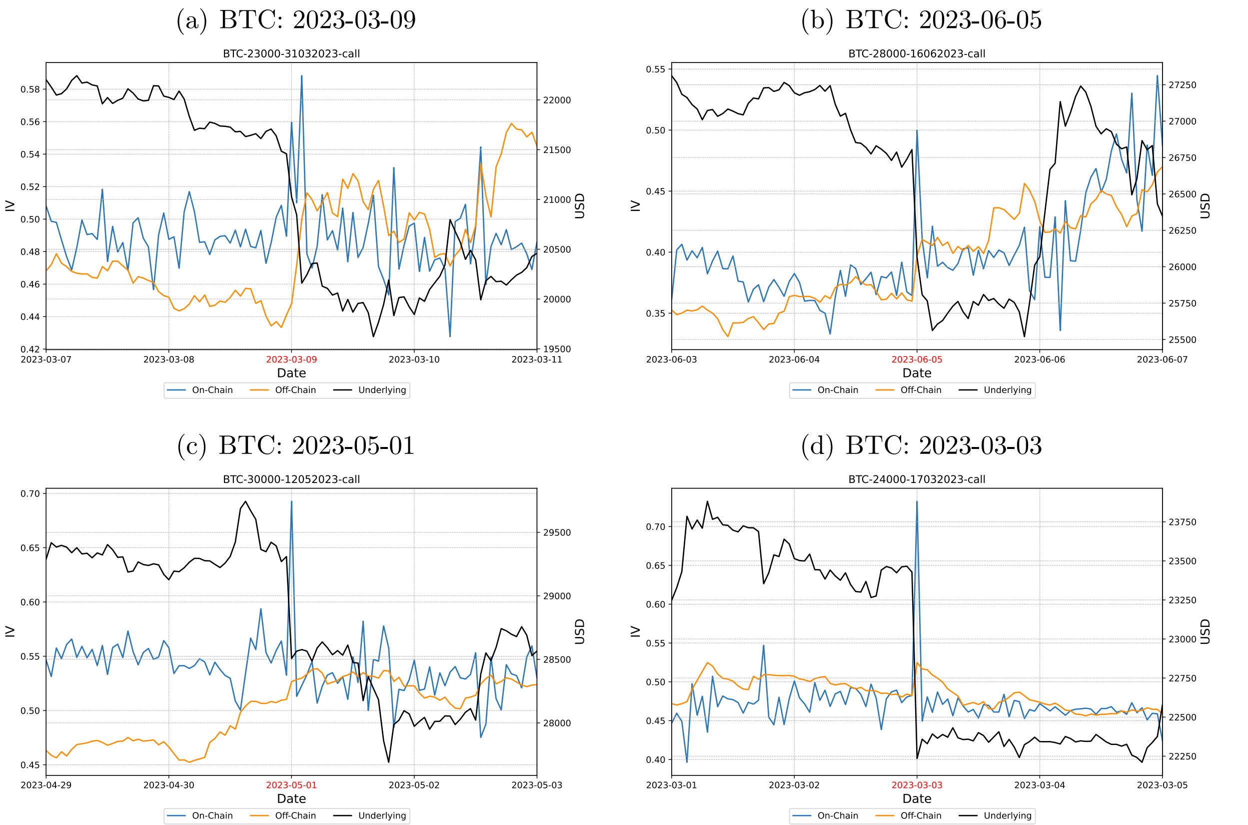
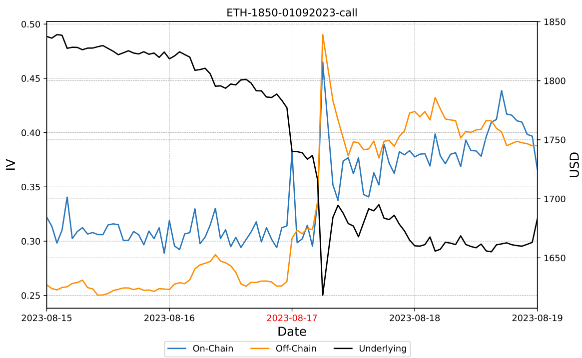
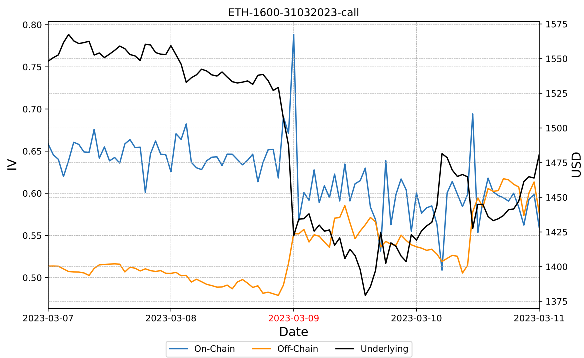


Figure 5.15: Market Stress and IV – On-Chain vs. Off-Chain – BTC. This figure displays the IV for the selected option-ids before and after the drawdown in the underlying. The option-ids are selected as the option contracts with the largest difference in IV (for the respective date). For BTC the worst days (returns are reported in the brackets) in our sample were (a) 2023-03-09 (-0.068), followed by (b) 2023-06-05 (-0.058), (c) 2023-05-01 (-0.05), and (d) 2023-03-03 (-0.048). The quote data is given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

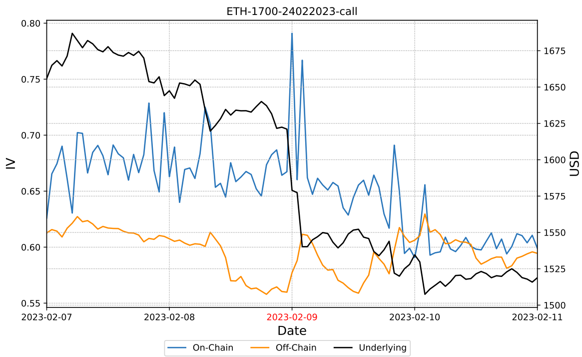
(a) ETH: 2023-08-17



(b) ETH: 2023-03-09



(c) ETH: 2023-02-09



(d) ETH: 2023-04-19

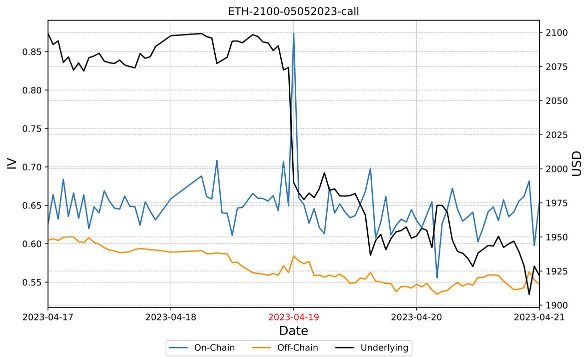


Figure 5.16: Market Stress and IV – On-Chain vs. Off-Chain – ETH. This figure displays the IV for the selected option-ids before and after the drawdown in the underlying. The option-ids are selected as the option contracts with the largest difference in IV (for the respective date). For BTC the worst days (returns are reported in the brackets) in our sample were (a) 2023-08-17 (-0.12), followed by (b) 2023-03-09 (-0.076), (c) 2023-02-09 (-0.071), and (d) 2023-04-19 (-0.058) The quote data is given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

5.8 VAR Model – AMM Mechanism

To shed light on the pricing mechanism of the AMM and to contrast it from the trading mechanism on a CEX we estimate a Vector Autoregressive Model (VAR) which is defined as:

$$y_t = c + A_1 y_{t-1} + ... + A_p y_{t-p} + e_t, \tag{5.4}$$

where the optimal lag order of the VAR model is selected w.r.t the AIC. The data input is a vector of time series variables, that is IV, Spot Price fee, Vega fee, Variance fee, Option Price fee, Delta (Pool), Vega (Pool), Underlying Return, and Volume. The trade data is aggregated across option-ids and resampled on an hourly frequency. We estimate a VAR model for each option type (call or put), for buy and sell orders separately, and for On-Chain trades and for Off-Chain separately. In the main part of this paper, we focus on ETH, the results for BTC are in the Appendix C.1 and are qualitatively similar.

Figure 5.17 and Figure 5.18 display the impulse response functions (IRFS) of the ETH IV for long call options (Panel (a)) and long put options (Panel (b)). From Figure 5.17 (Panel (a) – calls) one can infer that the Spot Price fee and the Variance fee decrease the successive traded IV, while the Option Price fee increases the IV. In addition, the IV is positively affected by the Pool Vega, shocks to the underlying, and the trading volume (demand pressure). For Panel (b) (puts) the results are qualitatively similar, with the exception that the Vega fee and the pool Delta (significantly) increase the traded IV. For Off-Chain (Figure 5.18), the aggregated Delta and Vega increase the successively traded IV. For call options, shocks to the underlying propagate positively to the traded IV. The volume only affects the IV for put options. A larger Bid-Ask spread lowers the demand and hence decreases the successive IV.

To summarize the main difference in our findings: On-Chain the traded IV is positively affected by the trading volume, contrary to Off-Chain, where the volume does not affect the IV. While Off-Chain the bid-ask spread decreases the traded IV, On-Chain an increase in the Vega fee and the Option Price fee increases successive IV.

(a) Long Call – ETH (b) Long Put – ETH

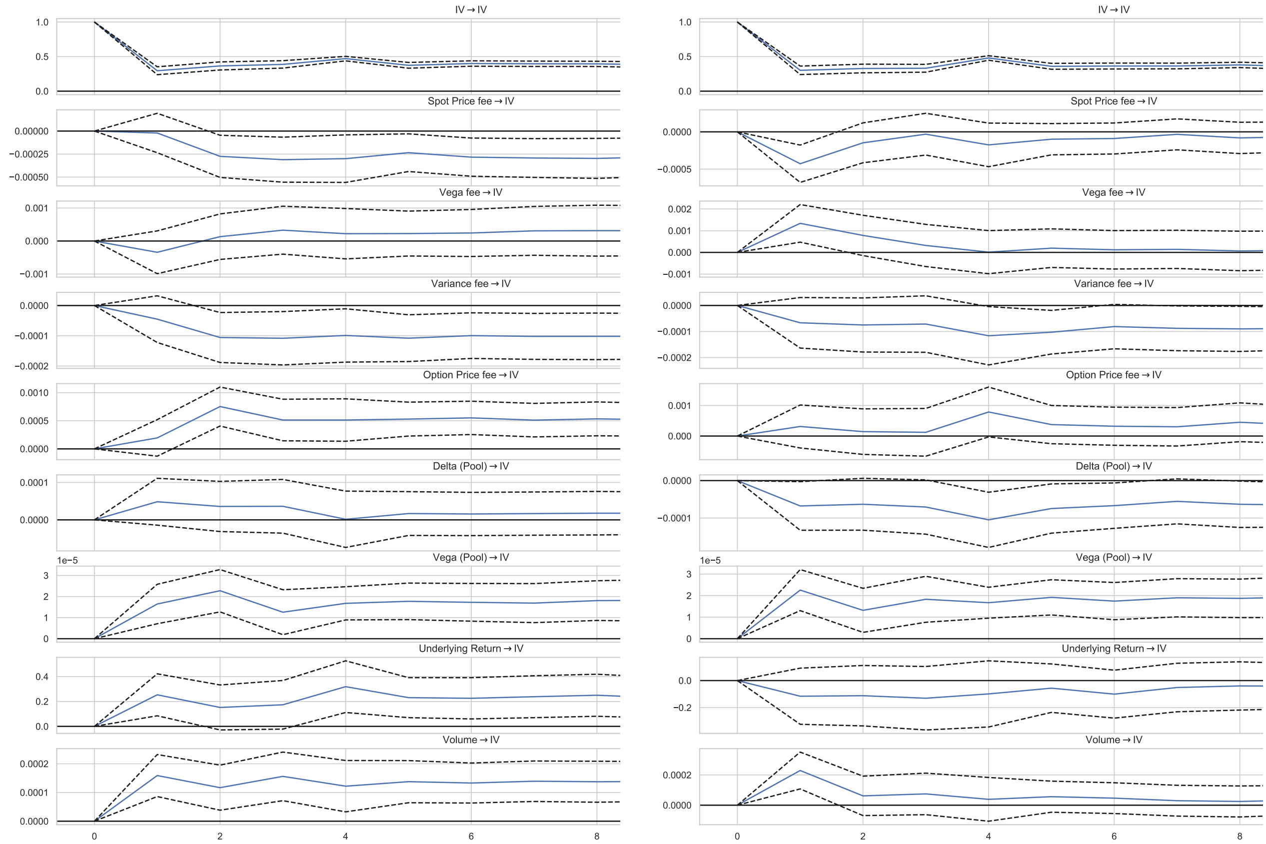


Figure 5.17: On-Chain – ETH – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the ETH IV for long call options (Panel (a)) and long put (Panel (b)). IV denotes the traded IV. The vega and delta of the pool are calculated following Section 3.2.2. Volume denotes the aggregate of traded volume for each point in time. The Underlying Return is calculated for the respective underlying (ETH). The On-Chain data is obtained from Lyra deployed on Arbitrum. The components of the fees are mentioned in equation (3.6). Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

(a) Long Call – ETH (b) Long Put – ETH

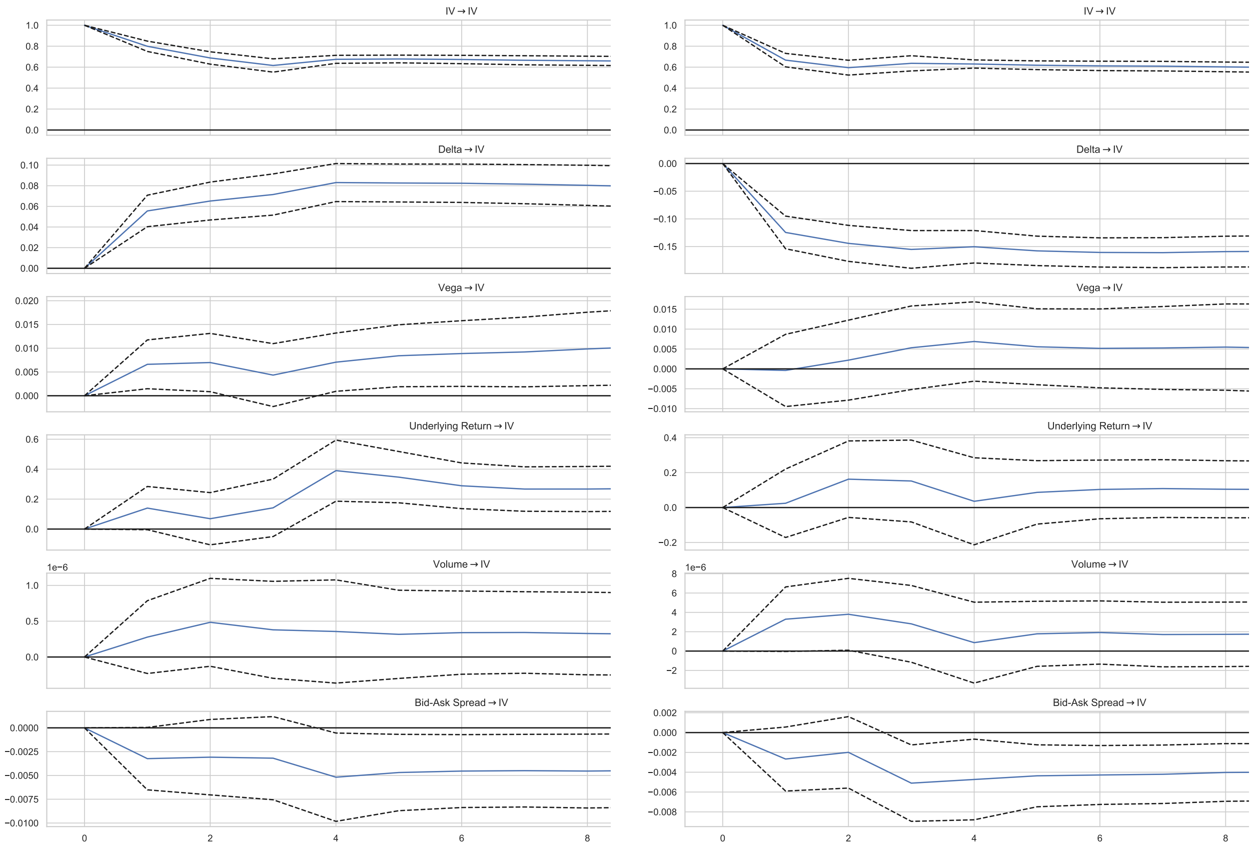


Figure 5.18: Off-Chain – ETH – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the ETH IV for long call options (Panel (a)) and long put (Panel (b)). IV denotes the traded IV. The Vega, Delta, and Volume are calculated as aggregated from the options for each point in time. The Underlying Return is calculated for the respective underlying (ETH). The Off-Chain data is obtained from Deribit. The fees are calculated as the Bid-Ask-Spread. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

5.9 Net Buying Pressure

In this section, we follow Bollen and Whaley (2004) to examine the relation between net buying pressure and the shape of the IV of options on cryptocurrencies. The regression specification is the following,

$$\begin{aligned}\text{Delta IV}_t = \beta_0 &+ \beta_1 \text{Underlying Return}_t + \beta_2 \text{Underlying Volume}_t \\ &+ \beta_3 \text{Net Buying Pressure}_t + \beta_4 \text{Delta IV}_{t-1} + \epsilon. \end{aligned} \tag{5.5}$$

We perform this regression for three different moneyness quantiles (deep OTM, OTM, and ATM), and for call and put options separately. The Delta IV denotes the changes in the average of the traded IV across all traded options in the same quantile, type, and for the respective day. The net buying pressure (NBP) for a given type and moneyness group is defined as

$$\text{NBP}_t = \frac{(\text{Buy Volume}_t - \text{Sell Volume}_t) \times \text{Abs Delta}_t}{\text{Total Volume}_t}. \tag{5.6}$$

We standardize all variables to have unit root and zero mean. Table 5.7 and Table 5.8 present the results for ETH traded On-Chain and Off-Chain: On-Chain, the NPB positively affects OTM call options (column 1 and 2), atm options (at a 10% significance), and deep OTM put options (column 4). Off-Chain the NPB only displays significance for deep OTM call (column 1) and deep OTM put options (column 4).[14] The findings suggest that changes in IV are directly linked to net buying pressure from public order flow.

[14]The results differ when analyzing Bitcoin as an underlying (Table C.1 and Table C.2): The NBP increases the IV, OnChain only for deep OTM calls (column 1) and OTM puts (column 5). In contrast, Off-Chain, the NPB loads positively on changes in IV for ATM calls (column 3) and puts for all moneyness levels (columns 4,5,6).

Variable	$Call_{q1}$ Delta IV	$Call_{q2}$ Delta IV	$Call_{q3}$ Delta IV	Put_{q1} Delta IV	Put_{q2} Delta IV	Put_{q3} Delta IV
Intercept	-0.00000	0.00000	0.00000	-0.00000	-0.00000	-0.00000
	(1.00000)	(1.00000)	(1.00000)	(1.00000)	(1.00000)	(1.00000)
Underlying Return	0.20923	0.10629	-0.01384	-0.07028	-0.20387	-0.10626
	(0.00062)	(0.12235)	(0.85556)	(0.15953)	(0.00057)	(0.16138)
Underlying Volume	0.14831	0.20361	0.20261	-0.04285	0.07001	0.13182
	(0.03731)	(0.00106)	(0.00155)	(0.49937)	(0.19978)	(0.02651)
Net Buying Pressure	0.20254	0.17446	0.11149	0.21193	0.07766	0.02543
	(0.00103)	(0.00896)	(0.10900)	(0.00016)	(0.28345)	(0.73659)
Delta IV L1	-0.21543	-0.14118	-0.19513	-0.16986	-0.20931	-0.23899
	(0.00246)	(0.15091)	(0.03951)	(0.00646)	(0.00104)	(0.00571)
Rsquared	0.15	0.10	0.09	0.08	0.10	0.08
Rsquared Adj	0.14	0.08	0.07	0.06	0.08	0.06
Nobs	218	231	217	219	229	182

Table 5.7: Regression Results – Net Buying Pressure – Trades On-Chain – ETH. The table reports the results, i.e., the coefficient and the p-values in brackets from the regression as specified in (5.5). The columns progress from the 1st quantile to the 3rd quantile, first representing call options and then put options. The initial quantile represents deep OTM options, while the final quantile represents at-the-money (ATM) options. The trades On-Chain data is obtained from Lyra V2 deployed on Arbitrum. All variables are sampled on a daily frequency. The underlying asset is Ethereum (ETH).

Variable	$Call_{q1}$ Delta IV	$Call_{q2}$ Delta IV	$Call_{q3}$ Delta IV	Put_{q1} Delta IV	Put_{q2} Delta IV	Put_{q3} Delta IV
Intercept	0.00000	0.00000	-0.00000	0.00000	-0.00000	-0.00000
	(1.00000)	(1.00000)	(1.00000)	(1.00000)	(1.00000)	(1.00000)
Underlying Return	0.18794	0.14044	0.10529	-0.15940	-0.14408	-0.06815
	(0.01728)	(0.05408)	(0.16253)	(0.01762)	(0.02295)	(0.31587)
Underlying Volume	0.18251	0.23946	0.27212	0.13846	0.22159	0.27903
	(0.01279)	(0.00028)	(0.00003)	(0.08290)	(0.00155)	(0.00003)
Net Buying Pressure	0.11686	0.07664	0.02076	0.10604	0.07079	0.05494
	(0.01430)	(0.21876)	(0.65818)	(0.02835)	(0.26291)	(0.23911)
Delta IV L1	-0.03295	-0.01458	-0.03800	-0.11189	-0.07044	-0.03010
	(0.56779)	(0.77410)	(0.48544)	(0.06088)	(0.19280)	(0.61805)
Rsquared	0.10	0.10	0.09	0.06	0.07	0.08
Rsquared Adj	0.09	0.09	0.08	0.05	0.06	0.07
Nobs	280	314	314	297	314	314

Table 5.8: Regression Results – Net Buying Pressure – Trades Off-Chain – ETH. The table reports the results, i.e., the coefficient and the p-values in brackets from the regression as specified in (5.5). The columns progress from the 1st quantile to the 3rd quantile, first representing call options and then put options. The initial quantile represents deep OTM options, while the final quantile represents at-the-money (ATM) options. The Off-Chain data is from Deribit. All variables are sampled on a daily frequency. The underlying asset is Ethereum (ETH).

6 Robustness

In the following, we carry out a series of additional tests that confirm the robustness of our main findings for various alternative exchanges.

6.1 Lyra V2 on Optimism

The results for Lyra V2 on Optimism (starting in May 2023) are presented in Appendix D. As visible from Table D.1 and Table D.2, for trades, the unconditional On-Chain and Off-Chain IVs are comparable while for quotes the On-Chain IV exceeds the Off-Chain IV. Figure D.7 displays the gap between On-Chain and Off-Chain IV across maturity and confirms the results as reported in the main part of the paper. The regression analysis is repeated and displayed in Table D.3 – Table D.6: The differences in IV are larger for call options with increasing maturity and close to ATM. Figures D.3 and D.4 compare Optimism trading fees. BTC On-Chain trades are cheaper (20.49 USD vs. 23.58 USD Off-Chain), whereas for ETH, it's the opposite (13.94 USD On-Chain vs. 10.05 USD Off-Chain). Per unit, BTC incurs 41.96 USD On-Chain and 49.51 USD Off-Chain, while ETH sees 1.99 USD On-Chain and 0.77 USD Off-Chain.

6.2 Aevo

Internet Appendix I reports the results comparing the DEX Aevo to Deribit. Due to data availability, for Aevo, only trades are sourced. The data ranges from July to November 2023. Figure I.4 confirms the findings for Lyra, the On-Chain IV is larger than the Off-Chain IV.

6.3 Lyra V1

Internet Appendix II presents the results for Lyra V1, which was only deployed on Optimism, until May 2023. The results confirm the findings in the main paper, displaying even larger gaps in IV than as for Lyra V2 (see Figure II.9, and Figure II.10). Figure II.5 and Figure II.6 illustrate the trading fees on the Optimism network which are cheaper Off-Chain as compared to On-Chain (20.32 USD, compared to 18.01 USD for BTC, and 13.05 USD as compared to 7.37 USD for ETH).

6.4 Lyra V2 and Aevo

A comparison of the IVs across two DEXs, Lyra V2 on Arbitrum, and Aevo, is presented in Internet Appendix III. As before, the IVs display a strong comovement across strikes and maturity (Figure III.12).

6.5 Okex and Lyra

A comparison of the IVs generated by Lyra V2 on Abitrum and Okex, a major decentralized exchange (DEX), is outlined in Internet Appendix IV. The examination affirms the existence of a positive difference between On-Chain and Off-Chain IVs.

6.6 Bitcom and Lyra

A contrast between the IVs obtained from Lyra V2 on Abitrum and Bitcom, a major decentralized exchange (DEX), is outlined in Internet Appendix V. The comparison affirms the presence of a positive disparity between On-Chain and Off-Chain IVs.

7 Conclusion

As the market for cryptocurrencies matures, on-chain options are poised to play a crucial role in shaping its future. By embracing the advantages of blockchain technology, these options provide a decentralized and efficient way for individuals and institutions to engage in options trading.

Our primary analysis centers on the options AMM, exemplified by Lyra, which dynamically adjusts option prices (IV) based on demand for different strikes and maturities. This enables the AMM to replicate well-known volatility surface characteristics like the smile and smirk. Utilizing the adjusted IV, the AMM calculates option prices and associated trading fees. The fees, stemming from the pool's risk management, including delta and vega exposure hedging, are distributed to the protocol, pools, and ultimately, liquidity providers (LPs).

A key focus of our analysis lies on the IV of options, a crucial factor influencing option prices and reflecting market expectations for future price volatility. Examining a broad range of OTM options for BTC and ETH with varying maturities and strikes, we compare On-Chain and Off-Chain IVs. Notably, our findings show that On-Chain options exhibit, on average, higher IVs than their Off-Chain counterparts. This difference increases with option maturity and proximity to being at the money (ATM), leading to the identification of an "On-Chain risk premium." To capture the premium we sell (high IV) On-Chain options and buy (low IV) Off-Chain options. Despite its strong performance, transaction costs can reduce profitability, as per the "limits of arbitrage" literature.

In our next analysis, we compare On-Chain and Off-Chain IVs during the most volatile five days for the assets. We find a notable IV surge during significant price drops, particularly pronounced in On-Chain options. To analyze the effect of the On-Chain fee mechanism on the IV, we exploit a VAR model that provides evidence that On-Chain fees increase the subsequent IV. In addition, the VAR model reveals that the trading volume affects traded IVs differently On-Chain and Off-Chain. On-Chain, a surge in volume consistently raises IV, while Off-Chain, the effect is weaker and mainly noticeable for puts. Our subsequent analysis indicates that net buying pressure effectively explains changes in On-Chain IVs across all call option moneyness levels and deep OTM put options. However, for Off-Chain options, it's only significant for ATM call options and deep OTM put options.

Conclusively, the realm of decentralized options trading unveils a compelling pathway for continued investigation, providing decentralized and inventive solutions that hold the capacity to redefine the trajectory of derivatives markets for cryptocurrencies.

References

Carol Alexander, Jun Deng, Jianfen Feng, and Huning Wan. Net buying pressure and the information in bitcoin option trades. *Journal of Financial Markets*, 63:100764, 2023. ISSN 1386-4181. doi: https://doi.org/10.1016/j.finmar.2022.100764. URL https://www.sciencedirect.com/science/article/pii/S1386418122000544.

Matteo Aquilina, Jon Frost, and Andreas Schrimpf. Decentralised finance (defi): a functional approach. *SSRN Manuscript*, 2023. URL https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4325095.

Andrea Barbon and Angelo Ranaldo. On the quality of cryptocurrency markets: Centralized versus decentralized exchanges. *arXiv Manuscript*, 2021. URL https://arxiv.org/abs/2112.07386.

Fischer Black and Myron Scholes. The pricing of options and corporate liabilities. *Journal of Political Economy*, 81(3):637–654, 1973. ISSN 00223808, 1537534X. URL http://www.jstor.org/stable/1831029.

Nicolas P. B. Bollen and Robert E. Whaley. Does Net Buying Pressure Affect the Shape of Implied Volatility Functions? *The Journal of Finance*, 59:711–753, 2004.

Phelim P Boyle and Ton Vorst. Option Replication in Discrete Time with Transaction Costs. *Journal of Finance*, 1992.

Melanie Cao and Batur Celik. Valuation of bitcoin options. *Journal of Futures Markets*, 41(7): 1007–1026, 2021. doi: https://doi.org/10.1002/fut.22214. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/fut.22214.

Agostino Capponi and Ruizhe Jia. Liquidity provision on blockchain-based decentralized exchanges. *SSRN Manuscript*, 2024. URL https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3805095.

Kalok Chan, Y Peter Chung, and Wai-Ming Fong. The Informational Role of Stock and Option Volume. *The Review of Financial Studies*, 15(4), 2002.

Young-Hye Cho and Robert Engle. Modeling the Impacts of Market Activity on Bid-Ask Spreads in the Option Market. Technical report, 1999.

Lin William Cong, Ye Li, and Neng Wang. Tokenomics: Dynamic adoption and valuation. *The Review of Financial Studies*, 34(3):1105–1155, 2021. ISSN 0893-9454. doi: https://doi.org/10.1093/rfs/hhaa089.

Lin William Cong, Zhiheng He, and Ke Tang. Staking, token pricing, and crypto carry. *SSRN Manuscript*, 2022. URL https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4059460.

Sean Dawson, Nick Forster, Dominic Romanowski, and Michael Spain. Impermanent Loss in Extreme Market Conditions. 07 2021a.

Sean Dawson, Nick Forster, Dominic Romanowski, and Michael Spain. Lyra. 05 2021b.

Patrick Dennis and Stewart Mayhew. Risk-Neutral Skewness: Evidence from Stock Options. *The Journal of Financial and Quantitative Analysis*, 37(3), 2002.

Gregory W. Eaton, T. Clifton Green, Brian Roseman, and Yanbin Wu. Retail option traders and the implied volatility surface. *SSRN Manuscript*, 2023. URL https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4104788.

Robert Engle and Breno Neri. The Impact of Hedging Costs on the Bid and Ask Spread in the Options Market. 2010.

Thomas W. Epps and Mary Lee Epps. The stochastic dependence of security price changes and transaction volumes: Implications for the mixture-of-distributions hypothesis. *Econometrica*, 44(2):305–321, 1976. ISSN 00129682, 14680262. URL http://www.jstor.org/stable/1912726.

Itay Goldstein, Deeksha Gupta, and Ruslan Sverchkov. Utility tokens as a commitment to competition. *SSRN Manuscript*, 2023. URL https://ssrn.com/abstract=3484627.

Denis Gromb and Dimitri Vayanos. Limits of arbitrage. *Annual Review of Financial Economics*, 2(1):251–275, 2010. URL https://EconPapers.repec.org/RePEc:anr:refeco:v:2:y:2010:p:251-275.

Sebastian Gryglewicz, Simon Mayer, and Erwan Morellec. Optimal financing with tokens. *Journal of Financial Economics*, 142(3):1038–1067, 2021. ISSN 0304-405X. doi: https://doi.org/10.1016/j.jfineco.2021.05.004.

Nicolae Gârleanu, Lasse Heje Pedersen, and Allen M. Poteshman. Demand-Based Option Pricing. *Review of Financial Studies*, 22(10):4259–4299, 2009.

Campbell R. Harvey, Ashwin Ramachandran, and Joey Santoro. *DeFi and the Future of Finance*. John Wiley & Sons, Inc., Hoboken, New Jersey, U.S.A., 1 edition, 2021. ISBN 9781119836018.

Wolfgang Karl Härdle, Campbell R Harvey, and Raphael C G Reule. Understanding cryptocurrencies. *Journal of Financial Econometrics*, 18(2):181–208, 02 2020. ISSN 1479-8409. doi: https://doi.org/10.1093/jjfinec/nbz033.

Mel Jameson and William Wilhelm. Market Making in the Options Markets and the Costs of Discrete Hedge Rebalancing. *Journal of Finance*, 1992.

Bhaskar Krishnamachari, Qi Feng, and Eugenio Grippo. Dynamic curves for decentralized autonomous cryptocurrency exchanges. *arXiv Manuscript*, 2021. URL `https://arxiv.org/abs/2101.02778`.

Alfred Lehar and Christine Parlour. Decentralized exchange: The uniswap automated market maker. *SSRN Manuscript*, 2023. URL `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3905316`.

Thomas Li, Siddharth Nail, Andrew Papanicolaou, and Lorenzo Schoenleber. Yield farming for liquidity provision. *SSRN Manuscript*, 2023. URL `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4422213`.

Igor Makarov and Antoinette Schoar. Cryptocurrencies and decentralized finance. *SSRN Manuscript*, 2022. URL `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4104550`.

Jason Milionis, Ciamac C. Moallemi, Tim Roughgarden, and Anthony Lee Zhang. Automated market making and loss-versus-rebalancing. *arXiv Manuscript*, 2023. URL `https://arxiv.org/abs/2208.06046`.

Dmitriy Muravyev. Order Flow and Expected Option Returns. 2015.

Jun Pan. The jump-risk premia implicit in options: evidence from an integrated time-series study. *Journal of Financial Economics*, 63(1):3–50, 2002.

Andreas Park. The conceptual flaws of decentralized automated market making. *Management Science*, 69(11):6731–6751, 2023. doi: 10.1287/mnsc.2021.02802. URL `https://doi.org/10.1287/mnsc.2021.02802`.

Julien Prat, Vincent Danos, and Stefania Marcassa. Fundamental pricing of utility tokens. *THEMA Working Paper n2019-11. Université de Cergy-Pontoise*, 2019. URL https://hal.science/hal-03096267.

Andrei Shleifer and Robert W. Vishny. The limits of arbitrage. *The Journal of Finance*, 52(1):35–55, 1997. doi: https://doi.org/10.1111/j.1540-6261.1997.tb03807.x. URL https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1540-6261.1997.tb03807.x.

Michael Sockin and Wei Xiong. A model of cryptocurrencies. *Management Science, Forthcoming*, 2023. ISSN 0025-1909. doi: https://doi.org/10.1287/mnsc.2023.4756.

George E. Tauchen and Mark Pitts. The price variability-volume relationship on speculative markets. *Econometrica*, 51(2):485–505, 1983. ISSN 00129682, 14680262. URL http://www.jstor.org/stable/1912002.

Anand M Vijh. Liquidity of the CBOE Equity Options. *Journal of Finance*, 1990.

Yuhang Xing, Xiaoyan Zhang, and Rui Zhao. What Does the Individual Option Volatility Smirk Tell Us About Future Equity Returns? *Journal of Financial and Quantitative Analysis*, 45 (3):641–662, 2010.

Jiahua Xu, Krzysztof Paruch, Simon Cousaert, and Yebo Feng. Sok: Decentralized exchanges (DEX) with automated market maker (AMM) protocols. *ACM Computing Surveys*, 55(11): 1–50, 2023. ISSN 0360-0300. doi: https://dl.acm.org/doi/10.1145/3570639.

Shu Yan. Jump risk, stock returns, and slope of implied volatility smile. *Journal of Financial Economics*, 99(1):216–233, 2011.

Appendix A Additional Tables

DEX	total Notional Volume	total Premium Volume	TVL
aevo	219973121.66	3023767.34	6831118.11
hegic	106237826.57	3031224.66	7631050.21
lyra	251923855.47	8936025.41	11962292.63
rysk-finance	–	–	1225141.01
thales	8374235.50	5042071.26	1822593.86
typus	621150.09	6592.67	229964.89
premia v2	93141777.42	2800678.67	1680734.98
premia v3	1312098.21	33278.12	1568684.98

Table A.1: Summary Statistics TVL – Options DEXs. The table displays the summary statistics (total Notional Volume, total Premium Volume, and Total Value locked (TVL)) of different DEXs for options trading. The data is obtained from DeFILlama.com and represents a snapshot of the 26th of November 2023.

Appendix B Lyra – Details and Nuances

B.1 Geometric Time-Weighted Average (GWAV)

The geometric time-weighted average volatility (GWAV) is a time-weighted average of either the baseline volatility for an expiry (b) or the skew ratio of a specific listing R. Let (σ_i, t_i) denote the i^{th} entry in a given time series of observations recorded on the smart contracts, with t_i being the time σ_i was recorded. Each observation is the instantaneous value of either a baseline volatility or a particular listing skew at a given moment in time. The geometric time-weighted average volatility over the time interval $t \in [t_a, t_b]$ is defined as

$$GWAV\left(t_a, t_b\right) = \left(\prod_{i=a}^{b-1} \sigma_i^{t_{i+1}-t_i}\right)^{\frac{1}{t_b-t_a}}$$

where the index i iterates over all volatilities σ_i that occur in the interval $T = t_b - t_a$. We say that T is the length of the GWAV (as of the 24th of October 2023 this is set to six hours).

B.2 Lyra's V2 Liquidation Engine

The decentralized liquidation mechanism in Lyra's version 2 is integral to the platform's risk management strategy and aims to enhance user experience and mitigate systemic risk.

Key Features:

- *Transparent Liquidation Process:* On-chain liquidations are transparent; any user can flag a subaccount for liquidation if it falls below margin requirements.

- *Partial Liquidations:* A significant innovation is the introduction of partial liquidations, which allows traders to maintain a portion of their exposure. If a subaccount's value V falls below a threshold θ, a fraction ϕ of the assets is liquidated.

- *Buffer Margin:* Implemented as a safety measure, the buffer margin exceeds the mark-to-market price of the portfolio, providing a cushion against market volatility. During the solvent auction, users are liquidated so that BM$= 0$.

$$\text{BM} = mtm + \text{buffer} + 0.15 \times \text{buffer}.$$

- *Auction Process:* The two-phase auction process involves a solvent auction, where liquidators acquire a discounted percentage of the subaccount, and if needed, an insolvent auction to compensate liquidators for assuming the portfolio.

Liquidation Dynamics:

- *Solvent Portfolios:* After the post-liquidation fee, portfolios enter a solvent auction, where liquidators can acquire a discounted portion unless the Buffer Margin is above 0. In case of insolvency, an insolvent auction is triggered, bypassing the solvent auction.

- *Insolvent Portfolios:* Auction offers start at the portfolio's mark-to-market value, increasing over an hour to the maintenance margin. Negative offers indicate compensation from the Security Module (SM) to liquidators. They must meet cash requirements to cover the maintenance margin minus the liquidation proceeds.

- *Auction Closure:* An auction concludes when the portfolio is fully liquidated or its value exceeds the maintenance margin. Liquidators must maintain a minimum cash balance.

B.3 Variance Fee

In addition to the fee components in equation (3.6), recently a variance fee which depends on the volatility of the underlying asset has been introduced.[15] During periods of elevated volatility, liquidity providers face increased risk, particularly concerning impermanent loss. The variance fee is intended to assist in managing this risk. For a specific trade i at time t the variance fee, $f_{var,t,i}$, is defined as,

$$f_{var,t,i} = c_0 \left(v_0 + v_1 vega_{t,i} \right) \left(s_0 + s_1 \left| SR_0 - SR_{t,i} \right| \right) \left(b_0 + b_1 \left| \sigma_{GWAV,t,i} - \sigma_{t,i} \right| \right), \tag{B.1}$$

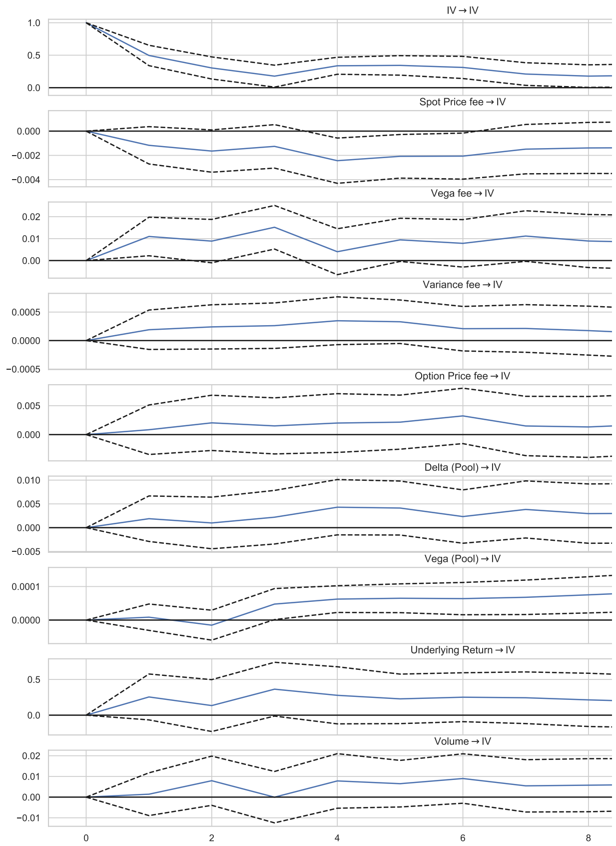
where, $c_0, v_0, v_1, s_0, s_1, b_0, b_1, SR_0$ are coefficients. The variables $vega_{t,i}$ and $SR_{t,i}$ are defined as in Section 3.2. The variables $\sigma_{t,i}$ and $\sigma_{GWAV,t,i}$ are the spot and GWAV of the ATM IV, respectively. Thus, the variance fee increases when the vega of the option increases (high volatility risk). Additionally, the variance fee increases also when the skew of the specific option trade increases, for example, the IV smile is more convex. Finally, the variance fee also increases when the IV for the ATM option increases.

[15] https://leaps.lyra.finance/leaps/leap-18/

Appendix C Lyra V2 on Arbitrum

C.1 VAR Model – AMM Mechanism - BTC

(a) Long Call – BTC



(b) Long Put – BTC

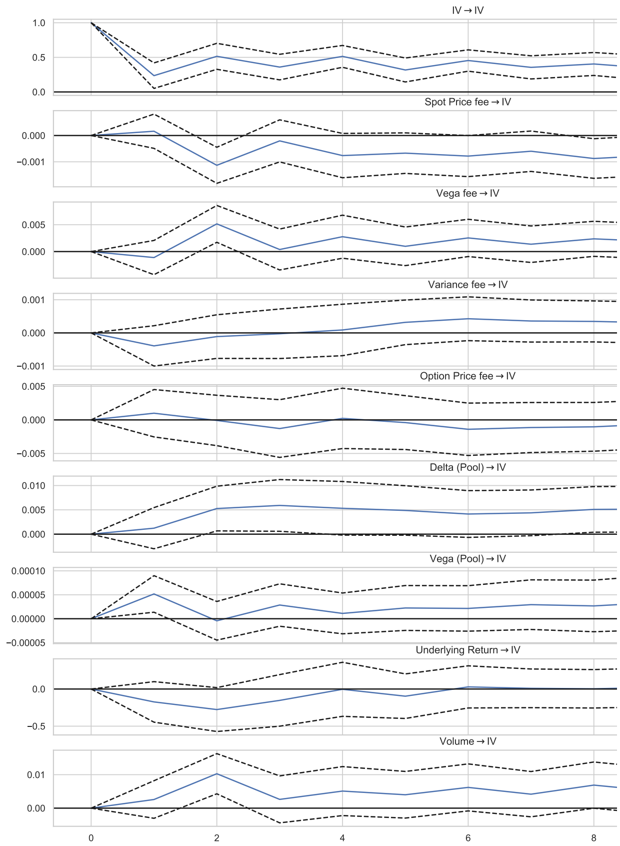


Figure C.1: On-Chain – BTC – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the BTC IV for long call options (Panel (a)) and long put (Panel (b)). IV denotes the traded IV. The vega and delta of the pool are calculated following Section 3.2.2. Volume denotes the aggregate of traded volume for each point in time. The Underlying Return is calculated for the respective underlying (BTC). The On-Chain data is obtained from Lyra deployed on Arbitrum. The components of the fees are mentioned in equation (3.6). Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

(a) Long Call – BTC (b) Long Put – BTC

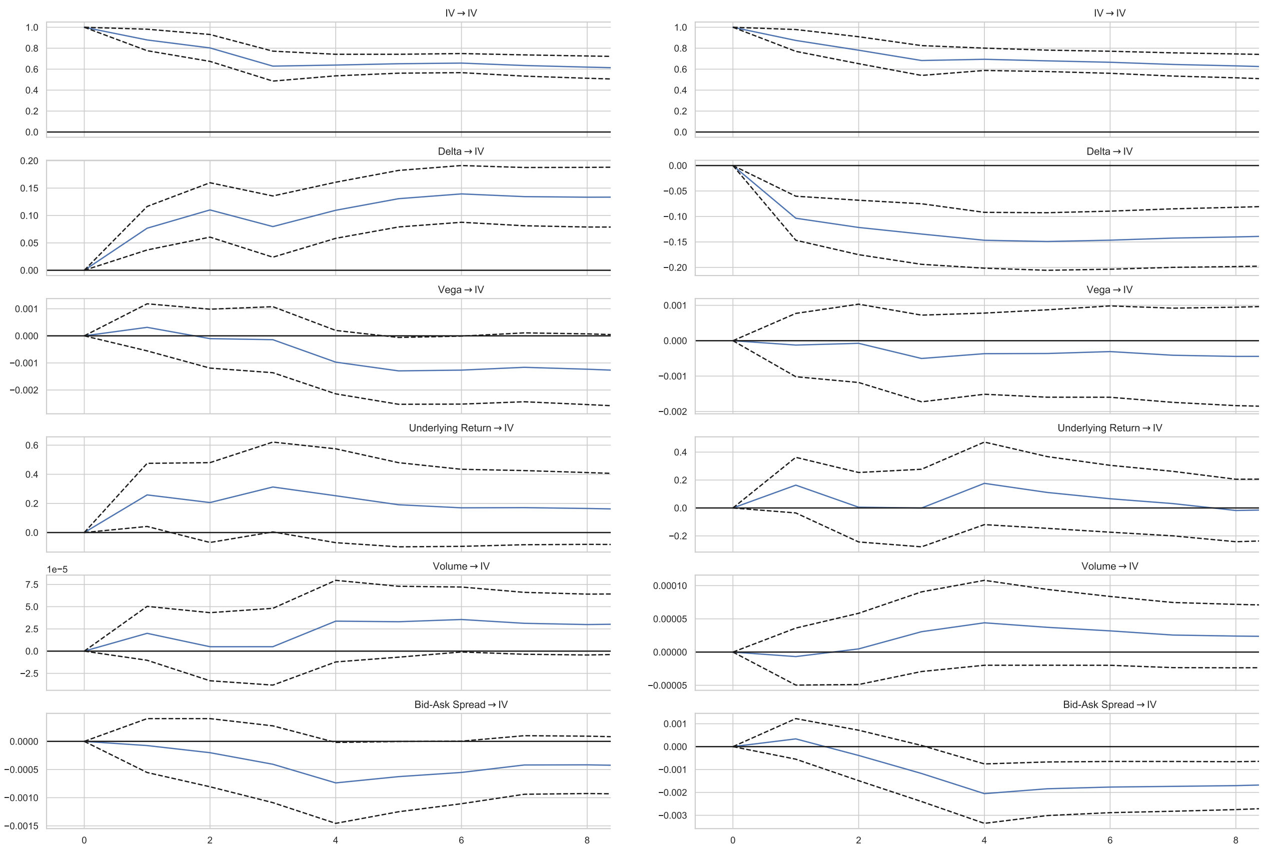


Figure C.2: Off-Chain – BTC – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the BTC IV for long call options (Panel (a)) and long put (Panel (b)). IV denotes the traded IV. The Vega, Delta, and Volume are calculated as aggregated from the options for each point in time. The Underlying Return is calculated for the respective underlying (BTC). The Off-Chain data is obtained from Deribit. The fees are calculated as the Bid-Ask-Spread. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

C.2 Net Buying Pressure - BTC

	Call_{q1}	Call_{q2}	Call_{q3}	Put_{q1}	Put_{q2}	Put_{q3}
Variable	Delta IV	Delta IV	Delta IV	Delta IV	Delta IV	Delta IV
Intercept	0.00000	0.00000	-0.00000	-0.00000	-0.00000	-0.00000
	(1.00000)	(1.00000)	(1.00000)	(1.00000)	(1.00000)	(1.00000)
Underlying Return	0.02540	0.11604	0.01975	0.16189	-0.37412	-0.45730
	(0.83115)	(0.43805)	(0.85259)	(0.28789)	(0.01002)	(0.00027)
Underlying Volume	0.00248	0.45366	0.19439	0.12912	0.16620	-0.15246
	(0.98661)	(0.00151)	(0.25450)	(0.64627)	(0.26827)	(0.24107)
Net Buying Pressure	0.20417	0.16264	-0.02190	-0.17462	0.22776	0.07850
	(0.05357)	(0.29998)	(0.89287)	(0.31901)	(0.08382)	(0.53258)
Delta IV L1	-0.23242	-0.36076	-0.26765	-0.41957	-0.03734	-0.19924
	(0.09536)	(0.09577)	(0.10662)	(0.00542)	(0.82252)	(0.02129)
Rsquared	0.10	0.25	0.10	0.29	0.17	0.34
Rsquared Adj	0.04	0.16	-0.04	0.22	0.09	0.29
Nobs	63	38	31	47	47	62

Table C.1: Regression Results – Net Buying Pressure — Trades On-Chain – BTC. The table reports the results, i.e., the coefficient and the p-values in brackets from the regression as specified in (5.5). The columns progress from the 1st quantile to the 3rd quantile, first representing call options and then put options. The initial quantile represents deep out-of-the-money (OTM) options, while the final quantile represents at-the-money (ATM) options. The trades On-Chain data is obtained from Lyra V2 deployed on Arbitrum. All variables are sampled on a daily frequency. The underlying asset is Bitcoin (BTC).

Variable	Call_{q1} Delta IV	Call_{q2} Delta IV	Call_{q3} Delta IV	Put_{q1} Delta IV	Put_{q2} Delta IV	Put_{q3} Delta IV
Intercept	-0.00000	-0.00000	0.00000	0.00000	-0.00000	0.00000
	(1.00000)	(1.00000)	(1.00000)	(1.00000)	(1.00000)	(1.00000)
Underlying Return	0.22124	0.25282	0.17779	-0.04952	-0.01670	0.08105
	(0.02957)	(0.00023)	(0.01539)	(0.47865)	(0.84077)	(0.32445)
Underlying Volume	0.22451	0.19105	0.22112	0.17285	0.27541	0.27331
	(0.01135)	(0.00306)	(0.00156)	(0.03186)	(0.00051)	(0.00050)
Net Buying Pressure	-0.01586	0.06806	0.17197	0.14984	0.11347	0.16004
	(0.75576)	(0.16561)	(0.00009)	(0.00253)	(0.04139)	(0.00150)
Delta IV L1	0.00901	0.09753	0.08897	-0.03289	0.00706	0.02101
	(0.91609)	(0.08482)	(0.14660)	(0.66095)	(0.91395)	(0.71993)
Rsquared	0.13	0.17	0.17	0.05	0.09	0.12
Rsquared Adj	0.12	0.15	0.16	0.04	0.07	0.11
Nobs	311	314	314	307	314	314

Table C.2: Regression Results – Net Buying Pressure — Trades Off-Chain – BTC. The table reports the results, i.e., the coefficient and the p-values in brackets from the regression as specified in (5.5). The columns progress from the 1st quantile to the 3rd quantile, first representing call options and then put options. The initial quantile represents deep out-of-the-money (OTM) options, while the final quantile represents at-the-money (ATM) options. The Off-Chain data is from Deribit. All variables are sampled on a daily frequency. The underlying asset is Bitcoin (BTC).

Appendix D Lyra V2 on Optimism

D.1 Summary Statistics

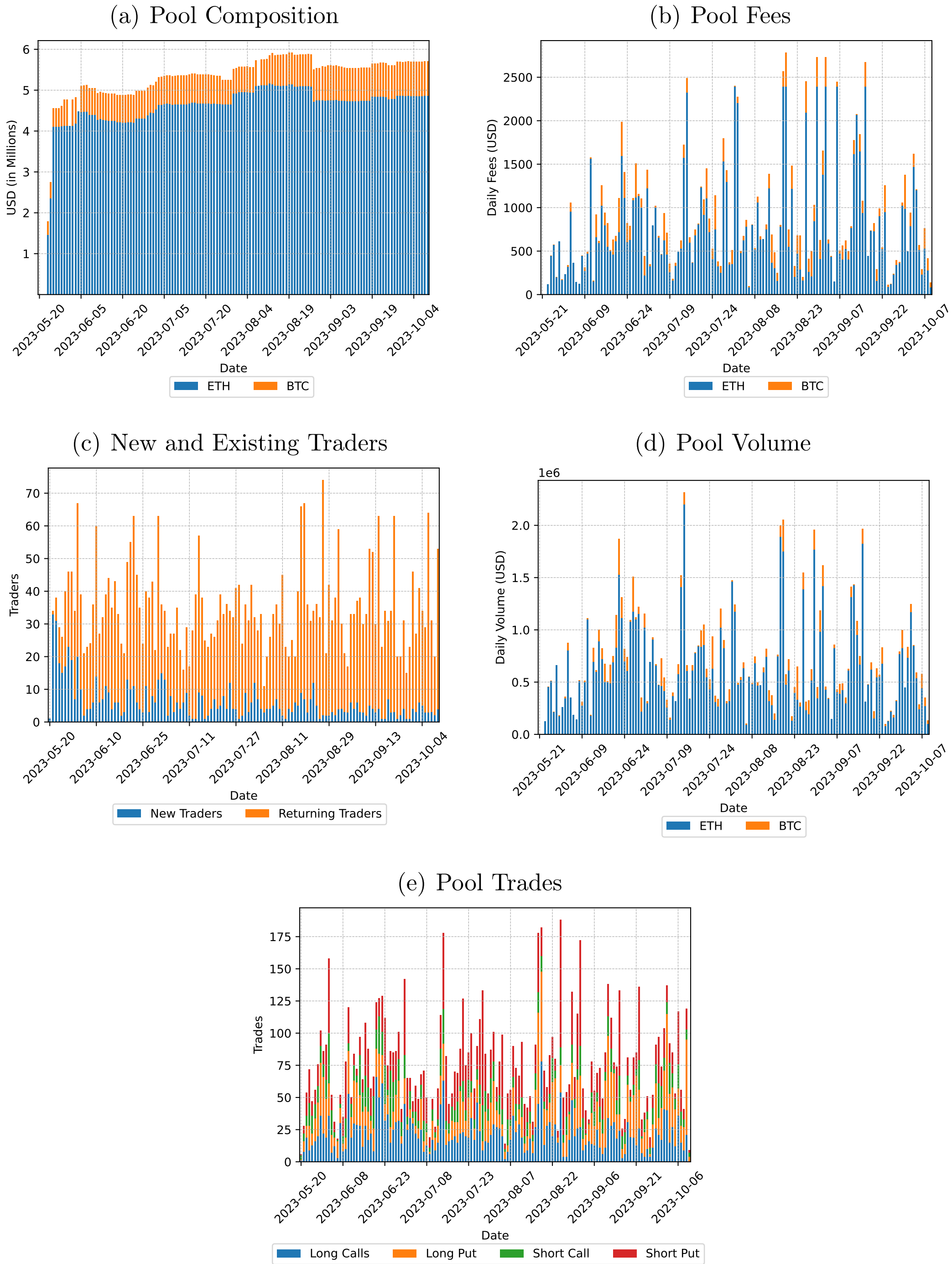


Figure D.1: Lyra Stats - Pool Overviews. The figure shows key quantities for Lyra pools over time: Pool Composition (Panel (a)), the daily occurring Pool Fees (Panel (b)), New and Existing Traders (Panel (c)), daily Pool Volume (Panel (d)), and the Pool Trades (Panel(e)). The options underlying assets are Bitcoin (BTC) and Ethereum (ETH). The data is obtained from Lyra V2 deployed on Optimism. The data is winzorized at the 1% quantile. The sample period ranges from 05-2023 to 11-2023.

(a) Profit and Loss (b) Pool Performance

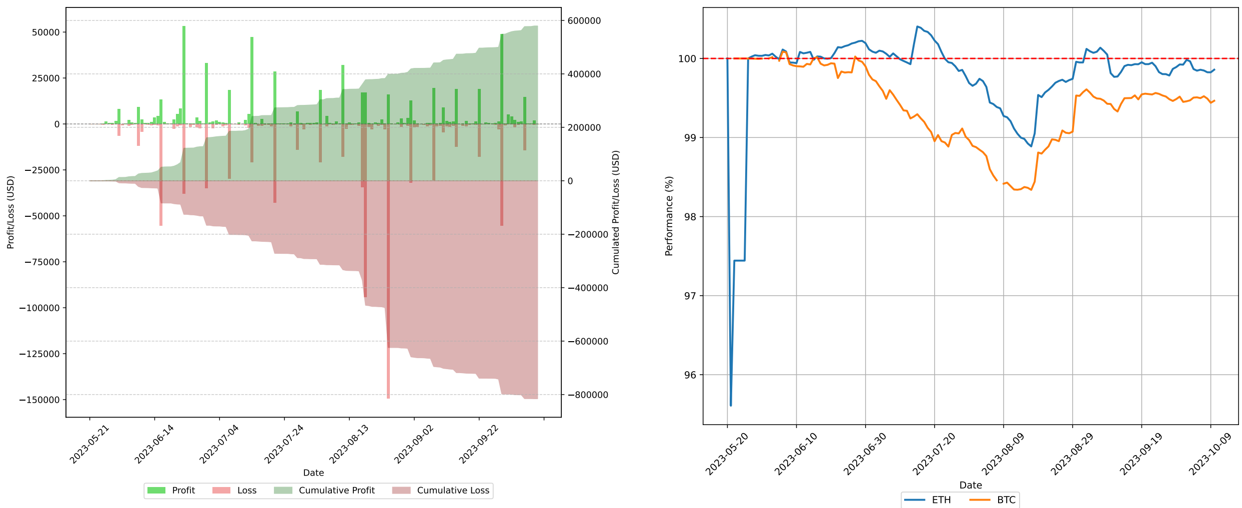
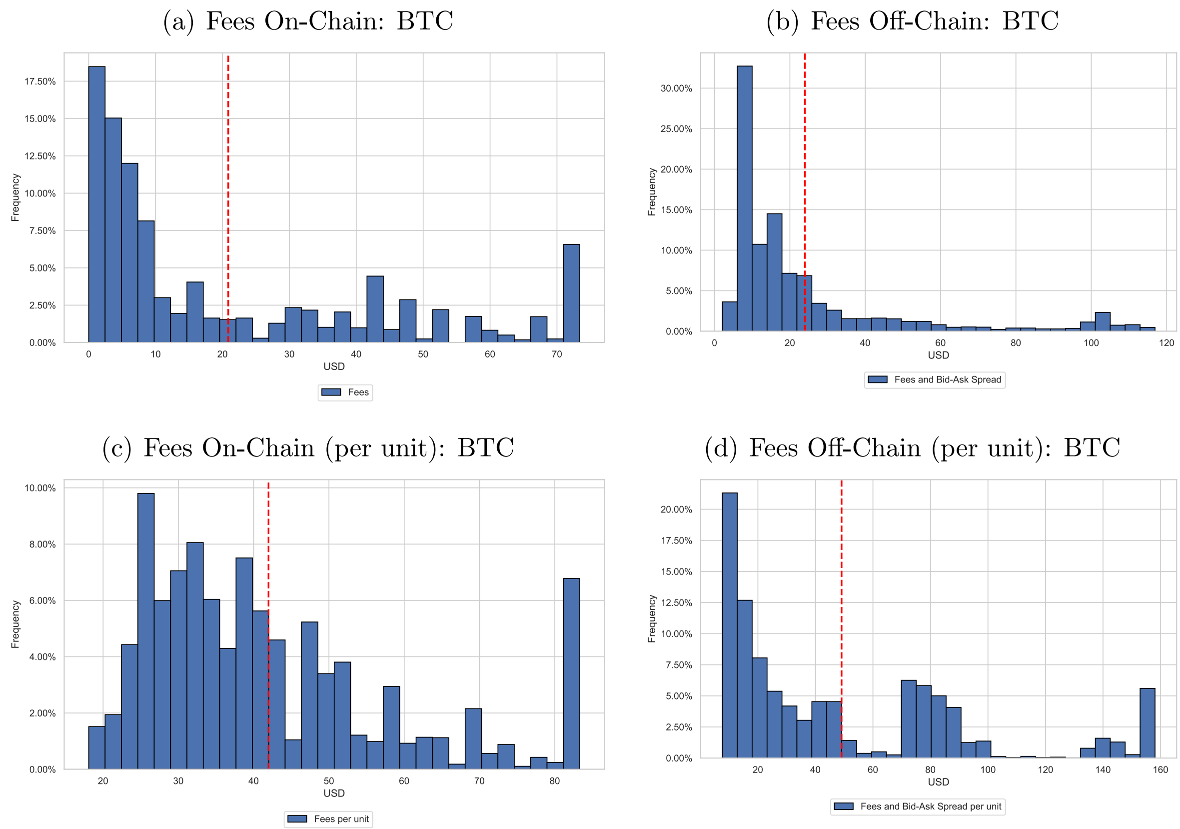


Figure D.2: Lyra Stats - Pool Performance. The figure shows the Profit and Loss (Panel (a)) and the Pool Performance (Panel (b)) over time. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH). The data is obtained from Lyra V2 deployed on Optimism. The sample period ranges from 05-2023 to 11-2023.

D.2 On-Chain and Off-Chain — Transaction Fees



(a) Fees On-Chain: BTC

(b) Fees Off-Chain: BTC

(c) Fees On-Chain (per unit): BTC

(d) Fees Off-Chain (per unit): BTC

Figure D.3: Transaction Fees – On-Chain vs. Off-Chain – BTC. The figure shows the histogram of total trading fees (Panel (a) and Panel (b)), and trading fee per unit (Panel (c) and Panel (d)), On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The fees On-Chain are calculated according to equation (3.6) and Off-Chain as described in Section 3.1. The options underlying asset is Bitcoin (BTC). The dashed red line denotes the unconditional average. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 5% quantile. The sample period ranges from 05-2023 to 11-2023.

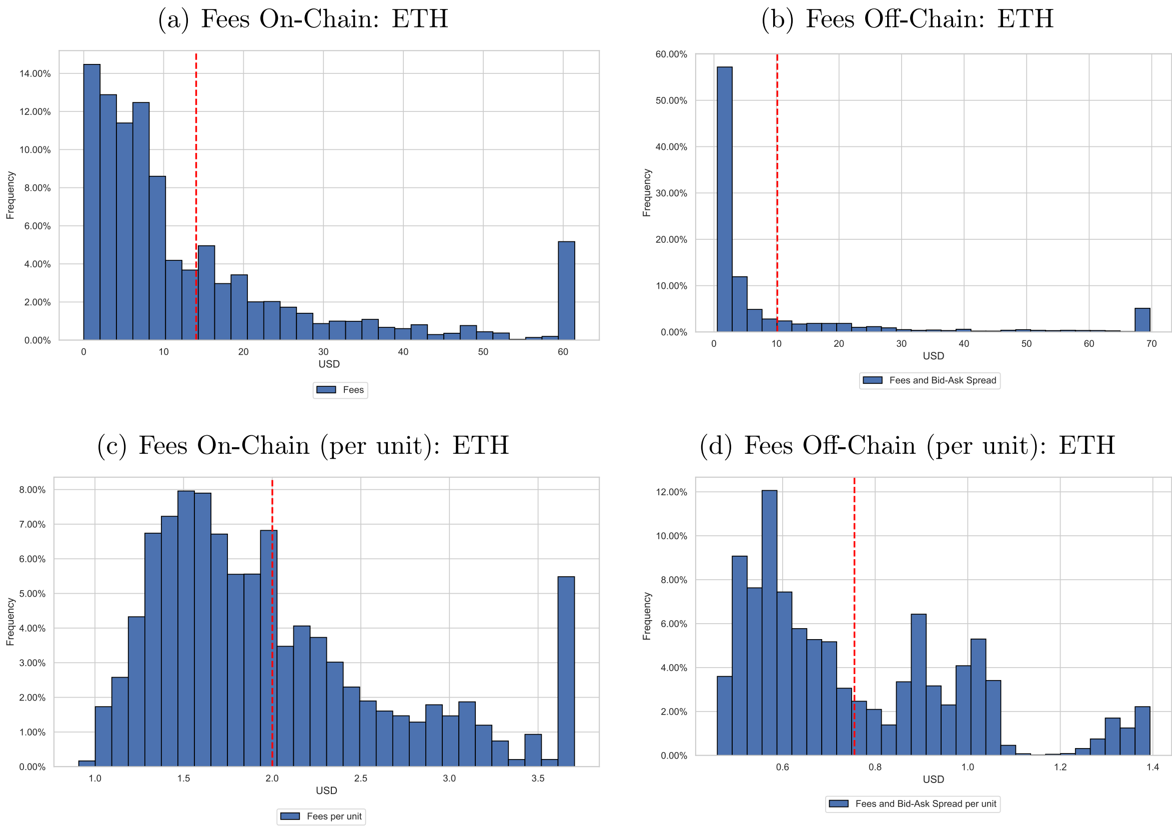


Figure D.4: Transaction Fees – On-Chain vs. Off-Chain – ETH. The figure shows the histogram of total trading fees (Panel (a) and Panel (b))), and trading fee per unit (Panel (c) and Panel (d))), On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra v2 deployed on Optimism, while the Off-Chain data is from Deribit. The fees On-Chain are calculated according to equation (3.6) and Off-Chain as described in Section 3.1. The options underlying asset is Ethereum (ETH). The dashed red line denotes the unconditional average. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 6% quantile. The sample period ranges from 05-2023 to 11-2023.

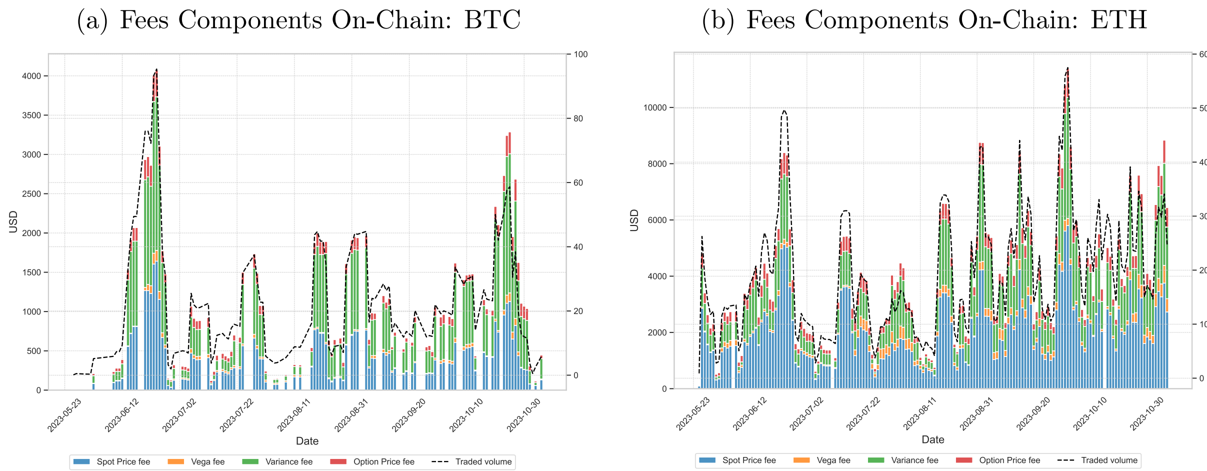


Figure D.5: Fee Components – On-Chain. The figure displays the fee components and volume (dashed line) for Bitcoin (BTC) (Panel (a)) and Ethereum (ETC) (Panel (b)) in USD. The On-Chain data is obtained from Lyra V2 deployed on Optimism. The components of the fees are calculated in equation (3.6). Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 5% quantile. The sample period ranges from 05-2023 to 11-2023.

D.3 On-Chain and Off-Chain — IVs

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	6592	6592	47198	47198
Instruments	154	154	296	296
Min Date	2023-05-26	2023-05-26	2023-05-25	2023-05-25
Max Date	2023-11-05	2023-11-05	2023-11-06	2023-11-06
Min Strike	22000	22000	1350	1350
Max Strike	38000	38000	2300	2300
IV mean	0.42	0.43	0.39	0.39
IV std	0.07	0.10	0.06	0.08
Price mean	456.81	462.40	23.91	22.64
Price std	307.52	304.38	14.02	12.40
Size mean	0.45	2.98	7.42	33.04
Size std	0.42	17.75	10.25	217.40

Table D.1: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 05-2023 to 11-2023.

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	57999	57999	72979	72979
Instruments	343	341	400	397
Min Date	2023-05-19	2023-05-19	2023-05-19	2023-05-19
Max Date	2023-11-02	2023-11-02	2023-11-02	2023-11-02
Min Strike	22000	22000	1300	1300
Max Strike	38000	38000	2300	2300
IV mean	0.42	0.40	0.40	0.39
IV std	0.06	0.07	0.06	0.07
Price mean	365.34	333.55	21.36	19.76
Price std	301.85	271.10	16.48	14.47

Table D.2: Summary Statistics – Quotes. The table displays the summary statistics of the quoted options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. Only OTM options with maturity between 6 and 30 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

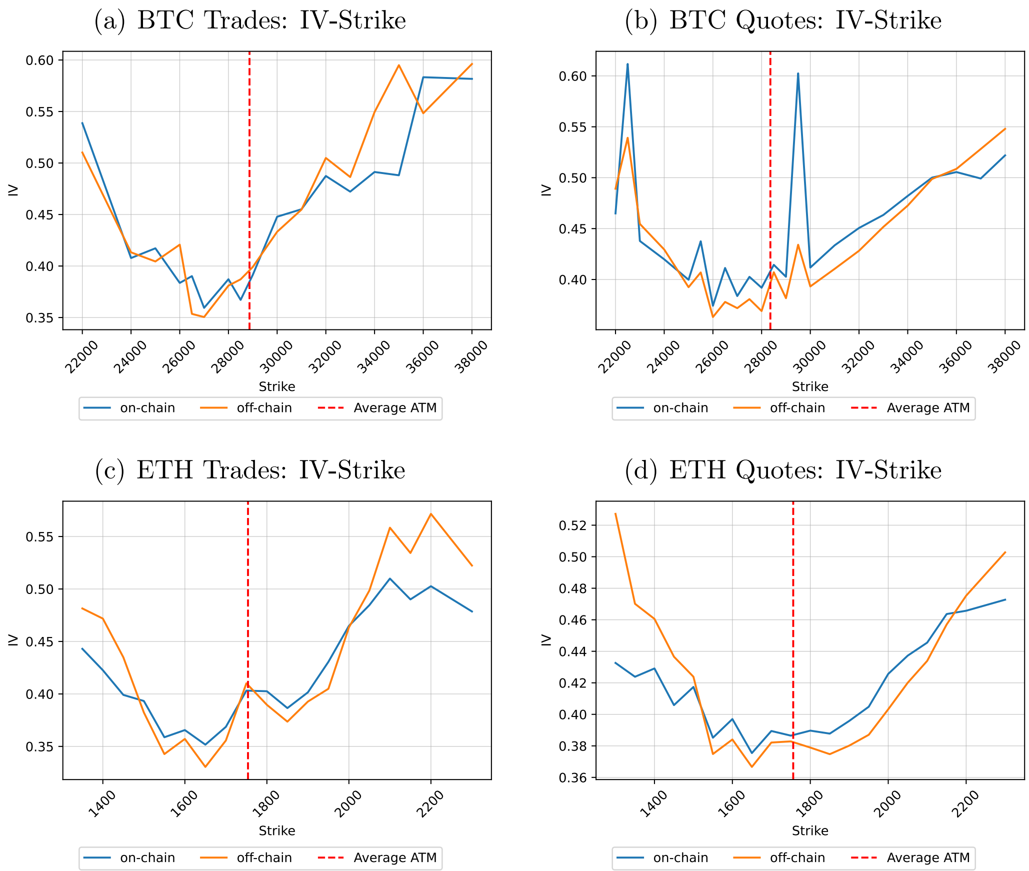
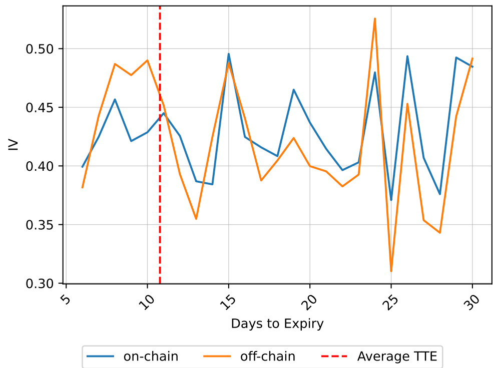
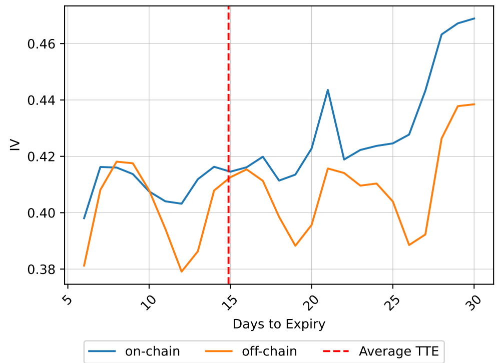


Figure D.6: Implied Volatility and Strike Price. The figure shows the traded and quoted implied volatility from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the strike price in USD. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level while the quotes are given on an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

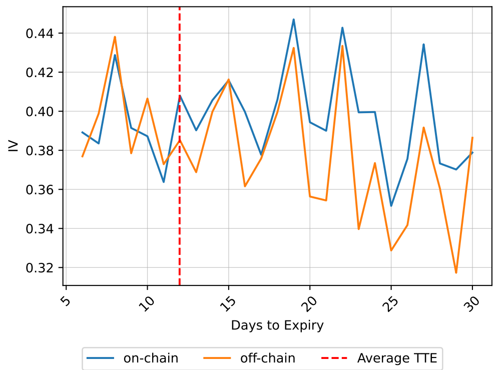
(a) BTC Trades: IV-Maturity



(b) BTC Quotes: IV-Maturity



(c) ETH Trades: IV-Maturity



(d) ETH Quotes: IV-Maturity

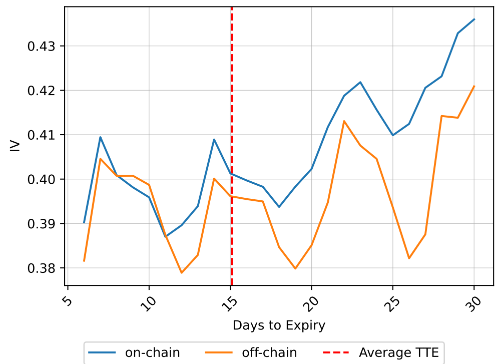


Figure D.7: Implied Volatility and Maturity. The figure shows the traded and quoted implied volatility from call and put options, On-Chain, and Off-Chain, averaged for different maturities. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the maturity in days. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level while the quotes are given on an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

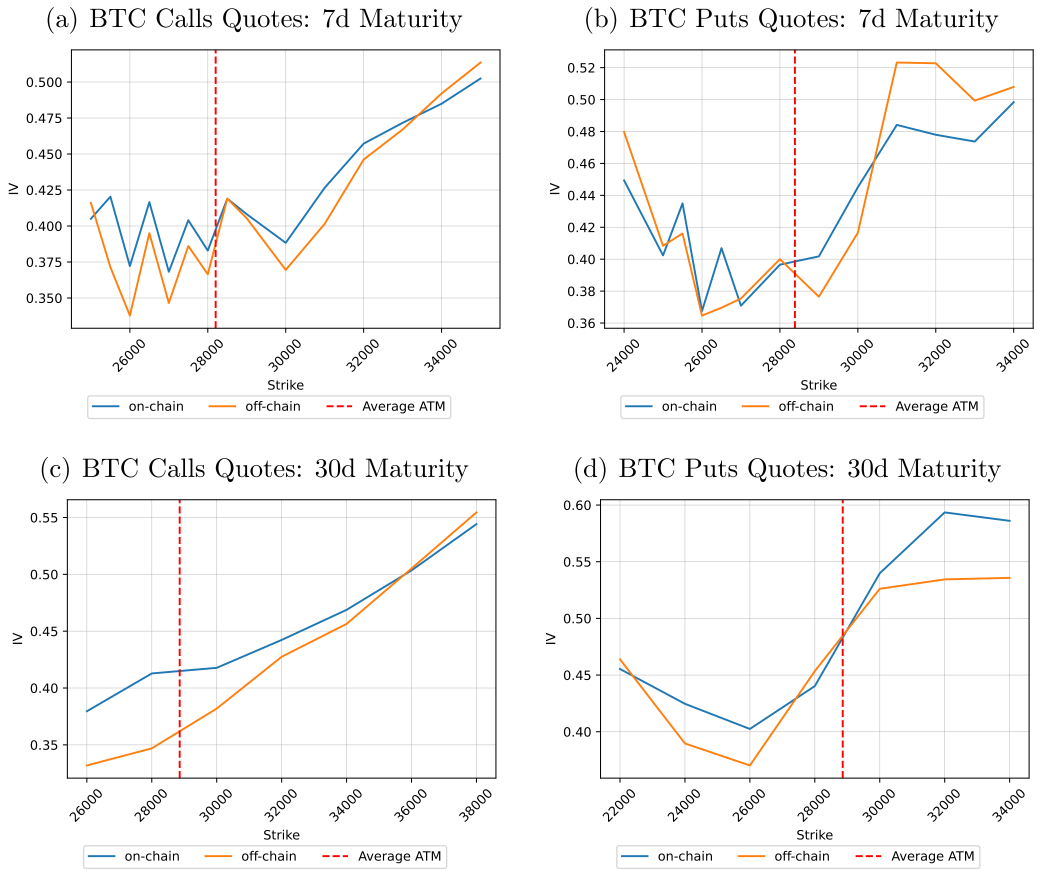


Figure D.8: Implied Volatility for BTC and Strike Price – Call and Puts. The figure shows the quoted implied volatility from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The underlying asset is Bitcoin (BTC). The x-axis represents the strike price in USD. In panels (a) and (b) only OTM options with maturity between 6 and 8 days are selected, while in panels (c) and (d) only OTM options with a maturity of 28-32 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

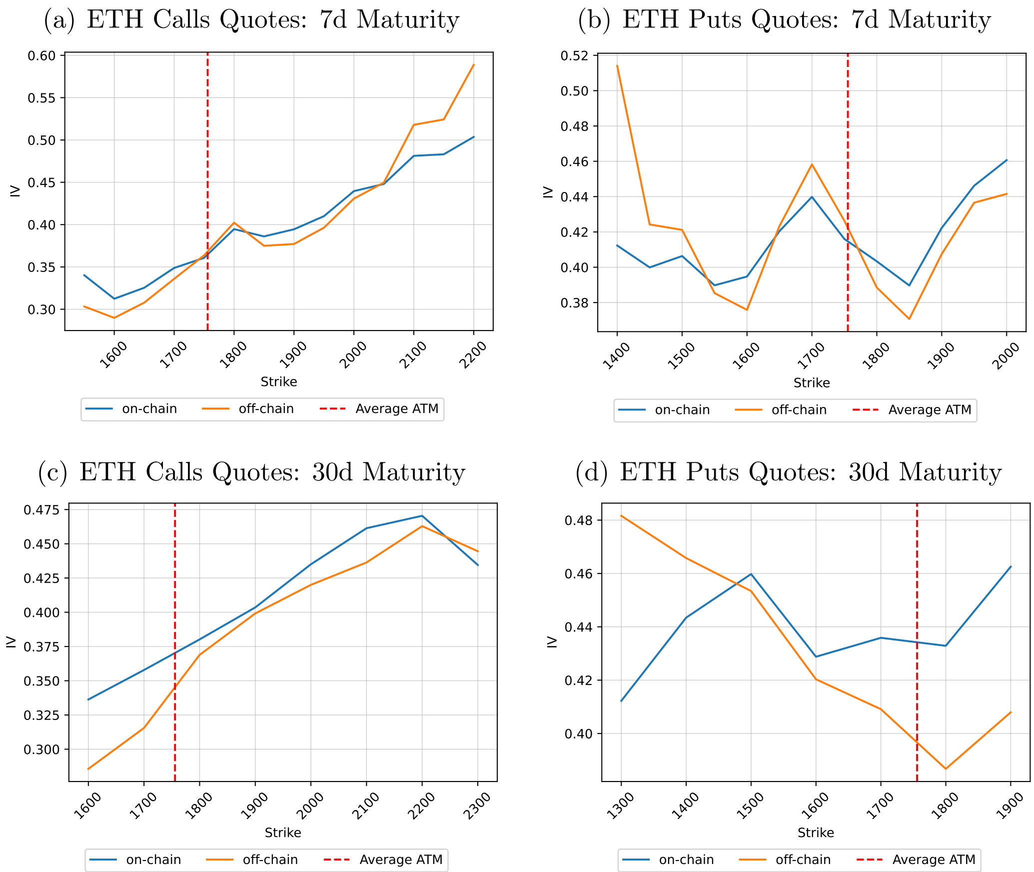


Figure D.9: Implied Volatility for ETH and Strike Price – Call and Puts. The figure shows the quoted implied volatility from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The x-axis represents the strike price in USD. In panels (a) and (b) only OTM options with maturity between 6 and 8 days are selected, while in panels (c) and (d) only OTM options with a maturity of 28-32 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

D.4 Regression Analysis – On-Chain and Off-Chain – IVs

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.49601	-0.41279	-0.54292	-0.03294	-0.05260	-0.04424
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.01996		0.01783			
	(0.00000)		(0.00000)			
Maturity	0.00235	0.00362	0.00243			
	(0.00000)	(0.00000)	(0.00000)			
Mness	0.49622	0.39828	0.54634			
	(0.00000)	(0.00000)	(0.00000)			
Abs. Delta				0.11437	0.10702	0.07435
				(0.00000)	(0.00000)	(0.00000)
Vega				0.00001	0.00003	0.00003
				(0.00000)	(0.00000)	(0.00000)
R-squared	0.2309	0.1770	0.4021	0.2308	0.2239	0.4469
Adj. R-squared	0.2308			0.2308		
Observations	57999	57999	57999	57999	57999	57999
Entities		343			343	
Time Periods			3897			3897
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table D.3: Regression Results – IV – On-Chain vs. Off-Chain – BTC – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Bitcoin (BTC). The quote data is given on an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.57569	-0.55680	-0.58883	-0.04746	-0.04916	-0.04998
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.00906		0.00877			
	(0.00000)		(0.00000)			
Maturity	0.00217	0.00264	0.00225			
	(0.00000)	(0.00000)	(0.00000)			
Mness	0.58370	0.56073	0.59644			
	(0.00000)	(0.00000)	(0.00000)			
Abs. Delta				0.10075	0.13573	0.09786
				(0.00000)	(0.00000)	(0.00000)
Vega				0.00032	0.00026	0.00035
				(0.00000)	(0.00000)	(0.00000)
R-squared	0.3205	0.2145	0.4471	0.3595	0.2952	0.5159
Adj. R-squared	0.3204			0.3595		
Observations	72979	72979	72979	72979	72979	72979
Entities		400			400	
Time Periods			3896			3896
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table D.4: Regression Results – IV – On-Chain vs. Off-Chain – ETH – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Ethereum (ETH). The quote data is given on an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.53331	-0.09131	-0.28358	-0.04510	-0.01412	-0.02461
	(0.00000)	(0.54804)	(0.18698)	(0.00000)	(0.24197)	(0.20795)
Call	0.01365		-0.00256			
	(0.00000)		(0.87208)			
Maturity	0.00224	0.00115	0.00149			
	(0.00000)	(0.09348)	(0.18909)			
Mness	0.51245	0.09359	0.29020			
	(0.00000)	(0.55019)	(0.19328)			
Abs. Delta				0.03578	0.05605	0.05669
				(0.00400)	(0.26452)	(0.52576)
Vega				0.00002	0.00001	0.00001
				(0.00000)	(0.59556)	(0.54367)
R-squared	0.0598	0.0184	0.1067	0.0285	0.0275	0.1244
Adj. R-squared	0.0594			0.0282		
Observations	6933	400	400	6933	400	400
Entities		156			156	
Time Periods			325			325
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

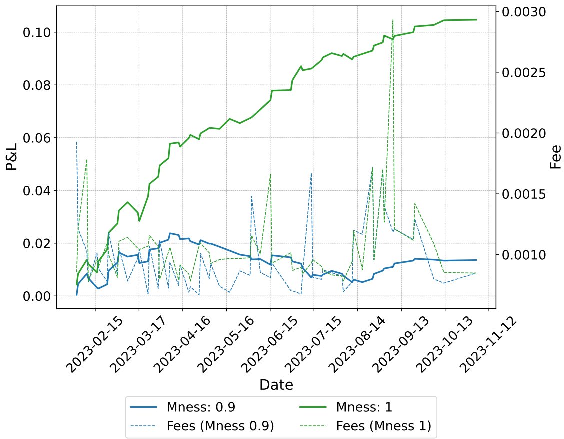
Table D.5: Regression Results – IV – On-Chain vs. Off-Chain – BTC – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The trades On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Bitcoin (BTC). The trade data is sampled on a tick level and resampled to hourly frequency. The sample period ranges from 05-2023 to 11-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.91979	-0.60608	-0.47268	-0.07037	-0.04279	-0.02995
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.00644		0.00320			
	(0.00000)		(0.09689)			
Maturity	0.00227	0.00249	0.00178			
	(0.00000)	(0.00000)	(0.00000)			
Mness	0.93529	0.61871	0.48753			
	(0.00000)	(0.00000)	(0.00000)			
Abs. Delta				0.17608	0.07945	0.05949
				(0.00000)	(0.00000)	(0.00000)
Vega				0.00026	0.00036	0.00029
				(0.00000)	(0.00000)	(0.00000)
R-squared	0.2663	0.2562	0.3476	0.2667	0.2784	0.3731
Adj. R-squared	0.2663			0.2667		
Observations	47976	2274	2274	47976	2274	2274
Entities		296			296	
Time Periods			1360			1360
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table D.6: Regression Results – IV – On-Chain vs. Off-Chain – ETH – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The trades On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Ethereum (ETH). The trade data is sampled on a tick level and resampled to hourly frequency. The sample period ranges from 05-2023 to 11-2023.

D.5 Risk Factor – On-Chain and Off-Chain – IVs – Trades

(a) Factor (traded, net of fees): 7d Maturity



(b) Factor (traded, net of fees): 15d Maturity

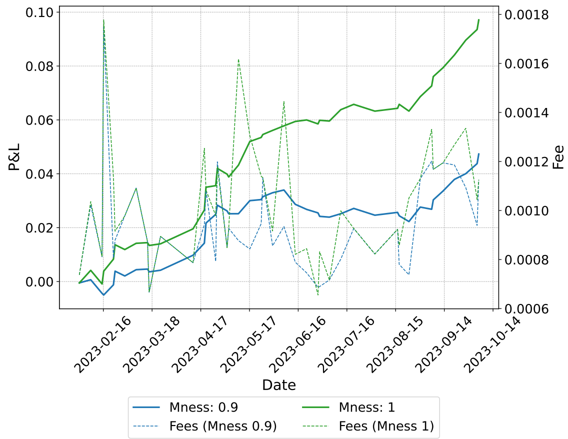
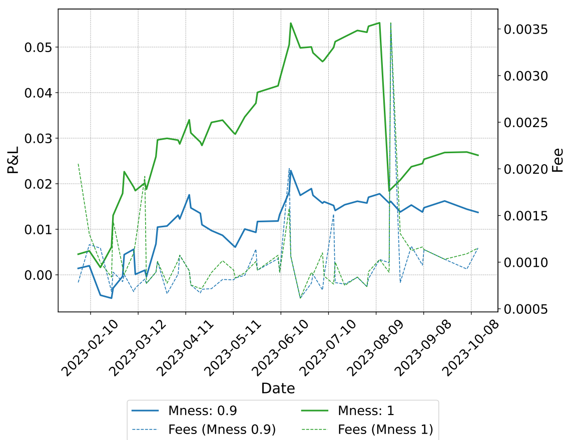


Figure D.10: Factor – Calls – ETH – Trades with Fees. The figure displays the P&L (in ETH) (left axis) of the factor that aims to profit from the convergence of IV between the two exchanges over time, i.e., selling the On-Chain call options and buying the Off-Chain call options for a given maturity, and moneyness. The factor is constructed considering trades including realized fees. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The right y-axis displays the fees paid (in ETH). The factor is constructed on a weekly frequency at 10 am. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

(a) Factor (traded, net of fees): 7d Maturity



(b) Factor (traded, net of fees): 15d Maturity

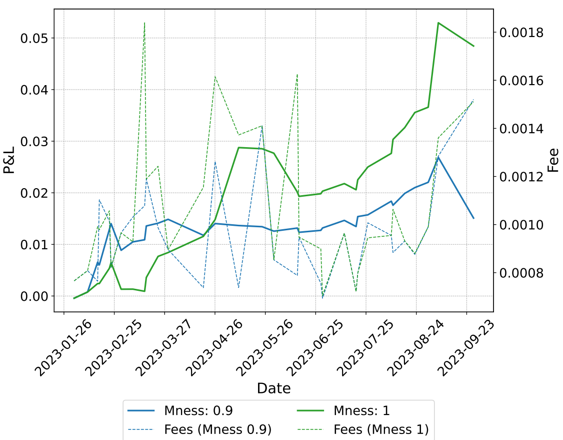


Figure D.11: Factor – Puts – ETH – Trades with Fees. The figure displays the P&L (in ETH) (left axis) of the factor that aims to profit from the convergence of IV between the two exchanges over time, i.e., selling the On-Chain put options and buying the Off-Chain put options for a given maturity, and moneyness. The factor is constructed considering trades including realized fees. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The right y-axis displays the fees paid (in ETH). The factor is constructed on a weekly frequency at 10 am. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

Internet Appendix

I Aevo

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	1093	1093	25014	25014
Instruments	66	66	317	317
Min Date	2023-06-05	2023-06-05	2023-06-05	2023-06-05
Max Date	2023-11-05	2023-11-05	2023-11-05	2023-11-05
Min Strike	24000	24000	1150	1150
Max Strike	35000	35000	2100	2100
IV mean	0.43	0.43	0.44	0.43
IV std	0.09	0.09	0.11	0.09
Price mean	479.03	445.31	40.48	39.02
Price std	339.89	299.50	29.85	28.82
Size mean	0.41	2.34	13.30	25.78
Size std	0.57	12.28	34.49	143.26

Table I.1: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is obtained from Aevo, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 11-2023.

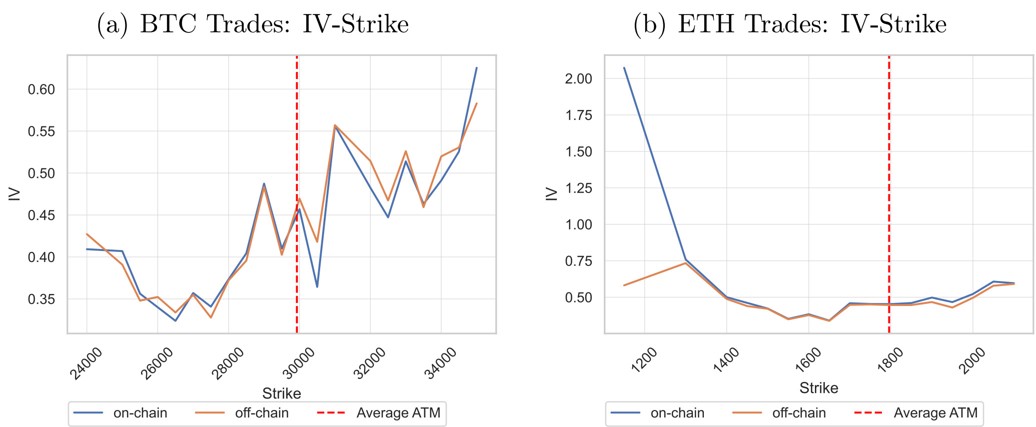


Figure I.1: Implied Volatility and Strike Price. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Aevo, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the strike price in USD. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 11-2023.

(a) BTC Trades: IV-Maturity (b) ETH Trades: IV-Maturity

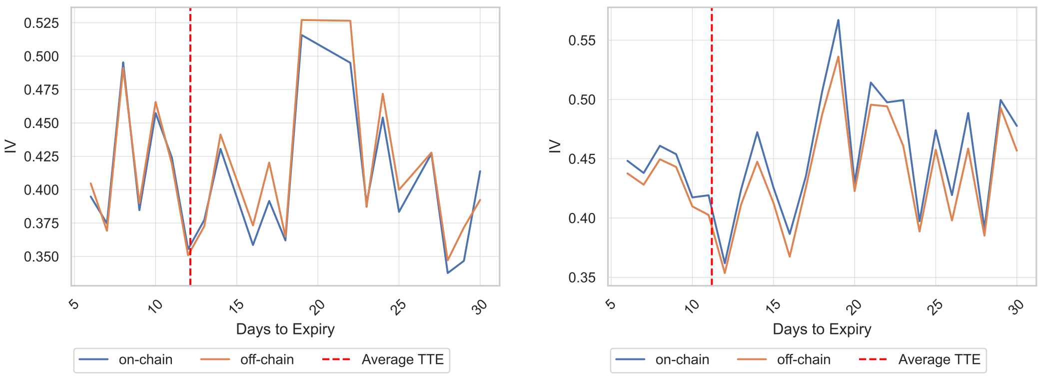


Figure I.2: Implied Volatility and Maturity. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different maturities. The On-Chain data is obtained from Aevo, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the maturity in days. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 11-2023.

(a) BTC Calls Trades: IV-Maturity (b) BTC Puts Trades: IV-Maturity

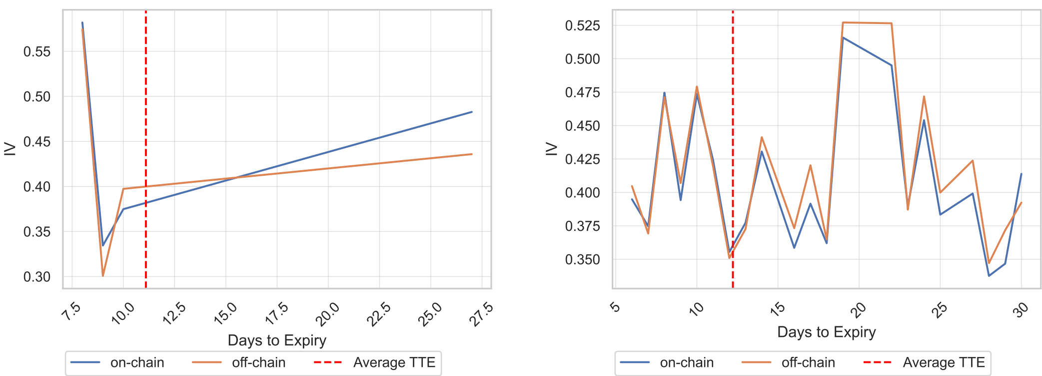


Figure I.3: Implied Volatility for BTC and Maturity – Call and Puts. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different maturities. The On-Chain data is obtained from Aevo, while the Off-Chain data is from Deribit. The underlying asset is Bitcoin (BTC). The x-axis represents the maturity in days. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 11-2023.

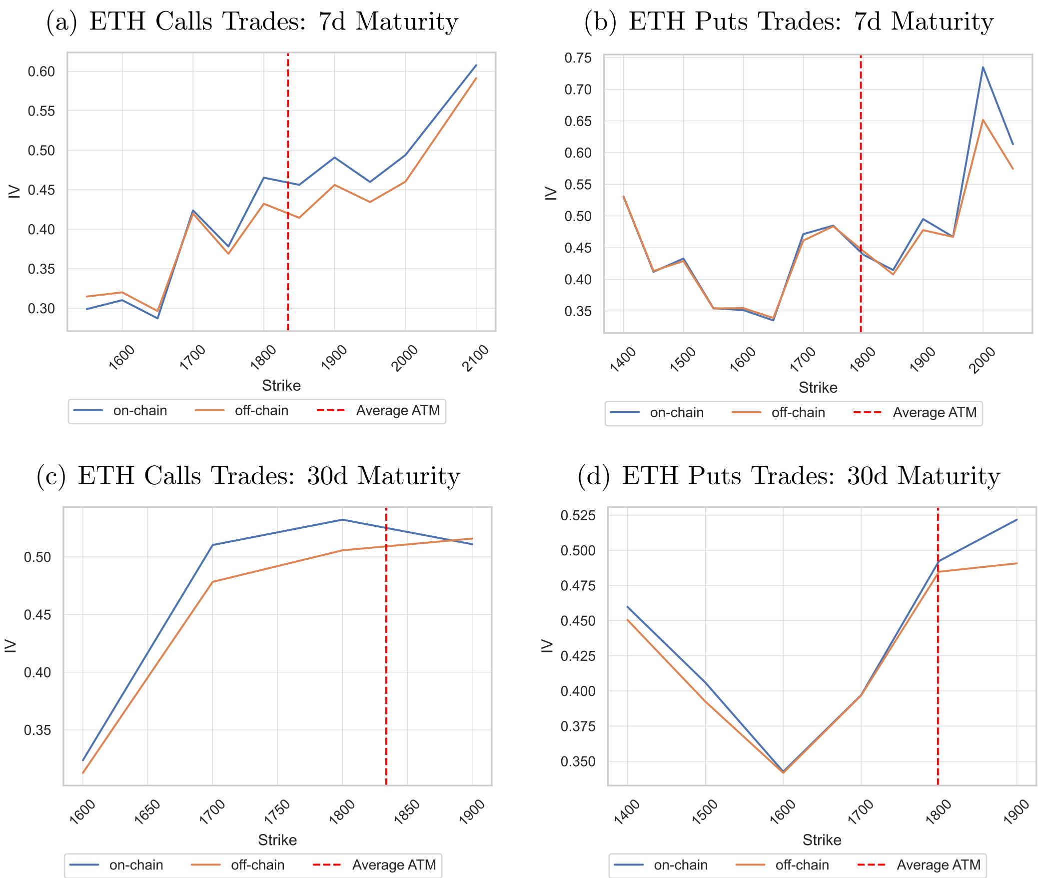


Figure I.4: Implied Volatility for ETH and Strike Price – Call and Puts. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Aevo, while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The x-axis represents the strike price in USD. In panels (a) and (b) only OTM options with maturity between 6 and 7 days are selected, while in panels (c) and (d) only OTM options with a maturity of 28-30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 11-2023.

II Lyra V1 on Optimism

II.1 On-Chain and Off-Chain — Transaction Fees

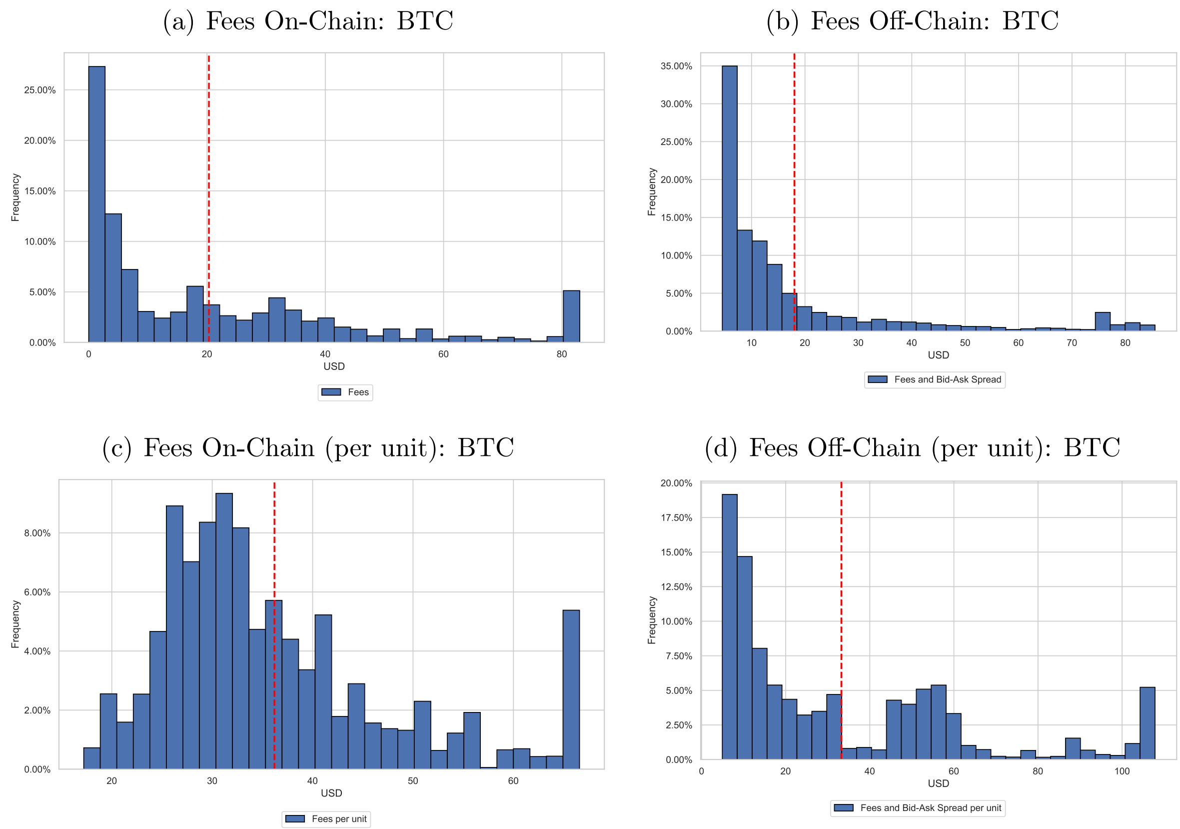


Figure II.5: Transaction Fees – On-Chain vs. Off-Chain – BTC. The figure shows the histogram of total trading fees (Panel (a) and Panel (b))), and trading fee per unit (Panel (c) and Panel (d)), On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The fees On-Chain are calculated according to equation (3.6) and Off-Chain as described in Section 3.1. The options underlying asset is Bitcoin (BTC). The dashed red line denotes the unconditional average. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 5% quantile. The sample period ranges from 08-2022 to 05-2023.

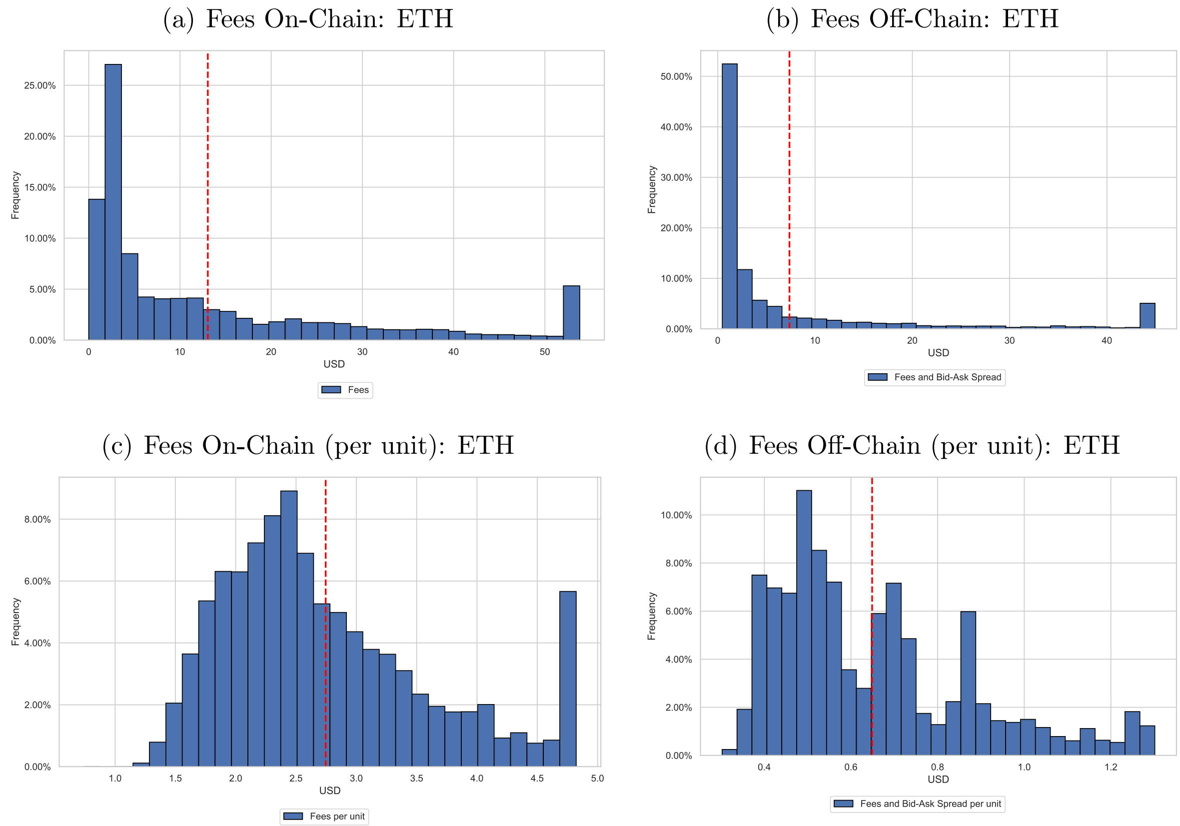


Figure II.6: Transaction Fees – On-Chain vs. Off-Chain – ETH. The figure shows the histogram of total trading fees (Panel (a) and Panel (b))), and trading fee per unit (Panel (c) and Panel (d))), On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The fees On-Chain are calculated according to equation (3.6) and Off-Chain as described in Section 3.1. The options underlying asset is Ethereum (ETH). The dashed red line denotes the unconditional average. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 5% quantile. The sample period ranges from 06-2022 to 05-2023.

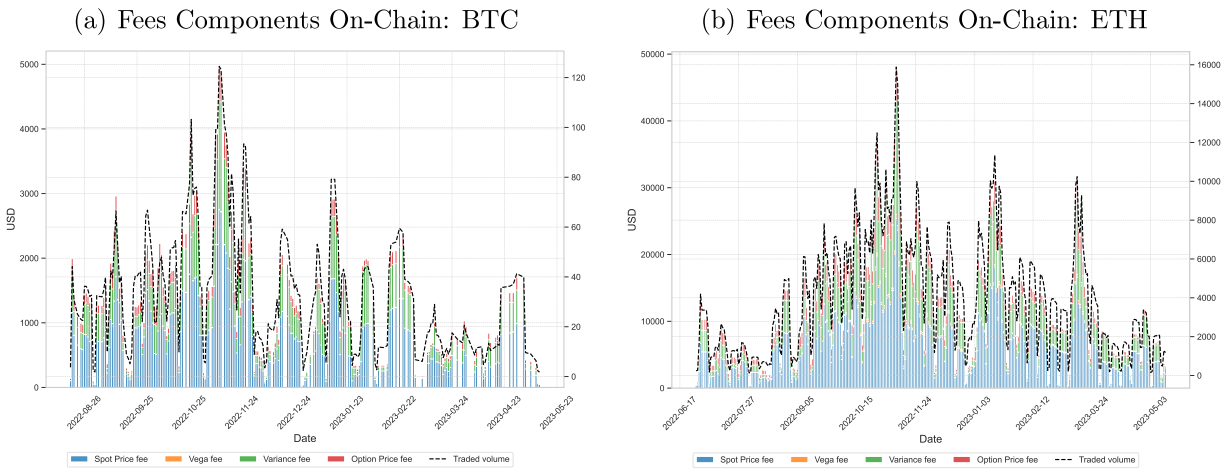


Figure II.7: Fee Components – On-Chain. The figure displays the fee components and volume (dashed line) for Bitcoin (BTC) (Panel (a)) and Ethereum (ETC) (Panel (b)) in USD. The On-Chain data is obtained from Lyra V1 deployed on Optimism. The components of the fees are mentioned in equation (3.6). Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The data is winzorized at the 5% quantile. The sample period ranges from 06-2022 to 05-2023.

II.2 On-Chain and Off-Chain -— IVs

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	22222	22222	339183	339183
Instruments	298	298	613	612
Min Date	2022-08-18	2022-08-17	2022-06-28	2022-06-28
Max Date	2023-05-13	2023-05-13	2023-05-13	2023-05-13
Min Strike	13000	13000	800	800
Max Strike	34000	34000	2600	2600
IV mean	0.63	0.63	0.78	0.76
IV std	0.14	0.19	0.21	0.21
Price mean	377.59	387.03	33.62	32.79
Price std	231.28	254.73	24.02	22.98
Size mean	0.58	3.11	5.80	25.27
Size std	0.90	15.01	11.62	124.80

Table II.2: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2022 to 05-2023.

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	74264	74264	109358	109358
Instruments	490	490	668	667
Min Date	2022-08-18	2022-08-18	2022-06-28	2022-06-28
Max Date	2023-05-13	2023-05-13	2023-05-13	2023-05-13
Min Strike	13000	13000	800	800
Max Strike	36000	36000	3200	3200
IV mean	0.63	0.60	0.83	0.80
IV std	0.13	0.12	0.24	0.21
Price mean	393.33	361.20	37.08	33.73
Price std	302.23	278.87	30.31	27.10

Table II.3: Summary Statistics – Quotes. The table displays the summary statistics of the quoted options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. Only OTM options with maturity between 6 and 30 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 06-2022 to 05-2023.

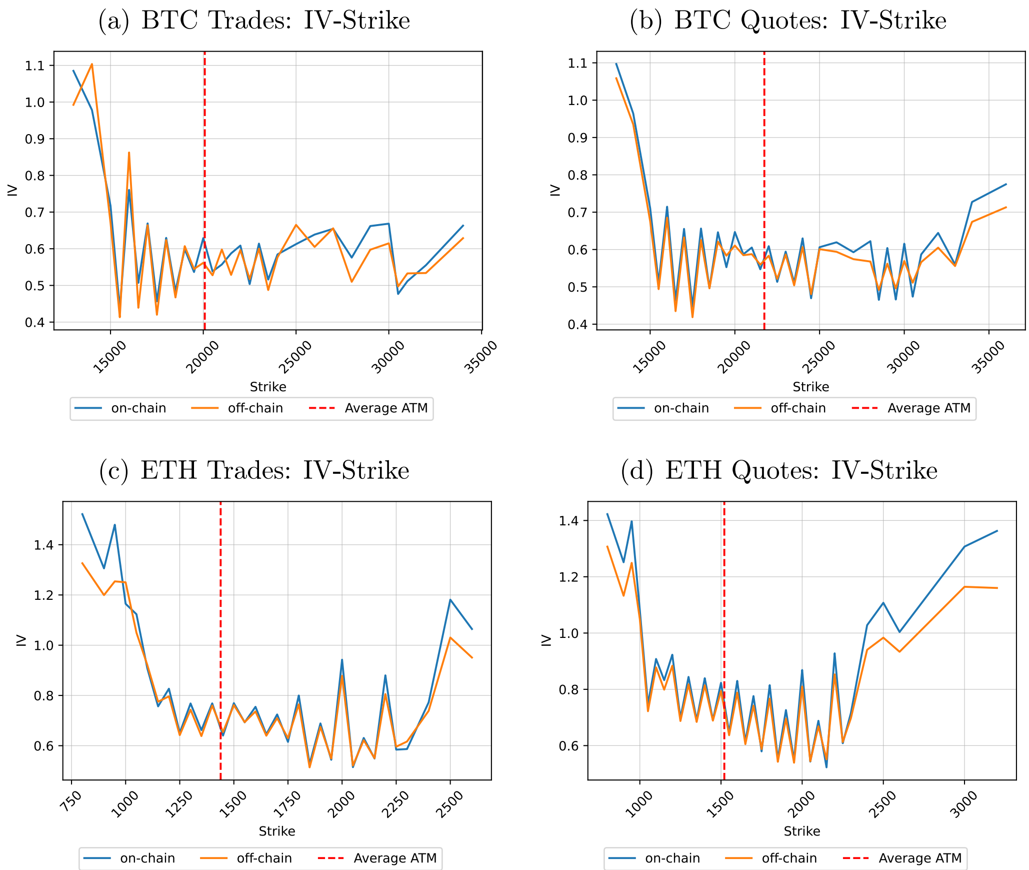


Figure II.8: Implied Volatility and Strike Price. The figure shows the traded and quoted IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the strike price in USD. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level while the quotes are given on an hourly frequency. The sample period ranges from 06-2022 to 05-2023.

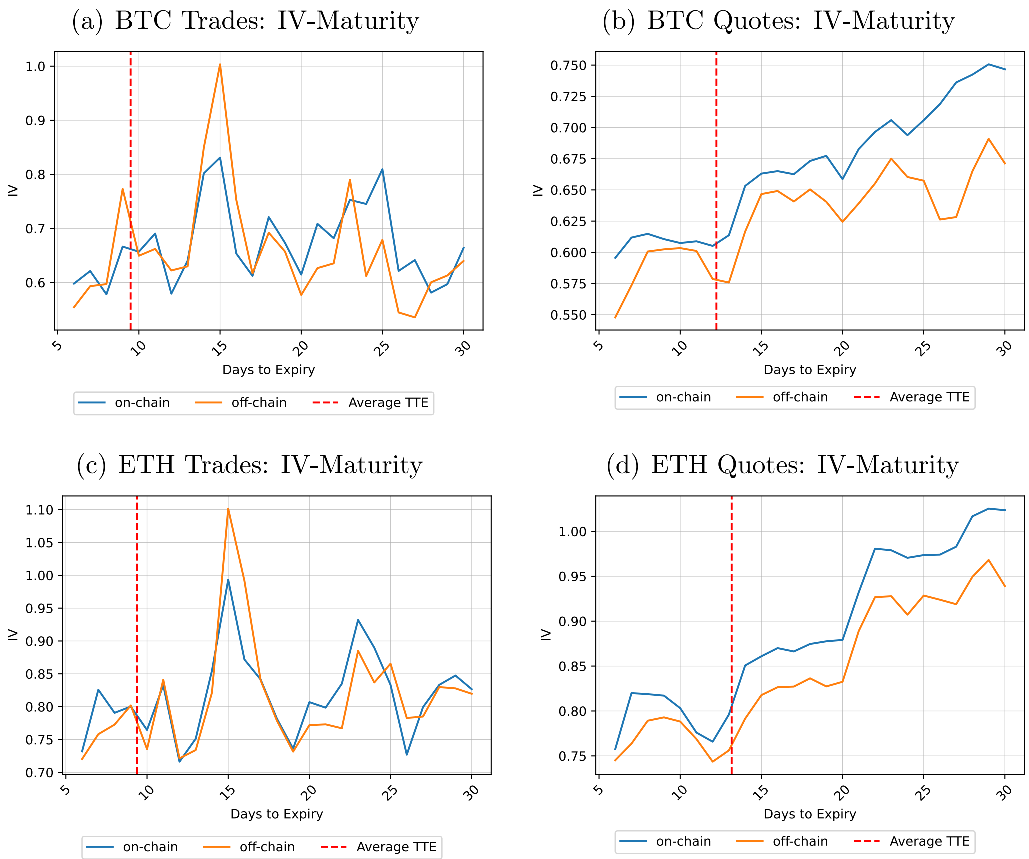


Figure II.9: Implied Volatility and Maturity. The figure shows the traded and quoted IV from call and put options, On-Chain, and Off-Chain, averaged for different maturities. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the maturity in days. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level while the quotes are given on an hourly frequency. The sample period ranges from 06-2022 to 05-2023.

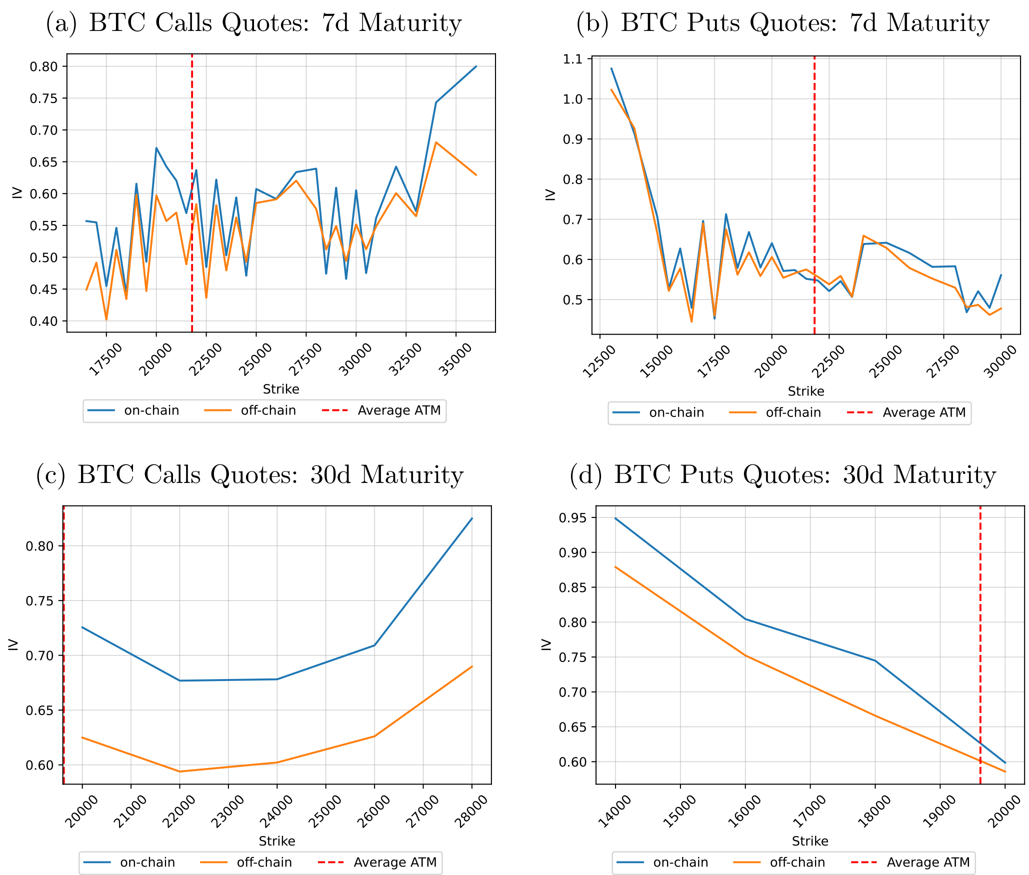


Figure II.10: Implied Volatility for BTC and Strike Price – Call and Puts. The figure shows the quoted IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The underlying asset is Bitcoin (BTC). The x-axis represents the strike price in USD. In panels (a) and (b) only OTM options with maturity between 6 and 8 days are selected, while in panels (c) and (d) only OTM options with a maturity of 28-32 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 08-2022 to 05-2023.

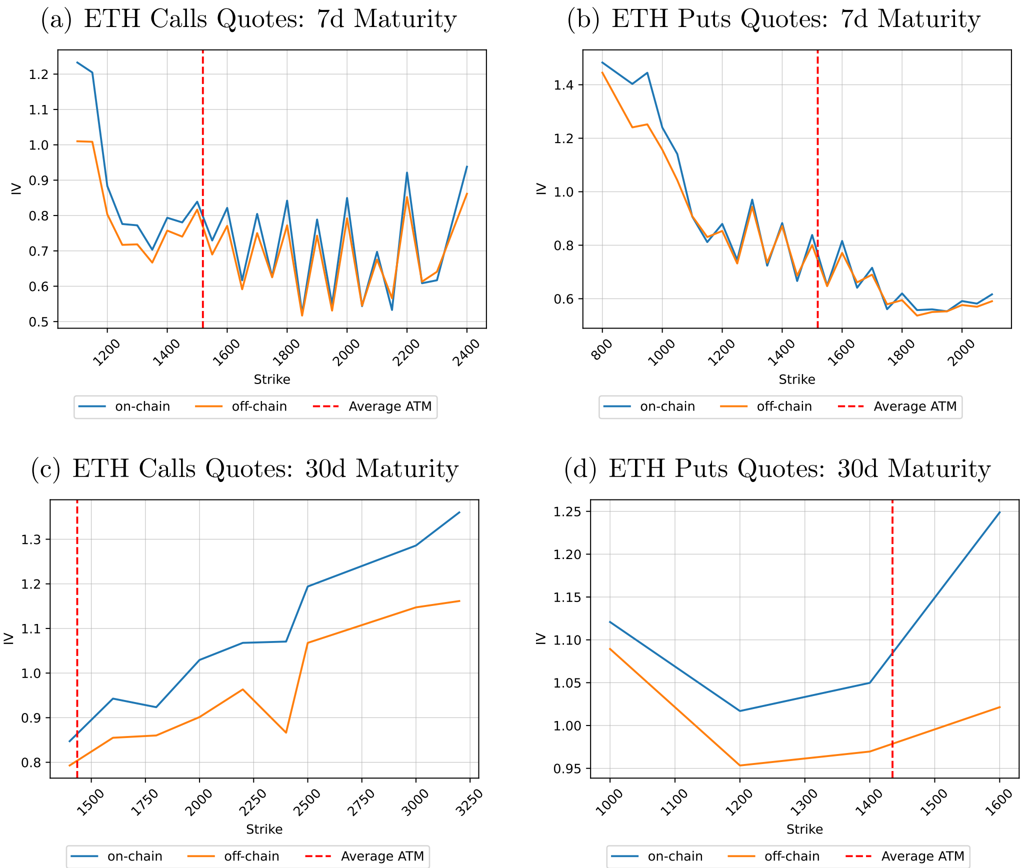


Figure II.11: Implied Volatility for ETH and Strike Price – Call and Puts. The figure shows the quoted IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The underlying asset is Ethereum (ETH). The x-axis represents the strike price in USD. In panels (a) and (b) only OTM options with maturity between 6 and 8 days are selected, while in panels (c) and (d) only OTM options with a maturity of 28-32 days are considered. The quote data is given on an hourly frequency. The sample period ranges from 06-2022 to 05-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.35407	-0.08442	-0.00245	0.05147	0.08244	-0.06398
	(0.00000)	(0.49345)	(0.99957)	(0.00000)	(0.00000)	(0.95533)
Call	0.02549		0.04727			
	(0.00000)		(0.83994)			
Maturity	-0.00341	-0.00314	0.01012			
	(0.00000)	(0.00008)	(0.93743)			
Mness	0.40080	0.15845	-0.10093			
	(0.00000)	(0.23481)	(0.98192)			
Abs. Delta				0.07813	0.06365	-0.36122
				(0.00000)	(0.31262)	(0.92546)
Vega				-0.00709	-0.00663	0.01849
				(0.00000)	(0.00049)	(0.92740)
R-squared	0.0830	0.0409	0.3303	0.0299	0.0533	0.1814
Adj. R-squared	0.0829			0.0298		
Observations	22222	1143	1143	22222	1143	1143
Entities		298			298	
Time Periods			1134			1134
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table II.4: Regression Results – IV – On-Chain vs. Off-Chain – BTC – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The trades On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Bitcoin (BTC). The trade data is sampled on a tick level and resampled to hourly frequency. The sample period ranges from 08-2022 to 5-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.11564	-0.23779	-0.16590	0.01778	0.01587	-0.00351
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.22723)
Call	0.03469		0.02345			
	(0.00000)		(0.00000)			
Maturity	-0.00107	-0.00007	0.00133			
	(0.00000)	(0.74095)	(0.00000)			
Mness	0.12594	0.29418	0.18528			
	(0.00000)	(0.00000)	(0.00000)			
Abs. Delta				0.11752	0.09871	0.07565
				(0.00000)	(0.00000)	(0.00000)
Vega				-0.05138	-0.01547	0.01767
				(0.00000)	(0.01278)	(0.00090)
R-squared	0.0379	0.0242	0.1008	0.0119	0.0092	0.0653
Adj. R-squared	0.0378			0.0119		
Observations	339183	9707	9707	339183	9707	9707
Entities		613			613	
Time Periods			4144			4144
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table II.5: Regression Results – IV – On-Chain vs. Off-Chain – ETH – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The trades On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Ethereum (ETH). The trade data is sampled on a tick level and resampled to hourly frequency. The sample period ranges from 06-2022 to 5-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	-0.08440	-0.16807	-0.19393	-0.00267	0.01142	-0.01027
	(0.00000)	(0.00000)	(0.00000)	(0.00140)	(0.00000)	(0.00000)
Call	0.01553		0.01154			
	(0.00000)		(0.00000)			
Maturity	0.00142	-0.00170	0.00247			
	(0.00000)	(0.00000)	(0.00000)			
Mness	0.09180	0.23379	0.19967			
	(0.00000)	(0.00000)	(0.00000)			
Abs. Delta				0.11093	0.32950	0.08580
				(0.00000)	(0.00000)	(0.00000)
Vega				0.00000	-0.00006	0.00001
				(0.57158)	(0.00000)	(0.00000)
R-squared	0.0258	0.0295	0.0976	0.0512	0.0867	0.1345
Adj. R-squared	0.0258			0.0512		
Observations	74264	74255	74255	74264	74255	74255
Entities		490			490	
Time Periods			6323			6323
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table II.6: Regression Results – IV – On-Chain vs. Off-Chain – BTC – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Bitcoin (BTC). The quote data is given on an hourly frequency. The sample period ranges from 08-2022 to 5-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Intercept	0.00993	-0.23682	-0.16813	-0.00826	-0.00739	-0.00815
	(0.04834)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.01687		0.01656			
	(0.00000)		(0.00000)			
Maturity	0.00168	-0.00001	0.00153			
	(0.00000)	(0.81477)	(0.00000)			
Mness	-0.00654	0.30688	0.19669			
	(0.20008)	(0.00000)	(0.00000)			
Abs. Delta				0.13493	0.33565	0.12916
				(0.00000)	(0.00000)	(0.00000)
Vega				0.00013	-0.00048	0.00014
				(0.00000)	(0.00000)	(0.00000)
R-squared	0.0197	0.0323	0.0786	0.0596	0.0937	0.1300
Adj. R-squared	0.0197			0.0595		
Observations	109358	109353	109353	109358	109353	109353
Entities		668			668	
Time Periods			7664			7664
Option-Id FE	No	Yes	No	No	Yes	No
Time FE	No	No	Yes	No	No	Yes

Table II.7: Regression Results – IV – On-Chain vs. Off-Chain – ETH – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (5.2) - (5.3). Thereby *Call* equals 1 if the instrument is a call option, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The Greeks: Abs. *Delta*, and *Vega* are calculated under Black and Scholes (1973). The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The underlying asset is Ethereum (ETH). The quote data is given on an hourly frequency. The sample period ranges from 06-2022 to 5-2023.

III Aevo and Lyra

	Aevo	Lyra
N	568	568
Instruments	119	119
Min Date	2023-02-08	2023-02-08
Max Date	2023-11-06	2023-11-06
Min Strike	1400	1400
Max Strike	2100	2100
IV mean	0.43	0.44
IV std	0.11	0.09
Price mean	43.83	43.80
Price std	30.50	30.03
Size mean	6.09	7.25
Size std	16.61	16.13

Table III.8: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum and from Aevo. The options underlying asset is Ethereum (ETH). Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

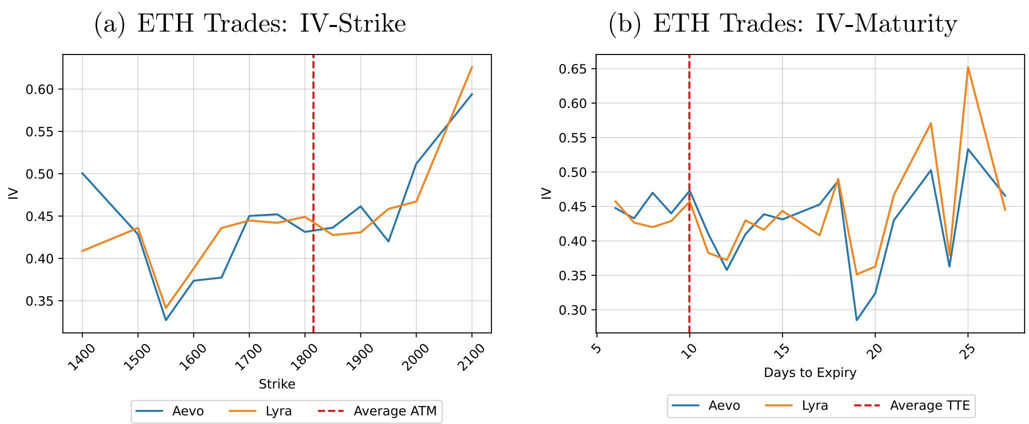


Figure III.12: Implied Volatility, Strike Price and Maturity. The figure shows the traded IV from call and put options On-Chain averaged for different strike prices and maturities, shown respectively on the left and right panels. The On-Chain data is obtained from Lyra and Aevo. The options underlying asset is Ethereum (ETH). The x-axis represents the strike price in USD. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

IV Okex and Lyra

IV.1 Lyra V2 on Arbitrum

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	1584	1584	6773	6773
Instruments	143	143	358	358
Min Date	2023-03-03	2023-03-03	2023-02-01	2023-02-01
Max Date	2023-08-19	2023-08-19	2023-11-06	2023-11-06
Min Strike	19000	19000	1300	1300
Max Strike	35000	35000	2400	2400
IV mean	0.48	0.45	0.50	0.47
IV std	0.09	0.08	0.12	0.11
Price mean	418.50	376.65	30.47	27.35
Price std	251.24	230.45	19.19	16.88
Size mean	0.71	63.81	9.83	72.26
Size std	0.75	205.14	20.65	262.40

Table IV.9: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH), respectively. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

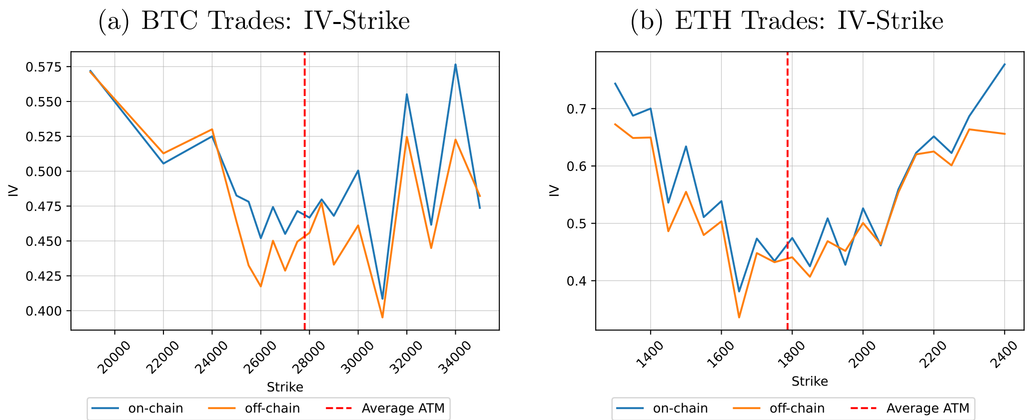


Figure IV.13: Implied Volatility and Strike Price. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the strike price in USD. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

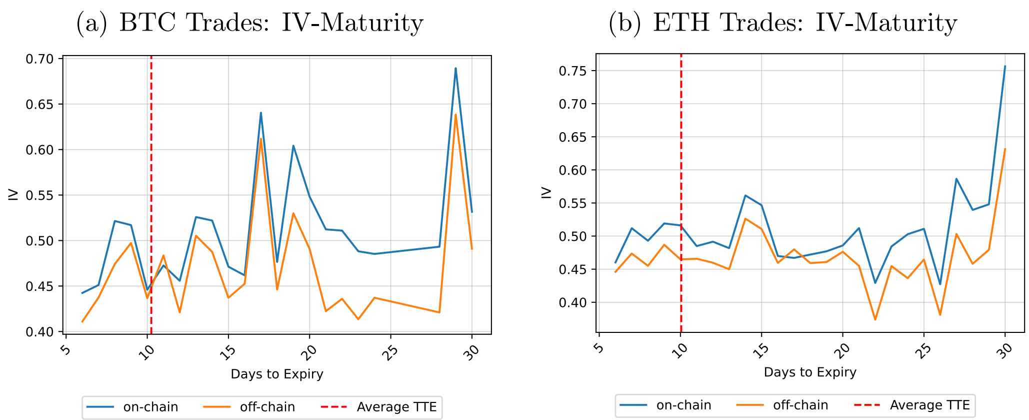


Figure IV.14: Implied Volatility and Maturity. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different maturities. The On-Chain data is obtained from Lyra V2 deployed on Arbitrum, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the maturity in days. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

IV.2 Lyra V2 on Optimism

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	334	334	2166	2166
Instruments	56	56	153	153
Min Date	2023-05-27	2023-05-27	2023-05-25	2023-05-25
Max Date	2023-11-04	2023-11-04	2023-11-06	2023-11-06
Min Strike	24000	24000	1400	1400
Max Strike	38000	38000	2200	2200
IV mean	0.43	0.42	0.42	0.40
IV std	0.06	0.09	0.06	0.08
Price mean	479.77	452.08	27.32	26.06
Price std	276.49	284.34	13.20	13.12
Size mean	0.42	102.46	9.44	67.66
Size std	0.47	236.39	14.93	276.21

Table IV.10: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH), respectively. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 05-2023 to 11-2023.

(a) BTC Trades: IV-Strike

(b) ETH Trades: IV-Strike

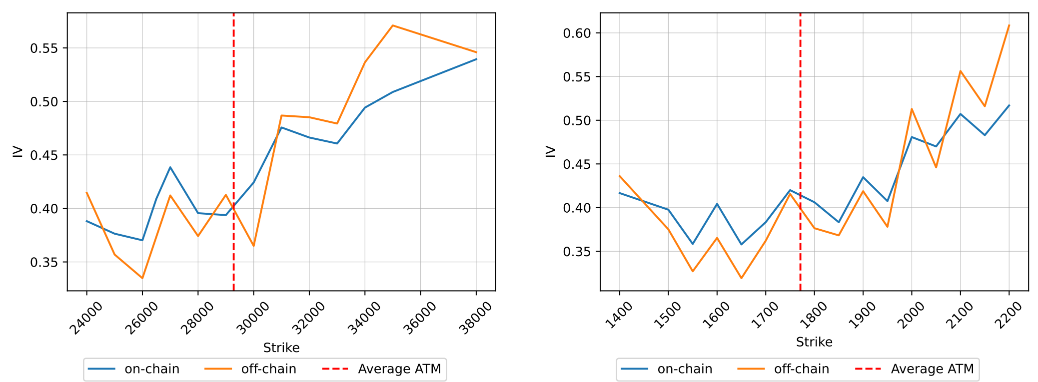


Figure IV.15: Implied Volatility and Strike Price. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the strike price in USD. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 05-2023 to 11-2023.

(a) BTC Trades: IV-Maturity (b) ETH Trades: IV-Maturity

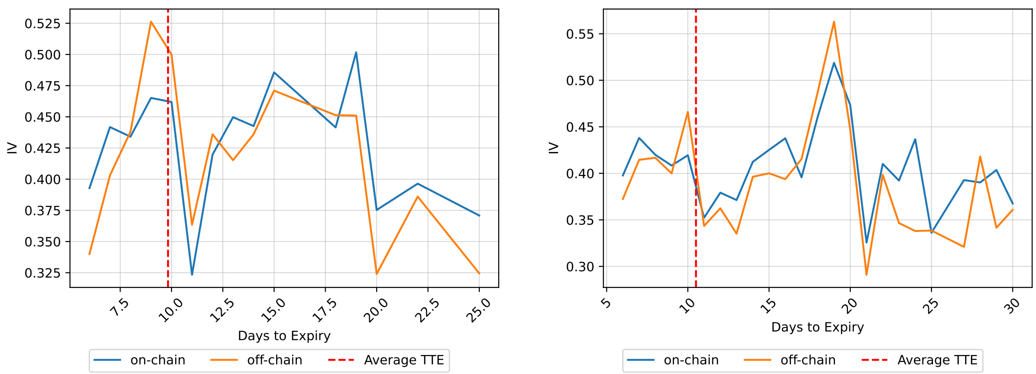


Figure IV.16: Implied Volatility and Maturity. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different maturities. The On-Chain data is obtained from Lyra V2 deployed on Optimism, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the maturity in days. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 05-2023 to 11-2023.

IV.3 Lyra V1 on Optimism

	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	426	426	8048	8048
Instruments	96	96	459	458
Min Date	2022-08-18	2022-08-18	2022-06-28	2022-06-28
Max Date	2023-05-13	2023-05-13	2023-05-13	2023-05-13
Min Strike	13000	13000	800	800
Max Strike	30000	30000	2600	2600
IV mean	0.60	0.62	0.73	0.72
IV std	0.11	0.13	0.21	0.20
Price mean	358.67	384.36	31.50	29.71
Price std	234.88	272.12	22.04	21.09
Size mean	0.63	65.59	4.09	127.16
Size std	0.51	233.85	9.69	530.91

Table IV.11: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH), respectively. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2022 to 05-2023.

(a) BTC Trades: IV-Strike (b) ETH Trades: IV-Strike

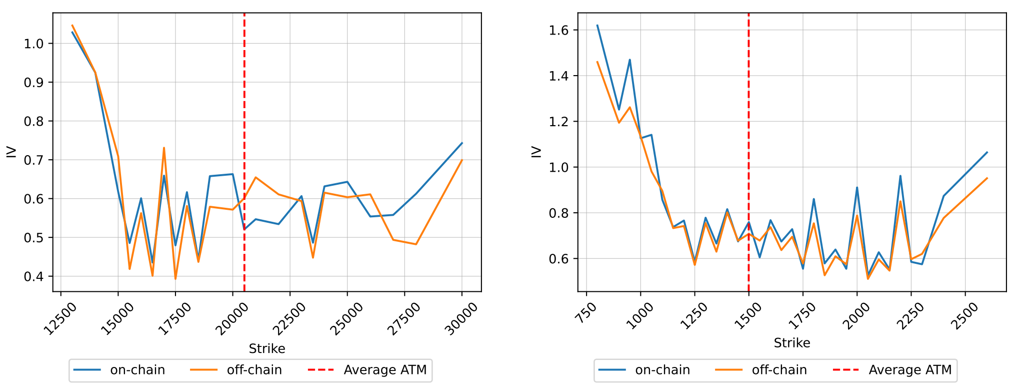


Figure IV.17: Implied Volatility and Strike Price. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the strike price in USD. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2022 to 05-2023.

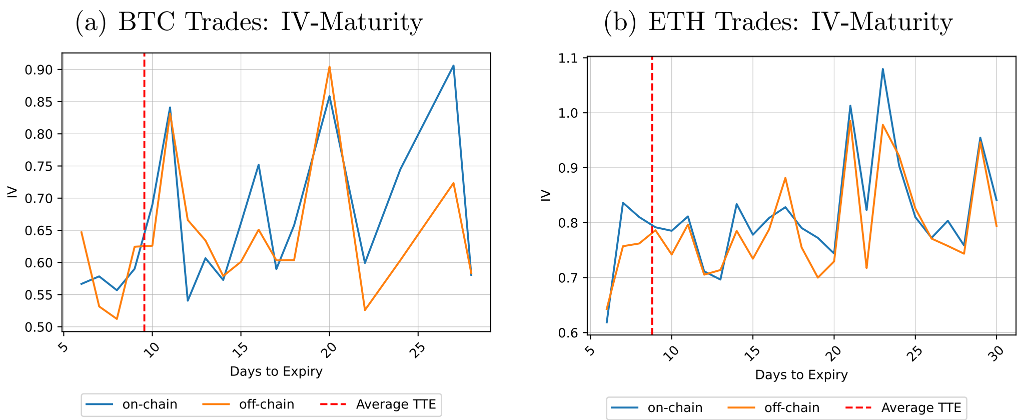


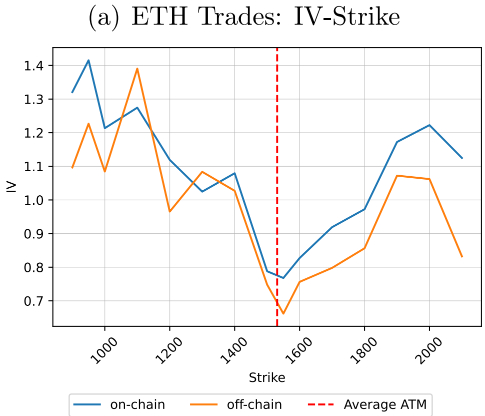
Figure IV.18: Implied Volatility and Maturity. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different maturities. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Okex. The options underlying assets are Bitcoin (BTC) and Ethereum (ETH) respectively. The x-axis represents the maturity in days. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2022 to 05-2023.

V Bitcom and Lyra

V.1 Lyra V1 on Optimism

	On-Chain	Off-Chain
N	190	190
Instruments	47	47
Min Date	2022-06-30	2022-06-30
Max Date	2022-11-11	2022-11-11
Min Strike	900	900
Max Strike	2100	2100
IV mean	1.00	0.96
IV std	0.17	0.18
Price mean	57.03	50.48
Price std	35.72	36.27
Size mean	4.47	8.83
Size std	10.97	18.82

Table V.12: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Bitcom. The options underlying asset is Ethereum (ETH). Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2022 to 11-2022.



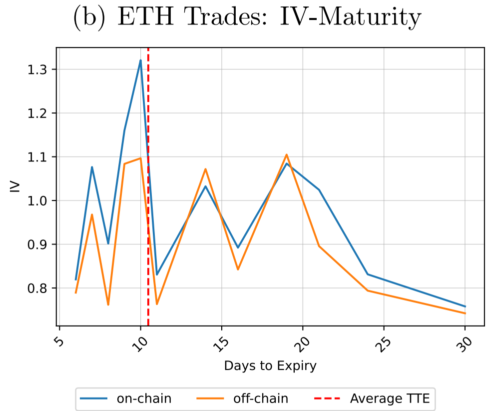


Figure V.19: Implied Volatility, Strike Price and Maturity. The figure shows the traded IV from call and put options, On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data is obtained from Lyra V1 deployed on Optimism, while the Off-Chain data is from Bitcom. The options underlying asset is Ethereum (ETH). The x-axis represents the strike price in USD and the maturity in days. Only OTM options with maturity between 6 and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2022 to 11-2022.