Decentralized and Centralized Options Trading: A Risk Premia Perspective*

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Abstract

On-Chain options refer to option contracts, traded directly on a decentralized exchange on a blockchain. We report a novel set of stylized facts about the functioning of this so-called automated market making for options trading. We document the extent to which the On-Chain options differ from their Off-Chain counterparts traded on centralized exchanges. In particular, we find that On-Chain options exhibit larger implied volatilities than Off-Chain options, attributing it to the complex On-Chain fee structure, trading volume, and net demand pressure. We propose a theory explaining the difference in implied volatilities and empirically verify key model implications.

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

JEL Classification Codes: G10, G13, G14, G20, O30

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1 Introduction

In late 2022, decentralized exchanges (*DEXs*) began offering *On-Chain* options trading, leveraging blockchain technology and marking a new milestone in decentralized markets.[1] Traditionally, option contracts trading, relying on the familiar central limit order book model, happens *Off-Chain* through centralized exchanges (*CEXs*). Both types of exchanges provide different trade-offs in terms of pricing and fees. Recent studies argue that well-designed DEXs for token trading could save investors billions since they offer improved risk-sharing for *liquidity providers (LPs)* (Malinova and Park (2024)) and less price impact for liquidity takers (Lehar and Parlour (2023)).

The main objective of this paper is to analyze this new market form of decentralized options trading and to compare it with the long-existing centralized derivative market. This is the first paper to conduct such an analysis and it provides insights into the evolving options trading landscape across decentralized and centralized platforms and its market impact. Our main contributions are as follows: i) We report a novel set of stylized facts about decentralized options trading, ii) using On-Chain and Off-Chain data, we document that the *implied volatility (IV)* of On-Chain options exceeds that of Off-Chain options, and we investigate if this can be interpreted as a risk premium, iii) we identify the reasons for this discovered difference such as the On-Chain fee mechanism, trading volume, and the net demand pressure, iv) we present a theory, highlighting how a DEX offers immediate liquidity, while a CEX uses a limit order book (LOB), with inventory costs accounted for in both markets.

An *automated market maker (AMM)* is a decentralized trading protocol that uses algorithms to determine asset prices and facilitate trading without order books, allowing users to trade directly. Our analysis focuses on the Lyra protocol (Dawson et al. (2021b)),

[1] On-Chain options are smart contracts, which are digital agreements written in code and executed automatically on a blockchain. They operate leveraging blockchain's decentralization, immutability, and transparency. Once deployed, smart contracts cannot be altered, ensuring trust and security. Implementing a financial derivative as a smart contract was first proposed by Fries et al. (2019).

a crypto options platform implemented as smart contracts on Ethereum layer 2 solutions like Arbitrum and Optimism.[2] Unlike AMMs for token trading, which have a single price per token, the AMM mechanism for options (*options AMM*) balances demand and supply across the entire option surface. The options AMM adjusts the option price (i.e., its IV) selectively, based on the demand for the option type, strike, and maturity, mimicking the smile of the volatility surface. For example, each AMM purchase or sale in a specific expiry changes the IV for that expiry by 1 percentage point.

The AMM also calculates a trading fee resulting from the pool's internal risk management, that is, hedging the pool's delta and vega exposure: for example, to reduce the delta risk, the AMM will automatically trade the underlying, while to reduce the vega risk, the AMM will lower the trader's fee if their trade is reducing the pool's vega exposure. Hence, per construction, the AMMs minimize the inventory risk, which directly affects option prices (Muravyev (2016)). In addition to the just outlined *Delta Fees* and *Vega Fees*, the pool also charges *Option Price Fees*, and *Variance Fees*. This fee structure influences supply and demand pressure patterns, potentially leading to significant differences in price behavior, as documented in standard option markets (Bollen and Whaley (2004), Gârleanu et al. (2009)). Off-Chain, the market maker charges only the bid-ask spread and linear fees based on the underlying price.

We focus on option IVs, analyzing a large cross-section of trades and quotes for European out-of-the-money (OTM) options across various underlyings (Bitcoin (BTC) and Ethereum (ETH)), maturities, and strikes, both On-Chain and Off-Chain. Whereas the Off-Chain data is proprietary and exchange-specific, the On-Chain data is directly accessible from the blockchain. We find that On-Chain IVs generally exceed Off-Chain IVs, with the gap widening for longer maturities and near-at-the-money (ATM) options. For example, the On-Chain IV for options on ETH with 30 days to maturity is on average

[2]See `https://www.lyra.finance/`. In August 2024 Lyra was renamed to derive.xyz. An overview of other existing DEXs for options trading and their TVL is given in Table A.1 and in Rahman et al. (2022).

almost 20% larger than for the same options Off-Chain. The results are robust, including fixed effects for time and the option's contract.

To monetize the IV difference, we construct a trading strategy by selling higher IV options On-Chain and buying lower IV options Off-Chain. The strategy potentially represents an "On-Chain risk premium," showing strong performance with a monthly profit of about 0.01 ETH per unit of trade. The strategy's profitability can be explained by the Lyra governance token's (LYRA) price and a Fear & Greed sentiment indicator, yielding higher returns when LYRA's price is elevated, indicating future profit expectations (Cong et al. (2021)), and outperforming during periods of fear when investors seek greater compensation for increased risk. Consistent with the limits of arbitrage literature (Shleifer and Vishny (1997), Gromb and Vayanos (2010)), incorporating transaction costs cuts strategy profitability by 50% and causes negative performance in some cases.

Option overpricing occurs when intermediaries charge a premium due to their concentrated risk (Dew-Becker and Giglio (2024)). The AMM charges additional trading fees due to the pool's internal risk management, and to examine how these fees affect IVs, we use a Vector Autoregression (VAR) model to mimic the AMM's operational dynamics. We estimate the model including IV, fees, and trading volume. We repeat the estimation Off-Chain considering only the bid-ask spread as a fee component. We find that On-Chain, a high Vega Fee and Option Price Fee lead to an increase in IV, whereas for Off-Chain, the bid-ask spread does not impact the IV. Another finding lies in the impact of trading volume on the IV (Epps and Epps (1976), Tauchen and Pitts (1983), and Bollen and Whaley (2004)). On-Chain, a positive shock to the volume leads to a persistent IV increase, while Off-Chain, the effect is smaller and limited to puts.

Recently, retail investors have significantly impacted cryptocurrency markets and options trading by favoring OTM calls (Eaton et al. (2023)), which has led to a surge in demand that influences IV (Bogousslavsky and Muravyev (2024)). Following Bollen and Whaley (2004), we construct net buying pressure (NBP), noting that Volume and NBP do not always strongly correlate, as high trading volume days with equal buy and sell orders can result in zero NBP. Our findings indicate that NBP explains changes in On-Chain IVs across all call moneyness levels and deep OTM puts. For example, a one-standard-deviation increase in NBP increases the changes in On-Chain IVs for far OTM calls by 0.20 standard deviations. Conversely, Off-Chain, NBP can explain only the dynamics of ATM calls and deep OTM puts. Our results suggest that retail investors drive NBP's impact on IV due to their preference for calls over puts.

We present a theory explaining our main finding that the IV On-Chain exceeds the IV Off-Chain.[3] Adapting Stoll (1978), the AMM functions as a monopolistic dealer providing immediate liquidity, while a CEX uses a LOB for trading. In both markets, we account for inventory costs. Our empirical evidence shows that the pool is skewed toward long options, highlighting the importance of NBP. In the model, when aggregate demand exceeds a threshold, the DEX option price exceeds the CEX price. This threshold rises with the liquidity pool size and AMM inventory but decreases with the average dealer inventory and the number of dealers on the CEX. On-Chain, a larger pool size improves AMM efficiency and lower prices, while Off-Chain, higher dealer inventory, and competition enhance CEX efficiency, also reducing prices. We empirically verify some model implications, such as the correlation between higher aggregate demand and greater On-Chain IV relative to Off-Chain.

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 and Lyra V1 on Optimism. In addition, we investigate the difference in IV, comparing other DEXs (Aevo) and CEXs (OKX, and Bitcom). In summary, our findings consistently show across all exchanges that the On-Chain IVs exceed the Off-Chain IVs.

[3] We acknowledge other reasons (preferences) investors pay a premium to trade on DEXs: they offer control over funds, no identity verification, and global access. Unlike Deribit, which is unlicensed in the US, DEXs avoid counterparty risks highlighted by events like the FTX bankruptcy and SEC lawsuits against Binance. Additionally, selling options On-Chain requires higher margins, secured in a smart contract, exposing underwriters to blockchain and protocol risks.

2 Literature Review

The growing literature on Decentralized Finance (DeFi) includes studies on tokens, covering platform adoption, valuation, and financing (Prat et al. (2019); Gryglewicz et al. (2021); Goldstein et al. (2023); Sockin and Xiong (2023)). 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 reporting stylized facts of one particular platform, that is, the decentralized trading of options.

For token trading, there are differences between DEXs and CEXs (Härdle et al. (2020), Harvey et al. (2021), Makarov and Schoar (2022), and Aquilina et al. (2023), Harvey et al. (2024)), in terms of market quality (Barbon and Ranaldo (2021), Aoyagi and Ito (2024)) and arbitrage rents and order-processing mechanisms (Capponi and Jia (2024), Lehar and Parlour (2023), and Park (2023)). We contribute to this literature by analyzing some of the aforementioned aspects of options trading on DEXs.

The literature on cybersecurity risks finds that firm-level cyber risk significantly increases firms' IV (Florackis et al. (2022), Jamilov et al. (2023)). In addition, there is the additional risk of trading on L2 layers (compared to Ethereum) as emphasized by Chemaya and Liu (2022). Following these arguments, the elevated IV on a DEX potentially represents a blockchain risk.

Demand pressure can have effects on option prices and IV (Alexander et al. (2023)). The pricing of BTC options is discussed in Cao and Celik (2021). Another strand of literature focuses on microstructure in options: Boyle and Vorst (1992) and Engle and Neri (2010) highlight how liquidity imbalances, delta, and gamma influence IV. LPs are subject to inventory risk (Muravyev (2016)) and quote revisions in options markets (Jameson and Wilhelm (1992) and Chan et al. (2002)). The literature links narrower bid-ask spreads to improved market maker hedging (Cho and Engle (1999)) and a lower impact of information asymmetry on liquidity (Vijh (1990)). Our paper extends the literature by comparing On-Chain and classic Off-Chain options across these key dimensions.

3 Functioning of Decentralized Options Exchanges

Before discussing the innovation in a DEX for option trading, a short overview of the functioning of traditional CEX is provided.

3.1 Centralized Exchanges

Typically, a centralized LOB is utilized in a traditional options exchange. The exchange matches orders with counterparties, and the options clearinghouse oversees the final settlement. The largest exchange for trading (centralized) crypto options is Deribit, on which options are quoted directly in the numeraire (e.g., BTC or ETH) rather than in USD.[4] Deribit utilizes a maker-taker fee model, charging 0.03% of the underlying BTC or ETH per options contract for both makers and takers. In addition, a 0.015% fee for delivery (settlement) is charged.[5]

3.2 Decentralized Option Exchanges – Lyra

One of the striking features of a DEX for crypto options is that, instead of a centralized LOB, it pioneers a novel form of liquidity provision, via an evolved (options) AMM. The main goal of an AMM is to find the price of an option (i.e., its IV) that balances supply and demand. In such markets, LPs do not explicitly set prices, but rather passively supply liquidity, that is, they 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, alongside potential profits or losses based on their underwritten position's performance trajectory. Traders' price impact is determined by the rule-based AMM, where opening a long position involves paying the option price to the liquidity pool, with payoffs from the pool's reserves if the option expires in the money. When traders short an option, they deposit the quoted asset

[4]Source: `https://www.theblock.co/data/crypto-markets/options`.
[5]Source: `https://www.deribit.com/kb/fees`.

or a base asset as collateral, and if their collateral falls below the minimum requirement, the protocol triggers liquidation.

One example of such an AMM is Lyra (Dawson et al. (2021b)), which operates as an open protocol for European options trading on the Ethereum blockchain, that is, Layer 2 solutions such as Arbitrum and Optimism.[6] It is decentralized, meaning 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. Lyra enables options trading for various cryptocurrencies, including ETH and BTC.[7]

3.2.1 Options AMM

An AMM aims to find an IV value that balances supply and demand. This equilibrium lets the AMM profit from transaction fees, without incurring any risk, by buying and selling options in the same proportion. This IV is then used to calculate the Black and Scholes (1973) option 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.

Upon listing an option, an initial baseline volatility (IV_j), along with ratios of listed strike volatilities, are initialized based on current market data from the nearest ATM strike on Deribit. The AMM assumes that price impact is proportional to trade size, using the concept of a standard size (SS) to adjust pricing parameters accordingly. As SS increases, the slippage for traders decreases.[8] For every SS that the AMM buys or sells in a given expiry, the baseline IV will increase or decrease, respectively, for that

[6]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.

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

[8]The SS for sETH is 25.0 and for sBTC it is 0.32. In addition, the SS is continuous, so 1/10th of an SS moves the volatility by 0.1%. The protocol may adjust these parameters based on stress-testing of the AMM and LP economics due to slippage.

expiry by 1 percentage point, as follows

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

The Black-Scholes model fails to incorporate the volatility smile 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,

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

Hence, if 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) 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 option price is computed using the Black and Scholes (1973) model for $IV_{i,j}$, adjusted by an internal risk management fee (f), as explained next.

3.2.2 Pool Risk Management – Delta and Vega Risks

Lyra offers options in rounds lasting 28 days, with expiries at 7, 14, 21, and 28 days from each round's start. The liquidity will be split into two sub-pools: i) Collateral pool (collateralized options and pays/receives premia), and ii) Delta pool, which hedges the delta exposure of the AMM by trading the underlying. The net delta and vega positions define the risk profile, allowing for hedging actions to be undertaken when exposure is unacceptably high. The AMM incentivizes to open positions so that the risk of the AMM is reduced by adjusting fees based on whether the trader's position increases or decreases overall risk, charging higher (lower) fees accordingly.

Delta risk defines the exposure of an option's position to a move in the underlying, with the delta ($\delta_{i,j}$) of an option 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 calculated as 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 on a spot exchange.

Vega risk defines the exposure of an option to move in the IV.[9] This effect is amplified at the pool level via the pool's net position. For the AMM, the vega is directly connected to the *impermanent loss (IL)*.[10] The vega for an individual position ($vega_{i,j}$) 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 $vega_{i,j}$ times a normalization factor $N_j = \frac{30}{T_j - t}$, where the latter incorporates the time-dependent risk profile of the 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 follows:

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

The vega utilization (VU_t) at time t quantifies in dollar terms the risk of changes in IV to the options AMM and 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 options AMM mitigates delta and vega risks—quantified as vega utilization—by incorporating their exposure into the fee imposed on trades, defined as follows:

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

[9] For example, if an option has a vega of 0.25 and the IV increases by 15%, the vega in dollar terms would be $0.25 \times 0.15 = 0.0375$ USD.

[10] The IL for an AMM is explained in Section 3.2.3 in more detail. For example, if the AMM sells a call with a vega of 0.0375 USD at 150 vol and buys it back for 165 it realizes a loss of 0.0375 USD $\times (165 - 150) = 0.5625$ USD.

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 (2016)).[11]

3.2.3 Liquidity Provision for Options

LPs deposit stablecoins as collateral (sUSD or USDC) for underwriting options. Even though the liquidity provision is in stablecoins, the LP is exposed to IL, which emerges through the change in the option price and not through the underlying token as when providing liquidity for token trading (see Milionis et al. (2023) and Li et al. (2023)).[12]

The LPs can deposit or withdraw funds only three days in advance after they signal their intention. 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 (see Appendix I.2). For withdrawal, there is a fee of 0.3%.

3.2.4 Trading Options

When traders open a long position, they pay the option price to the liquidity pool. When a trader opens a short position, the option price received is kept as collateral. If this collateral drops below the minimum requirement, bots called *keepers* can trigger liquidation of the position.[13] During liquidation, the trader is compelled to repurchase the option in a manner that benefits (in expectation) the options AMM. Subsequently,

[11]In 2022, the protocol introduced a Variance Fee, as detailed in Appendix I.1.

[12]The IL occurs when the prices (IV) of the options in the liquidity pool change. Because liquidity was provided at a specific IV, the AMM will adjust the IV in the pool to reflect the new prices. Hence, the IL is the adverse selection faced by LPs. If in periods of market turmoil, the "true" IV 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 IL on Lyra is analyzed in great detail in Dawson et al. (2021a).

[13]The liquidation engine is explained in greater detail in Appendix I.3.

a flat percentage is deducted from the trader's remaining liquidity, with this penalty being distributed among the liquidator, the AMM, and the security module, which is a mechanism that secures the protocol in a shortfall event.[14] 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 payoff, and, hence, only the quoted asset can be deposited. Traders cannot open positions in options with less than 12 hours to expiry or with absolute deltas outside the 10-90 range, excluding extremely deep ITM and OTM options.

4 Data and Methodology

We obtain Off-Chain option data through amberdata,[15] encompassing trades at a tick level and hourly quotes. The dataset spans multiple CEXs and includes BTC and ETH as underlying. The On-Chain data is obtained directly from the respective DEX using the methodology provided by The Graph, a protocol that helps access information on the Ethereum blockchain via their querying language (GraphQL). For Lyra, we source trades at a tick level and hourly quotes.[16] We calculate the relevant fields for our analysis, such as the IV and the options Greeks. We follow this procedure for Lyra Version 1 and Version 2, and Arbitrum and Optimism respectively. Our examination focuses on ATM and OTM options with a maturity between 7 and 30 days.

The On-Chain and Off-Chain options (trades and quotes) are matched based on their underlying, time to expiry, strike price, type, and observation time.[17] The hourly recording of On-Chain and Off-Chain quotes enables perfect matching. For tick-level trades, we limit the observation time difference between On-Chain and Off-Chain options to no

[14] The security module is explained in greater detail in Appendix I.4.

[15] Source: `https://www.amberdata.io/`.

[16] At the end of 2023, Lyra transitioned from using an AMM to an off-chain order book. As a result, we only consider data up to that point.

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

more than one hour. By doing so we ensure that the On-Chain option and the Off-Chain option truly represent the same contract.

The net buying pressure (NBP) following Bollen and Whaley (2004) for a given option type, and the moneyness group is defined as

$$\text{NBP}_t = \frac{(\text{Buy Volume}_t - \text{Sell Volume}_t) \times \text{Abs Delta}_t}{\text{Total Volume}_t}. \tag{4.1}$$

We source the time series of daily transactions on Ethereum per day (TxGrowth) and the total number of contracts verified daily (# Contracts) from Etherscan.io. The crypto fear and greed index (FearGreed) is obtained from alternative.me. We rescale the index ranging from -100 to 100 by multiplying the index by two and subtracting 100 from it. Negative values of the index indicate fear while positive values indicate greed. We obtain price data for the native governance token of the Lyra protocol (LYRA) on a tick level from dex.guru. We source the underlying volume for ETH and BTC from coinmarketcap.

In the empirical analysis presented next, we focus on Lyra V2 on Arbitrum, because data availability and trading activity are the highest. The results for Lyra V1 and Lyra V2 on Optimism can be found in the robustness section.

5 Facts – On-Chain and Off-Chain Derivatives Trading

5.1 Lyra – Summary Statistics

Our analysis begins with a basic overview of Lyra. Figure 5.1 presents key quantities for Lyra pools over time.[18] As shown in Panel (a), most traded options are on ETH (on average 75.68%). The fees that the pool generates are displayed in Panel (b): For ETH (BTC), the average is 1996.19 USD (585.24 USD) per day, with the fees distributed to the LPs. Panel (c) displays the daily pool volume, which is 1,528,985.80 USD (477,946.61

[18] As depicted in Figure B.1, Panel (a) illustrates that traders incur a net loss, totaling $-261,977$ USD. In contrast, Panel (b) shows that liquidity provision yields an overall return of 3.18% for ETH, while BTC experiences a decline of -2.69% over the sample period.

USD) for ETH (BTC). Finally, from Panel (d) 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 shown, the pool's composition is time-varying, which underlines the importance of the inventory risk for the AMM and, ultimately for the LP.[19] The prevalence of long call trades suggests that demand pressure influences option prices and implied volatility—a hypothesis we will confirm later.

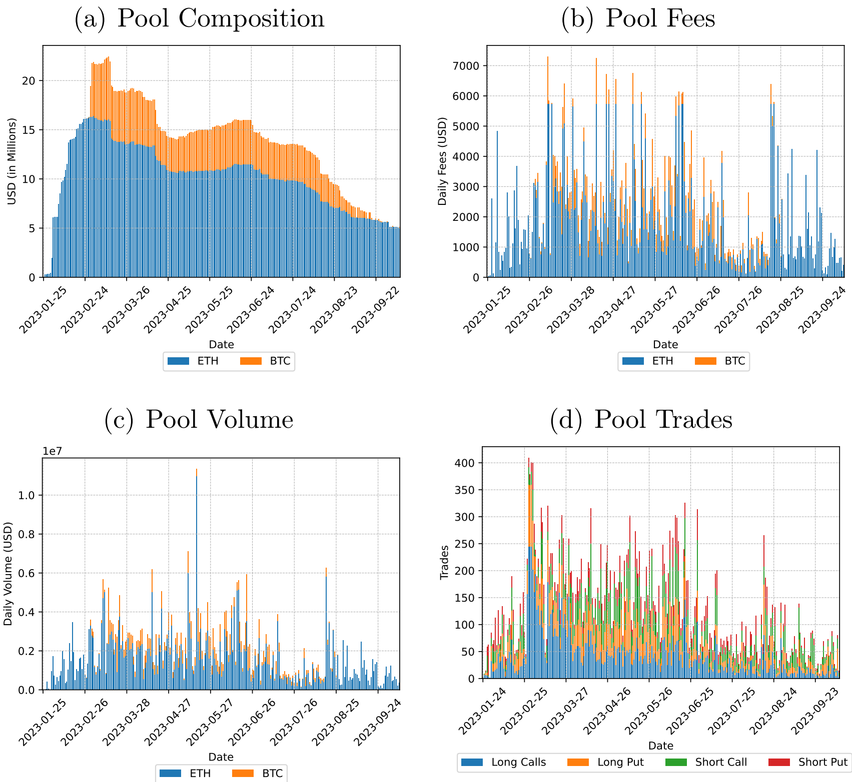


Figure 5.1: Lyra Stats - Pool Overviews. The figure shows key quantities for Lyra pools over time: Pool Composition (Panel (a)), the daily occurring total Pool Fees (Panel (b)), daily Pool Volume (Panel (c)), and the Pool Trades (Panel(d)). The data is from Lyra on Arbitrum and winzorized at the 1% quantile. The sample period ranges from 01-2023 to 11-2023.

[19] Figure B.3 shows the net Greeks of the ETH and BTC liquidity pools over time, offering insights into their AMM risk profiles. On average, the ETH pool shows a near-linear relationship with a delta of 1.992, while the BTC pool has a lower delta of 0.043, indicating less sensitivity to price changes. The pool Vega for BTC is on average even lower, at -374.286, compared to ETH's -311.571, indicating a greater decrease in option value for the same volatility increase. The gamma for the ETH pool (-1.598) suggests a decrease in delta as ETH's price rises (the BTC pool has a gamma of -0.004).

5.2 Strikes

Figure 5.2 illustrates the availability of strikes On-Chain and Off-Chain for each underlying over time. A noticeable discrepancy is evident: In the case of BTC, Off-Chain trading sees an average of 51 strikes quoted, whereas On-Chain trading registers only around 16 strikes quoted. Similarly, for ETH, Off-Chain there are 37 quoted whereas On-Chain trading shows only about 19 strikes quoted.

(a) BTC Quotes: Strikes

(b) ETH Quotes: Strikes

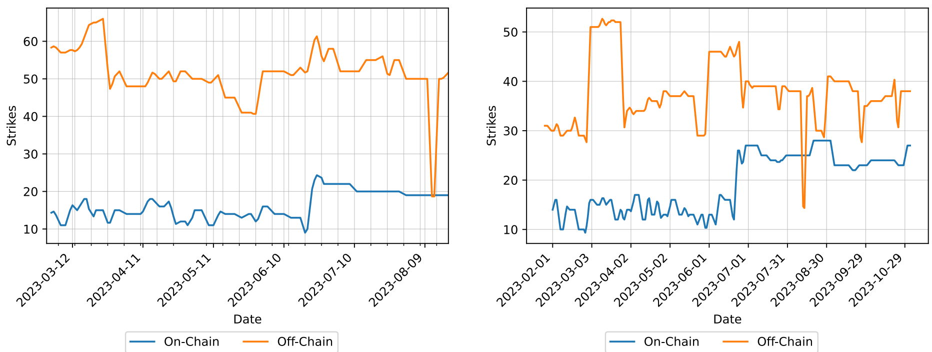


Figure 5.2: On-Chain and Off-Chain – Available Strikes over Time. The figure shows the total number of quoted strikes from calls and puts, On-Chain, and Off-Chain, averaged for each day. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The quotes are given at an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

5.3 Margin Requirements

In the following, we compare the maintenance margin (MM) and initial margin (IM) On-Chain and Off-Chain. Let β be the out-of-the-money amount ($K - S$ for call options and $S - K$ for put options). The margin requirements for On-Chain vs. Off-Chain are stated in Table 5.1. For example: An OTM BTC call with a strike at 75k USD and a spot price of 70k USD with a monthly maturity and an IV of 0.6 would result in an IM of 0.170 (On-Chain) vs. 0.140 (Off-Chain). In USD terms this equals 11962 USD vs. 9862 USD, and hence corresponds to a substantial difference of over 2000 USD.

We extend this example by comparing the margins (in USD) for different OTM levels for BTC and ETH, as displayed in Figure 5.3. As visible the difference in margin between

Platform	Option Type	MM	IM
On-Chain	Call	$0.09 + W$	$W + \max(0.15 - \frac{\beta}{S}, 0.13)$
Off-Chain	Call	$0.075 + W$	$W + \max(0.15 - \frac{\beta}{S}, 0.1)$
On-Chain	Put	$\max(0.09, 0.09 \times W) + W$	$\max(W + \max(0.15 - \frac{\beta}{S}, 0.13), 1.05\text{MM})$
Off-Chain	Put	$\max(0.075, 0.075 \times W) + W$	$\max(W + \max(0.15 - \frac{\beta}{S}, 0.1), \text{MM})$

Table 5.1: Margin Requirements – On-Chain vs. Off-Chain. The table reports the maintenance and initial margin requirements for Lyra and Deribit. Thereby W is the option price in numeraire (BTC or ETH), β is the out-of-the-money amount, and S is the underlying price.

On-Chain and Off-Chain is widening for options further OTM.

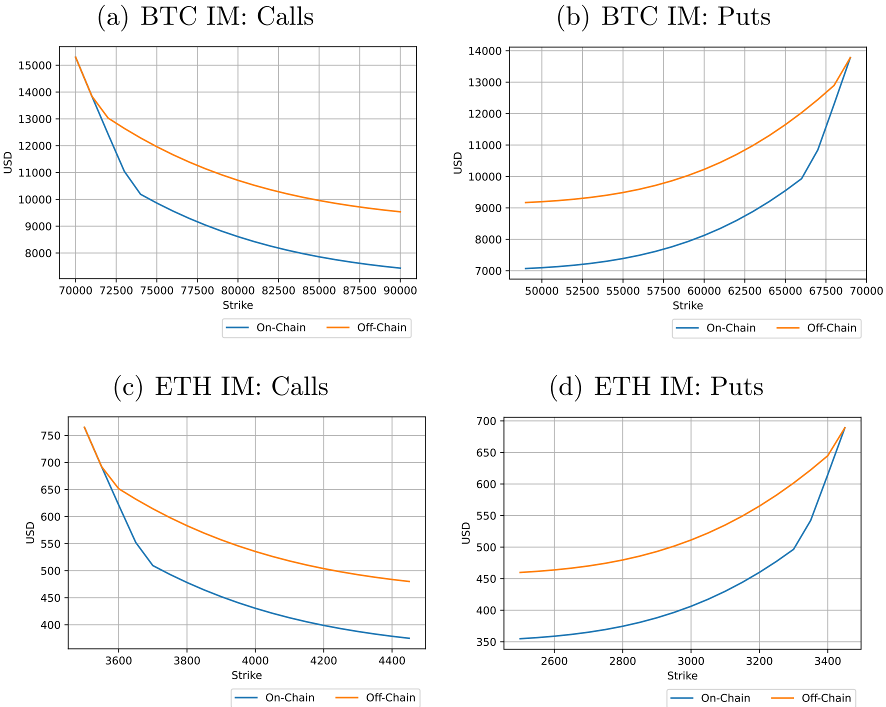


Figure 5.3: Initial Margin – On-Chain vs. Off-Chain. The figure shows the initial margin (IM) requirements for Lyra and Deribit for different option types (call or put) and different strike prices. The margin is calculated following the equations in Table 5.1. The option price is calculated with Black and Scholes (1973).

5.4 Transaction Fees

Figure 5.4 depicts the trading fees for a liquidity taker On-Chain and Off-Chain for BTC (Panel (a), and Panel (b)) and ETH (Panel (c), and Panel (d)), respectively. The

Lyra fees are defined as in equation (3.6) and the Deribit fees, as introduced in Section 3.1, are computed as

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

where S_t is given in USD and x_t is the trade size. Overall, for BTC, trading On-Chain is cheaper than Off-Chain: The trading fees per unit (total fees per trade divided by the trade size) On-Chain are on average 30.14 USD, while the Off-Chain average is 44.65 USD. The disparity in trading fees is less pronounced for ETH, with 1.87 USD for On-Chain and 0.76 USD for Off-Chain transactions.[20]

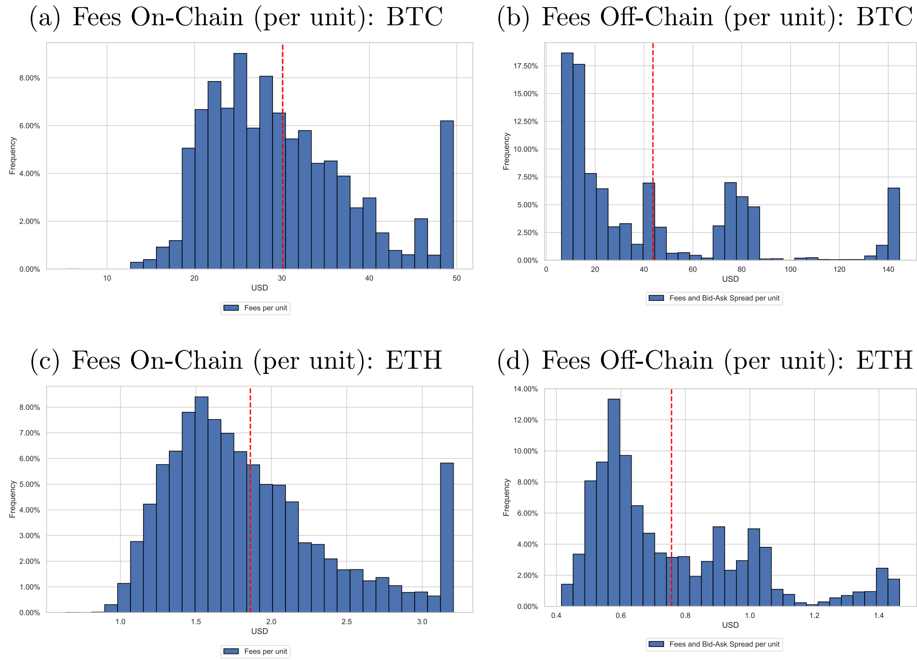


Figure 5.4: Transaction Fees – On-Chain vs. Off-Chain. The figure shows the histogram of the trading fee per unit for BTC (Panel (a) and Panel (b)) and for ETH (Panel (c) and Panel (d)), On-Chain, and Off-Chain. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The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

Figure 5.5 displays the individual components of the respective On-Chain trading fees.

[20] Figure B.2 displays the total trading fees: For BTC, trading fees On-Chain are on average 18.20 USD, while Off-Chain they are 26.24 USD. For ETH, the differences in trading fees are comparable: 12.97 USD (On-Chain) vs. 11.83 USD (Off-Chain).

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 shown in 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).

(a) Fees Components On-Chain: BTC (b) Fees Components On-Chain: ETH

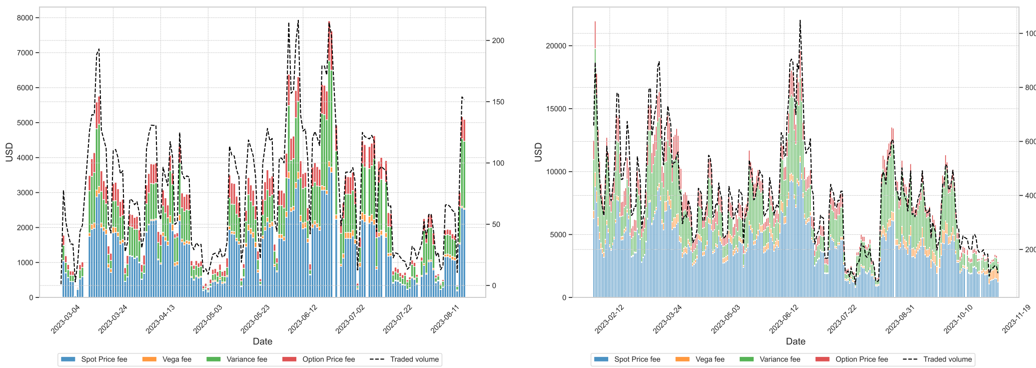


Figure 5.5: Fee Components – On-Chain. The figure displays the fee components and volume (dashed line) for BTC (Panel (a)) and ETH (Panel (b)) in USD. The components of the fees are explained in equation (3.6). The On-Chain data is from Lyra on Arbitrum. The trade data is sampled on a tick level and is winzorized at the 5% quantile. The sample period ranges from 02-2023 to 11-2023.

5.5 Trading Statistics

We present average traded premia and size in Table 5.2. For BTC, the average call (put) premium is 352.60 USD (394.84 USD). Similarly, for ETH, the average call (put) premium is 298.96 USD (324.71 USD). For BTC, the average call size is 0.62, and the put size is slightly larger at 0.77. Given the lower price of ETH, the contract sizes are larger, with call contracts averaging at 6.86 and put contracts at 8.74. The statistics suggest that mostly retail traders are active in these markets. However, in the 95th percentile, contract sizes for both ETH and BTC options indicate larger quantities: for BTC, both call and put contract sizes are 2.00. In contrast, ETH contract sizes are 22.77 for calls and 30.00 for puts.

Statistic	BTC				ETH			
	Call		Put		Call		Put	
	Premium	Size	Premium	Size	Premium	Size	Premium	Size
Mean	352.60	0.62	394.84	0.77	298.96	6.86	324.71	8.74
5% Quantile	1.72	0.01	5.81	0.01	4.92	0.22	4.47	0.20
25% Quantile	27.29	0.10	46.82	0.13	48.09	1.00	28.36	1.00
50% Quantile	100.19	0.33	164.37	0.50	106.15	3.00	95.16	2.50
75% Quantile	336.88	1.00	466.82	1.00	243.14	8.00	236.27	10.00
95% Quantile	1290.71	2.00	1279.70	2.00	860.64	22.77	1074.36	30.00

Table 5.2: Summary Statistics – Traders. The table displays the summary statistics of the traded options, On-Chain, for BTC and ETH, and for calls and puts separately. The On-Chain data is from Lyra V2 on Arbitrum. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

6 Differences in IVs – On-Chain and Off-Chain

This section shows that On-Chain options consistently have higher IVs than Off-Chain options, with the gap widening for longer maturities and near-ATM options. To exploit this, we propose selling high-IV On-Chain options and buying low-IV Off-Chain options, with strategy returns driven by LYRA price and a Fear & Greed indicator, yielding higher profits during elevated LYRA prices or market fear.

We start by analyzing the difference between the On-Chain and Off-Chain IVs. Table 6.1 presents the summary statistics On-Chain and Off-Chain for trades and quotes. Unconditionally, the option prices and IVs are larger On-Chain, 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.[21]

To better understand the emergence of the difference in IV, the On-Chain and Off-Chain IVs from quotes for each underlying and averaged for different strikes and maturities are shown in Figure 6.1. As demonstrated, the On-Chain and Off-Chain IVs display a strong comovement and similarity in levels. Nevertheless, the IVs begin to diverge for low and high strike prices. Panel (c) and Panel (d) display the IVs averaged over maturities rather than of strikes. As previously, the On-Chain and Off-Chain IVs display a strong

[21]The results are similar considering the trade data as inferable from Table B.1.

	BTC		ETH	
	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 6.1: Summary Statistics – Quotes. The table displays the summary statistics of the quoted options, both On-Chain, and Off-Chain. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The quote data is given on an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

comovement even though the gap between the IVs is widening for longer maturity options and can reach up to 0.15-0.2.[22] We repeat the plots using trade data in Figure B.4, the results are qualitatively similar.

Next, we analyze the difference between On-Chain and Off-Chain IVs, both with and without fees. To obtain the IV with fees we recalculate the IV using the traded option prices including the occurred fees for the trade. We split the sample into On-Chain and Off-Chain trades and long and short trades. The results are displayed in Table 6.2: The IV with fees is on average four percentage points larger without fees for On-Chain long trades (0.5335 vs. 0.4931), which translates into a difference of more than eight percentage (in relative terms). In particular, the one-side t-test indicates that the IV with fees is on average larger than without fees. For On-Chain short trades, the difference is only significant at a 5% level.

[22]Figure B.5 resembles Figure 6.1 but for calls and puts separately and investigating only 7 and 30 days to maturity. As depicted, in Figure B.5 Panel (c) the gap between On-Chain and Off-Chain is the widest for far ATM calls, with a total difference of 0.15. For 30-day puts on ETH, Panel (h) displays a consistent positive gap between the On-Chain and Off-Chain IV. The pattern is less clear for puts on BTC, where the difference in IV is negative (positive) for low (high) strikes.

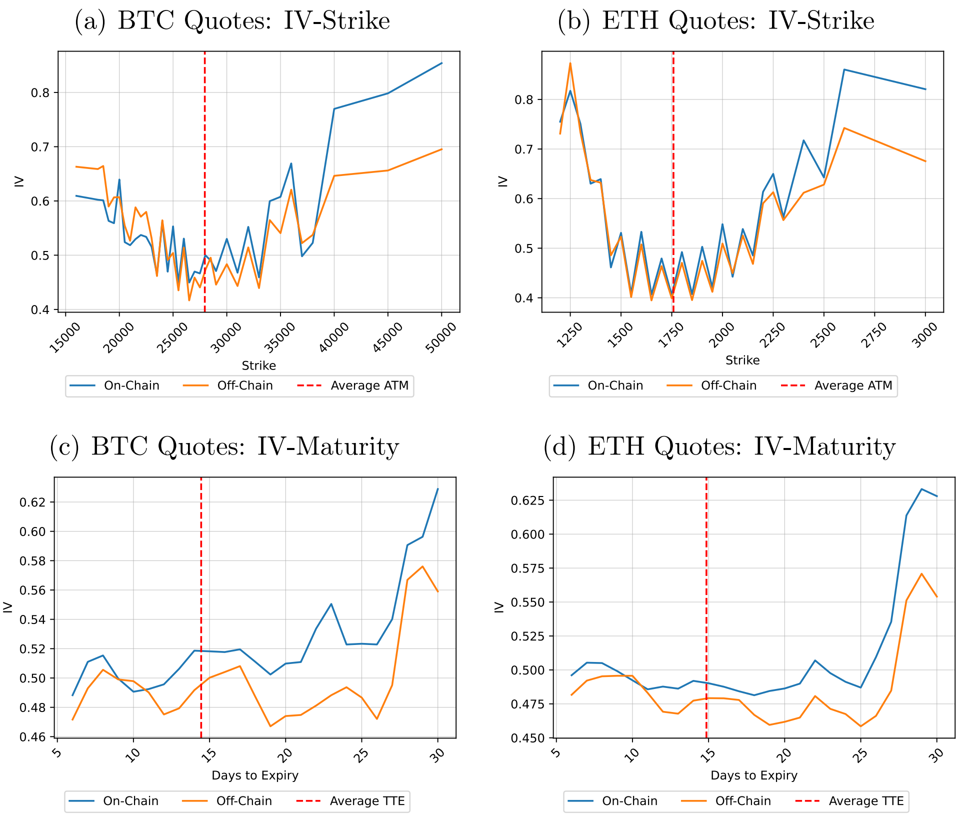


Figure 6.1: IV, Strike Price, and Maturity. The figure shows the quoted IV from calls and puts, On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The x-axis represents the strike price (USD) or the maturity (days). The quotes are given at an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

6.1 Regression Analysis

We expand on 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), the On-Chain fees, and the (absolute) Delta and Vega (see Section 3.2.2) that are relevant for the On-Chain option pricing. The Delta for OTM options ranges from 0 to 0.5; 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 fees and the pool's Delta and Vega risk, we especially focus

	IV with Fees	IV	t-stat	p-value
		BTC		
On-Chain Long	0.5121	0.4730	31.5050	0.0000
On-Chain Short	0.4768	0.4778	-0.8613	0.8055
Off-Chain Long	0.5072	0.4751	23.0722	0.0000
Off-Chain Short	0.4896	0.4569	25.2926	0.0000
		ETH		
On-Chain Long	0.5335	0.4931	54.1256	0.0000
On-Chain Short	0.5149	0.5137	1.8383	0.0330
Off-Chain Long	0.5083	0.4818	36.1128	0.0000
Off-Chain Short	0.5080	0.4794	42.7450	0.0000

Table 6.2: IV with Fees vs. IV without Fees – Summary Statistics. The table displays the average IV of the traded options, both On-Chain, and Off-Chain with and without fees. The t-stat and p-value are obtained from a one-sided t-test, testing the hypothesis that the IV with Fees is greater than the IV. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The trade data is on a tick level and the sample period ranges from 02-2023 to 11-2023.

on their coefficients and how they influence the difference in IVs.

We run the panel regression as outlined by equations (6.1)–(6.3). The difference in IV can be observed for each matched option-id over time. The first specification (6.1) regresses the differences in IVs simply on the options' key characteristics, where *Call* equals 1 if the option is a call (and 0 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 (6.2) regresses the differences in IVs on the options on the On-Chain Fees, the Off-Chain Quoted Spread (best ask - best bid), the On-Chain Size, or the On-Chain Scaled Fees (On-Chain Fees divided by trade size). The third specification (6.3) also takes into account the options Delta and Vega associated with the AMMs risk management engine:

$$\text{Diff IV}_{i,t} = \beta_0 + \beta_1 \text{Call}_i + \beta_2 \text{Maturity}_{i,t} + \beta_3 \text{Mness}_{i,t} + \epsilon, \tag{6.1}$$

$$\text{Diff IV}_{i,t} = \beta_0 + \beta_1 \text{On-Chain Fees}_{i,t} + \beta_2 \text{Off-Chain Fees}_{i,t} + \beta_3 \text{On-Chain Size}_{i,t} + \epsilon. \tag{6.2}$$

$$\text{Diff IV}_{i,t} = \beta_0 + \beta_1 \text{Abs. Delta}_{i,t} + \beta_2 \text{Vega}_{i,t} + \epsilon. \tag{6.3}$$

Tables 6.3 present the regression results for BTC and ETH trades, indicating that the gap in IV tends to increase for longer-dated options, those closer to ATM, and for calls. Larger On-Chain fees increase the difference in IVs, while a larger Quoted Spread Off-Chain decreases the gap. Consistently, increases in On-Chain trade size and On-Chain Scaled Fees both contribute positively to the difference in IV. Furthermore, an increase in absolute delta toward ATM and higher Vega widen the IV gap. In most specifications, the significance of the coefficients with BTC as underlying is not as strong as for ETH.

Table B.2 provides the results of a similar regression analysis but for quotes rather than trades. In addition, the findings remain consistent even with the inclusion of fixed effects as visible from Table B.3. Overall the results largely mirror those observations presented in the main part of the paper. However, there are some notable differences, specifically, the significance of the Call and Absolute Delta coefficients (including fixed effects) diminishes for BTC trades.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Panel A: BTC					
Intercept	-0.40036	-0.41717	-0.40165	-0.42275	-0.05484
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	-0.00040	-0.00045	-0.00033	-0.00027	
	(0.68057)	(0.63454)	(0.73471)	(0.77794)	
Maturity	0.00363	0.00374	0.00364	0.00379	
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	
Mness	0.39392	0.42059	0.39497	0.42749	
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	
On-Chain Fees		0.00003			
		(0.14231)			
Off-Chain Quotes Spread		-0.00104		-0.00104	
		(0.00000)		(0.00000)	
On-Chain Scaled Fees				-0.00005	
				(0.35064)	
On-Chain Size			0.00071	0.00103	
			(0.32771)	(0.15138)	
Abs. Delta					0.03363
					(0.00000)
Vega					0.00004
					(0.00000)
Adj. R-squared	0.0905	0.1277	0.0910	0.1280	0.1132
Observations	25847	25847	25847	25847	25847
Panel B: ETH					
Intercept	-0.35380	-0.36579	-0.35664	-0.34249	-0.04622
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.01167	0.01130	0.01179	0.01090	
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	
Maturity	0.00194	0.00194	0.00195	0.00188	
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	
Mness	0.36788	0.38392	0.37024	0.35213	
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	
On-Chain Fees		0.00004			
		(0.00000)			
Off-Chain Quotes Spread		-0.00602		-0.00629	
		(0.00000)		(0.00000)	
On-Chain Scaled Fees				0.00451	
				(0.00000)	
On-Chain Size			0.00006	0.00002	
			(0.00001)	(0.09066)	
Abs. Delta					0.13586
					(0.00000)
Vega					0.00031
					(0.00000)
Adj. R-squared	0.0843	0.1042	0.0846	0.1058	0.1910
Observations	146438	146438	146438	146438	146438

Table 6.3: Regressions – IV – On-Chain vs. Off-Chain – BTC and ETH – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (6.1) - (6.3). Thereby *Call* equals 1 if the instrument is a call, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. Fees, Size, Abs. Delta and Vega are constructed from the trade data. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

6.2 Trading Strategy

We capitalize on disparities in IV between On-Chain and Off-Chain options, selling those with relatively higher IV On-Chain and buying those with comparatively lower IV Off-Chain, aiming to exploit this pricing differential. Since we buy and sell the same option, the payoffs at the maturity offset each other. We construct the strategy on a weekly frequency at 10:00 am. We implement this strategy separately for 7 and 15 days to maturity, for puts and calls, and for different moneyness levels (ranging from 0.9 to 1).

We consider quotes to construct our trading strategy and, initially, we neglect the influence of transaction costs. The P&L of the strategy (in ETH) is shown in Figure 6.2 for calls in Panel (a) and Panel (b) and for puts in Panel (c) and Panel (d). Based on the regression findings outlined in Section 6.1, which demonstrate a greater discrepancy in IV for options nearing ATM, the trading strategy tends to yield higher returns for moneyness levels closer to 1 (ATM).

Transaction costs can erode profits if not accounted for, so we evaluate the trading strategy's performance with transaction costs included. We estimate an average fee from the trade data, which we apply for the construction of our trading strategy based on the quotes data. By doing so, we incorporate the fee structure On-Chain. We estimate the average transaction fees for sell 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 rather than the mark price as before, including a fee of 0.0003 ETH. Therefore, when constructing the trading strategy one receives the premium net of fees from selling On-Chain and pays the premium, including fees from buying Off-Chain. The P&L (net of fees) of the strategy (in ETH) is shown in Figure 6.3. As shown, the strategies suffer dramatically from the transaction costs and are less profitable. For the trading strategy with the low maturity (Panel (a)), the P&L stagnates over time. The trading strategy for the options with a maturity of 15 days remains profitable but only

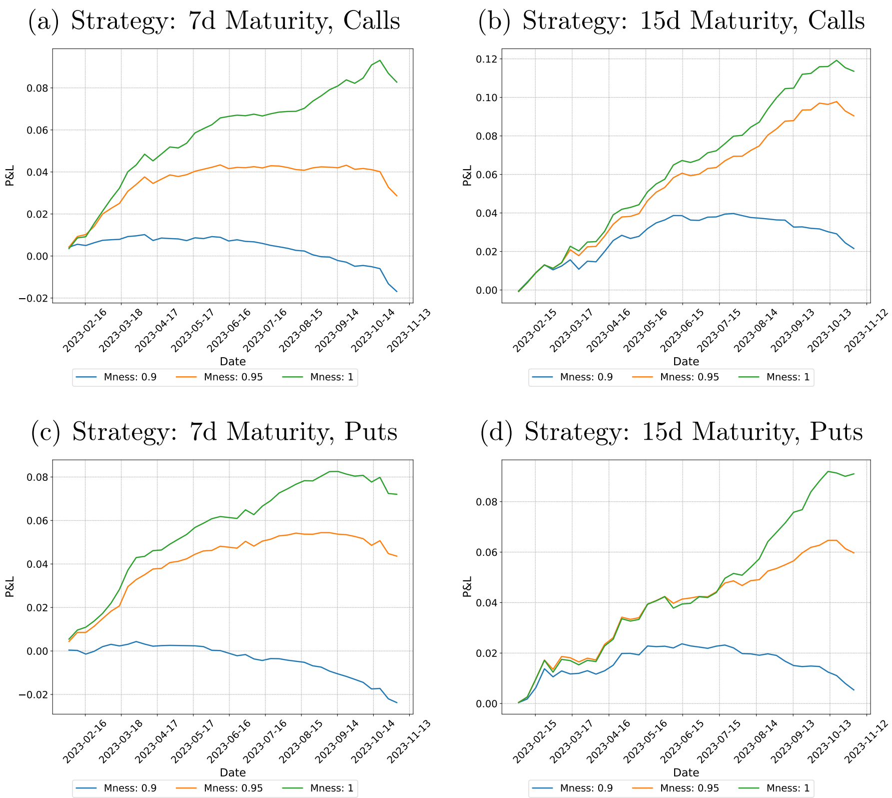


Figure 6.2: Strategy – ETH – Quotes. The figure displays the P&L (in ETH) of the trading strategy selling the On-Chain (calls or puts) and buying the Off-Chain (calls or puts) for a given maturity and moneyness. The On-Chain data is from Lyra on Arbitrum, the Off-Chain data is from Deribit. The y-axis represents the cumulative P&L in ETH. The trading strategy is constructed on a weekly frequency at 10:00 am. The sample period ranges from 02-2023 to 11-2023.

for the highest moneyness range (ATM). To some extent, our results confirm the "limit to arbitrage" hypothesis (Shleifer and Vishny (1997)).[23]

6.2.1 Regression Analysis

In the next part of this empirical analysis, we perform a time series regression to uncover the origin of the return of the outlined investment strategy. We estimate the following two time-series models:

$$Ret_{t,i} = \beta_0 + \beta_1 \text{Delta (Pool)}_{i,t} + \beta_1 \text{Vega (Pool)}_{i,t} + \beta_2 \text{Underlying Volume}_{i,t} + \beta_3 \text{NBP}_{i,t} + \varepsilon_{i,t} \tag{6.4}$$

[23]In Figure III.10 we report the P&L of the trading strategy using trade data and incurred transaction fees. The performance is in between the trading strategy from quotes without and with transaction fees.

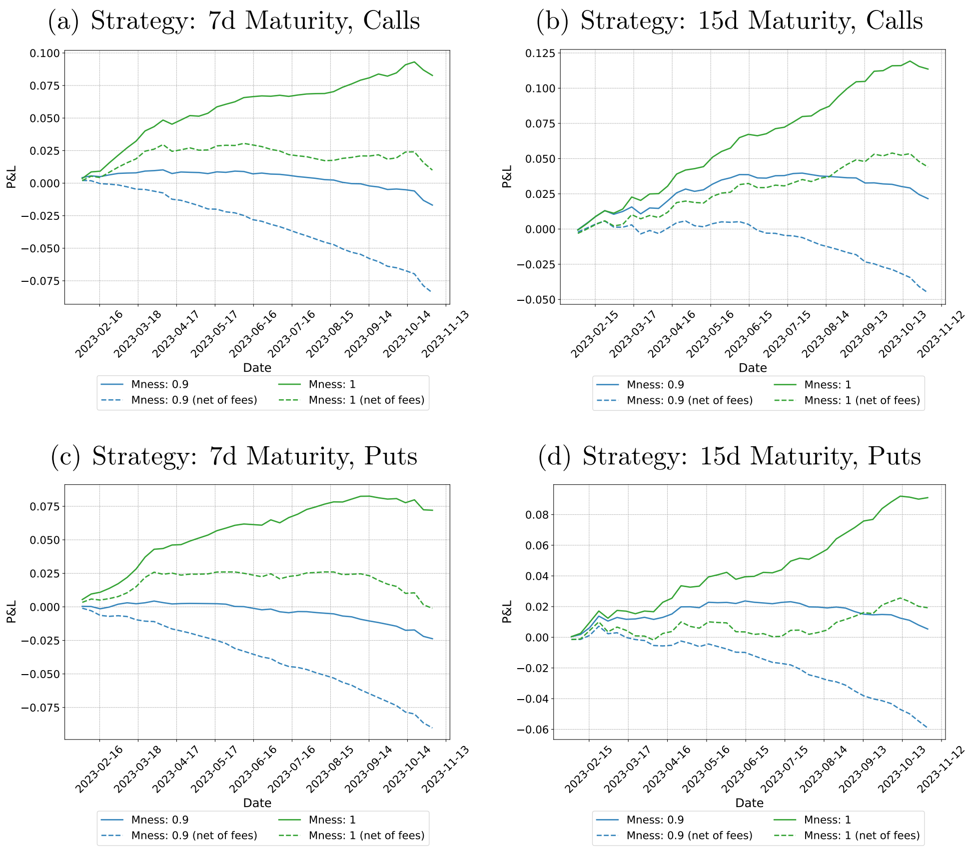


Figure 6.3: Strategy – Quotes with Fees. The figure displays the P&L (in ETH) of the trading strategy (net of fees) selling the On-Chain (calls or puts) and buying the Off-Chain (calls or puts) for a given maturity and moneyness. The fees are estimated On-Chain as the average fees from the respective sell trades and Off-Chain as 0.0003 ETH. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The y-axis represents the cumulative P&L in ETH. The trading strategy is constructed on a weekly frequency at 10:00 am. The sample period ranges from 02-2023 to 11-2023.

$$Ret_{t,i} = \beta_0 + \beta_1 \text{LYRA}_{i,t} + \beta_1 \text{TxGrowth}_{i,t} + \beta_2 \#\text{Contracts}_{i,t} + \beta_5 \text{FearGreed}_{i,t} + \varepsilon_{i,t} \tag{6.5}$$

where $Ret_{t,i}$ represents the weekly return in percentage (based on the cumulative P&L in ETH) of strategy i, where i denotes the strategies utilizing either calls or puts, with maturities of 7 and 15 days. As explanatory variables, we consider the aggregated Delta (Pool) and Vega (Pool) of the liquidity pool, Underlying Volume, the NBP (as calculated in equation (4.1)), LYRA (the USD price of the native governance token of the Lyra protocol), the transactions on Ethereum per day (TxGrowth), the verified Ethereum contracts (# Contracts), and the rescaled crypto fear and greed index (FearGreed). Section 4 provides a more detailed description of the variables.

The results for the regression as outlined in equation (6.4) show that none of the exchange-related measures can explain the returns from the trading strategy, as presented in Table B.4. The results of the second specification appear more relevant (equation (6.5)) as shown in Table 6.4. The coefficient on the LYRA token is positive and significant meaning that the strategy delivers a higher return whenever the LYRA token price is high: The price of the LYRA token represents the expected value of all the future profits from the protocol and depends on the platform's productivity (Cong et al. (2021)). FearGreed displays a negative and significant coefficient, meaning that whenever the index sentiment is greed the return of the strategy is low. The other way around, high fear (negative index values) corresponds to a larger return on the strategy: During times of fear, higher expected returns are required to compensate investors for the additional risk when investing in riskier strategies.

	Call		Put	
Variable	7	15	7	15
LYRA	537.1840	-1304.7638	361.9476	2098.1037
	(0.010)	(0.259)	(0.000)	(0.012)
TxGrowth	-0.0000	0.0001	0.0000	-0.0001
	(0.136)	(0.146)	(0.353)	(0.205)
# Contracts	-0.0494	0.3492	-0.0443	-0.4930
	(0.557)	(0.255)	(0.200)	(0.040)
FearGreed	-0.2818	-0.8912	-0.1999	0.2921
	(0.041)	(0.152)	(0.010)	(0.538)
Rsquared	0.48	0.21	0.66	0.54
Adj. R-squared	0.42	0.12	0.62	0.48
Observations	39.00	39.00	38.00	39.00

Table 6.4: Timeseries Regressions – Strategy – Protocol Specific Regressors. The table reports the results, that is, the coefficient and the p-values in brackets from the regression as specified in (6.5). The columns show the returns from selling On-Chain (call or put) ATM options and buying Off-Chain (call or put) ATM options for a given maturity. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. As explanatory variables, we consider LYRA (in USD), the daily transactions on Ethereum per day (TxGrowth), the daily verified Ethereum contracts (# Contracts), and the rescaled crypto fear and greed index (FearGreed). A more precise description of the variables is given in Section 4. The sample period ranges from 02-2023 to 11-2023.

6.3 Bear Markets

In the next step, we investigate the difference in IV (On-Chain vs. Off-Chain) for the three worst days of the respective underlying. For each day we select the option with the largest positive difference in IV. The results are presented in Figure 6.4, 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 calls. 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), and (c) 2023-05-01 (-0.05).[24] Evidently, there is a strong increase in IV when the underlying experiences a large drawdown (leverage effect). The effect is amplified for options traded On-Chain. For example, in Panel (c), the call (BTC-30000-12052023-call) with a strike price of 30000 and maturity of eleven days displays a jump in IV from around 0.50 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), and (c) 2023-02-09 (-0.071).[25] The results are presented in Figure 6.4 and are qualitatively similar. For dates with a lower drawdown in the underlying (Panel (f)), the Off-Chain IV almost does not respond.

6.4 VAR Model – AMM Mechanism

To shed light on the pricing mechanism of the AMM w.r.t the multivariate fee structure, and to contrast it with the pricing mechanism Off-Chain, we estimate a Vector Autoregressive Model (VAR) which is defined as

$$y_t = c + A_1 y_{t-1} + ... + A_p y_{t-p} + e_t, \tag{6.6}$$

[24]The collapse of the Silicon Valley Bank occurred on March 9, 2023. On June 5, 2023, the U.S. securities regulator filed a lawsuit against the crypto exchange Binance. On May 1, 2023, Bitcoin's price fell after the Federal Reserve decided to maintain current interest rates.

[25]On August 17, 2023, the cryptocurrency market crashed due to rising U.S. bond yields and regulatory uncertainties surrounding the crypto industry. On February 9, 2023, the Biden administration faced accusations of discreetly attempting to ban Bitcoin, Ethereum, and other cryptocurrencies.

(a) BTC: 2023-03-09 (b) BTC: 2023-06-05 (c) BTC: 2023-05-01

(d) ETH: 2023-08-17 (e) ETH: 2023-03-09 (f) ETH: 2023-02-09

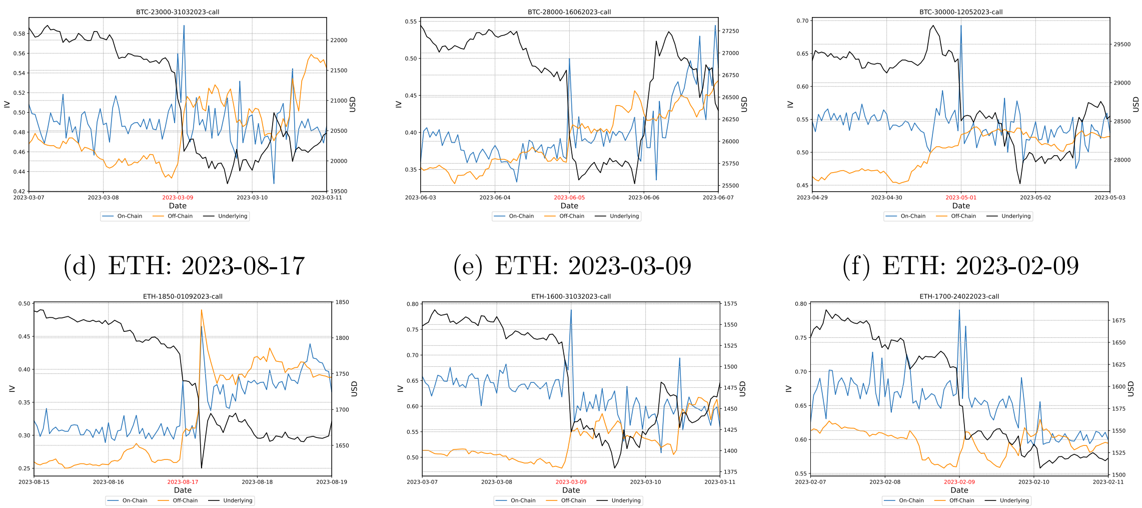


Figure 6.4: Market Stress and IV – On-Chain vs. Off-Chain – BTC and ETH. The figure displays the IV for the selected option-ids (chosen for their largest IV differences) before and after the underlying's drawdown. For BTC, the worst days in our sample were (a) 2023-03-09 (-0.068), followed by (b) 2023-06-05 (-0.058), and (c) 2023-05-01 (-0.05). For ETH, the worst days in our sample were (a) 2023-08-17 (-0.12), followed by (b) 2023-03-09 (-0.076), and (c) 2023-02-09 (-0.071). The quote data is given at an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

where the optimal lag order of the model is selected w.r.t the AIC. The data input is a vector of time series variables, that are IV, Option Price Fee, Spot Price Fee, Variance Fee, Vega Fee, and the Volume. We rescale the fees by dividing the fee per trade by the trade size. We do not include the Underlying Return given the high correlation with the Spot Price Fees, and we exclude the Vega which is highly correlated with the Vega Fees. The trade data is aggregated across option-ids and resampled at an hourly frequency. We estimate a VAR for each option type (call or put), for buy and sell orders, and for On-Chain and Off-Chain trades separately. We estimate the Off-Chain VAR including the IV, the Bid-Ask Spread, and the Volume. We focus on ETH; the results for BTC are in Appendix B.4 and are qualitatively similar but display on average less significance.

First, we formally conduct a test for Granger causality, which assesses whether past values of our system have predictive power over future values of IV, suggesting a causal relationship between them. For On-Chain long calls, Granger causality is evident for the Spot Price Fee, Option Price Fee, and Volume. For long puts, On-Chain Granger causality is observed for the Option Price Fee, Variance Fee, Vega Fee, and Volume. Off-Chain, the Granger causality analysis reveals that neither the Bid-Ask Spread nor the Volume exhibits a causal relationship with the subsequent IV.

Figure 6.5 and Figure 6.6 display the impulse response functions (IRFS) of the ETH IV for long calls (left panels) and long puts (right panels). From Figure 6.5 (left panels – calls), one can infer that the Option Price Fee, the Spot Price Fee, and the Vega Fee increase the successive IV. For the right panel (puts), the results are qualitatively similar, with the addition that the Vega Fee displays significance over the full horizon. Off-Chain (Figure 6.6) the Bid-Ask Spread and the Volume affect the IV positively but without displaying any significance.[26]

To summarize the main difference in our findings: On-Chain, the traded IV is positively affected by the fees and the trading volume, contrary to Off-Chain, where the volume nor the bid-ask spread affect the IVs. On-Chain an increase in the Option Price Fee, and the Vega Fee increases successive IVs.

6.5 IVs and Net Buying Pressure (NBP)

We examine the relation between NBP and the Delta IV, which denotes the daily changes in the average of the daily traded IV across all traded options in the same quantile and type. The regression specification is

$$\begin{aligned}\text{Delta IV}_t = \beta_0 + \beta_1 \text{Underlying Return}_t + \beta_2 \text{Underlying Volume}_t \\ + \beta_3 \text{Net Buying Pressure}_t + \beta_4 \text{Delta IV}_{t-1} + \epsilon.\end{aligned} \tag{6.7}$$

[26] In Internet Appendix II.1, we report a VAR without the fees, consisting of the IV, Delta, Vega, Underlying Return, and Volume. On-Chain, for long calls, Granger causality is evident for the Vega and Volume. For long puts, Granger causality is also given for Delta. The IRFS for the alternative specification are displayed in Figure II.1. For long calls, the Vega, the Underlying Return and the Volume increase the successive IV. For long-puts, the results are similar. We repeat the analysis for Off-Chain trades: For long calls the Delta, Vega, Underlying Return, and Volume, Granger causes IV. For long puts only the Delta Granger causes IV. The IRFS are displayed in Figure II.2. We repeat the analysis for BTC and report the results in the Internet Appendix II.2.

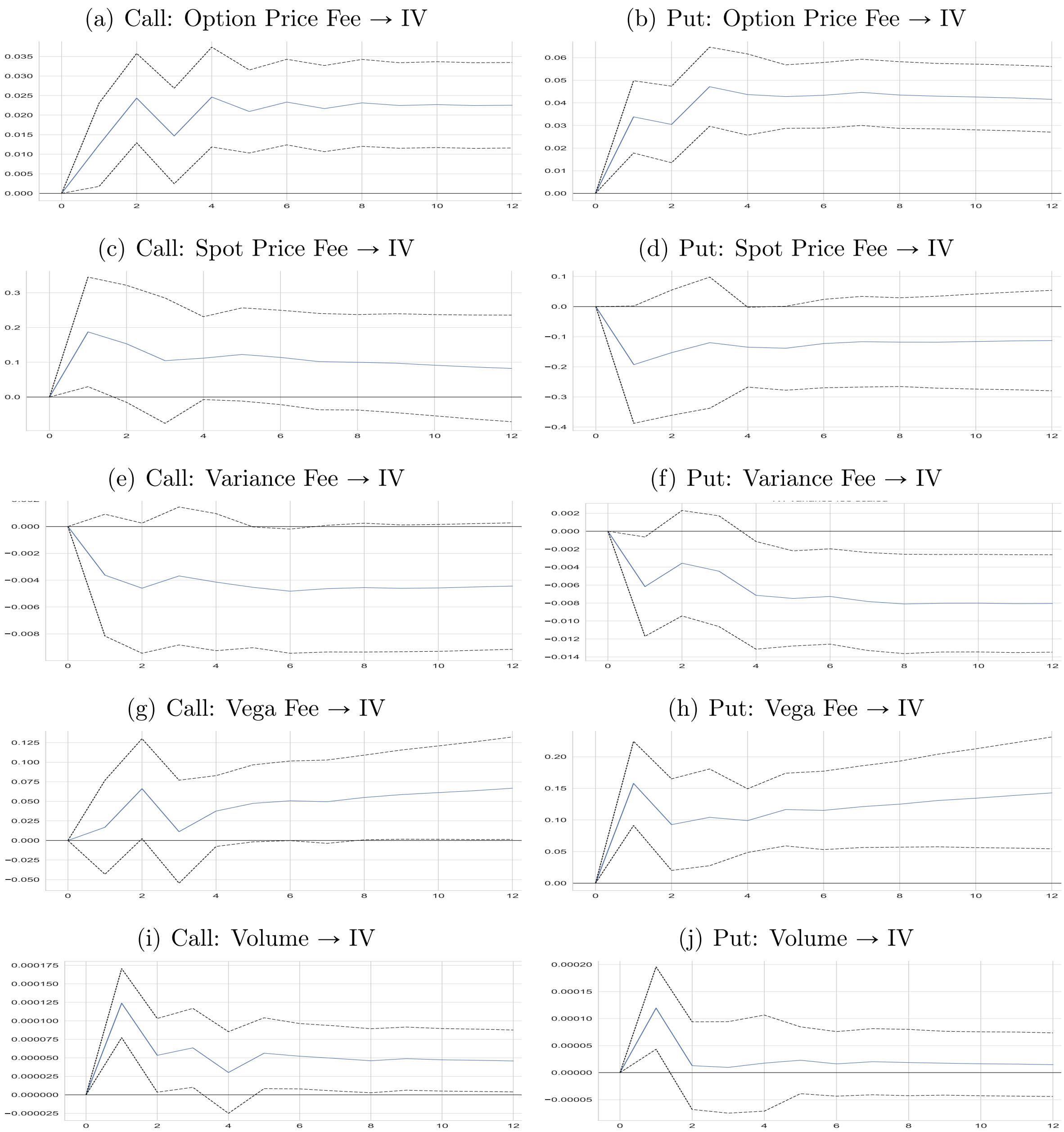


Figure 6.5: On-Chain – ETH – Long Call and Long Put. The figure displays the IRFS of the traded ETH IV for long calls (left panels) and long puts (right panels). The components of the fees are mentioned in equation (3.6). Volume denotes the aggregate of traded volume. The On-Chain data is from Lyra on Arbitrum. The trade data is sampled hourly, and the sample period ranges from 02-2023 to 11-2023.

We perform this regression separately for three different moneyness quantiles (deep OTM, OTM, and ATM), and for calls and puts. We standardize all variables to have unit root and zero mean. Table 6.5 presents the results for ETH traded On-Chain (Panel A) and

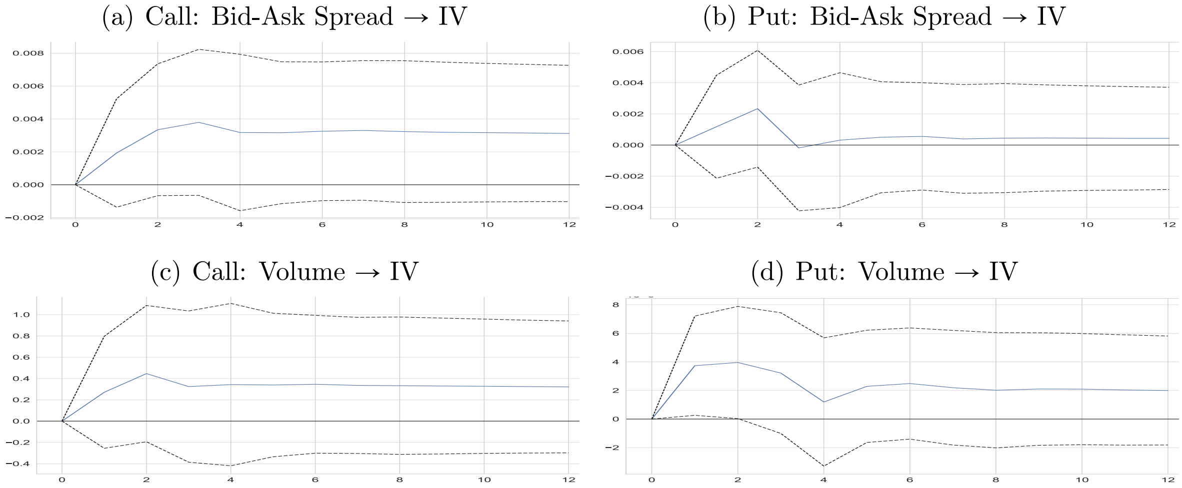


Figure 6.6: Off-Chain – ETH – Long Call and Long Put. The figure displays the IRFS of the traded ETH IV for long calls (left panels) and long puts (right panels). The Volume is calculated as aggregated from the options. The fees are calculated as the Bid-Ask-Spread. The Off-Chain data is from Deribit. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

Off-Chain (Panel B): On-Chain, the NPB positively affects OTM calls (Columns 1 and 2), ATM options (at a 10% significance), and deep OTM puts (Column 4). Off-Chain the NPB displays significance only for deep OTM calls (Column 1) and deep OTM puts (Column 4).[27] The findings suggest that changes in IV are directly linked to NBP from public order flow.

7 Theoretical Explanation

In the following, we present a theory explaining our main finding that the IV On-Chain exceeds the IV Off-Chain. Adapting the Stoll (1978) model as in de Jong and Rindi (2009), the AMM operates as a monopolistic dealer, offering investors immediate liquidity while accounting for real costs, such as inventory. In contrast, on a CEX, trading takes place in a LOB, where investors provide liquidity through limit orders, incurring both real and informational costs.

[27]The results differ when analyzing Bitcoin (Table B.5): The NBP increases the IV, OnChain only for deep OTM calls and OTM puts (Column 1 and 5). In contrast, Off-Chain, the NPB loads positively on changes in IV for ATM calls and puts for all moneyness levels (Columns 3, 4,5, and 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
Panel A: On-Chain						
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
Adj. R-squared	0.14	0.08	0.07	0.06	0.08	0.06
Observations	218	231	217	219	229	182
Panel A: Off-Chain						
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
Adj. R-squared	0.09	0.09	0.08	0.05	0.06	0.07
Observations	280	314	314	297	314	314

Table 6.5: Regression Results – Net Buying Pressure – Trades On-Chain – ETH. The table reports the results, that is, the coefficient and the p-values in brackets from the regression as specified in (6.7). The columns progress from the 1st quantile to the 3rd quantile, first representing calls and then puts. The initial quantile represents deep OTM options, while the final quantile represents ATM options. The On-Chain data is from Lyra on Arbitrum. All variables are sampled on a daily frequency. The underlying is ETH.

Our model shows that when the aggregate demand surpasses a certain threshold, the option price (IV) on a DEX exceeds that on a CEX. This threshold increases with the liquidity pool size and AMM inventory, while it decreases with the dealers' inventory and the number of dealers on the CEX. On-chain, a larger pool size improves AMM efficiency and reduces On-Chain prices. Off-Chain, greater dealer inventory, and increased competition among dealers enhance CEX efficiency, leading to lower Off-Chain prices.

Specifically, we will assume that there is only one traded risky asset in each exchange, with a price distribution $\tilde{F}_h \sim N\left(\bar{F}, \sigma^2\right)$. In both exchanges, LPs face identical inventory costs, but their methods of managing these costs differ. In addition, we assume a CARA utility function with risk aversion coefficient A, a market consisting of one risky asset (the option) and a risk-free asset (a stablecoin), with liquidity traders submitting market orders modeled as $x \sim (\bar{x}, \sigma_x^2)$.

7.1 DEX – The AMM as a Monopolistic Dealer

The AMM can be viewed as a representative agent, even with a liquidity pool composed of multiple LPs since i) the theoretical price is uniquely determined from market conditions, ii) the effective price is uniquely determined by considering inventory costs, and is a function of a single risk aversion coefficient, iii) profits are redistributed proportionally to the LPs' wealth, disregarding their risk preferences, so variations in risk aversion among agents do not impact prices or returns.[28]

We consider a two-period model in which the AMM quotes the best bid and ask prices (effective price) where we assume that there is only one trade at the time. The risk-averse AMM demands compensation when providing liquidity. To achieve this, the AMM adjusts prices away from the efficient portfolio frontier, ensuring that the expected utility of terminal wealth on the frontier, W^{EF}, matches the expected utility when taking the opposite side of an aggregated demand x. This ensures adequate compensation for the AMM to the market.[29]

The AMM chooses an initial portfolio of risky and risk-free assets equal to:

$$p_s q_s + p_h q_h = W_0, \tag{7.1}$$

[28]In a concentrated liquidity framework, this would not hold since LPs would select different price ranges and earn profits based on their preferences.

[29]We assume that at time t, only one asset is traded. This result can be generalized to multiple risk assets and, multiple trades, where the covariance matrix of the options becomes relevant—higher correlation and volatility lead to increased inventory costs.

where p are the prices of the risky asset, h, and stablecoin, s, and q is their optimal holding at time $t = 0$. The terminal wealth (delta wealth) of the initial portfolio, when no trade occurs between time $t = 0$ and $t = 1$, equals:

$$\tilde{W}_1^{EF} = \Sigma_{n=[s,h]} \left(\tilde{F}_n - p_n \right) q_n = \frac{\left(\tilde{F}_h - p_h \right) q_h}{\Sigma_{n=[s,h]} p_n q_n} \Sigma_{n=[s,h]} p_n q_n = R W_0, \tag{7.2}$$

where $\tilde{F}_h \sim N \left(\bar{F}, \sigma^2 \right)$ is the price of the option at $t = 1$, and R is the return on the portfolio that lies on the AMMs' efficient frontier. The terminal wealth of the new portfolio, when a trade equal to $q_{h,1} - q_{h,0} = -x$ occurs at time $t = 0$, is instead:

$$\tilde{W}_1^{\text{AMM}} = \left(\tilde{F}_h - p_h \right) q_h + x \left(p_{trade} - \tilde{F}_h \right), \tag{7.3}$$

where p_{trade} is equal to the ask price p^A_{trade}, when the incoming customer submits a buy order of size $x > 0$ and the dealer sells $-x = q_{h,1} - q_{h,0} < 0$. Conversely, p_{trade} equals the bid price p^B_{trade} when the customer sells $x < 0$ and the dealer buys $-x = q_{h,1} - q_{h,0} > 0$ from the customer.

The AMM sets competitive prices by equating the expected utility of the end-of-period wealth from the initial and new portfolios. Given the normality of the asset returns and an exponential utility function, this is equivalent to:

$$E\left[\tilde{W}^{EF} \right] - \frac{A}{2} \text{Var} \left[\tilde{W}^{EF} \right] = E\left[\tilde{W}^{\text{AMM}} \right] - \frac{A}{2} \text{Var} \left[\tilde{W}^{\text{AMM}} \right]. \tag{7.4}$$

Assume now that the position in the risky asset h already deviates from the optimal level, $q_{h,0}$, due to an initial inventory I_h. Hence, after a trade of size x the quantity held by the AMM is $q_{h,1} - q_{h,0} = I_h - x_h$. We can work out the expected payoff and variance to find:

$$E\left[\tilde{W}^{\text{AMM}} \right] = E\left[\tilde{W}^{EF} \right] + \left(\bar{F}_h - p_h \right) \left(I_h - x_i \right) \tag{7.5}$$

$$\text{Var} \left[\tilde{W}^{\text{AMM}} \right] = \text{Var} \left[\tilde{W}^{EF} \right] + \left(I_h - x_h \right)^2 \sigma^2 + 2 W_0 \left(I_h - x_h \right) \sigma_{*,h} \tag{7.6}$$

where $\sigma_*^2 = \frac{q_0^2}{W_0^2}\sigma^2$ denotes the portfolio variance. Substituting these expressions into equation (7.4), we derive the quoted price for asset h for a trade of size x:

$$p_{trade}^{\text{AMM}} = \bar{F}_h - AW_0\sigma_{*,h} - \frac{A}{2}\left(I_h - x_h\right)\sigma^2. \tag{7.7}$$

The expression combines the equilibrium price—equal to the expected payoff minus a discount for systematic risk—with the additional risk introduced by the transaction. A larger pool value, and consequently a larger pool size, enhances AMM efficiency (Lehar and Parlour (2023)). AMM fees are determined by a single risk aversion parameter, A.

7.2 CEX – Limit Order Market Model

In a CEX, the participants place limit orders in the order book, specifying price and quantity. These orders are adjusted based on market conditions, inventory levels, and risk management to optimize trading. We assume that there are M risk-averse dealers submitting limit orders for a single risky asset (the option). Each dealer's endowment is I_j, with the average $\bar{I} = \left(\sum_{j=1}^{M} I_j\right)/M$. Each dealer will submit a limit order shaped as a demand function, specifying the units to trade at p_h. This demand function is the solution to each dealer's j expected utility maximization of the terminal wealth $\tilde{W}_j$:

$$\text{Max}_{q_j}\, E\left[\tilde{W}_j\right] - \frac{A}{2}\,\text{Var}\left[\tilde{W}_j\right] \tag{7.8}$$

with $E\left[\tilde{W}_j\right] = (\bar{F}_h - p_h)q_j + I_j\bar{F}_h$ and $\text{Var}\left[\tilde{W}_j\right] = \sigma^2\left[q_j^2 + I_j^2 + 2I_jq_j\right]$. From the first-order conditions we obtain

$$q_j = \frac{\bar{F}_h - p_h}{A\sigma^2} - I_j = \frac{\bar{F}_h - I_jA\sigma^2 - p_h}{A\sigma^2} = \frac{\varphi_j - p_h}{A\sigma^2}, \tag{7.9}$$

where $\varphi_j = \bar{F}_h - I_jA\sigma^2$ is the dealer's marginal evaluation for the asset. The dealer's order size increases with the expected value of the risky asset, $\bar{F}_h$, but decreases with larger inventory due to a lower marginal evaluation. The dealer will buy if the marginal evaluation exceeds the price, p_h. Given the traders' orders, the uniform pricing rule can be obtained from the market clearing condition:

$$\sum_{j=1}^{M} q_j + x = 0. \tag{7.10}$$

Substituting q_j from equation (7.9) and solving for p_h, we obtain:

$$p_{trade}^{\text{CEX}} = \bar{F}_h - \bar{I}A\sigma^2 + \frac{A\sigma^2}{M}x. \tag{7.11}$$

The expression combines the equilibrium price—calculated as the expected payoff minus a discount for systematic risk. As visible an increase in the number of dealers and a larger inventory will further improve CEX efficiency.

7.3 DEX vs. CEX

We now compare the DEX and CEX cases, focusing on when the DEX price (7.7) is higher than the CEX price (7.11):

$$\bar{F} - AW_0\sigma^2 - \frac{A}{2}\left(I - x_{AMM}\right)\sigma^2 \geqslant \bar{F} - \bar{I}A\sigma^2 + \frac{A\sigma^2}{M}x_{CEX} \tag{7.12}$$

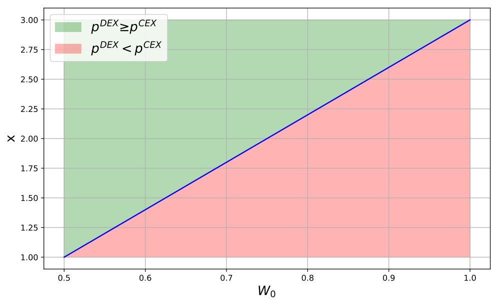
$$\Leftrightarrow \quad W_0 + \frac{1}{2}\left(I - x_{AMM}\right) \leqslant \bar{I} - \frac{1}{M}x_{CEX} \tag{7.13}$$

Assuming the AMM and the CEX have the same net aggregate demand $x = x_{AMM} = x_{CEX}$,

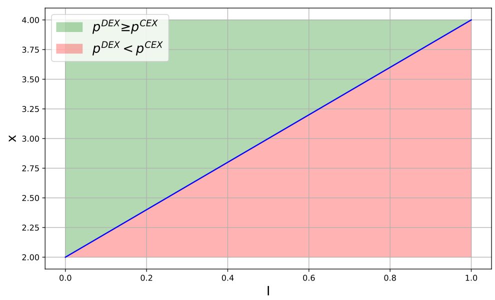
$$W_0 + \frac{1}{2}\left(I - x\right) \leqslant \bar{I} - \frac{1}{M}x \quad \Leftrightarrow \quad x \geqslant \left(W_0 + \frac{1}{2}I - \bar{I}\right)\frac{2M}{M-2}. \tag{7.14}$$

Hence the DEX price is above the CEX price whenever the net aggregate demand (x) is larger than some lower bound. The necessary net aggregate demand increases with the pool value and the difference between inventories, while it decreases with the number of LPs. Figure 7.1 shows the values of x as one variable in (7.14) changes. The green area highlights the values of x where $p^{DEX} \geqslant p^{CEX}$. For instance, in Panel (a), when the pool size is 0.7, p^{DEX} surpasses p^{CEX} if x is greater than 1.75. As visible, in Panels (a) and (b) the necessary demand so that $p^{DEX} \geqslant p^{CEX}$ is increasing in the pool size and the inventory of the AMM. In Panels (c) and (d) the opposite is true: An increase in dealers' average inventory ($\bar{I}$) or the number of dealers results in lower prices on the CEX, which reduces the necessary net aggregate such that $p^{DEX} \geqslant p^{CEX}$.

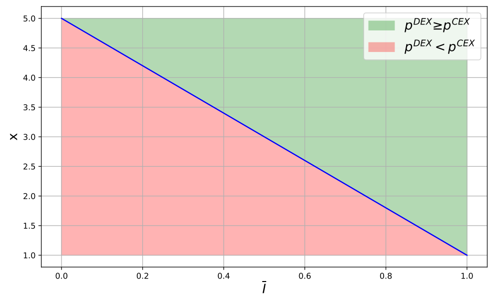
(a) x as function of W_0



(b) x as function of I



(c) x as function of $\bar{I}$



(d) x as function of M

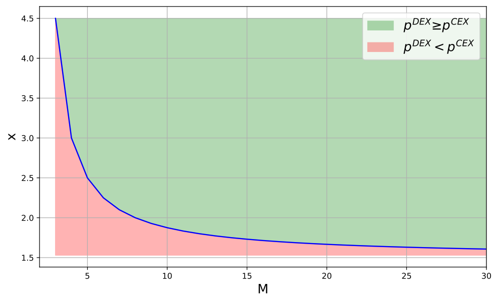


Figure 7.1: Model Price – DEX vs. CEX. The figure displays the values for x as given by equation (7.14). The green (red) area highlights the values of x where p^{DEX} exceeds (is below) p^{CEX}. In each plot, equation (7.14) is evaluated for varying values of either $W_0, I, \bar{I}$ or M. The other variables are kept constant where the baseline specifications are $W_0 = 1, I = 0.5, \bar{I} = 0.5$, and $M = 4$. In the plots, we evaluate equation (7.14) with W_0 ranging from 0.5 to 1, I and $\bar{I}$ from 0 to 1, and M from 3 to 30.

7.4 Model Implications - Empirical Investigation

In this section, we empirically test some of the model's predictions. In our analysis, we utilize the matched On-Chain and Off-Chain trades, concentrating specifically on transactions with comparable demand, where the difference in trade size, $|x_{DEX} - x_{CEX}|$, is less than 5.[30] Given that at the same time, the demands on both DEX and CEX are

[30]We obtain similar findings with lower thresholds.

similar, it is evident that the overall demand does not drive the observed difference in IV. Rather, our focus shifts to the impact of the level of demand, equation (7.14), we observe that higher aggregate demand correlates with a greater IV On-Chain relative to Off-Chain, as shown in Figure 7.2. A panel regression to examine the variations in traded

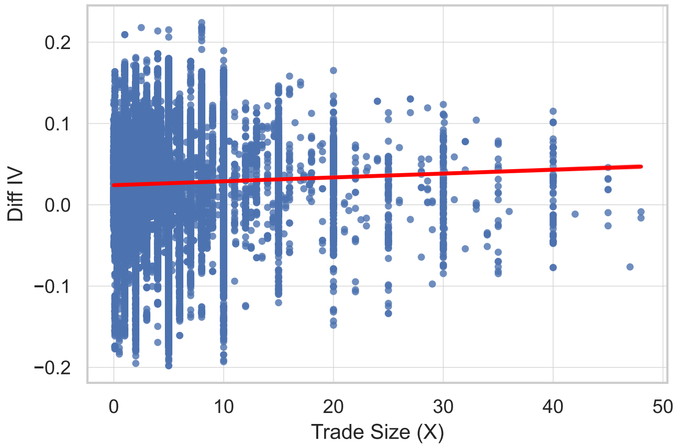


Figure 7.2: Trades Size and Difference in IV. The figure shows the difference in traded IV between On-Chain and Off-Chain options on ETH across their trade size (X). The On-Chain data is from Lyra V2 on Arbitrum, and the Off-Chain data is from Deribit, the underlying is ETH. The x-axis represents the trade size (X). Only OTM options with maturity between six 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 for each option over time, as detailed in

$$\text{Diff IV}_{i,t} = \beta_0 + \beta_1 \text{Call}_i + \beta_2 \text{Maturity}_{i,t} + \beta_3 \text{Mness}_{i,t} + \beta_4 \text{X}_{i,t} + \epsilon, \tag{7.15}$$

$$\text{Diff IV}_{i,t} = \beta_0 + \beta_1 \text{X}_{i,t} + \epsilon. \tag{7.16}$$

supports our observation: The regression results in Table 7.1 show that higher aggregate demand leads to a larger disparity in IV.

The difference in IV may also be attributed to the presence of a negative inventory On-Chain. Indeed, LPs could adjust their pricing to incentivize liquidity takers towards selling rather than purchasing options, thereby mitigating inventory risks — such as the net exposure to delta and vega. To assess if DEX inventory impacts IV differences as indicated by equation (7.14), we analyze the net position of call options. Daily inventory is derived from the net balance, which is the daily aggregate size of short positions minus

Variable	Diff IV	Diff IV
Intercept	0.0241	-0.3887
	(0.000)	(0.000)
X	0.0005	0.0002
	(0.000)	(0.017)
Call		0.0150
		(0.000)
Maturity		0.0020
		(0.000)
Mness		0.4022
		(0.000)
R-squared	0.001	0.108
Adj. R-squared	0.001	0.108
Observations	70006	70006

Table 7.1: Regressions – Difference in IV – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the regression as specified in (7.15) and (7.16). Thereby *Call* equals 1 if the instrument is a call, *Maturity* denotes the maturity in days, *Mness* denotes the moneyness of the option. The On-Chain data is from Lyra V2 on Arbitrum, while the Off-Chain data is from Deribit, the underlying asset is ETH. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

long positions in calls. The effect of each trade persists until the option's maturity, influencing the inventory over this duration. We compute daily inventories by summing trades per day and calculating net positions. The data is grouped into three categories based on the 5th and 95th inventory percentiles. Figure 7.3 shows the difference in IV between On-Chain and Off-Chain options on ETH across net inventory percentiles. Periods with negative inventory exhibit greater volatility and, on average, higher IV.

8 Robustness

Next, we conduct additional tests that confirm the robustness of our main findings for various alternative exchanges.

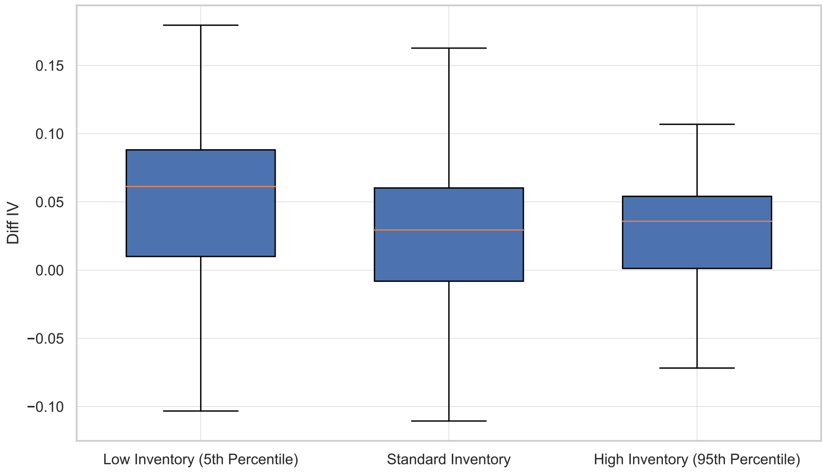


Figure 7.3: Inventory and Difference in IV. The figure shows the difference in traded IV (Diff IV) between On-Chain and Off-Chain options across net inventory percentiles. The On-Chain data is from Lyra V2 on Arbitrum, and the Off-Chain data is from Deribit, the underlying asset is ETH. The net inventory is grouped into low inventory (5th percentile), standard inventory (5th-95th percentile), and high inventory (95th percentile). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

8.1 Lyra V2 on Arbitrum

In Appendix B we present additional plots and tables repeating the analysis in the main body of the paper considering trades or quotes and for BTC as underlying. Appendix B.1 details the profit and loss from liquidity provision on Lyra, revealing that it was profitable for ETH but not for BTC. In Appendix B.2 we present the total fees On-Chain and Off-Chain. Appendix B.3 analyzes the difference in IV using trade data and includes the corresponding fixed effects regression analysis. Appendix B.4 and Appendix II.2 demonstrate the results of the VAR model for BTC and show alternative specifications. Appendix B.5 contains the analysis of the NBP for BTC. Overall, the main results for ETH also apply to BTC, though the significance is sometimes weaker for BTC.

8.2 Lyra V2 on Optimism

The results for Lyra V2 on Optimism (starting in May 2023) are presented in Internet Appendix III. As evident from Table III.1 and Table III.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 III.8 displays the gap between On-Chain and Off-Chain IV across maturity and confirms the results in the main part of the paper. The regression analysis is repeated and displayed in Table III.3 and Table III.4: The differences in IV are larger for calls with increasing maturity and close to ATM. Figure III.6 compares trading fees. BTC On-Chain trades are cheaper (20.49 USD vs. 23.58 USD Off-Chain), whereas for ETH, it is the opposite (13.94 USD On-Chain vs. 10.05 USD Off-Chain).

8.3 Aevo

Internet Appendix IV reports the results comparing Aevo to Deribit. Due to data availability, for Aevo, only trades are sourced. The data ranges from July to November 2023. Figure IV.12 shows that the On-Chain IV is larger than the Off-Chain IV.

8.4 Lyra V1

Internet Appendix V presents the results for Lyra V1, which was deployed only on Optimism, until May 2023. The results confirm the main findings, displaying even larger gaps in IV than for Lyra V2 (see Figure V.15 and Figure V.16). Figure V.13 illustrates the trading fees, 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).

8.5 Lyra V2 and Aevo

A comparison of the IVs across two DEXs, Lyra V2 on Arbitrum, and Aevo is presented in Internet Appendix VI. The IVs display a strong comovement across strikes and maturity (Figure VI.17).

8.6 Okx and Lyra

A comparison of the IVs by Lyra V2 on Abitrum and OKX, a major DEX, is outlined in Internet Appendix VII – Internet Appendix IX. The analysis confirms a positive difference between On-Chain and Off-Chain IVs.

8.7 Bitcom and Lyra

A comparison of the IVs from Lyra V2 on Arbitrum and Bitcom, a major DEX, is detailed in Internet Appendix X. The comparison confirms a positive disparity between On-Chain and Off-Chain IVs.

8.8 Deribit and OKX

Internet Appendix XI provides a comparison between two off-chain exchanges Deribit and OKX. As visible in Figure XI.22 and Figure XI.23 there is no visible difference between the IVs.

9 Conclusion

Interest in cryptocurrency options has surged, with trading volumes reaching 3.12 trillion USD by July 2023,[31] highlighting the growing significance of On-Chain options in shaping the future of the maturing cryptocurrency derivatives market. As the market for cryptocurrency derivatives 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. The additional trading fees charged by the AMM, stemming from the pool's risk management, aim to reduce the overall delta and vega risk exposure of the pool.

[31] Source: `https://shorturl.at/2Pmg0`.

We compare On-Chain and Off-Chain IVs across a range of OTM BTC and ETH options with varying maturities and strikes, finding that On-Chain options typically exhibit higher IVs than Off-Chain options. This difference increases with option maturity and proximity to being ATM. To capture the difference in a trading strategy we sell (high IV) On-Chain options and buy (low IV) Off-Chain options. Despite the strategies' strong performance, transaction costs can reduce profitability. We identify various reasons for the difference in IV: The fee structure, the trading volume, and the NBP effectively explain changes in On-Chain IVs while the same conclusion cannot be drawn for Off-Chain options. For example, the net buying pressure affects On-Chain IVs for all calls' moneyness levels, while influencing Off-Chain IV dynamics only for ATM calls. Our results are consistent with the provided theoretical insights.

In conclusion, decentralized options trading presents a promising avenue for further exploration, offering fresh and innovative approaches to transform cryptocurrency derivatives markets. One such approach is the integration of on-chain derivatives with tokenized Real-World Assets (RWAs), which could greatly improve financial markets by combining the benefits of blockchain technology with those of traditional asset classes.

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Appendix A Additional Tables

DEX	total Notional Volume	total Premium Volume	TVL
aevo	219,973,121.66	3,023,767.34	6,831,118.11
hegic	106,237,826.57	3,031,224.66	7,631,050.21
lyra	251,923,855.47	8,936,025.41	11,962,292.63
rysk-finance	–	–	1,225,141.01
thales	8,374,235.50	5,042,071.26	1,822,593.86
typus	621,150.09	6,592.67	229,964.89
premia v2	93,141,777.42	2,800,678.67	1,680,734.98
premia v3	1,312,098.21	33,278.12	1,568,684.98

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 V2 on Arbitrum

B.1 P&L from Liquidity Provision on an Option DEX

(a) Profit and Loss (b) Pool Performance

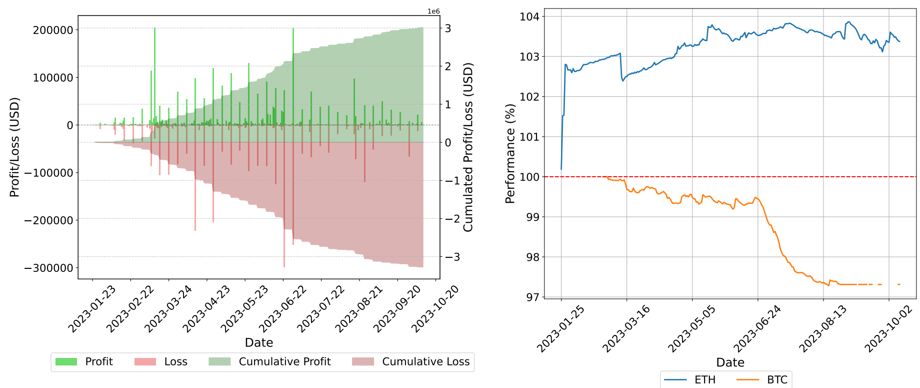


Figure B.1: Lyra Stats – Pool Performance. The figure shows the trader's profit and loss (Panel (a)) and the LPs pool performance (Panel (b)) over time. The data is obtained from Lyra deployed on Arbitrum. The sample period ranges from 01-2023 to 11-2023.

B.2 On-Chain and Off-Chain – Transaction Fees and Pool Greeks

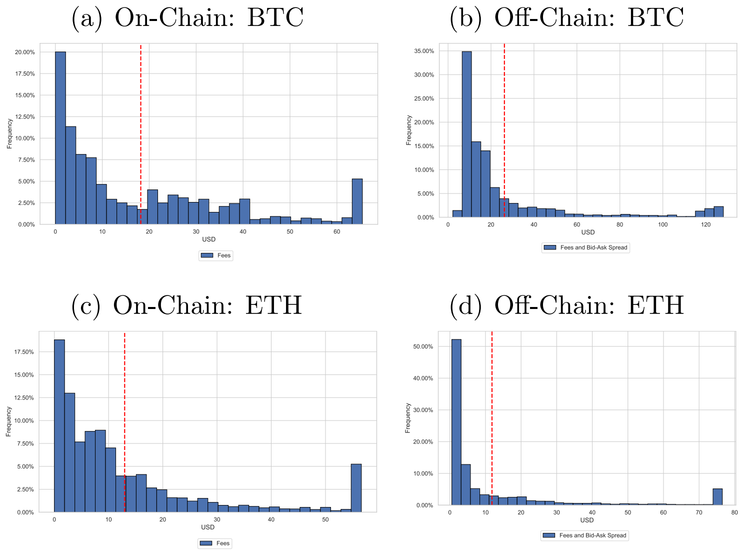


Figure B.2: Transaction Fees – On-Chain vs. Off-Chain. The figure shows the histogram of total trading fees for BTC (Panel (a),(b)) and ETH (Panel (c),(d)), On-Chain, and Off-Chain. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The fees On-Chain are calculated according to equation (3.6) and Off-Chain, as described in Section 3.1. The dashed red line denotes the unconditional average. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

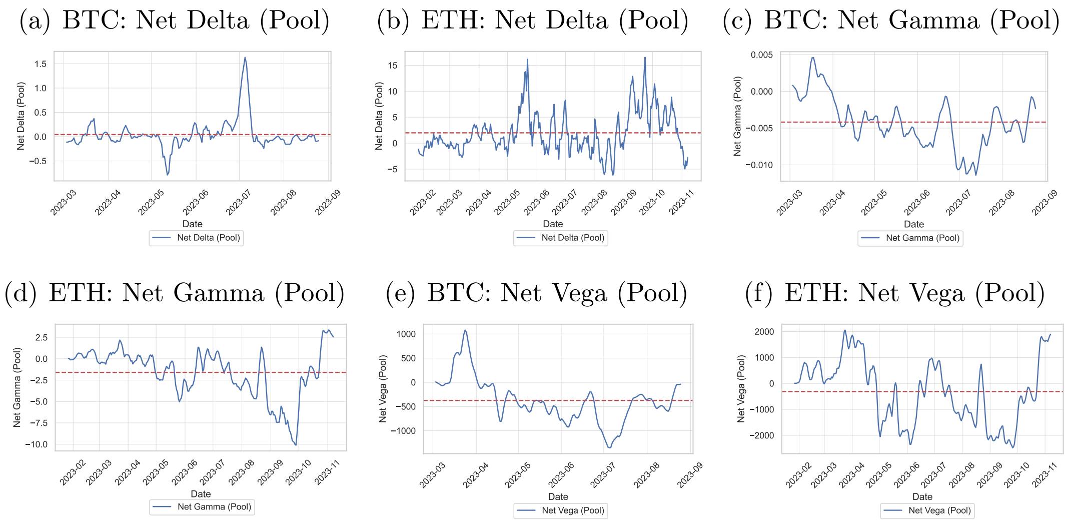


Figure B.3: Net Pool Greeks. The figure shows the net Greeks exposure at the pool level On-Chain. The On-Chain data is from Lyra V2 on Arbitrum. The sample period ranges from 02-2023 to 11-2023.

B.3 On-Chain and Off-Chain – IVs

	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 B.1: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. Price is denoted in USD and Size represents the trading size. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

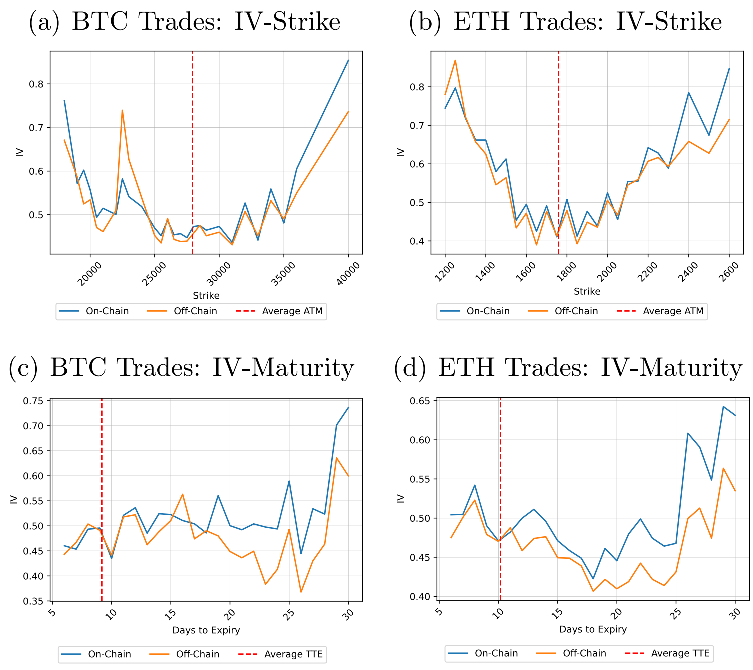


Figure B.4: IV, Strike Price, and Maturity. The figure shows the traded IV (calls and puts), On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The x-axis represents the strike price (USD) or the maturity (days). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

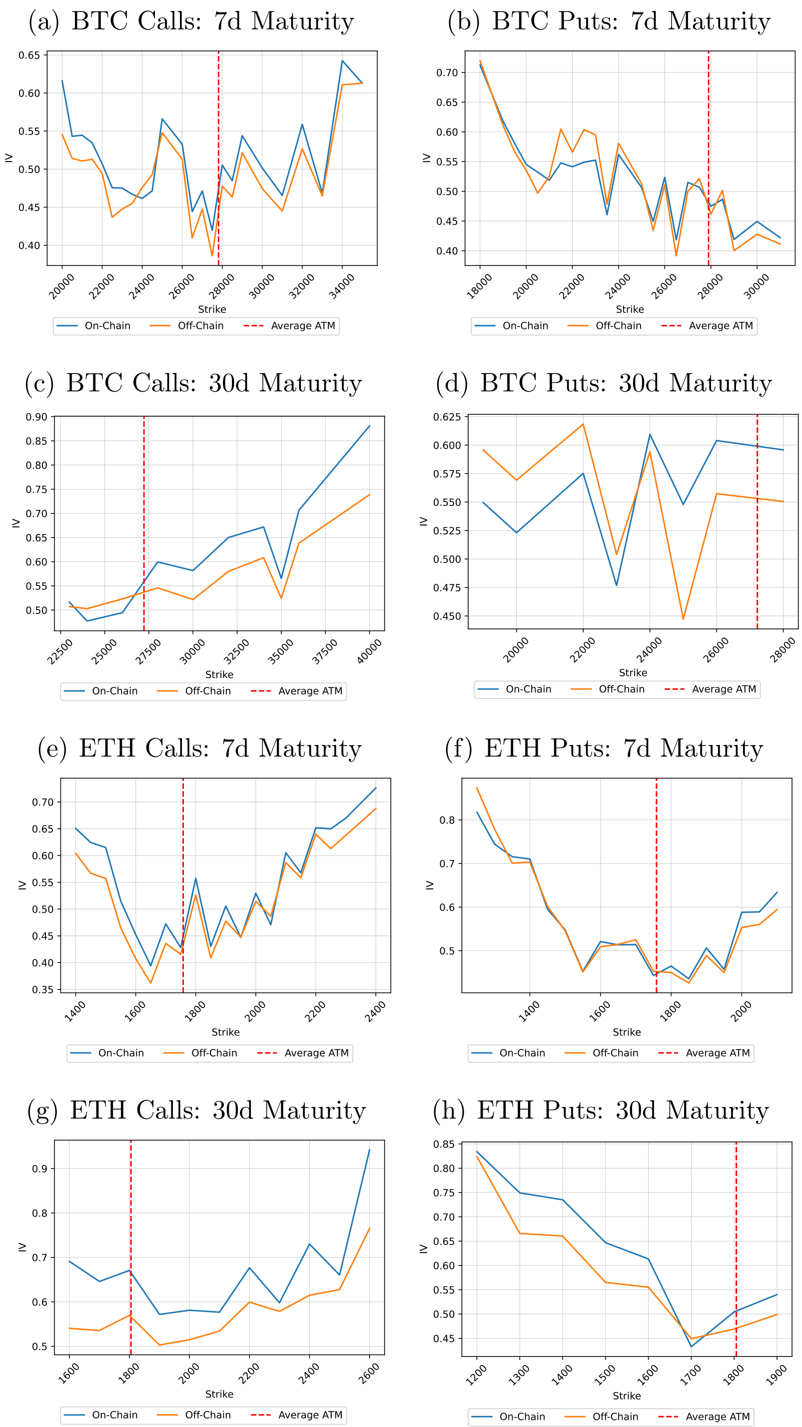


Figure B.5: IVs for BTC and ETH and Strike Price – Call and Puts – Quotes. The figure shows the quoted IV from calls and puts, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The x-axis represents the strike price (USD). Panels (a), (b), (e), and (f) include OTM options with 6-8 day maturity, while panels (c), (d), (g), and (h) feature OTM options with 28-32 day maturity. The quote data is given at 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
Panel A: BTC						
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
Panel B: ETH						
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 B.2: Regressions – IVs – On-Chain vs. Off-Chain – BTC and ETH – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (6.1) and (6.2). *Call* equals 1 if the instrument is a call, *Maturity* denotes the maturity in days, and *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 from Lyra on Arbitrum, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The quote data is given at an hourly frequency. The sample period ranges from 02-2023 to 11-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	
Panel A: BTC					
Intercept	-0.28877	-0.28546	-0.21019	-0.01928	-0.03797
	(0.00003)	(0.00003)	(0.00631)	(0.00003)	(0.00000)
Call	0.00486	0.00495	0.00274		
	(0.19116)	(0.18233)	(0.46365)		
Maturity	0.00384	0.00381	0.00336		
	(0.00000)	(0.00000)	(0.00000)		
Mness	0.28382	0.27690	0.18595		
	(0.00005)	(0.00007)	(0.02160)		
On-Chain Fees		-0.00002			
		(0.81155)			
Off-Chain Quoted Spread		0.00042	0.00040		
		(0.00798)	(0.00724)		
On-Chain Scaled Fees			0.00060		
			(0.01088)		
On-Chain Size			-0.00253		
			(0.50334)		
Abs. Delta				0.03160	-0.03175
				(0.16491)	(0.15229)
Vega				0.00002	0.00005
				(0.00000)	(0.00000)
R-squared	0.2963	0.3046	0.3220	0.0987	0.3435
Observations	1371	1371	1371	1371	1371
Entities				258	
Time Periods	934	934	934		934
Option-Id FE	No	No	No	Yes	No
Time FE	Yes	Yes	Yes	No	Yes
Panel B: ETH					
Intercept	-0.28825	-0.28980	-0.23507	-0.02598	-0.02531
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.00537	0.00535	0.00500		
	(0.00000)	(0.00000)	(0.00001)		
Maturity	0.00254	0.00254	0.00221		
	(0.00000)	(0.00000)	(0.00000)		
Mness	0.30035	0.30194	0.22664		
	(0.00000)	(0.00000)	(0.00000)		
On-Chain Fees		0.00002			
		(0.02349)			
Off-Chain Quotes Spread		-0.00043	-0.00102		
		(0.79891)	(0.50678)		
On-Chain Scaled Fees			0.01195		
			(0.00000)		
On-Chain Size			-0.00006		
			(0.18003)		
Abs. Delta				0.08844	0.03204
				(0.00000)	(0.00000)
Vega				0.00029	0.00045
				(0.00000)	(0.00000)
R-squared	0.2586	0.2602	0.2866	0.1789	0.3294
Observations	6767	6767	6767	6767	6767
Entities				561	
Time Periods	3233	3233	3233		3233
Option-Id FE	No	No	No	Yes	No
Time FE	Yes	Yes	Yes	No	Yes

Table B.3: Regression with Fixed Effects – IVs – BTC and ETH – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (6.1) - (6.3) including fixed effects. Thereby *Call* equals 1 if the instrument is a call, *Maturity* denotes the maturity (days), and *Mness* denotes the moneyness of the option. Fees, Size, Abs. Delta and Vega are constructed from the trade data. The trades On-Chain data is from Lyra V2 on Arbitrum, while the Off-Chain data is from Deribit. The sample period ranges from 02-2023 to 11-2023.

	Call		Put	
Variable	7	15	7	15
Delta (Pool)	0.1321	-0.2335	-0.0507	0.9077
	(0.434)	(0.771)	(0.468)	(0.287)
Vega (Pool)	0.0038	-0.0096	0.0021	0.0088
	(0.094)	(0.301)	(0.151)	(0.343)
Underlying Volume	0.0000	0.0000	0.0000	0.0000
	(0.296)	(0.268)	(0.235)	(0.886)
NBP call ATM	22.4574	-79.8933	-	-
	(0.327)	(0.319)	-	-
NBP put ATM	-	-	-4.0583	8.6164
	-	-	(0.570)	(0.780)
Rsquared	0.13	0.10	0.13	0.03
Adj. R-squared	0.03	-0.00	0.02	-0.08
Observations	39.00	39.00	38.00	39.00

Table B.4: Timeseries Regressions – Strategy – Pool Specific Regressors. The table reports the results, that is, the coefficient and the p-values in brackets from the regression as specified in (6.4). The columns represent the returns of the different parameters of the trading strategy, that is, selling the On-Chain (call or put) ATM options and buying the Off-Chain (call or put) ATM options for a given maturity. The On-Chain data is from Lyra V2 on Arbitrum, while the Off-Chain data is from Deribit. As explanatory variables, we consider the Delta (Pool) and Vega (Pool), the Underlying Volume, and the NBP (as calculated in equation (4.1)). A more precise description of the variables is given in Section 4. The sample period ranges from 02-2023 to 11-2023.

B.4 VAR Model – AMM Mechanism – BTC

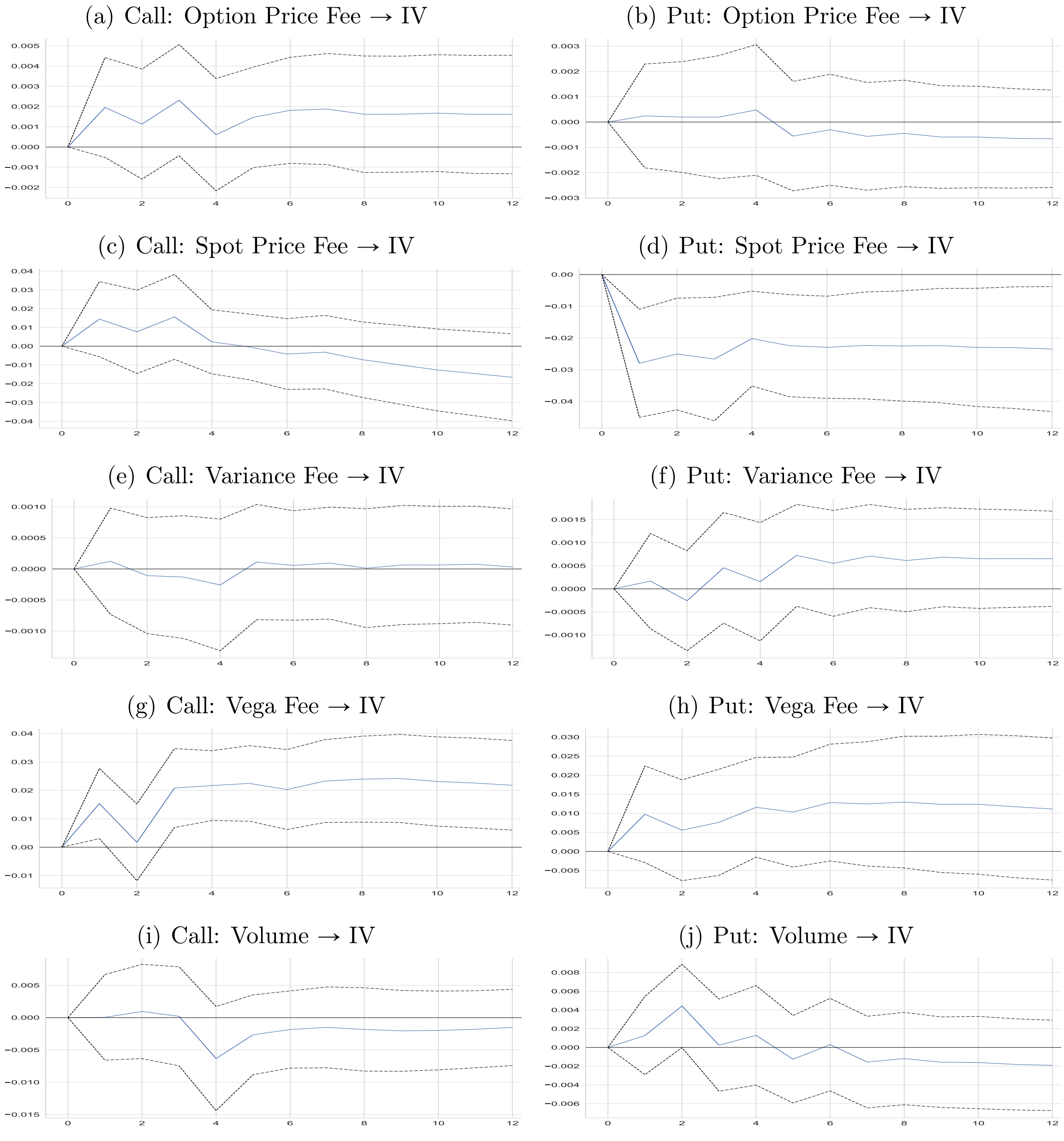


Figure B.6: On-Chain – BTC – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the traded BTC IV for long calls (left panels)) and long puts (right panels). Volume denotes the aggregate of traded volume. The On-Chain data is from Lyra on Arbitrum. The components of the fees are mentioned in equation (3.6). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

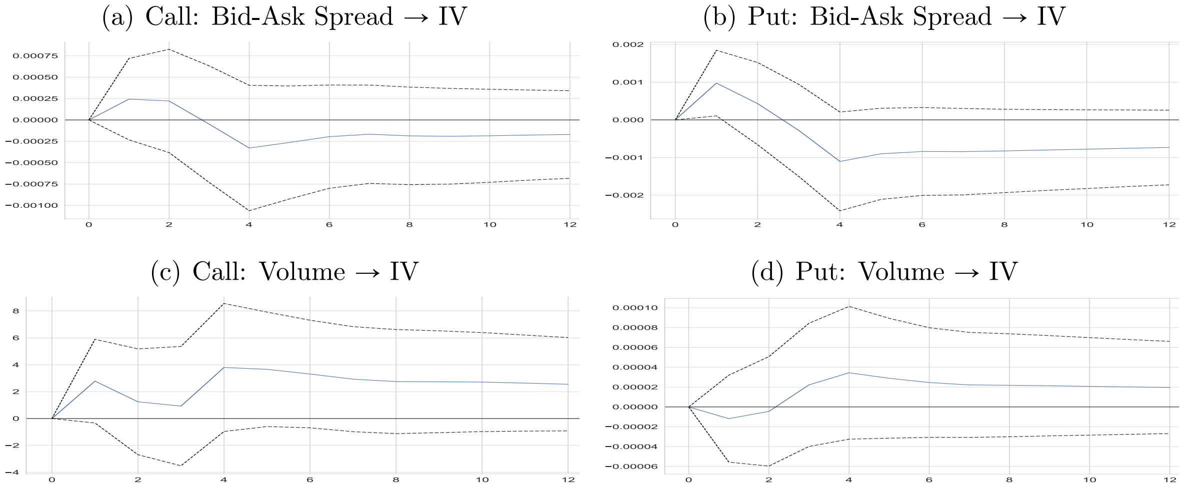


Figure B.7: Off-Chain – BTC – Long Call and Long Put. The figure displays the IRFS of the traded BTC IV for long calls (left panels) and long put (right panels). The Volume is calculated as aggregated from the options. The fees are calculated as the Bid-Ask-Spread. The Off-Chain data is from Deribit. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

B.5 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
Panel A: On-Chain						
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
Adj. R-squared	0.04	0.16	-0.04	0.22	0.09	0.29
Observations	63	38	31	47	47	62
Panel B: Off-Chain						
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
Adj. R-squared	0.12	0.15	0.16	0.04	0.07	0.11
Observations	311	314	314	307	314	314

Table B.5: Regressions – Net Buying Pressure — Trades On-Chain and Off-Chain – BTC. The table reports the results, i.e., the coefficient and the p-values in brackets from the regression as specified in (6.7). The columns progress from the 1st quantile to the 3rd quantile, first representing calls and then puts. The initial (final) quantile represents OTM (ATM) options. The trades On-Chain data is from Lyra V2 on Arbitrum. The Off-Chain data is from Deribit. All variables are sampled on a daily frequency. All variables are sampled on a daily frequency. The sample period ranges from 02-2023 to 11-2023.

Internet Appendix

I Lyra – Details and Nuances

I.1 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.[32] During high volatility, liquidity providers face increased risk, especially from impermanent loss. The variance fee helps manage this risk. For a specific trade i at time t the variance fee, $f_{var,t,i}$, is defined as,

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

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. The variance fee increases with the option's vega (high volatility risk). The variance fee increases with the option trade's skew, such as a more convex IV smile, and when the ATM option's IV increases.

I.2 Geometric Time-Weighted Average Volatility (GWAV)

The GWAV is a time-weighted average of either the baseline volatility for an expiry (b) or the skew ratio of a specific listing R. The GWAV 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 $T = t_b - t_a$. T is the length of the GWAV (as of the 24th of October 2023 it is set to six hours). For more information see Lyra (2022).

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

I.3 Lyra's V2 Liquidation Engine

Lyra's version 2 decentralized liquidation mechanism enhances user experience and mitigates systemic risk as part of its risk management strategy.

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:* The buffer margin (BM), defined as $\text{BM} = \text{mtm} + \text{buffer} + 0.15 \times \text{buffer}$, exceeds the portfolio's mark-to-market price to cushion against market volatility. During the solvent auction, users are liquidated until $BM = 0$.
- *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 for discounted acquisition by liquidators, unless the Buffer Margin is above 0. If insolvent, an insolvent auction bypasses the solvent auction.
- *Insolvent Portfolios:* Auction offers start at the portfolio's mark-to-market value and rise to the maintenance margin over an hour. Negative offers mean the Security Module compensates liquidators, who must cover the maintenance margin minus liquidation proceeds.

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

I.4 The Security Module

The security module is comprised of a blend of collateral types such as stablecoins, ETH/BTC, and the Lyra token (LYRA), offering yield-generating opportunities through diverse mechanisms. i) It secures a base yield by lending in governance-approved stablecoins, renowned for their reliability in generating safer yields. ii) Furthermore, it earns a percentage of the fees generated by the Lyra protocol. iii) Additionally, it benefits from increased returns through longer-term stakes in Lyra. iv) Moreover, it holds priority liquidation rights within a margining system, with liquidation returns from keepers being directed to the module.

II Lyra V2 on Arbitrum

II.1 VAR Model – Alternative Specifications – ETH

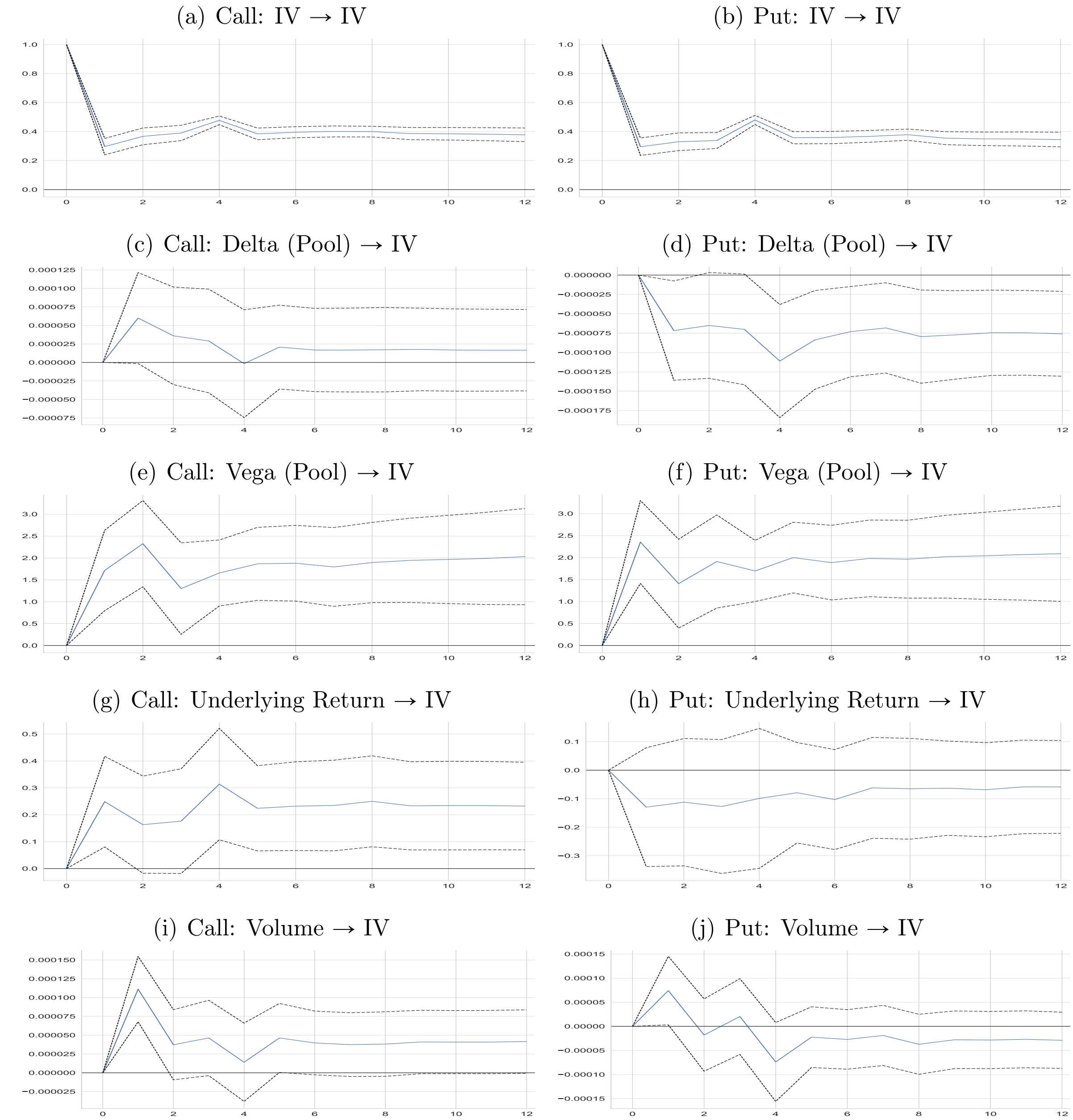


Figure II.1: On-Chain – ETH – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the traded ETH IV for long calls (left panels) and long put (right panels). The Vega (Pool) and Delta (Pool) are calculated following Section 3.2.2. The Underlying Return is calculated for ETH. The On-Chain data is from Lyra on Arbitrum. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

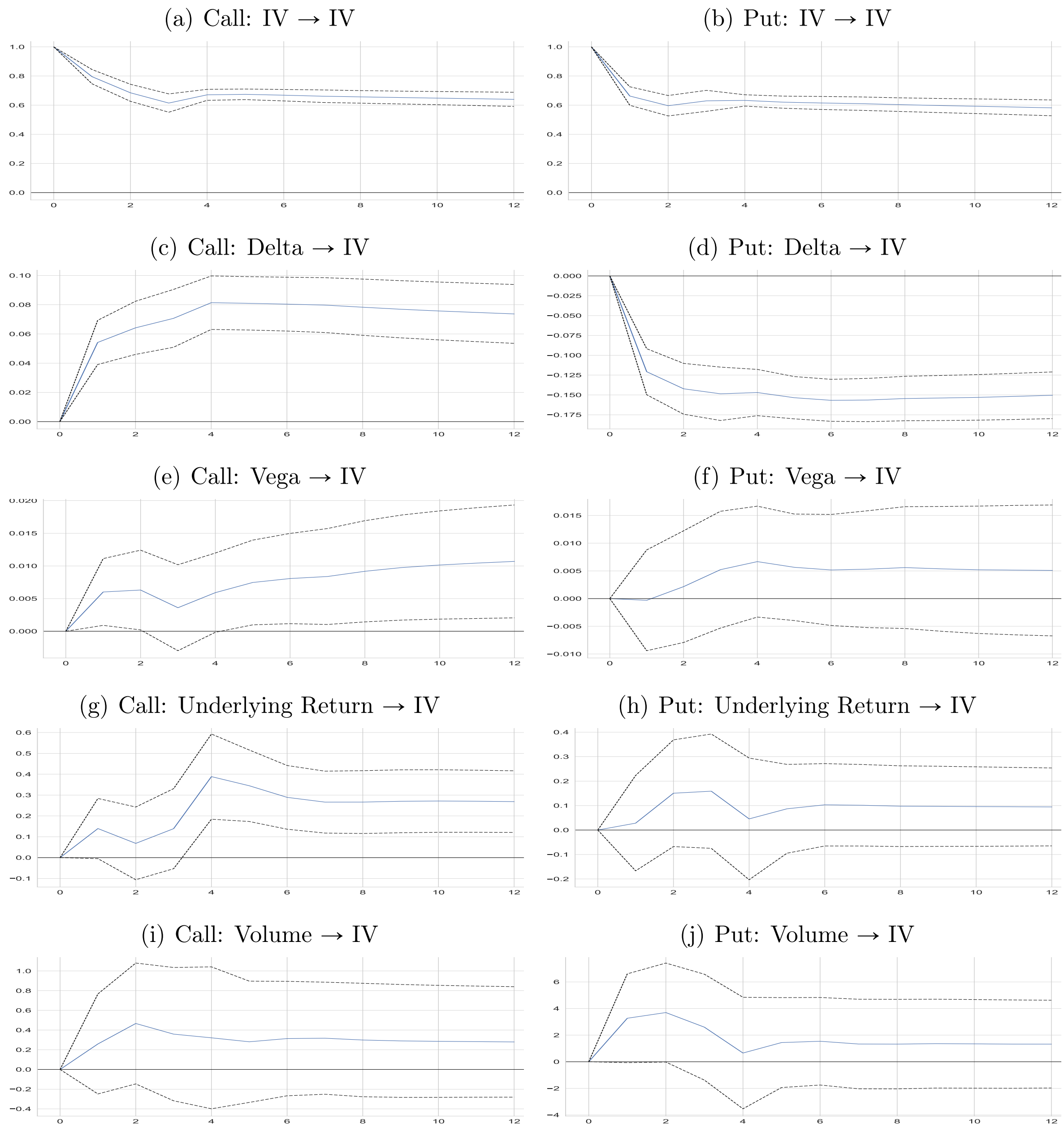


Figure II.2: Off-Chain – ETH – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the traded ETH IV for long calls (left panels) and long put (right panels). The Vega and Delta are calculated as the aggregate from the options. The Underlying Return is calculated for the ETH. The Off-Chain data is from Deribit. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

II.2 VAR Model – Alternative Specifications – BTC

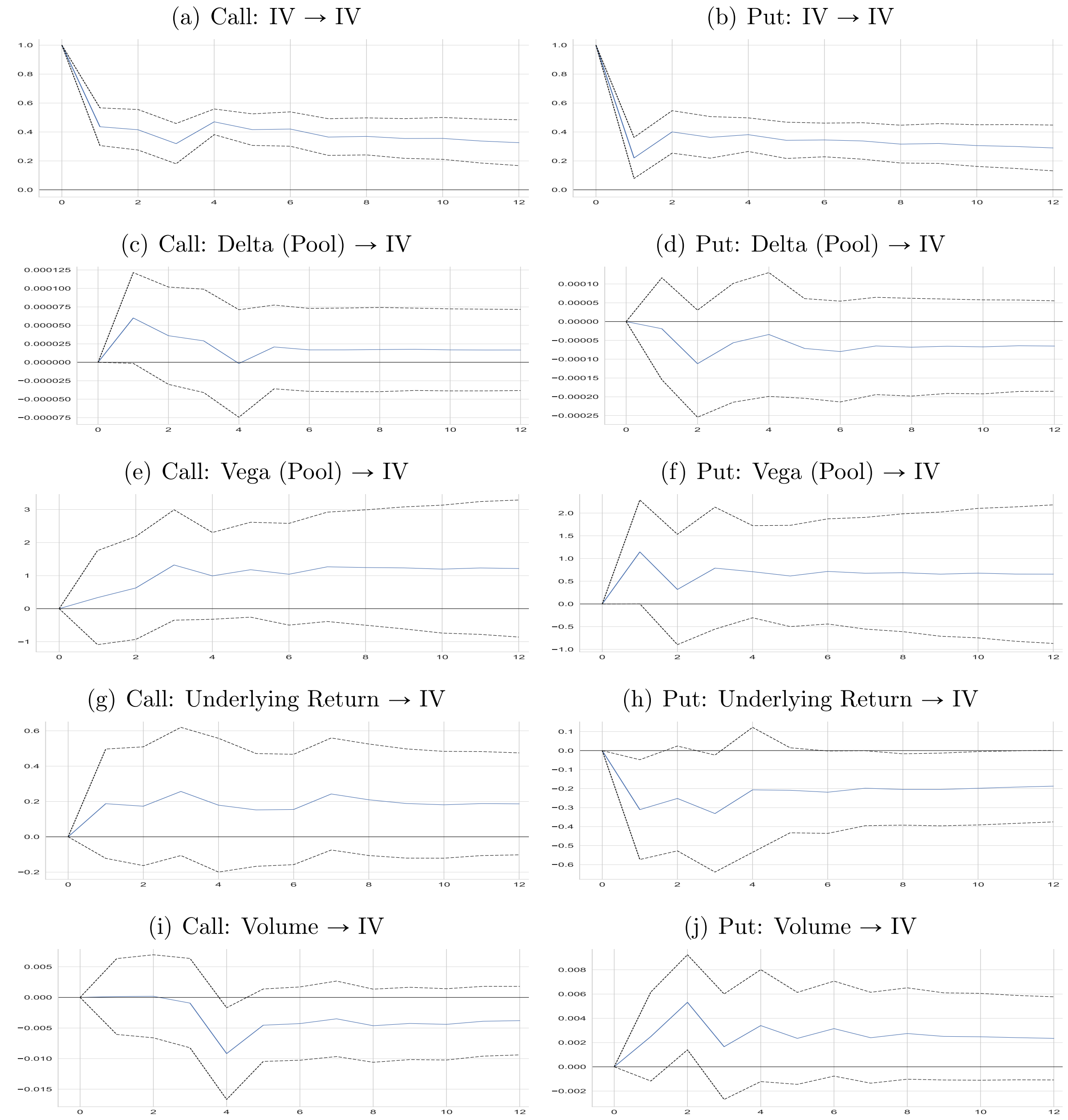


Figure II.3: On-Chain – BTC – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the traded BTC IV for long calls (left panels) and long put (right panels). The Delta (Pool) and Vega (Pool) are calculated following Section 3.2.2. The Underlying Return is calculated for BTC. The On-Chain data is from Lyra on Arbitrum. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

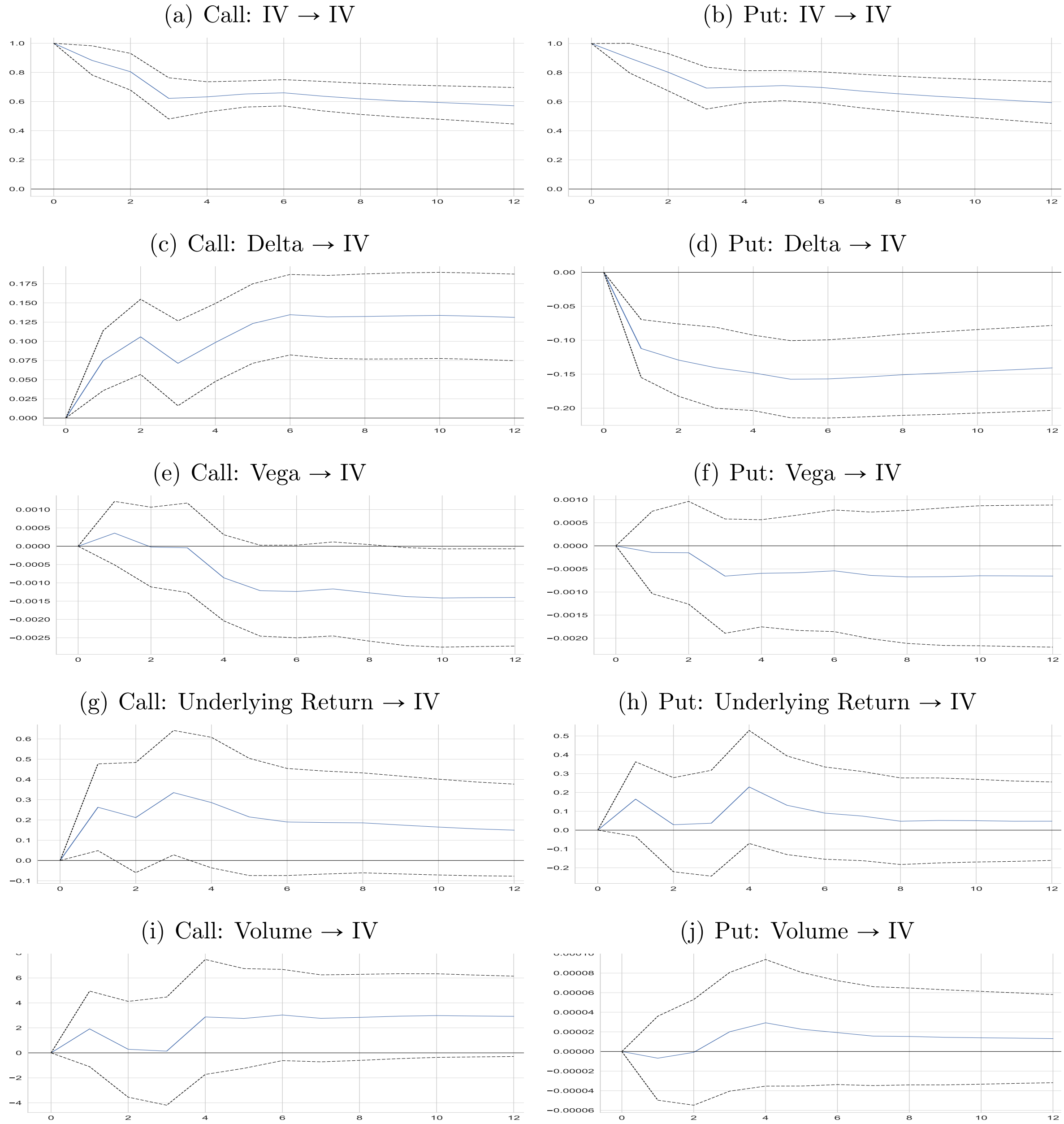


Figure II.4: Off-Chain – BTC – Long Call and Long Put. The figure displays the impulse response functions (IRFS) of the traded BTC IV for long calls (left panels) and long put (right panels). The Vega and Delta are calculated as aggregated from the options for each point in time. The Underlying Return is calculated for BTC. The Off-Chain data is from Deribit. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled hourly and the sample period ranges from 02-2023 to 11-2023.

III Lyra V2 on Optimism

III.1 Summary Statistics

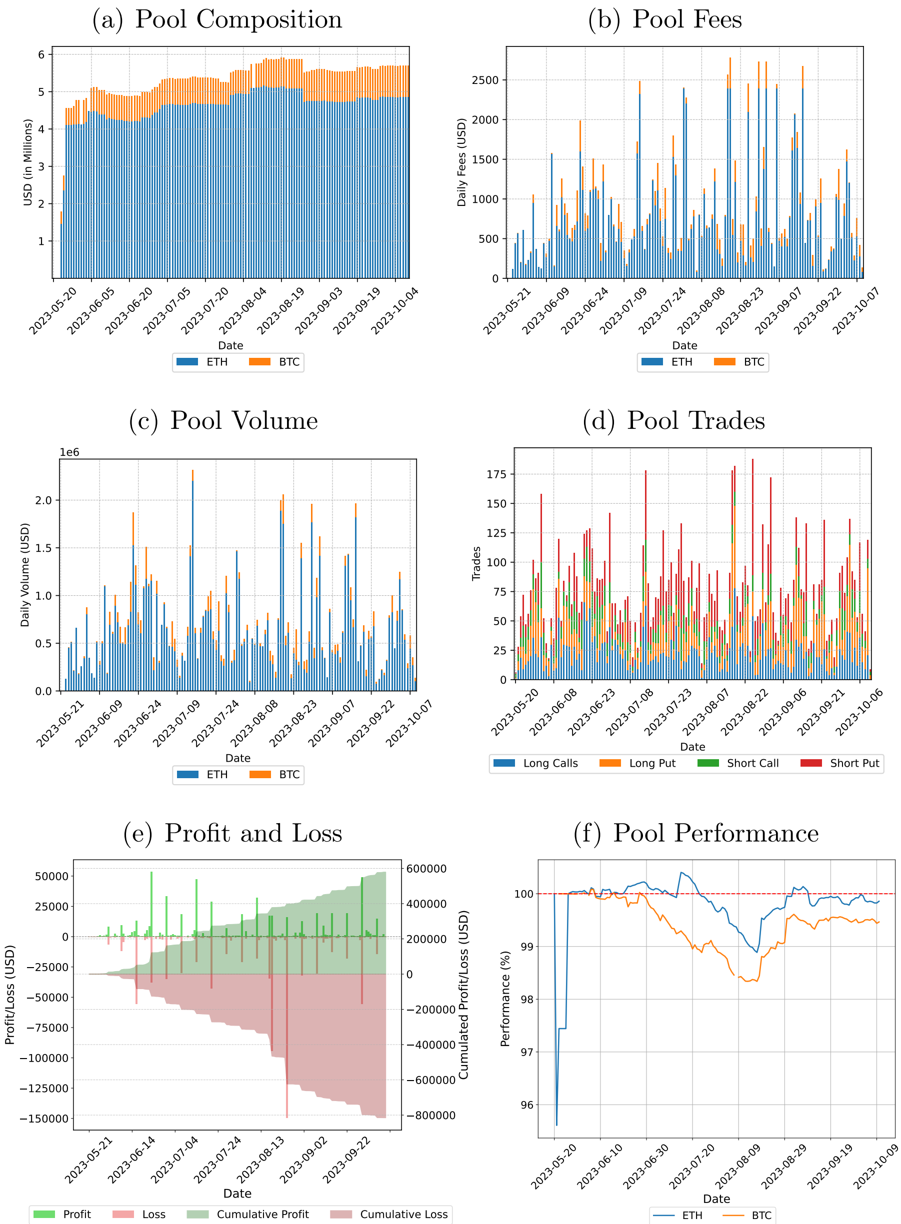


Figure III.5: Lyra Stats - Pool Overviews and Pool Performance. The figure shows key quantities for Lyra pools over time: Pool Composition (Panel (a)), the daily occurring Pool Fees (Panel (b)), daily Pool Volume (Panel (c)), the Pool Trades (Panel(d)), Profit and Loss (Panel (e)), and the Pool Performance (Panel (f)) over time. The data is from Lyra V2 on Optimism. The data is winzorized at the 1% quantile. The sample period ranges from 05-2023 to 11-2023.

III.2 On-Chain and Off-Chain – Transaction Fees

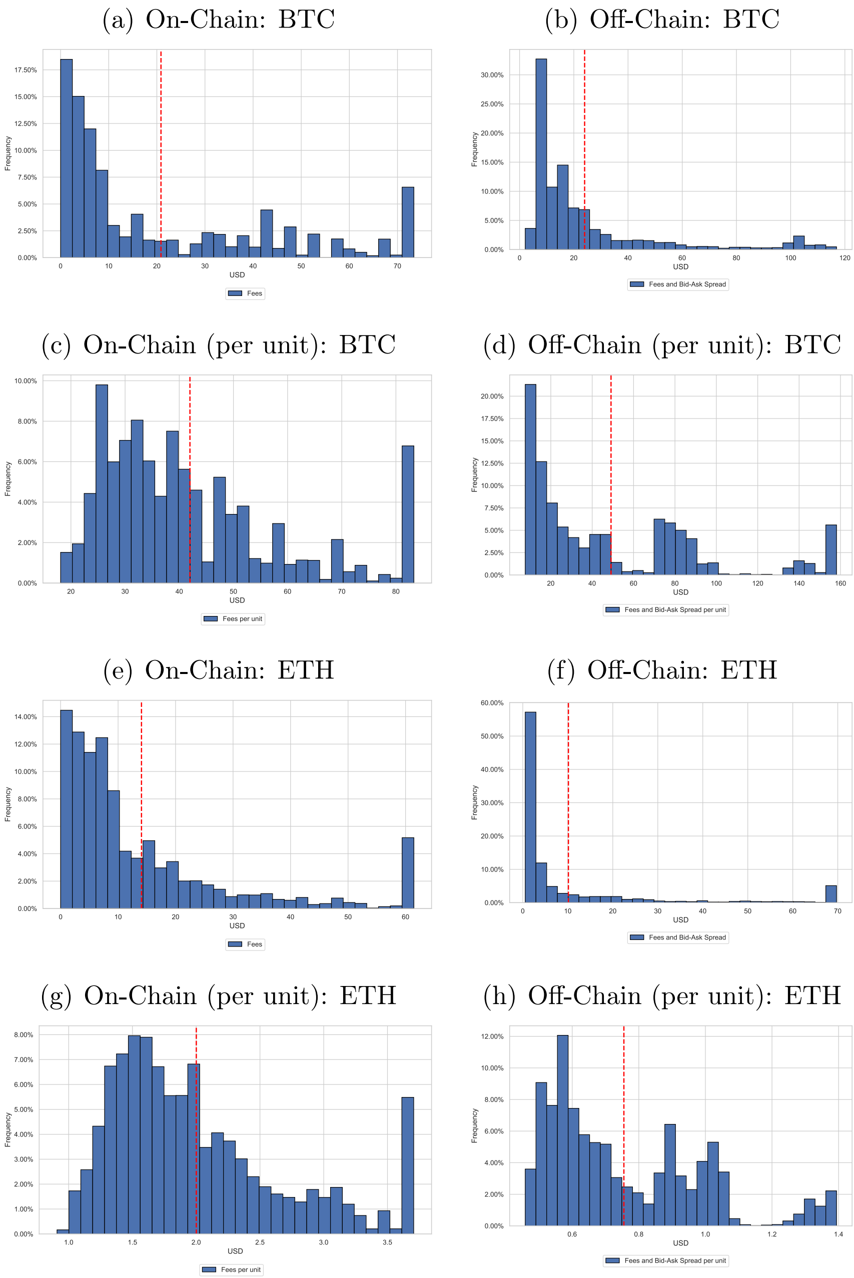
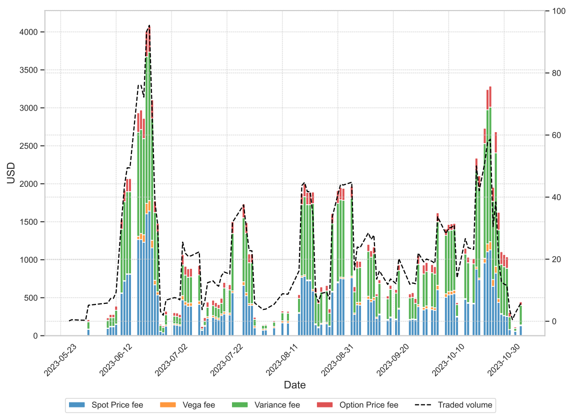


Figure III.6: Transaction Fees – On-Chain vs. Off-Chain – BTC and ETH. The figure shows the histogram of total trading fees (Panel (a), (b), (e), (f)), and the trading fee per unit (Panel (c), (d), (g), (h)), On-Chain, and Off-Chain for BTC and ETH. The On-Chain data is from Lyra V2 on Optimism, while 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 dashed red line denotes the unconditional average. Only OTM options with maturity between six 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) Fees Components On-Chain: BTC



(b) Fees Components On-Chain: ETH

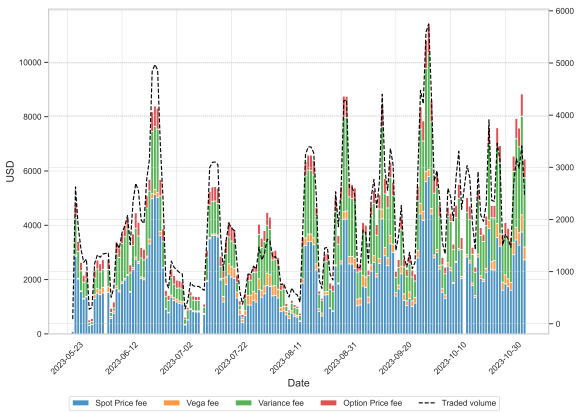


Figure III.7: Fee Components – On-Chain. The figure displays the fee components and volume (dashed line) for BTC (Panel (a)) and ETC (Panel (b)) in USD. The On-Chain data is from Lyra V2 on Optimism. The components of the fees are calculated in equation (3.6). Only OTM options with maturity between six 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.

III.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 III.1: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is from Lyra V2 on Optimism, while the Off-Chain data is from Deribit. Only OTM options with maturity between six 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 III.2: Summary Statistics – Quotes. The table displays the summary statistics of the quoted options, On-Chain, and Off-Chain. The On-Chain data is from Lyra V2 on Optimism, while the Off-Chain data is from Deribit. Only OTM options with maturity between six and 30 days are considered. The quote data is given at an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

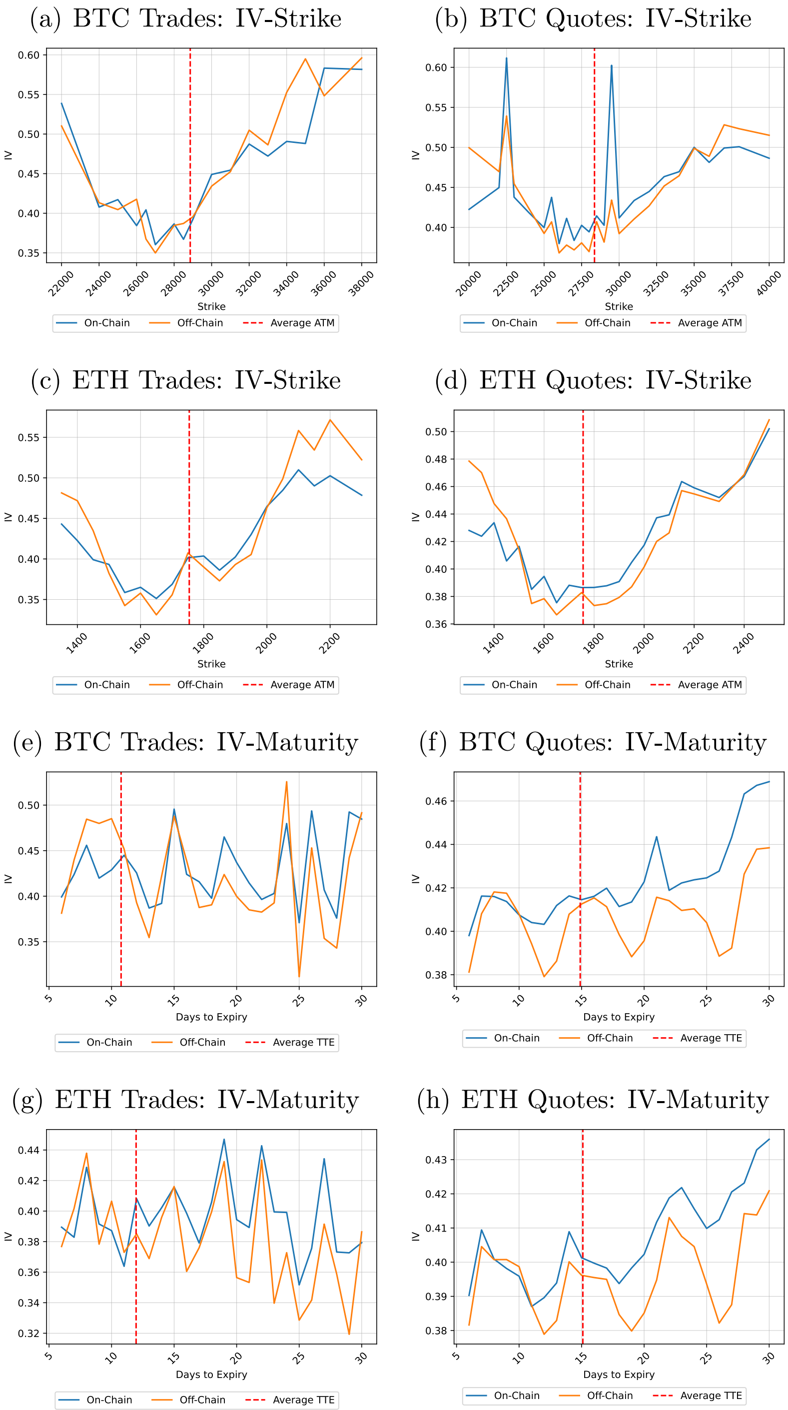


Figure III.8: IV, Strike Price, and Maturity. The figure shows the traded and quoted IVs from calls and puts, On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data is from Lyra V2 on Optimism, while the Off-Chain data is from Deribit. The x-axis represents the strike price (USD) or the maturity (days). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level, while the quotes are given at an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

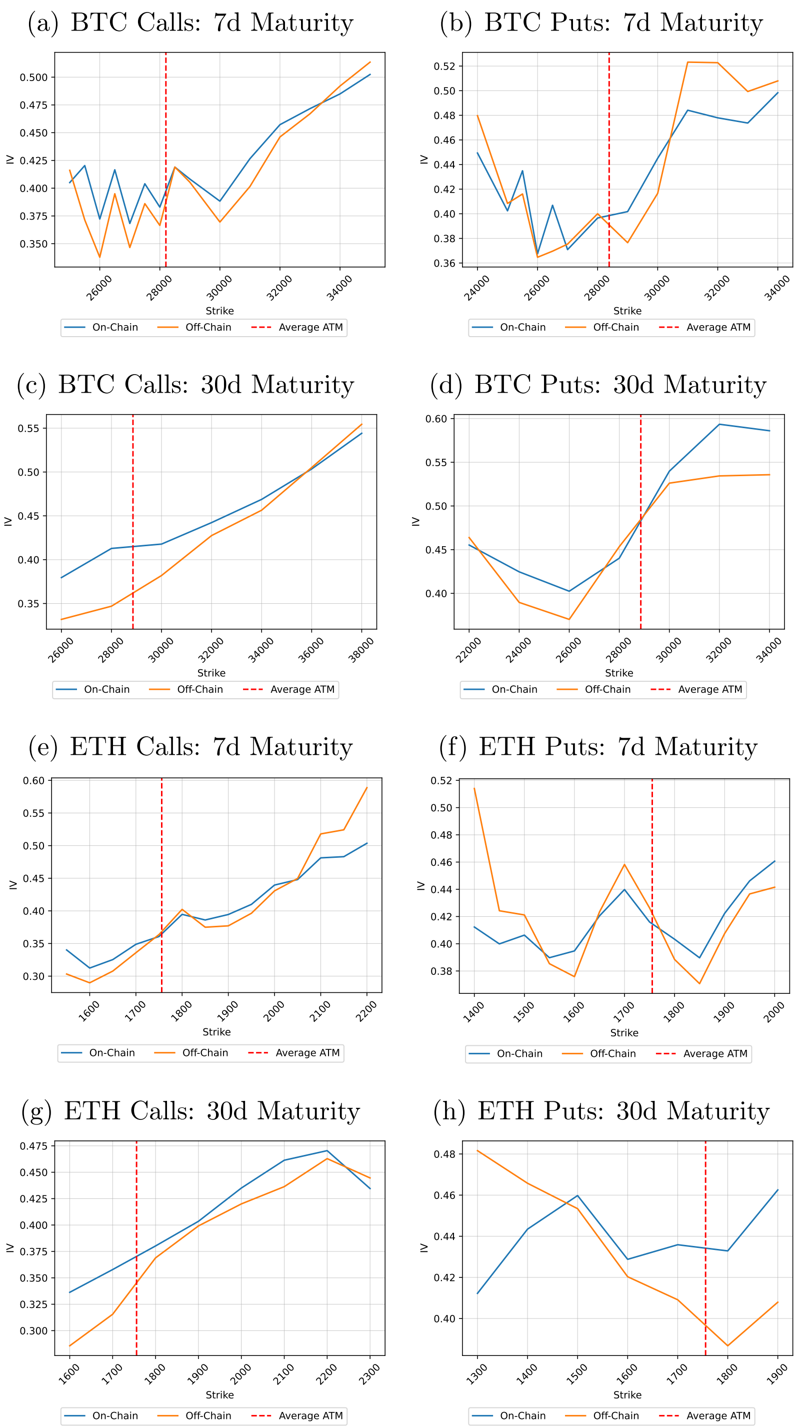


Figure III.9: IVs for BTC and ETH – Strike Price – Call and Puts. The figure shows the quoted IVs from calls and puts, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is from Lyra V2 on Optimism, while the Off-Chain data is from Deribit. The x-axis represents the strike price (USD). Panels (a), (b), (e), and (f) include OTM options with six and 8 days maturity, while panels (c), (d), (g), and (h) feature OTM options with 28-32 days maturity. The quote data is given at an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

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

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Panel A: BTC						
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
Panel B: ETH						
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 III.3: Regressions – IVs – On-Chain vs. Off-Chain – BTC and ETH – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (6.1) and (6.2). Thereby *Call* equals 1 if the instrument is a call, *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 from Lyra V2 on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The quote data is given at an hourly frequency. The sample period ranges from 05-2023 to 11-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Panel A: BTC					
Intercept	-0.28358	-0.26032	-0.32213	-0.01412	-0.02461
	(0.18698)	(0.19822)	(0.18251)	(0.24197)	(0.20795)
Call	-0.00256	-0.00029	0.00063		
	(0.87208)	(0.98439)	(0.96661)		
Maturity	0.00149	0.00167	0.00197		
	(0.18909)	(0.08457)	(0.07061)		
Mness	0.29020	0.27526	0.35236		
	(0.19328)	(0.18599)	(0.16608)		
On-Chain Fees		-0.00049			
		(0.18076)			
Off-Chain Quotes Spread		-0.00012	-0.00013		
		(0.00000)	(0.00000)		
On-Chain Scaled Fees			-0.00043		
			(0.45478)		
On-Chain Size			-0.01978		
			(0.31549)		
Abs. Delta				0.05605	0.05669
				(0.26452)	(0.52576)
Vega				0.00001	0.00001
				(0.59556)	(0.54367)
R-squared	0.1067	0.4153	0.4052	0.0275	0.1244
Observations	400	400	400	400	400
Entities				156	
Time Periods	325	325	325		325
Option-Id FE	No	No	No	Yes	No
Time FE	Yes	Yes	Yes	No	Yes
Panel A: ETH					
Intercept	-0.47268	-0.52094	-0.45551	-0.04279	-0.02995
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Call	0.00320	0.00269	0.00257		
	(0.09689)	(0.12082)	(0.13257)		
Maturity	0.00178	0.00188	0.00165		
	(0.00000)	(0.00000)	(0.00000)		
Mness	0.48753	0.54422	0.46360		
	(0.00000)	(0.00000)	(0.00000)		
On-Chain Fees		0.00008			
		(0.02955)			
Off-Chain Quotes Spread		-0.01518	-0.01584		
		(0.00358)	(0.00169)		
On-Chain Scaled Fees			0.00822		
			(0.00000)		
On-Chain Size			0.00003		
			(0.83126)		
Abs. Delta				0.07945	0.05949
				(0.00000)	(0.00000)
Vega				0.00036	0.00029
				(0.00000)	(0.00000)
R-squared	0.3476	0.4327	0.4554	0.2784	0.3731
Observations	2274	2274	2274	2274	2274
Entities				296	
Time Periods	1360	1360	1360		1360
Option-Id FE	No	No	No	Yes	No
Time FE	Yes	Yes	Yes	No	Yes

Table III.4: Regression with Fixed Effects – IVs – BTC and ETH – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (6.1) - (6.3) including fixed effects. Thereby *Call* equals 1 if the instrument is a call, *Maturity* denotes the maturity (days), and *Mness* denotes the moneyness of the option. Fees, Size, Abs. Delta and Vega are constructed from the trade data. The trades On-Chain data is from Lyra V2 on Optimism, while the Off-Chain data is from Deribit. The sample period ranges from 05-2023 to 11-2023.

III.5 Trading Strategy – On-Chain and Off-Chain – IVs – Trades

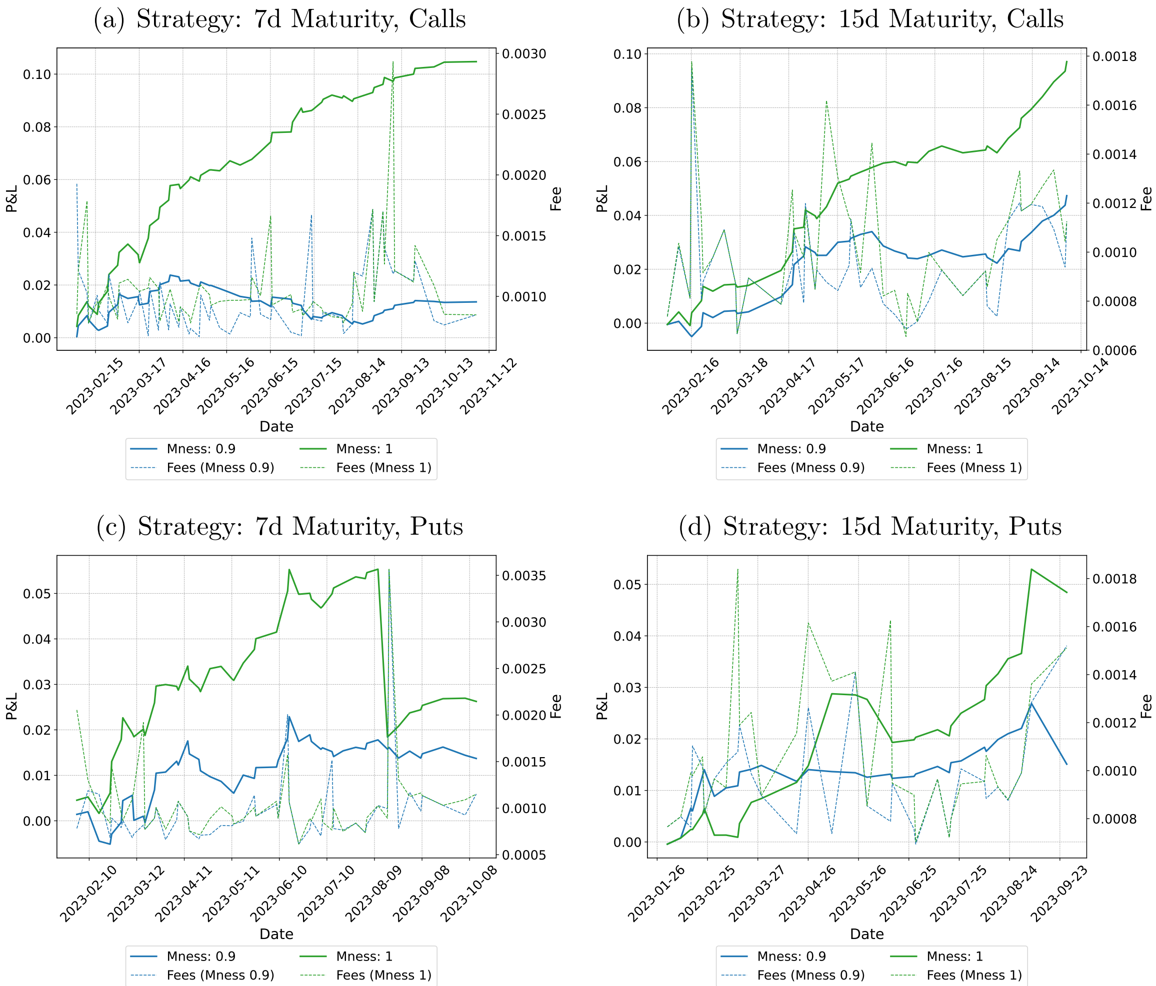


Figure III.10: Strategy – ETH – Trades with Fees. The figure displays the P&L (in ETH) of the trading strategy (net of fees) selling the On-Chain (call or put) options and buying the Off-Chain (call or put) options for a given maturity and moneyness. The strategy is constructed considering trades including realized fees. The On-Chain data is from Lyra V2 on Arbitrum, the Off-Chain data is from Deribit. The y-axis represents the cumulative P&L in ETH. The trading strategy is constructed on a weekly frequency at 10:00 am. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

IV 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 IV.5: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is from Aevo, the Off-Chain data is from Deribit. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 11-2023.

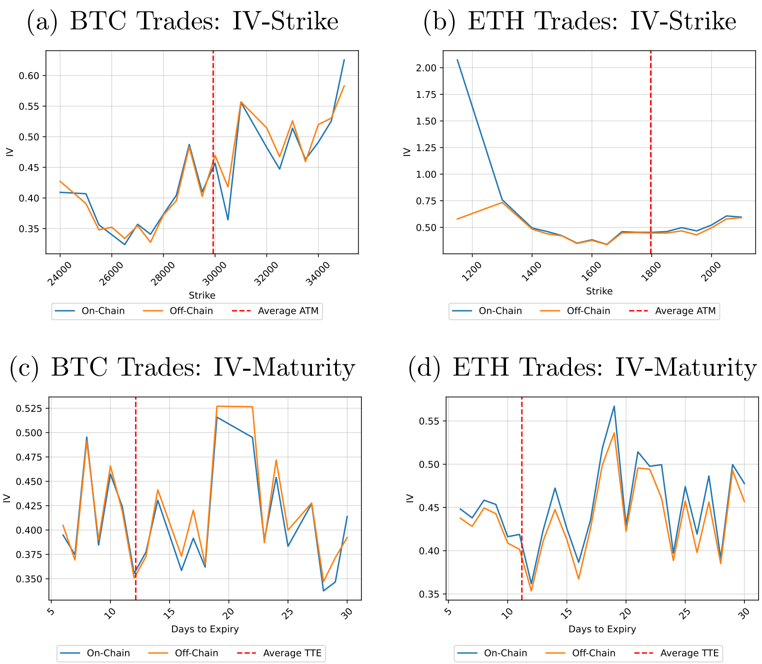


Figure IV.11: IV, Strike Price and Maturity. The figure shows the traded IV (calls and puts), On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data comes from Aevo, and the Off-Chain data is from Deribit. The x-axis represents the strike price (USD) or the maturity (days). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 11-2023.

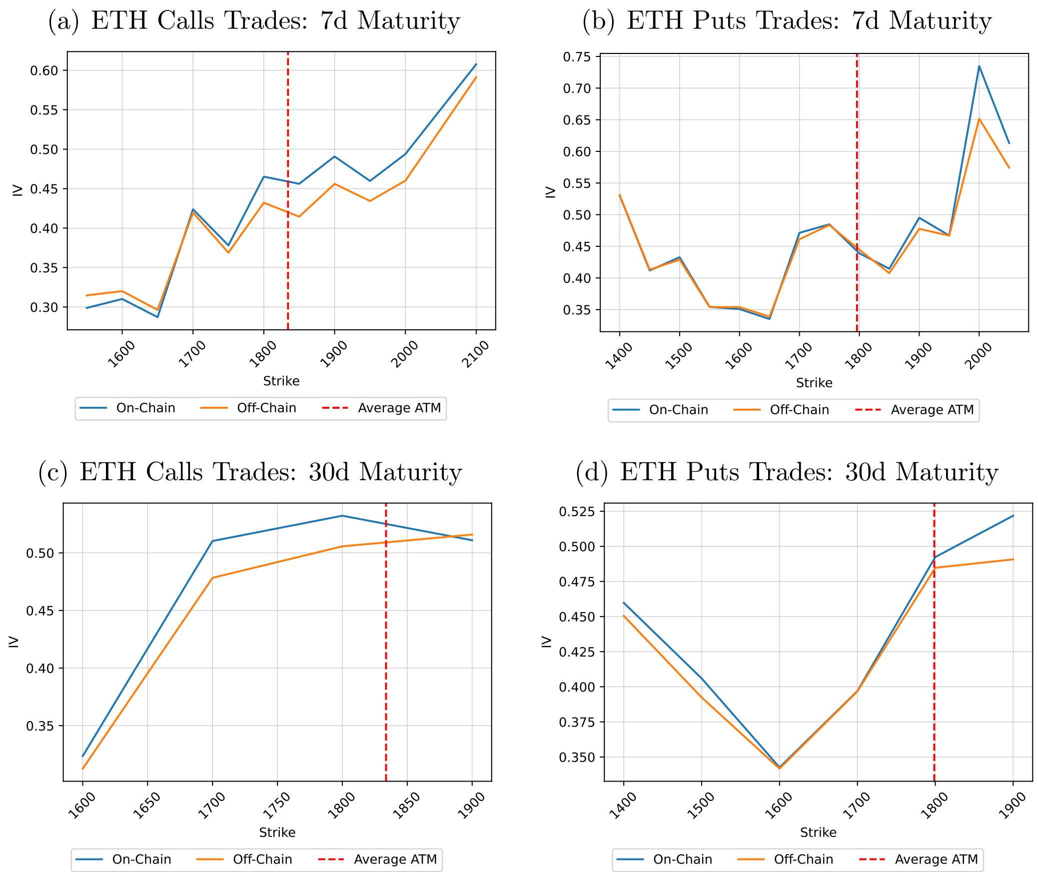


Figure IV.12: IVs for ETH and Strike Price – Call and Puts. The figure shows the traded IV from calls and puts, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is from Aevo, while the Off-Chain data is from Deribit. The x-axis represents the strike price (USD). Panels (a), and (b) include OTM options with six and eight-day maturity, while panels (c), and (d), feature OTM options with 28-32-day maturity. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 11-2023.

V Lyra V1 on Optimism

V.1 On-Chain and Off-Chain – Transaction Fees

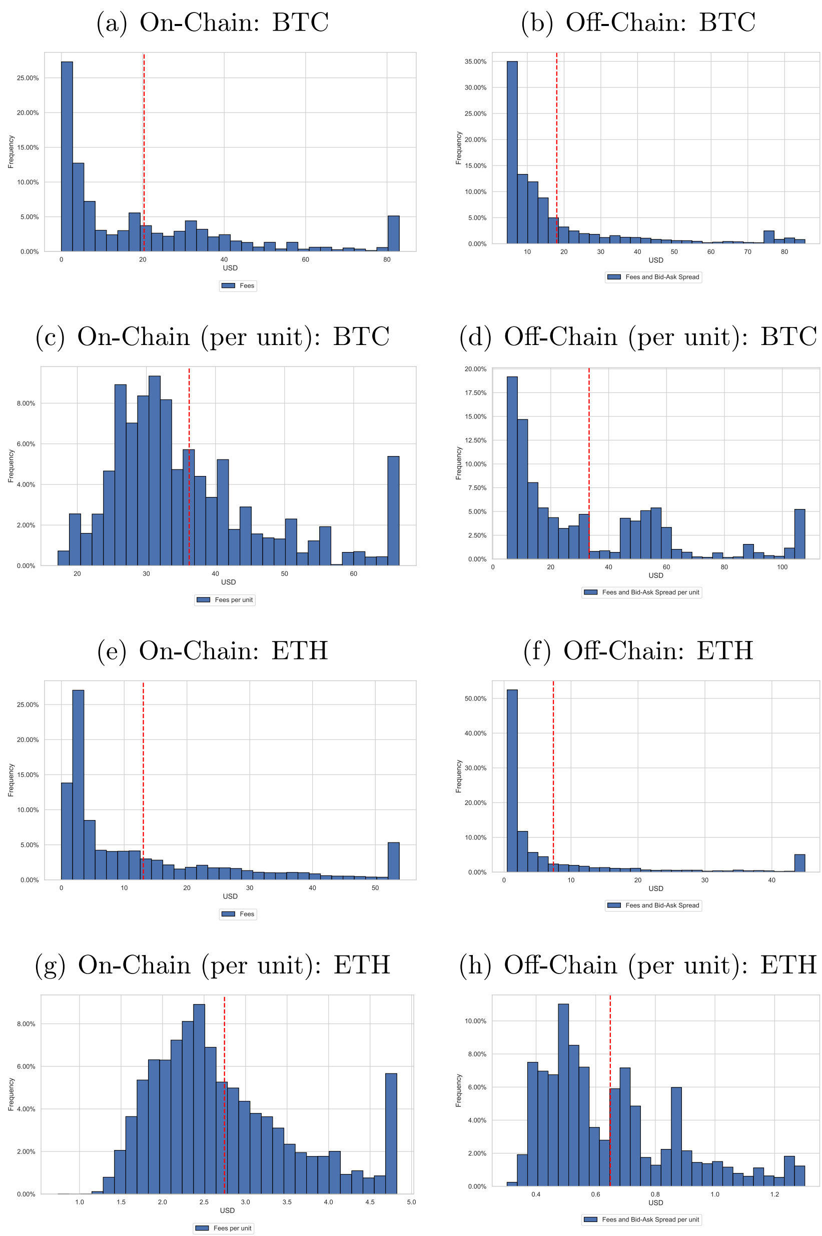


Figure V.13: Transaction Fees – On-Chain vs. Off-Chain – BTC and ETH. The figure shows the histogram of total trading fees (Panel (a), (b), (e), (f)), and trading fee per unit (Panel (c), (d), (g), (h)), On-Chain, and Off-Chain for BTC and ETH. The On-Chain data is from Lyra V1 on Optimism, while the 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 dashed red line denotes the unconditional average. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 08-2022 to 05-2023.

(a) Fees Components On-Chain: BTC (b) Fees Components On-Chain: ETH

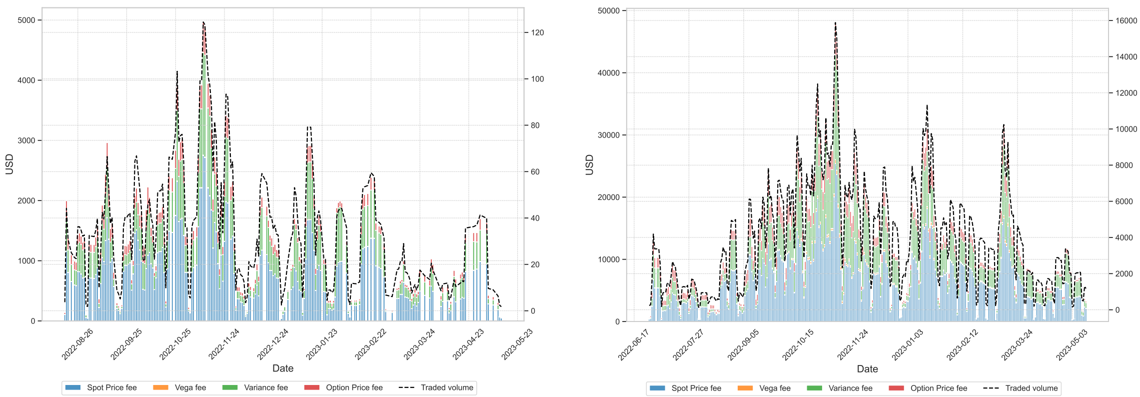


Figure V.14: Fee Components – On-Chain. The figure displays the fee components and volume (dashed line) for BTC (Panel (a)) and ETC (Panel (b)) in USD. The components of the fees are mentioned in equation (3.6). The On-Chain data is from Lyra V1 on Optimism. Only OTM options with maturity between six 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.

V.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 V.6: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is from Lyra V1 on Optimism, while the Off-Chain data is from Deribit. Only OTM options with maturity between six 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 V.7: Summary Statistics – Quotes. The table displays the summary statistics of the quoted options, On-Chain, and Off-Chain. The On-Chain data is from Lyra V1 on Optimism, while the Off-Chain data is from Deribit. Only OTM options with maturity between six and 30 days are considered. The quote data is given at an hourly frequency. The sample period ranges from 06-2022 to 05-2023.

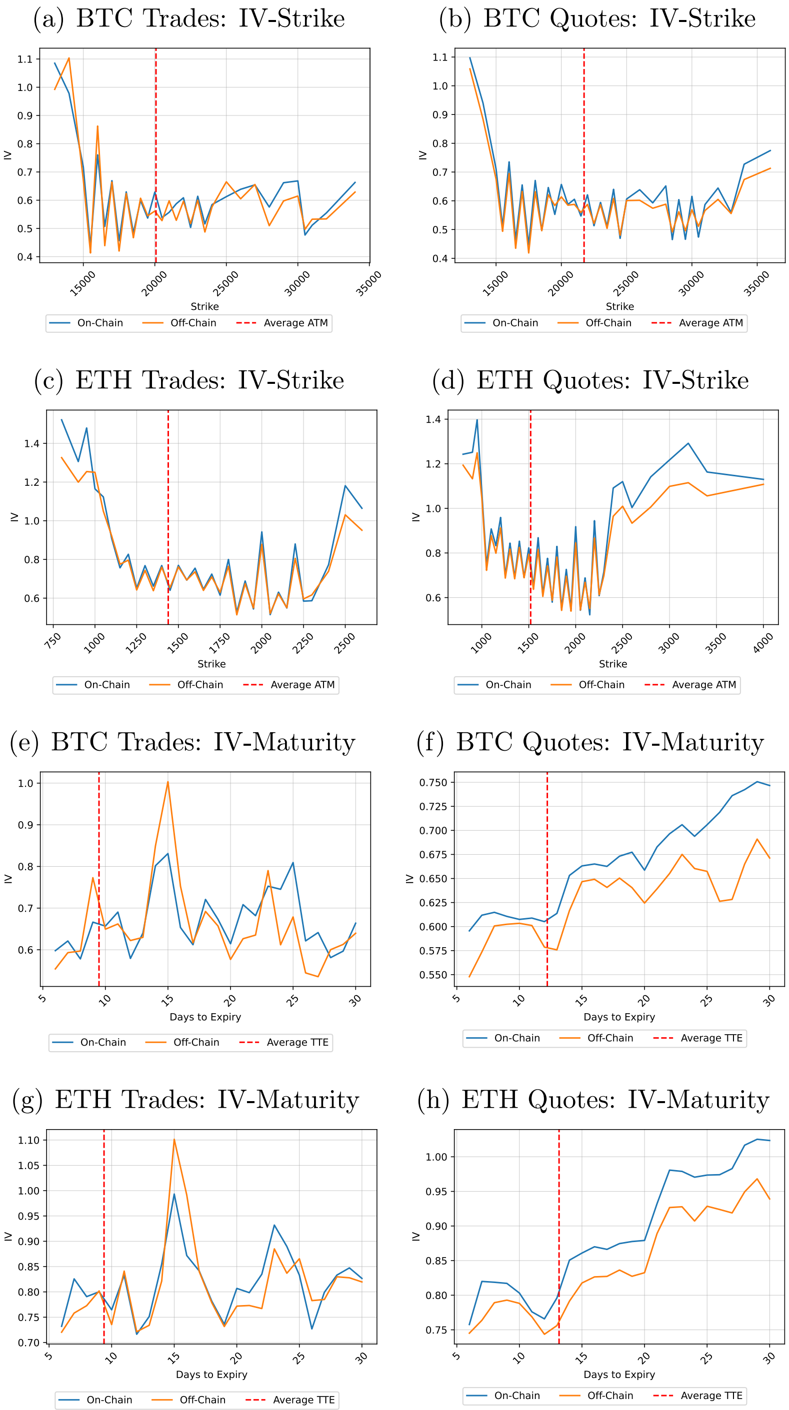


Figure V.15: IVs, Strike Price, and Maturity. The figure shows the traded and quoted IV from calls and puts, On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data is from Lyra V1 on Optimism, while the Off-Chain data is from Deribit. The x-axis represents the strike price (USD) or maturity (days). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level, while the quotes are given at an hourly frequency. The sample period ranges from 06-2022 to 05-2023.

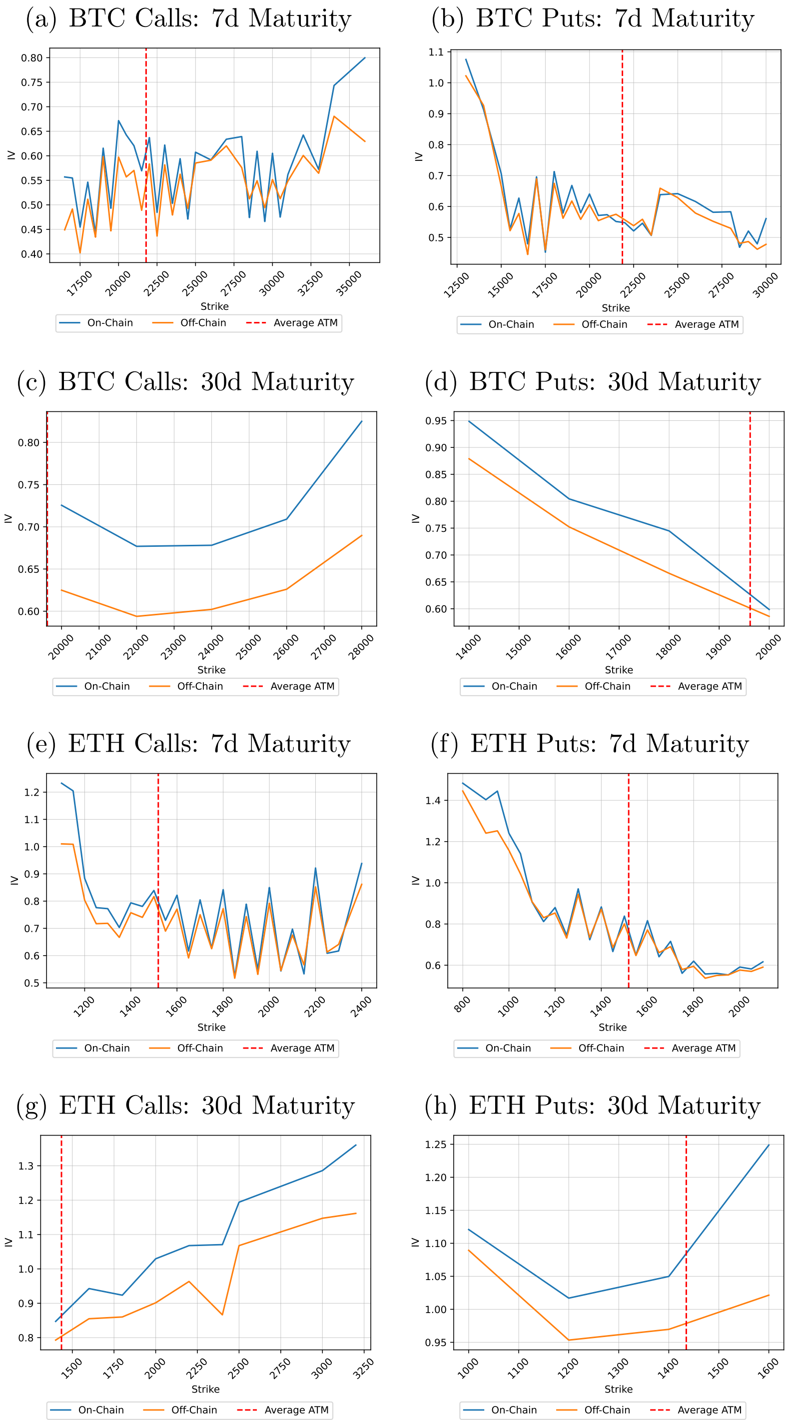


Figure V.16: IVs for BTC and ETH – Strike Price – Call and Puts. The figure shows the quoted IV from calls and puts, On-Chain, and Off-Chain, averaged for different strike prices. The On-Chain data is from Lyra V1 on Optimism, while the Off-Chain data is from Deribit. The x-axis represents the strike price (USD). Panels (a), (b), (e), and (f) include OTM options with six and 8 days maturity, while panels (c), (d), (g), and (h) feature OTM options with 28-32 days maturity. The quote data is given at an hourly frequency. The sample period ranges from 08-2022 to 05-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Panel A: BTC						
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
Panel B: ETH						
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 V.8: Regressions – IV – On-Chain vs. Off-Chain – BTC and ETH – Quotes. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (6.1) and (6.2). Thereby *Call* equals 1 if the instrument is a call, *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 from Lyra V1 on Optimism, while the Off-Chain data is from Deribit. The regressions are performed on an instrument level. The quote data is given at an hourly frequency. The sample period ranges from 08-2022 to 5-2023.

Variable	Diff IV	Diff IV	Diff IV	Diff IV	Diff IV
Panel A: BTC					
Intercept	-0.14880	-0.17565	-0.10621	0.07146	-0.00393
	(0.31641)	(0.26177)	(0.52284)	(0.00000)	(0.84646)
Call	0.01765	0.01593	0.01497		
	(0.14856)	(0.19936)	(0.22905)		
Maturity	0.00199	0.00195	0.00119		
	(0.16322)	(0.17233)	(0.43691)		
Mness	0.16075	0.18914	0.07797		
	(0.30514)	(0.25318)	(0.66357)		
On-Chain Fees		0.00018			
		(0.28071)			
Off-Chain Quotes Spread		-0.00026	-0.00035		
		(0.10809)	(0.04108)		
On-Chain Scaled Fees			0.00129		
			(0.12710)		
On-Chain Size			0.00379		
			(0.71646)		
Abs. Delta				0.01235	0.01000
				(0.85459)	(0.88390)
Vega				-0.00420	0.00303
				(0.02849)	(0.26578)
R-squared	0.0810	0.1030	0.1474	0.0343	0.0489
Observations	960	960	960	960	960
Entities				298	
Time Periods	771	771	771		771
Option-Id FE	No	No	No	Yes	No
Time FE	Yes	Yes	Yes	No	Yes
Panel A: ETH					
Intercept	-0.16590	-0.16792	-0.11903	0.01587	-0.00351
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.22723)
Call	0.02345	0.02384	0.02437		
	(0.00000)	(0.00000)	(0.00000)		
Maturity	0.00133	0.00133	0.00096		
	(0.00000)	(0.00000)	(0.00000)		
Mness	0.18528	0.18674	0.10144		
	(0.00000)	(0.00000)	(0.00000)		
On-Chain Fees		0.00007			
		(0.00495)			
Off-Chain Quotes Spread		-0.00141	-0.00165		
		(0.18132)	(0.11046)		
On-Chain Scaled Fees			0.01298		
			(0.00000)		
On-Chain Size			0.00011		
			(0.23923)		
Abs. Delta				0.09871	0.07565
				(0.00000)	(0.00000)
Vega				-0.01547	0.01767
				(0.01278)	(0.00090)
R-squared	0.1008	0.1063	0.1231	0.0092	0.0653
Observations	9707	9707	9707	9707	9707
Entities				613	
Time Periods	4144	4144	4144		4144
Option-Id FE	No	No	No	Yes	No
Time FE	Yes	Yes	Yes	No	Yes

Table V.9: Regression with Fixed Effects – IVs – BTC and ETH – Trades. The table reports the results, i.e., the coefficient and the p-values in brackets, from the panel regression as specified in (6.1) - (6.3) including fixed effects. Thereby *Call* equals 1 if the instrument is a call, *Maturity* denotes the maturity (days), and *Mness* denotes the moneyness of the option. Fees, Size, Abs. Delta and Vega are constructed from the trade data. The trades On-Chain data is from Lyra V1 on Optimism, while the Off-Chain data is from Deribit. The sample period ranges from 05-2023 to 11-2023.

VI 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 VI.10: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain. The On-Chain data is from Lyra V2 on Arbitrum and from Aevo. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

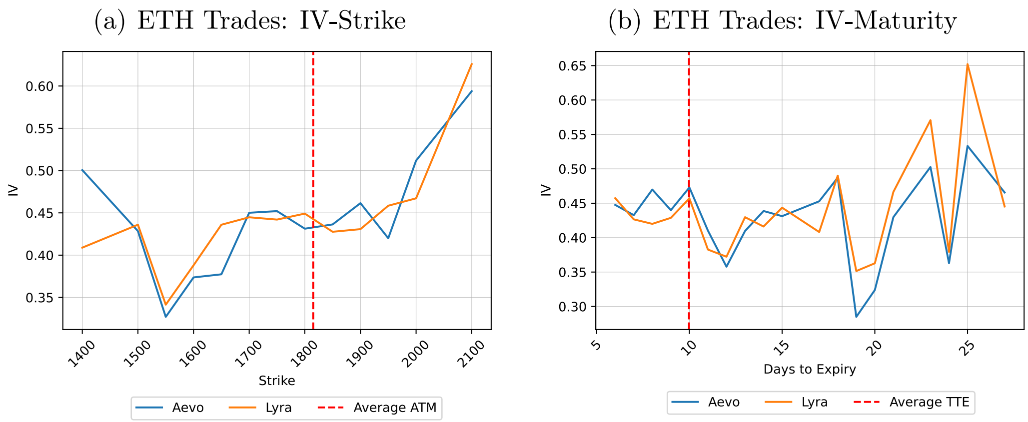


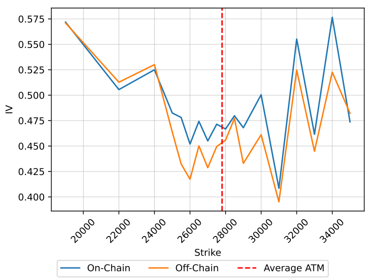
Figure VI.17: Implied Volatility, Strike Price and Maturity. The figure shows the traded IV from calls and puts On-Chain averaged for different strike prices and maturities, shown respectively on the left and right panels. The On-Chain data is obtained from Lyra and Aevo. The x-axis represents the strike price in USD. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

VII OKX and Lyra V2 on Arbitrum

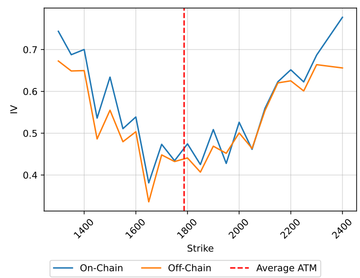
	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	1584	1584	6773	6773
Instruments	143	143	358	358
Min Date	2023-03-03	2023-03-03	2023-02-01	2023-02-01
Max Date	2023-08-19	2023-08-19	2023-11-06	2023-11-06
Min Strike	19000	19000	1300	1300
Max Strike	35000	35000	2400	2400
IV mean	0.48	0.45	0.50	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 VII.11: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. On-Chain data is from Lyra V2 on Arbitrum, while the Off-Chain data is from OKX. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

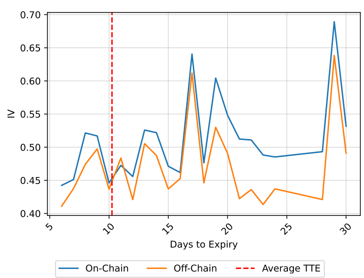
(a) BTC Trades: IV-Strike



(b) ETH Trades: IV-Strike



(c) BTC Trades: IV-Maturity



(d) ETH Trades: IV-Maturity

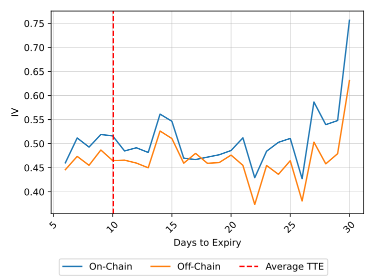


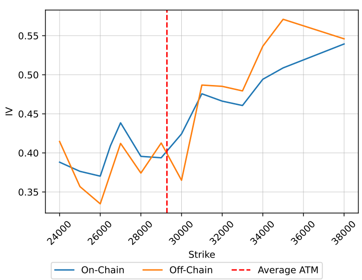
Figure VII.18: IV, Strike Price and Maturity. The figure shows the traded IV (calls and puts), On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data is from Lyra V2 on Arbitrum, and the Off-Chain data is from OKX. The x-axis represents the strike price (USD) or the maturity (days). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

VIII OKX and Lyra V2 on Optimism

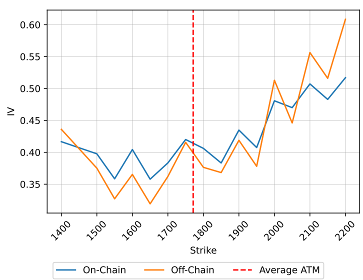
	Bitcoin		Ethereum	
	On-Chain	Off-Chain	On-Chain	Off-Chain
N	334	334	2166	2166
Instruments	56	56	153	153
Min Date	2023-05-27	2023-05-27	2023-05-25	2023-05-25
Max Date	2023-11-04	2023-11-04	2023-11-06	2023-11-06
Min Strike	24000	24000	1400	1400
Max Strike	38000	38000	2200	2200
IV mean	0.43	0.42	0.42	0.40
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 VIII.12: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. On-Chain data is from Lyra V2 on Optimism, and Off-Chain data is from OKX. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

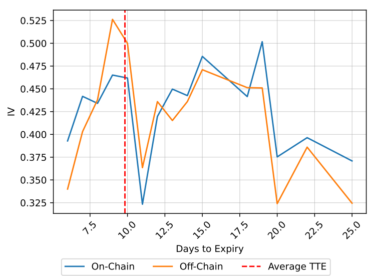
(a) BTC Trades: IV-Strike



(b) ETH Trades: IV-Strike



(c) BTC Trades: IV-Maturity



(d) ETH Trades: IV-Maturity

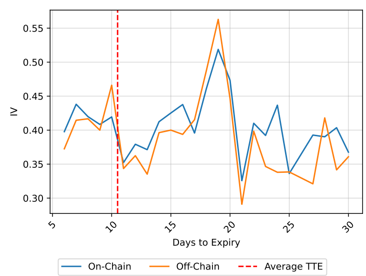


Figure VIII.19: IV, Strike Price and Maturity. The figure shows the traded IV (calls and puts), On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data comes from Lyra V2 on Optimism, and the Off-Chain data is from OKX. The x-axis represents the strike price (USD) or the maturity (days). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

IX OKX and 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 IX.13: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. On-Chain data is from Lyra V1 on Optimism, and Off-Chain data is from OKX. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2023 to 05-2023.

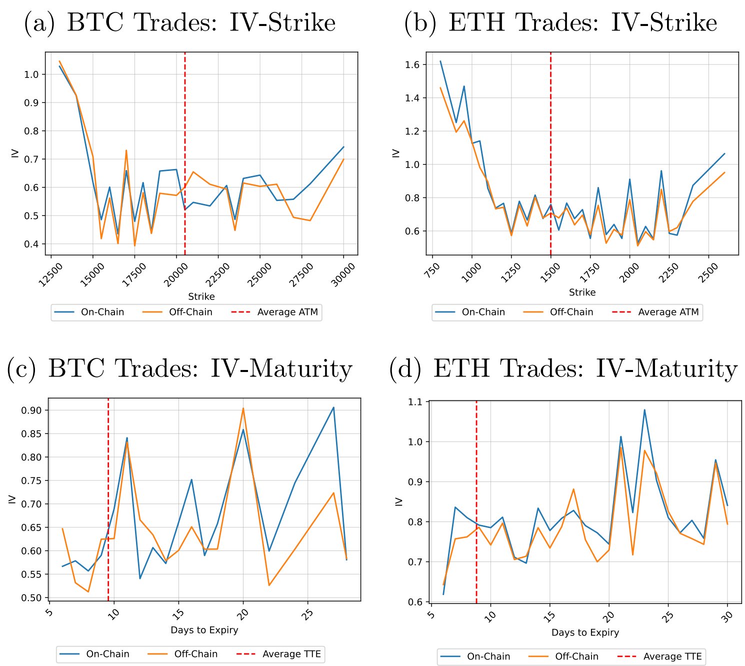


Figure IX.20: IV, Strike Price and Maturity. The figure shows the traded IV (calls and puts), On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data is from Lyra V1 on Optimism, and the Off-Chain data is from OKX. The x-axis represents the strike price (USD) or the maturity (days). Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 02-2023 to 11-2023.

X Bitcom and 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 X.14: Summary Statistics – Trades. The table displays the summary statistics of the traded options, On-Chain, and Off-Chain. The On-Chain data is from Lyra V1 on Optimism, while the Off-Chain data is from Bitcom. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2022 to 11-2022.

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

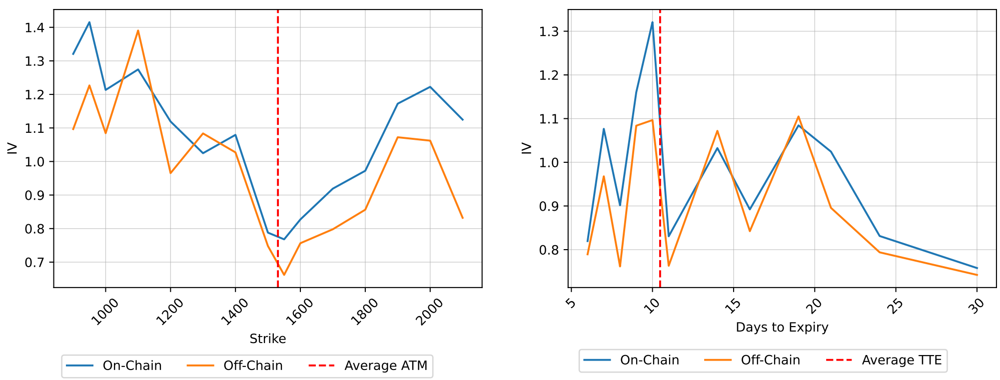


Figure X.21: IV, Strike Price, and Maturity. The figure shows the traded IV from calls and puts, On-Chain, and Off-Chain, averaged for different strike prices and maturities. The On-Chain data is from Lyra V1 on Optimism, and the Off-Chain data is from Bitcom. The x-axis represents the strike price in USD and the maturity in days. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2022 to 11-2022.

XI Deribit and OKX

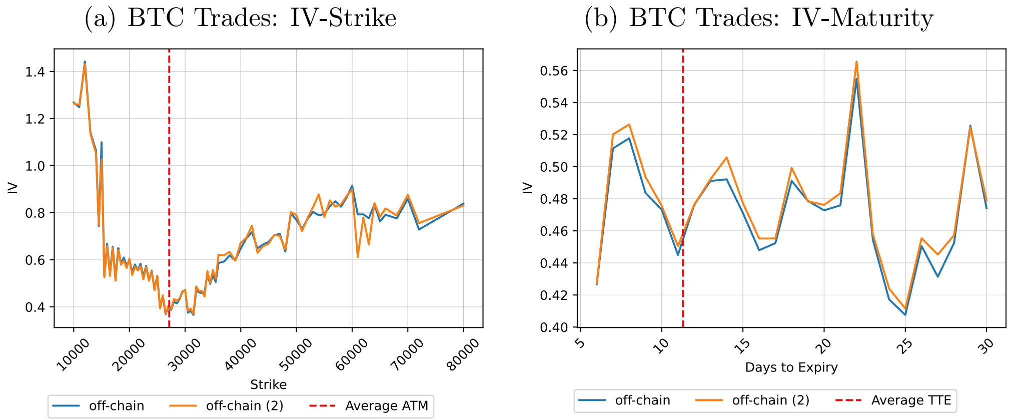


Figure XI.22: IV, Strike Price, and Maturity. The figure shows the traded IV from calls and puts, Off-Chain, averaged for different strike prices and maturities. The Off-Chain data is from Deribit, and the Off-Chain (2) data is from OKX. The x-axis represents the strike price in USD and the maturity in days. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2021 to 11-2023.

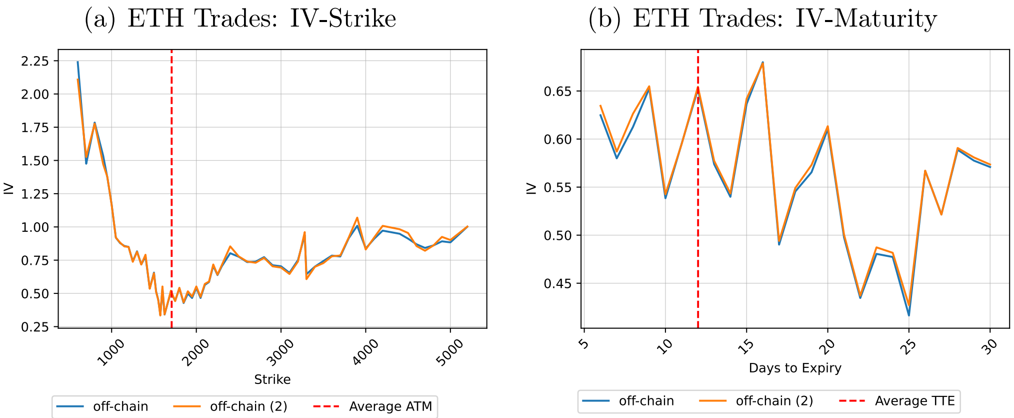


Figure XI.23: IV, Strike Price, and Maturity. The figure shows the traded IV from calls and puts, Off-Chain, averaged for different strike prices and maturities. The Off-Chain data is from Deribit, and the Off-Chain (2) data is from OKX. The x-axis represents the strike price in USD and the maturity in days. Only OTM options with maturity between six and 30 days are considered. The trade data is sampled on a tick level. The sample period ranges from 06-2021 to 11-2023.