Cross-Rollup MEV: Non-Atomic Arbitrage On Layer-2 Blockchains

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Abstract. Non-atomic arbitrage is the largest source of MEV on Ethereum but it remains unexplored on rollups, Layer-2 (L2) blockchains. This study quantifies the non-atomic arbitrage opportunities across decentralized exchanges (DEXs) on major rollups, as well as between rollup DEXs and centralized exchanges (CEXs). By measuring execution costs, swap paths, and cross-venue price discrepancies, we identify more than 500,000 previously untapped arbitrage opportunities across Arbitrum, Base, Optimism, and ZKsync. These opportunities correspond to 0.03–0.05% of trading volume on Arbitrum, Base, and Optimism, and approximately 0.25% on ZKsync. Because many price deviations persist for 10–20 blocks, we introduce an adjusted Loss-Versus-Rebalancing (LVR) metric to prevent double-counting in the presence of multi-block arbitrage windows. Our findings demonstrate that non-atomic arbitrage on rollups is economically meaningful and structurally distinct from L1 Ethereum, calling for new MEV extraction strategies.

Keywords: MEV · Arbitrage · Automated Market Maker · Rollup

1 Introduction

Decentralized Finance (DeFi) is moving onto rollups, the Layer-2 (L2) scaling solutions for Ethereum. The primary motivation for this shift is that mature rollups provide equivalent security guarantees as Ethereum while significantly reducing gas fees. Rollups offload complex computations outside the Ethereum network, storing only compressed batches of transactions on-chain. In March 2023, Ethereum underwent the Dencun upgrade [7], the most substantial change since the Merge, which significantly lowered gas fees on rollups.

The trading volume on Decentralized Exchanges (DEXs) within L2s is increasing, with certain rollups surpassing Ethereum's daily swap counts [5,16]. DEXs within L2s present new opportunities for arbitrageurs aiming to capitalize on price disparities across rollups or between rollups and Centralized Exchange (CEX). However, while arbitrage on Ethereum is currently facilitated through

Maximal Extractable Value (MEV) boost auctions [14], such mechanisms are yet unavailable on rollups. Most L2s rely on centralized sequencers to produce blocks and aggregate them into Layer-1 batches, employing the first-come-first-served rule. In addition, the transaction mempool is private and block time ranges from 200ms to 2 seconds, as opposed to Ethereum's 12-second block time [25] and public mempool. The combination of reduced gas costs and faster block production allows arbitrageurs to exploit minor price differences at a faster pace.

Arbitrage can be classified into one of two types: i) atomic arbitrage within DEXs on the same blockchain (cycling arbitrage [27]) or ii) non-atomic arbitrage involving CEX or DEX on a different blockchain [14]. Currently, 71% of the MEV transaction volume on Ethereum is related to arbitrage, and in excess of 60% of that arbitrage volume stems from non-atomic transaction [6,14,9]. Cycling arbitrage on L2 can be executed as atomic transactions [27], but non-atomic arbitrage faces a risk of state (price) drift. With the significantly reduced gas fees following the Dencun upgrade, non-atomic arbitrage can be exploited by posting a large amount of prospective arbitrage transactions that are reverted if unsuccessful. The number of revered transactions on L2s increased from 2% to 6% after the Dencun upgrade [8]. Another strategy employed by L2 arbitrageurs is the physical location of centralized sequencers, a service sometimes provided by DeFi solvers [3]. Transactions originating from the same data center as the centralized sequencer are likely to be executed first due to lower network delays [18,28].

The centralized sequencers and the associated censorship risk remain a concern within L2 DeFi. Additional risks include the transaction finality, the time period until an L2 transaction becomes irrevocable from the rollup (soft finality) or the underlying L1 blockchain (hard finality) [30]. Rollups can be categorized into optimistic and Zero-Knowledge (ZK) rollups based on transaction validity and proof mechanisms [11]. Despite the seven-day hard finality period, optimistic rollups have gained user adoption more rapidly due to higher compatibility with Ethereum Virtual Machine (EVM) . However, ZK-rollups offer higher transaction compression, throughput, and faster hard finality, ranging from minutes to hours. The aforementioned factors — reduced gas fees, absence of MEV auctions, varying finality times, and faster block production — contribute to distinct arbitrage dynamics on rollups, which requires further investigation.

With the emergence of decentralized sequencers [22], the adverse practices associated with front-running MEV on Ethereum [4,24,26] transfer to L2 DeFi. To address this concern, a time-boost mechanism within sequencers has been proposed [19]. This mechanism is specifically designed to allow only back-running MEVs while preventing front-running. Front-running MEV can enable various forms of adversarial actions, such as sandwich attacks on traders [15,20] and Just-In-Time (JIT) liquidity attacks on Liquidity Providers (LPs) [31]. In contrast, back-running MEV enables arbitrage in DEXs and liquidations at lending protocols. Faster arbitrage execution benefits traders, as it eliminates price discrepancies between trading venues. Additionally, MEV time-boost auctions can generate new revenue for sequencer operators.

This paper contributes to the research on L2 DeFi by quantifying the potential arbitrage opportunities across rollups and between rollups and CEXs. Our measurement can be the basis for the revenue estimate from the time-boost MEV auctions in the rollup sequencers and shared sequencers. Moreover, we empirically examine the swap dynamics and fees breakdown on L2s.

Related Work. The Loss Versus Rebalancing metric (LVR), which compares arbitrageur profits with those of LPs, was introduced by Milionis et al. [21] and empirically measured by Fritsch et al. [10] on L1. Our investigation quantifies the absolute profit of arbitrageurs, also known as the net LVR (per block), incorporating significant adjustments for empirical measurements. First, LVR assumes that the price discrepancies between AMMs and target exchanges, such as CEXs, disappear after each block. Our findings confirm this assumption for Uniswap (v3) on Ethereum; nonetheless, the decay period of price discrepancies on rollups extends over multiple blocks. Our methodology adjusts the LVR to this scenario and prevents double counting of the same arbitrage opportunities. Second, LVR and the rebalancing portfolio assess the LP's loss relative to arbitrageurs, thereby containing impermanent loss. Our metrics measure the absolute profit of the arbitrageur. Practically, arbitrageurs do not replicate the rebalancing portfolio but instead capitalize on arbitrage opportunities [14].

The persistence of price disparities on AMMs within zkSync Era, a ZK rollup, was initially reported by Gogol et al. [12]. Our paper builds on that research by providing: i) a comprehensive analysis of rollups (Arbitrum, Base, Optimism, in addition to zkSync Era) alongside Ethereum, ii) enhanced precision in market price accuracy and per-block analysis. Heimbach et al. [14] focus on the estimation of arbitrage executed through MEV auctions on Ethereum, specifically addressing non-atomic arbitrage opportunities between AMMs and CEXs. Our research extends this investigation by examining rollups, where MEV auctions have not yet been implemented. Similarly, we establish the minimum threshold for arbitrage opportunities and derive the arbitrage value using AMM formulas. However, this work seeks to quantify the unexploited arbitrage, which occasionally persisted for several minutes, in contrast to the arbitrage realized via MEV on Ethereum. Other studies on arbitrage [1,17,2] focus primarily on AMM-DEX on Ethereum and/or cyclic arbitrage opportunities. Torres et al. [27] is the first effort to quantify MEV in rollups, especially atomic arbitrage.

Contributions. This work contributes to the research on DeFi and MEV on L2s by quantifying the potential of non-atomic arbitrage on rollups:

L2 Non-atomic Arbitrage and Its Decay Time: By examining the price differences between Binance and Uniswap (v3) WETH-USDC pools on L2s, we discover over 0.5 million unexploited arbitrage opportunities on rollups. We show that price misalignment last for 10–20 blocks in rollups and present an empirical framework that avoid the double counting of the same opportunities. Such empirical method, which filters out repeated arbitrage, results in five times lower arbitrage profits compared to the Loss-Versus-Rebalancing (LVR) metric.

L2 Swap Dynamics and Cost Breakdown: We break down the costs of swapping on rollups and compare it to Ethereum. The analyzed WETH-USDC swap transactions on rollups occured 2–3 times more frequently than on Ethereum but are smaller in size. Furthermore, these swaps are generally not impacted by front- or back-running block slippage within the same block.

Cross-Rollup MEV: We estimated the potential for cross-rollup MEV by analyzing the price disparities among WETH-USDC Uniswap (v3) pools on major L2s. The arbitrageurs profits are impacted by the price impact (of AMM) and, therefore, are the highest between the AMM pools with the highest token reserves.

2 Theory of Arbitrage

Price disparities between different trading platforms (both DEXs and CEXs) present arbitrage opportunities. In this section, we calculate the transaction volume required to align prices between AMM-DEX and CEX, and two AMM-DEXs, given the existing token reserves in the AMM liquidity pools. Trading this volume maximizes the arbitrageur's profit, which is called net LVR [21], or the Maximal Arbitrage Value (MAV) [12]. For simplicity, we further assume that trading on the CEX has no price impact due to the typically higher reserves compared to AMM-DEXs.

Consider a scenario of two tokens - X and Y - in which there is a price discrepancy between a CEX and an AMM, the CEX having a substantially higher market depth, resulting in zero market impact. Let P_{CEX} and P_{AMM} be the exchange prices of the token X for Y at CEX and AMM, respectively. Assuming that $P_{CEX} < P_{AMM}$, the arbitrageur buys V amount of tokens X at CEX and sells them at AMM. His profit, denominated in Y, is

$$V \cdot P_{AMM}(1 - \rho(V)) - V P_{CEX}$$

where $\rho(V)$ is the *percentage price impact* of his transaction on the AMM price.

CPMM-CEX Arbitrage. Let us assume that the respective reserves of tokens X and Y in the AMM liquidity pool are x and y. Assuming AMM follows CPMM, the percentage price impact is given by $\Delta y/y$ for a swap of Δx for Δy [29,12] . The MAV can be expressed as:

$$MAV = V_{max} \cdot (P_{AMM} - P_{CEX}) - \frac{V_{max}^2 P_{AMM}}{x}, \tag{1}$$

Following [12] we can compute the first derivative of Eq. (1) with respect to V_{max} to find the max points, receiving:

$$V_{max} = \frac{x \cdot (P_{AMM} - P_{CEX})}{2P_{AMM}}. \tag{2}$$

And, by substituting (2) into (1) the MAV is written as:

$$MAV = \frac{x \cdot (P_{AMM} - P_{CEX})^2}{4P_{AMM}}. \tag{3}$$

CPMM-CPMM Arbitrage. Following analogous calculation, we can derive the formal for MAX between two CPMMs, with reserves of token X in their liquidity pools given by x_1 and x_2, and spot prices P_1 and P_2:

$$MAV = \frac{1}{4}\frac{(P_1 - P_2)^2}{\frac{P_1}{x_1} - \frac{P_2}{x_2}}. \tag{4}$$

CLMM-CEX Arbitrage. Following [12], we generalize the MAV formula of CPMM - Uniswap (v3) for concentrated liquidy in Uniswap (v3). The conservation function of a Uniswap v3 pool aggregates individual LPs' conservation functions for different ticks, each dependent on the exchange rate range specified by the LP.

Ticks occur at each price $p(i) = 1.0001^i, i \in [1, 2, ...]$. Suppose that an LP offers liquidity (x, y) exclusively to users trading within a specific range of exchange rates defined by two surrounding consecutive ticks, i.e. $[P_a/\alpha, P_a\alpha]$ with $\alpha > 1$ and $P_a = \frac{x}{y}$ as the current spot price. By definition, there exists some i such that $[P_a/\alpha, P_a\alpha] \to [p(i), p(i+1)]$, and thus we denote for the sake of clarity (x, y) as (x_i, y_i). Within this setting, the shape of the trading function is identical to the case of liquidity provision of equivalent reserves

$$x_i^{equiv} = \frac{x_i}{1 - 1/\sqrt{\alpha}}, \text{ and } y_i^{equiv} = \frac{y_i}{1 - 1/\sqrt{\alpha}} \tag{5}$$

under Uniswap v2.

We now allow the proportion of reserves to vary within the price range defined by the two ticks under consideration, and for simplicity, define $r_{i,x}, r_{i,y} \geq 0$ as such varying quantities. Clearly, there is an upper bound to the change in reserves due to the implied movement to the next adjacent tick bounds. This translates into $0 \leq r_{i,x} \leq x_i \cdot (\sqrt{\alpha} + 1)$ and $0 \leq r_{i,y} \leq y_i \cdot (\sqrt{\alpha} + 1)^2$. Thus, we can derive (similarly as for Uniswap v2) the percentage price impact when trading within two ticks $[p(i), p(i+1)]$ on Uniswap v3 [29]. This is

$$\rho_i(\Delta y) = \frac{\Delta x}{r_{i,x} + \frac{x_i}{\sqrt{\alpha} - 1}}, \tag{6}$$

with the constraint that $\Delta y \leq r_{i,y}$, since otherwise we deplete one of the two reserves and move to the next tick. Thus, our MAV formula becomes

$$MAV_i = V_{i,max} \cdot (P_a - P_c) - V_{max} \cdot P_a \cdot \rho_i(V_{i,max}), \tag{7}$$

where $p(i) \leq P_c \leq p(i+1)$, and which needs to be solved enforcing the constraint $\Delta y \leq r_{i,y}$.

If the price misalignment spans multiple ticks, one then needs to iteratively compute MAV_i and sum the related profits until realignment, i.e.

$$MAV_{Uniswap\_v3} = \sum_{i:P_a \in [p(i), p(i+1)]}^{i:P_c \in [p(i), p(i+1)]} MAV_i. \tag{8}$$

Table 1: List of analyzed WETH-USDC and WETH-USDC.e liquidity pools on Uniswap (v3) on Ethereum and its rollups, spanning the period from 31st December 2023 to 30th April 2024.

Chain	**Swaps**	**Transactions**	**Blocks**	**Block Range**
Ethereum	761 005	749 818	475 409	18 908 896–19 771 559
Arbitrum	2 400 000	2 367 361	1 709 619	187 373 628–206 540 031
Arbitrum (USDC.e)	2 258 469	2 232 543	1 648 839	165 788 868–206 540 037
Base	1 687 530	1 636 196	1 145 789	8 638 929–13 866 123
Optimism (USDC.e)	1 186 780	1 136 839	902 789	114 234 215–119 461 410
zkSync Era (USDC.e)	46 417	46 379	45 364	22 909 923–32 843 035

3 Data Collection

We analyze swap data from Ethereum and its rollups with the highest trading volumes. This includes Arbitrum, Base, and Optimism (optimistic rollups), and zkSync Era (ZK-rollup). For each blockchain, we focus on the most actively traded pool, WETH-USDC on Uniswap (v3), during the period from December 31st, 2023, to April 30th, 2024. Although the Uniswap (v3) deployment on zkSync Era did not initially have a graphical user interface, users could interact with it via DEX aggregators such as Oku Analytics.

The data set is sourced from the blockchain archive nodes provided by Nansen [23]. The number of analyzed swaps, transactions, and block ranges is detailed in Table 1. Using the event logs of the *Swap* method, we recalculate the historical spot prices and liquidity in ticks within the USDC-WETH pools. For Uniswap (v3), the spot price after the swap is obtained from *sqrtPriceX96* in the event logs. Market data for the ETH-USDC exchange rate on CEX are sourced from Binance. We examine 1-second Binance closing prices, noting that block production on Ethereum occurs every 12 seconds, while it is around 1–2 seconds on Base, Optimism, and zkSync Era. On Arbitrum, block production can be as fast as 0.25 seconds. Thus, for each blockchain, except for Arbitrum, computations are performed at the block level. For Arbitrum, we analyze the last block in a second. The DEX spot price is determined by the last swap within the block.

Native USDC and Bridged USDC.e. USDC is a fiat-backed stablecoin issued by Circle. It takes one of two forms: native or bridged token. The native USDC is directly backed by Circle's off-chain reserves, while USDC.e is bridged, typically from Ethereum. The bridged stablecoin, USDC.e, is faster to launch on new blockchains, but the issuance of the native USDC stablecoin typically follows. Consequently, in most rollups, USDC and USDC.e tokens coexist for legacy purposes.

4 Cost of Swapping on L2s

The total cost of executing swap transactions on an AMM includes gas costs and explicit and implicit DEX fees [29,13]. For clarity, we express this as follows.

$$\text{Total Fees} = \underbrace{\text{L1 Fee} + \text{L2 Fee}}_{\text{Gas Fee}} + \text{LP Fee} + \underbrace{\text{Block Slippage} + \text{Price Impact}}_{\text{Implicit Fee}}, \quad (9)$$

Gas Fee. Unlike gas fees on L1 blockchains, the gas fees for rollup transactions are not predetermined as they consist of two parts: those charged by the sequencer and those charged by the underlying L1 network. The sequencer estimates the gas fee for a transaction, and this estimated amount is deducted from the originating address. Later, once the transaction, along with others, is posted on the L1 chain, the exact gas fees from L1 are determined. Depending on the specific rollup implementations, any overpayment by the transaction originator is either refunded immediately (e.g., zkSync Era) or during the next transaction (e.g., Arbitrum).

LP Fee. Also known as trading fees, LP fees are the explicit fees paid by the trader to the DEX to swap tokens. They typically range between 1 and 50 basis points (0.01% and 0.05%) of the swap volume, and are fully or partially redistributed to LPs.

Block Slippage. This represents an implicit swap cost when trading on an AMM and can result in unexpected changes in the execution price due to the order of transactions within a block. The impact of slippage can be either positive or negative, depending on whether it benefits or disadvantages the trader in terms of the executed price.

Price Impact. Price impact is the effect of an individual trade on the market price of the underlying asset pair. It is directly related to the size of the trade and the amount of liquidity available in the AMM's pool.

Swap Fee Analysis. Tables 2 and 3 present the characteristics of WETH-USDC swaps on rollups, while table 4 breaks down the costs of swapping. The corresponding values of Ethereum are provided as a benchmark. As shown in Table 2, swap transactions on rollups have a lower volume compared to those on Ethereum, although they occur more frequently. On average, there are 2–3 times more swaps on rollups, but the trading volume is about five times lower. Consequently, the median swap volume on Ethereum is 4239.45 USD, while it is 2201.23 USD on Arbitrum, 173.46 USD on Base, 331.28 USD on Optimism, and only 20 USD on zkSync Era.

Table 3 explains the effect of block times on rollup swap transactions. Despite having a higher number of swaps, there are fewer swaps per block on rollups because of faster block production. In Ethereum, there are, on average, 0.88 swaps in every block, with every block containing swap transactions having 1.6 swap events. In contrast, every third block on Base, fifth block on Optimism,

Table 2: Swap volumes in WETH-USDC and WETH-USDC.e pools on Uniswap v3 (31 Dec 2023–30 Apr 2024).

Chain	Swaps	Volume (mn)	Avg Volume	Std Dev	Median
Ethereum	761,005	35,175	46,222.26	142,890.62	4,239.45
Arbitrum	2,400,000	7,266	3,027.66	6,738.06	1,125.01
Arbitrum (USDC.e)	2,258,469	8,159	3,612.86	5,976.01	2,201.23
Base	1,687,530	2,996	1,775.55	5,611.25	173.46
Optimism (USDC.e)	1,186,780	1,457	1,228.30	2,842.73	331.28
zkSync (USDC.e)	46,417	8.01	172.67	426.52	20.99

Table 3: Swaps per transaction and block in WETH-USDC and WETH-USDC.e pools on Uniswap v3 (31 Dec 2023–30 Apr 2024).

Chain	Block Time (s)	Swaps/Block	Swaps/Tx	Swaps/Block (with Tx)
Ethereum	12.0	0.88	1.01	1.60
Arbitrum	0.25	0.13	1.01	1.40
Arbitrum (USDC.e)	0.25	0.06	1.01	1.37
Base	2.00	0.32	1.03	1.47
Optimism (USDC.e)	2.00	0.23	1.04	1.31
zkSync Era (USDC.e)	1.05	0.00	1.00	1.02

and tenth block on Arbitrum contain a swap. Furthermore, there are fewer swap events per block with swap transactions (approximately 1–1.47) on rollups.

On average, there are slightly more swap events per transaction (1.01) on both rollups and Ethereum, indicating that some swaps are performed in batches. This could imply the exploitation of MEV by certain wallets or decentralized exchange (DEX) aggregators initiating swaps on behalf of users.

Table 4 shows the costs of swapping on L2s before and after the Dencun upgrade. While total costs and average gas fees decreased, the percentage costs of swaps often remained unchanged or increased. This is due to the smaller swap sizes on rollups post-upgrade.

5 Methodology

To avoid double-counting the same arbitrage opportunities that span across multiple blocks, we use the MAV methodology from [12] and adapt it for block-by-block analysis.

Block Intervals. We analyze Binance ETH-USDC closing prices every second, and compare them with the spot price on the AMM-DEX at every block. The spot price on the DEX is determined based on the last swap within the block. The block production on Ethereum takes approximately 12 seconds, followed by

Table 4: Breakdown of swap fees at the WETH-USDC and WETH-USDC.e pools at Uniswap (v3) at Ethereum and its rollups during the period 12.31-30.04, 13.03-30.04.24 (pre-blobs) and 14.3-30.04.24 (post-blobs).

Chain	Total Fee	Gas Fee	LP Fee	Slippage and Price Impact
Whole Period:				
Ethereum	97.20 (21bps)	37.13 (8bps)	23.11 (5bps)	65.33 (14bps)
Arbitrum	2.46 (8bps)	0.65 (2bps)	1.51 (5bps)	1.82 (6bps)
Arbitrum (USDC.e)	5.55 (15bps)	3.41 (9bps)	1.81 (5bps)	2.18 (6bps)
Base	1.76 (10bps)	0.52 (3bps)	0.89 (5bps)	1.24 (7bps)
Optimism (USDC.e)	1.33 (11bps)	0.31 (2bps)	0.61 (5bps)	1.10 (9bps)
zkSync (USDC.e)	0.87 (50bps)	0.25 (15bps)	0.52 (30bps)	0.65 (38bps)
Pre-Blobs:				
Ethereum	92.96 (22bps)	39.30 (9bps)	20.94 (5bps)	59.43 (14bps)
Arbitrum	9.68 (10bps)	4.16 (4bps)	4.73 (5bps)	5.76 (6bps)
Arbitrum (USDC.e)	6.28 (11bps)	3.08 (6bps)	2.77 (5bps)	3.30 (6bps)
Base	0.43 (22bps)	0.11 (6bps)	0.10 (5bps)	0.36 (18bps)
Optimism (USDC.e)	1.55 (10bps)	0.36 (2bps)	0.78 (5bps)	1.27 (8bps)
zkSync (USDC.e)	1.37 (49bps)	0.37 (13bps)	0.83 (30bps)	1.03 (37bps)
Post-Blobs:				
Ethereum	102.26 (20bps)	34.56 (7bps)	25.69 (5bps)	72.35 (14bps)
Arbitrum	2.00 (8bps)	0.42 (2bps)	1.31 (5bps)	1.57 (6bps)
Arbitrum (USDC.e)	5.05 (22bps)	3.64 (16bps)	1.15 (5bps)	1.41 (6bps)
Base	1.99 (10bps)	0.59 (3bps)	1.02 (5bps)	1.40 (7bps)
Optimism (USDC.e)	1.17 (12bps)	0.26 (3bps)	0.49 (5bps)	0.97 (10bps)
zkSync (USDC.e)	0.32 (56bps)	0.12 (21bps)	0.17 (30bps)	0.24 (40bps)

around 2 seconds on Base, Optimism, and zkSync Era. On Arbitrum, blocks can be produced more quickly, approximately every 0.25 seconds. In such cases, we analyze the last block within the second.

Price Re-Alignment Threshold. We only consider the price deviations that surpass a set threshold. This threshold is determined from the empirical distribution of price differences, mainly focusing on outlier values (i.e., those beyond 1.5 times the interquartile range above the third quartile). This selected threshold ensures that prices are generally aligned but allows for adjustments to enhance flexibility.

Empirical MAV. If a price difference continues for a prolonged duration of multiple blocks, we document only the highest MAV within each time segment of price discrepancy until re-alignment happens. This approach avoids counting the same ongoing price discrepancy multiple times.

Decay Time. Once all instances of empirical MAV (i.e., the peak MAV during periods of price misalignment) are identified, we determine the duration required for prices to re-align (i.e., when the magnitude of the price difference drops below the specified threshold).

Table 5: Assessment of arbitrage opportunities within the WETH-USDC and WETH-USDC.e liquidity pools on Uniswap (v3) on Ethereum and its rollups from 31 December 2023 to 30 April 2024. The metrics encompass the total Maximal Arbitrage Value (MAV) and net Loss-Versus-Rebalancing (LVR), both in absolute terms and as percentages of trading volume.

Chain	MAV	% Volume	Net LVR	% Volume
Ethereum	52 488 479.88	0.15	126 531 170.12	0.36
Arbitrum	2 699 032.60	0.04	20 686 037.49	0.28
Arbitrum (USDC.e)	2 707 008.96	0.03	19 332 648.22	0.24
Base	1 293 771.96	0.04	32 663 704.76	1.09
Optimism (USDC.e)	690 868.44	0.05	3 893 401.00	0.27
zkSync Era (USDC.e)	20 110.31	0.25	96 016.54	1.20

6 Empirical Results

This section examines the WETH-USDC price misalignment. We measure arbitrage opportunities between rollup AMMs and CEX, and across rollups. We also analyze the decay time of these discrepancies and quantify the arbitrage opportunities using the Maximal Arbitrage Value (MAV) approach.

L2 DEX - CEX Arbitrage. Arbitrage profit opportunities increase with price disparity, and potential profit depends on trade volume and pool reserves. Table 5 shows total arbitrage opportunities (MAV) during the study periods, as an absolute number and a percentage of trading volume. Although the highest price differences are on Ethereum, offering about 0.15% of trading volume in arbitrage opportunities, these may not be fully realized due to gas fees and MEV auction costs. Additionally, specific details in the Binance order book, unavailable from 1-second data interval research, can contribute to untapped opportunities.

Non-atomic arbitrage on rollups presents significant differences from Ethereum. MAV in Arbitrum, Base, and Optimism pools ranges from 0.03% to 0.05% of trading volume, whereas in zkSync, it is around 0.25%, resulting from price misaligment occurring in multiple blocks. Empirical MAV, filtering identical arbitrage opportunities across blocks, results in lower rewards than cumulative net LVR. LVR ranges from 0.24% to 1.2%, about five times higher than MAV.

Table 6 provides further insight into the opportunities analyzed. The highest quantity of arbitrage opportunities is observed in the two Arbitrum pools, which can be attributed to higher block production rates. Base and Optimism also exhibit more arbitrage opportunities compared to the Ethereum pool. In particular, the average MAV is significantly lower on rollups, approximately 5–20 USD compared to over 700 USD on Ethereum. However, the transaction volume required to achieve this arbitrage is also lower (approximately 2.000–5.000 USD on rollups and 0.5 million USD on Ethereum).

The average decay on rollups varies: for Arbitrum, it is approximately 7–9 seconds (with a 0.25-second block time), followed by 19 seconds on Optimism

Table 6: Assessment of arbitrage opportunities within the WETH-USDC and WETH-USDC.e liquidity pools on Uniswap (v3) on Ethereum and its rollups from December 31st, 2023 to April 30th, 2024. The metrics encompass the quantity of identified arbitrage opportunities, mean Maximal Arbitrage Value (MAV), average transaction volume yielding maximal arbitrage, and mean decay time of the price disparities.

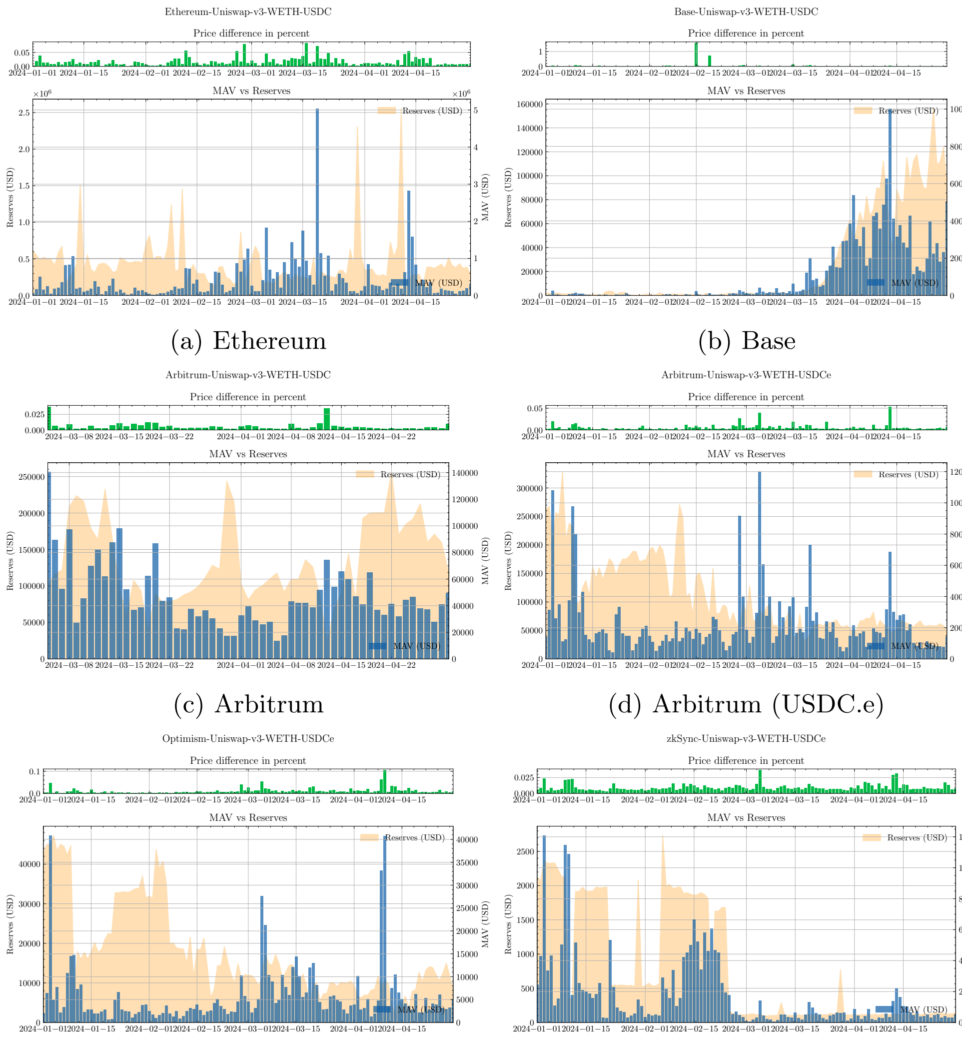
Chain	Points	Avg MAV	V_{max}	Avg Decay (s)
Ethereum	71 135	737.87	499 667.10	31
Arbitrum	137 162	19.68	56 476.35	6.9
Arbitrum (USDC.e)	164 080	16.50	41 370.11	8.8
Base	75 729	17.08	22 620.17	420
Optimism (USDC.e)	113 428	6.09	8477.60	19
zkSync Era (USDC.e)	3970	5.07	1966.76	370

(2-second block time), 370 seconds on zkSync (1.05-second block time), and 420 seconds on Base (2-second block time). In each instance, the spans cover 10–20 blocks or more.

Figure 1 illustrates the changes in price over time, MAV, and the pool's virtual reserves within the current tick for the most active pool analyzed, WETH-USDC on Arbitrum and other rollups. It specifically shows the maximum daily price difference, the daily total of observed MAV, and the end-of-day liquidity in the current pool. The data reveal that the daily MAV ranges from \$2000 to \$140 000, with the lowest point occurring during low trading volumes between March and April 2024. The smaller price differences with Binance during this period result in a lower MAV. Importantly, the days with the highest daily MAV align with those with the largest price differences.

Figure 1 provides an analysis of MAV on Ethereum, Base, Arbitrum, and Optimism. In particular, even with the introduction of native USDC on Arbitrum and its corresponding pool on Uniswap (v3), trading activity and associated arbitrage opportunities remain stable for both native USDC and bridged USDC tokens. A significant link between arbitrage opportunities and the size of reserves and liquidity within the current tick is observed in the zkSync Era pool. The highest arbitrage opportunities occurred on days when liquidity within the current tick was at its maximum. In contrast, on Optimism, arbitrage opportunities are closely linked to price differences. This can be explained by the relatively small size of the pool on zkSync Era. Despite the rise in reserves on Base, there is no corresponding increase in arbitrage profits. This indicates that the estimation of arbitrage opportunities is complex and should be evaluated based on price discrepancies, fees, and pool liquidity.

Cross-Rollup DEX Arbitrage. Cross-rollup arbitrage involves carefully planned steps on at least two rollups and revenue from arbitrage must cover all fees. If a token's price is lower on one rollup than another, arbitrageurs buy low on the first rollup and sell high on the second to profit from the price difference.



(a) Ethereum (b) Base

(c) Arbitrum (d) Arbitrum (USDC.e)

(e) Optimism (USDC.e) (f) zkSync Era (USDC.e)

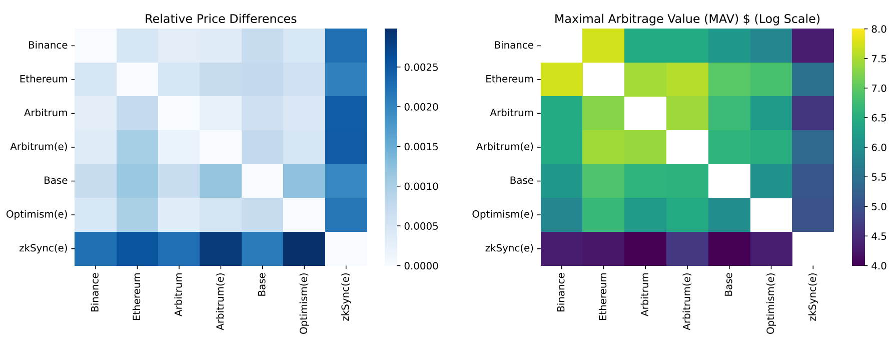
Fig. 1: Empirical Maximal Arbitrage Value (MAV), price misalignment with Binance, and liquidity within the spot price tick of the WETH-USDC pool on Uniswap (v3) across Ethereum and its rollups from December 31st, 2023, to April 30th, 2024.

Figure 2a presents the WETH-USD price misalignment among the Uniswap (v3) pools on different rollups. For comparative analysis, we incorporate data from Binance and Uniswap (v3) on Ethereum. Figure 2b illustrates the maximum arbitrage value (MAV) that could be achieved within the study period.

The most significant average price discrepancies, approximately 20 basis points (0.0020), are observed between zkSync and other rollups, which can be attributed to the still limited token reserves in the Uniswap (v3) liquidity pools on zkSync, as illustrated in Figure 1. These constrained reserves cause the highest price volatility, due to the AMM's price impact, and restrict arbitrage opportunities. Consequently, the arbitrage opportunities between zkSync and other rollups circulated around 10,000 to 100,000 units during the studied period.

The second most significant price differences with Binance are observed on Uniswap on Ethereum. This is due to Ethereum's slower block production rate of about 12 seconds, compared with 0.25 to 2 seconds on rollups. The largest arbitrage opportunities are found between Ethereum and Binance, with values reaching up to $100 million. However, cross-rollup arbitrage opportunities exceed $1 million in Arbitrum, Base, and Optimism and account for about 40 basis points of trading volume, compared to 4 basis points of trading volume on Ethereum.

Notably, the cross-rollup arbitrage opportunities within the analyzed AMM pools on Arbitrum, Base and Optimism already surpassed the value of arbitrage between these rollups and CEX. This can be attributed to the higher price volatility observed in rollup AMMs compared to CEX.



(a) Mean (relative) price difference.

(b) Maximal Arbitrage Value in USD.

Fig. 2: A comparative analysis of price disparities and arbitrage opportunities across rollups for the WETH-USDC and WETH-USDC.e (e) pools on Uniswap (v3). For reference, the Ethereum WETH-USDC Uniswap (v3) pool and Binance are included.

7 Conclusions

This paper quantifies the potential MEV in rollups that can arise from price disparities among rollups, and between rollups and CEXs. We study WETH-USDC, the most traded cryptocurrency pair in the Ethereum ecosystem, and source prices the liquidity pools of Uniswap (v3) on Ethereum and its L2s: Arbitrum, Base, Optimism and zkSync Era. Binance is used as a reference CEX.

By analyzing price discrepancies after each block, we identify more than half million unexploited arbitrage opportunities. Significantly, these opportunities persist on average for a period of 10 to 20 blocks. Thus, to avoid double counting of the same opportunity, we record only the Maximal Arbitrage Value (MAV) in each price misalignment period. The estimated MAV on Arbitrum, Base and Optimism pools ranges from 0.03% to 0.05% of trading volume, and oscilates around 0.25% in the newly deployed Uniswap (v3) WETH-USDC pool on zkSync Era. The empirical MAV approach, filtering repeated price misalignments, results in five-time lower arbitrage profits compared to the Loss-Versus-Rebalancing (LVR) metric.

We observed that lower-volume swaps are more frequent on rollups compared to Ethereum. Swaps occur 2–3 times more often on L2s, but trade volumes are approximately five times lower. Block times impact rollup transactions; Ethereum averages one swap per block, while rollups have fewer swaps per block despite higher total swaps. Specifically, swaps occur every third block on Base, fifth on Optimism, and tenth on Arbitrum. These insights contribute to ongoing discussions on rollup design and optimization, particularly in the context of MEV auctions at sequencers.

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