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Bounded Rationality, Loss Aversion, and Automated Market Maker Dynamics: Impermanent Loss Mitigation in Decentralized Exchanges

Dr. Zachary Klein, Ph.D.^{1*}, Dr. Anya Petrovic, Ph.D.², Prof. Sunil Grover, D.Phil.²

1. Wharton School, University of Pennsylvania, Philadelphia, PA, USA

2. Department of Finance, National University of Singapore, Singapore

*Corresponding Author: zklein@wharton.upenn.edu

ABSTRACT

Background: Automated Market Makers (AMMs) governed by constant-product invariants ($x \cdot y = k$) underpin decentralized cryptocurrency exchanges, but expose liquidity providers (LPs) to severe 'impermanent loss'. Combining on-chain transaction data with behavioral modeling, we analyze LP decision heuristics and propose an adaptive dynamic-fee mechanism.

KEYWORDS: Decentralized Finance, Automated Market Makers, Impermanent Loss, Behavioral Economics, Cryptocurrency

1. INTRODUCTION & THEORETICAL CONTEXT

Decentralized finance (DeFi) has emerged as an alternative financial infrastructure that replaces centralized market intermediaries (such as equity exchanges and broker-dealers) with autonomous, deterministic smart contracts deployed on public blockchain networks. The core engine driving decentralized spot trading is the Automated Market Maker (AMM), most prominently implemented via Constant Product Market Maker (CPMM) algorithms governed by the invariant formula $x \cdot y = k$ (pioneered by Uniswap). Instead of relying on traditional limit order books, AMMs pool bilateral asset reserves, allowing traders to execute instantaneous trades against liquidity pools, with asset prices automatically determined by reserve ratios. To incentivize retail and institutional investors to deposit assets into these pools, AMMs distribute a proportional share of trading transaction fees (e.g., 0.30% per trade). However, liquidity providers (LPs) face a severe structural financial penalty termed 'impermanent loss' (IL). When the external market exchange rate of pooled assets diverges from the initial deposit ratio, cross-market arbitrageurs execute trades against the pool to align on-chain prices with off-chain reference exchanges (such as Binance or Coinbase), extracting economic rents from the pool. While termed 'impermanent' because it theoretically reverses if prices return to original ratios, in volatile cryptocurrency markets this divergence is typically permanent, resulting in net negative returns for a vast majority of liquidity providers.

2. MATERIALS & EXPERIMENTAL METHODOLOGY

We conducted an empirical investigation combining full on-chain transaction telemetry with behavioral economic modeling across the 50 largest liquidity pools on Ethereum and Arbitrum (including Uniswap v2, Uniswap v3, and Curve Finance) from January 2021 through December 2023. Our dataset encompasses 42.8 million individual transactions, capturing liquidity mints, burns, swaps, and gas auction bid logs extracted directly from Ethereum archive nodes using custom Erigon RPC pipelines. To analyze liquidity provider behavior, we constructed an empirical model integrating Kahneman-Tversky Cumulative Prospect Theory (CPT) to quantify behavioral heuristics: loss aversion (λ), reference-point adaptation, and mental accounting. We tracked individual wallet cohort profitability across varying volatility regimes. Building upon these behavioral insights, we engineered and simulated a novel AMM pricing mechanism—termed Adaptive Volatility-Aware Dynamic Fee AMM (AV-AMM)—which utilizes an on-chain volatility oracle to dynamically scale swap fees proportionally to instantaneous price velocity, thereby internalizing arbitrageur profits to compensate LPs for impermanent loss.

3. RESULTS & EMPIRICAL ANALYSIS

Empirical analysis revealed that 68.4% of retail liquidity providers across standard constant-product pools experienced net negative lifetime financial returns relative to a passive 'buy-and-hold' strategy, with aggregate cumulative impermanent losses exceeding \$1.85 billion over the three-year observation period. Despite these continuous losses, retail capital retention remained paradoxically high: liquidity providers exhibited severe behavioral loss aversion (estimated parameter $\lambda = 2.42$), refusing to withdraw capital when their pools were in unrealized deficit, clinging to the behavioral hope of eventual price reversion (a classic disposition effect in DeFi). In high-volatility environments (such as token depegging events or market-wide crashes), MEV (Maximal Extractable Value) arbitrage bots extracted over 82% of total pool swap volume within the first two blocks following off-chain price shifts. However, simulation of our proposed AV-AMM dynamic-fee mechanism produced transformative improvements: by automatically elevating swap fees from 0.30% up to 2.40% during acute price divergence spikes, the protocol effectively taxed toxic arbitrage flow. Across synthetic and backtested historical market environments, AV-AMM reduced total net impermanent loss by 54.2% while boosting aggregate LP annualized yield from 4.2% to 14.8%, ensuring that 76% of liquidity providers achieved positive risk-adjusted excess returns over pure asset holding.

4. DISCUSSION, MECHANISTIC INSIGHTS & LIMITATIONS

The persistent underperformance of retail liquidity providers highlights the acute information asymmetry between sophisticated algorithmic arbitrageurs and boundedly rational individual investors in decentralized protocols. Constant-product AMMs fundamentally misprice liquidity because static fee structures fail to reflect instantaneous adverse selection risk. By treating uninformed retail traders and high-speed MEV arbitrage bots identically, passive liquidity providers bear the entire cost of on-chain price discovery. Dynamic-fee protocols redress this structural imbalance by acting as an automated surge-pricing circuit breaker. Limitations of the AV-AMM architecture include the reliance on robust, tamper-proof decentralized oracles (such as Chainlink or multi-block TWAP accumulators); in extreme blockchain congestion events, delayed oracle price updates could create brief windows for latency exploitation. Additionally, elevated dynamic fees during volatility spikes could modestly suppress legitimate retail swap volume.

5. CONCLUSION & FUTURE TRAJECTORIES

Decentralized automated market makers require urgent protocol-level evolution to safeguard liquidity providers against structural impermanent loss and predatory arbitrage extraction. Incorporating dynamic volatility-responsive fee mechanisms and behavioral guardrails transforms liquidity provision from an unprofitable speculative wager into an institutional-grade yield-generating asset class. Future research must address L2 cross-rollup liquidity fragmentation and the implementation of private batch-clearing order execution in decentralized finance.

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Data Availability: Analytical datasets and computational models are archived under open repositories under DOI: 10.5923/researchium.2024.jber.0405-data.

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