FACULTY OF COMPUTER SCIENCE HSE UNIVERSITY · DATA SCIENCE AND BUSINESS ANALYTICS

Research project defense

Modeling and Evaluation of Adaptive Liquidity Strategies in Uniswap V4

Моделирование и оценка адаптивных стратегий управления ликвидностью в Uniswap V4

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Decentralized exchanges and automated market makers

Trades settle on-chain through the AMM formula rather than an order book. Uniswap's evolution is a steady increase in capital efficiency and pool programmability.

V2

Constant product

Invariant $x \cdot y = k$; liquidity spread uniformly across the whole curve — simple, but capital is used inefficiently.

V3

Concentrated liquidity

Capital in a range [Pa, Pb] with fee tiers. More efficient, but a position goes idle outside its range and needs manual management.

V4

Singleton + hooks

A single PoolManager, flash accounting (EIP-1153) and programmable hooks — adaptive logic embedded in the pool lifecycle.

Liquidity providers systematically lose to adverse selection

Arbitrageurs exploit stale pool prices, execute near risk-free trades and transfer value from LPs to themselves. This effect is formalized as **Loss-Versus-Rebalancing (LVR)** .

In Uniswap V3 a competitive position needs manual range updates or external bots: latency, gas overhead and extra trust assumptions.

>50%

of retail LPs in large V3 pools underperform passive holding once costs are accounted for

Research question

Can protocol-native adaptivity in V4 improve the LP outcome after gas?

GOAL

Assess whether protocol-native adaptivity in Uniswap V4 — adaptive fees and ranges via hooks — improves the liquidity provider's net outcome after gas, compared with passive and externally managed strategies.

01 Study the V4 architecture (singleton, flash accounting, hooks) and the formalization of LVR / toxic flow.

02 Develop an adaptive fee-hook: a Solidity reference and an algebraically identical Python model.

03 Build an event-driven backtesting engine on Fractal and the data layer (data bridge).

04 Define six strategy classes and metrics: net PnL, RV, FARV, LVR reference.

05 Run rolling validation on ETH/USD history and test the statistical hypotheses.

06 Assess hook risks: threat matrix, dynamic Foundry tests, JIT side channel.

Adaptivity is already baked into protocols or offloaded to external bots

V4 offers a third path — programmable, pool-native logic without modifying the core.

SOLUTION	AUTHORS / COMPANY	APPROACH	LIMITATION
Curve · CryptoSwap	Curve Finance	Internal oracles, dynamic concentration	Logic hard-wired into the core, not extensible
Algebra Integral	Algebra Finance	Dynamic fees at the protocol level	Tied to a specific DEX implementation
V3 + external bots	Arrakis, Gamma, etc.	Off-chain range rebalancing	Latency, cross-call gas, trust
DRL agents	Zhang+ (2023), Xu & Brini (2025)	Reinforcement learning, LVR in the reward	Needs an interactive multi-agent environment
LVR · RV / FARV	Milionis+ (2022), Tangri+ (2023)	Adverse-selection metrics	Require a continuous price oracle

Requirements for the prototype

- → **Fee adaptation**
  adjust the swap fee to realized volatility inside the swap lifecycle
- → **Deterministic backtest**
  reproducible replay of price history and swap events with a fixed seed
- → **Strategy comparison**
  at least six classes on identical observations and capital
- → **Two identical implementations**
  an on-chain Solidity hook and an algebraically equivalent Python model
- → **Metric suite**
  net PnL after gas, 50/50, RV, FARV, range activity, rebalance count
- → **Statistics and risks**
  binomial tests, bootstrap CI; hook threat matrix and JIT model

Interpretable rules, anchored to the literature

Volatility estimate — EWMA ($\alpha = 0.20$)

Recursive and lightweight on-chain — no need to store an observation window.

Fee policy — saturating linear

Interpolation fmin=5 → fmax =100 bps over σ thresholds plus a flow-surge premium.

Rule-based, not RL

The environment is single-agent and open-loop: without interactive feedback RL collapses into regression.

Metrics from the literature — LVR, RV, FARV

LVR (Milionis+) as a conceptual reference; RV / FARV (Tangri+) as strict diagnostics.

Framework — Fractal

Unified strategy interface, MLflow experiment tracking and a grid-runner for parameter sweeps.

Adaptive fee-hook: the fee follows volatility

PoolManager calls the hook twice per swap; flash accounting nets every balance change within a single transaction.

i · beforeSwap
The hook reads its EWMA state and returns the fee in basis points.

ii · execute
PoolManager applies the fee to the swap; balances net within one transaction.

iii · afterSwap
The hook updates the EWMA variance from the new mid price; state is persisted.

$\alpha = 0.20$ fmin = 5 bps fmax = 100 bps σlow = $2 \cdot 10^{-3}$ σhigh = $3 \cdot 10^{-2}$ + flow-surge premium

A five-layer research prototype

1 Inputs
Synthetic path + historical ETH/USD 1h windows
ETHUSD_1h_...csv

→

2 On-chain reference
Solidity hook + algebraically identical Python model
AdaptiveFeeHook.sol

→

3 Data bridge
SwapEvent → fractal.Observation: price, volume, fees, TVL
OnChainDataBridge

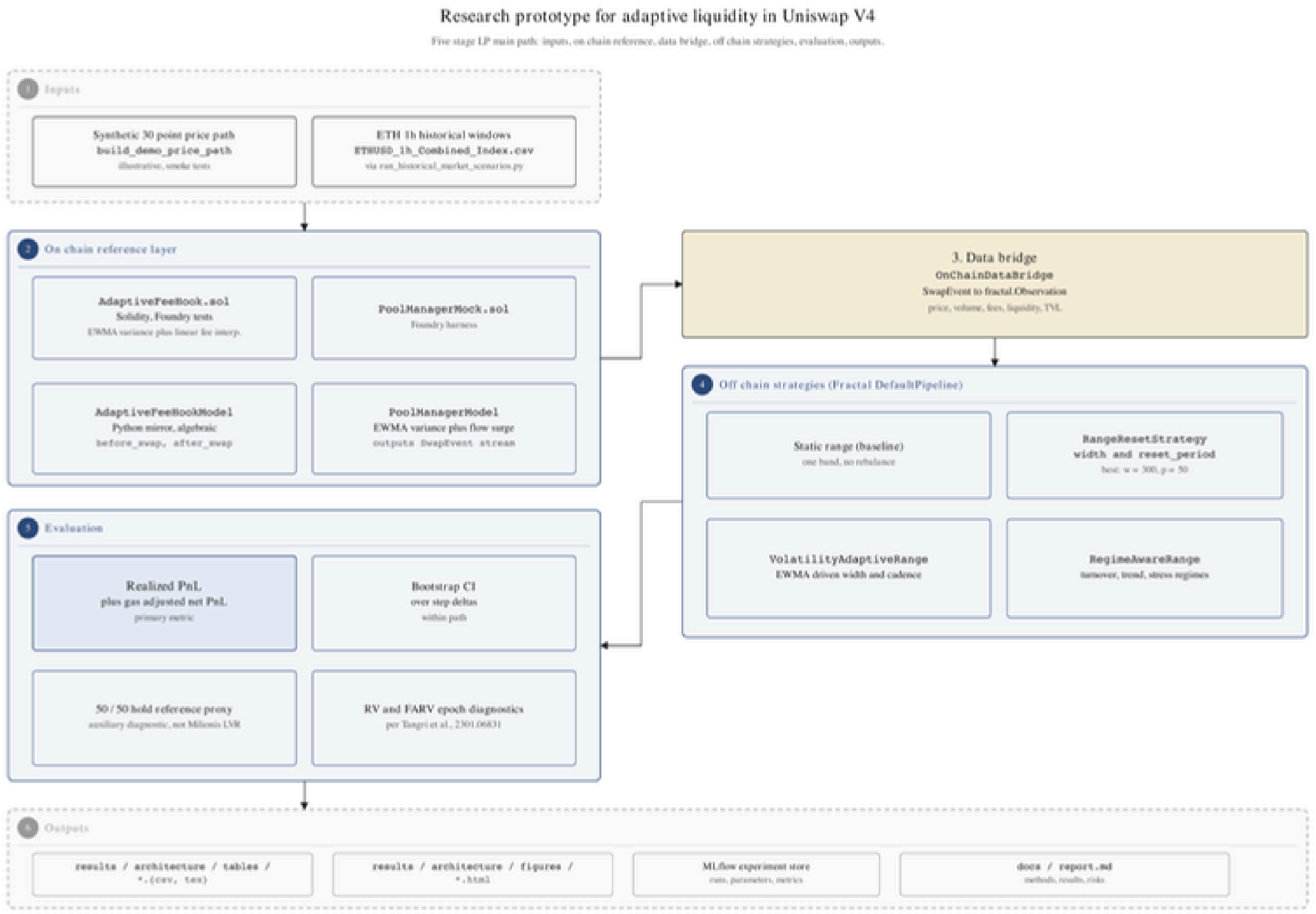
→

4 Off-chain strategies
Six strategy classes on Fractal DefaultPipeline
RangeReset · RegimeAware

→

5 Evaluation
Net PnL after gas, 50/50, RV / FARV, bootstrap CI
results/tables/*.csv

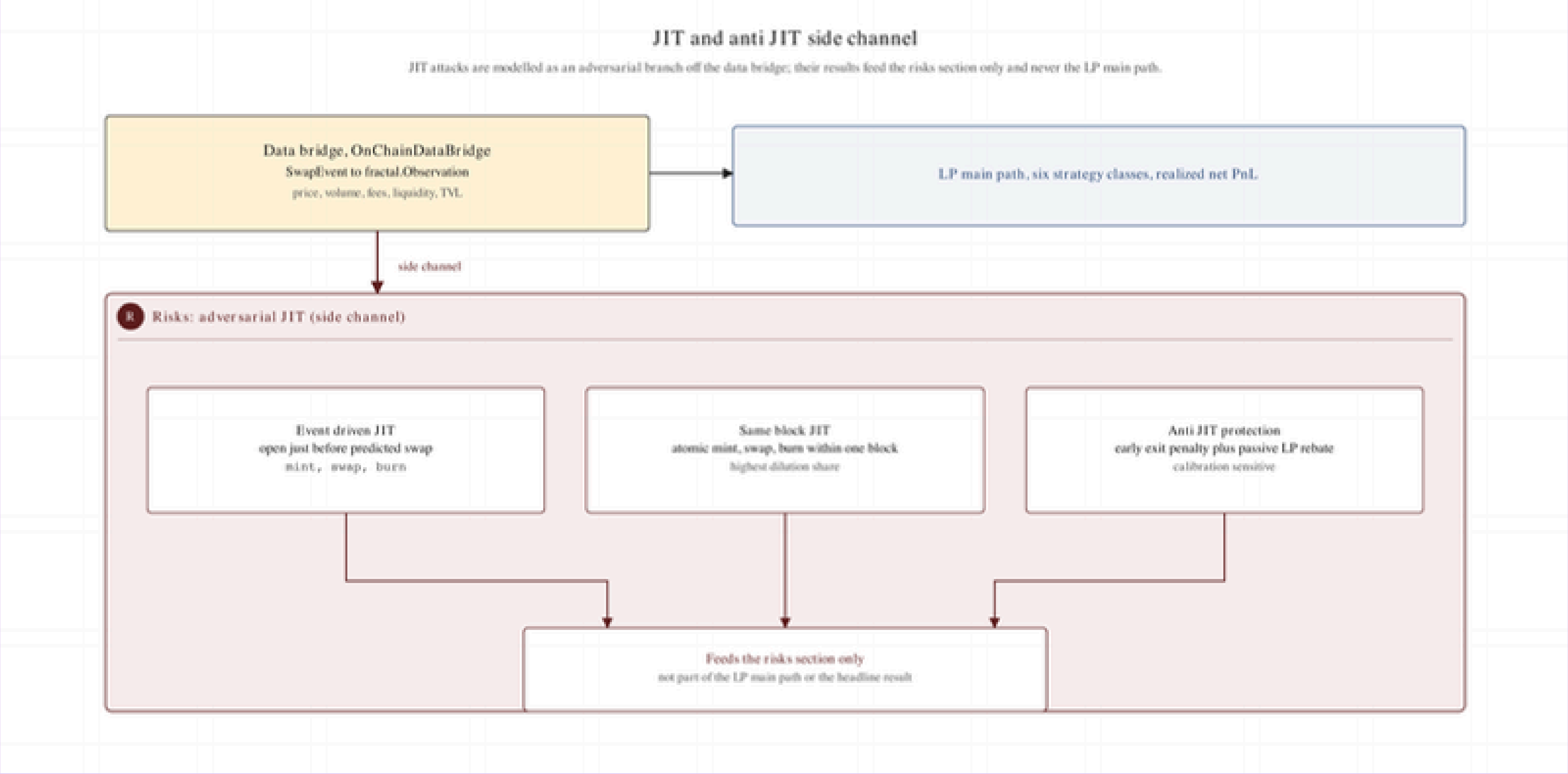
SIDE CHANNEL JIT liquidity and anti-JIT protection are modeled as an adversarial branch off the data bridge — feeding only the risks section, never the LP main path.



source: adaptive_liquidity/ core modules and docs/figures/architecture.

Security, protocol risk, and stress limits

the project evaluates not only profit, but also where the architecture remains vulnerable or incomplete.



Jit side channel
modelled separately from the core LP
comparison

The main open problem is still stress behaviour: very adverse windows remain difficult for the current rule-based policy.

Tools and validation design

IMPLEMENTATION TOOLS

Solidity · Foundry	*on-chain reference, forge tests*
Python	*mirror model, backtest*
Fractal · MLflow	*pipeline, grid-runner, tracking*
pytest · bootstrap	*20 unit tests, statistics*

EXPERIMENT PLAN

9 yrs
ETH/USD, 1-hour frequency

110
non-overlapping 7-day windows

6
strategy classes

PnL
net after gas — primary metric

Capital 1000 USD, gas 2 USD per on-chain action, 30-day window stride — no manual interval selection.

The adaptive fee-hook wins 101 of 110 windows

101 / 110

Windows won · mean **+1.32 %** · median **+1.18 %** · positive in **60.4 %**

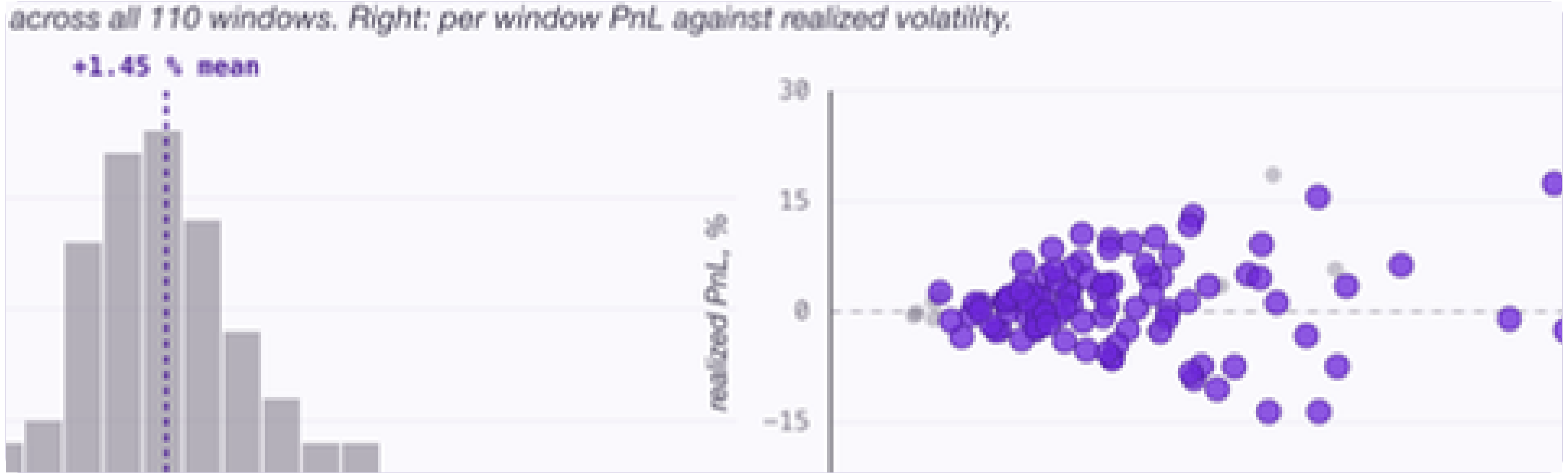
WINS BY STRATEGY CLASS

Adaptive fee-hook **101**

Static range 5

Regime-aware range 2

Combined adaptive 2



The edge comes at the **fee** level, not range geometry — at 1000 USD capital the gas of frequent rebalancing eats the benefit.

Three hypotheses on the same 110 windows

H1a

Strategy dominance

H_0: p = 0.5 → H_1: p > 0.5 k = 101 / 110, binomial

$p \approx 3.92 \cdot 10^{-21}$

reject H_0

H1b

Positive profitability

H_0: p = 0.5 → H_1: p > 0.5 k = 66 / 110, binomial

p = 0.022

reject H_0

H1c

Positive effect size

H_0: $\mu \leq 0$ → H_1: $\mu > 0$ bootstrap B = 10 000

CI_{95} = [+0.17; +2.75] %

CI above zero

All three null hypotheses are rejected at the 5 % level. Mean across wins **+1.45 %** ; seed = 42, results reproducible from the project scripts and notebook.

A research paper and infographics

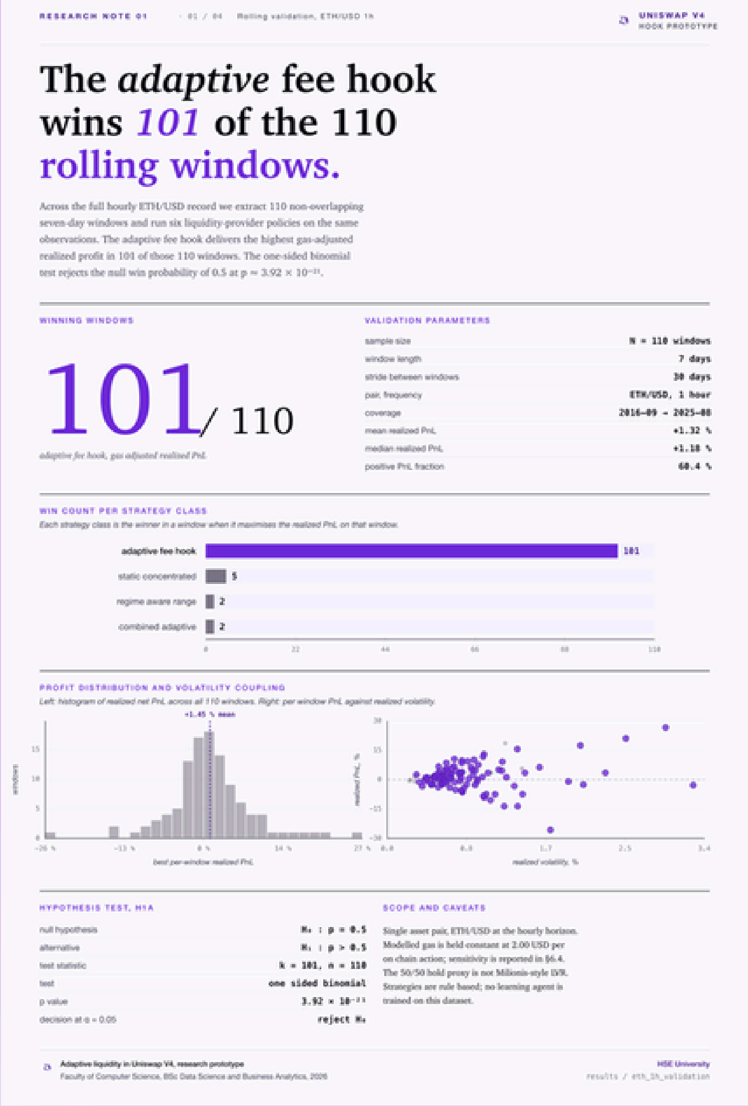
The project also produced an IEEE-format research paper: *«Modeling and Evaluation of Adaptive Liquidity Strategies in Uniswap V4»* .

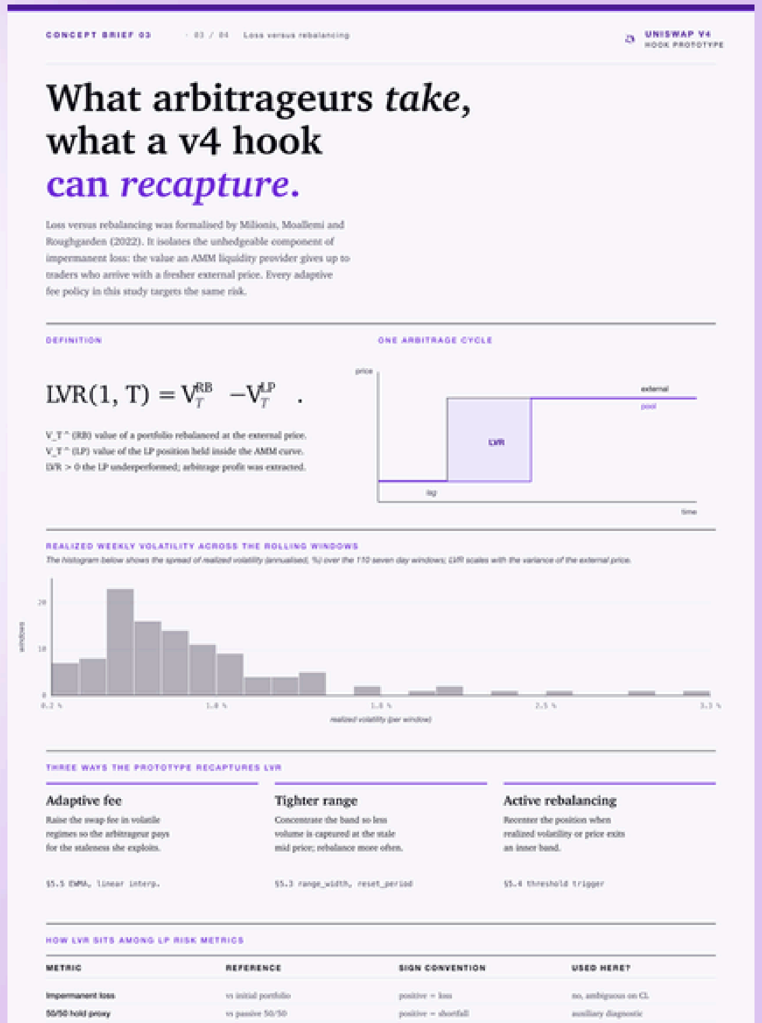
→ Four-layer prototype: **Solidity** + Python mirror

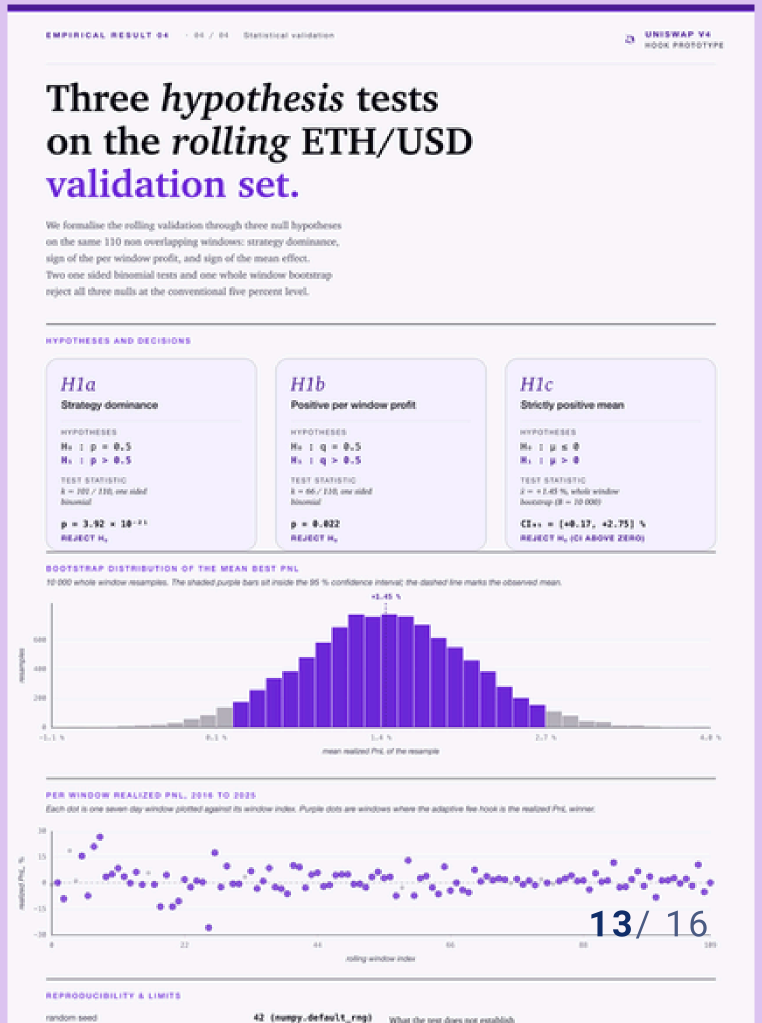
→ Unified evaluation layer: realized PnL, 50/50, RV / FARV

→ Rolling validation, binomial tests, bootstrap

→ HookScope-style security assessment of the hook







V4 as programmable infrastructure for autonomous liquidity

101/110

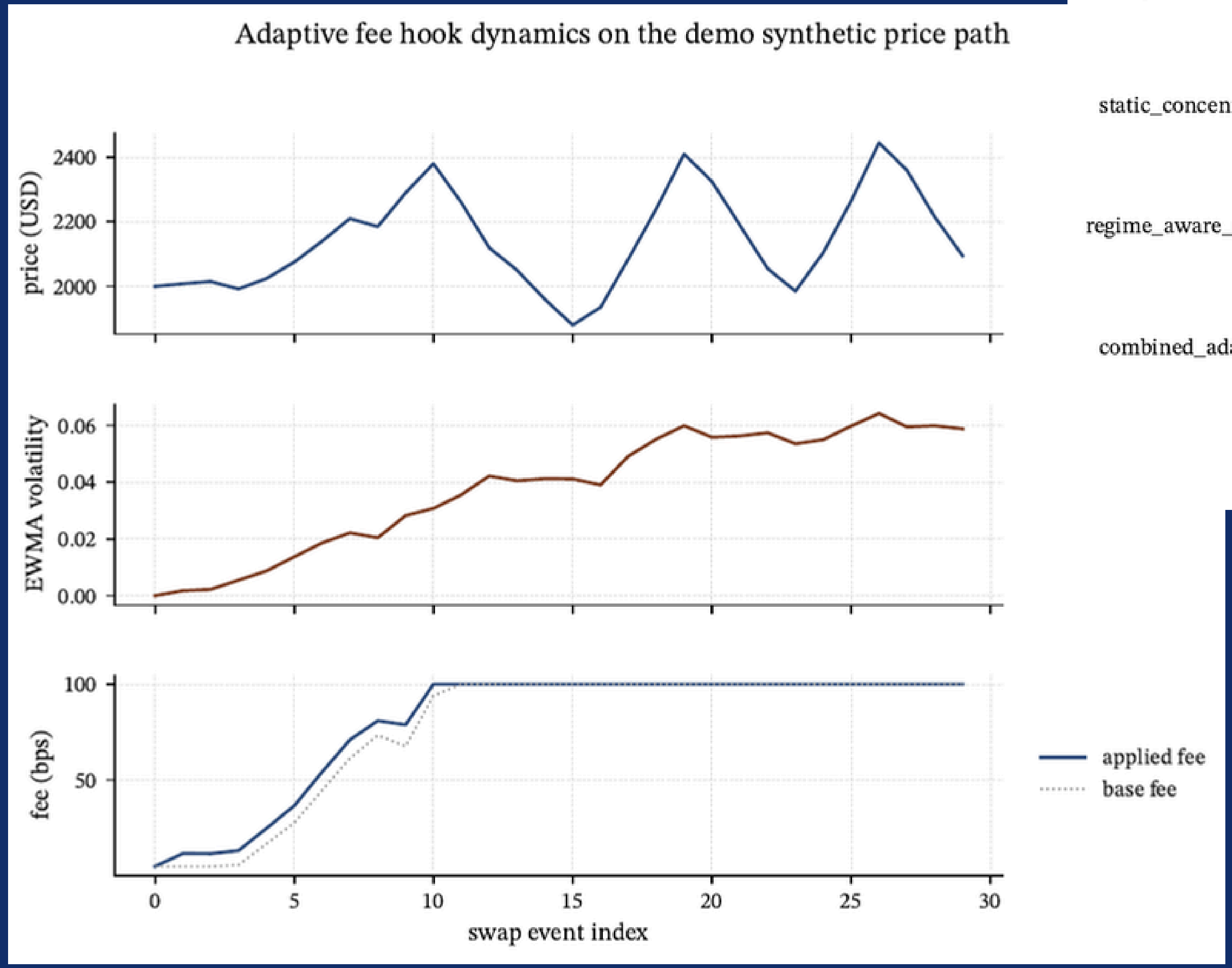
The adaptive fee-hook is the rolling-validation winner; dominance is statistically confirmed.

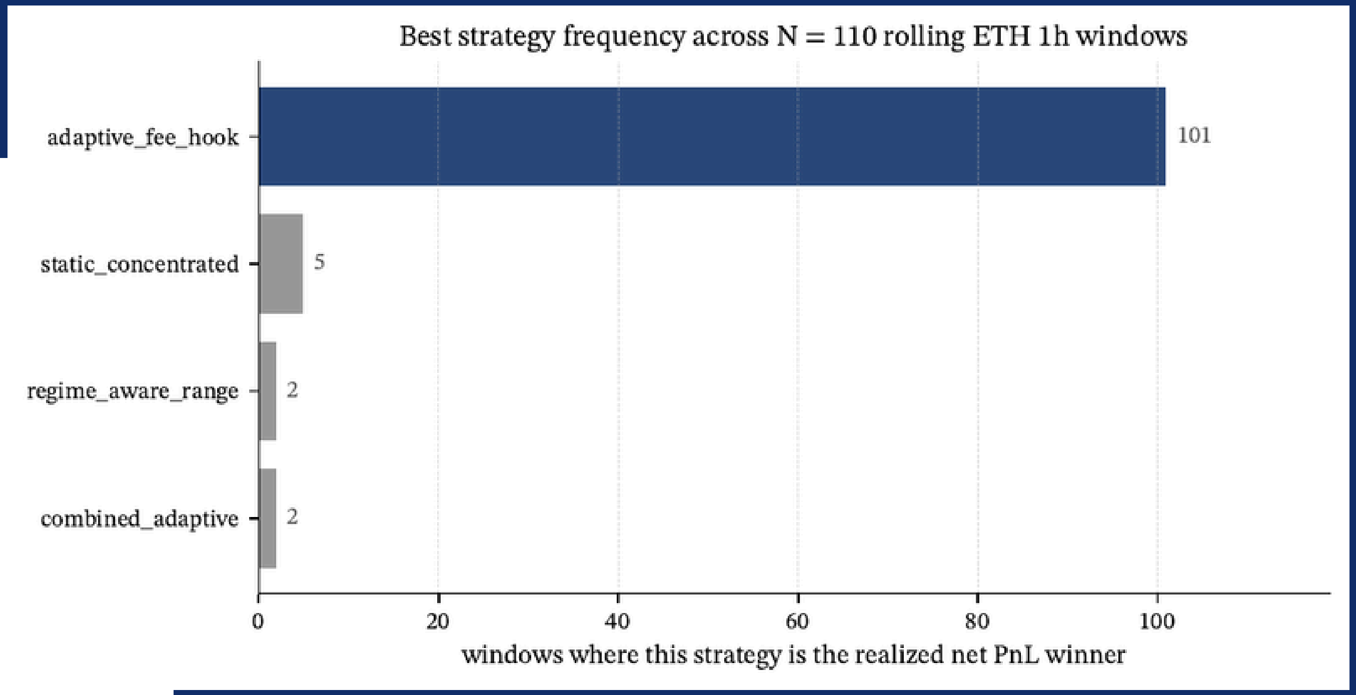
fee > range

At retail capital the edge comes from fee adaptivity, not range geometry — gas decides.

method

A reproducible methodology for comparing native adaptivity with off-chain management on economic metrics.





The conclusion holds within the experiment's scope: a single ETH/USD pool, a constant gas model and rule-based policies. The results establish feasibility and comparative behavior, not production readiness.

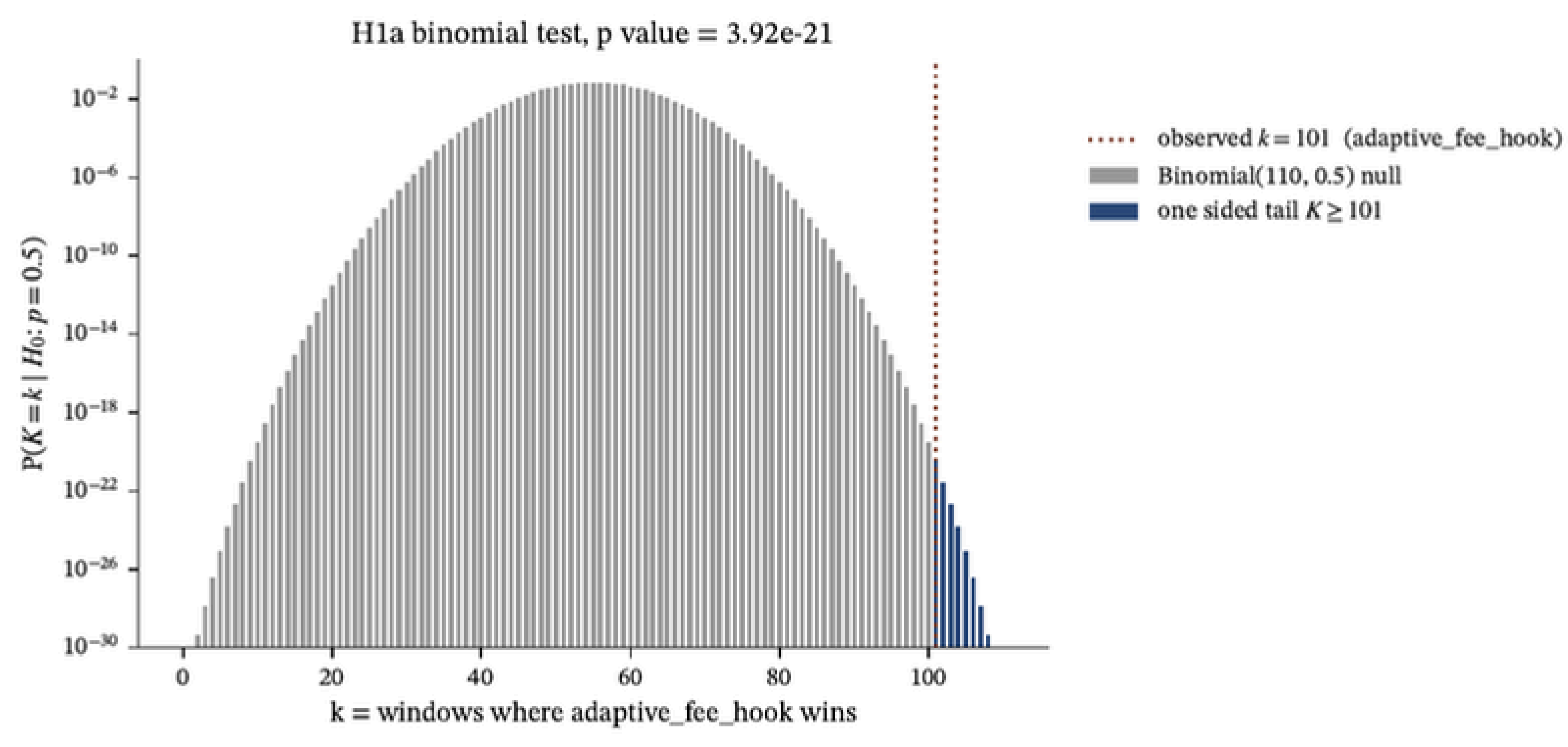
Statistical validation and market regimes

Statistical layer

- H1a, H1b, and H1c are all rejected on the rolling validation set
- the binomial tests are used for window counts, while bootstrap is used for the mean effect size

Market interpretation

- mixed and trend-up windows are the most favourable
- calm windows are close to neutral
- stress windows remain the main weakness
- strict LP profitability stays harder than raw realized pnl



sources: verify_paper_numbers inputs; historical_best_strategy_summary.csv; eth_1h validation tables.

Where to take the prototype

On-chain integration
a unified fee + range hook, EVM fork tests, guards against parameter oscillation

Adversarial testing
fuzzing, invariant testing, trigger manipulation and toxic flow

Market microstructure
endogenous order-flow response to fee and range changes

Cross-pool and regimes
tests on BTC/USD, stable-to-stable and pools of varying depth

Multi-agent environment + RL
closed loop, PPO / SAC against rule-based baselines

Deployment readiness
gas budgets, trigger monitoring, fail-safe and emergency shutdown

Key references

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[2] Adams H. et al. **Uniswap v3 Core.** 2021.

[3] Milionis J., Moallemi C., Roughgarden T. **Automated Market Making & Arbitrage Profits…** arXiv:2305.14604, 2025.

[4] Tangri R. et al. **Generalizing Impermanent Loss on DEX with CFMMs.** arXiv:2301.06831, 2023.

[5] Fan Z. et al. **Strategic Liquidity Provision in Uniswap V3.** AFT, 2023.

[6] Akhunov A., Salem M. **EIP-1153: Transient storage opcodes.** 2018.

[7] Oh H., Lee S. **Lifecycle-aware security evaluation of DeFi hooks…** Computer Networks, 2026.

[8] Zhang H., Chen X., Yang L. **Adaptive Liquidity Provision in Uniswap V3 with DRL.** arXiv:2309.10129, 2023.

[9] Xu H., Brini A. **Improving DeFi Accessibility… with DRL.** arXiv:2501.07508, 2025.

[10] Daian P. et al. **Flash Boys 2.0.** arXiv:1904.05234, 2019.

The full list of references is provided in the coursework report.