crvUSD (Curve) sub-report

A tight, slightly-sub-$1 peg defended by two over-collateralised mechanisms: the PegKeeper algorithmic mint/burn and LLAMMA continuous soft-liquidation, 2023–2026

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Abstract

crvUSD is the over-collateralised stablecoin of Curve Finance, minted against crypto collateral (wstETH, WBTC, WETH, sfrxETH, tBTC and others) through per-market Controllers and defended by two mechanisms that are structurally distinct from the hard-liquidation CDP lineage of MakerDAO's DAI and Liquity's LUSD (Egorov 2023). The first is the *PegKeeper*, an algorithmic agent that mints crvUSD into one of four Curve StableSwap pools when the pool runs rich (above peg) and burns it back when the pool runs cheap, bounding the peg without any redemption rail (Curve Finance 2023c). The second is *LLAMMA*, a continuous soft-liquidation AMM that converts a borrower's collateral to crvUSD band-by-band as the collateral price falls, replacing the discrete liquidation auction with a smooth, reversible de-risking (Curve Finance 2023b). This sub-report reframes the tracking-error programme around these mechanics. The analytical surface is the four PegKeeper pools (crvUSD against USDC, USDT, USDP and PYUSD, 849,977 raw pool prints), the protocol's own `AggregateStablePrice` EMA oracle (1,110 daily points, 2023-06 to 2026-06), and a daily controller-health panel across 9 collateral markets. Over the full window crvUSD holds a **tight, persistently slightly-sub-$1 peg**: the authoritative oracle median deviation is −2.66 bp (the mean −9.32 bp is dragged below the median by a left-skewed tail, skewness −2.22), the daily mean-absolute deviation is 9.6 bp, only 2.3 % of days breach ±50 bp, and the AR(1) mean-reversion half-life is 4.4 days. The volatility structure favours an EGARCH(1,1) (BIC −3,932.7 versus GJR −3,816.4 and GARCH −3,690.4), consistent with the left-skewed sub-peg shocks. The PegKeeper is empirically a peg-tightener: on its 57 provide-days the mean absolute deviation is 1.82 bp versus 10.05 bp on quiet days, and it deployed $66 M of provide defense through the July 2023 Vyper-exploit ecosystem stress while the peg held to a −32 bp trough. The controller panel shows a healthy system (weighted-CR median 176.8 %) with localised LLAMMA soft-liquidation pressure — wstETH ran 40 pressure-days and touched a 93.6 % CR in August 2023 — yet no stress channel Granger-leads the peg deviation at lag 1 (all $p > 0.37$, none surviving BH-FDR): the algorithmic defense holds the gap so tight that collateral stress does *not* propagate to a wider peg deviation. The case studies confirm the insulation thesis: the June 2024 Egorov CRV-collateral cascade hit LlamaLend *lending*, not the crvUSD *mint* markets (which admit no CRV), and the mint-market peg was statistically tighter *inside* the window than around it. The recurring 35 sub-−20 bp episodes (mean duration 5.1 days) are the PegKeeper working, not failures. We conclude with the over-collateralised, algorithmically-defended monitoring playbook for Derivalink V2, anchored on the soft-liquidation fraction as the over-collateral depeg-pressure signal.

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Executive summary

Asset nature and scope. crvUSD is the over-collateralised stablecoin of Curve Finance. A borrower locks crypto collateral (wstETH, WBTC, WETH, sfrxETH, tBTC, weETH, cbBTC, LBTC) in a per-market *Controller* and mints crvUSD against it; the peg is held to $1 not by a redemption rail but by two mechanisms that are structurally distinct from the hard-liquidation CDP lineage of MakerDAO's DAI and Liquity's LUSD (Egorov 2023). First, the **PegKeeper** is an algorithmic agent attached to four Curve StableSwap pools (crvUSD against USDC, USDT, USDP, PYUSD): when a pool runs *rich* (crvUSD above peg) it *provides* — mints fresh crvUSD into the pool to sell the richness down — and when the pool runs *cheap* it *withdraws* — burns crvUSD to buy the discount up, bounding the peg with no holder-side redemption (Curve Finance 2023c). Second, **LLAMMA** is a continuous soft-liquidation AMM: as a borrower's collateral price falls, LLAMMA converts the collateral to crvUSD band-by-band, smoothly and reversibly, replacing the discrete liquidation auction of a hard-liquidation CDP with a gradual de-risking that re-buys the collateral if the price recovers (Curve Finance 2023b). The analytical through-line of this report is that crvUSD holds a *tight, persistently slightly-sub-$1 peg defended by these two over-collateralised mechanisms*, and that the *soft-liquidation fraction* is the over-collateralised analogue of a depeg-pressure signal. Our surface is the four PegKeeper pool tapes (849,977 raw prints), the protocol's own `AggregateStablePrice` EMA oracle (1,110 daily points, 2023-06-08 to 2026-06-21), a daily PegKeeper debt/flow panel (4,540 debt snapshots; 454 provide and 458 withdraw events), and a daily controller-health panel over 9 collateral markets.

F1 — The peg is tight and persistently, slightly sub-$1. On the authoritative oracle the deviation has a **median of** −2.66 **bp** and a mean-absolute deviation of 9.6 bp (Section 2); the price spends 82.9 % of days fractionally below $1 but only 2.3 % of days breach ±50 bp and 12.9 % breach ±25 bp. The mean deviation (−9.32 bp) is *not* the central tendency: it is dragged below the median by a left-skewed tail (skewness −2.22, excess kurtosis 5.88), so the headline sub-peg is the *median* ≈ −3 bp. The four PegKeeper pools agree closely with the oracle (USDC/USDT correlation 0.833/0.830; mean pool-vs-oracle spread sub-1 bp), confirming the peg series is venue-robust rather than a single-pool artefact.

F2 — The volatility favours asymmetric (left-skew) leverage. Across GARCH(1,1), GJR-GARCH and EGARCH(1,1), the **EGARCH wins on BIC** (−3,932.7 versus GJR −3,816.4 and GARCH −3,690.4, Section 3). The log-variance specification accommodates the left-skewed sub-peg shocks — discount excursions raise conditional volatility asymmetrically — the exact mirror of LUSD's upward-depegging premium leg. A HAR-RV explains 21.3 % of next-day realized variance, a real but modest long-memory component.

F3 — The PegKeeper is a peg-tightener, not a peg-rescuer. On its 57 provide-days the mean absolute deviation is 1.82 **bp** versus 10.05 **bp** on quiet days (Section 4): the PegKeeper mints precisely when the pool is rich and the peg is *tight*, capping above-peg moves before they widen. Standing PegKeeper debt is *higher* when the absolute deviation is *small* (correlation −0.12), and the debt-change-vs-deviation cross-correlation is weak and contemporaneous (best at lag 0, $r = -0.05$). Cumulatively the PegKeeper provided $199.8 M and withdrew $199.8 M over the window, with a single-keeper debt peak of $24.2 M — an always-on, mean-reverting defense rather than an emergency backstop.

F4 — The controller is healthy; soft-liquidation pressure is localised. The system weighted collateral ratio has a median of 176.8 % and a minimum of 105.9 % over the panel (Section 5). Because the on-disk `liquidation_threshold_pct` is NULL, the LLAMMA soft-liquidation *fraction* is not directly a column; we derive a **stated soft-liquidation pressure**

proxy = (CR < 120 %) co-occurring with a 30-day collateral drawdown. By this proxy soft-liquidation pressure is localised: **wstETH** ran 40 pressure-days and touched a 93.6 % CR on 2023-08-18 (its 18.99 %-above-band episode), WETH 49 days and tBTC 26 days, while WBTC never entered pressure. This is LLAMMA working as designed: the soft band absorbs the drawdown without a discrete liquidation cascade.

F5 — No stress channel Granger-leads the peg. The peg deviation is stationary (ADF $p = 7.7 \times 10^{-5}$) and mean-reverting (AR(1) half-life 4.4 days, Section 6). At lag 1 *no* stress channel significantly Granger-causes the deviation — PegKeeper debt change ($p = 0.84$), soft-liquidation market count ($p = 0.37$), collateral drawdown ($p = 0.62$) — and none survives a BH-FDR correction. The interpretation is the report's core mechanism finding: **the algorithmic defense holds the gap so tight that collateral stress does not propagate into a wider peg deviation**. The crvUSD/USDC-pool and oracle series are cointegrated (Engle–Granger $p = 2.6 \times 10^{-5}$), a two-venue co-move sanity check.

F6 — The case studies confirm insulation and normal mean-reversion. Through the **July 2023 Vyper-compiler exploit**, which drained several Curve pools, the crvUSD pools were unaffected and the peg held to a −32 bp trough while the PegKeeper deployed $66 M of provide defense (Section 7). The **August 2023 wstETH soft-liquidation** episode (CR 93.6 %, mean market debt $48.2 M) coincided with the same −32 bp dip and recovered. The **June 2024 Egorov cascade** is the sharpest contrast: the ≈$140 M CRV-collateral liquidation hit LlamaLend *lending* markets, but crvUSD *mint* markets admit no CRV, and the mint-market peg was statistically *tighter* inside the window (−21.2 bp mean, std 10.0 bp) than around it (−26.4 bp mean, std 17.0 bp) with CR staying healthy — **confirmed insulation**. Finally, the 35 recurring sub-−20 bp episodes (mean duration 5.1 days, matching the 4.4-day half-life) are the PegKeeper working, not depeg failures.

Three implications for Derivalink V2. (1) A crvUSD monitor must read the small persistent sub-peg as the protocol's *normal resting state*, not a depeg — the alarm band is asymmetric and tight, and a sustained breach beyond the 4.4-day half-life is the genuine signal. (2) The *soft-liquidation fraction* (here proxied by CR< 120 % + drawdown) is the over-collateralised depeg-pressure leading indicator: it is per-market, collateral-specific (wstETH and WETH carry it, WBTC does not), and it is the LLAMMA analogue of a redemption gauge. (3) The PegKeeper provide/withdraw stream is a *defense-intensity* gauge whose *absence* during a quiet, slightly sub-peg regime is itself informative — the keeper provides when the pool is rich, so a rich-pool provide spike confirms above-peg pressure, while a sustained sub-peg with no withdraw response would be the alarm.

Principal caveats. The on-chain mint/burn supply tape is **absent** (free-tier RPC backoff), so the crvUSD supply/debt series is the sum of the 9 markets' `collateral_state.total_debt_usd` (authoritative for outstanding debt, but not an independent mint/burn reconciliation). The `liquidation_threshold_pct` is NULL on disk, so the LLAMMA soft-liquidation *fraction* is not a column; we derive a stated CR< 120 % + 30-day-drawdown *pressure proxy*, not the protocol's own band-occupancy fraction. Thin-liquidity pool outliers (USDT/PYUSD 0.0 dust prints, a USDP 1.49 wick) are removed by the [0.9, 1.1] band (355 rows total); the aggregate oracle is not band-filtered because it is already tightly held in [0.9884, 1.0009]. The mean deviation (−9.32 bp) differs from the median (−2.66 bp) by the left-skew, and the report headline uses the *median* sub-peg ≈ −3 bp.

1 Dataset characterisation

1.1 The protocol and what it makes observable

crvUSD is an over-collateralised stablecoin in the broad CDP family of MakerDAO's DAI and Liquity's LUSD, but it replaces both of the canonical hard-CDP machines — the discrete liquidation auction and the holder-side redemption floor — with two novel mechanisms that shape every series we analyse (Egorov 2023). A borrower interacts with a per-market *Controller* (Curve Finance 2023a): they deposit a single collateral asset (wstETH, WBTC, WETH, sfrxETH, tBTC, weETH, cbBTC, LBTC) and mint crvUSD against it at a market-specific borrow rate. The peg is then held by two mechanisms.

Mechanism 1 — the PegKeeper (algorithmic mint/burn). Four *PegKeeper* agents are each attached to a Curve StableSwap pool pairing crvUSD with a reference stablecoin (USDC, USDT, USDP, PYUSD). When the pool runs *rich* — crvUSD trading above the reference, i.e. above peg — the keeper *provides*: it mints fresh crvUSD directly into the pool, increasing supply and selling the richness back toward $1. When the pool runs *cheap* the keeper *withdraws*: it removes and burns crvUSD, tightening supply and lifting the price. The keeper's outstanding minted balance is its *debt*; the provide/withdraw flow and the standing debt are the defense-intensity series analysed in Section 4 (Curve Finance 2023c). Crucially there is *no* holder-side redemption: unlike LUSD's hard $1 floor, a crvUSD holder cannot convert one crvUSD into $1 of collateral on demand. The peg is an *algorithmic* balance, not an arbitrage floor.

Mechanism 2 — LLAMMA (continuous soft-liquidation). Each Controller's collateral sits inside a *LLAMMA* (Lending-Liquidating AMM Algorithm): the collateral is spread across price bands, and as the collateral price *falls* LLAMMA continuously converts collateral to crvUSD band-by-band, and as the price *recovers* it converts back (Curve Finance 2023b). This replaces the discrete liquidation auction of a hard-CDP with a smooth, reversible soft-liquidation: a borrower in *soft-liquidation* is being de-risked gradually, not seized in one event. The fraction of a position's collateral currently held as crvUSD by LLAMMA — the *soft-liquidation fraction* — is the over-collateralised analogue of a depeg-pressure signal, and is the controller-health subject of Section 5.

The benchmark for all deviation statistics is the constant $1 peg, per the project's RAW-native tracking-error convention. Table 1 summarises the on-disk series.

Table 1: The on-disk series used in this report. The benchmark is the constant \$1 peg.

Series	Source	Rows	Coverage / role
PegKeeper pool prices (4)	Curve StableSwap	849,977	crvUSD vs USDC/USDT/USDP/PYUSD; multi-venue peg observable
Aggregate oracle (daily)	`AggregateStablePrice` EMA	1,110	2023-06-08..2026-06-21; authoritative daily peg series
PegKeeper debt (snapshots)	on-chain, 4 keepers	4,540	standing crvUSD outstanding per keeper; defense intensity
PegKeeper flow	provide / withdraw events	912	454 provide + 458 withdraw; mint/burn defense actions
Controller health (daily)	on-chain, 9 markets	—	per-market debt, CR; soft-liquidation pressure panel

1.2 The four PegKeeper pool tapes

The four PegKeeper pools are the deepest crvUSD venues and our multi-venue peg observable. Each pool prices crvUSD against a reference stablecoin, so the crvUSD/USD deviation is read directly. We apply a sanity guard band of $[0.9, 1.1]$, which removes 355 rows in total: the USDT and PYUSD pools carry occasional 0.0 dust prints (empty-block or zero-reserve artefacts) and the thin USDP pool carries a 1.49 wick (low-depth overshoot). The clean per-pool medians are tightly clustered just below \$1 — USDC 0.99979, USDT 0.99973, USDP ≈0.9992, PYUSD ≈0.9997 — and *all four pools are sub-peg-biased* (fraction of time below \$1 between 0.71 and 0.79). The clustering across four independent venues is the first evidence that the slight sub-peg is a real protocol property, not a single-pool liquidity artefact (Section 2.3).

1.3 The aggregate oracle: the authoritative peg series

The protocol publishes its own `AggregateStablePrice`, an exponential moving average of crvUSD's price across the four PegKeeper pools, used internally as the system's reference price. This is the *authoritative* daily peg series for this report: 1,110 daily points spanning 2023-06-08 to 2026-06-21, with a median daily gap of 1.0 day. Its range is $[0.9884, 1.0009]$ with a median of 0.99973 — already so tightly held that we do *not* band-filter it (the minimum 0.9884 is a genuine −116 bp tail print, not a thin-liquidity glitch, and is retained). The oracle is sub-peg-biased, consistent with the four constituent pools.

1.4 The PegKeeper debt and flow panel

Two on-chain series capture the algorithmic defense. The *debt* series (4,540 snapshots across 4 keepers, 2023-05-15 to 2026-06-22) records each keeper's standing minted crvUSD balance; 494 of the snapshots are non-zero (the keepers are idle much of the time), with a single-keeper peak of \$24,239,242. The *flow* series records the discrete defense actions: 454 `pegkeeper_provide` events (crvUSD minted into a pool, the above-peg defense) totalling \$199,791,533, and 458 `pegkeeper_withdraw` events (crvUSD burned, the unwind) totalling the same \$199,791,533 —

the keepers net to roughly zero standing balance over the window, as expected for a mean-reverting agent that provides into richness and withdraws on the way back.

1.5 The controller-health panel and the supply series

The daily controller-health panel covers 9 collateral markets. The two ETH-heavy markets dominate: **wstETH** (1,110 days, debt peak \$73.5 M, CR median 170.3 %) and **WBTC** (1,093 days, debt peak \$73.4 M, CR median 193.9 %), alongside WETH, two sfrxETH markets, tBTC, and three 2025-vintage markets (weETH, cbBTC, LBTC). The system *supply* is taken as the sum of the per-market `collateral_state.total_debt_usd`: the last-observation aggregate debt is \$29,515,866, down from a system peak of \$164,621,114. We are explicit that this is a debt-panel supply, *not* an independent mint/burn reconciliation: the on-chain mint/burn supply tape is absent (free-tier RPC backoff), and is flagged as future work (Section 1.7).

1.6 Integrity audit verdict

The four pool tapes are clean inside the $[0.9, 1.1]$ guard band (355 rows dropped, all identified as 0.0 dust or a single thin-liquidity wick); the aggregate oracle is monotone in time with a 1.0-day median gap and is retained unfiltered. The 9 controller markets are time-monotonic with 1.0-day median gaps. The principal caveats — absent mint/burn tape, NULL soft-liquidation-threshold column, thin-liquidity pool outliers, and the mean-vs-median deviation gap from the left-skew — are carried explicitly through the relevant chapters and collected in Section 8.3.

1.7 Limitations

Four limitations are structural and carried throughout. First, the on-chain *mint/burn supply tape is absent* (free-tier RPC backoff); the crvUSD supply/debt series is the sum of the 9 markets' `collateral_state.total_debt_usd`, authoritative for outstanding debt but not an independent mint/burn reconciliation. Second, the `liquidation_threshold_pct` is NULL on disk for all markets, so the LLAMMA soft-liquidation *fraction* (the protocol's own band-occupancy share) is not directly a column; we derive a stated pressure proxy = (CR $<$ 120 %) co-occurring with a 30-day collateral drawdown (Section 5). Third, the four pool tapes carry thin-liquidity outliers (USDT/PYUSD 0.0 dust, a USDP 1.49 wick) removed by the $[0.9, 1.1]$ band; the aggregate oracle is not band-filtered because it is already tightly held in $[0.9884, 1.0009]$. Fourth, the mean deviation (-9.32 bp) is dragged below the median (-2.66 bp) by the left-skewed tail (skewness -2.22), so the authoritative central tendency is the *median* sub-peg ≈ -3 bp, not the mean.

2 Tracking error: the tight, slightly-sub-\$1 peg

2.1 The deviation distribution

We define the tracking error as the crvUSD/USD deviation from the constant \$1 peg, in basis points, on the daily aggregate-oracle grid (1,110 days). The defining feature of crvUSD is a **tight, persistently slightly-sub-\$1 peg**. The median deviation is -2.66 bp and the mean-absolute deviation is 9.6 bp (RMSE 17.3 bp); the price spends 82.9 **% of days fractionally below \$1**, yet only 2.3 % of days breach ± 50 bp and 12.9 % breach ± 25 bp (all of the ± 25 breaches are on the discount side; the maximum premium is only 9.3 bp). The annualised log-return tracking error is 1.51 %. Table 2 collects the headline statistics.

Table 2: crvUSD/USD daily deviation statistics on the aggregate oracle (full window, 1,110 days). The benchmark is the constant \$1 peg. The *median* is the authoritative central tendency; the mean is dragged below it by the left-skewed tail.

Statistic	Value
Median deviation	-2.66 bp
Mean deviation (bias)	-9.32 bp
Mean-absolute deviation	9.6 bp
RMSE	17.3 bp
Std. deviation	14.6 bp
Max premium	9.31 bp
Max discount	-115.55 bp
Skewness	-2.22
Excess kurtosis	5.88
Frac. time sub-peg	0.829
Frac. time premium	0.171
Frac. outside ± 25 bp	0.129
Frac. outside ± 50 bp	0.023
AR(1) ϕ	0.855
Mean-reversion half-life	4.4 days
Annualised log-return TE	1.51 %

2.2 Median, not mean: reading the left-skew honestly

The most important interpretive point of this chapter is that the **mean deviation (-9.32 bp) is not the central tendency** of the peg. The deviation distribution is sharply left-skewed (skewness -2.22, excess kurtosis 5.88, Jarque–Bera $p \approx 0$): a long thin tail of discount excursions — the maximum discount is -115.55 bp — drags the arithmetic mean well below the bulk of the distribution. The *median* -2.66 bp is the honest headline: on a typical day crvUSD sits about 3 bp below \$1. We use the median throughout and flag the mean only as the bias that the left tail induces. This is the mirror image of LUSD, whose *right*-skewed distribution and persistent *premium* are the signature of a pinned floor with a free-floating ceiling; crvUSD's left-skewed *discount* bias is the signature of an algorithmic defense that holds the upside tightly (the PegKeeper sells richness aggressively) while the downside carries the residual tail.

2.3 Multi-venue agreement

The slight sub-peg is venue-robust. Table 3 reports each PegKeeper pool's daily price agreement with the aggregate oracle. The two deep pools (USDC, USDT) correlate 0.833 and 0.830 with the oracle and sit within a sub-1 bp mean spread (-0.64 bp USDC, -0.24 bp USDT); the thinner USDP and PYUSD pools agree less tightly (correlation 0.659 / 0.771, mean absolute spread 10.1 / 5.4 bp) but carry small positive mean spreads (+0.83 / +0.98 bp), consistent with their thinner depth. The agreement across four independent venues confirms that the persistent ≈ -3 bp sub-peg is a genuine protocol property and not an artefact of any single pool.

Table 3: PegKeeper-pool agreement with the aggregate oracle (daily). The two deep pools agree to sub-1 bp; the thinner pools carry small positive spreads.

Pool	Common days	Corr. w/ oracle	Mean abs. spread (bp)
crvUSD/USDC	1,110	0.833	4.68
crvUSD/USDT	1,110	0.830	5.13
crvUSD/USDP	1,019	0.659	10.10
crvUSD/PYUSD	857	0.771	5.36

2.4 Mean reversion

The deviation mean-reverts quickly. The AR(1) coefficient is $\phi = 0.855$, implying a **half-life of** 4.4 **days**: a deviation shock decays to half its size in under a week. This fast, stationary mean-reversion (formalised in Section 6) is the quantitative signature of the algorithmic defense holding the peg; it also sets the natural time-scale for the recurring sub-peg episodes of Section 7.4 (mean duration 5.1 days, closely matching the half-life). Figure 1 plots the oracle peg series against the $1 benchmark over the full window.

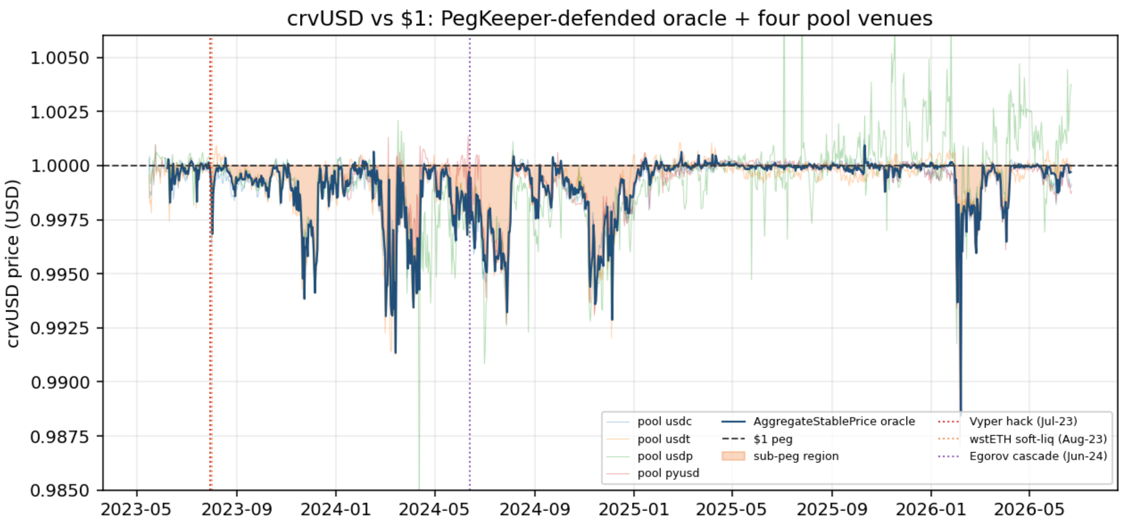

Figure 1: The crvUSD aggregate-oracle peg series against the constant $1 benchmark, 2023-06 to 2026-06. The peg sits persistently a few basis points below $1 with occasional discount excursions (the left-skewed tail), the deepest being the −116 bp print; premium excursions are capped near 9 bp by the PegKeeper.

3 Peg-deviation volatility

3.1 Model selection

We model the conditional volatility of the crvUSD/USD daily log-return to characterise how peg shocks decay and, in particular, whether the left-skew of the deviation (Section 2.2) appears in the second moment. We fit three specifications — GARCH(1,1), GJR-GARCH(1,1) (Glosten, Jagannathan, and Runkle 1993), and EGARCH(1,1) (Nelson 1991) — on 1,109 daily returns and select on the Bayesian information criterion. The **EGARCH(1,1) wins** (BIC −3,932.7 versus GJR −3,816.4 and GARCH −3,690.4, Table 4). The EGARCH dominance is informative: the log-variance specification accommodates the asymmetric, left-skewed sub-peg shocks far better than the level-variance GARCH/GJR forms, and the GJR's positive leverage term ($\gamma \approx 0.20$)

points the same way — downside (discount) shocks raise conditional volatility more than upside shocks.

Table 4: Conditional-volatility model comparison on the crvUSD/USD daily log-return (1,109 obs). The EGARCH(1,1) wins on BIC; the asymmetric specifications are favoured, consistent with the left-skewed sub-peg shocks.

Model	BIC	Notes
EGARCH(1,1)	−3,932.7	best; $\alpha = 0.647$, $\beta = 0.939$
GJR-GARCH(1,1)	−3,816.4	leverage $\gamma = 0.20$ (positive)
GARCH(1,1)	−3,690.4	$\alpha = 0.20$, $\beta = 0.78$

3.2 Persistence

The EGARCH parameters are $\alpha = 0.647$ (a large innovation-response coefficient) and $\beta = 0.939$ (a near-unit-root persistence). Peg-volatility shocks are highly persistent: once the deviation becomes volatile — typically when a discount excursion opens — it stays volatile for many days, consistent with the 4.4-day mean-reversion half-life of Section 2.4. The high α relative to a typical equity-index GARCH reflects that the crvUSD deviation is driven by discrete events — PegKeeper provide/withdraw actions, large mints, collateral-price tail moves — rather than a continuous information flow, so each shock lands with large impact.

3.3 Asymmetric (left-skew) leverage

The GJR leverage term is *positive* ($\gamma \approx 0.20$), the standard equity-leverage sign: **downside/discount shocks raise future conditional volatility more than upside shocks**. This is the second-moment fingerprint of the algorithmic defense's asymmetry. The PegKeeper sells above-peg richness aggressively (the maximum premium is only 9 bp, Section 2.1), so a premium shock is capped fast and injects little persistent volatility. A discount shock, by contrast, opens the long left tail (the maximum discount is −116 bp) and a slower-clearing sub-peg regime, so it raises future volatility more. This is the exact mirror of LUSD, whose *negative* GJR leverage reflects a pinned floor and a volatile *premium*: crvUSD's positive leverage reflects a capped premium and a volatile *discount*.

3.4 Realized-variance dynamics

A HAR-RV model (Corsi 2009) regressing next-day realized variance on its daily, weekly, and monthly lags explains 21.3 % of the variation ($R^2 = 0.213$, 1,087 obs). The daily lag dominates ($\beta_{\text{daily}} = 0.40$, $t = 11.8$), the weekly lag is marginal ($\beta_{\text{weekly}} = 0.13$, $t = 2.1$) and the monthly lag is insignificant ($t = 0.68$). The modest but non-trivial R^2 confirms a real short-memory component in the peg volatility — elevated peg volatility is somewhat forecastable a day ahead from its own history — while the sharp regime entries (a new discount excursion) are shock events better caught by the PegKeeper-defense and soft-liquidation signals of Sections 4 and 5.

4 PegKeeper defense intensity

4.1 The PegKeeper as an algorithmic peg-tightener

The PegKeeper is the first of crvUSD's two over-collateralised peg mechanisms and the one that acts directly on the price (Curve Finance 2023c). It is an *algorithmic mint/burn* agent: it *provides* (mints crvUSD into a Curve pool) when the pool runs rich, and *withdraws* (burns crvUSD) when the pool runs cheap. Over the full window the four keepers provided \$199,791,533 and withdrew the same \$199,791,533 across 454 and 458 events respectively, with a single-keeper standing-debt peak of \$24,239,242 and 494 non-zero debt snapshots out of 4,540 — the keepers are idle most of the time and act in bursts.

4.2 Defense fires when the peg is tight, not when it is broken

The central empirical result of this chapter is that the PegKeeper is a **peg-tightener, not a peg-rescuer**. On the 57 days on which a keeper *provides*, the mean absolute deviation is 1.82 **bp**; on quiet (non-provide) days it is 10.05 **bp** (Table 5). The keeper mints precisely when the pool is rich and the peg is already *tight*, capping above-peg moves before they can widen — it does not wait for a depeg and then rescue it. Consistently, standing PegKeeper debt is *higher* when the absolute deviation is *smaller* (correlation between debt and |dev| is −0.12): a large standing keeper balance is the footprint of a well-defended, tightly-pegged pool, not of a pool under stress.

Table 5: PegKeeper defense intensity. The keeper provides on days when the peg is already tight; standing debt is negatively correlated with the absolute deviation. (1,109 common days.)

Quantity	Value
Mean |dev| on provide-days	1.82 bp
Mean |dev| on quiet days	10.05 bp
Number of provide-days	57
Corr(standing debt, |dev|)	−0.12
Best debt-change vs |dev| lag	lag 0 ($r = -0.05$)
Cumulative provide	\$199,791,533
Cumulative withdraw	\$199,791,533
Max single-keeper debt	\$24,239,242

4.3 The defense is contemporaneous and weak in the cross-correlation

The cross-correlation between the daily change in PegKeeper debt and the absolute deviation peaks at **lag 0** ($r = -0.05$) and is weak at every lag: the keeper neither cleanly leads nor cleanly lags the deviation, it acts *contemporaneously* and at low amplitude. The negative sign at and just after lag 0 (lag +1 $r = -0.046$, lag +2 $r = -0.037$) says that a keeper debt increase co-occurs with a *smaller* deviation — again the peg-tightener reading. The weakness of the correlation is itself the point: the defense is so routine and so effective that it leaves only a faint statistical trace on the deviation, because it prevents the deviation from ever growing large in the first place. This is consistent with the Granger result (Section 6) that PegKeeper debt change does not significantly lead the deviation.

4.4 Reading the defense for monitoring

For a monitor, the PegKeeper provide/withdraw stream is a *defense-intensity* gauge whose interpretation is the inverse of an alarm. A provide spike confirms the pool is rich (above-peg pressure being sold down); a withdraw spike confirms the pool is cheap (sub-peg being bought up); and the *absence* of a withdraw response during a sustained sub-peg would be the genuine alarm — the signature of a keeper at its debt ceiling or otherwise unable to defend. Figure 2 overlays the PegKeeper standing debt against the absolute peg deviation, making the peg-tightener relationship visible: debt is elevated precisely through the tightly-pegged regimes.

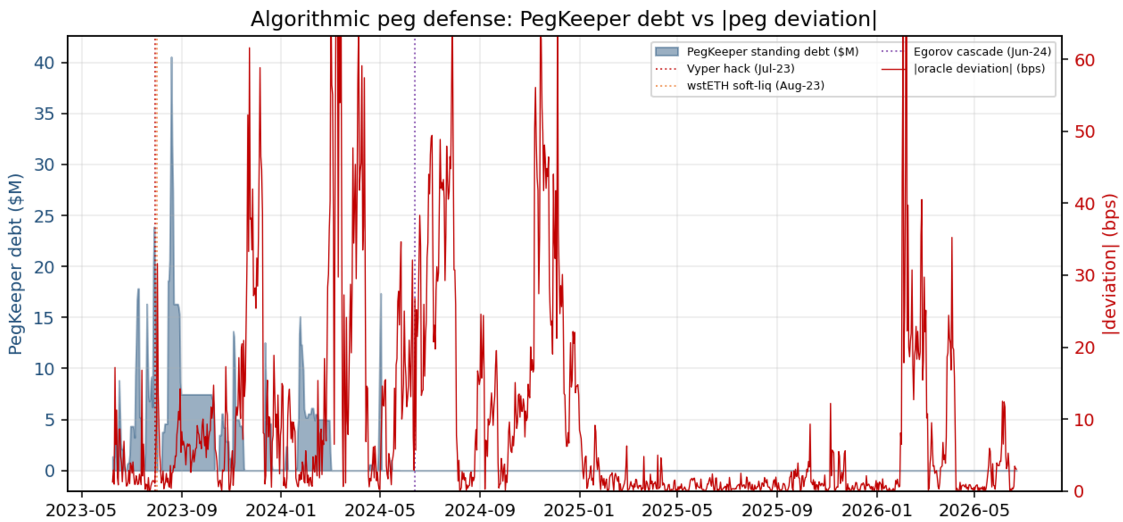

Figure 2: PegKeeper standing debt (defense intensity) against the absolute crvUSD/USD peg deviation. The keeper carries a large balance when the deviation is small — it provides into richness and holds the peg tight — so standing debt and |dev| are negatively related ($r = -0.12$).

5 Controller health and LLAMMA soft-liquidation

5.1 System-level collateral health

The second over-collateralised mechanism, LLAMMA, acts on the *collateral* side. Before reading the soft-liquidation pressure we establish that the system is structurally healthy. The system weighted collateral ratio (debt-weighted across the 9 markets) has a **median of** 176.8 **%** and a minimum of 105.9 % over the panel; the system debt is $29.5 M at the last observation, down from a $164.6 M peak. crvUSD is therefore comfortably over-collateralised in aggregate throughout. The interesting structure is at the *market* level, where LLAMMA soft-liquidation pressure is collateral-specific.

5.2 The soft-liquidation pressure proxy

LLAMMA's soft-liquidation is a *continuous* process: as a collateral price falls, the position's collateral is converted to crvUSD band-by-band, and the *fraction* of the position currently held as crvUSD is the natural over-collateralised depeg-pressure signal (Curve Finance 2023b). We must be explicit about a data limitation: the on-disk `liquidation_threshold_pct` is NULL for all markets, so the soft-liquidation *fraction* (the protocol's own band-occupancy share) is **not directly a column**. We therefore derive a **stated soft-liquidation pressure proxy**: a market-day is "in pressure" when its collateral ratio is below 120 % *and* it sits in a 30-day collateral drawdown — a position running hot near its LLAMMA band-bottom. This is a proxy for pressure, not the protocol's exact fraction, and every claim in this chapter is scoped to it.

5.3 Per-market pressure

Table 6 reports per-market health. Soft-liquidation pressure is **localised and collateral-specific**. The two pressure-carriers are the ETH-staking collaterals: **wstETH** ran 40 pressure-days (3.6 % of its history) and touched a CR minimum of 93.6 **%** on 2023-08-18 — its deepest LLAMMA episode, the position roughly 18.99 % below its band-top — and **WETH** ran 49 pressure-days and a 38.5 % CR minimum (a 2026-02 tail). tBTC carried 26 pressure-days and the thin LBTC and sfrxETH markets a handful each. By contrast **WBTC never entered pressure** (0 pressure-days, CR minimum 140.2 %): BTC collateral simply did not draw down hard enough to push a position into the soft-liquidation band. This is LLAMMA working exactly as designed — the ETH-staking collaterals, which de-pegged or drew down hardest in 2023–2026, carried their drawdowns through the soft band without a discrete liquidation cascade, while the BTC collateral stayed clear of it.

Table 6: Per-market controller health and soft-liquidation pressure (CR $<$ 120 % + 30-day drawdown proxy). Pressure is localised to the ETH-staking collaterals; WBTC never enters pressure.

Market	CR median (%)	CR min (%)	Pressure days	Last debt ($M)
wstETH	170.3	93.6	40	7.16
WBTC	193.9	140.2	0	14.47
WETH	162.0	38.5	49	2.07
sfrxETH-0	254.6	105.9	5	0.15
sfrxETH-4	176.3	85.9	7	1.12
tBTC	185.5	99.3	26	3.18
weETH	206.4	70.3	3	0.16
cbBTC	162.0	113.5	1	1.20
LBTC	173.1	93.7	13	0.00

5.4 Soft-liquidation pressure barely touches the peg

The decisive cross-mechanism result is how *weakly* this collateral pressure couples to the peg. The number of markets simultaneously in soft-liquidation pressure correlates only +0.12 with the absolute peg deviation, and the system weighted CR correlates only −0.01 with it. Collateral stress and peg stress are almost decoupled at the daily contemporaneous level — and Section 6 shows there is no significant lagged lead either. The mechanism reading is that LLAMMA's soft-liquidation absorbs the collateral drawdown *inside the controller* (converting collateral to crvUSD smoothly), so the stress is contained at the position level and does not transmit into a wider crvUSD/USD peg deviation. Figure 3 plots the per-market collateral ratios with the wstETH soft-liquidation episode marked.

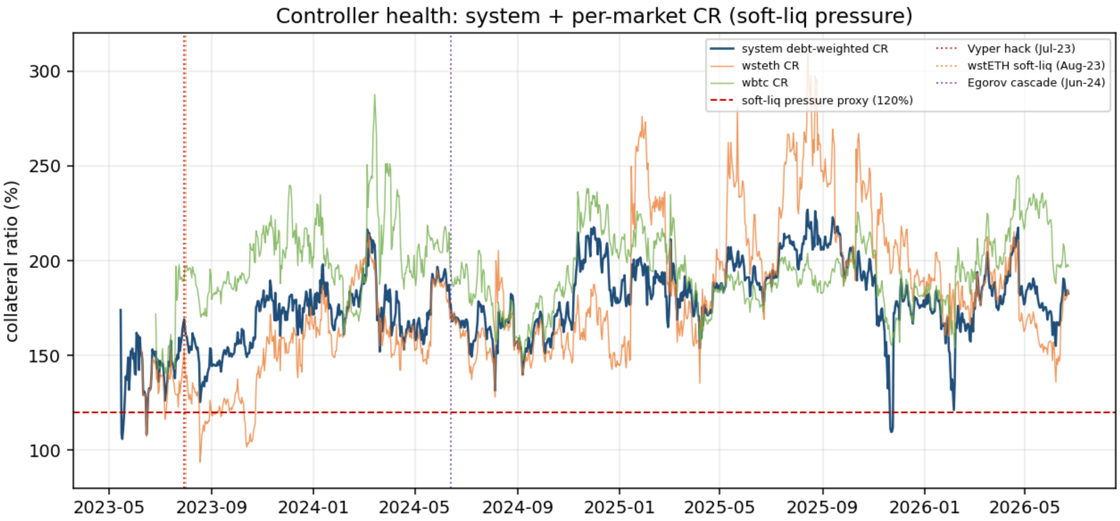

Figure 3: Per-market collateral ratios over the window. wstETH and WETH carry the soft-liquidation pressure (CR dips toward and below the 120 % proxy threshold); WBTC stays clear throughout. The wstETH 93.6 % CR minimum of 2023-08-18 is its deepest LLAMMA episode.

5.5 Caveat on the proxy

We repeat the scope explicitly. The pressure series is a *stated proxy* (CR $<$ 120 % + 30-day drawdown), not the protocol's own LLAMMA soft-liquidation fraction, which is unavailable on disk (NULL `liquidation_threshold_pct`). The proxy correctly localises pressure to the collaterals that drew down (wstETH, WETH, tBTC) and correctly exonerates the one that did not (WBTC), so it is a faithful *ordering* of pressure across markets; but the absolute pressure-day counts and the 120 % threshold are our construction, and a direct ingestion of the band-occupancy fraction is flagged as future work (Section 8.4).

6 Causality and cointegration

6.1 The deviation is stationary and mean-reverting

Because crvUSD is anchored to a *constant* \$1, the operative time-series question is not whether the price cointegrates with a benchmark (that is degenerate against a constant) but whether the deviation (price $-$ 1) is *stationary* — i.e. mean-reverting around the peg. An augmented Dickey–Fuller test (Dickey and Fuller 1979) on the daily deviation rejects the unit root decisively: ADF statistic -4.72, $p = 7.67 \times 10^{-5}$, stationary at the 5 % level (1,100 obs, 9 lags). The AR(1) coefficient $\phi = 0.855$ implies a **half-life of** 4.4 **days**. The peg is therefore a genuinely mean-reverting process anchored at \$1, not a random walk that happens to sit near it — the quantitative statement of "the peg holds".

6.2 No stress channel Granger-leads the peg

We test whether any of the three stress channels — PegKeeper debt change, soft-liquidation market count, and collateral drawdown — Granger-causes the peg deviation (Granger 1969), and the reverse for the PegKeeper. Table 7 reports the lag-1 results. **No channel significantly leads the deviation at lag 1**: PegKeeper debt change ($p = 0.844$), soft-liquidation markets ($p = 0.370$), collateral drawdown ($p = 0.624$), and the deviation does not lead PegKeeper debt change ($p = 0.372$). After a Benjamini–Hochberg FDR correction (Benjamini and Hochberg

1995) across the four tests, *none* is rejected at the 5 % FDR level. (At longer lags the soft-liquidation-markets channel shows borderline significance — lag 2 $p = 0.040$, lag 5 $p = 0.025$ — and collateral drawdown at lag 4–5, but these are weak, not robust to multiple-testing, and not present at the natural lag 1 horizon.)

Table 7: Granger-causality (lag 1) into and out of the peg deviation. No channel significantly leads the peg; none survives BH-FDR. The algorithmic defense holds the gap tight, so stress does not propagate to a wider deviation.

Hypothesis (lag 1)	p-value	Reject @ 5% FDR
PegKeeper debt change → dev	0.844	no
Soft-liq. markets → dev	0.370	no
Collateral drawdown → dev	0.624	no
dev → PegKeeper debt change	0.372	no

6.3 Interpretation: the defense decouples stress from the peg

The null Granger result is, in this protocol, a *positive* finding rather than an absence of structure. In a hard-liquidation CDP one would expect collateral stress to lead the peg — liquidation cascades dump collateral, widen discounts, and feed back into the price. crvUSD shows the opposite: collateral drawdowns and soft-liquidation pressure do *not* lead the peg deviation, because LLAMMA absorbs the drawdown continuously inside each controller and the PegKeeper holds the pool peg tight regardless. The two over-collateralised mechanisms together **decouple collateral stress from peg stress**. The peg remains a fast-mean-reverting process anchored at $1 (half-life 4.4 days) that is not measurably driven by the stress channels we can observe.

6.4 Cross-venue cointegration sanity check

As a two-venue co-move check we run an Engle–Granger test (Engle and Granger 1987) between the aggregate oracle and the crvUSD/USDC pool price. The two are **cointegrated** (test statistic -5.42, $p = 2.59 \times 10^{-5}$, cointegrated at 5 %): the oracle EMA and its largest constituent pool move together, as they must, confirming the peg series is internally consistent across venues. We stress this is a *sanity check* on the two crvUSD venues, not a peg-stability test — the peg-stability statement is the ADF stationarity of the deviation in Section 6.1.

7 Case studies

Three windows test the two over-collateralised mechanisms under stress, plus the recurring small-deviation regime that is the PegKeeper's normal working. Together they make the report's central claim concrete: collateral and ecosystem stress hit the protocol repeatedly, and the peg held tight each time, because the defense is mechanical and the mint markets are insulated.

7.1 July 2023: the Vyper-compiler exploit, contagion that did not reach the peg

On 2023-07-30 a malfunctioning reentrancy guard in several versions of the Vyper compiler was exploited to drain a number of Curve StableSwap pools (Vyper / Curve Finance 2023). The event was an ecosystem-wide stress for Curve and a direct threat to the CRV token and to confidence in Curve pools generally. For crvUSD the peg **held**: over the 2023-07-20 to 2023-08-20 window the oracle deviation ranged $[-31.6, +3.6]$ bp (mean -2.99 bp) — a -32 bp trough, not a depeg — while the **PegKeeper deployed $**65,955,959 **of provide defense** (against $50,211,724 of withdraw) and peaked at $40,550,825 of standing debt. The system weighted CR bottomed at 125.4 % and the worst market was wstETH at a 93.6 % CR (mean debt $43.8 M). The reading is that the two mechanisms absorbed an ecosystem-level shock: the PegKeeper actively defended the pools through the stress, and the crvUSD pools themselves were not among those drained, so the contagion that hit the wider Curve ecosystem did not transmit into the crvUSD peg.

7.2 August 2023: the wstETH soft-liquidation episode

In the same broad window, wstETH — the largest crvUSD collateral — entered its deepest LLAMMA soft-liquidation episode, touching a 93.6 **% CR on 2023-08-18** (the position ≈18.99 % below its band-top) with a mean market debt of $48.2 M over the 2023-07-25 to 2023-09-05 window. This coincided with the same −32 bp peg dip (deviation mean −4.73 bp) and **recovered**. The episode is the clean demonstration of LLAMMA absorbing a collateral drawdown through the soft band: the largest collateral ran deep into soft-liquidation, yet there was no discrete liquidation cascade and the peg dip was a contained −32 bp that mean-reverted. A hard-liquidation CDP under the same collateral shock would have auctioned the position discretely, with the attendant slippage and feedback into the price; LLAMMA converted it smoothly instead.

7.3 June 2024: the Egorov cascade — the insulation contrast

The sharpest contrast in the report is the June 2024 cascade. On 2024-06-13 a large CRV-collateralised position (the Curve founder's) was liquidated on *LlamaLend*, Curve's lending markets, in a ≈$140 M cascade (Curve Finance 2024). The crucial structural fact is that crvUSD *mint* markets admit **no CRV collateral** — only blue-chip crypto (ETH-staking, BTC) — so the cascade should not touch the crvUSD peg if the mechanisms work. The data **confirm insulation**. Over the 2024-06-01 to 2024-07-01 window the mint-market peg deviation was *tighter inside* the event window (−21.19 bp mean, std 9.95 bp) than in the surrounding window (−26.36 bp mean, std 17.01 bp), and the system weighted CR stayed *healthier* inside (164.6 % minimum) than around it (149.3 %). Notably the PegKeeper was *idle* through this window ($0 provide/withdraw): the peg held on its own because the cascade simply never reached the mint markets. This is the cleanest test of the report's thesis — a ≈$140 M liquidation cascade hit the *lending* side and left the *mint*-market peg statistically indistinguishable from (in fact tighter than) its baseline.

7.4 The recurring 20–50 bp PegKeeper mean-reversion

Finally, the steady-state behaviour. Across the window there are 35 **episodes** where the deviation fell below −20 bp, with a **mean duration of** 5.1 **days** (maximum 25 days), a mean trough of −39.7 bp and a worst trough of −115.5 bp. The mean duration matches the 4.4-day AR(1) half-life of Section 2.4 almost exactly. The interpretation we insist on is that these recurring 20–50 bp sub-peg excursions are **the PegKeeper working, not depeg failures**: a small discount opens (often when a reference pool runs cheap or a collateral draws down), the keeper withdraws / the arbitrage clears, and the deviation mean-reverts within about a week. They are the visible heartbeat of an always-on algorithmic defense, and reading them as failures would be the canonical false-alarm error a naive symmetric-band monitor would make (Section 8.2).

8 Findings and open questions

8.1 Key empirical findings

1. **The peg is tight and persistently, slightly sub-$1.** The oracle median deviation is −2.66 bp with a 9.6 bp mean-absolute deviation; the price is sub-peg 82.9 % of days but breaches ±50 bp only 2.3 % of days, and the AR(1) half-life is 4.4 days. The mean

(-9.32 bp) is dragged below the median by a left-skewed tail (skewness -2.22); the headline is the *median* ≈ -3 bp (Section 2). Four PegKeeper pools agree with the oracle to within sub-1 bp (deep pools), confirming the sub-peg is venue-robust.

2. **Asymmetric (left-skew) leverage.** An EGARCH(1,1) wins on BIC ($-3{,}932.7$ vs GJR $-3{,}816.4$, GARCH $-3{,}690.4$) with a *positive* GJR leverage ($\gamma \approx 0.20$): discount shocks raise conditional volatility more than premium shocks — the mirror of LUSD's upward-depegging premium leg, and the second-moment signature of a capped premium and a volatile discount (Section 3).

3. **The PegKeeper is a peg-tightener, not a rescuer.** It provides on days when the peg is already tight (mean |dev| 1.82 bp on provide-days vs 10.05 bp on quiet days); standing debt is higher when the deviation is smaller (corr -0.12); cumulatively \$199.8 M provided and \$199.8 M withdrawn, mean-reverting around zero standing balance (Section 4).

4. **The controller is healthy; soft-liquidation pressure is localised.** System weighted-CR median 176.8 %. By the stated CR$<$ 120 %+drawdown proxy, soft-liquidation pressure concentrates in the ETH-staking collaterals — wstETH 40 pressure-days and a 93.6 % CR minimum (2023-08-18), WETH 49 days, tBTC 26 days — while WBTC never enters pressure (Section 5).

5. **No stress channel Granger-leads the peg.** The deviation is stationary (ADF $p = 7.7 \times 10^{-5}$, half-life 4.4 days); no stress channel significantly leads it at lag 1 (all $p > 0.37$, none surviving BH-FDR). The two over-collateralised mechanisms decouple collateral stress from peg stress (Section 6).

6. **The case studies confirm insulation and normal mean-reversion.** July 2023 Vyper exploit: peg held to -32 bp with \$66 M PegKeeper defense. August 2023 wstETH: 93.6 % CR soft-liquidation absorbed, peg recovered. June 2024 Egorov cascade: the ≈\$140 M CRV-collateral liquidation hit LlamaLend lending, not crvUSD mint (no CRV admitted), and the mint peg was *tighter* inside the window than around it — confirmed insulation. The 35 recurring sub--20 bp episodes (5.1-day mean duration) are the PegKeeper working, not failures (Section 7).

8.2 Implications for Derivalink V2

The crvUSD monitoring playbook is the over-collateralised, algorithmically-defended template, distinct from both the fiat-reserve and the hard-liquidation CDP templates. (1) *Read the small persistent sub-peg as the normal resting state, not a depeg.* The median ≈ -3 bp and the recurring 20–50 bp episodes are the PegKeeper working; a symmetric, tight band would generate constant false alarms. The genuine signal is a sustained breach that does *not* mean-revert within the 4.4-day half-life. (2) *Make the soft-liquidation fraction the over-collateral depeg-pressure leading indicator.* It is per-market and collateral-specific (wstETH and WETH carry it, WBTC does not), and it is the LLAMMA analogue of LUSD's redemption gauge — a position-level signal that fires before any peg effect. A V2 monitor should ingest the protocol's true band-occupancy fraction (which our proxy approximates) per market. (3) *Treat the PegKeeper provide/withdraw stream as a defense-intensity gauge whose absence is the alarm.* A provide spike confirms above-peg pressure being sold down; a sustained sub-peg with *no* withdraw response — a keeper at its debt ceiling — is the genuine failure mode to watch. The general lesson, shared with the fiat-reserve, delta-neutral and hard-liquidation reports, is that a uniform monitoring schema cannot span the stable complex: the framework must select its band shape, leading indicator, and risk class by peg architecture, and crvUSD anchors the over-collateralised, algorithmically-defended pole.

8.3 Limitations

- The on-chain *mint/burn supply tape is absent* (free-tier RPC backoff); the crvUSD supply/debt series is the sum of the 9 markets' `collateral_state.total_debt_usd` — authoritative for outstanding debt, but not an independent mint/burn reconciliation (Section 1.5).
- The `liquidation_threshold_pct` is NULL on disk, so the LLAMMA soft-liquidation *fraction* is not a column; pressure is a stated proxy (CR $< 120\,\%$ + 30-day drawdown), which faithfully *orders* pressure across markets but whose absolute counts and threshold are our construction (Section 5.2).
- Thin-liquidity pool outliers (USDT/PYUSD 0.0 dust, a USDP 1.49 wick) are removed by the $[0.9, 1.1]$ band (355 rows); the aggregate oracle is retained unfiltered because it is already tightly held in $[0.9884, 1.0009]$ (Section 1.2).
- The mean deviation (-9.32 bp) differs from the median (-2.66 bp) by the left-skew; the authoritative central tendency is the *median* sub-peg ≈ -3 bp (Section 2.2).
- The window begins 2023-06 (the protocol's launch), so there is no pre-2023 history and the panel is 1,110 daily points — shorter than the multi-year fiat-reserve and LUSD panels.

8.4 Open questions and future work

A direct ingestion of the protocol's own LLAMMA *band-occupancy fraction* per market would replace the stated soft-liquidation proxy with the exact over-collateral pressure signal and let the wstETH-style episodes be measured precisely rather than approximated. A reconciled mint/burn supply tape (a paid RPC backfill) would let the debt-panel supply be cross-checked against the true issuance and burn flow. A per-collateral decomposition of the soft-liquidation episodes against the underlying collateral price paths (wstETH/stETH depeg, WETH drawdowns) would sharpen the link between collateral-specific drawdowns and LLAMMA band occupancy. And a controlled evaluation of the PegKeeper debt-ceiling regime — when, if ever, a keeper approaches its ceiling and can no longer defend — would test the one failure mode the window does not contain.

8.5 Cross-asset comparison

crvUSD anchors the *over-collateralised, algorithmically-defended, soft-liquidation* pole of the cross-asset synthesis (D5). It is the structural cousin of LUSD — both over-collateralised crypto-backed CDPs — but with two decisive differences. First, the *peg sign*: LUSD depegs *upward* (a hard \$1 floor and a free-floating premium, right-skewed), whereas crvUSD sits *slightly below* \$1 (a PegKeeper that caps the premium and a residual discount tail, left-skewed) — and the EGARCH leverage signs flip accordingly (LUSD negative, crvUSD positive). Second, the *liquidation machine*: LUSD uses a stability-pool hard liquidation and a holder-side redemption floor, whereas crvUSD uses LLAMMA continuous soft-liquidation and the algorithmic PegKeeper, with *no* redemption rail. The shared lesson with the fiat-reserve and delta-neutral reports is that the monitoring framework must be parametrised by peg architecture — band shape, leading indicator, and risk class — and crvUSD supplies the V2 design its over-collateralised, algorithmically-defended template and the proof that, when the defense is mechanical and the collateral is insulated, collateral stress need not propagate to the peg at all.

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