Dynamical Correlations Across Momentum Scales in the Quark–Gluon Plasma

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Introduction: From Radial Flow to Fluctuation Probe

- The p_T-differential radial flow fluctuation observable $v_0(p_T)$ has recently been measured by ATLAS [1] and ALICE [2].
- Hydrodynamic calculations describe the low-p_T rise [3, 4], but generically predict monotonic behavior.
- Experiments show a rise–plateau–downturn structure with species hierarchy.
- **Key Question:** What dynamical structure across momentum scales produces the observed rise–plateau–downturn behavior?

$v_0(p_T)$: Projection and Degeneracy

$$v_0(p_T) = \frac{\langle \delta n(p_T)\, \delta[p_T] \rangle}{\langle n(p_T) \rangle\, \sigma_{[p_T]}}$$

Two distinct effects shape $v_0(p_T)$:

- **Dilution:** uncorrelated yield modifies normalization via $\langle n(p_T) \rangle$ without changing fluctuation rank.
- **Dynamical correlations:** coherent or anti-correlated soft–mid–hard fluctuations.

Limitation: $v_0(p_T)$ is a one-dimensional projection: inter-bin correlations are lost. It cannot determine:

- How many independent fluctuation modes exist.
- Where decorrelation is anchored in p_T.
- Whether hard-sector fluctuations are coherent or anti-correlated.

Different dynamical scenarios can produce similar $v_0(p_T)$ trends.

From Projection to Fluctuation Topology

The reference-aligned covariance matrix:

$$V_0(p_{T1}, p_{T2}) = \langle [\delta n(p_{T1}) \delta[p_T]][\delta n(p_{T2}) \delta[p_T]] \rangle$$

retains full cross-momentum correlation structure and thus contains strictly more information than its projection $v_0(p_T)$.

Effective Fluctuation Dimensionality

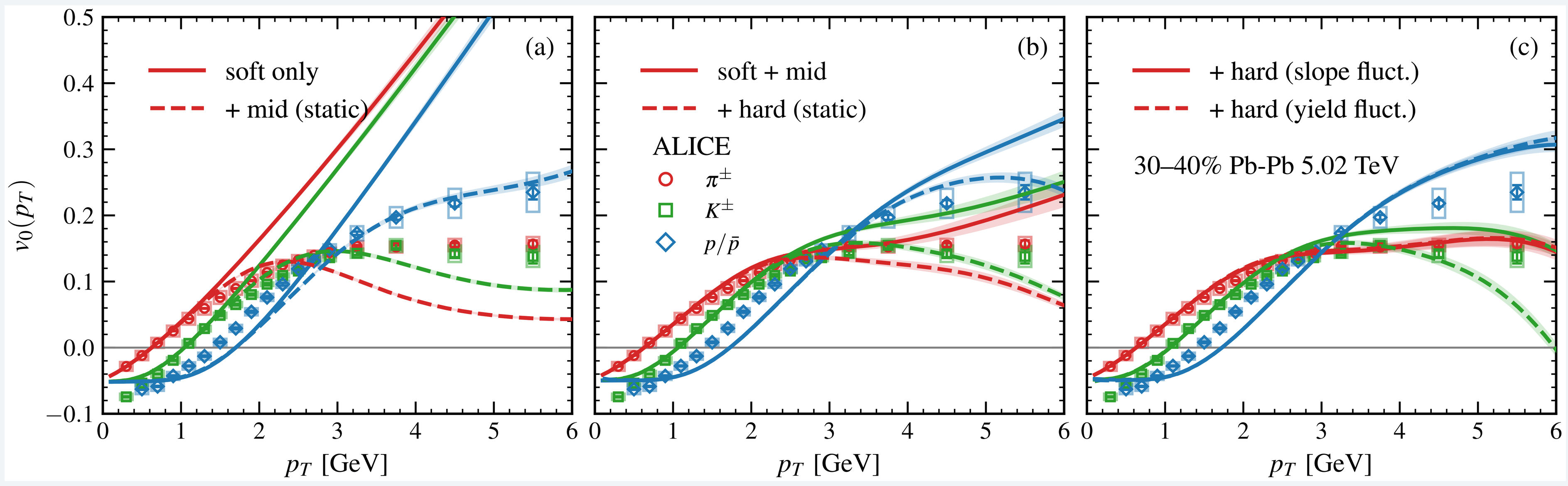
$$V_0(p_{T1}, p_{T2}) = \sum_i \lambda_i\, u_i(p_{T1}) u_i(p_{T2})$$

The eigenvalue ratio λ_2/λ_1 measures the number and relative strength of independent fluctuation modes.

- Small $\lambda_2/\lambda_1 \Rightarrow$ effectively one-dimensional collective system.
- Larger $\lambda_2/\lambda_1 \Rightarrow$ independent dynamical modes emerge.
- Sign-changing eigenvector $\Rightarrow$ soft–hard anti-correlation.

Fluctuation dimensionality becomes experimentally measurable.

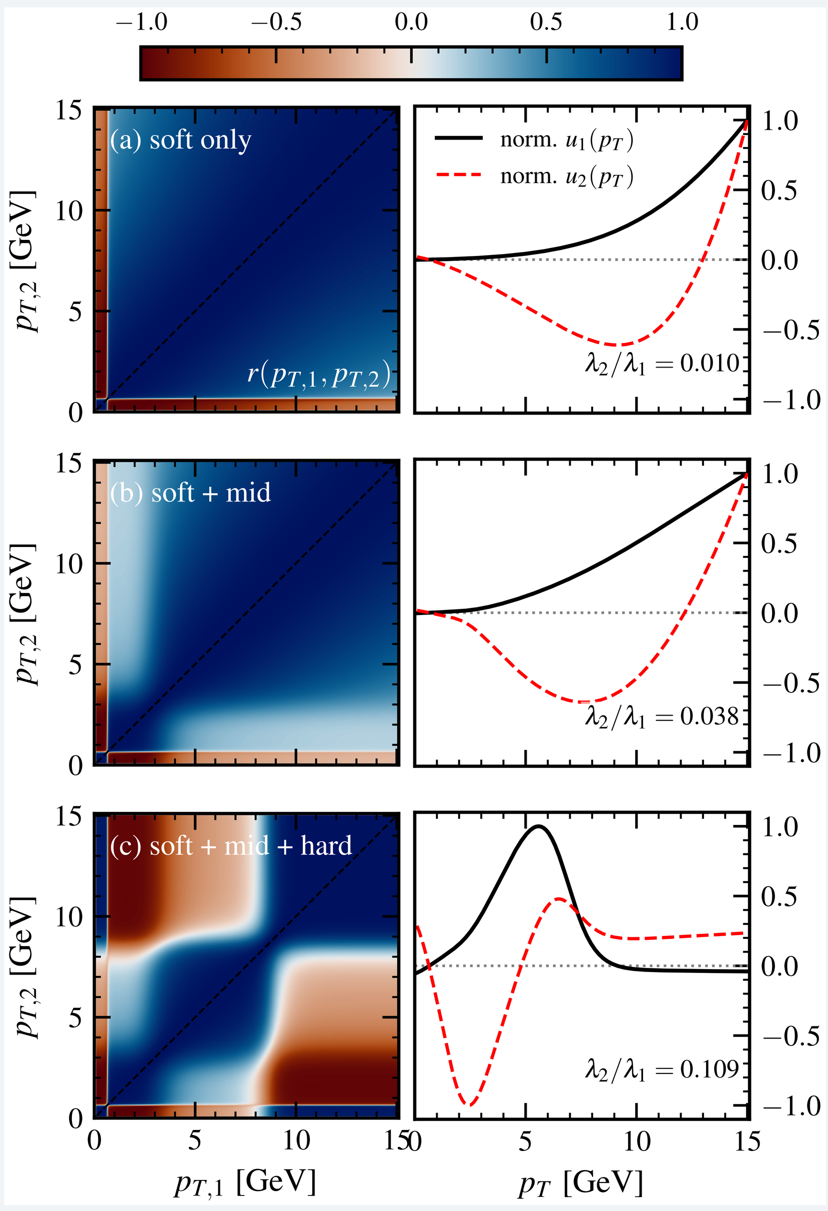
Sequential Activation of Fluctuation Modes



The rise–plateau–downturn structure reflects changing correlation topology across momentum scales:

- **Soft-only**: monotonic rise (single coherent mode).
- **Soft + Mid**: plateau at $p_T \approx 3$ GeV (partial decorrelation + dilution).
- **Soft + Mid + Hard**: downturn at $p_T \gtrsim 6$ GeV (anti-correlation + dilution).

Factorization and Eigenmode Structure



Fluctuation Topology Revealed

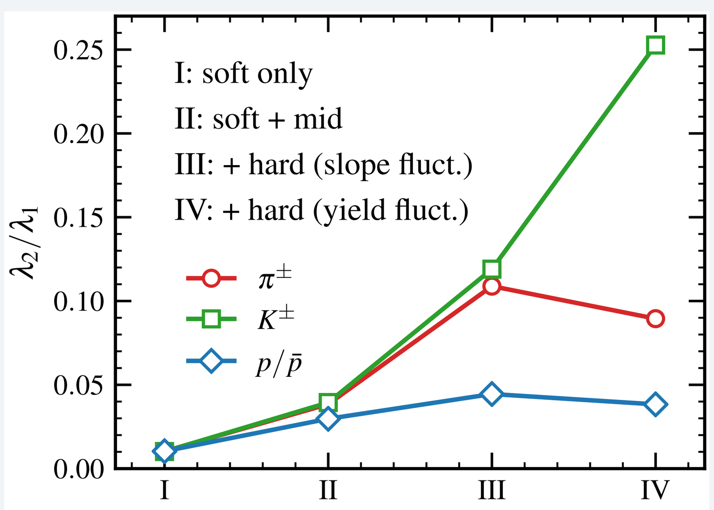
- **Soft-only:** $r \equiv V_0/\sqrt{V_0 V_0} \approx 1$ (normalized covariance), $\lambda_2/\lambda_1 \sim 0.01 \Rightarrow$ effectively single-mode dynamics.
- **Soft + Mid:** Factorization breaking and emergence of a second eigenmode $\Rightarrow$ partial independence of fluctuation sources.
- **Soft + Mid + Hard:** Sign-changing eigenvector and enhanced $\lambda_2/\lambda_1 \Rightarrow$ genuine soft–hard anti-correlation.

Degeneracy Breaking: Distinct dynamical scenarios that produce similar $v_0(p_T)$ shapes are separated by their eigenvalue hierarchy and sign structure.

Eigenvectors identify where decorrelation is anchored in p_T.

Structural information is lost in projected observables like $v_0(p_T)$.

Species-Dependent Dimensionality



Effective Fluctuation Dimensionality λ_2/λ_1

- **Soft-only:** ~ 0.01
- **Soft + Mid:** Increase for all species; baryon-meson splitting
- **Soft + Mid + Hard:** $\lambda_2/\lambda_1(K) > \lambda_2/\lambda_1(\pi) > \lambda_2/\lambda_1(p)$

Kaons are most sensitive due to strong soft–mid–hard mixing in $3 \lesssim p_T \lesssim 5$ GeV.

Conclusion: $v_0(p_T)$ Reinterpretation and Structural Discovery

- $v_0(p_T)$ is reinterpreted as a cross-scale fluctuation probe, beyond a soft-sector flow observable.
- The reference-aligned covariance matrix $V_0(p_{T1}, p_{T2})$ exposes full correlation topology, beyond one-dimensional projections.
- The eigenvalue hierarchy quantifies effective fluctuation dimensionality and identifies momentum-resolved coherence and anti-correlation.
- Fluctuation dimensionality is experimentally measurable via the eigenvalue ratio λ_2/λ_1, while eigenvectors identify where decorrelation is anchored in p_T.

References

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Acknowledgements

This work (arXiv: 2512.10265) was supported in part by the US Department of Energy, Office of Science, Office of Nuclear Physics under grant number DE-AC02-05CH11231.