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From collective flow to hadronization dynamics: Tracing soft–to–hard interplay with the radial-flow fluctuations $v_0(p_T)$

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We present a comprehensive study of the momentum-differential radial-flow fluctuations $v_0(p_T)$, which quantifies event-by-event correlations between the mean transverse momentum and the spectral shape, over the full measured range up to 10 GeV/c. Using a Bayesian-calibrated multistage hydrodynamic framework, we identify a universal scaling of $v_0(p_T)$ at low p_T, revealing a robust collective expansion that remains remarkably insensitive to model variations across RHIC and LHC energies [L. Du, arXiv: 2508.07184]. The study establishes $v_0(p_T)$ at low p_T as a clean probe of the bulk medium's collective response and provides quantitative constraints on QGP transport coefficients and initial-state granularity. Interestingly, the model-data comparison shows a noticeably larger deviation for kaons than for pions or protons, suggesting a possible strangeness-related sensitivity in the underlying dynamics.

Building on this foundation, we extend the analysis into the intermediate- and high-p_T regions, where quark coalescence and partonic energy loss become important, and investigate how $v_0(p_T)$ encodes the evolving correlations among these momentum regimes [L. Du and P. Jacobs, in preparation]. The observed pattern, a linear rise at low p_T, followed by a flattening or mild decrease at higher momenta, reveals a continuous transition of the dominant production mechanisms. We establish $v_0(p_T)$ as a differential probe of the interplay between hydrodynamic flow, quark recombination, and hard fragmentation. Its species dependence, including strange hadrons, provides a novel handle on hadronization dynamics and the coupling between the collective bulk and emerging partonic degrees of freedom. These results position $v_0(p_T)$ as a sensitive and complementary observable for constraining the dynamical evolution and hadronization of QCD matter from the soft thermal regime to the semi-hard transition region.

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