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Eigen-microstate Signatures of Criticality in Relativistic Heavy-Ion Collisions

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We develop the eigen-microstate framework as a new approach to identify criticality in relativistic heavy-ion collisions. We construct the original microstate, defined as the final-state particle fluctuations of a single event. By examining ensembles of such original microstates with and without critical signals, we demonstrate that the corresponding eigen-microstate can extract and reveal the dominant critical mode, with the largest eigenvalue serving as a robust order parameter. This framework avoids equilibrium assumptions and the approach is directly applicable to RHIC Beam Energy Scan data, offering a powerful new tool in the search for the QCD critical point.

We also present a comprehensive model study of the eigen-microstate approach (EMA) for identifying critical fluctuations in relativistic heavy-ion collisions. Using UrQMD and two stochastic baseline models, we demonstrate that EMA is insensitive to conventional short-range correlations and effectively filters out non-critical backgrounds. Critical fluctuations embedded via event-level or particle-level replacement with critical Monte-Carlo (CMC) events generate characteristic cluster-like eigen-microstate patterns and enhanced leading eigenvalues, with event-level criticality producing stronger responses. The eigen microstates exhibit the same pattern across different scales, demonstrating that the fractal nature of critical fluctuations is captured by the eigen microstates. Finite-size scaling of eigenvalue ratios exhibits fixed-point behavior, confirming the largest eigenvalue as an effective order-parameter-like quantity. These results demonstrate that EMA offers a robust and background-independent method for critical-point searches in current and future heavy-ion experiments.

Author: WU, Yuanfang (Central China Normal University)

Presenter: WU, Yuanfang (Central China Normal University)

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