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Microscopic encoding of macroscopic universality: How do the universal behaviors near the QCD transition arise from quarks and gluons?

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The core goal of heavy-ion collision experiments is to shed light on how the phases and properties of strong-interaction matter arise from the fundamental constituents and interactions of Quantum chromodynamics (QCD). To this end, heavy-ion collision experiments are searching for universal signs of criticality in the QCD phase diagram by measuring various macroscopic quantities. When those signatures of criticality are observed the ultimate scientific question will still remain unanswered—how do these universal behaviors at the macroscale arise from the microscopic degrees of freedom, quarks and gluons? In this talk we will answer this question.

Macroscopic properties of the strong interaction near its chiral phase transition exhibit scaling behaviors, which are the same as those observed close to the magnetic transition in a 3-dimensional classical spin system with $O(4)$ symmetry. We show the universal scaling properties of the chiral phase transition in Quantum Chromodynamics (QCD) at the macroscale are, in fact, encoded within the microscopic energy levels of its fundamental constituents, the quarks. We first establish a connection between the cumulants of the chiral order parameter, i.e. the chiral condensate, and the correlations among the energy levels of quarks in the background of gluons, i.e. the eigenspectra of the massless QCD Dirac operator. This relation elucidates how the fluctuations of the chiral condensate arise from the correlations within the infrared part of the energy spectra of quarks, and naturally leads to generalizations of the Banks–Casher relation for the cumulants of the chiral condensate. Then, through (2+1)-flavor lattice QCD calculations with varying light quark masses near the QCD chiral transition, we demonstrate the correlations among the infrared part of the Dirac eigenvalue spectra exhibit same universal scaling behaviors as expected of the cumulants of the chiral condensate. We find that these universal scaling behaviors extend up to the physical values of the up and down quark masses. Our study reveals how the hidden scaling features at the microscale give rise to the macroscopic universal properties of QCD.

Category

Theory

Collaboration (if applicable)

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