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Microscopic Encoding of Macroscopic Universality: Scaling properties of Dirac Eigenspectra near QCD Chiral Phase Transition

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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 QCD. But even if macroscopic critical behaviors are finally established in experiments, how do they arise from the microscopic degrees of freedom, the quarks and gluons, remains to be solved. In this talk we will answer this question.

We 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 [1]. 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 [1]. Our study reveals how the hidden scaling features at the microscale give rise to the macroscopic universal properties of QCD. Furthermore, for higher temperatures away from the critical window we see dilute instanton gas picture goes from breakdown to restoration by investigating the correlation among Dirac eigenvalues at physical point [2], where a non-trivial region appears.

Reference:

[1] H.-T. Ding, W.-P. Huang, S. Mukherjee, and P. Petreczky, Phys. Rev. Lett. 131, 161903 (2023)
[2] H.-T. Ding, W.-P. Huang, Y. Zhang, et al., work in progress.

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