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Hadron Mass and Trace-Anomaly Decompositions from Gradient-Flow-Based Renormalization of the QCD EMT

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We present a lattice-QCD validation of multiple sum rules associated with quark–gluon decomposition of hadron mass by computing all relevant tensor components of the quark and gluon energy–momentum tensor matrix elements from first principles. We achieve this through nonperturbative renormalization of the QCD energy–momentum tensor, including its trace, in a gradient-flow scheme, followed by continuum extrapolations, two-loop matching to the $\overline{\text{MS}}$ scheme, and zero-flow-time extrapolations. These ingredients enable a direct and simultaneous verification, in a common renormalization scheme and scale, of multiple energy-density-based and trace-based mass decomposition sum rules proposed in the literature. We demonstrate the framework for the η_c and J/ψ charmonia using three fine lattice spacings with a physical strange-quark and near-physical up- and down-quark masses. The method is general and can be straightforwardly adopted for lattice-QCD calculations of mass and spin decompositions as well as gravitational form factors of other hadrons and nuclei.

Primary authors: BOLLWEG, Dennis; DING, Heng-Tong; GAO, Xiang (BNL); LUO, Ran; MUKHERJEE, Swagato

Presenter: GAO, Xiang (BNL)

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