

Finite-Volume Gluon Trace-Anomaly Matrix Elements in the (ρ) -Resonant $(\pi\pi)$ Channel

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Understanding how gluonic dynamics manifests itself in unstable hadrons remains an important challenge in studies of hadron mass generation. We investigate the gluon trace anomaly in the isovector (P) -wave $(\pi\pi)$ channel containing the (ρ) resonance using lattice QCD. A variational basis composed of quark-antiquark (ρ) operators and two-pion operators projected onto the appropriate finite-volume irreducible representations is employed. Solving the generalized eigenvalue problem isolates a tower of interacting finite-volume energy eigenstates. For each optimized state, we calculate a vacuum-subtracted gluonic insertion proportional to $(\beta(g)F_{\mu\nu}F_{\mu\nu}/(2g))$ and extract the corresponding diagonal matrix element using the summed-ratio method. Away from the resonance region, the matrix elements approximately follow the behavior expected for weakly interacting two-pion states. Near the (ρ) resonance, however, we observe a pronounced peak in the gluon trace-anomaly contribution, correlated with the resonant behavior of the finite-volume spectrum and the changing (ρ) - and $(\pi\pi)$ -operator overlaps. The enhancement indicates that the gluonic response of the interacting two-pion system is significantly stronger in the resonance region than the approximate sum of the individual-pion contributions. Our results demonstrate that gluonic trace operators provide a sensitive probe of resonance formation and establish a framework for studying the gluonic structure of unstable hadrons through finite-volume matrix elements.

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