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Improved Regge Kinematics and All-Path-Length Corrections to Momentum Broadening in the Quark–Gluon Plasma

We present a detailed study of transverse momentum broadening for high-energy partons traversing the quark–gluon plasma (QGP), extending the Gyulassy–Levai–Vitev (GLV) formalism to include both all-path-length (APL) corrections and improved sub-Regge kinematics. The standard GLV framework relies on the large separation distance and large formation time approximations, which are well justified in large nuclei but may break down in small collision systems, such as high-multiplicity pp and p/dA collisions, where characteristic path lengths and coherence scales become comparable. Working to first order in the opacity expansion, we derive analytic expressions for the transverse momentum broadening distribution and the corresponding momentum transport coefficient, $\hat{q}$, while systematically relaxing these approximations. Relaxing the large separation distance approximation gives rise to the APL correction, while the sub-Regge and combined sub-Regge-APL corrections are obtained using an improved set of Regge kinematics that extends beyond the strict Regge limit. We find that these corrections can significantly modify both the transverse momentum broadening distribution and the corresponding momentum transport coefficient, $\hat{q}$, particularly in small collision systems, providing a more controlled theoretical framework for describing jet–medium interactions beyond the standard GLV approximations and highlighting the importance of finite path-length and sub-Regge effects in precision studies of jet quenching.

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