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Radiative quark $p_\perp$-broadening in a quark-gluon plasma beyond the soft gluon approximation

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Interaction of fast partons with quark-gluon plasma (QGP) leads to jet modification in AA-collisions. It is dominated by radiative parton energy loss [1–4] due to parton multiple scattering in the QGP. The medium modification of jet fragmentation functions due to induced gluon emission leads to a strong suppression of hadron spectra in AA collisions at RHIC and LHC energies. It is characterized by the nuclear modification factor R_{AA}. In the last years the data on R_{AA} from RHIC and LHC have been actively used for tomographic analyses of the QGP produced in AA collisions. The suppression of particle spectra are related to modification of the jet parton distribution in the longitudinal (along the momentum of the initial hard parton) fractional momentum. Multiple parton scattering in the QGP can also modify the transverse jet distribution due to $p_\perp$-broadening of fast partons [5]. It should contribute to dijet and photon-jet angular decorrelation in AA collisions. Similarly to suppression of the hadron spectra, the observation of this effect could potentially give information on the density of the produced QCD matter.

For a single parton traversing a medium $p_\perp$-broadening is usually characterized by the transport coefficient $\hat{q}$ [1, 5]: the mean squared momentum transfer for a gluon passing through a uniform medium of thickness L is $\langle p_\perp^2\rangle = \hat{q}L$ (and for a quark $\langle p_\perp^2\rangle = \hat{q}LC_F/C_A$). The radiative processes can give an additional contribution to $p_\perp$-broadening. The radiative contribution to $\langle p_\perp^2\rangle$ has been addressed in recent papers [6–8]. It has been found that the radiative contribution may be rather large. It mostly comes from the double logarithmic term $\ln^2(L/l_0)$ (where l_0 is about the plasma Debye radius) [7]. The analyses [6–8] have been performed in the approximation of soft gluons. In the present letter we address radiative $p_\perp$-broadening beyond the soft gluon approximation and the logarithmic approximation used in [7]. We show that this reduces drastically the radiative contribution, that can even become negative. The analysis is based on the light-cone path integral (LCPI) [2] approach. The general LCPI formulas for $p_\perp$ distribution in a $a \to bc$ transition have been obtained in [9].

We consider a fast quark with energy E produced at $z = 0$ (we choose the z-axis along the initial momentum of the quark) traversing a uniform medium of thickness L. We account for only single gluon emission. Then, the final states include the quark and the quark-gluon system. We neglect collisional energy loss (which is relatively small [10]), then the energy of the final quark without gluon emission equals E. In this approximation the medium does not change the energy for the one- and two-body states. The presence of the medium modifies the relative fraction of the one-parton state and its transverse momentum distribution, and for the two-parton channel the medium modifies both the longitudinal and transverse momentum distributions. As in [7, 8], we calculate the radiative correction to $p_\perp$-broadening of the final quark that includes both the one- and two-parton channels, i.e., irrespectively to the longitudinal quark energy loss for the qg-state. In this formulation the radiative contribution to $\langle p_\perp^2\rangle$ reads

$$\langle p_\perp^2\rangle_{\rm rad} = \int dx_q d\mathbf{p}\mathbf{p}^2 \left[\frac{dP}{dx_q d\mathbf{p}} + \frac{d\tilde{P}}{dx_q d\mathbf{p}}\right], \quad (1)$$

where $\frac{dP}{dx_q d\mathbf{p}}$ is the distribution for real splitting $q \to qg$ in the transverse momentum of the final quark $\mathbf{p}$ and its fractional longitudinal momentum x_q, $\frac{d\tilde{P}}{dx_q d\mathbf{p}}$ is the distribution for the virtual process $q \to qg \to q$. In the latter case x_q means the quark fractional momentum in the intermediate qg system, but $\mathbf{p}$, as for the real process, corresponds to the final quark. The x_q-integration in (1) can equivalently be written in terms of the gluon fractional momentum $x_g = 1 - x_q$. Diagrammatically the spectrum for $a \to bc$ process in the formalism of [9] is shown in Fig. 1.

To make estimates of $\langle p_\perp^2\rangle_{\rm rad}$ we use the quasiparticle masses $m_q = 300$ and $m_g = 400$ MeV, that have been used in our previous analyses [11, 12] of the RHIC and LHC data on the nuclear modification factor R_{AA}. As in [7], we use constant $\hat{q}$ and α_s. To make our estimates as accurate as possible we adjusted the value of

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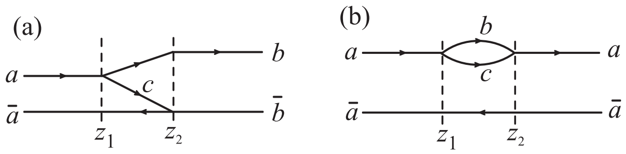

Fig. 1. Diagrammatic representation of $dP/dx_b d\mathbf{p}$ ($a \to bc$ process) (a) and of its virtual counterpart $d\tilde{P}/dx_b d\mathbf{p}$ ($a \to bc \to a$ process) (b). There are more two graphs with interexchange of vertices between the upper and lower lines.

$\hat{q}$ to reproduce the quark energy loss ΔE for running α_s in the model of [12] with the Debye mass from the lattice calculations [13] for the QGP with Bjorken's longitudinal expansion, which corresponds to $\hat{q} \propto 1/\tau$. As in [7], we take $\alpha_s = 1/3$ and $L = 5\,\mathrm{fm}$. We obtained $\hat{q} \approx 0.27\,\mathrm{GeV}^3$ at $E = 30\,\mathrm{GeV}$ for Au + Au collisions at $\sqrt{s} = 0.2\,\mathrm{TeV}$ and $\hat{q} \approx 0.32\,\mathrm{GeV}^3$ at $E = 100\,\mathrm{GeV}$ for Pb + Pb collisions at $\sqrt{s} = 2.76\,\mathrm{TeV}$. The above values of $\hat{q}$ correspond to the radiated gluons with the typical energy $\bar{\omega} \sim 3{-}5\,\mathrm{GeV}$ for a quark with $E \sim 30{-}100\,\mathrm{GeV}$. However, for the initial and final quarks the energy is much larger than $\bar{\omega}$. As a result for them the rescatterings are controlled by the transport coefficient at the quark energy (we denote it $\hat{q}'$). Since $E \gg \bar{\omega}$, the ratio $r = \hat{q}'/\hat{q}$ may differ significantly from unity. Calculations with the Debye mass from [13] and running α_s parametrized as in our previous jet quenching analysis [12] give

$$r \approx 2.4(2.63) \tag{2}$$

at $E = 30(100)$ GeV for quark jets for RHIC(LHC) conditions.

For our RHIC(LHC) versions we obtained

$$\langle p_\perp^2 \rangle_{\mathrm{rad}} / \langle p_\perp^2 \rangle_0 \approx -0.632(-0.692), \quad r = 2.4(2.63), \tag{3}$$

where $\langle p_\perp^2 \rangle_0$ corresponds to nonradiative $p_\perp$-broadening. And if we ignore the difference between $\hat{q}'$ and $\hat{q}$

$$\langle p_\perp^2 \rangle_{\mathrm{rad}} / \langle p_\perp^2 \rangle_0 \approx -0.378(-0.165), \quad r = 1(1). \tag{4}$$

One sees that in all the cases the radiative contribution to the mean squared $p_\perp$ is negative. This differs drastically from the prediction of [7] $\langle p_\perp^2 \rangle_{\mathrm{rad}} \approx 0.75\hat{q}L$. In the form used in (3), (4) it reads $\langle p_\perp^2 \rangle_{\mathrm{rad}} / \langle p_\perp^2 \rangle_0 \approx 0.75\frac{C_A}{rC_F} \approx 1.7/r$. The negative values of (3), (4) are due to a large negative contribution from the two terms related to the difference in the $p_\perp$-broadening of the initial quarks for the real and virtual diagrams in Fig. 1. These terms have not been accounted for in [7]. For this reason it is interesting to compare prediction of [7] with our results without them. In this case we obtained $\langle p_\perp^2 \rangle_{\mathrm{rad}}$ that is smaller than $\langle p_\perp^2 \rangle_{\mathrm{rad}}$ from [7] by a factor of $\sim 3.9(2)$ for the RHIC(LHC) cases. This discrepancy says that the logarithmic approximation used in [7] is rather crude.

Thus, we have found that the radiative contribution to $p_\perp$-broadening may be negative, or at least strongly suppressed as compared to the predictions of [7, 8]. This seems to be supported by the recent STAR measurement of the hadron-jet correlations [14], in which no evidence for large-angle jet scattering in the medium has been found.

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