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Interference effect in elastic parton energy loss in a finite medium

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Abstract

Similar to the radiative parton energy loss due to gluon bremsstrahlung, elastic energy loss of a parton undergoing multiple scattering in a finite medium is demonstrated to be sensitive to interference effect. The interference between amplitudes of elastic scattering via a gluon exchange and that of gluon radiation reduces the effective elastic energy loss in a finite medium and gives rise to a non-trivial length dependence. The reduction is most significant for a propagation length $L < 4/\pi T$ in a medium with a temperature T. Though the finite size effect is not significant for the average parton propagation in the most central heavy-ion collisions, it will affect the centrality dependence of its effect on jet quenching.

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One of the remarkable phenomena observed in central nucleus–nucleus collisions at the Relativistic Heavy-Ion Collider (RHIC) is jet quenching as manifested in the suppression of high transverse momentum hadron spectra [1–3], azimuthal angle anisotropy [4] and suppression of the away-side two-hadron correlations [5]. The observed patterns of jet quenching, their centrality, momentum and colliding energy dependence in light hadron spectra and correlations are consistent with the picture of parton energy loss [6]. However, recent experimental data on measurements of single non-photonic electron spectra [7] seem to indicate a suppression of heavy quarks that is not consistent with the theoretical predictions based on current implementation of heavy quark energy loss [8–10]. This has led to a renewed interest in the elastic (or collisional) energy loss and its effects in the observed jet quenching phenomena [11–13].

Elastic energy loss by a fast propagating parton in general is caused by its elastic scattering with thermal partons in the medium through one-gluon exchange. The gluon exchange can be considered as the emission and subsequent absorption of gluons by two scattering partons and therefore should also be subject to formation time of the virtual gluon due to interference. In a finite medium when the propagation length is comparable to the formation time, the interference should reduce the effective elastic energy loss as compared to an infinite medium. Since the typical energy exchange with a thermal parton is $\omega \sim T$, the average formation time is therefore controlled by the temperature of the medium. In a recent study by Peigne et al. [14], however, collisional energy loss was found to be suppressed significantly for considerably large medium size. This might be partially due to the complication of subtraction of induced radiation associated with the acceleration of color charges within a finite period of time in the semi-classical approach.

In recent comparative studies of energy losses [11–13], elastic and radiative processes are studied in different frameworks where the controlling parameters such as jet transport parameter or averaged transverse momentum broadening are calculated differently. For a consistent comparison, one needs to study the elastic and inelastic processes within the same framework.

For partons produced via a hard process that go through further multiple scattering, elastic scattering via one-gluon exchange often bears many similarities to the radiative (or gluon bremsstrahlung) processes. In this Letter, we will consider the elastic scattering within the same framework of multiple parton scattering that was employed to study the radiative energy loss [15,16]. We will show that it is the same interference between

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the amplitudes of elastic scattering and induced radiation that leads to the reduction of the elastic energy loss. Such a reduction gives rise to a non-trivial medium size dependence of the elastic energy loss.

For the purpose of illustration and derivation, we start with the double quark scattering processes in deeply inelastic scattering (DIS) off a nucleus and their effects on the nuclear modification of the effective quark fragmentation functions. The differential cross section of semi-inclusive processes $e(L_1) + A(p) \longrightarrow e(L_2) + h(\ell_h) + X$ in DIS can be expressed in general as

$$E_{L_2} E_{\ell_h} \frac{d\sigma_{\mathrm{DIS}}^h}{d^3 L_2\, d^3\ell_h} = \frac{\alpha_{\mathrm{EM}}^2}{2\pi s} \frac{1}{Q^4} L_{\mu\nu} E_{\ell_h} \frac{dW^{\mu\nu}}{d^3\ell_h}, \tag{1}$$

in terms of the semi-inclusive hadronic tensor,

$$E_{\ell_h} \frac{dW^{\mu\nu}}{d^3\ell_h} = \frac{1}{2} \sum_X \langle A|J^\mu(0)|X,h\rangle\langle X,h|J^\nu(0)|A\rangle \times 2\pi\delta^4(q+p-p_X-\ell_h), \tag{2}$$

and the leptonic tensor, $L_{\mu\nu} = \frac{1}{2}\mathrm{Tr}(\gamma\cdot L_1\gamma_\mu\gamma\cdot L_2\gamma_\nu)$, where $q = [-Q^2/2q^-, q^-, \vec{0}_\perp]$ is the four-momentum of the virtual photon, $p = [p^+, 0, \vec{0}_\perp]$ is the momentum of the target per nucleon, $s = (p+L_1)^2$ is the total invariant mass of the lepton–nucleon system, J_μ is the hadronic electromagnetic (EM) current, $J_\mu = e_q \bar\psi_q \gamma_\mu \psi_q$, and $\sum_X$ runs over all possible intermediate states.

The leading-twist contribution to the semi-inclusive hadronic tensor to the lowest order in the strong coupling constant comes from a single virtual photon and quark scattering,

$$\frac{dW_{\mu\nu}^{S(0)}}{dz_h} = \sum_q f_q^A(x) H_{\mu\nu}^{(0)}(x,p,q) D_{q\to h}(z_h), \tag{3}$$

where $f_q^A(x)$ is the quark distribution in the nucleus, $x = Q^2/2p^+q^-$ the Bjoken variable, $D_{q\to h}(z_h)$ the quark fragmentation function and

$$H_{\mu\nu}^{(0)}(x,p,q) = e_q^2 \frac{\pi}{2p^+q^-} \mathrm{Tr}\big(\gamma\cdot p\gamma_\mu\gamma\cdot(q+xp)\gamma_\nu\big) \tag{4}$$

the hard part of $\gamma^* + q$ partonic scattering.

For the simplest case, let us consider multiple scattering between two quarks with different flavors in DIS off a large nucleus as illustrated in Fig. 1 (with the central cut). In this process, a quark (q) knocked out by the virtual photon undergoes a secondary scattering with another quark q' from the nucleus. It contributes to the semi-inclusive DIS at twist four

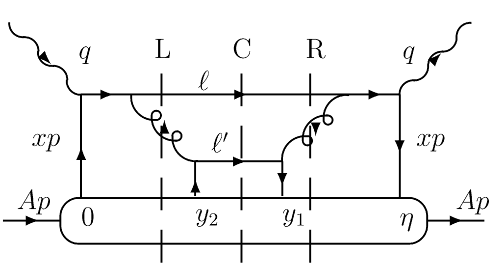

Fig. 1. Cut diagrams for double quark–quark scattering in DIS off a nucleus.

similarly as multiple scattering with gluons in the discussion of induced gluon radiation. We assume the flavors of the two quarks to be different so that there is no contribution from crossing diagrams. The contribution from the central-cut diagram in Fig. 1 to the semi-inclusive tensor is, as given in Ref. [15],

$$\begin{aligned} \frac{dW_{\mu\nu}^{D(C)}}{dz_h} = {}& \frac{\alpha_s C_F}{2\pi} \int \frac{d\ell_T^2}{\ell_T^2} \int_{z_h}^1 \frac{dz}{z} \bigg[D_{q\to h}(z_h/z) \frac{1+z^2}{(1-z)^2} \\ & + D_{q'\to h}(z_h/z) \frac{1+(1-z)^2}{z^2} \bigg] \\ & \times \frac{x}{Q^2} \frac{2\pi\alpha_s}{N_C} T_{qq'}^{A(C)}(x,x_L) H_{\mu\nu}^{(0)}(x,p,q), \end{aligned} \tag{5}$$

where

$$\begin{aligned} & T_{qq'}^{A(C)}(x,x_L) \\ & = p^+ \int \frac{d\eta^-}{2\pi} dy_1^- dy_2^- e^{i(x+x_L)p^+\eta^-} \big(1 - e^{-ix_L p^+ y_2^-}\big) \\ & \quad \times \big(1 - e^{-ix_L p^+(\eta^- - y_1^-)}\big) \\ & \quad \times \langle A|\bar\psi_q(0) \frac{\gamma^+}{2} \psi_q(\eta^-) \bar\psi_{q'}(y_1^-) \frac{\gamma^+}{2} \psi_{q'}(y_2^-)|A\rangle \\ & \quad \times \theta(-y_2^-)\theta(\eta^- - y_1^-) \end{aligned} \tag{6}$$

is the two-quark correlation function in the nucleus. The four terms with different phase factors in the above matrix element correspond to hard–soft, double hard quark scattering and their interferences, similarly to the Landau–Pomeranchuck–Migdal (LPM) interference in the processes of induced gluon radiation [15].

In the hard–soft quark scattering, the first or leading quark that was knocked out of the nucleus by the hard virtual photon becomes off-shell. It then radiates a real gluon which interacts with another soft quark that carries zero fractional momentum (+ component) in the collinear limit (neglecting the initial transverse momentum of the quark) and converts it into the final quark with momentum ℓ'. In this case, the final total longitudinal fractional momentum of the two quarks $x_L = (\ell^+ + \ell'^+)/p^+ = \ell_T^2/2p^+q^- z(1-z)$ comes from the initial leading quark before its interaction with the virtual photon. This kinematics corresponds to the induced emission of a secondary quark like the case of induced gluon radiation. Note that quarks from the matrix elements normally are off-shell and carry transverse momentum. The kinematics in the hard-soft quark scattering process will then allow both finite fractional longitudinal and transverse momentum when the secondary quark is off-shell. It is only in the collinear approximation, i.e. neglecting the initial transverse momentum, that the quark lines from the nucleus can be considered on-shell. The kinematics in the hard–soft processes then requires the secondary quark to carry zero fractional longitudinal momentum.

In the process of double hard quark scattering, the leading quark becomes on-shell after its interaction with the virtual photon. It then scatters with another quark that carries finite momentum fraction x_L. Therefore, the final total longitudinal fractional momentum of the two quarks x_L is transferred from