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Nuclear Physics A 1005 (2021) 122003

NUCLEAR PHYSICS A

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XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2019)

Parton Energy Loss in the Generalized High-Twist Approach

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Abstract

We calculate the radiative parton energy loss in the deeply inelastic scattering (DIS) off a large nucleus within a generalized high-twist approach. The final gluon radiation spectrum is a convolution of the hard partonic part and the transverse momentum dependent (TMD) quark-gluon correlation function, without the twist expansion in the transverse momentum of the initial gluons used in original high twist approach. The TMD quark-gluon correlation function can be factorized approximately as the product of initial quark distribution and TMD gluon distribution which can be used to define the generalized or TMD jet transport coefficient. The radiation spectrum will recover the Gylassy-Levai-Vitev (GLV) result in the first order of the opacity expansion, under the static scattering center and soft gluon radiation approximation. We also investigate numerically the difference as a result of the soft gluon radiation approximation, under the static scattering center approximation.

Keywords: QCD, DIS, Cold Nuclear Matter Effect, Radiative Energy Loss

1. Introduction

In high-energy heavy-ion collisions, the energetic parton undergoes multiple scattering and losses energy along its path in the hot quark gluon plasma (QGP). This phenomenon is known as jet quenching. Similar processes of multiple parton scattering and parton energy loss also occur in deeply inelastic scattering (DIS) off a large nucleus. There are elastic and radiative energy loss for the energetic parton tranversing the medium. We focus on the radiative energy loss.

There are several approaches based on perturbative QCD (pQCD) to calculate the radiative energy loss : BDMPS-Z (Baier-Dokshitzer-Mueller-Peigne-Schiff and Zakharov), GLV (Gyulassy-Levai-Vitev) and Wiedemann, AMY (Arnold, Moore and Yaffe), and High-Twist approach [1]. The detailed comparison between these pQCD models can be found in Ref. [2].

In our study, we calculate the radiative gluon spectrum without twist expansion as in high-twist approach [1] .

https://doi.org/10.1016/j.nuclphysa.2020.122003

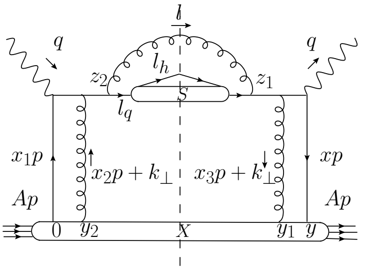

Fig. 1. One central-cut digram of medium induced gluon radiation.

2. Medium induced Radiation

For semi-inclusive DIS process $e(l_1) + A(p) \rightarrow e(l_2) + h(l_h) + \mathcal{Z}$, the cross section can be written as a product of leptonic tensor and hadronic tensor. The hadronic tensor with final state vacuum radiation is

$$\frac{dW^{\mu\nu}}{dz_h} = \int dx f_q^A(x) H_{(0)}^{\mu\nu}(x) \frac{\alpha_s}{2\pi} C_F \int_{z_h}^{1} \frac{dz}{z} \int_0^{\mu^2} \frac{dl_\perp^2}{l_\perp^2} \frac{1+z^2}{1-z} D_{q\rightarrow h}(z_h/z). \tag{1}$$

The vacuum radiation is induced by the hard photon-quark scattering and the final state parton does not scatter with the medium. For processes with medium-induded radiation, there are 9 central cut diagrams, 7 left cut diagrams, and 7 right cut diagrams. The hadronic tensor can be generically factorized as

$$\frac{dW^{\mu\nu}}{dz_h} = \frac{\alpha_s}{2\pi} \frac{2\pi\alpha_s}{N_c} \otimes \mathcal{F}_c\left(\vec{l}_\perp, \vec{k}_\perp\right) \otimes P_{qg}(z) \otimes H_{(0)}^{\mu\nu}(x) \otimes \frac{D_{q\rightarrow h}(z_h/z)}{z} \otimes T_{qg}^A(x, x_1, x_2). \tag{2}$$

For one of the central cut diagrams in Fig. 1 as an example, we have

$$\mathcal{F}_c = \frac{C_F}{[\vec{l}_\perp - (1-z)\vec{k}_\perp]^2} \qquad T_{qg}^A(x, x_1, x_2) = T_{qg}^A(x, x_L + x_D, x_L + x_D) \tag{3}$$

For different diagrams, we have different combination of $\mathcal{F}_c$ and $T_{qg}^A(x, x_1, x_2)$.

3. Quark-gluon correlation funtion and TMD $\hat{q}(\vec{k}_\perp)$

The generic quark-gluon correlation function is

$$\begin{aligned} T_{qg}^A(x, x_1, x_2) = &\int \frac{dy^-}{2\pi} dy_1^- dy_2^- \int d^2\vec{y}_{12\perp} e^{-ixp^+y^-} e^{-ix_2p^+(y_1^- - y_2^-)} e^{i(x-x_1)p^+y_1^-} e^{i\vec{k}_\perp\cdot\vec{y}_{12\perp}} \\ &\times \langle A|\bar{\psi}(y^-)\frac{\gamma^+}{2} A^+(y_1^-, \vec{y}_{1\perp}) A^+(y_2^-, \vec{y}_{2\perp}) \psi(0)|A\rangle \theta(f_1)\theta(f_2). \end{aligned} \tag{4}$$

For the central, left and right cut diagrams, the $\theta(f_1)\theta(f_2)$ function are different. These θ functions contrain the integration regions of y_1^-, y_2^-. If the integration region is $0 < y_1^- < y_2^- < y^-$, these are just contact terms in which the intial quark and initial gluon come from the same nucleon. For other terms whose y_1^- and y_2^- can run over the whole nuclei, the initial quark and gluon can come from different nucleons, these terms have nuclear enhancement.

If we neglect the correlation between nucleons inside the nuclei, we can approximately factorize the correlation function as

$$T_{qg}^A(x, x_1, x_2) = C f_q^A(x) \int dy_1^- \rho\left(y_1^-, \vec{y}_\perp\right) e^{i(x-x_1)p^+y_1^-} \frac{\phi(x_2, \vec{k}_\perp)}{k_\perp^2} \tag{5}$$

The $f_q^A(x)$ is the nuclear quark distribution function, and the $\phi(x_2, \vec{k}_\perp)$ is the TMD gluon distribution function, which relates to TMD jet transport parameter $\hat{q}(\vec{k}_\perp)$ [3].

The jet transport parameter is defined as the averaged transverse momentum broadening squared per unit length $\hat{q}_R \equiv \langle \rho \int dk_\perp^2 \frac{d^2\sigma_R}{dk_\perp^2} k_\perp^2 \rangle$. If one considers the process of one jet parton scattering with a nucleon, using its cross section $d\sigma_R$ in $\hat{q}_R$, we get

$$\hat{q}_R \equiv \int \frac{d^2k_\perp}{(2\pi)^2} \hat{q}_R(\vec{k}_\perp), \quad \hat{q}_R(\vec{k}_\perp) \equiv \int dx \delta(x - \frac{k_\perp^2}{2p^+l^-}) \frac{4\pi^2\alpha_s C_2(R)}{N_c^2 - 1} \rho(y)\phi(x, \vec{k}_\perp). \tag{6}$$

The TMD gluon distribution $\phi(x, \vec{k}_\perp)$ emerges in the TMD jet transport coefficient $\hat{q}_R(\vec{k}_\perp)$,

$$\phi(x, \vec{k}_\perp) = \int \frac{dy_{12}^-}{2\pi p^+} \int d^2\vec{y}_{12\perp} e^{-ixp^+y_{12}^- + i\vec{k}_\perp \cdot \vec{y}_{12\perp}} \langle p| F_\alpha{}^+(y_{12}^-, \vec{y}_{12\perp}) F^{+\alpha}(0, \vec{0}_\perp)|p\rangle. \tag{7}$$

4. Soft and static approximation

After getting the hadronic tensor in terms of TMD gluon distribution function, we can get the radiative gluon spectrum $\frac{dN_g}{dl_\perp^2 dz}$ from the hadronic tensor $\frac{dW^{\mu\nu}}{dz_h}$ as

$$\frac{dW^{\mu\nu}}{dz_h} = \int dx f_q^A(x) H_{(0)}^{\mu\nu}(x) \int \frac{dz}{z} D_{q\to h}(z_h/z) \int dl_\perp^2 \frac{dN_g}{dl_\perp^2 dz} \tag{8}$$

The gluon spectrum can be simplified under different approximations.

1) Static scattering approximation: the energy transfer in the scattering between jet and medium parton is negligible as compared to the hard scattering energy scale. In this case, $x_B \gg x_L, \frac{x_D}{1-z}$,

$$\phi(x_L + x_D, \vec{k}_\perp) \approx \phi(\frac{z}{1-z} x_D, \vec{k}_\perp) \approx \phi(x_D^0, \vec{k}_\perp) \approx \phi(0, \vec{k}_\perp), \quad f_q^A(x_B + x_L + \frac{x_D}{1-z}) \approx f(x_B + x_L) \approx f_q^A(x_B). \tag{9}$$

The gluon spectrum is simplified as

$$\begin{aligned}\frac{dN_g^{\text{static}}}{dl_\perp^2 dz} =& \pi \frac{\alpha_s}{2\pi} \frac{1 + (1-z)^2}{z} \frac{2\pi\alpha_s}{N_c} \int \frac{d^2k_\perp}{(2\pi)^2} \int dy_1^- \rho(y_1^-, \vec{y}_{1\perp}) \Bigg\{ C_F \left[\frac{1}{(\vec{l}_\perp - z\vec{k}_\perp)^2} - \frac{1}{l_\perp^2} \right] \\ &+ C_A \left[\frac{2}{(\vec{l}_\perp - \vec{k}_\perp)^2} - \frac{\vec{l}_\perp \cdot (\vec{l}_\perp - \vec{k}_\perp)}{l_\perp^2 (\vec{l}_\perp - \vec{k}_\perp)^2} - \frac{(\vec{l}_\perp - \vec{k}_\perp) \cdot (\vec{l}_\perp - z\vec{k}_\perp)}{(l_\perp - k_\perp)^2 (\vec{l}_\perp - z\vec{k}_\perp)^2} \right] \times (1 - \cos[(x_L + \frac{x_D}{1-z}) p^+ y_1^-]) \\ &+ \frac{1}{N_c} \left[\frac{\vec{l}_\perp \cdot (\vec{l}_\perp - z\vec{k}_\perp)}{l_\perp^2 (\vec{l}_\perp - z\vec{k}_\perp)^2} - \frac{1}{l_\perp^2} \right] \times (1 - \cos[x_L p^+ y_1^-]) \Bigg\} \frac{\phi(0, \vec{k}_\perp)}{k_\perp^2}. \end{aligned} \tag{10}$$

There are three kinds of divergences: $\vec{l}_\perp = 0$, $\vec{l}_\perp - \vec{k}_\perp = 0$ and $\vec{l}_\perp - z\vec{k}_\perp = 0$, all of them belong to collinear divergences and can be regularized by renormalized quark-gluon correlation, LPM effect and renormalized quark fragmentation function respectively.

2) Static scattering center and soft radiative gluon approximation: In this limit, one requires $x_B \gg x_L, \frac{x_D}{1-z}$ when $z \to 0$, $z = l^-/q^-$ is the momentum fraction of the radiated gluon. The gluon spectrum is

$$\frac{dN_g^{\text{static+soft}}}{dl_\perp^2 dz} = \pi \frac{\alpha_s}{2\pi} P_{qg}(z) \frac{2\pi\alpha_s}{N_c} \int \frac{d^2k_\perp}{(2\pi)^2} \int dy_1^- \rho_A(y_1^-, \vec{y}_\perp) C_A \frac{2\vec{k}_\perp \cdot \vec{l}_\perp}{l_\perp^2 (\vec{l}_\perp - \vec{k}_\perp)^2} \left(1 - \cos[(x_L + \frac{x_D}{1-z}) p^+ y_1^-]\right) \frac{\phi(0, \vec{k}_\perp)}{k_\perp^2}. \tag{11}$$

For $\phi(0, \vec{k}_\perp)$, we consider pQCD cross section for elastic scattering between jet and medium parton in the jet transport coefficient $\hat{q}$. In Eq. (6), we get the expression $\phi(0, \vec{k}_\perp)/k_\perp^2 = 4\alpha_s C_2(T)/(k_\perp^2 + \mu_D^2)^2$.

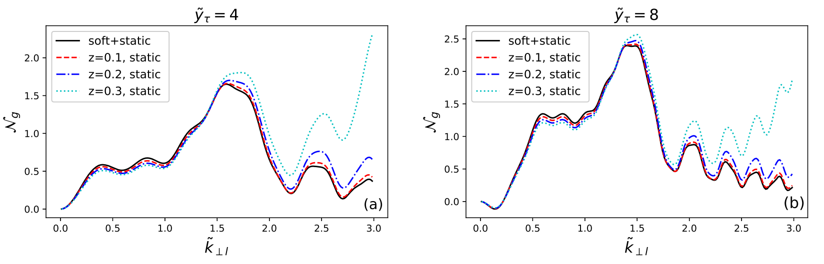

Fig. 2. The scaled gluon spectrum $\mathcal{N}_g^{\rm static}$ and $\mathcal{N}_g^{\rm static+soft}$

Substitute it into the gluon spectrum, the gluon spectrum recovers that of GLV [4] in the first order opacity approximation.

To compare gluon spectra under different approximations numerically, we define a dimensionless scaled spectrum $\mathcal{N}_g$

$$\frac{dN_g}{dl_\perp^2 dz} = \int_{y^-}^{\infty} dy_1^- \rho_A(y_1^-, \vec{y}_\perp) \frac{2\pi\alpha_s}{N_c} \pi \int \frac{dk_\perp^2}{(2\pi)^2} \frac{\phi(0, \vec{k}_\perp)}{k_\perp^2} \pi \frac{\alpha_s}{2\pi} P_{qg}(z) \frac{C_A}{l_\perp^2} \mathcal{N}_g(z, k_\perp, l_\perp, y_1^-), \tag{12}$$

where $\mathcal{N}_g$ is a function of z, $\tilde{k}_{\perp l} \equiv k_\perp / l_\perp$ and $\tilde{y}_\tau \equiv y_1^- l_\perp^2 / [2q^- z(1-z)] \equiv y_1^- / \tau_f$ (τ_f is the formation time of the radiated gluon). We plot $\mathcal{N}_g^{\rm static}$ and $\mathcal{N}_g^{\rm static+soft}$ with $\tilde{y}_\tau = 4, 8$ for different $z = 0.1, 0.2, 0.3$. One can see the difference between $\mathcal{N}_g^{\rm static}$ and $\mathcal{N}_g^{\rm static+soft}$ increase when z increase from $z = 0.1$ to $z = 0.3$.

Such a approach of jet energy and medium energy scale dependent $\hat{q}$ has also been tried in [5], in the limit of collinear factorization.

5. Summary

We compute the radiated gluon spectrum in DIS off a large nucleus, expressed in terms of TMD gluon distribution function, which is also related to the TMD jet tranport coefficient. We also discuss gluon spectra under different approximations.

6. Acknowledgement

This work is supported in part by NSFC under Grants Nos. 11935007, 11221504, 11775095, 11890711 and 11890714, by DOE under Contract No. DE-AC02-05CH11231, and by NSF under Grant No. ACI-1550228 within the JETSCAPE Collaboration.

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