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Probe Initial Parton Density and Formation Time via Jet Quenching

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Medium modification of jet fragmentation function due to multiple scattering and induced gluon radiation leads directly to jet quenching or suppression of leading particle distribution from jet fragmentation. One can extract an effective total parton energy loss which can be related to the total transverse momentum broadening. For an expanding medium, both are shown to be sensitive to the initial parton density and formation time. Therefore, one can extract the initial parton density and formation time from simultaneous measurements of parton energy loss and transverse momentum broadening. Implication of the recent experimental data on effects of detailed balance in parton energy loss is also discussed.

1. Introduction

In high-energy heavy-ion collisions, one of the pressing issues is the direct determination of the initial parton density of the dense medium and its formation time. Jet quenching or attenuation of leading particles from jet fragmentation can provide an effective tool to measure directly the parton density of the medium with which the jet interacts strongly during its propagation. Recent theoretical studies [1–5] have shown that parton energy loss via induced radiation is directly related to the gluon density of the medium. The attenuation will suppress the final leading hadron distribution giving rise to modified parton fragmentation functions [6]. By measuring the medium modification of the fragmentation function one can thus extract the effective parton energy loss. Most importantly, one can compare the effective parton energy loss extracted from heavy-ion collisions to that of cold nuclei and extract the initial parton density of the hot dense medium relative to a cold nucleus.

2. Parton Energy Loss in Cold Nuclei

In deeply inelastic scattering (DIS) off a nuclear target, a quark suffers multiple scattering with other nucleons inside the nucleus after it was knocked out of its parent nucleon. The induced gluon bremsstrahlung before hadronization leads to suppression of leading hadrons and gives rise to a modified quark fragmentation function. Including the leading twist-4 contributions from double scattering processes, the nuclear medium induced correction to the fragmentation function is found to be similar to the radiative correction in
the vacuum except that the normal splitting functions are replaced by the modified ones. These modified splitting functions are found [7] to depend on the quark-gluon correlation function $T_{qq}^{A}(x,x_L)/q_{A}(x)$. Here

$$T_{qq}^{A}(x,x_L) = \int \frac{dy_{1}^{-}}{2\pi} dy_{1}^{-} dy_{2}^{-} e^{i(x+x_L)p^{+}y_{1}^{-} + i\tau y_{1}^{-}} \left( 1 - e^{-i\tau p^{+} y_{1}^{-}} \right) \left( 1 - e^{-i\tau p^{+} y_{2}^{-}} \right)$$

$$\frac{1}{2} \left< A | \bar{\psi}_{q}(0) \gamma^{+} F_{\sigma}^{\tau\tau}(y_{1}^{-}) F_{\sigma}^{\tau\tau}(y_{1}^{-}) \psi_{q}(y_{1}^{-}) | A \right> \theta(-y_{2}^{-}) \theta(y_{1}^{-} - y_{2}^{-})$$

(1)

and $q_{A}(x)$ is the twist-two quark distribution of the nucleus. Such a two-parton correlation function contains essentially four independent twist-4 parton matrix elements in a nucleus $[x_{T} = \langle k_{T}^{2} \rangle / 2 p^{+} q^{-} z(1-z)]$. The dipole-like form-factor $(1 - e^{-i\tau p^{+} y_{1}^{-}})(1 - e^{-i\tau p^{+} y_{2}^{-}})$ arises from the interference between the final state radiation of the $\gamma^{*}q$ scattering and the gluon bremsstrahlung induced by the secondary quark-gluon scattering. By generalizing the factorization assumption to these twist-four parton matrices, we have

$$T_{qq}^{A}(x,x_L)/q_{A}(x) \approx \tilde{C}(Q^{2}) m_{N} R_{A}(1 - e^{-x_{L}^{2}/x_{A}^{2}}),$$

(2)

with a Gaussian nuclear distribution $\rho(r) \sim \exp(-r^{2}/2R_{A}^{2})$, $R_{A} = 1.12A^{1/3}$ fm. Here, $x_{A} = 1/m_{N} R_{A}$, and $m_{N}$ is the nucleon mass.

Since the two interference terms in the dipole-like form-factor involve transferring momentum $x_{L}p^{+}$ between different nucleons inside a nucleus, they should be suppressed for large nuclear size or large momentum fraction $x_{L}$. Notice that $\tau_{f} = 1/x_{L}p^{+}$ is the gluon's formation time. Thus, $x_{L}/x_{A} = L_{A}/\tau_{f}$, with $L_{A} = R_{A} m_{N}/p^{+}$ being the nuclear size in the infinite momentum frame. The effective parton correlation and the induced gluon emission vanishes when the formation time is much larger than the nuclear size, $x_{L}/x_{A} \ll 1$, because of the Landau-Pomeranchuk-Migdal (LPM) interference effect. Therefore, the LPM interference restricts the radiated gluon to have a minimum transverse momentum $p_{T}^{\min} \sim Q^{2}/m_{N} R_{A} \sim Q^{2}/A^{1/3}$. The nuclear corrections to the fragmentation function due to double parton scattering will then be in the order of $\alpha_{s} A^{1/3}/p_{T}^{\min} \sim \alpha_{s} A^{2/3}/Q^{2}$, which depends quadratically on the nuclear size. For large values of $A$ and $Q^{2}$, these corrections are leading; yet the requirement $p_{T}^{\min} \ll Q^{2}$ for the logarithmic approximation When deriving the modified fragmentation function is still valid.

Shown in Fig. 1 are the calculated nuclear modification factor of the fragmentation functions for $^{14}N$ and $^{84}Kr$ targets as compared to the recent HERMES data [8]. The predicted shape of the $z$- and energy dependence agrees well with the experimental data. A remarkable feature of the prediction is the quadratic $A^{2/3}$ nuclear size dependence, which is verified for the first time by an experiment. The only parameter in our calculation is found to be $\tilde{C}(Q^{2}) = 0.0060$ GeV$^{2}$ with $\alpha_{s}(Q^{2}) = 0.33$ at $Q^{2} \approx 3$ GeV$^{2}$.

If one defines theoretically the quark energy loss as that carried by the radiated gluons, then the averaged total energy loss is,

$$\Delta E = \nu \langle \Delta z \rangle \approx \tilde{C} \alpha_{s}^{2}(Q^{2}) m_{N} R_{A}^{2}(C_{A}/N_{c}) 3 \ln(1/2x_{B}).$$

(3)

With the determined value of $\tilde{C}$, $\langle x_{B} \rangle \approx 0.124$ in the HERMES experiment [8] and the average distance $\langle L_{A} \rangle = R_{A}\sqrt{2/\pi}$ for the assumed Gaussian nuclear distribution, one gets the quark energy loss $dE/dL \approx 0.5$ GeV/fm inside a Au nucleus.
Figure 1. Predicted nuclear modification of jet fragmentation function is compared to the HERMES data [8] on ratios of hadron distributions between $A$ and $D$ targets in DIS.

Figure 2. Calculated nuclear modification factor compared to PHENIX data [10]. The lower dashed line used the energy loss as given in Eq. (9).

One can also calculate the transverse momentum broadening of the quark jet which is also related to a similar twist-four parton matrix elements.

$$\langle \Delta q^2 \rangle = \frac{2\pi \alpha_0}{N_c} \frac{T_{qq}(x_B)}{q_A(x_B)} \approx \frac{C_\pi \alpha_0}{N_c} m_N R_A \approx 0.011 A^{1/3} \text{GeV}^2$$

(4)

3. Initial Parton Density in $Au + Au$ at RHIC

To extend our study to jets in heavy-ion collisions, we assume $\langle k_T^2 \rangle \approx \mu^2$ (the Debye screening mass) and a gluon density profile $\rho(y) = (\tau_0/\tau_0)\theta(R_A - y)\rho_0$ for a 1-dimensional expanding system. Since the initial jet production rate is independent of the final gluon density which can be related to the parton-gluon scattering cross section [2] $\alpha_s x_T G(x_T) \sim \mu^2 \sigma_g$, one has then

$$\frac{\alpha_s T_{qq}(x_B,x_L)}{f_{q_A}(x_B)} \sim \mu^2 \int dy \sigma_g(y)[1 - \cos(y/\tau_f)],$$

(5)

where $\tau_f = 2E \tau(1 - z)/\mu_T^2$ is the gluon formation time. One can recover the form of energy loss in a thin plasma obtained in the opacity expansion approach [4],

$$\langle \frac{dE}{dL} \rangle \approx \frac{\pi C_A \alpha_s^3}{R_A} \int_{m}^{R_A} d\tau \rho(\tau)(\tau - \tau_0) \ln \frac{2E}{\tau \mu^2},$$

(6)

where we have assumed $\sigma_g \approx C_A 2\pi \alpha_s^2/\mu^2$ ($C_A = 1$ for $gg$ and $9/4$ for $gq$ scattering).

Neglecting the logarithmic dependence on $\tau$, the averaged energy loss in a 1-dimensional expanding system can be expressed as [9]

$$\langle \frac{dE}{dL} \rangle_{\text{av}} \approx \frac{dE_0}{dL} \frac{2\tau_0}{R_A}, \quad \frac{dE_0}{dL} \approx \frac{\pi C_A \alpha_s^3}{2} \rho_0 R_A \ln \frac{2E}{\tau_0 \mu^2}$$

(7)
where \(dE_0/dL\) is the energy loss in a static medium with the same gluon density \(\rho_0\) as in a 1-d expanding system at an initial time \(\tau_0\). Because of the expansion, the averaged energy loss \(\langle dE/dL \rangle_{id}\) is suppressed as compared to the static case and does not depend linearly on the system size. Similarly, one has the total transverse momentum broadening in an expanding system,

\[
\langle \Delta q^2 \rangle = 2\pi C_A a_s^2 \int_{\tau_0}^{\infty} d\tau \rho(\tau) = \langle \Delta q^2 \rangle_0 \frac{\tau_0}{R_A} \ln \frac{R_A}{\tau_0}; \quad \langle \Delta q^2 \rangle_0 = 2\pi C_A a_s^2 \rho_0
\]  

(8)

Fitting the PHENIX data [10] on suppression of large \(p_T\) \(\pi_0\) spectra in Fig. 2 yields \(\langle dE/dL \rangle_{id} \approx 0.34 \ln E/\ln 5\) GeV/fm. Taking into account the expansion, this would be equivalent to \((dE/dL)_0 = 0.34(R_A/2\tau_0) \ln E/\ln 5\) in a static system with the same gluon density as the initial value of the expanding system at \(\tau_0\). With \(R_A \sim 6\) fm and assuming \(\tau_0 \sim 0.2\) fm, this would give \((dE/dL)_0 \approx 7.3\) GeV/fm for a 10-GeV parton. Since the parton energy loss is directly proportional to gluon density of the medium, this implies that the gluon density in the initial stage of \(Au+Au\) collisions at \(\tau_0 = 0.2\) fm/c is about 15 times higher than that inside a cold nucleus. To extract the parton density and the initial formation time, one has to measure the energy loss and \(q_T\) broadening simultaneously.

In Fig. 2, we also show the predicted suppression factor at large \(p_T\) with the same logarithmic energy-dependence of the energy loss as in the cold nuclear matter which gives a suppression factor that increases with \(p_T\). However, new RHIC data [10] at 200 GeV show a constant suppression factor at larger \(p_T\). This indicates the importance of the detailed balance [11] which gives much stronger energy dependence of the energy loss. We show as the lower dashed line in Fig. 2 the result for an effective parton energy loss \(\Delta E \propto (E/\mu - 1.6)^{1.20}/(7.5 + E/\mu)\)

(9)

which is parameterized according to the result from Ref. [11] where both stimulated gluon emission and thermal absorption are included in the calculation of the total energy loss. The detailed balance between emission and absorption reduces the effective parton energy loss and on the other hand increases the energy dependence. The threshold is the consequence of gluon absorption that competes with radiation that effectively shuts off the energy loss. The parameter \(\mu\) is set to be 1 GeV in the calculation shown in Fig. 2.

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REFERENCES