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Medium Recoil and Jet Modification in Heavy Ion Collisions

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Abstract

A complete set of elastic processes and induced gluon radiation within the higher-twist approach have been implemented in the Linear Boltzmann Transport model for jet propagation and interaction with quark-gluon plasma in high-energy heavy-ion collisions. We impose global energy momentum conservation in the $2 \to n$ processes of induced radiation which will influence the final gluon spectra. We will compare the elastic and the radiative energy loss of partons and their effects on reconstructed jets. The energy loss of a leading parton is found to have a quadratic distance dependence only for a short distance, but will have much weak distance dependence because of the accumulated energy loss and the strong energy dependence of the local energy loss rate. Since reconstructed jets recover some of the energy lost by the leading parton, the quadratic path length dependence persists for a longer distance. The spatial distribution and time evolution of the jet-induced medium excitation are also discussed.

Keywords: Jet quenching, Boltzmann Transport, quark-gluon plasma

1. Introduction

Jet quenching has been considered as one of the most useful probes [1, 2] to study properties of the quark-gluon plasma in high-energy heavy-ion collisions [3, 4, 5, 6]. Energetic partons produced in a hard scattering at the very beginning of heavy-ion collisions will interact with thermal partons in the quark-gluon plasma and lose energy. Therefore, the study of large p_T hadron spectra and reconstructed jets can provide important information about parton-medium interaction. When jets travel through the thermal medium, the interaction between hard partons and the medium will also lead to the excitation of recoil partons from the medium. It is very important to take into account the jet-induced medium recoil partons in the reconstruction of jet energy in addition to parton energy loss [7, 8, 9].

2. Linear Boltzmann Jet Transport (LBT) model

In LBT simulations we consider both elastic $2 \to 2$ scatterings and $2 \to 2 + n$ multiple gluon emissions. We follow the propagation of all the particles including shower partons, radiated gluons and recoil partons induced by jet-medium interaction, and allow them to scatter further in the medium. The total scattering probability for a jet parton 1 scattering with a thermal parton in the quark-gluon plasma is $\Gamma_1 = \sum_{2(34)} \Gamma_{12\to 34}$, where $\Gamma_{12\to 34}$ is the scattering rate via a single channel [10] in the complete set of elastic processes. After we determine whether there is a parton-medium scattering in a time step Δt according to the Poisson distribution $P_1 = 1 - e^{-\Gamma_1 \Delta t}$, we select the scattering channel according to the relative weight of scattering rates.

When an energetic parton 1 propagates through a thermal medium with fluid velocity $u = (1, \vec{v})/\sqrt{1 - \vec{v}^2}$ and local temperature T, it may interact with a light quark (antiquark) or a gluon denoted as parton 2 inside the hot medium. We describe the elastic scattering processes according to a linear Boltzmann transport e-

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quation,

$$p_1 \cdot \partial f_1(p_1) = -\int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \sum_{2(3,4)} [f_1(p_1)f_2(p_2) - f_3(p_3)f_4(p_4)] \, |M_{12\to 34}|^2 \times S_2(s,t,u)(2\pi)^4 \delta^4(p_1+p_2-p_3-p_4), \tag{1}$$

where the square of the scattering amplitude $|M_{12\to 34}|^2$ is calculated via perturbative QCD in terms of kinetic variables s, t, u and constrained by a Lorentz-invariant regularization condition $S_2(s,t,u) = \theta(s \geq 2\mu_D^2)\theta(-s + \mu_D^2 \leq t \leq -\mu_D^2)$ [10], where the Debye screening mass squared is $\mu_D^2 = \frac{g^2T^2}{3}(N_c + \frac{N_f}{2})$, f_i $(i = 2, 4)$ are the thermal Bose-Einstein distribution for gluons and Fermi-Dirac distributions for quarks (antiquarks). Since we assume partons to be point-like, the phase-space density for jet shower partons is denoted as $f_i = (2\pi)^3\delta^3(\vec{p} - \vec{p}_i)\delta^3(\vec{x} - \vec{x}_i - \vec{v}_i t)$ $(i = 1, 3)$ before and after the interaction. Bose enhancement and Pauli blocking are neglected in the current simulations and we fix the strong coupling constant $\alpha_s = g^2/4\pi$ at 0.3 throughout this study.

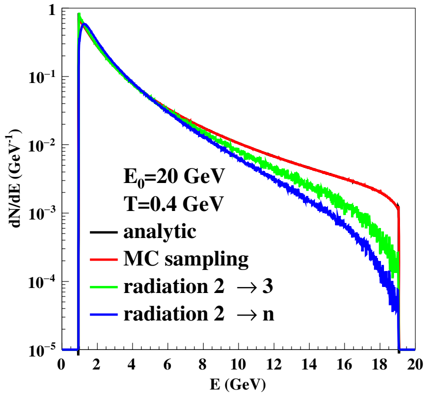
We follow a higher-twist approach to include the gluon radiation induced by the jet-medium interaction,

$$\frac{dN_g^a}{dz dk_\perp^2 dt} = \frac{6\alpha_s P(z)}{\pi k_\perp^4}(\hat{p}\cdot u)\hat{q}_a \sin^2\frac{t - t_i}{2\tau_f}, \tag{2}$$

where $P(z) = [(1-z)(1+(1-z)^2)]/z$ is the splitting function for quarks and $P(z) = 2(1-z+z^2)^3/[z(1-z)]$ for gluons respectively. The formation time of the radiated gluon with energy fraction z and transverse momentum $k_\perp$ is $\tau_f = 2Ez(1-z)/k_\perp^2$. Multiple gluon emissions are introduced by a Poisson distribution. Interactions among jet shower partons, recoil partons and radiated gluons are neglected in this Linear Boltzmann transport model.

3. Results

When an energetic parton propagates through the hot medium, it will suffer both collisional energy loss via scattering with thermal partons and radiative energy loss due to the induced gluon emissions. The radiative energy loss is the dominant source of the energy loss. To study radiative energy loss in detail, we first calculate the energy distribution of the radiated gluon in $q \to q + g$ and $g \to g + g$ respectively in Fig. 1. The difference between the upper and lower figures is due to different splitting kernels in $q \to q + g$ and $g \to g + g$ processes.



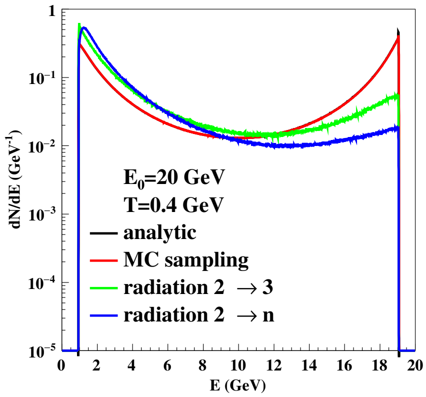


Figure 1: (Color online) Energy distributions of radiated gluons in $q \to q+g$ (upper) and $g \to g+g$ (lower) radiation processes with initial parton energy E_0 = 20 GeV in a thermal medium at a temperature T = 400 MeV. Black lines are results from Eq. (9) with direct integration while red lines are from Monte Carlo sampling, and green and blue lines are results from the 2 → 3 and 2 → n processes, respectively, from LBT simulations.

For two identical outgoing partons in $g \to g+g$ process, there is also a peak at $z = 1$. We verify the Monte Carlo sampling by comparing the simulation with results from numerical integration. The gluon spectra is suppressed at high energy in the 2 → 3 simulation by the global energy momentum conservation that we impose, and this effect becomes stronger in multiple radiation processes.

In Fig. 2 (upper) we show the distance (propagation time) dependence of the elastic energy loss and total energy loss of a quark and a gluon in a uniform medium. One can clearly see the dominance of the radiative energy loss, and that the energy loss of a gluon is considerably larger than that of a quark at the early stage due to different color degrees of freedom. The difference however becomes smaller at the later stage because of the energy consumption as the jet parton propagates through the medium.