Constraining of jet medium interaction in high-energy heavy-ion collisions

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Abstract. In this talk, we discuss jet medium interaction, in particular, γ-tagged jet energy loss and γ-jet correlation in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV within a linearized Boltzmann transport (LBT) model. It is shown that both recoiled and radiated partons have considerable contribution to the energy of a reconstructed jet. LBT results agree well with experimental data and also indicate a sizable azimuthal angle broadening of γ-jet correlation which should be observable with reduced experimental uncertainties. A γ-tagged jet fragmentation function is also shown as a better measure of jet quenching.

1. Introduction

As a result of multiple scattering and medium induced gluon radiation during the propagation of high p_T partons in the deconfined phase in high energy heavy-ion collisions, jets are strongly quenched [1] as observed in Au+Au collisions at RHIC and Pb+Pb collisions at LHC in terms of the suppression and p_T broadening of high-p_T hadrons and jets with respect to p+p collisions. Meanwhile, the medium should also be excited by the lost energy and momenta. These processes of jet-medium interaction can be simulated in a linearized Boltzmann transport (LBT) model [2, 3].

There are two building blocks in the LBT model. The first one is the simulation of the elastic scattering according to the Boltzmann transport equation,

$$p_1 \cdot \partial f_1(p_1) = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4)|M_{12 \to 34}|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4), \qquad (1)$$

where we have neglected the Bose enhancement and Pauli blocking factor, $dp_i = d^3 p_i/[2E_i(2\pi)^3]$, and use the square of elastic scattering amplitude in a small angle approximation $|M_{12 \to 34}|^2 = Cg^4(\hat{s}^2 + \hat{u}^2)/(-\hat{t} + \mu_D^2)^2$ with $\hat{s}$, $\hat{t}$, and $\hat{u}$ as the Mandelstam variables, and μ_D is the Debye mass. In the above, $C = 1$ (9/4) is the color factor for quark-gluon (gluon-gluon) scattering, phase-space distributions $f_i = 1/(e^{p \cdot u/T} \pm 1)$ $(i = 2, 4)$ for thermal partons with local temperature T and fluid velocity $u = (1, \vec{v})/\sqrt{1 - \vec{v}^2}$, and $f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p_i})\delta^3(\vec{x} - \vec{x_i} - \vec{v_i}t)$ $(i = 1, 3)$ for shower partons, before and after scattering.
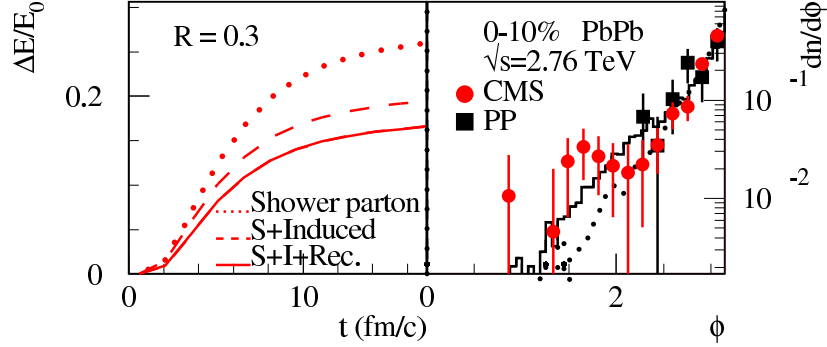
Figure 1. Averaged energy loss as a function of time (left) and azimuthal distribution relative to the γ (right) for γ-tagged jets in central (0%–10%) Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV. LBT results are obtained with $\alpha_s = 0.2$ in a 3+1D hydro medium.

After each scattering, both shower (p_3) and recoiled medium partons (p_4) are propagated along classical trajectories before the next scattering. The scattering center of the next scattering is determined with the probability of scattering, $P_a = 1 - \exp[-\sum_j (\Delta x_j \cdot u) \sum_b \sigma_{ab} \rho_b(x_j)]$ for a parton a, with σ_{ab} its scattering cross section with another parton b. The local thermal parton density is ρ_b and the sum over time steps $\Delta t_j = \Delta x_j$ (in natural units) starts from the last scattering point. Moreover, the initial thermal partons (p_2) before the scattering, denoted as "negative" partons, are also propagated according to the Boltzmann equation, and are subtracted from observables as the back-reaction of medium excitation.

Another building block of LBT is the simulation of medium induced radiations. To this end, we assume that the induced radiation can accompany each elastic scattering, and the radiation probability and the spectrum are given by the higher-twist approach[4],

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

with energy fraction of gluon z and transverse momentum $k_\perp$ emitted from a parent parton a with energy E. The splitting function is $P(z) = [1 + (1 - z)^2]/z$ and the formation time of the radiated gluon is $\tau_f = 2Ez(1 - z)/k_\perp^2$. $\hat{q}_a = \sum_b \rho_b \int d\hat{t} q_\perp^2 d\sigma_{ab}/d\hat{t}$ is the jet transport parameter. Multiple gluon emissions induced by a single scattering are assumed to satisfy a Poisson distribution. In the determination of energies and momenta of radiated gluons with Eq. (2), Debye mass μ_D is set as the infrared cutoff and on-shell condition is imposed to all radiated gluons. We neglect the interaction between shower, radiated and recoiled partons. The fixed value of strong coupling constant $\alpha_s = g^2/(4\pi)$ will be determined via comparisons to experimental data.

2. γ-jet Correlations

Photons created from hard scattering can be used to measure the initial energy of γ-tagged jets since they don't participate in strong interaction. In this presentation, jet quenching and γ-tagged jet modification in heavy-ion collisions at the LHC are studied within LBT model. To study jet quenching, the anti-k_t algorithm within FASTJET [5] is used to reconstruct jets.

To understand γ-jet correlation in the experimental data for Pb+Pb collisions at the LHC, we simulate propagation of γ-tagged jets within LBT in bulk medium whose evolution is given by a (3+1)D hydrodynamic model [6]. Initial γ-tagged jets at parton level are taken from HIJING[7] and embedded in LBT according to the overlap function of two nuclei with a Wood-Saxon distribution. Debye screening mass $\mu_D^2 = 4\pi\alpha_s T^2$ is used in LBT simulation. Event selectors
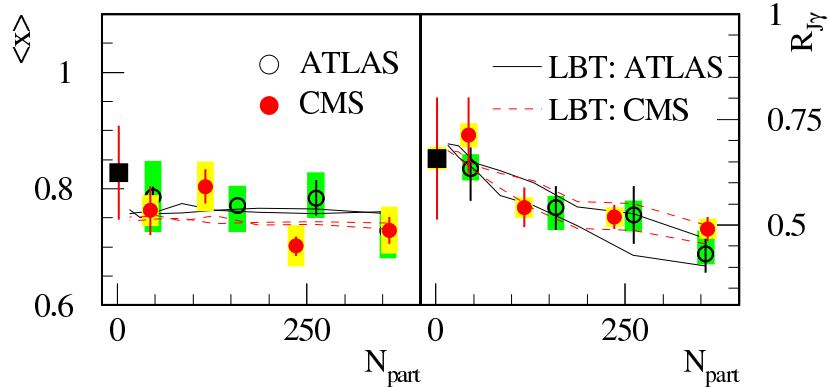
Figure 2. Averaged γ-jet asymmetry $\langle x \rangle = \langle p_T^{\text{jet}}/p_T^\gamma \rangle$ (left) and jet survival rate (right) as functions of the number of participant nucleons in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV from LBT as compared to CMS data [8] with $\alpha_{\rm s} = 0.15$–0.23 in LBT(dashed line), and ATLAS data[9] with 0.2–0.27 (solid line), respectively.

are used for CMS and ATLAS accordingly: For CMS data [8], $p_T^\gamma > 60$ GeV, $|\eta^\gamma| < 1.44$, $p_T^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 1.6$, and $\Delta\phi = |\phi^{\text{jet}} - \phi^\gamma| > 7\pi/8$, and for ATLAS data, [9], $60 < p_T^\gamma < 90$ GeV, $|\eta^\gamma| < 1.3$, $p_T^{\text{jet}} > 25$ GeV, $|\eta^{\text{jet}}| < 2.1$, and $\Delta\phi > 7\pi/8$. As background has been subtracted in the experimental data, we refrain to add and subtract that from underlying events in our simulation. Jets are reconstructed with all partons from the simulation before hadronization. We have verified that the difference between jets reconstructed from partons and hadrons are rather small. In Fig. 1, we show the average energy loss as a function of time (left), and γ-jet azimuthal angle distribution (right) with $\alpha_{\rm s} = 0.2$. The energy loss rises up initially, and saturates at $t \approx 10$ fm/c because of the decrease with time of the jet transport parameter $\hat{q}_a = \hat{q}_a^0(\tau_0/\tau)^{1+\alpha}$ with $\alpha \geq 0$ in an expanding medium, which eventually terminates parton energy loss. The analysis of the jet energy loss from different contributions, such as shower parton (p_3), recoiled thermal parton (p_4), as well radiated parton sampled from eq. (2), tells us that recoiled and radiated partons have non-negligible contributions to the jet energy inside the jet cone. On the right panel of Fig. 1, we found that the γ-jet azimuthal angle distribution (solid histograms) has a very good agreement with the data (points), which clearly shows a small broadening relative to the p+p (dotted line) reference in the large angle, while errors in the data are too big to confirm this. Therefore, we expect that experimental measurements are able to verify the small broadening when the errors are reduced significantly. In Fig. 2, we show the averaged γ-jet asymmetry $\langle x \rangle = \langle p_T^{\text{jet}}/p_T^\gamma \rangle$ and jet survival rate $R_{J\gamma}$ from LBT (lines) and experimental data from CMS [8] and ATLAS [9]. With fixed values of $\alpha_{\rm s} = 0.15$–0.23 for CMS and 0.2–0.27 for ATLAS, LBT results are consistent with CMS and ATLAS data, yet have small dependence on the experimental cutoff. We also notice that $R_{J\gamma}$ is more sensitive to jet quenching than $\langle x \rangle$.

An enhancement at both small and large $z_{\text{jet}} = p_L/E_{\text{jet}}$ in jet fragmentation function was observed at LHC[10]. The phenomena can be explained as a result of the large energy fraction of leading particles in a reconstructed jet. To verify this, we make a comparison study of reconstructed (left) and γ-tagged (right) jet fragmentation function in Fig. 3. On the left panel, the reconstructed jet fragmentation function shows a similar property as the experimental observation. However, the γ-tagged jet fragmentation function on the right panel indeed shows an enhancement at small z_γ but a significant reduction at large z_γ. This γ-tagged fragmentation function is more sensitive to jet medium interaction, and therefore a better probe of medium properties and jet transport parameter.
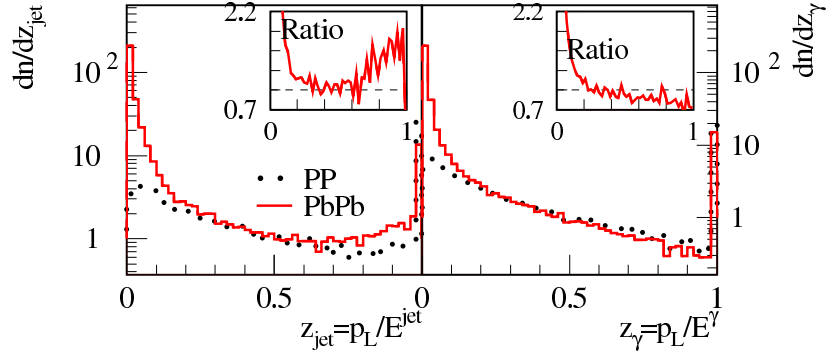
Figure 3. The reconstructed (left) and γ-tagged jet fragmentation functions (right) within a jet cone $R = 0.3$ of γ-tagged jets in central (0%–10%) Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV.

3. Conclusion

In this talk, we have discussed jet quenching and γ-jet correlations within a linearized Boltzmann transport model at LHC. With the value of $\alpha_s \approx 0.2$, we have observed that the 15% energy fraction of reconstructed jet is redistributed out side the jet-cone due to multiple elastic scattering and induced radiation in a hot QCD medium. The recoiled and radiated partons are observed to have important contributions to the energy of the reconstructed jet. By comparing γ-jet azimuthal angle distribution with CMS data, we observed a nice agreement between them. In addition, a noticeable broadening on the tail of the $\gamma-$jet azimuthal angle distribution in Pb+Pb as compared to p+p collisions is observed, which, hopefully, is going to be observable in more precise experimental measurements with reduced errors in the future. A nice agreement between γ-jet asymmetry and jet survival rate with fixed α_s in LBT with CMS and ATLAS data shown that jet survival rate is a better probe for jet quenching and medium properties. The reconstructed jet fragmentation function from LBT exhibits an enhancement at both small and large z_{jet} due to the dominance of leading particle in a reconstructed jet. We have shown that the γ-tagged jet fragmentation function is a better measurement of parton energy loss and a sensitive probe of the jet transport parameters as it's more sensible to jet quenching.

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