Medium Modification of $\gamma$ Jets in High-Energy Heavy-Ion Collisions

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Two puzzling features in the experimental study of jet quenching in central Pb+Pb collisions at the LHC are explained within a linearized Boltzmann transport model for jet propagation. A $\gamma$-tagged jet is found to lose about 15% of its initial energy while its azimuthal angle remains almost unchanged due to rapid cooling of the medium. The reconstructed jet fragmentation function is found to have some modest enhancement at both small and large fractional momenta as compared to that in the vacuum because of the increased contribution of leading particles to the reconstructed jet energy and induced gluon radiation and recoiled partons. A $\gamma$-tagged jet fragmentation function is proposed that is more sensitive to jet-medium interaction and the jet transport parameter in the medium. The effects of recoiled medium partons on the reconstructed jets are also discussed.

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Parton energy loss due to multiple scattering and bremsstrahlung in dense medium should be accompanied by transverse momentum ($p_T$) broadening [1]. One therefore should expect to see suppression of the yield and $p_T$ broadening of leading hadrons from jet fragmentation. This is the main mechanism behind the observed jet quenching [2] phenomena as manifested in the suppression of large $p_T$ hadron spectra, dihadron and $\gamma$-hadron correlations in high-energy heavy-ion collisions.

The jet quenching study has also been extended to full jets [3], which are reconstructed with a jet-finding algorithm [4] and consist of collimated clusters of hadrons (or partons in a partonic description) within a jet cone $\sqrt{(\phi - \phi_J)^2 + (\eta - \eta_J)^2} \leq R$, where $\eta (\eta_J)$ and $\phi (\phi_J)$ are hadrons’ (jet’s) pseudorapidity and azimuthal angle, respectively. Since some jet shower partons can be transported outside the jet cone through multiple scattering and bremsstrahlung, one should also expect to see a reduction of the reconstructed jet energy and change of its azimuthal angle. In addition, one also expects to see a modification of the jet fragmentation function and jet transverse profile. A large dijet asymmetry in central Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV is indeed observed at the Large Hadron Collider (LHC) [5], consistent with the picture of jet quenching [6–10]. However, two puzzles in jet modification still lack satisfactory explanations. Despite the large dijet asymmetry, there is no apparent azimuthal angle broadening within experimental errors. The reconstructed jet fragmentation function has a modest but interesting modification with enhancement at both large and small momentum fractions $z_{\text{jet}} = p_L/E_{\text{jet}}$ [11].

Back-to-back $\gamma$ jets are considered “golden channels” for the study of jet quenching since they have less trigger bias [12] than dijets. Although $\gamma$-jet asymmetry as measured in Pb+Pb collisions at the LHC [13, 14] can be explained by parton energy loss [13, 16], there is still a lack of satisfactory explanations of the apparent puzzles in the structure of the medium modified jets. In this Letter, we will report a first study of medium modification of $\gamma$-tagged jets within a linearized Boltzmann transport (LBT) model [17] and address the aforementioned puzzles in the measured jet structure in high-energy heavy-ion collisions at the LHC. We further propose measurements of the $\gamma$-tagged jet fragmentation function and its medium modification that are more sensitive to jet-medium interaction and the jet transport parameter. We will also discuss the effects of jet-induced medium excitation since the LBT model tracks the transport of both shower and recoiled partons.

Within the LBT model, the propagation of jet shower partons and medium excitation is simulated according to a linearized Boltzmann equation

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

(1)

where $dp_i = d^3p_i/[2E_i(2\pi)^3]$, $f_i = 1/(e^{p_iu/T} \pm 1)$ ($i = 2, 4$) are parton phase-space distributions in a thermal medium with local temperature $T$ and fluid velocity $u = (1, \vec{v})/\sqrt{1 - \vec{v}^2}$, and $f_i = (2\pi)^3 \delta^3(p - p_i^0) \delta^3(\vec{x} - \vec{x}_i - \vec{v}_i t)$ ($i = 1, 3$) are the parton phase-space densities before and after scattering. We assume a small angle approximation for the elastic scattering amplitude $|M_{12-34}|^2 = C g^4 (s^2 + \hat{u}^2)/(-t + \mu_D^2)$ with Debye screening mass $\mu_D$, where $s$, $t$, and $\hat{u}$ are Mandelstam variables, and $C = 1$ (9/4) is the color factor for quark-gluon (gluon-gluon) scattering. The strong coupling constant $\alpha_s = g^2/4\pi$ is fixed and will be determined via comparisons to experimental data.

Partons are assumed to propagate along classical trajectories between two adjacent collisions. The probabil-


\[ \frac{dN_{a}}{d\Omega d\mu} = \frac{4\pi P(z)}{z} \left( \hat{p} \cdot u \right) \hat{q}_{a} \sin^{2} \frac{t - t_{i}}{2\tau_{f}}, \]

(2)

where \( z \) and \( k_{\perp} \) are the energy fraction and transverse momentum of the radiated gluon, \( \hat{p}_{a} = p_{a}/p_{0} \), \( P(z) = [1 + (1 - z)^{2}] / z \) the splitting function, \( \tau_{f} = 2E_{\gamma}(1 - z) / k_{\perp}^{2} \) the gluon formation time, and \( \hat{q}_{a} = \sum_{b} p_{b} d\Omega d\sigma_{ab} / d\ell \) the jet transport parameter. The Debye screening mass \( \mu_{D} \) is used as an infrared cutoff for the gluon’s energy. Multiple gluon emissions induced by a single scattering are included according to a Poisson distribution. All radiated gluons are assumed to be on-shell, and their 4-momenta are successively determined from Eq. (2).

For initial configurations of \( \gamma \) jets, we use HIJING 19 for \( p + p \) collisions at \( \sqrt{s} = 2.76 \) TeV with a trigger on the transverse momentum transfer \( q_{T} \geq 30 \) GeV in the c.m. frame of two colliding partons. Further selections are made for events with \( p_{T}^{\gamma} > 60 \) GeV. Jet shower partons, including those from both initial- and final-state radiation, are transported through a thermal medium within the LBT model. The final partons, including negative partons, are used for jet reconstruction using a modified version of the anti-\( k_{t} \) algorithm in FASTJET 4, in which energies and momenta of negative partons are subtracted from the final jet observables. The energies of jets reconstructed from the final hadrons and partons differ only about 1 GeV in \( p + p \) collisions from HIJING.

According to Eq. (2), the radiative energy loss of a single parton going through multiple scattering is

\[ \Delta E_{\gamma} \approx \frac{3\alpha_{s}}{2} \int d\tau (\tau - \tau_{0}) (\hat{p} \cdot u) \hat{q}_{a} \ln \frac{2E}{(\tau - \tau_{0})\mu_{D}^{2}}. \]

(3)

The corresponding \( p_{T} \) broadening is

\[ \langle \Delta p_{T}^{2} \rangle = \int d\tau (\hat{p} \cdot u) \hat{q}_{a}. \]

(4)

In a static and uniform medium, the total parton energy loss has an approximate quadratic dependence on the propagation length while the \( p_{T} \) broadening has a linear dependence. In high-energy heavy-ion collisions, the jet transport parameter should have a time dependence \( \hat{q}_{a} = \hat{q}_{a}^{0}(\tau_{0}/\tau)^{1 + \alpha} \) with \( \alpha \geq 0 \) whose value becomes bigger in the later stage of evolution due to fast 3D expansion. In this case, the total energy loss is approximately linear in the propagation length while the \( p_{T} \) broadening has a logarithmic dependence or less. These length dependences should be the same for reconstructed jets as we will show. It is important to keep in mind that fast expansion in heavy-ion collisions results in much bigger reduction in the \( p_{T} \) broadening than the jet energy loss.

To illustrate the connection between energy loss and azimuthal broadening for reconstructed jets, we consider first the propagation of \( \gamma \)-tagged jets in a uniform and static gluonic medium at temperature \( T = 300 \) MeV. We set \( \alpha_{s} = 0.4 \) and \( \mu_{D}^{2} = 1 \) GeV\(^2\) for simplicity and use a jet-cone size \( R = 0.4 \). Shown in Fig. 1 (left) is the jet energy loss that has a clear quadratic time dependence during the early times. The corresponding \( p_{T} \) broadening of single partons should increase linearly during early times. This leads to a significant azimuthal angle broadening of the reconstructed jets, as shown in Fig. 1 (right). If we include only jet shower partons (dotted line) in the jet reconstruction, the energy loss is considerably larger than when radiated gluons (dashed line) or all (shower + radiated + recoiled) partons (solid line) are included. Both radiated gluons and recoiled medium partons enter the jet cone and become part of the reconstructed jets.

For the study of \( \gamma \)-tagged jets in heavy-ion collisions within the LBT model, we use the space-time profile of temperature and fluid velocity in the quark-gluon phase from (3+1)D ideal hydrodynamical simulations 20 of Pb+Pb collisions at the LHC. The initial \( \gamma \)-jet production from HIJING is distributed according to the overlap function of two colliding nuclei with a Woods-Saxon nuclear geometry. Whenever comparisons are made to the experimental data, we apply the same kinematic cuts to the LBT results. For CMS data 13, \( p_{T}^{\gamma} > 60 \) 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 14,
$60 < p_T^γ < 90$ GeV, $|η^γ| < 1.3$, $p_T^{jet} > 25$ GeV, $|η^{jet}| < 2.1$, and $Δφ > 7π/8$. In LBT simulations, we use a Debye screening mass $μ_D^2 = 4πα_s T^2$.

Following experiments at the LHC [13, 14], we first calculate the $γ$-jet asymmetry distribution $dN/dx$ with $x = p_T^{jet}/p_T^γ$. Shown in Fig. 2 are $γ$-jet asymmetry distributions from LBT simulations (histogram) as compared to CMS data [13] (solid circles) in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV with four different centralities and for a jet-cone size $R = 0.3$. Because of initial-state radiation, $γ$ jets are produced with a large momentum asymmetry in $p+p$ and peripheral Pb+Pb collisions where there is no or little medium-induced jet energy loss. The LBT results can fit the experimental data of both $p+p$ and Pb+Pb with different centralities quite well with a fixed value of $α_s = 0.2$. The asymmetry distributions in $x$ seem to depend very weakly on the centrality even though there is significant jet energy loss as we will show below.

One can further quantify the $γ$-jet asymmetry in heavy-ion collisions by the averaged asymmetry or ratio of the jet and photon transverse momenta $⟨x⟩ = ⟨p_T^{jet}/p_T^γ⟩$ and the jet survival rate or fraction of $γ$-tagged jets $R_{γγ}$ with $p_T^{jet} > 30$ GeV (CMS cut) or $x = p_T^{jet}/p_T^γ > 0.42$ (ATLAS cut). Shown in Fig. 3 are LBT results (lines) on the averaged $γ$-jet asymmetry $⟨x⟩$ and jet survival rate $R_{γγ}$ as functions of the number of participant nucleons are compared to CMS (solid circles and squares) [13] and ATLAS (open circles) data [14]. Note those kinematic cuts in ATLAS data, which are also truncated with $x < 0.42$, are somewhat different from that in CMS data. In LBT calculations, $α_s = 0.15–0.23$ are used with the CMS cuts (dashed) while $α_s = 0.2–0.27$ for the ATLAS cuts (solid). One can see that the averaged momentum asymmetry $⟨x⟩$ has a very weak centrality dependence and is not very sensitive to the value of $α_s$. The jet survival rate $R_{γγ}$ has, however, a stronger dependence on the centrality and the value of $α_s$ or the strength of the jet-medium interaction.

With the jet-medium interaction strength fixed by the experimental data on $γ$-jet asymmetry, we can now turn to the net jet energy loss and azimuthal angle broadening. Shown in Fig. 3 (left) is the averaged jet energy loss as a function of time in the most central 10% of Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV for a jet-cone size $R = 0.3$ from LBT simulations with $α_s = 0.2$. Because of rapid cooling due to 3D expansion, jet energy loss saturates approximately 10 fm/$c$ after an initial linear rise with the final fractional jet energy loss of about 15% (solid line). In such an expanding system, one also expects a reduction in the $p_T$ broadening. As a consequence, the jet azimuthal distribution in central Pb+Pb collisions (solid line) as shown in Fig. 4 (right) remains almost unchanged in the opposite direction of $γ$ as compared to that in $p+p$ collisions (dotted line), in agreement with CMS data [13] within errors. There is still, however, significant difference between Pb+Pb and $p+p$ collisions at large values of azimuthal angle asymmetry $Δφ = φ − π ∼$.

FIG. 2: Distribution of $γ$-jet asymmetry $x = p_T^{jet}/p_T^γ$ in Pb+Pb collisions with four centralities at $\sqrt{s} = 2.76$ TeV from LBT with $α_s = 0.2$ as compared to CMS data [13].

FIG. 3: Averaged $γ$-jet asymmetry $⟨x⟩ = ⟨p_T^{jet}/p_T^γ⟩$ (left) and jet survival rate $R_{γγ}$ (right) as functions of the number of participant nucleons in Pb+Pb at $\sqrt{s} = 2.76$ TeV from LBT as compared to experimental data [13, 14]. Values of $α_s = 0.15–0.23$ (dashed line) and 0.2–0.27 (solid line) are used for LBT calculations with CMS and ATLAS cuts, respectively.

FIG. 4: 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.
The momentum fraction is defined as \( \gamma = \frac{p_L}{E_{\text{jet}}} \). In summary, we have studied the medium modification of \( \gamma \)-tagged jets in high-energy heavy-ion collisions within the LBT model that includes both multiple scattering and medium-induced bremsstrahlung. The model can reproduce well recent experimental data on \( \gamma \)-jet asymmetry and the survival rate in \( \text{Pb} + \text{Pb} \) collisions at the LHC. Through an examination of jet energy loss and azimuthal angle broadening of \( \gamma \)-tagged jets in both a uniform medium and the 3D expanding matter in heavy-ion collisions, we have explained two puzzling features observed in recent experimental data at the LHC. We illustrate within the LBT model that the rapid cooling of the expanding medium and different length dependences of the jet energy loss and \( p_T \) broadening lead to large \( \gamma \)-jet asymmetry and yet little azimuthal broadening. Because some soft partons are transported outside the jet cone causing jet energy loss, the leading partons have increased their contribution to the reconstructed jet energy. This leads to a very small modification to the reconstructed jet fragmentation and even enhancement at large \( z_{\text{jet}} \). We have further proposed a \( \gamma \)-tagged jet fragmentation function that uses \( E_\gamma \) to define the momentum fraction \( z_\gamma \). Its suppression at large \( z_\gamma \) is shown to be more sensitive to jet-medium interaction and the jet transport parameter in medium. We also show that the inclusion of recoil partons from jet-induced medium excitation tends to reduce the effective energy loss of a reconstructed jet. Such effects should be included for any precision studies of jet modification.

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FIG. 5: The reconstructed (left) and \( \gamma \)-tagged jet fragmentation functions (right) within a jet cone \( R = 0.3 \) of \( \gamma \)-tagged jets in central (0%-10%) \( \text{Pb} + \text{Pb} \) collisions at \( \sqrt{s} = 2.76 \) TeV.
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