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γ-jet fragmentation function and jet-induced medium excitation

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We carry out the study of the medium modification of γ-jet fragmentation function in relativistic heavy-ion collisions. To simultaneously do simulation of both jet transport and the dynamical evolution of the bulk medium, we develop CoLBT-hydro model–Coupled Linear Boltzmann Transport (LBT) and (3+1)D relativistic hydrodynamics model in real time. The lost energy and momentum by propagating jet shower partons via collisional and radiative processes are deposited into the medium and update the surrounding bulk medium for the subsequent jet transport. We use the model to calculate γ-jet fragmentation function in a function of ξ^{jet} and ξ_T^{γ} in Pb+Pb collisions at 5.02A TeV for different centralities, and the corresponding medium modification function in comparison with p+p collisions generated by Pythia8. The CoLBT-hydro results show the centrality dependence of the enhancement of high p_T hadrons and the enhancement of low p_T hadrons inside jets due to parton energy loss and jet-induced medium excitation.

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1. Introduction

In relativistic heavy-ion collisions at the Relativistic Heavy-ion Collider(RHIC) and Large Hadron Collider (LHC), plenty of important evidence has been provided for the formation of a deconfined state of quarks and gluons, called quark-gluon plasma (QGP). Energetic jet shower partons, produced in hard processes at very early time, will lose part of their energy and momentum due to the interaction with medium constituents during propagation. The phenomena, commonly referred to as jet quenching, relate to the modification of the jets and act as probes of the inner structure of the bulk medium. The final quenched jet will be determined by energy loss of the leading jet shower partons but also how the lose energy is redistributed with the evolution of bulk medium through induced radiation, rescattering and jet-induced medium excitation(j.i.m.e.).

We have carried out the first study with CoLBT-hydro of the medium modification of γ-hadron correlations in heavy-ion collisions at RHIC [1], and get two unique features of j.i.m.e : the onset of soft hadron enhancement at a constant p_T^h with broadened angular distribution and depletion of soft hadrons in the γ direction. In this work, we apply CoLBT-hydro model to study the medium modification of γ-jet fragmentation function at collison energy $\sqrt{s}$=5.02A TeV. In this coupled approach, jet transport and bulk medium evolution are described by LBT and (3+1)D hydrodynamic model, separately. The interaction between jet shower partons and medium constituent is accompanied by the transfer of energy and momentum. It can be considered as source term of hydrodynamic equations for medium evolution, and update the bulk medium profile for subsequent jet transport in the next time step.

2. CoLBT-hydro model

The LBT model is designed to describe jet transport in QGP medium in high-energy heavy-ion collisions [2]. The model has been recently improved with the implementation of the complete set of elastic $2 \rightarrow 2$ scattering processes. Inelastic processes $2 \rightarrow 2$ + n with multiple gluon radiation and global energy-momentum conservation have also been implemented more consistently in the latest version. The transport of both jet shower and thermal recoil partons are simulated by a set of linear Boltzmann equations:

$$p_a \cdot \partial f_a = \frac{\gamma_b}{2} \int \prod_{i=b,c,d} d[p_i](f_c f_d - f_a f_b)|M_{ab \rightarrow cd}|^2 S_2(\hat{s},\hat{t},\hat{u})(2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) + inelastic \quad (2.1)$$

where $d[p_i] = d^3 p_i/[2E_i(2\pi)^3]$, γ_b is the spin degeneracy for parton b, $f_i = 1/(e^{p_i \cdot u/T} \pm 1)(i = b,d)$ are parton phase-space distribution in a thermal medium with local temperature T and fluid velocity u. $f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p}_i)\delta^3(\vec{x} - \vec{x}_i - \vec{v}_i t)(i = a,c)$ are the phase-space density for jet shower partons before and after scattering. To regulate the collinear (u, $t \rightarrow 0$) divergence of the matrix element $|M_{ab \rightarrow cd}|^2$, $S_2(\hat{s},\hat{t},\hat{u}) = \theta(\hat{s} \geq 2\mu_D^2)\theta(-\hat{s} + \mu_D^2 \leq -\mu_D^2)$ is imposed in which $\mu_D^2 = g^2 T^2 (N_c + \frac{N_f}{2})/3$ is the Debye screening mass.

In the above linear Boltzmann transport equation, the inelastic processes include only induced gluon radiation accompanying elastic scattering in the current version of LBT. The radiative gluon spectrum is simulated according to the high-twist approach [3],

$$\frac{dN_g^a}{dzdk_\perp^2 dt} = \frac{6\alpha_s P_a(z) k_\perp^4}{\pi(k_\perp^2 + z^2 m^2)^4} \cdot \frac{p \cdot u}{p_0} \hat{q}_a(x) sin^2(\frac{\tau - \tau_i}{\tau_f}), \tag{2.2}$$

where m is the mass of the propagating parton a, z and $k_\perp$ are the energy fraction and transverse momentum of the radiated gluon, $P_a(z)$ the splitting function. $\tau_f = 2p_0 z(1-z)/(k_\perp^2 + z^2 m^2)$ the gluon formation time, $\hat{q}_a = \sum_{bcd} \rho_b(x) \int d\hat{t} q_\perp^2 d\sigma_{ab\to cd}/d\hat{t}$ the transverse momentum transfer squared per mean-free-path or jet transport parameter in the local comoving frame, $\rho_b(x)$ is the parton density and τ_i is the time of the last gluon emission. μ_D is used as an infrared cut-off for the gluon energy.

The CoLBT-hydro model is developed to combine the pQCD approach for the propagation of energetic jet shower partons with the hydrodynamic evolution of the strongly coupled QGP medium, including j.i.m.e. [1]. The jet-medium interaction or the transfer of energy and moment between them can be characterized by a source term in the hydrodynamic equation.

$$j^\nu = \sum_i \frac{\theta(p_{cut}^0 - p_i \cdot u) p_i^\nu / \Delta\tau}{\tau(2\pi)^{3/2} \sigma_r^2 \sigma_{\eta_s}} \exp[-\frac{(\vec{x}_\perp - \vec{x}_{\perp i})^2}{2\sigma_r^2} - \frac{(\eta_s - \eta_{si})^2}{2\sigma_{\eta_s}^2}] \tag{2.3}$$

which is the energy-momentum deposition by soft ($p \cdot u < p_{cut}^0$) and negative partons ($p \cdot u < 0$) from LBT with a Gaussian smearing. The threshold p_{cut}^0 is a tunable parameter and set to 2 GeV/c in the following calculation. Gaussian widths σ_r and σ_{η_s} are 0.2 fm. We employ the CCNU-LBNL viscous (CLVisc) code [4] to solve the (3+1)D hydrodynamics with the above source term and a parametrized equation of state (EoS) s95p-v1. The updated medium information are provided in turn for subsequent hard partons ($p \cdot u > p_{cut}^0$) transport.

To take into account the effect of the transverse and longitudinal fluctuation, the initial condition for energy-momentum density distributions for event-by-event hydro simulations are obtained from partons in A Multi-Phase Transport (AMPT) model [5] with a Gaussian smearing. The initial position of the γ-jet process is sampled according to the spatial distribution of binary hard processes from the same AMPT event. We use Pythia8 Monte Carlo model [6] to generate initial jet shower partons for γ-jet events in p+p collisions. In order to get the final hadron spectrum, A parton recombination model [7] developed by the Texas A & M University group within the JET Collaboration is used for hadronization of both jet shower and recoil medium partons, while Cooper-Frye formula [8] is used to calculate the hadron spectrum of different species from ideal hydrodynamics. The contribution from the medium background simulated by pure hydrodynamic model in the same initial condition without γ-jet needs to be subtracted.

3. Results for γ-jet fragmentation function

Triggered photons in γ-jet events generated by Pythia8 for p+p collisions satisfy the condition: p_T^γ > 60 GeV/c and $|\eta^\gamma|$<1.44. The particle-flow algorithm is used for the jet reconstruction with the anti-k_T algorithm within jet resolution parameter R=0.3 fm. Reconstructed jets with $|\eta^{jet}|$<1.6 and p_T^{jet}>30 GeV/c are selected for analysis. The azimuthal angle between triggerd photon and reconstructed jet is required to be $\Delta\phi_{j\gamma} = |\phi^{jet} - \phi^\gamma| < 7\pi/8$. Note that the reconstructed jets in Pb+Pb collisions should include hadrons from jet-induced medium excitation in the jet cone.

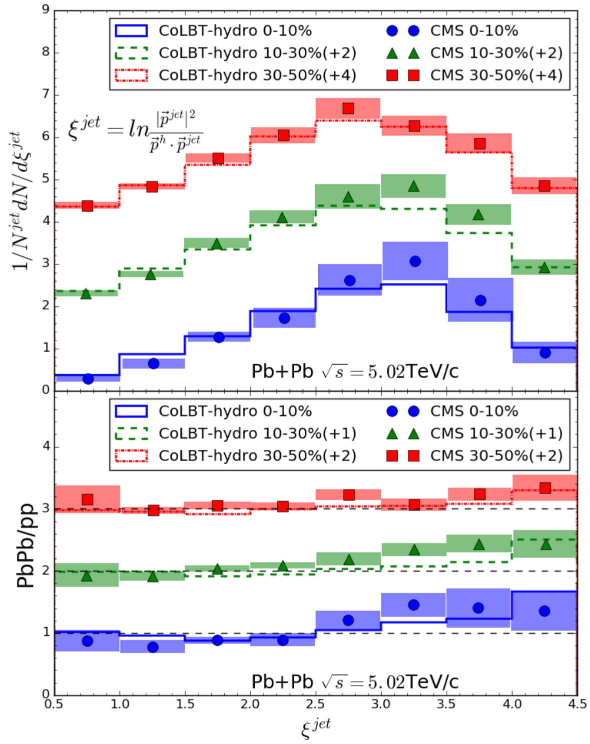

Figure 1: γ-jet fragamentation function as a function of ξ^{jet} in Pb+Pb collisions at $\sqrt{s}$=5.02A TeV for different centrality classes (upper panel) and the corresponding ratio of the Pb+Pb to p+p results (lower panel) as compared to CMS data.

Shown in Fig.1 are CoLBT-hydro results for γ-jet fragamentation function as a function of ξ^{jet} ($\xi^{jet} = \ln[|\vec{p}^{jet}|^2/(\vec{p}^h \cdot \vec{p}^{jet})]$) in different centrality (0-10%, 10-30% and 30-50%) Pb+Pb collisions at $\sqrt{s}$=5.02A TeV and the corresponding ratio of the Pb+Pb to p+p results. $\vec{p}^{jet}$ and $\vec{p}^h$ are the 3-momenta of the reconstructed jets and charged hadrons with p_T>1 GeV/c, respectively. The calculated γ-jet fragmentation function is normalized by the total number of photon-jet pair N^{jet}. CoLBT-hydro can describe well the slight suppression of leading hadrons with 0.5<ξ^{jet}<2.5 observed in CMS data for each centrality class. This is due to energy loss of hard partons within LBT. And the small enhancement of soft hadrons at ξ^{jet}>2.5 is due to the contribution from jet-induced medium excitation. Both the enhancement and suppression effect don't show much centrality dependence. The transition point (PbPb/pp=1) doesn't shift with centrality and stays at $\xi^{jet} = 2.5$.

We also show in Fig.2 CoLBT-hydro results for the γ-jet fragmentation function as a function of ξ_T^γ ($\xi_T^\gamma = \ln[-|\vec{p}_T^\gamma|^2/(\vec{p}_T^h \cdot \vec{p}_T^\gamma)]$) in Pb+Pb collisions at $\sqrt{s}$=5.02A TeV together with their ratio to p+p collisions. $\vec{p}_T^\gamma$ and $\vec{p}^h$ are the transverse momenta of the triggered photon and charged hadrons with p_T>1 GeV/c in jet cone, respectively. Compared to p+p collisions, the low-p_T hadron yield at $\xi_T^\gamma > 3.5$ increases and the high-p_T hadron yield at $0.5 < \xi_T^\gamma < 3.5$ is suppressed in Pb+Pb collisions. The magnitude of both the enhancement and suppression increases due to the centrality dependence of the in-medium path length and the temperature distribution as Pb+Pb collisions become more central. The ξ_T^γ corresponding to the transition point is 3.5. The ratio PbPb/pp measured in CMS is 10-30% larger than the calculated results with CoLBT-hydro for $\xi_T^\gamma > 3.0$.

The ξ^{jet} and ξ_T^γ at the transition point slightly depend on the collision centrality and the corresponding p_T is in the range $2 < p_T < 3$ GeV/c, which is consistent with the conclusion we obtained

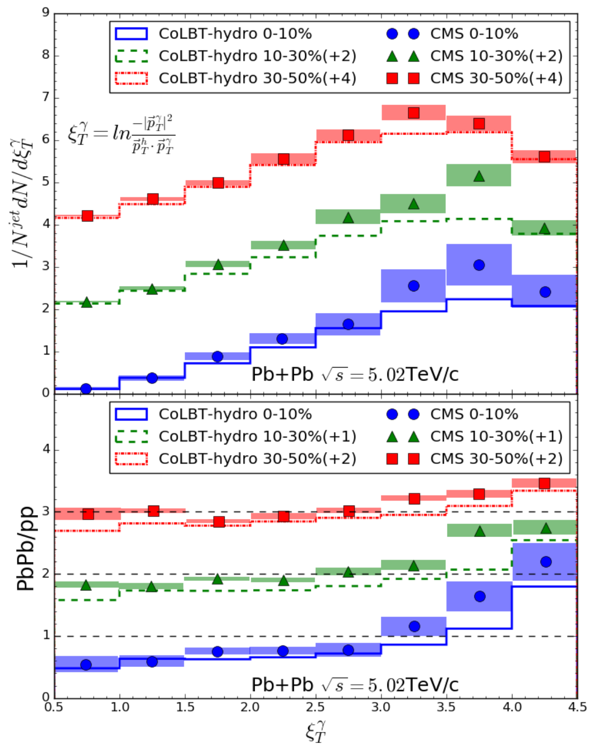

Figure 2: γ-jet fragamentation function as a function of ξ_T^γ in Pb+Pb collisions at $\sqrt{s}$=5.02A TeV for different centrality classes (upper panel) and the corresponding ratio of the Pb+Pb to p+p results (lower panel) as compared to CMS data.

from the calculation of γ-hadron correlation at RHIC energy: The hadrons from j.i.m.e. carry the average thermal energy which is independent of jet energy. The enhancement and suppression of the fragmentation function with ξ_T^γ related to initial parton energy is more pronounced than the one with ξ^{jet} related to the final reconstructed jet energy. This's because out-of-cone particles from jet-induced medium excitation and medium-induced gluon radiation are not included in the jet cone and due to the effects of jet quenching by QGP medium. These effects lower the final reconstructed jet momentum with respect to that of initial parton, and then result in the shift of these distributions to lower values for ξ^{jet} compared to ξ_T^γ in both p+p and Pb+Pb collisions.

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