Jet-induced medium excitation in $\gamma$-hadron correlation at RHIC

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Abstract

Both jet transport and jet-induced medium excitation are investigated simultaneously within the coupled Linear Boltzmann Transport and hydro (CoLBT-hydro) model. In this coupled approach, energy-momentum deposition from propagating jet shower partons in the elastic and radiation processes is taken as a source term in hydrodynamics and the hydro background for LBT simulation is updated for next time step. We use CoLBT-hydro model to simulate $\gamma$-jet events of $Au+Au$ collisions at RHIC. Hadron spectra from both the hadronization of jet shower partons and jet-induced medium excitation are calculated and compared to experimental data. Parton energy loss of jet shower partons leads to the suppression of hadron yields at large $z_T=p_T^h/p_T^p$ while medium excitations leads to enhancement of hadron yields at small $z_T$. Meanwhile, a significant broadening of low $p_T$ hadron yields and the depletion of soft hadrons in the $\gamma$ direction are observed in the calculation of $\gamma$-hadron angular correlation.

Keywords:
Linear Boltzmann Transport, hydrodynamic, $\gamma$-hadron correlation

1. Introduction

Energetic partons produced in the early hard scattering lose their energy and momentum into the medium due to the jet-medium interaction during the propagation. These phenomena are often referred to as jet-quenching. In the experiment, $\gamma$-jet is considered as a “golden channel” for studying jet quenching, because the momentum of the triggered photon in initial hard scattering will approximately balance that of the opposing parton before any medium modification and can provide direct measurement of initial jet parton’s energy. Therefore the analysis of $\gamma$-hadron correlations can in part reflect the mechanism of parton energy loss in the dense medium and the properties of quark-gluon plasma.[1, 2]

In this paper, we will briefly introduce the framework of CoLBT-hydro model in which Linear Boltzmann jet Transport model[3, 4, 5] is coupled with 3+1D hydrodynamic model[6]. Then we will calculate $\gamma$-triggered fragmentation function and its medium modification in different $p_T^\gamma$ range with CoLBT-hydro model, which will be compared with experimental data at RHIC in both low and high $p_T^h$ range. We will also calculate the $\gamma$-hadron angle correlations in different $p_T^h$ range.
2. CoLBT-hydro model

In CoLBT-hydro model, both jet transport and medium evolution are formulated in the Milne coordinates. Both elastic scattering and induced gluon radiation are simulated with LBT model within the background of the evolving bulk medium which is described by a (3+1)D hydrodynamic model. The energy-momentum deposition of soft partons produced in these processes and "negative" partons ( thermal partons before the collision that is subtracted from the medium ) contribute to a source term in the hydrodynamic equation, \( \partial_\mu T^{\mu\nu} = J' \),

\[
J' = \sum_{i=1}^{n} \frac{P'_{\text{soft}}}{\Delta\tau} \delta^{3}(\vec{X} - \vec{X}_{i}) - \sum_{i=1}^{m} \frac{P'_{\text{neg}}}{\Delta\tau} \delta^{3}(\vec{X} - \vec{X}_{i})
\]

(1)

where \( n, m \) is the number of deposited soft partons and "negative" partons, respectively. \( \frac{dP'_{\text{soft}}}{\Delta\tau} \) and \( \vec{X}_{i} \) are energy-momentum and space-time information of the \( i \)-th parton deposited into the medium during time interval \( \Delta\tau \).

For each time step \( \Delta\tau \), both jet shower partons and thermal recoil partons are determined whether to take part in collision and radiation processes according to the interaction rates that depend on bulk medium information, such as temperature and flow velocity distribution. The updated partons after collisions are divided into two groups by parton energy cut-off \( p_{\text{cut}}^{0} \) : soft partons \( (p \cdot u < p_{\text{cut}}^{0}) \) and hard partons \( (p \cdot u > p_{\text{cut}}^{0}) \). The further propagation of hard partons are simulated by LBT model while the energy-momentum deposition of soft ones are collected as a source term for hydrodynamics and will update the local medium information at the time \( \tau + \Delta\tau \). We iterate this process until the end of hydrodynamic evolution. We employ the parton recombination model[7] from Texas A&M group for hadronization of hard partons and Cooper-Frye formula[8] for the spectra from thermal medium in the hydrodynamics. The final hadron spectrum is the sum of two parts minus the thermal background without \( \gamma \)-jet in the same initial condition.

We carry out event-by-event simulations with different initial conditions for each event. The initial energy density conditions are obtained from particles in A Multi-Phase Transport (AMPT) model[9], the...
initial position of the γ-jet is sampled according to the spatial distribution of binary hard processes from the same AMPT event and initial jet shower partons information is generated by Pythia 8 for CoLBT-hydro simulation.

3. Simulation and results

We focus on the modification of γ-hadron correlations in this paper to study jet quenching and jet-induced medium excitation in heavy-ion collisions. Fig.1 shows CoLBT-hydro results of the γ-triggered fragmentation function $D(z_T)$ as a function of $z_T$ in p+p and 0-12% Au+Au collisions at $\sqrt{s}=200$ AGeV. $D(z_T)$ are determined from the associated hadron yields at away side $|\Delta\phi - \pi| < 1.4$ and $|\eta| < 1$ within $12 < p_T^γ < 20$ GeV/c.

$$D(z_T) = \frac{dN_h}{dz_T} |_{\text{LBT}} + \frac{dN_h^{\text{w/jet}}}{dz_T} |_{\text{hydro}} - \frac{dN_h^{\text{p/jet}}}{dz_T} |_{\text{hydro}},$$

(2)

where $z_T \equiv p_T^γ / p_T^γ$. We see that CoLBT-hydro results with the only parameter $\alpha_s=0.3$ agree well with STAR experimental data. We see the suppression of the away-side hadron yields at large $z_T$ due to jet quenching and the significant enhancement at small $z_T$ as a result of jet-induced medium excitation.

The corresponding medium modification factor $I_{AA} = D_{AA}(z_T) / D_{pp}(z_T)$ is shown in the lower panel of Fig.1. Without the medium modification, $I_{AA}$ would equal to 1. In the low $z_T$ region, soft hadron yield from jet-induced medium excitation accounts for a non-neglected fraction of hadron yield and makes the value of $I_{AA}$ exceed 1 and soft hadron enhancement.

To study the structure of soft hadron enhancement due to jet-induced medium excitation in detail, the medium modification factor of γ-triggered fragmentation function with different $p_T^γ$ are calculated as a function of the variable $\xi = \ln(1/z_T)$. We compare them with PHENIX experimental data[11] for $|\eta| < 0.35$ and $|\Delta\phi - \pi| < \pi/2$ in 0-40% and 0-12% Au+Au collisions at $\sqrt{s}=200$ AGeV. Fig.2 shows $I_{AA}$ increases with $\xi$ and transits from suppression to enhancement, which indicates the lost energy of jet partons leads to the suppression of leading hadrons and enhancement of soft hadron yields. Furthermore, the transition
point from suppression to enhancement shifts to larger $\xi$ with $p_T^\gamma$ range increasing. This means that the corresponding $p_T$ value of transition point is at the fixed $p_T$, about 1-2 GeV/c at RHIC energy, and it is independent of $p_T^\gamma$ range. One can therefore conclude that the enhancement at large $\xi$ is from jet-induced medium excitations with characteristic $p_T$ from the thermal medium.

Fig.3 shows the $\gamma$-hadron azimuthal angle correlation with different associated hadron $p_T$ ranges in 0-12\% Au+Au collisions at $\sqrt{s}=200$ AGeV. High $p_T$ hadron yields show a large suppression in Au+Au collision with approximately unchanged width of azimuthal correlation distribution compared to p+p baseline, while low $p_T$ hadron yields are significantly enhanced with a broadened width relative to the jet direction. It illustrates that the lost energy-momentum from high $p_T$ jet partons along the jet direction is transformed into low $p_T$ hadrons at large angle. The most interesting phenomenon is smaller hadron yields in Au+Au relative to p+p collision in the $\gamma$ direction at low $p_T$. It is a result of the diffusion wake associated with jet-induced medium excitation.

4. Summary

We have developed a new and more realistic CoLBT-hydro model to study jet quenching and jet-induced medium excitation simultaneously. We used CoLBT-hydro to study the medium modification of $\gamma$-hadron correlations at RHIC. It describes well both the suppression of leading hadrons due to parton energy loss and enhancement of soft hadrons due to jet-induced medium excitation. It also predicted soft hadron depletion in the $\gamma$ direction due to the diffusion wake of jet-induced medium excitation.

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