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Authors
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Heavy and light hadron production and D-hadron correlation in relativistic heavy-ion collisions

Shanshan Cao[a,b], Tan Luo[c], Yayun He[c,b], Guang-You Qin[c], Xin-Nian Wang[c,b]

[a]Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA
[b]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[c]Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan, 430079, China

Abstract

We establish a linear Boltzmann transport (LBT) model coupled to hydrodynamical background to study hard parton evolution in heavy-ion collisions. Both elastic and inelastic scatterings are included in our calculations; and heavy and light flavor partons are treated on the same footing. Within this LBT model, we provide good descriptions of heavy and light hadron suppression and anisotropic flow in heavy-ion collisions. Angular correlation functions between heavy and light flavor hadrons are studied for the first time and shown able to quantify not only the amount of heavy quark energy loss, but also how the parton energy is re-distributed in parton showers.

Keywords: relativistic nuclear collisions, jet energy loss, heavy quark, angular correlation function

1. Introduction

Heavy quarks and high p_T light partons serve as excellent probes of the quark-gluon plasma (QGP) matter created in ultrarelativistic heavy-ion collisions [1, 2]. Sophisticated studies have been implemented in understanding the parton-medium interaction via various jet quenching observables. However, a fully consistent picture has not been achieved about the nuclear modification of partons and hadrons of different flavors in different collision systems and energies. For instance, the comparable nuclear modification factors of D mesons and light flavor hadrons at high p_T seem contradictory to the conventional expectation from the color and mass dependences of parton energy loss; and a great challenge still remains in simultaneously describing the suppression (R_{AA}) and elliptic flow (v_2) for both heavy and light flavor hadrons. We establish a linear Boltzmann transport (LBT) model that treats the in-medium evolution of heavy and light flavor partons on the same footing. Within this approach, a simultaneous description of heavy and light flavor hadron R_{AA} is naturally obtained for various collision systems at RHIC and the LHC. A sophisticated calculation of heavy-light flavor hadron correlation is also implemented for the first time.

2. A linear Boltzmann transport model and single hadron production in heavy-ion collisions

We follow our previous work [3, 4] and describe the scatterings of energetic partons inside a thermal medium using the Boltzmann equation, in which the phase space evolution of an incoming parton "a" is

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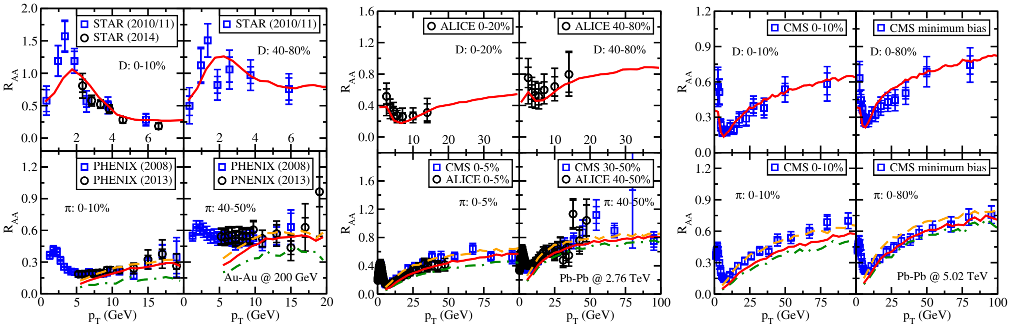

Fig. 1. (Color online) R_{AA} of D and π from RHIC to the LHC energies.

written as

$$p_a \cdot \partial f_a(x_a, p_a) = E_a(C_{\mathrm{el}} + C_{\mathrm{inel}}), \tag{1}$$

in which C_{el} and C_{inel} are collision integrals for elastic and inelastic scatterings.

For the elastic scattering process, the collision term C_{el} is evaluated with the leading-order matrix elements for all possible $ab \to cd$ processes between the given jet parton "a" and a thermal parton "b" from the medium background. Possible collinear $(u, t \to 0)$ divergence of the matrix element is regulated by imposing $S_2(s,t,u) = \theta(s \geq 2\mu_{\mathrm{D}}^2)\theta(-s + \mu_{\mathrm{D}}^2 \leq t \leq -\mu_{\mathrm{D}}^2)$ in which $\mu_{\mathrm{D}}^2 = g^2T^2(N_c + N_f/2)/3$ is the Debye screening mass. With this setup, one may evaluate the elastic scattering rate of parton "a" (Γ_{el}^a) [3], and thus the probability of elastic scattering for parton "a" in each time step Δt is $P_{\mathrm{el}}^a = \Gamma_{\mathrm{el}}^a \Delta t$.

For the inelastic process, the average number of emitted gluons from a hard parton in each time step Δt is evaluated as [5, 6, 3]

$$\langle N_g^a \rangle (E, T, t, \Delta t) = \Delta t \int dx dk_\perp^2 \frac{1}{1+\delta_g^a} \frac{dN_g^a}{dx dk_\perp^2 dt}, \tag{2}$$

in which the radiated gluon spectrum is taken from the higher-twist energy loss formalism [7, 8, 9]:

$$\frac{dN_g^a}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A \hat{q}^a P^a(x) k_\perp^4}{\pi \left(k_\perp^2 + x^2 m^2\right)^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right). \tag{3}$$

Here x and $k_\perp$ are the fractional energy and transverse momentum of the emitted gluon with respect to its parent parton, α_s is the strong coupling constant, $P^a(x)$ is the splitting function, and $\hat{q}^a$ is the quark/gluon transport coefficient (transverse momentum broadening per unit time) due to elastic scattering. Eq. (3) contains the mass dependence for heavy quark radiative energy loss. The initial time t_i denotes the production time of the "parent" parton from which the gluon is radiated, and $\tau_f = 2Ex(1-x)/(k_\perp^2 + x^2m^2)$ is the formation time of the radiation. A lower energy cut-off for the emitted gluon $x_{\min} = \mu_D/E$ is implemented to regulate the divergence as $x \to 0$. Equation (3) is based on single soft scattering induced single gluon emission, in which the "sin" term comes from the interference between this soft scattering and the initial hard scattering. However, in realistic simulation, multiple gluon emission is allowed in each Δt by assuming the number n of radiated gluons obeys a Poisson distribution with the mean as $\langle N_g^a \rangle$. Thus, the probability for such inelastic scattering process is $P_{\mathrm{inel}}^a = 1 - e^{-\langle N_g^a \rangle}$. Note that with δ_g^a in Eq. (2), a factor of 1/2 is imposed for $g \to gg$ to avoid double counting of the splitting process.

To combine elastic and inelastic processes, the scattering probability is divided into two regions: pure elastic with probability $P_{\mathrm{el}}^a(1 - P_{\mathrm{inel}}^a)$ and inelastic with P_{inel}^a. Therefore, the total scattering probability is $P_{\mathrm{tot}}^a = P_{\mathrm{el}}^a + P_{\mathrm{inel}}^a - P_{\mathrm{el}}^a P_{\mathrm{inel}}^a$. Based on these probabilities, the Monte-Carlo (MC) method is applied to determine whether a given jet parton is scattered with the medium constituents at each time step, and whether the scattering is pure elastic or inelastic. One crucial quantity that controls jet-medium interaction is the strong coupling constant α_s. Considering the fact that the variation of the medium temperature is small

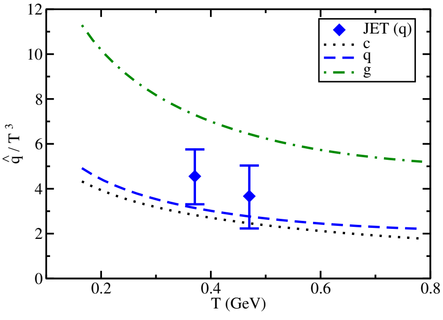

Fig. 2. (Color online) Temperature dependence of $\hat{q}$ for different parton flavors.

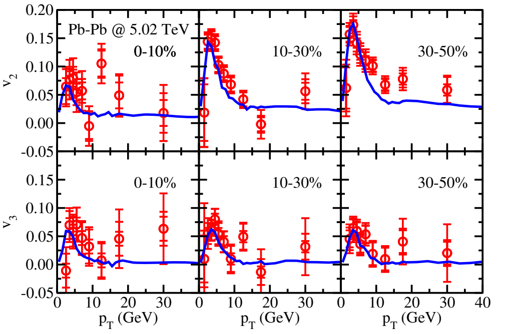

Fig. 3. (Color online) v_2 and v_3 of heavy mesons at 5.02 ATeV Pb-Pb collisions.

compared to that of the jet energy, we use a fixed coupling $\alpha_s = 0.15$ for the interaction vertices connecting directly to thermal partons. But for the vertices connecting to hard partons, we take the running coupling as: $\alpha_s(Q^2) = 4\pi/[(11 - 2n_f/3)\ln(Q^2/\Lambda^2)]$, with $Q^2 = 2ET$ and $\Lambda = 0.2$ GeV. In this work, heavy quarks hadronize within a fragmentation + heavy-thermal coalescence model [3], while light partons hadronize within only fragmentation. Thus, one obtains reliable results for light hadrons only at high p_T.

With this setup, we present in Fig. 1 the nuclear modification factors R_{AA} for D and π in 200 AGeV Au-Au collisions at RHIC, 2.76 ATeV and 5.02 ATeV Pb-Pb collisions at the LHC: upper panels show the R_{AA} of D mesons, and lower panels show the R_{AA} of π in which three curves are presented separately – upper for π from quark jet, lower for π from gluon jet and middle for the mixture. Note that since all heavy quarks are produced from initial hard scatterings, their full p_T spectra of R_{AA} can be obtained. On the other hand, reliable calculation for light hadron is only available at high p_T at this moment. We also note that since our transport coefficients are obtained from LO pQCD calculation, we apply a K factor for jet transport coefficients at low momentum in order to describe the low p_T heavy meson data. Here we use $K_p = 1 + A_p e^{-|\vec{p}|^2/2\sigma_p^2}$ with $A_p = 5$ and $\sigma_p = 5$ GeV following our previous study [4].

With the extracted α_s from the model-to-data comparison, we calculate and present in Fig. 2 the temperature dependence of the transport coefficients $\hat{q}$ for gluon, light quark and charm quark. They are consistent with the values constrained by the JET Collaboration [2] for quark jet at 10 GeV. In addition, with the α_s constrained by hadron R_{AA}, our predictions of the D meson elliptic flow v_2 and triangular flow v_3 at Pb-Pb 5.02 ATeV collisions are consistent with the CMS data. One can observe non-zero v_2 for the full p_T range of D mesons. For v_3 on the other hand, it is significant at low p_T but is consistent with zero at high p_T.

3. *D*-hadron correlation function

While single hadron observables (R_{AA} and v_2) nicely quantify the amount of parton energy loss, in order to investigate the detailed energy loss mechanism and how this lost energy is re-distributed in parton showers, one needs correlation functions. With the newly developed LBT model that simultaneously describes heavy and light parton evolution, one is able to investigate correlation functions not only between heavy meson pairs [10, 11], but also between heavy and light flavor hadrons for the first time.

In Fig. 4, we present our preliminary study on the angular correlation functions between the associate light flavor hadrons with respect to the triggered D meson, normalized to per triggered event. The p-p baseline is simulated using Pythia 8. For Au-Au, we take into account of charged hadrons from all possible sources: heavy and light parton showers, recoiled parton from the QGP medium and back reaction to the medium as well. Note that thermal hadrons emitted by the QGP are not included here, which in principle could be subtracted using the mixed event method in experiment. In Fig. 4(a), we observe a clear enhancement of $dN/d\phi$ at all ϕ due to the medium modified parton showers in Au-Au. It is more interesting to look at the $dE/d\phi$ distribution in Fig. 4(b): one observes a clear enhancement at the near side due to the

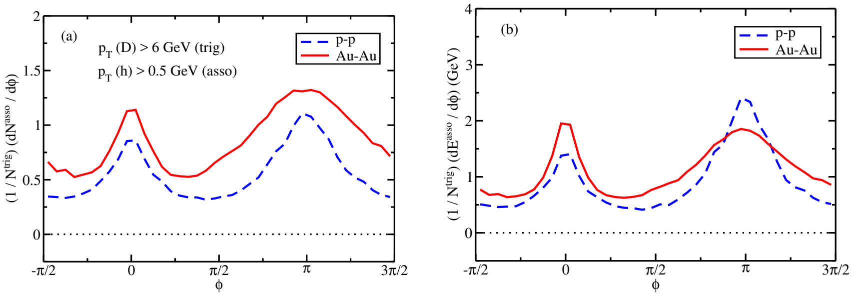

Fig. 4. (Color online) *D*-hadron correlation functions for (a) number distribution and (b) energy distribution.

energy loss of charm quark in Au-Au; at the away side, the energy distribution in Au-Au is broadened due to parton showers and scatterings inside the QGP. More quantitative study on these energy loss and momentum broadening effects will be implemented in our upcoming work.

4. Summary

To conclude, we have established a Linear Boltzmann Transport (LBT) model that treats heavy and light parton evolution on the same footing and simultaneously incorporates their elastic and inelastic scattering inside the QGP. Within this LBT framework, we have provided reasonable descriptions of heavy and light hadron suppression and anisotropic flows at RHIC and the LHC. In addition, sophisticated calculation of *D*-hadron correlation functions has been discussed for the first time and shown able to quantify not only the amount of heavy quark energy loss, but also how the parton energy is re-distributed in parton showers. More detailed quantitative study will be implemented soon.

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References

[1] A. Andronic, et al., Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions, Eur. Phys. J. C76 (3) (2016) 107. arXiv:1506.03981, doi:10.1140/epjc/s10052-015-3819-5.

[2] K. M. Burke, et al., Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions, Phys. Rev. C90 (1) (2014) 014909. arXiv:1312.5003, doi:10.1103/PhysRevC.90.014909.

[3] S. Cao, T. Luo, G.-Y. Qin, X.-N. Wang, Linearized Boltzmann transport model for jet propagation in the quark-gluon plasma: Heavy quark evolution, Phys. Rev. C94 (1) (2016) 014909. arXiv:1605.06447, doi:10.1103/PhysRevC.94.014909.

[4] S. Cao, T. Luo, G.-Y. Qin, X.-N. Wang, Heavy and light flavor jet quenching at RHIC and LHC energies, arXiv:1703.00822.

[5] S. Cao, G.-Y. Qin, S. A. Bass, Heavy quark dynamics and hadronization in ultra-relativistic heavy-ion collisions: collisional versus radiative energy loss, Phys. Rev. C88 (2013) 044907. arXiv:1308.0617, doi:10.1103/PhysRevC.88.044907.

[6] S. Cao, G.-Y. Qin, S. A. Bass, Energy loss, hadronization and hadronic interactions of heavy flavors in relativistic heavy-ion collisions, Phys. Rev. C92 (2015) 024907. arXiv:1505.01413, doi:10.1103/PhysRevC.92.024907.

[7] X.-F. Guo, X.-N. Wang, Multiple scattering, parton energy loss and modified fragmentation functions in deeply inelastic e A scattering, Phys. Rev. Lett. 85 (2000) 3591–3594. arXiv:hep-ph/0005044, doi:10.1103/PhysRevLett.85.3591.

[8] A. Majumder, Hard collinear gluon radiation and multiple scattering in a medium, Phys. Rev. D85 (2012) 014023. arXiv:0912.2987, doi:10.1103/PhysRevD.85.014023.

[9] B.-W. Zhang, E. Wang, X.-N. Wang, Heavy quark energy loss in nuclear medium, Phys. Rev. Lett. 93 (2004) 072301. arXiv:nucl-th/0309040, doi:10.1103/PhysRevLett.93.072301.

[10] S. Cao, G.-Y. Qin, S. A. Bass, Dynamical Evolution, Hadronization and Angular De-correlation of Heavy Flavor in a Hot and Dense QCD Medium, Nucl.Phys. A932 (2014) 38. arXiv:1404.1081, doi:10.1016/j.nuclphysa.2014.08.047.

[11] S. Cao, G.-Y. Qin, S. A. Bass, Modeling of heavy-flavor pair correlations in Au-Au collisions at 200A GeV at the BNL Relativistic Heavy Ion Collider, Phys. Rev. C92 (5) (2015) 054909. arXiv:1505.01869, doi:10.1103/PhysRevC.92.054909.