Jet tomography of AA-collisions at RHIC and LHC energies

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We present our recent results on jet tomography of AA-collisions at RHIC and LHC. We focus on flavor dependence of the nuclear modification factor. The computations are performed accounting for radiative and collisional parton energy loss with running coupling constant.

1. In this talk I present results of jet tomographic analysis of the RHIC and LHC data on the nuclear modification factor R_{AA} for light hadrons, single electrons, and D-mesons. A major purpose of this study is to examine whether it is possible in the pQCD picture of parton energy loss in the quark-gluon plasma (QGP) to describe simultaneously quenching of light and heavy flavors. One can expect that predictions for variation of R_{AA} from light to heavy flavors should be more robust than that for R_{AA} itself, which have significant theoretical uncertainties. The analysis is based on the light-cone path integral approach [1,2]. We evaluate R_{AA} using the scheme developed in [3].

2. We define the nuclear modification factor for a given impact parameter b as

$$R_{AA}(b)=\frac{dN(A+A\to h+X)/d\mathbf{p}_T dy}{T_{AA}(b)d\sigma(N+N\to h+X)/d\mathbf{p}_T dy}\,, \tag{1}$$

where $\mathbf{p}_T$ is the particle transverse momentum, y is rapidity (we consider the central region near $y=0$), $T_{AA}(b)=\int d\boldsymbol{\rho} T_A(\boldsymbol{\rho})T_A(\boldsymbol{\rho}-\mathbf{b})$, T_A is the nucleus profile function. We write the differential yield for $A+A\to h+X$ process in the numerator in the form

$$\frac{dN(A+A\to h+X)}{d\mathbf{p}_T dy}=\int d\boldsymbol{\rho} T_A(\boldsymbol{\rho})T_A(\boldsymbol{\rho}-\mathbf{b})\frac{d\sigma_m(N+N\to h+X)}{d\mathbf{p}_T dy}\,, \tag{2}$$

where $d\sigma_m(N+N\to h+X)/d\mathbf{p}_T dy$ is the medium-modified cross section for the $N+N\to h+X$ process. As in the ordinary pQCD formula, we write it as

$$\frac{d\sigma_m(N+N\to h+X)}{d\mathbf{p}_T dy}=\sum_i\int_0^1\frac{dz}{z^2}D_{h/i}^m(z,Q)\frac{d\sigma(N+N\to i+X)}{d\mathbf{p}_T^i dy}\,, \tag{3}$$

where $\mathbf{p}_T^i=\mathbf{p}_T/z$ is the parton transverse momentum, $d\sigma(N+N\to i+X)/d\mathbf{p}_T^i dy$ is the hard cross section, $D_{h/i}^m$ is the medium-modified fragmentation function (FF) for transition of a parton i into the observed particle h. For the parton virtuality scale Q we take the parton transverse momentum p_T^i.

In first approximation, overlap between the DGLAP and induced stages of the parton showering can be neglected at $p_T\lesssim 100$ GeV [3]. Then, assuming that the final particle h is formed outside the medium, the medium-modified FF can be written as

$$D_{h/i}^m(Q)\approx D_{h/j}(Q_0)\otimes D_{j/k}^{in}\otimes D_{k/i}(Q)\,. \tag{4}$$

Here $\otimes$ denotes z-convolution, $D_{k/i}$ is the ordinary DGLAP FF for $i \to k$ parton transition, $D^{in}_{j/k}$ is the FF for $j \to k$ parton transition in the QGP due to induced gluon emission, and $D_{h/j}$ describes fragmentation of the parton j into the detected particle h outside of the QGP.

We computed the DGLAP FFs with the help of the PYTHIA event generator [4]. For the stage outside the QGP for light partons we use for $D_{h/j}(Q_0)$ the KKP [5] FFs with $Q_0 = 2$ GeV. We treat the formation of single electrons from heavy quarks as the two-step fragmentations $c \to D \to e$ and $b \to B \to e$. For the $c \to D$ and $b \to B$ transitions we use the Peterson FF with parameters $\epsilon_c = 0.06$ and $\epsilon_b = 0.006$. The z-distributions for the $B/D \to e$ transitions have been calculated using the CLEO data [6,7] on the electron spectra in the B/D-meson decays. We did not include the $B \to D \to e$ process, which gives a negligible contribution.

The one gluon induced spectrum has been computed using the method elaborated in [8]. We take $m_q = 300$ and $m_g = 400$ MeV for the quark and gluon quasiparticle masses, for heavy quarks we take $m_c = 1.2$ GeV, and $m_b = 4.75$ GeV. We use the Debye mass obtained in the lattice calculations [9] that give $\mu_D/T \sim 2.5 \div 3$. We use the running α_s frozen at some value α_s^{fr} at low momenta. For vacuum a reasonable choice is $\alpha_s^{fr} \approx 0.7$ [10]. In plasma α_s can be reduced due to thermal effects, and we regard α_s^{fr} as a free parameter of the model. The multiple gluon emission has been accounted for employing Landau's method (for details see [3]).

We incorporate the collisional energy loss, which is relatively small [11], by renormalizing the initial temperature of the QGP, T_0, for the radiative FFs according to the following condition: $\Delta E_{rad}(T_0^{'}) = \Delta E_{rad}(T_0) + \Delta E_{col}(T_0)$, where $\Delta E_{rad/col}$ is the radiative/collisional energy loss, T_0 is the real initial temperature of the QGP, and $T_0^{'}$ is the renormalized temperature. We calculate the collisional energy loss within Bjorken's method with an accurate treatment of kinematics of the $2 \to 2$ processes (for details see [11]) with the same parametrization of $\alpha_s(Q)$ as for the radiative one.

We calculate the hard cross sections using the LO pQCD formula with the CTEQ6 [12] PDFs. To simulate the higher order K-factor we take for the virtuality scale in α_s the value cQ with $c = 0.265$ as in the PYTHIA event generator [4]. The nuclear modification of the parton densities (which leads to some small deviation of R_{AA} from unity even without parton energy loss) has been incorporated with the help of the EKS98 correction [13].

We describe the QGP in the Bjorken model with 1+1D expansion, which gives $T_0^3\tau_0 = T^3\tau$. We take $\tau_0 = 0.5$ fm. For simplicity we ignore variation of the initial temperature T_0 in the transverse directions in the overlapping of two nuclei. We fix T_0 using the entropy/multiplicity ratio $dS/dy \Big/ dN_{ch}/d\eta \approx 7.67$ obtained in [14]. It gives for central Au+Au collisions at $\sqrt{s} = 200$ GeV $T_0 \approx 320$ MeV and for Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV $T_0 \approx 420$ MeV. The fast parton path length in the QGP, L, has been calculated according to the geometry of the hard process and AA-collision. To account for the fact that at times about $1 \div 2$ units of the nucleus radius the transverse expansion should lead to a fast cooling of the hot QCD matter we impose the condition $L < L_{max}$. We take $L_{max} = 8$ ($L_{max} = 10$ fm gives almost the same).

3. Fig. 1 shows comparison of our predictions for R_{AA} for $\alpha_s^{fr} = 0.4$ and 0.5 in 0–5% centrality bin for (a) π^0-mesons in Au+Au collisions at $\sqrt{s} = 200$ GeV to PHENIX data [15], and for (b,c) charged hadrons in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV to (b) ALICE [16] and (c) CMS [17] data. We show the total R_{AA} with radiative and collisional energy loss and for purely radiative energy loss. One can see that the effect of the collisional mechanism is relatively small (especially for LHC). We present the results for $p_T \gtrsim 5$ GeV since for smaller momenta our calculations of the induced gluon emission (based on the relativistic approximation) are hardly robust. Fig. 1 shows that for light hadrons the window $\alpha_s^{fr} \sim 0.4 \div 0.5$ leads to a reasonable magnitude of R_{AA}. For RHIC the agreement of the theoretical R_{AA} (radiative plus collisional energy loss) with the data is better for $\alpha_s^{fr} = 0.5$. And for LHC the value $\alpha_s^{fr} = 0.4$ seems to be preferred by the data (if one considers the complete p_T range).

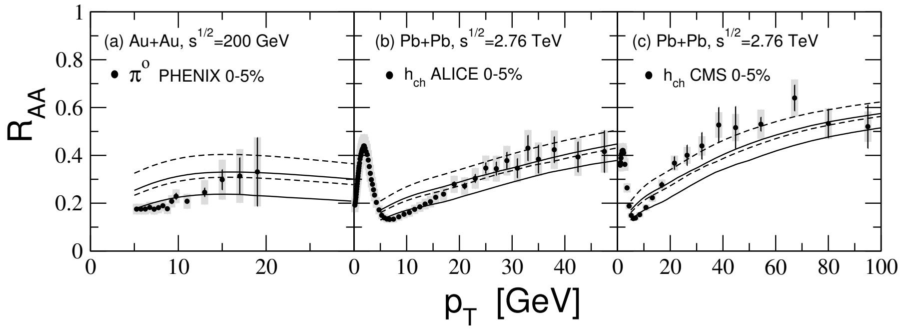

Figure 1: (a) R_{AA} for π^0 for 0–5% central Au+Au collisions at $\sqrt{s} = 200$ GeV from our calculations compared to data from PHENIX [15]. (b,c) R_{AA} for charged hadrons for 0–5% central Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV from our calculations compared to data from (b) ALICE [16] and (c) CMS [17]. Systematic experimental errors are shown as shaded areas. The curves show our calculations for radiative and collisional energy loss (solid), and for purely radiative energy loss (dashed) for $\alpha_s^{fr} = 0.4$ (upper curves) and 0.5 (lower curves).

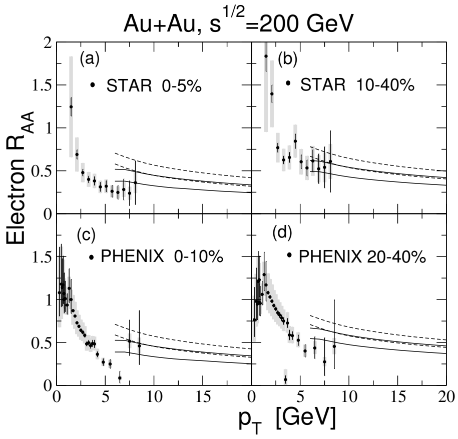

Figure 2: The electron R_{AA} in Au+Au collisions at $\sqrt{s} = 200$ GeV for (a) 0–5%, (b) 10–40%, (c) 0–10%, (d) 20–40% centrality classes. The curves show calculations for radiative and collisional energy loss (solid), and for purely radiative energy loss (dashed) including charm and bottom contributions for $\alpha_s^{fr} = 0.4$ (upper curves) and 0.5 (lower curves). Data points are from STAR [19] and PHENIX [20]. Systematic errors are shown as shaded areas.

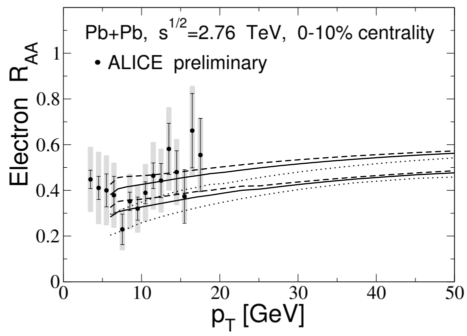

Figure 3: The electron R_{AA} for 0–10% central Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV for $\alpha_s^{fr} = 0.4$ (upper curves) and 0.5 (lower curves). The total $c+b \to e$ R_{AA} (solid), $c \to e$ (dashed), $b \to e$ (dotted) with collisional energy loss. Data points are the preliminary ALICE data [21]. Systematic errors are shown as shaded areas.

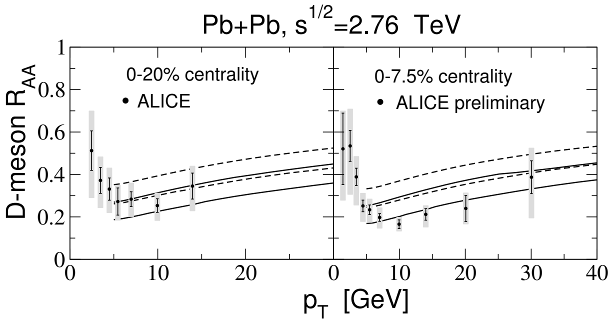

Figure 4: R_{AA} of D-mesons for 0–20% (left) and 0–7.5% (right) central Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV for $\alpha_s^{fr} = 0.4$ (upper curves) and 0.5 (lower curves). The solid line: radiative and collisional energy loss. The dashed line: purely radiative mechanism. Data points are from ALICE [22] (left), [23] (right). Systematic errors are shown as shaded areas.

The tendency of the decrease of α_s^{fr} from RHIC to LHC, observed first in [18], is natural, since the thermal reduction of α_s should be stronger at the LHC energies. Thus, the values $\alpha_s^{fr} = 0.5$ and 0.4 seem to be reasonable benchmarks for calculations of nuclear suppression for heavy flavors at RHIC and LHC energies.

In Fig. 2 we compare results of our model with STAR [19] and PHENIX [20] data on the electron R_{AA}. In Fig. 2 we show the total (charm plus bottom) R_{AA} with and without collisional energy loss. Comparison to the data from ALICE [21] is shown in Fig. 3. There we show the total (charm plus bottom) and separately charm and bottom R_{AA} with collisional energy loss. Figs. 2, 3 demonstrate that the same window of α_s^{fr} as for light hadrons leads to a quite satisfactory agreement with data on the electron R_{AA}. Similarly to data for light hadrons the electron data support $\alpha_s^{fr} \approx 0.5$ for RHIC, and $\alpha_s^{fr} \approx 0.4$ for LHC. Thus, the simultaneous description of the nuclear suppression of light hadrons and single electrons in the pQCD picture seems quite possible.

In Fig. 4 we compare our results with the ALICE data [22,23] on the R_{AA} for D-mesons in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV for 0–20% and 0–7.5% centrality bins. Fig. 4 shows the results for the $c \to D$ fragmentation. We have found that the process $b \to B \to D$ increases R_{AA} only by about 2%. From Fig. 4 we can conclude that the same window in α_s^{fr} as for light hadrons allows to obtain a fairly reasonable description of the D-meson data as well.

4. In summary, we have analyzed the RHIC and LHC data on R_{AA} for light hadrons, single electrons, and D-mesons. We have found that once α_s is fixed from data on R_{AA} for light hadrons it gives a satisfactory agreement with data on the electron and D-meson R_{AA} as well. Our results give support for the pQCD picture of parton energy loss both for light and heavy flavors.

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