Jet tomography of AA-collisions at RHIC and LHC energies

B.G. ZAKHAROV
L.D. Landau Institute for Theoretical Physics, GSP-1, 117940, Kosygina Str. 2, 117334 Moscow, Russia

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

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

(1)

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

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

(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

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

(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, $D_{h/i}^{m,i}(Q)$ 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 $p_T$.

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

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

(4)
Here $\otimes$ denotes z-convolution, $D_{k/i}$ is the ordinary DGLAP FF for $i \to k$ parton transition, $D_{j/k}^{in}$ 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. For the stage outside the QGP for light partons we use for $D_{h/j}(Q_0)$ the KKP 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 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. 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 that give $\mu_D/T \sim 2.5/3$. We use the running $\alpha_s$ frozen at some value $\alpha_s^{fr}$ at low momenta. For vacuum a reasonable choice is $\alpha_s^{fr} \approx 0.7$. In plasma $\alpha_s$ can be reduced due to thermal effects, and we regard $\alpha_s^{fr}$ as a free parameter of the model. The multiple gluon emission has been accounted for employing Landau’s method (for details see).

We incorporate the collisional energy loss, which is relatively small, 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 $\Delta E_{rad/coll}$ 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) 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 PDFs. To simulate the higher order K-factor we take for the virtuality scale in $\alpha_s$ the value $cQ$ with $c = 0.265$ as in the PYTHIA event generator. 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.

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 $dS/d\eta/dN_{ch}/d\eta \approx 7.67$ obtained in. 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 1/2 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) $\pi^+$-mesons in Au+Au collisions at $\sqrt{s} = 200$ GeV to PHENIX data, and for (b,c) charged hadrons in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV to (b) ALICE and (c) CMS 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).
The tendency of the decrease of $\alpha_f^{fr}$ from RHIC to LHC, observed first in $^{18}$, is natural, since the thermal reduction of $\alpha_s$ should be stronger at the LHC energies. Thus, the values $\alpha_f^{fr} = 0.5$ 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 $\alpha_s^{fr}$ 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 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 $\alpha_s^{fr}$ 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 $\alpha_s$ 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.

Acknowledgments

I am grateful to the organizers for such an enjoyable and stimulating meeting and for financial support of my participation.

References

1. B.G. Zakharov, JETP Lett. 63, 952 (1996); *ibid* 65, 615 (1997); 70, 176 (1999); Phys. Atom. Nucl. 61, 838 (1998).
2. R. Baier, D. Schiff, and B.G. Zakharov, Ann. Rev. Nucl. Part. 50, 37 (2000).
3. B.G. Zakharov, JETP Lett. 88, 781 (2008) [arXiv:0811.0445].
4. T. Sjostrand, L. Lonnblad, S. Mrenna, and P. Skands, arXiv:hep-ph/0308153.
5. B.A. Kniehl, G. Kramer, and B. Potter, Nucl. Phys. B582, 514 (2000).
6. A.H. Mahmood *et al.* [CLEO Collaboration], Phys. Rev. D70, 032003 (2004).
7. R. Poling, invited talk at 4th Flavor Physics and CP Violation Conference, Vancouver, British Columbia, Canada, 9-12 Apr 2006, arXiv:hep-ex/0606016.
8. B.G. Zakharov, JETP Lett. 80, 617 (2004) [arXiv:hep-ph/0410321].
9. O. Kaczmarek and F. Zantow, Phys. Rev. D71, 114510 (2005).
10. N.N. Nikolaev and B.G. Zakharov, Phys. Lett. B327, 149 (1994).
11. B.G. Zakharov, JETP Lett. 86, 444 (2007) [arXiv:0708.0816].
12. S. Kretzer, H.L. Lai, F. Olness, and W.K. Tung, Phys. Rev. D69, 114005 (2004).
13. K.J. Eskola, V.J. Kolhinen, and C.A. Salgado, Eur. Phys. J. C9, 61 (1999).
14. B. Müller and K. Rajagopal, Eur. Phys. J. C43, 15 (2005).
15. A. Adare *et al.* [PHENIX Collaboration], arXiv:1208.2254.
16. B. Abelev *et al.* [ALICE Collaboration], Phys. Lett. B720, 52 (2013).
17. S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C72, 1945 (2012).
18. B.G. Zakharov, JETP Lett. 93, 683 (2011) [arXiv:1105.2028].
19. B.I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. 98, 192301 (2007) [arXiv:nucl-ex/0607012], Erratum-ibid. 106 (2011) 159902.
20. A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C84, 044905 (2011).
21. S. Sakai, for the ALICE Collaboration, contribution to the Quark Matter 2012 Conf., http://qm2012.bnl.gov/default.asp.
22. B. Abelev *et al.* [ALICE Collaboration], JHEP 1209, 112 (2012) [arXiv:1203.2160].
23. A. Grelli, for the ALICE Collaboration, contribution to the Quark Matter 2012 Conf., http://qm2012.bnl.gov/default.asp