JET QUENCHING FROM RHIC TO LHC

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We perform a joint analysis of the data from PHENIX at RHIC and ALICE at LHC on the nuclear modification factor $R_{AA}$. The computations are performed within the light-cone path integral approach to induced gluon emission. Our results show that slow variation of $R_{AA}$ from RHIC to LHC energies indicates that the QCD coupling constant is suppressed in the quark-gluon plasma produced at LHC.

1. One of the most striking results of experiments at RHIC is strong suppression of high-$p_T$ hadrons in $AA$-collisions\cite{1} (called “jet quenching”). Recently, a similar effect has been observed in the ALICE experiment at LHC\cite{2} for $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV. The most natural reason for this phenomenon is parton energy loss (radiative and collisional) in the hot quark-gluon plasma (QGP) produced in the initial stage of $AA$-collisions. It is of great interest to perform a joint analysis of the RHIC and LHC data. It is interesting since variation of the nuclear modification factor $R_{AA}$ from RHIC to LHC energies should not be very sensitive to the systematic theoretical uncertainties that are rather large. These uncertainties come mostly from multiple induced gluon emission. The available theoretical approaches to radiative induced gluon emission\cite{3,4,5,6,7,8} are restricted to one gluon emission, and the multiple gluon emission is usually evaluated in the approximation of independent gluon radiation\cite{9}.

In this talk, I will present results of an analysis of the data on $R_{AA}$ for $Au + Au$ collisions at $\sqrt{s} = 200$ GeV from PHENIX\cite{10} and for $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV from ALICE\cite{2}. The analysis is based on the light-cone path integral (LCPI) approach\cite{4}. We evaluate the nuclear modification factor using the method developed in\cite{11}. A major purpose of this analysis is to decide whether the variation of $R_{AA}$ from RHIC to LHC indicates that the QCD coupling constant becomes smaller in the plasma produced at LHC, which is hotter than that at RHIC.

2. The nuclear modification factor $R_{AA}$ for a given impact parameter $b$ can be written as

$$R_{AA}(b) = \frac{dN(A + A \rightarrow h + X)/dp_Tdy}{T_{AA}(b)d\sigma(N + N \rightarrow h + X)/dp_Tdy}.$$  \hspace{1cm} (1)

Here $p_T$ is the hadron transverse momentum, $y$ is rapidity (we consider the central region $y = 0$), $T_{AA}(b) = \int d\rho T_A(\rho)T_A(\rho - b)$, $T_A$ is the nucleus profile function. The differential yield for high-$p_T$ hadron production in $AA$-collision can be written in the form

$$\frac{dN(A + A \rightarrow h + X)}{dp_Tdy} = \int d\rho T_A(\rho)T_A(\rho - b)\frac{d\sigma_m(N + N \rightarrow h + X)}{dp_Tdy},$$  \hspace{1cm} (2)
where \( ds_{m}(N + N \rightarrow h + X)/dp_{T}dy \) is the medium-modified cross section for the \( N + N \rightarrow h + X \) process. Similarly to the ordinary pQCD formula, we write it as
\[
\frac{ds_{m}(N + N \rightarrow h + X)}{dp_{T}dy} = \sum_{i} \int_{0}^{1} \frac{dz}{z^{2}} D_{h/i}^{m}(z, Q) \frac{dσ(N + N \rightarrow i + X)}{dp_{T}^{i}dy}.
\] (3)

Here \( p_{T}^{i} = p_{T}/z \) is the parton transverse momentum, \( dσ(N + N \rightarrow i + X)/dp_{T}^{i}dy \) 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 hadron \( h \). For the parton virtuality scale \( Q \) we take the parton transverse momentum \( p_{T} \). We assume that hadronization occurs outside of the QGP. For jets with \( E \lesssim 100 \) GeV the hadronization scale, \( \mu_{h} \), is relatively small. Indeed, one can easily show that the \( L \) dependence of the parton virtuality reads \( Q^{2}(L) \sim \max(Q/L, Q_{0}^{2}) \), where \( Q_{0} \approx 1 - 2 \) GeV is some minimal nonperturbative scale. For RHIC and LHC, when \( τ_{QGP} \sim R_{A} (τ_{QGP} \) is the typical lifetime/size of the QGP, \( R_{A} \) is the nucleus radius), it gives \( μ_{h} \sim Q_{0} \) (for \( E \lesssim 100 \) GeV). Then we can write
\[
D_{h/i}^{m}(z, Q) \approx \int_{z}^{1} \frac{dz}{z^{2}} D_{h/i}^{m}(z/z', Q_{0}) D_{j/i}^{m}(z', Q_{0}, Q),
\] (4)

where \( D_{h/j}(z, Q_{0}) \) is the vacuum FF, and \( D_{j/l}^{m}(z', Q_{0}, Q) \) is the medium-modified FF for transition of the initial parton \( i \) with virtuality \( Q \) to a parton \( j \) with virtuality \( Q_{0} \). For partons with \( E \lesssim 100 \) GeV the typical length scale dominating the energy loss in the DGLAP stage is relatively small \( \sim 0.3 - 1 \) fm. This length is of the order of the formation time of the QGP \( τ_{0} \approx 0.5 \) fm. Since the induced radiation stage occurs at larger length scale \( l \sim τ_{0} / τ_{QGP} \), to the first approximation one can ignore the overlap of the DGLAP and induced radiation stages at all. Then we can write
\[
D_{j/l}^{m}(z, Q_{0}, Q) = \int_{z}^{1} \frac{dz}{z'} D^{ind}_{j/l}(z/z', E_{l}) D_{l}^{DGLAP}(z', Q_{0}, Q),
\] (5)

where \( E_{l} = Qz/z' \), \( D^{ind}_{j/l} \) is the induced radiation FF (it depends on the parton energy \( E \), but not virtuality), and \( D_{l}^{DGLAP} \) is the vacuum DGLAP FF.

We have computed the DGLAP FFs with the help of the PYTHIA event generator. One gluon induced emission has been computed within the LCPI formalism using the method elaborated in. As in we take \( m_{q} = 300 \) and \( m_{g} = 400 \) MeV for the quark and gluon quasiparticle masses. Our method of calculation of the in-medium FF via the one gluon probability distribution is described in detail and need not to be repeated here. We just enumerate its basic aspects. The multiple gluon emission is accounted for employing Landau’s method as in. For quarks the leakage of the probability to the unphysical region of \( ΔE > E \) is accounted for by renormalizing the FF. We also take into account the \( q \rightarrow g \) FF. Its normalization is fixed from the momentum conservation for \( q \rightarrow q \) and \( q \rightarrow g \) transitions. The normalization of the \( g \rightarrow g \) FF is also fixed from the momentum sum rule. The collisional energy loss, which is small, is taken into account by renormalizing the temperature of the QGP for the radiative FFs using the condition: \( ΔE_{rad}(T_{0}') = ΔE_{rad}(T_{0}) + ΔE_{col}(T_{0}) \), where \( ΔE_{rad/col} \) 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 hard cross sections using the LO pQCD formula. 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. We account for the nuclear modification of the parton densities (which leads to some small deviation of \( R_{AA} \) from unity even without parton energy loss) with the help of the EKS98 correction. For the vacuum FFs we use the KKP parametrization.

As in we evaluated the induced gluon emission and the collisional energy loss for the running \( α_{s} \) frozen at some value \( α_{s}^{fr} \) at low momenta. For vacuum a reasonable choice is
\( \alpha_s^{fr} \approx 0.7 \). This value was previously obtained by fitting the low-\( x \) proton structure function \( F_2 \) within the dipole BFKL equation\(^1\). To study the role of the in-medium suppression of \( \alpha_s \) we perform the computations for several smaller values of \( \alpha_s^{fr} \).

3. We describe the QGP in the Bjorken model\(^2\) which gives \( T^3 \tau_0 = T^3 \tau \). We take \( \tau_0 = 0.5 \) fm. To simplify numerical computations for each impact parameter \( b \) we neglect variation of the initial temperature \( T_0 \) in the transverse directions. We evaluate its value using the entropy/multiplicity ratio \( dS/dy / dN_{ch}/d\eta \approx 7.67 \) obtained in\(^19\). For the central \( Au + Au \) collisions at \( \sqrt{s} = 200 \) GeV \( T_0 \approx 300 \) MeV and for \( Pb + Pb \) collisions at \( \sqrt{s} = 2.76 \) TeV \( T_0 \approx 400 \) MeV. For the nuclear density we use the Woods-Saxon nucleus density with parameters as in\(^2\). The fast parton path length in the QGP, \( L \), in the medium has been calculated according to the position of the hard reaction in the impact parameter plane. To take into account the fact that at times about 1 – 2 units of \( R_A \) the transverse expansion should lead to fast cooling of the hot QCD matter\(^18\) we also impose the condition \( L < L_{max} \). We performed the computations for \( L_{max} = 8 \) and 10 fm. The difference between these two versions is small.

4. In Fig. 1 the theoretical \( R_{AA} \) obtained for \( \alpha_s^{fr} = 0.7, 0.6, \) and 0.5 for the chemically equilibrium and purely gluonic plasmas is compared to the PHENIX data\(^10\) on \( \pi^0 \) production in the 0-5% central \( Au + Au \) collisions at \( \sqrt{s} = 200 \) GeV. The results are presented for radiative energy loss and with inclusion of collisional energy loss and radiative energy gain. The effect of the radiative energy gain on \( R_{AA} \) is practically negligible and can be safely neglected. The growth of \( R_{AA} \) for gluons in Fig. 1 is due to the \( q \rightarrow g \) transition which is usually neglected. However, it does not affect strongly the total \( R_{AA} \) since for \( \sqrt{s} = 200 \) GeV the gluon contribution to the hard cross section is small at \( p_T \gtrsim 15 \) GeV. In Fig. 2 we compare our results for \( \alpha_s^{fr} = 0.7, 0.5, \) and 0.4 with the ALICE data\(^2\) for charged hadrons in \( Pb + Pb \) collisions at \( \sqrt{s} = 2.76 \) TeV.

As can be seen from Figs. 1, 2, the collisional energy loss suppresses \( R_{AA} \) only by about 15-25%. For the equilibrium plasma the data for \( \sqrt{s} = 200 \) GeV can be described with \( \alpha_s^{fr} \approx 0.6 \div 0.7 \). The data for \( \sqrt{s} = 2.76 \) TeV agree better with \( \alpha_s^{fr} \approx 0.4 \div 0.5 \). It provides evidence for the thermal suppression of \( \alpha_s \) at LHC due to higher temperature of the QGP.

5. In summary, we have analyzed the data on \( R_{AA} \) obtained in the PHENIX experiment on
Figure 2: The same as in Fig. 1 for the charged hadrons in $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV for $\alpha_s^{fr} = 0.7$, 0.5 and 0.4. The experimental points are the ALICE data, as in the boxes contain the systematic errors.

$Au + Au$ collisions at $\sqrt{s} = 200$ GeV at RHIC and in the ALICE experiment on $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV at LHC. Our results show that slow variation of $R_{AA}$ from RHIC to LHC supports that the QCD coupling constant becomes smaller in the hotter QGP at LHC.

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