Jet energy loss in heavy ion collisions
from RHIC to LHC energies

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Abstract

The suppression of hadron production originated from the induced jet energy loss is one of the most accepted and well understood phenomena in heavy ion collisions, which indicates the formation of color deconfined matter consists of quarks, antiquarks and gluons. This phenomena has been seen at RHIC energies and now the first LHC results display a very similar effect. In fact, the suppression is so close to each other at 200 AGeV and 2.76 ATeV, that it is interesting to investigate if such a suppression pattern can exist at all. We use the Gyulassy-Levai-Vitev description of induced jet energy loss combined with different nuclear shadowing functions and describe the experimental data. We claim that a consistent picture can be obtained for the produced hot matter with a weak nuclear shadowing. The interplay between nuclear shadowing and jet energy loss plays a crucial role in the understanding of the experimental data.

Key words: Quark-gluon plasma, jet energy loss, nuclear shadowing

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1. Introduction

Energy loss of high energy quark and gluon jets penetrating dense deconfined matter produced in ultrarelativistic heavy ion collisions leads to jet quenching and thus probes the quark-gluon plasma formed in those reactions [1–8]. The non-abelian radiative energy loss suppresses the hadron production yield in the momentum range $2 - 3 \text{ GeV/c} < p_T < 15 - 20 \text{ GeV/c}$ at RHIC energies [9–12]. Recent preliminary experimental data on charged hadron production collected in PbPb collisions at LHC energies, especially at 2.76 ATeV, display the same phenomena [13]. Comparing the nuclear modification factor, $R_{AA}$, at RHIC and LHC energies, one can see that the measured values are very close to each other in the momentum range $5 \text{ GeV/c} < p_T < 15 \text{ GeV/c}$. This finding is very much surprising, since the measured charged hadron multiplicities display a factor of 2 enhancement at
LHC energy with respect to the values at RHIC energies [14]. Thus we expect a two times higher entropy production, which can be connected to a two times higher density of colored parton density formed in the central heavy ion collisions.

In order to investigate the influence of radiative energy loss on hadron production, we apply a perturbative QCD (pQCD) based description of heavy ion collisions, including energy loss prior to hadronization. First, we check that the applied pQCD description reproduces data on charged production in \( p + p \) collision at LHC energies. Our results are based on a leading order (LO) pQCD analysis. Detailed discussion of the formalism is published in Refs. [15–17]. We performed next to leading order calculations [18], the results will be indicated in \( pp \) collisions, however, for simplicity we would like to discuss our results at LO and compare the experimental data.

2. Parton model for \( pp \) collisions

Our pQCD calculations follows the general description of charged hadron production [15–17]:

\[
E_h \frac{d\sigma_{pp}}{d^3p} = \sum_{abcd} \int dx_1 dx_2 f_{a/p}(x_1, Q^2) f_{b/p}(x_2, Q^2) \frac{d\sigma}{dt} D_{h/c}(z_c, \hat{Q}^2) \pi z_c. \tag{1}
\]

Here we use LO parton distribution functions (PDF) from the MRST98 parameterization [19] and a LO set of fragmentation functions (FF) [20]. The applied scales are \( Q = \kappa p_T/z_c \) and \( \hat{Q} = \kappa p_T \). The NLO calculations are performed on the basis of Refs. [18].

![Graph showing charged hadron yield in pp-collisions at \( \sqrt{s} = 7 \) TeV measured by the CMS Collaboration [21]. The calculation is performed in LO (full line) and NLO (dashed line), see details in the text.](image)

Fig. 1. Charged hadron yield in pp-collisions at \( \sqrt{s} = 7 \) TeV measured by the CMS Collaboration [21]. The calculation is performed in LO (full line) and NLO (dashed line), see details in the text.
Utilizing available high transverse-momentum \((5 < p_T < 100 \text{ GeV/c})\) \(p + p\) data on charged hadron production at 7 TeV [21] we can determine the best fitting description. Fig. 1 shows a general agreement between the data and our calculations in LO and in NLO. The proper scale choice is \(\kappa = 1\) in LO and \(\kappa = 2\) in NLO calculations. Interesting to note that we do not need to introduce intrinsic-\(k_T\) at LHC energies, which ingredient was an essential part of proper description of hadron production at RHIC energies [17,18,22]. In fact we keep the earlier extracted intrinsic-\(k_T\) value at RHIC energies, but neglect it at LHC energies.

3. Nuclear effects in heavy ion collisions

Now we turn to the calculation for \(AA\) collision at RHIC and LHC energies. We include the isospin asymmetry and the nuclear modification (shadowing) into the nuclear PDF. We consider the average nuclear dependence of the PDF, and apply a scale independent parameterization with the shadowing function \(S_{a/A}(x)\):

\[
f_{a/A}(x) = S_{a/A}(x) \left[ \frac{Z}{A} f_{a/p}(x) + \left(1 - \frac{Z}{A}\right) f_{a/n}(x) \right].
\]

There are different shadowing functions to be applied, such as the relative weak old HIJING-shadowing function [23] and its newer version with and without \(b\)-dependence [24]. This new version contains a very large suppression at low-\(x\), which can be checked by the new LHC results. Another version, namely the EKS-shadowing function has been developed with a \(Q^2\)-dependence but with a weak suppression at low-\(x\), especially in the high-\(Q^2\) domain. In this calculation we will use the EKS99 [25], which is the basis of the later version and it is a LO-set.

At RHIC energy we follow our earlier calculations and include intrinsic-\(k_T\) and nuclear multiscattering [17,22,27], however, at LHC energies we neglect these contributions.

In our calculation jet quenching reduces the energy of the jet before fragmentation. We concentrate on \(y_{cm} = 0\), where the jet transverse momentum before fragmentation is shifted by the energy loss, \(p_T^e(L/L) = p_T - \Delta E(E,L)\). This shifts the \(z_e\) parameter in the integrand to \(z_e^* = z_e/(1 - \Delta E/p_c)\) [26]. The applied scale in the FF is similarly modified, \(Q = \kappa p_T / z_e^*\), while for the elementary hard reaction the scale remains \(Q = \kappa p_c\).

With these approximations the invariant cross section of hadron production in central \(A + A\) collision is given by [18]

\[
E_h \frac{d\sigma^{AA}_{bb}}{d^3p} = \int d^2b d^2r t_A(|b - r|) \times \\
\sum_{abcd} \int dx_1 dx_2 f_{a/A}(x_1, Q^2)f_{b/A}(x_2, Q^2) \frac{d\sigma}{dt} \left( \frac{z_e^*}{\pi z_e} \right) \frac{D_{b/c}(z_e^*, \tilde{Q}^2)}{z_e^*}.
\]

Here \(t_A(b) = \int dz \rho_A(b, z)\) denotes the nuclear thickness function, and it is normalized as usual: \(\int d^2b t_A(b) = A\). In case of heavy nuclei the Wood-Saxon formula is applied for the nuclear density distribution, \(\rho_A(b, z)\). The integral in \(b\) indicates the nuclear overlap in central collisions and the consideration of the Glauber geometry.
4. Averaged jet energy loss

Let us summarize our basic knowledge about non-abelian energy loss in hot dense matter. First estimates \cite{1,2} suggested a linear dependence on the plasma thickness, $L$, namely $\Delta E \approx 1 - 2 \text{GeV}(L/fm)$, as in abelian electrodynamics. In BDMS \cite{3,4}, however, non-abelian (radiated gluon final state interaction) effects were shown to lead to a quadratic dependence on $L$ with a larger magnitude of $\Delta E$. Similar results have been obtained from light-cone path integral formalism \cite{5,6}.

In the GLV formalism, applying opacity series (see Refs. \cite{7,8}), finite kinematic constraints were found to reduce greatly the energy loss at moderate jet energies. On the other hand, the quadratic dependence on $L$ has been recovered in wide energy region.

Non-abelian energy loss in pQCD has been calculated analytically in two limits. In the "thick plasma" limit, the mean number of jet scatterings, $\bar{n} = L/\lambda$, is assumed to be much greater than one. For asymptotic jet energies the eikonal approximation applies and the resummed energy loss (ignoring kinematic constraints) reduces to the following simple form \cite{3–6}:

$$\Delta E_{\text{BDMS}} = C_R \alpha_s \frac{L^2 \mu^2}{\lambda_g} \tilde{v},$$

where $C_R$ is the color Casimir of the jet ($= N_c$ for gluons), and $\mu^2/\lambda_g \propto \alpha_s^2 \rho$ is a transport coefficient of the medium proportional to the parton density, $\rho$. The factor, $\tilde{v} \sim 1 - 3$ depends logarithmically on $L$ and the color Debye screening scale, $\mu$. It is the radiated gluon mean free path, $\lambda_g$, that enters above.

In the "thin plasma" approximation \cite{7,8}, the opacity expansion was applied and in the first order the following expression was derived for the energy loss:

$$\Delta E^{(1)}_{\text{GLV}} = \frac{2C_R \alpha_s E L}{\pi} \mu \left\{ \int_0^1 dx \int_0^{k_{\text{max}}^2} \frac{dk_\perp^2}{k_\perp^2} \right\}
\int_0^{q_{\text{max}}^2} \frac{d^2q_\perp}{\pi (q_\perp^2 + \mu^2)^2} \frac{2 k_\perp \cdot q_\perp (k - q)^2 L^2}{16x^2E^2 + (k - q)^4 L^2}.$$  

(4)

Here the opacity factor $L/\lambda_g$ is the average number of final state interactions that the radiated gluons suffer in the plasma. The upper transverse kinematic limit is

$$k_{\text{max}}^2 = \min \left[ 4E^2 x^2, 4E^2 x(1 - x) \right],$$

and the upper kinematic bound on the momentum transfer is $q_{\text{max}}^2 = s/4 \approx 3E\mu$.

Furthermore, $\mu_{\text{eff}}^2/\mu^2 = 1 + \mu^2/q_{\text{max}}^2$. At RHIC energies, these finite limits cannot be ignored \cite{7,8}. The integral averages over a screened Yukawa interaction with scale $\mu$. The integrand is for an exponential density profile, $\rho \propto \exp(-2z/L)$, with the same mean thickness, $L/2$, as a uniform slab of plasma of width $L$.

It was shown in Refs. \cite{7,8} that in the asymptotic $E \to \infty$ limit, the first-order expression (4) reduces to the BDMS result \cite{3,4} up to a logarithmic factor $\log(E/\mu)$. Numerical solutions revealed that second and third order in opacity corrections to eq. (4) remain small ($< 20\%$) in the kinematic range of interest.
5. Numerical results

We have calculated jet energy loss at RHIC and LHC energies and compared our simplified model description to existed data. We applied the jet quenching effects for a generic plasma with an average screening scale $\mu = 0.5$ GeV, $\alpha_s = 0.3$, and an average gluon mean free path $\lambda_g = 1$ fm.

In Fig. 2 we display our results for charged hadrons including three types of shadowing (HIJING, EKS99, new-HIJING and b-dependent new-HIJING) and jet energy loss at RHIC energy $\sqrt{s} = 200$ AGeV. The opacity which reproduces the experimental data is between 5 and 6, we may choose $L/\lambda = 5.5$. This result is consistent with the gluon rapidity densities of $dN_g/dy = 1000 - 1400$ [28,29] and the charged hadron rapidity densities ($\sim 550 - 650$) [30,31]. One can see the weak dependence on nuclear shadowing, applying all three versions.

Fig. 3 displays the results in PbPb collisions at $\sqrt{s} = 2.76$ ATeV, applying opacities $L/\lambda = 5$ and 6. We can claim that using the new-HIJING shadowing [24] the requested opacity is also between $L/\lambda = 5$ and 6, so $L/\lambda = 5.5$ could give also a proper description.

However, this result indicates that both at RHIC and LHC energies we have the same densities of the colored deconfined matter to be produced. This result contradicts the total charged multiplicity values measured at RHIC and LHC energies [14].

Thus we increased the opacity and assumed a larger parton densities. Fig. 4 displays results, where the ALICE data are reproduced at $L/\lambda = 7$, but with the old HIJING and the EKS99 shadowing. This means a larger parton density because of the quadratic dependence on opacity.

In fact the experimental data on $R_{AA}$ is so close together at RHIC and LHC, that there is no room for a strong shadowing, jet energy loss explains the suppression pattern.
Fig. 3. Calculation of nuclear suppression for charged hadrons at LHC energy of $\sqrt{s} = 2.76$ ATeV, including different shadowing functions. We choose opacity $L/\lambda = 5$ (left panel) and $L/\lambda = 6$ (right panel). Experimental data are from ALICE Collaboration for charged particle (dots) [13].

Fig. 4. The nuclear modification factors at opacity value $L/\lambda = 7$ at different shadowing functions, compared to ALICE data at LHC energy [13]. The good agreement with the old HIJING [23] and EKS99 shadowing [25] is emphasized.
Finally, we would like to emphasize the nice agreement between ALICE data [13] and the jet quenching scenario at high-$p_T$, where the energy loss becomes weaker and suppression factor approaching unity. The flat nuclear modification factor seen at RHIC energies disappear. That flatness was the results of a nice interplay between nuclear shadowing and multiscattering with the jet quenching. As the flat nuclear modification factor disappear at LHC energy, then the simple geometrical explanation of nuclear modification factor also becomes obsolete. This statement is one of the strongest consequences of the ALICE data. The other consequence is the negligible role of shadowing at LHC energies.

Our analysis focused on induced jet energy loss and nuclear shadowing. The introduction of elastic energy loss beyond the radiative energy loss may change the results, but the basic conclusion on the presence of a weak nuclear shadowing will not be modified.

Furthermore, these calculations clearly indicate the perturbative QCD region, where the parton model including jet energy loss is applicable to explain the measured hadron suppression pattern in heavy ion collisions. This region is $p_T > 6 - 7$ GeV/c. Under this momentum value the behaviour of the nuclear modification factor decouples from the pQCD description. This means that very probably quark coalescence [32–34] dominates hadron production in the intermediate momentum region under 6-7 GeV/c, both at RHIC and LHC energies, although many questions connected to hadron-hadron correlations remained open.

The new ALICE data at $\sqrt{s} = 2.76$ ATeV [13] induced an extended discussion and many papers appeared after the publication of these data (see e.g. [35–40]). Final conclusion can be drawn after the new pp data collected at $\sqrt{s} = 2.76 TeV$ will be analysed and direct comparison to data with small statistical and systematical errors can be performed.

6. Conclusions

We have investigated jet energy loss at RHIC and LHC energies. Comparing the experimental data on nuclear modification factor measured in central Au+Au and Pb+Pb collisions, we can claim the presence of a weak nuclear shadowing effect to able to accommodate a larger jet energy loss at LHC energies with respect to the proper opacity values at RHIC energies. In case of weak nuclear modification factor the jet energy loss can explain the measured data. These calculations should be repeated when experimental data on reference pp-collisions will be available at $\sqrt{s} = 2.76$ TeV and a more precise nuclear modification factor will be displayed. On the other hand the decreasing tendency of the nuclear modification factor at $p_T > 8 − 10$ GeV/c clearly displays the presence of jet energy loss and these new data at LHC deny the presence of simple participant nucleon number scaling, which idea was very popular at RHIC energies to explain the very flat nuclear modification factor at high-$p_T$ in AuAu collisions.

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References

[1] M. Gyulassy and M. Plümmer, Phys. Lett. B243, 432 (1990); M. Gyulassy, M. Plümmer, M.H. Thoma, and X.-N. Wang, Nucl. Phys. A538, 37c (1992).
[2] X.-N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).
[3] R. Baier, Yu.L. Dokshitzer, A.H. Mueller, S. Peigné, and D. Schiff, Nucl. Phys. B483, 291 (1997); B484, 265 (1997).
[4] R. Baier, Yu.L. Dokshitzer, A.H. Mueller, and D. Schiff, Nucl. Phys. B531, 403 (1998); R. Baier, D. Schiff, and B.G. Zakharov, Ann. Rev. Nucl. Part. Sci. 50, 37 (2000).
[5] B.G. Zhakharov, JETP Lett. 63, 952 (1996); 65, 615 (1997).
[6] U.A. Wiedemann and M. Gyulassy, Nucl. Phys. B560, 345 (1999); U.A. Wiedemann, Nucl. Phys. B582, 409 (2000); B588, 303 (2000).
[7] M. Gyulassy, P. Lévai, and I. Vitev, Nucl. Phys. A661, 637; B571, 197 (2000).
[8] M. Gyulassy, P. Lévai, and I. Vitev, Phys. Rev. Letts. 85, 5535 (2000); Nucl. Phys. B594, 371 (2001); Phys. Lett. B538, 282 (2002).
[9] G. David for the PHENIX Coll., Nucl. Phys. A698, 227 (2002); K. Adcox et al. (PHENIX), Phys. Rev. Lett. 88, 022301 (2002).
[10] S.S. Adler et al. (PHENIX), Phys. Rev. Lett. 91, 072301 (2003); Phys. Rev. Lett. 96, 202301 (2006).
[11] A. Adare et al. (PHENIX), Phys. Rev. C69, 034910 (2004).
[12] C. Adler et al. (STAR), Phys. Rev. Lett. 89, 202301 (2002); J. Adams et al. (STAR), Phys. Rev. Lett. 91, 172302 (2003).
[13] K. Aamodt et al. (ALICE), Phys. Lett. B696, 30 (2011).
[14] K. Aamodt et al. (ALICE), Phys. Rev. Lett. 105, 252301 (2010).
[15] R.D. Field, Applications of Perturbative QCD, Addison-Wesley Publishing, Reading, 1989.
[16] G. Papp, P. Lévai, and G. Fai, Phys. Rev. C65, 034903 (2002).
[17] G.G. Barnaföldi, P. Lévai, G. Papp, G. Fai, and M. Gyulassy, Eur. Phys. J. C33, S609 (2004); Eur. Phys. J. C49, 333 (2007).
[18] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. C4, 463 (1998).
[19] B.A. Kniehl, G. Kramer, and B. Pötter, Nucl. Phys. B597 (2001) 337.
[20] S. Salur (CMS), arXiv: 1010.2919 [hep-ex]; CMS PAS QCD-10-008 (2010).
[21] X.-N. Wang, Phys. Rev. C61, 064910 (2000).
[22] X.-N. Wang and M. Gyulassy, Phys. Rev. D44, 3501 (1991).
[23] S.J. Li and X.N. Wang, Phys. Lett. B527, 85 (2002).
[24] K.J. Eskola, V.J. Kolhinen, and C.A. Salgado, Eur. Phys. J. C9, 69 (1999).
[25] X.-N. Wang and Z. Huang, Phys. Rev. C55, 3047 (1997).
[26] G. Papp, G.G. Barnaföldi, G. Fai, P. Lévai, and Y. Zhang, Nucl. Phys. A698, 627 (2002).
[27] M. Gyulassy and I. Vitev, Phys. Rev. Lett. 89, 252301 (2002).
[28] I. Vitev, Phys. Lett. B606, 303 (2005).
[29] B.B. Back et al. (PHOBOS), Phys. Rev. Letts. 85, 3100 (2000); 88, 022302 (2002).
[30] K. Adcox et al. (PHENIX), Phys. Rev. Lett. 86, 3500 (2001).
[31] R.C. Hwa and C.B. Yang, Phys. Rev. C66, 025205 (2002); Phys. Rev. Lett. 90, 212301 (2003); Phys. Rev. C70, 024905 (2004).
[32] V. Greco, C.M. Ko, and P. Lévai, Phys. Rev. Lett. 90, 202302 (2003); Phys. Rev. C68, 034904 (2003).
[33] J. Fries, S.A. Bass, B. Müller, and C. Nonaka, Phys. Rev. Lett. 90, 202303 (2003); Phys. Rev. C68, 044902 (2003).
[34] B.Z. Kopeliovich, I.K. Potashnikova, and I. Schmidt, Phys. Rev. C83, 021901 (2011).
[35] J. Xu and C.M. Ko, Phys. Rev. C83, 034904 (2011).
[36] X.F. Che, T. Hirano, E. Wang, X.N. Wang, and H. Zhang, arXiv: 1102.5614 [nucl-th].
[37] A. Majumder and C. Shen, arXiv: 1103.0890 [hep-ph].
[38] I.P. Lokhtin, A.V. Beljaev, and A.M. Snigirev, arXiv: 1103.1853 [hep-ph].
[39] W.A. Horowitz, arXiv: 1103.3018 [hep-ph].
[40] T. Renk, H. Holopainen, R. Paatelainen, and K.J. Eskola, arXiv: 1103.5308 [hep-ph].