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Jet Tomography as a Probe of Fluctuating Initial Conditions and Jet-Medium Coupling in Heavy-Ion Collisions

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Recent data on the nuclear modification factor R_{AA} collected in Pb+Pb collisions at the Large Hadron Collider (LHC) suggests that the jet-medium coupling in a Quark-Gluon Plasma at LHC energies is reduced as compared to energies reached at the Relativistic Heavy Ion Collider (RHIC). We find that the jet-medium coupling is reduced by approximantely 10% by applying a simple generic energy-loss model with $dE/dx \sim E^a$. This model also allows to examine different jet-energy loss prescriptions and we show that the most recent measurements of the nuclear modification factor at the LHC rule out any model with $E^{a>1/3}$.

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1. Introduction

The nuclear modification factor R_{AA} measured at the Large Hadron Collider (LHC) [1, 2] indicates that the jet-medium coupling is reduced as compared to fixed-coupling extrapolations [3] based on the data from the Relativistic Heavy Ion Collider (RHIC) [4]. Thus, those models constrained to RHIC data [3] tend to overquench at LHC energies, leading to a larger jet suppression than measured. On the other hand, the rapid increase of the R_{AA} with increasing transverse momentum p_T can readily be understood from generic perturbative physics [1].

In order to quantify the reduction of the jet-medium coupling, we consider a generic jet-energy loss model [5]

$$\frac{dP}{d\tau}(\vec{x}_\perp,\tau) = -\kappa[T(\vec{x}_\perp,\tau)]P^a(\tau)\,\tau^z\,T^{c=2-a+z}(\vec{x}_\perp,\tau)\,. \tag{1.1}$$

Here, the energy loss per unit length or momentum loss per unit time is proportional to the energy (momentum) dependence P^a, the path-length dependence τ^z, the local temperature dependence T^c, and the dimensionless coupling κ. The jet trajectory $\vec{x}_\perp(\tau) = \vec{x}_0 + \hat{n}(\phi)\tau$ is assumed to be perpendicular to the beam axis, starting at a production point $\vec{x}_0$ and moving in a direction ϕ relative to the reaction plane. We consider boost-invariant Bjorken hydrodynamics $T^3(\vec{x},\tau) = T^3(\vec{x},\tau_0)\tau_0/\tau$ with an initialization time of $\tau_0 = 1$ fm until a freeze-out temperature of $T_f \sim 100$ MeV is reached.

To contrast different initial conditions, we apply a Monte Carlo model introduced in Ref. [5] that initializes Glauber participant and binary initial geometries as well as CGC-like initial conditions which are obtained by deforming the Glauber initial geometry via [5]:

$$x \to \sqrt{\frac{\langle x^2\rangle_{\rm CGC}}{\langle x^2\rangle_{\rm Gl}}}\,x, \quad y \to \sqrt{\frac{\langle y^2\rangle_{\rm CGC}}{\langle y^2\rangle_{\rm Gl}}}\,y\,. \tag{1.2}$$

Here, the geometric average at a given impact parameter b is denoted by $\langle\circ\rangle$ and we determine the scaling factors by a fit to tabulated Glauber and MC-KLN second moments. We found that deformations with $f = 1.2\pm 0.1$ reproduce the numerical MC-KLN tables very well if we consider that the ratios of eccentricities ($\varepsilon = e_2$) for Glauber and CGC initial conditions are given by $\varepsilon_{\rm CGC} = f\cdot\varepsilon_{\rm Gl}$, [5]. In the following, we refer to those CGC-like initial conditions as 'dcgc1.2'.

2. Results and Discussions

Below we compare four different scenarios based on Eq. (1.1): I. (a=0, z=1, Glauber), II. (a=1/3, z=1, Glauber), III. (a=1/3, z=1, dcgc1.2), IV. (a=1, z=2, "Jia" dcgc1.2).

While the last scenario only consideres pure binary collisions as in Ref. [6], the first three scenarios are based upon a geometry with 14% binary and 86% participant collisions. Since it was shown in a most recent work [7] that $z = 1$ might be the correct description for *both* a pQCD and an AdS/CFT energy loss prescription, we do not further investigate the path-lengths dependencies in the following.

Scenario I ($a = 0, z = 1$) describes the deep Landau-Pomeranchuk-Migdal (LPM) pQCD limit. On the other hand, the prescription with ($a = 1/3, z = 1$) approximately characterizes both a pQCD and an AdS/CFT falling string case [8]: In a falling-string scenario, the ($a = 1/3$) power law is predicted to be the lower bound of the power a. However, numerically an $(E/T)^{1/3}$ energy

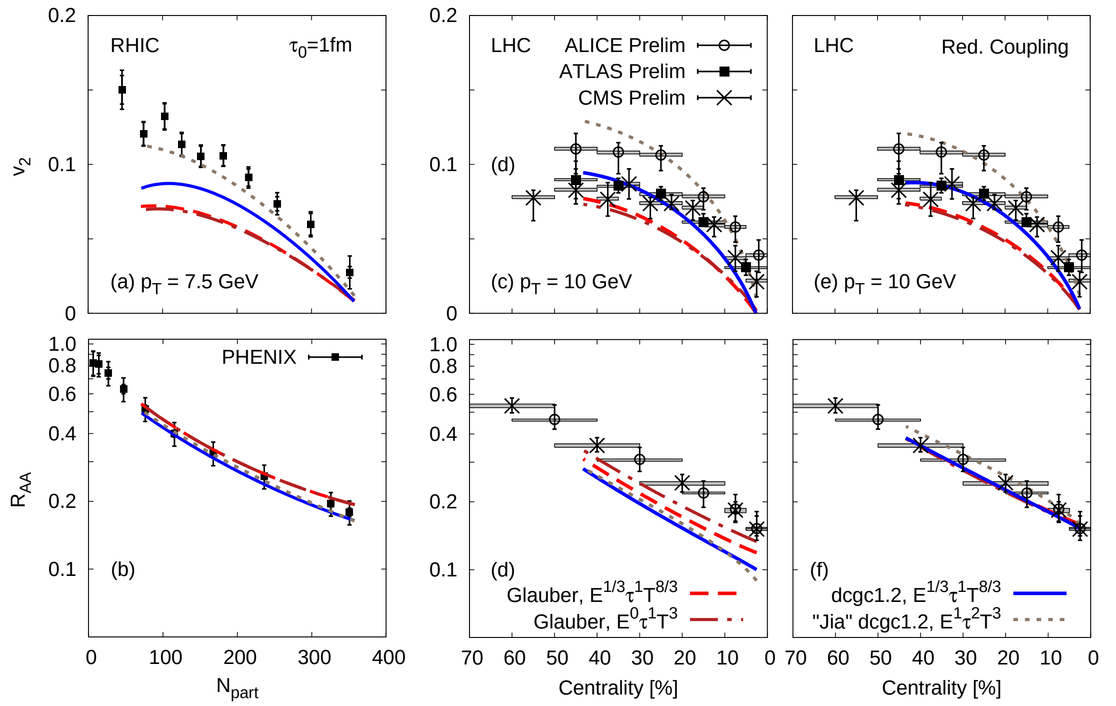

Figure 1: The elliptic flow (upper panels) and the nuclear modification factor (lower panels) of high-p_T pions for RHIC (left) and LHC energies (middle and right panel). The different lines represent various jet-energy loss prescriptions [5] that are explained in the text.

dependence is similar to the logarithmic $\log(E/T)$ dependence predicted by fixed-coupling pQCD energy loss relevant at LHC energies.

Fig. 1 displays the comparison of the nuclear modification factor (lower panel) and the elliptic flow (upper panel) for high-p_T pions as a function of centrality for RHIC (left panel) and LHC energies (middle and right panel) considering the four scenarios discussed above.

Fig. 1 (b) shows that once the coupling κ is fixed to reproduce the most central R_{AA}-data at RHIC energies, the nuclear modification factor at RHIC energies can be described well as a function of centrality for all four models considered. In contrast, the high-p_T elliptic flow depicted in Fig. 1 (a) seems only to be well described by the model with an energy loss of $dE/dx \sim E^1$.

Considering a straight extrapolation from RHIC to LHC energies (cf. the left and the middle panel of Fig. 1), the nuclear modification factor at LHC energies is clearly oversuppressed. However, reducing the jet-medium coupling (right panel of Fig. 1), this oversuppression can be revoked. Please note that the reduction of the jet-medium coupling obviously [see Fig. 1 (e)] does not have a major impact on the elliptic flow of high-p_T pions.

To quantify the jet-medium reduction between RHIC and LHC, we make use of the fact that for a pQCD radiative energy loss $\kappa \propto \alpha^3$. Then the strong coupling scales as

$$\alpha_{\rm LHC} = (\kappa_{\rm LHC}/\kappa_{\rm RHIC})^{1/3}\,\alpha_{\rm RHIC}\,, \tag{2.1}$$

where we assume that $\alpha_{\rm RHIC} \sim 0.3$. Inserting all values used for $\kappa_{\rm RHIC}$ and $\kappa_{\rm LHC}$ [5], we obtain a

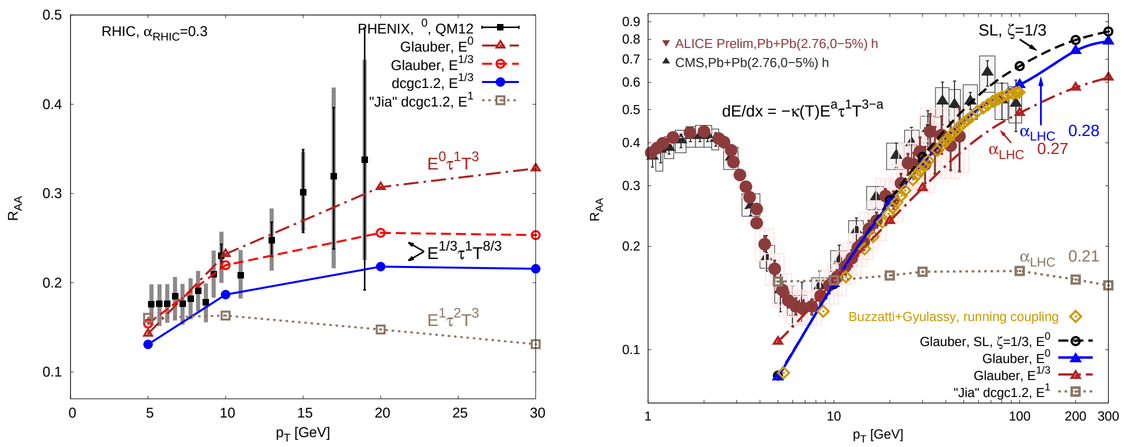

Figure 2: Momentum dependence of the nuclear modification factor measured at RHIC (left panel) [4] and at LHC energies (right panel) [1, 2]. The different lines correspond to various jet-energy loss prescriptions [5] explained in the text.

moderate reduction of the running coupling of $\kappa_{\rm LHC} \sim 0.24 - 0.28$. Please note that the running coupling is directly coupled to the coupling constant κ due to the relation $\kappa \propto \alpha^3$.

On the other hand, an effective jet-medium coupling in a falling-string scenario scales as $\kappa \propto \sqrt{\lambda}$ where λ is related to the square root of the t'Hooft coupling $\lambda = g^2_{YM} N_c$. In this case,

$$\lambda_{\rm LHC} \;=\; (\kappa_{\rm LHC}/\kappa_{\rm RHIC})^2\,\lambda_{\rm RHIC} \qquad (2.2)$$

leads to a reduction of the t'Hooft coupling $\kappa_{\rm LHC}$ up to a factor of four ($\kappa_{\rm RHIC} = 20$) [5]. So far, it is not clear if the current models allow for such a strong breaking of conformal symmetry.

Fig. 2 shows the nuclear modification factor as a function of transverse momentum for RHIC (left) and LHC (right). The figure demonstrates that the model with an energy loss of $dE/dx \sim E^1$ does not follow the trend of the data neither for RHIC nor for LHC energies. However, this model leads the best description for the R_{AA} and the high-p_T elliptic flow at RHIC (see left panel of Fig. 1) .

In contrast, for those models with $dE/dx \sim E^0$ and $dE/dx \sim E^{1/3}$, the $R_{AA}(p_T)$ is well described (Fig. 2) but there is a clear discrepancy between the results for the elliptic flow v_2 and the data taken at RHIC (see again upper left panel of Fig. 1).

The reason is that at RHIC the data are considered for an intermediate momentum range of $p_T = 7.5$ GeV. As already discussed in Ref. [9], at this intermediate p_T-range parton coalescence might enhance the measured elliptic flow by a factor of $2-3$. Therefore, one should *not* expect that pure jet fragmentation and absorption models as the one discussed here fully describe the intermediate p_T-range accessible at RHIC energies.

On the other hand, Fig. 2 proves that the energy-loss models with $dE/dx \sim E^0$ and $dE/dx \sim E^{1/3}$ follow the trend of the nuclear modification factor as a function of transverse momentum p_T.

The right panel of Fig. 2 additionally shows the results of two other jet-energy loss prescriptions based on (i) a temperture-dependent coupling as introduced in Ref. [10] by Shuryak and Liao (SL) (dashed black line) and (ii) on the CUJET code by Buzzatti and Gyulassy [11] (golden diamonds). The latter one is based on the Gyulasssy-Levai-Vitev (GLV) approach and includes a running coupling while the first case (SL model) assumes that the jet-medium coupling is enhanced by a factor of $\zeta = \kappa_1/\kappa_2 = 1/3$ in a mixed phase (κ_2, $113 < T < 173$ MeV) as compared to the QGP phase (κ_1, $T > 173$ MeV).

This Fig. 2 also demonstrates that all models based either on $dE/dx \sim E^0$ or $dE/dx \sim E^{1/3}$ follow the trend of the measured R_{AA} data up to a $p_T \sim 20-50$ GeV. However, the nuclear modification factor does not form a plateau-like structure at a $p_T > 100$ GeV as indicated by the measured data [1, 2, 12] for any of the above discussed models.

3. Summary

We estimate the reduction factor of the jet-medium coupling between RHIC and LHC based on a simple generic energy-loss model with $dE/dx \sim E^a$ and find that a moderate 10% reduction of the runnning coupling allows to simultaneously describe the nuclear modification factor and the elliptic flow of high-p_T pions as a function of p_T as well as a function of centrality at LHC energies. Additionally we demonstrated that models with an energy loss of $dE/dx \sim E^{a<1/3}$ follow the trend of the R_{AA}-data for *both* RHIC and LHC energies.

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References

[1] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72**, 1945 (2012).

[2] B. Abelev *et al.* [ALICE Collaboration], arXiv:1208.2711 [hep-ex].

[3] W. A. Horowitz and M. Gyulassy, Nucl. Phys. A **872**, 265 (2011).

[4] A. Adare *et al.* [PHENIX Collaboration], arXiv:1208.2254 [nucl-ex].

[5] B. Betz, M. Gyulassy and G. Torrieri, Phys. Rev. C **84**, 024913 (2011); B. Betz and M. Gyulassy, Phys. Rev. C **86**, 024903 (2012).

[6] A. Drees, H. Feng, and J. Jia, Phys. Rev. C **71**, 034909 (2005); J. Jia and R. Wei, Phys. Rev. C **82**, 024902 (2010).

[7] A. Ficnar, Phys. Rev. D **86**, 046010 (2012).

[8] S. S. Gubser, D. R. Gulotta, S. S. Pufu and F. D. Rocha, J. High Energy Phys. **10**, 052 (2008).

[9] D. Molnar, J. Phys. G **30**, S235 (2004).

[10] J. Liao and E. Shuryak, Phys. Rev. Lett. **102**, 202302 (2009).

[11] A. Buzzatti and M. Gyulassy, Phys. Rev. Lett. **108**, 022301 (2012).

[12] CMS Collaboration, CMS-PAS-HIN-12-004.