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Extracting $\hat{q}$ in event-by-event hydrodynamics and the centrality/energy puzzle

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Abstract

In our analysis, we combine event-by-event hydrodynamics, within the EKRT formulation, with jet quenching -ASW Quenching Weights- to obtain high-p_T $R_{\rm AA}$ for charged particles at RHIC and LHC energies for different centralities. By defining a K-factor that quantifies the departure of $\hat{q}$ from an ideal estimate, $K = \hat{q}/(2\epsilon^{3/4})$, we fit the single-inclusive experimental data for charged particles. This K-factor is larger at RHIC than at the LHC but, surprisingly, it is almost independent of the centrality of the collision.

Keywords: jet quenching, event-by-event hydrodynamics, energy loss

1. Introduction

Jet quenching is a fruitful tool to extract medium parameters that characterize the quark-gluon plasma formed in high-energy nuclear collisions. We perform here an extraction of the $\hat{q}$ parameter using RHIC and LHC data on the nuclear modification factor, $R_{\rm AA}$, for single-inclusive particle production at high transverse momentum. The formalism of Quenching Weights [1, 2, 3], embedded in EKRT event-by-event (EbyE) hydrodynamic model of the medium [4], is used.

We define the jet quenching parameter $K \equiv \hat{q}/(2\epsilon^{3/4})$, motivated by the ideal estimate $\hat{q}_{\rm ideal} \sim 2\epsilon^{3/4}$ [5], where ϵ is the energy density given by the EKRT hydrodynamic description. Our main conclusions are that this K-factor is $\sim 2-3$ times larger for RHIC than for the LHC and, unexpectedly, it is not dependent on the centrality of the collision.

2. Jet quenching formalism

Our analysis is restricted to the simplest observable, the nuclear modification factor, R_{AA}, given by:

$$R_{AA} = \frac{dN_{AA}/d^2p_Tdy}{\langle N_{coll}\rangle dN_{pp}/dp_T^2dy}\,; \quad (1)$$

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hence, both the vacuum and the medium single-inclusive cross sections need to be calculated.

The cross section of a hadron h at rapidity y and transverse momentum p_T can be described by

$$\frac{d\sigma^{AA\to h+X}}{dp_T dy} = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\frac{dz}{z}\sum_{i,j,k} x_1 f_{i/A}(x_1,Q^2)x_2 f_{j/A}(x_2,Q^2)\frac{d\hat{\sigma}^{ij\to k}}{d\hat{t}}D_{k\to h}(z,\mu_F^2)\,, \tag{2}$$

where A is the mass number of the nucleus, so $A = 1$ for the vacuum cross section. $f_{i/A}(x_1, Q^2)$ are the PDFs, $d\hat{\sigma}^{ij\to k}/d\hat{t}$ the partonic cross section and $D_{k\to h}(z,\mu_F^2)$ the fragmentation functions.

All these computations are done at NLO using the code [6], with the proton PDF set CTEQ6.6M [7] and DSS vacuum fragmentation functions [8]. The renormalization, fragmentation and factorization scales are taken as $\mu_F = p_T$. For the medium cross section, EPS09 nPDFs [9] are used and the energy loss is absorbed in a redefinition of the fragmentation functions:

$$D^{(med)}_{k\to h}(z,\mu_F^2) = \int_0^1 d\epsilon P_E(\epsilon)\frac{1}{1-\epsilon}D^{(vac)}_{k\to h}\left(\frac{z}{1-\epsilon},\mu_F^2\right)\,, \tag{3}$$

where $P_E(\epsilon)$ are the ASW Quenching Weights.

The Quenching Weights are the probability distribution of a fractional energy loss, $\epsilon = \Delta E/E$, of the fast parton in the medium. They are based on two main assumptions: fragmentation functions are not medium-modified and gluon emissions are independent, see [10]. These are good approximations for the total coherence case and for soft radiation [11, 12, 13]. Indeed, QW and rate equations are equivalent for soft radiation and no finite energy effects. In our study, the QW are used in the multiple soft approximation.

The quenching weights, $P_i(\Delta E/\omega_c, R)$, are dependent on two variables: $\omega_c = \frac{1}{2}\hat{q}L^2$, and $R = \omega_c L$. These variables, can be obtained for a dynamic medium by [2]

$$\omega_c^{eff}(x_0,y_0,\tau_{\rm prod},\phi) = \int d\xi\,\xi\,\hat{q}(\xi), \qquad R^{eff}(x_0,y_0,\tau_{\rm prod},\phi) = \frac{3}{2}\int d\xi\,\xi^2\,\hat{q}(\xi)\,. \tag{4}$$

So, we only need to specify the relation between the local value of the transport coefficient $\hat{q}(\xi)$ at a given point of the trajectory and the hydrodynamic properties of the medium:

$$\hat{q}(\xi) = K\cdot 2\epsilon^{3/4}(\xi)\,, \tag{5}$$

where $K \simeq 1$ would correspond to the ideal QGP [5]. The local energy density $\epsilon(\xi)$ is taken from the EKRT simulations [4].

3. EKRT hydrodynamics

We obtain the EbyE space-time distribution of the local energy density by solving the relativistic hydrodynamic equations with EKRT initial state, with constant shear viscosity $\eta/s = 0.2$ and starting time of viscous hydrodynamics $\tau_0 = 0.197$ fm [4]. In our previous analysis several smooth-averaged hydrodynamic simulations were used [10]. We show here that our current results are compatible with the previous ones.

There is an ambiguity on the definition of $\hat{q}$, Eq. (5), for times smaller than the thermalization time τ_0. Nevertheless, as τ_0 for the EKRT hydro is much smaller than for the smooth-averaged ones, the differences coming from the various extrapolations for times prior to thermalization are reduced. Hence, we consider here only one extrapolation:

$$\hat{q}(\xi) = \hat{q}(\tau_0) \quad \text{for} \quad \xi < \tau_0\,. \tag{6}$$

4. Results

We study the nuclear modification factor, R_{AA}, both at RHIC [14] and the LHC [15] at different centralities. A χ^2 fit to the best value of K for each energy and centrality is performed. The uncertainty band is determined by $\Delta\chi^2 = 1$. In Fig. 1, the different values of the K-parameter fitted to PHENIX [14] (left panel) and LHC [15] (rigth panel) data are plotted.

First of all, the fitted value at RHIC confirms large corrections to the ideal case, while the corresponding one at the LHC is close to the unity. The K-factor obtained is $\sim 2-3$ times larger for RHIC than for the LHC. Other groups [16] have found a factor ~ 1.25. Second, the LHC results are constant except for the most peripheral collisions. Consequently, the fitted value of K seems to be mostly dependent on the energy of the collision rather than on its centrality.

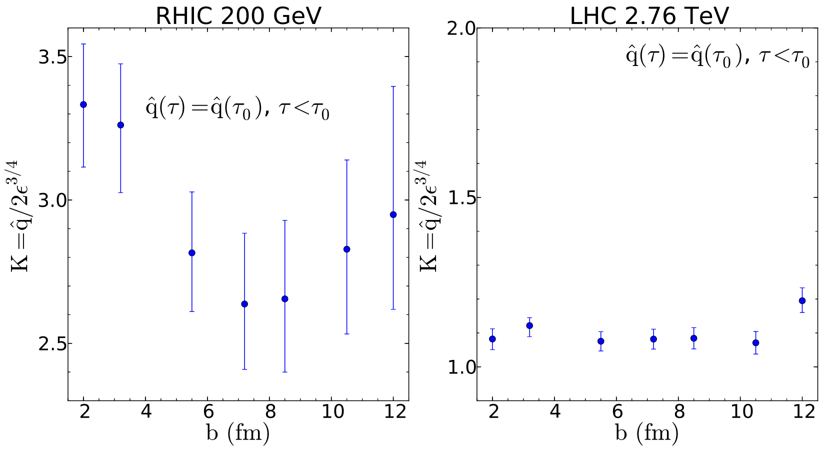

Fig. 1. K-factors obtained from fits to PHENIX R_{AA} data [14] *(left panel)* and to ALICE R_{AA} data [15] *(right panel)* versus the average impact parameter for each centrality class, b.

There is an overlap on typical temperatures (or energy densities) between semi-peripheral PbPb collisions at the LHC and central Au-Au at RHIC, however, the values of K do not coincide. To illustrate this we show in Figure 2, the K-factors obtained for different centralities and energies versus an energy density times formation time τ_0 extracted from the experimental data using Bjorken estimates [17, 18].

5. Conclusions

We have performed an analysis of the single-inclusive suppression of high-p_T particles as a function of centrality and the energy of the collision. A K-factor $\hat{q} \simeq 2\epsilon^{3/4}$ is defined. This factor is fitted to the corresponding experimental data at RHIC and LHC for different centralities. The fitted value at the LHC is close to unity, while the one at RHIC confirms large corrections to the ideal case.

The centrality dependences at RHIC and the LHC separately are rather flat. Therefore, the change in the K-factor is not only due to the different temperature, as there is a large region of overlap between RHIC and the LHC for different centralities. Its value would not depend on local properties of the QGP as temperature, but on global collision variables such as the center of mass energy. This result was completely unexpected. An analysis of the same data [19] advocates for the virtuality to be responsible of the difference at RHIC and LHC. If the virtuality is estimated by the measured p_T of the hadron our approach will give the same suppression irrespective of the collision energy even if virtuality is included in the energy loss mechanism. We notice that there is a region of overlap in p_T between RHIC and LHC which we reproduce with the same quality.

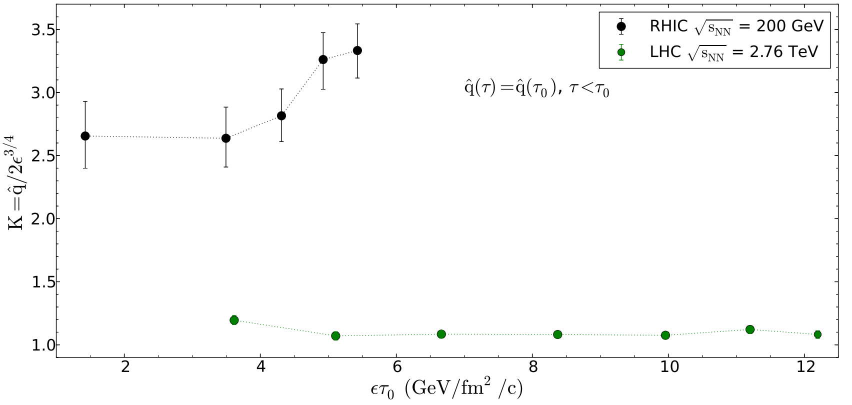

Fig. 2. *K*-factor at RHIC and LHC energies for different centrality classes versus an estimate of the energy density [17, 18]

Various limitations may affect the results. The two assumptions that support the QW-formalism could fail if color coherence is broken. Perturbative tails of the distributions are neglected in the multiple soft scattering approximation. This may enhance the energy loss. Collisional energy loss is absent in our formalism.

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