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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:

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

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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:

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