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Color transparency and suppression of high-p_T hadrons in nuclear collisions

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The production length l_p of a leading (large z_h) hadron produced in hadronization of a highly virtual high-p_T parton is short because of the very intensive vacuum gluon radiation and dissipation of energy at the early stage of the process. Therefore, the main part of nuclear suppression of high-p_T hadrons produced in heavy ion collisions is related to the survival probability of a colorless dipole propagating through a dense medium. This is subject to color transparency, which leads to a steep rise with p_T of the nuclear ratio $R_{AA}(p_T)$, in good agreement with the recent data from the ALICE experiment at the CERN Large Hadron Collider (LHC). No adjustment, except for the medium density, is made, and the transport coefficient is found to be $\hat{q}_0 = 0.8\ \mathrm{GeV}^2/\mathrm{fm}$. This is close to the value extracted from the analysis of BNL Relativistic Heavy Ion Collider (RHIC) data for J/Ψ suppression, but is an order of magnitude smaller than the value found from jet quenching data within the energy loss scenario. Although the present calculations have the status of a postdiction, the mechanism and all formulas have been published, and are applied here with no modification, except for the kinematics. At the same time, p_T dependence of R_{AA} at the energy of RHIC is rather flat due to the suppression factor steeply falling with rising x_T, related to the energy conservation constraints. This factor is irrelevant to the LHC data, since x_T is much smaller.

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I. INTRODUCTION

One of the first results of the heavy ion program at the CERN Large Hadron Collider (LHC) is the observation in the ALICE experiment [1] of a strong nuclear suppression of high-p_T charged hadrons. These data expose novel features compared with similar measurements at the BNL Relativistic Heavy Ion Collider (RHIC) [2,3]. First, the nuclear suppression factor R_{AA} reaches significantly smaller values. This is not a surprise, since at the LHC energies, hadrons originate mainly from hadronization of gluons, which have a larger color charge than quarks dominating at RHIC. Correspondingly, gluons dissipate energy with a higher rate. Second, $R_{AA}(p_T)$ steeply rises with p_T, while it exposes a rather flat p_T dependence in RHIC data. The latter is affected by the restrictions imposed by energy conservation [4]. It was predicted [5] that the production rate for hadrons and direct photons is suppressed in pA and AA collisions by the deficit of energy not only at forward rapidities, but also at large $x_T = 2p_T/\sqrt{s}$. Here we concentrate on the interpretation of LHC data, which are free of these complications, since the values of x_T are very small.

The popular model explaining the observed suppression of R_{AA} at high p_T relates it to the induced radiation energy loss by a parton propagating through the medium, which was created in the nuclear collision (e.g. see in Ref. [6]). This energy-loss scenario is based on the unjustified assumption that hadronization of the parton lasts longer than the time of propagation through the medium, and that the detected hadron is always produced outside the medium. However, because of the steeply falling p_T dependence of the cross section, most high-p_T hadrons carry a large fraction z_h of the jet momentum, and energy conservation constrains the production length l_p for such leading hadrons. It is expected to be rather short even within the simple string model [7,8], and should be much shorter in the case of intensive vacuum gluon radiation by a high-p_T parton.

One should clearly distinguish between the production time scales for a colorless dipole (pre-hadron) and for the final hadron. The former signals on color neutralization, which stops the intensive energy loss caused by vacuum radiation following the hard process, while the latter is a much longer time taken by the dipole to gain the certain hadronic mass, i.e., to develop the hadron wave function. While the former contracts $\propto (1 - z_h)$ at large fractional momentum z_h of the hadron, the latter keeps rising $\propto z_h$. These two time scales are frequently mixed up. The shortness of the production lengths at large z_h is dictated by energy conservation. Indeed, a parton originated from a hard reaction intensively radiates and loses energy, and this cannot last long, otherwise the parton energy will drop below the energy of the detected hadron.

One should also distinguish between the mean hadronization time of a jet, whose energy is shared among many hadrons, and specific events containing a leading hadron with $z_h \to 1$. Production of such a hadron in a jet is a small probability fluctuation, usually associated with large rapidity gap events. The space-time development of such an unusual jet is different from the usual averaged jet.

The controversy between the models with short and long production times has been under debate for the last two decades (see Refs. [5,9]), but no proof of a long time scale has been proposed so far, to the best of our knowledge. Of course, an experimental verification would be most convincing. Data on high-p_T hadron production in heavy ion collisions provide a rather poor test of the models. Too many uncertainties are involved, the medium properties are unknown, and their variation in space and time is based on simplified, even ad hoc models. The fractional energy z_h is not known but enters into the convolution of the initial parton distribution, hard cross section, and the fragmentation function. The important contribution of initial state effects (cold nuclear matter) can be only calculated within models.

Probably the best way to study the space-time development of hadronization is through the inclusive hadron production in deep inelastic scattering (DIS) on nuclei at large Bjorken x. In this case, the medium density and its spacial distribution are well known. The fractional energy z_h of the hadron is directly measured. A good model should predict the nuclear modification factor with no fitting. Indeed, such a prediction was provided in Ref. [10] within the hadronization model with a finite production length. Later, the first data from the HERMES experiment [11] confirmed well this prediction. Also the HERMES results on the broadening of transverse momentum, sensitive to the production length [9], were explained well in Ref. [12]. On the other hand, the comprehensive study of nuclear effects within the pure energy loss scenario performed recently in Ref. [13] led to striking disagreement with data for leading hadrons.

Here we rely on the model [14] for the production time distribution of leading hadrons in a jet, produced at the midrapidity. In this case, the initial parton energy and virtuality are equal,

$$E = Q = k_T = \frac{p_T}{z_h}, \quad (1)$$

where k_T and p_T are the transverse momenta of the parton initiating the jet and of the detected hadron, respectively. An example of the l_p distribution at $z_h = 0.7$ and different quark jet energies is shown in Fig. 1.

One can see that the l_p distribution narrows with energy but levels off at high energies. This happens because of compensation of several effects [14], acting in opposite directions. The Lorentz factor makes l_p longer with energy, while the increasing virtuality gives rise to a more intensive gluon radiation and energy loss in vacuum, leading to a shorter l_p. Moreover, the Sudakov suppression, essential at large z_h, also shortens l_p.

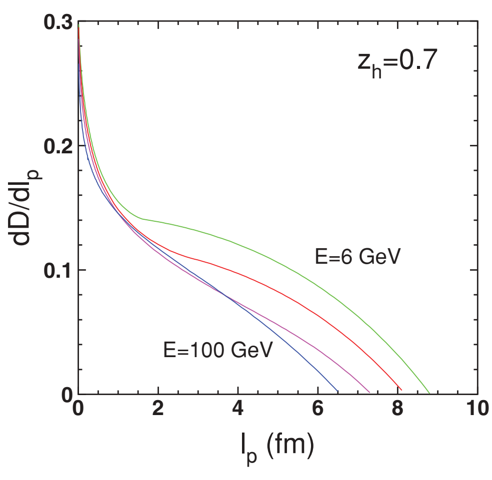

FIG. 1. (Color online) Prehadron production length distribution $\partial D(z)/\partial l_p$ (in arbitrary units) for a quark jet with energies $E = k_T = 6,\ 10,\ 20,\ 100\,\text{GeV}$ (from top to bottom) and $z_h = 0.7$.

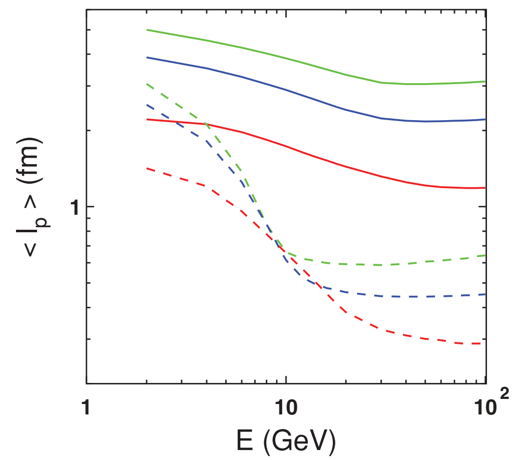

FIG. 2. (Color online) Mean production length as a function of energy for quark (solid curves) and gluon (dashed curves) jets. In both cases the curves are calculated at $z_h = 0.5,\ 0.7,\ 0.9$ (from top to bottom).

The mean value $\langle l_p \rangle$ for quark jets, weighted with the distribution dD/dl_p, is depicted by solid curves in Fig. 2, as a function of energy, for $z_h = 0.5,\ 0.7,\ 0.9$. Indeed, $\langle l_p \rangle$ saturates at high jet energies $E = k_T$.

Notice that in DIS the mean production length at fixed Q^2 rises linearly as a function of energy. This case is quite different from high-p_T, where the virtuality increases with energy.

For gluon jets, the energy loss is larger and the Sudakov suppression stronger due to the Casimir factor. This leads to a shorter production length. The mean value of l_p for gluon jets as a function of energy is depicted in Fig. 2 by dashed curves for several values of z_h. We see that at high energies, $\langle l_p \rangle < 1\,\text{fm}$. Thus, one can say that the prehadron is created almost instantaneously, because its production time is shorter than the expected time of medium creation, $t_0 \sim 1\,\text{fm}$.

An interesting possibility of a very dense medium was considered in Refs. [5,15]. If the medium were so dense that the mean free path of the produced dipole was vanishingly small, the nuclear suppression factor R_{AA} would be proportional to $\langle l_p^2 \rangle$, and could be predicted in a parameter-free way. Although such a possibility does not contradict RHIC data on jet quenching [5,15], the recent study of J/Ψ suppression in heavy ion collisions [16,17] found that the density of the medium is rather low. The maximal value of the transport coefficient reached at the time scale of the medium creation $t_0 \sim 1\,\text{fm}$ was found to be quite low, $\hat{q}_0 \sim 0.2\ \text{GeV}^2/\text{fm}$, an order of magnitude smaller than follows from hadron suppression data interpreted within the energy loss formalism [18]. Thus, the scenario of a very dense medium is not supported by data, and one should study the propagation of a colorless dipole through a moderately opaque medium.

Here we employ the same description of dipoles in a medium as was used for J/Ψ suppression [16], and apply it to high-p_T processes. The main difference is the time scale of formation of the final hadron: while it is very short for a heavy and slow J/Ψ [16,17], the formation of the wave function of a light $\bar{q}q$ dipole moving with a high momentum is rather long. Correcting for this, we apply the same description to the suppression nuclear factor $R_{AA}(p_T)$ for hadrons produced in central lead-lead collisions at LHC, and achieve good agreement with the recent data from the ALICE experiment [1]. Moreover, we found a value of the transport coefficient similar to what was found from J/Ψ data at RHIC.

II. ATTENUATION OF A SMALL SIZE DIPOLE IN A MEDIUM

A parton, which experienced a hard scattering with transverse momentum k_T, shakes off its color field in the form of a forward cone of gluon radiation, and starts propagating along a new direction, lacking the soft part of its field up to transverse frequencies $\lesssim k_T$. The parton starts regenerating its color field, with transverse size $r(l)$ expanding as function of path length l, starting from the initial small size $r_0 \sim 1/k_T$ at $l = 0$. At some distance l_p a colorless dipole, prehadron, is produced with a size of the order of the transverse size $r(l_p)$ of the regenerated field. We describe the regeneration process and gluon radiation within the dipole approach [19,20].

A small size dipole is expanding so fast that its initial size is quickly forgotten. Indeed, the speed of expansion of a dipole correlates with its size: the smaller the dipole is, the faster it is evolving. This is controlled by the uncertainty principle, $q \sim 1/r$.

$$\frac{dr}{dt} = 2v_T = \frac{2q}{E} \approx \frac{2}{E\,r}, \tag{2}$$

where $E = p_T$ is the dipole energy in the c.m. of the collision; v_T and $q \sim 1/r$ are the transverse velocity and momentum of the quark relative to the dipole momentum direction. The solution of this equation reads [16,17]

$$r^2(t) = \frac{4\,t}{p_T} + r_0^2, \tag{3}$$

where $r_0 \sim 1/p_T$ is the initial dipole size, neglected in what follows.

Propagation of a dipole over path length L in a medium is characterized by a survival probability

$$S(L) = \exp\left[-\int_0^L dl\,\sigma[r(l)]\,\rho(l)\right], \tag{4}$$

where the dipole cross section $\sigma(r)$ times the medium density ρ is the attenuation rate of the dipole.

The dipole cross section for small dipoles is $\sigma(r) = C\,r^2$. The factor C, for dipole-proton interactions, is known from DIS data. Its value for a hot medium is unknown, as well as the medium properties. It is convenient to express it in terms of the so-called transport coefficient, which is the broadening of a parton in the medium over the path length 1 fm. Indeed, the same factor C controls both the dipole cross section and broadening of a quark propagating through the medium [21,22]. So, the factor C in the dipole cross section is related to the transport coefficient $\hat{q}$ [23], which is the in-medium broadening per unit of length,

$$C = \frac{\hat{q}}{2\,\rho}. \tag{5}$$

Then, using Eq. (3) (with $t = l$) one can represent the survival probability of the dipole in the medium, Eq. (4), as

$$\begin{aligned} S(L) &= \exp\left[-\frac{1}{2}\int_0^L dl\,\hat{q}(l)\,r^2(l)\right] \\ &= \exp\left[-\frac{2}{p_T}\int_0^L dl\,l\,\hat{q}(l)\right]. \end{aligned} \tag{6}$$

Now we are in a position to calculate the nuclear attenuation factor for a high-p_T hadron produced in a heavy ion collision. For central ($b = 0$) collisions of two identical nuclei, one should integrate over the impact parameter $\vec{\tau}$ of the hard collision, with a weight factor $T_A^2(\tau)$, where $T_A(\tau) = \int_{-\infty}^{\infty} dz\,\rho_A(\vec{\tau}, z)$ is the nuclear thickness function, the integral of nuclear density along the collision direction:

$$R_{AA}(b = 0, p_T) = \frac{\int_0^\infty d^2\tau\,T_A^2(\tau)\,R_{AA}(\tau, p_T)}{\int_0^\infty d^2\tau\,T_A^2(\tau)}. \tag{7}$$

The factor $R_{AA}(\tau, p_T)$ is the nuclear suppression factor corresponding to production of a high-k_T parton at impact parameter $\vec{\tau}$, propagating then over a path length $\langle l_p\rangle$, radiating gluons and losing energy, and eventually producing a colorless dipole prehadron with transverse momentum $\vec{p}_T = \vec{k}_T/z_h$, which propagates through the nucleus, its size evolving according to Eq. (3). We rely on the above evaluation of $\langle l_p\rangle$ in vacuum, since the medium-induced energy loss is much smaller than the vacuum one. Besides, induced energy loss can make l_p only shorter, which will not affect the further calculations. This suppression factor has the form [16,17]

$$R_{AA}(\vec{\tau}, p_T)\Big|_{b=0} = \int_0^\pi \frac{d\phi}{\pi}\exp\left[-\frac{2}{p_T}\int_{l_{\max}}^\infty dl\,l\,\hat{q}(\vec{\tau}+\vec{l})\right], \tag{8}$$

where $l_{\max} = \max\{l_p, l_0\}$. Here $t_0 = l_0 \sim 1$ fm is the time scale of creation of the medium resulted from gluon radiation at midrapidities in heavy ion collisions. Since the production length for a gluon jet is short, $\langle l_p\rangle \lesssim l_0$, its actual value is not important.

The medium density is time dependent and is assumed to dilute as $\rho(t) = \rho_0\,t_0/t$ due to the longitudinal expansion of the produced medium. Correspondingly, the transport coefficient depends on impact parameter and time (path length) as [24]

$$\hat{q}(l, \vec{b}, \vec{\tau}) = \frac{\hat{q}_0\,l_0}{l}\,\frac{n_{\rm part}(\vec{b}, \vec{\tau})}{n_{\rm part}(0, 0)}, \tag{9}$$

where $n_{\rm part}(\vec{b}, \vec{\tau})$ is the number of participants; $\hat{q}_0$ corresponds to the maximum medium density produced at impact parameter $\tau = 0$ in central collisions ($b = 0$) at the time $t = t_0 = l_0$ after the collision. In what follows, we treat the transport coefficient $\hat{q}_0$ as an adjusted parameter.

III. RESULTS VS DATA

The results of the calculation with Eqs. (7) and (8) with $\hat{q}_0 = 0.8$ GeV^2/fm are shown by the solid curve in Fig. 3, in comparison with ALICE data [1]. Except for $\hat{q}_0$, no further adjustment was done, and agreement with data at large $p_T >$ 7 GeV is pretty good. Moreover, the transport coefficient turns

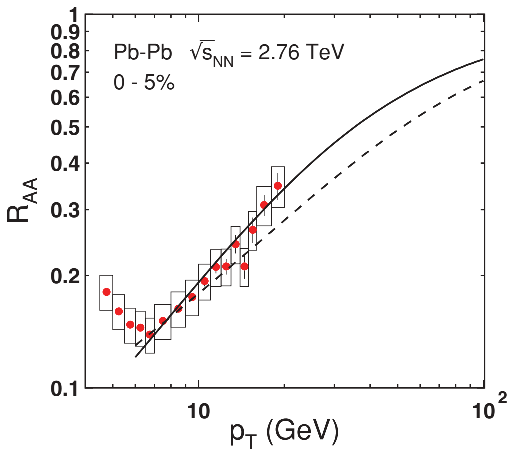

FIG. 3. (Color online) ALICE data for central, 0–5%, lead-lead collisions at $\sqrt{s} = 2.76$ GeV [1]. The solid curve corresponds to Eqs.(7) and (8) calculated with $l_p \leqslant l_0 = 1$ fm and $\hat{q}_0 = 0.8$ GeV^2/fm. The dashed curve, calculated with $l_p = 2$ fm, demonstrates sensitivity to l_p.

out to be of the same order as was found in Ref. [16] from data on J/Ψ production.

The dashed curve in Fig. 3 demonstrates the sensitivity to l_p. It is calculated at $\langle l_p \rangle = 2$ fm and accordingly adjusted $\hat{q}_0 = 1.6$ GeV^2/fm. Since at large $p_T \gtrsim 100$ GeV, valence quarks with larger l_p should dominate, the rise of R_{AA} with p_T should slightly slow down, deviating from the solid curve toward the dashed one.

We do not attempt here to describe R_{AA} at $p_T < 7$ GeV, since the dynamics becomes much more complicated. First, the production length becomes several time longer, as is depicted in Fig. 2. Second, one should take into account the Cronin effect in AA collisions, which is poorly known because of the large fraction of baryons in detected charged hadrons.

For the same reason, application of this mechanism to high-p_T hadron production at RHIC goes beyond the scope of this paper, since it involves a more complicated and model-dependent dynamics. Indeed, it was demonstrated in Ref. [4] that for particle production at forward rapidities, $x_F \gtrsim 0.1$, energy conservation becomes an issue. It causes additional nuclear suppression, steeply increasing with x_F. The same, of course, should happen at large $x_T = 2p_T/\sqrt{s}$. It was demonstrated in Ref. [5] that this mechanism leads to suppression of high-p_T hadrons and direct photons in pA and AA collisions. Therefore, besides other reasons (different kinematics, valence quark dominance, etc.), this mechanism makes the p_T dependence of $R_{AA}(p_T)$ significantly flatter at RHIC than at LHC. Detailed calculations for the RHIC energy domain will be published elsewhere.

IV. SUMMARY

Although these calculations have a postdiction status, the mechanism and all formulas have been already published, and we apply them here with no specific modification, except for the kinematics. The dynamics of nuclear suppression of high-p_T hadrons produced in central lead-lead collisions at $\sqrt{s} = 2.76$ GeV is based on the shortness of the production length of a prehadron, and its development and propagation through a dense medium. We performed calculations within the same scheme as was used for the analysis [16] of J/Ψ production data. Moreover, we arrived at a value of the transport coefficient, characterizing the properties of the medium, which is pretty close to the value extracted from J/Ψ data, and is an order of magnitude smaller than what was obtained from analyses of jet quenching RHIC data based on the energy loss scenario.

These calculations can be improved by replacing the simplified description of the dipole evolution, Eq. (3), with the rigorous quantum-mechanical approach [25] based on the path integral technique. This description can be also applied to RHIC data on jet quenching, but one should introduce a model-dependent suppression factor, which is related to the constraints on nuclear parton distributions imposed by energy conservation [4]. These further developments of the present approach will be published elsewhere.

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