Flavor-independent yield of high-p_T hadrons from nuclear collisions

B. Z. Kopeliovich [1,*] and J. Nemchik [2,3,†]

[1] *Departamento de Física, Universidad Técnica Federico Santa María, Avenida España 1680, Valparaíso, Chile*
[2] *Czech Technical University in Prague, FNSPE, Břehová 7, 11519 Prague, Czech Republic*
[3] *Institute of Experimental Physics SAS, Watsonova 47, 04001 Košice, Slovakia*

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Data on high-p_T hadron production in heavy ion collisions at Feynman $x_F = 0$ indicate at universality of the observed nuclear suppression. Our analysis of the production mechanisms demonstrates important role of the color transparency effects which make the survival probability of a quark-antiquark dipole independent of the quark flavor, provided that the hadron wave function is formed outside the medium. The latter condition imposes restrictions on the range of p_T, which should be sufficiently high to make the nuclear suppression universal. We also found that the in-medium broadening rate $\hat{q}$ (frequently called transport coefficient) significantly depends on the quark flavor, diminishing for heavy quarks.

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I. INTRODUCTION

Measurements of high-p_T hadron production in heavy ion collisions (HICs) from the ALICE experiment [1,2] revealed a remarkable universality of the nuclear suppression factors R_{AA} for different species of produced hadrons, such as pions, kaons, and protons. Besides, the ATLAS data on prompt production of J/Ψ [3] demonstrate a similar attenuation as was measured for the light hadrons. Such an observation can be hardly described by models based on the energy-loss scenario (see Ref. [4], for example) where only induced energy loss by a parton propagating through the dense medium represent the main reason for the high-p_T hadron suppression. Here the hadronization process, closely connected with a different radiation by light and heavy quarks, cannot lead to similar magnitudes of R_{AA} for the light and heavy flavored particles. Besides, different mechanisms for production of mesons and baryons should naturally exclude the universality of R_{AA}. In the present paper we demonstrate an alternative scenario of the in-medium hadronization process with a proven shortness of the hadronization length [5–8]. Then the main source of suppression of the production rate comes from the survival probability of the produced colorless dipoles propagating through the medium. Whereas at small and medium values of p_T the dipole size is controlled by quark masses, in the region of sufficiently high p_T it decreases with p_T and the quark mass does not play any role. This is a typical manifestation of the color transparency (CT) effect [9,10], which describes the flavor independent attenuation of propagating dipoles in the medium and thus allows to explain the observed universality in production of different hadrons.

The paper is organized as follows. In the next Sec. II we prove briefly that gluon radiation ceases shortly after a hard collision due to color neutralization and production of a colorless dipole. We demonstrate that the duration of this stage of hadronization, accompanied by the vacuum energy loss, is very short and decreases with the quark mass and p_T. In Sec. III we present model predictions for the nuclear modification factor R_{AA} as function of p_T for production of various hadronic species in HICs. We prove that the dominant source of suppression turns out to be related to propagation in the medium of high-p_T hadrons during formation of their wave functions. The regime of universal suppression onsets at sufficiently large $p_T > p_T|^h_{\rm min}$. The corresponding values of $p_T|^h_{\rm min}$ are evaluated for pions, kaons, J/ψ, Υ, as well as open heavy flavored D and B mesons. We demonstrate that model calculations are in a good agreement with available data. The results of the paper are summarized and discussed in Sec. IV.

[*] Contact author: boris.kopeliovich@usm.cl
[†] Contact author: jan.nemcik@fjfi.cvut.cz

II. PRODUCTION LENGTH IN VACUUM

The popular scenario for quenching of high-p_T hadrons in heavy ion collisions is based on the medium-induced energy loss model (see, e.g., Ref. [4]). The main assumption of the model, which has never been justified, is a long hadronization length. The process is assumed to end up with production of the detected hadron well outside of the dense medium created in HICs. This assumption was challenged in Refs. [5,6,11] with a detailed study of the hadronization dynamics, which led to a conclusion that hadronization length L_p is very short, of the order of $1 \div 2$ fm. The main reason for that is the intensive gluon radiation by a highly virtual parton originated from a high-p_T hard reaction. Here the important issue is energy conservation. Namely, a parton during the hadronization process may dissipate so much energy that cannot produce a hadron with large light-front (LF) momentum fraction z. Let us recall the main observations of that consideration:

(i) The mean hard scale of the process $\bar{Q} = \sqrt{q_T^2 + m^2}$ and the jet energy coincide. Here q_T and m are the transverse momentum and mass of the initially produced parton;

(ii) A parton originated from a hard process is lacking a part of its color field with transverse frequencies k_T up to the scale of the process $k_T \lesssim \bar{Q}$. It regenerates the stripped off field by radiating gluons. The perturbative spectrum of radiation reads,

$$\frac{dn_g}{dx dk_T^2} = \frac{2\alpha_s(k_T^2)}{3\pi x} \frac{k_T^2[1 + (1 - x)^2]}{[k_T^2 + x^2 m_Q^2]^2}, \qquad (1)$$

where x is the fractional LF momentum taken away by the radiated gluon. The gluons are radiated, i.e., get to mass shell, when lose the coherence with the source quark due to large a phase shift between the Fock components of the quark, $|q\rangle$ and $|qg\rangle$. So the coherence length for gluon radiation is given by

$$L_c^g = \frac{2Ex(1 - x)}{k_T^2 + x^2 m_q^2}. \qquad (2)$$

Here $E = E_T$ is the energy of the quark in the reference frame, where it has no longitudinal momentum.

As far as the radiation length is known, one can evaluate how much energy is radiated along the path length L,

$$\Delta E_{\rm rad}(L) = \int_{\lambda^2}^{\bar{Q}^2} dk_T^2 \int_0^1 dx\, \omega \frac{dn_g}{dx dk_T^2} \Theta(L - L_c^g), \qquad (3)$$

where $\omega = xE$ is the gluon energy and $\lambda = 0.2$ GeV is the soft cutoff parameter.

Now one can trace how much energy is radiated by a high-q_T quark as function of L. Some examples are depicted in Fig. 1 for different quark energies. One can see that a substantial fraction of the initial parton energy is radiated at a short path length of the order of fm. At longer distances radiation ceases;

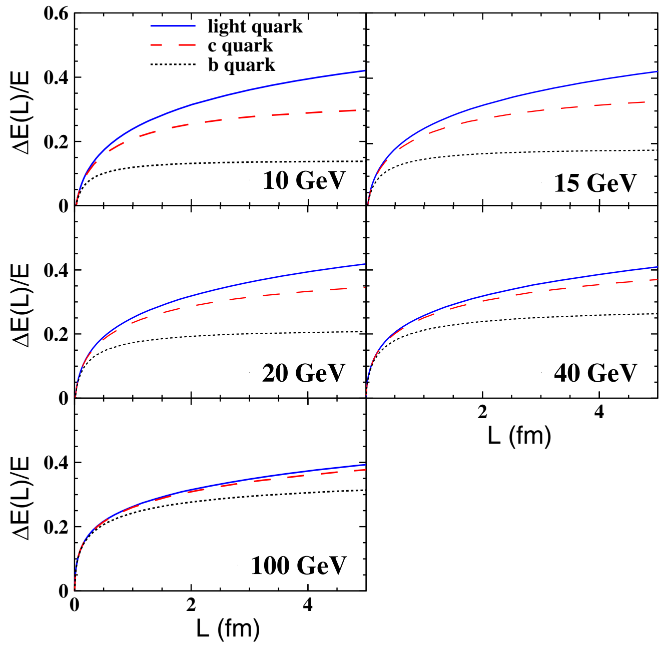

FIG. 1. Fractional radiational energy loss in vacuum by light (q), c and b quarks as function of path length for different initial quark energies $E = \sqrt{p_T^2 + m_q^2}$.

(iii) Figure 1 demonstrates that the fraction $\Delta E_{\rm rad}$ of the total radiated energy depends on the quark mass as was analyzed in Refs. [8,11,12]. The heaver the quark is, the smaller fraction of its energy can be radiated. This is a result of the *dead cone effect* [13] in accordance with Eq. (1). However, the rates of parton energy loss, extracted from experimental data in Ref. [14] using the Bayesian statistical analysis, exhibit an opposite trend vs quark masses, $\Delta E_q \sim \Delta E_c > \Delta E_b$. Similarity of energy loss for light and c quarks can be seen directly in the LHC data, which exhibit a comparable nuclear suppression for light hadrons and D mesons. Apparently, the results of this analysis are in contradiction with the dead cone effect, predicting an unambiguous hierarchy $\Delta E_q > \Delta E_c > \Delta E_b$ discussed in Ref. [15].

Figure 1 also shows a substantial difference between radiational dissipation of energy by heavy and light quarks [16–21]. One can see that radiation by heavy quarks ceases shortly. While heavy quarks radiate only a small fraction of their initial energy, $\Delta z = \Delta E_{\rm rad}/E$, light quarks lose for radiation most of the initial energy;

(iv) The p_T-dependence of the hadron production rate is given by convolution of the q_T dependent parton production cross section and the fragmentation function of a quark to hadron $D_{q/h}(z)$, where $z = p_T/q_T$,

$$\frac{d^2\sigma_{pp\to hX}}{d^2p_T} = \frac{1}{2\pi p_T E_T}\int d^2q_T \frac{d^2\sigma_{pp\to qX}}{d^2q_T} zD_{q/h}(z). \quad (4)$$

Extension to a gluon fragmentation is straightforward.

In the convolution Eq. (4) the mean value of $z\sim 0.6$–0.7 depending on the collision energy and hadron transverse momentum p_T as was evaluated in Ref. [5]. The corresponding calculations were based on the model-independent evaluation of the time of hadronization, which stops with the neutralization of the leading quark color by picking up an antiquark. Here we adopted the Berger model [22], which assumes equal sharing of the dipole LF momentum between q and $\bar{q}$.

III. PRODUCTION OF HIGH-p_T MESONS

A. Light mesons produced in HICs

Besides of energy dissipation in vacuum as was described in the previous Sec. II, an additional medium-induced energy loss makes the production length L_p even shorter.

In this section we consider nonstrange $|q\bar{q}\rangle$, as well as strange $|s\bar{q}\rangle$ mesons.

Shortness of the production length implies factorization of short and long distances in the cross section of high-p_T hadron production in collisions of nuclei AA (taken identical for the sake of simplicity) with relative impact parameter $\vec{b}$. Then the ratio of the AA-to-NN cross sections, properly normalized, can be represented as an integral over the transverse overlap of the colliding nuclei,

$$R_{AA}(p_T,b) = \frac{1}{T_{AA}(b)}\int d^2\tau T_A(\vec{\tau})T_A(\vec{b}-\vec{\tau}) \times \int_0^{2\pi}\frac{d\phi}{2\pi} S_{Q\bar{q}}(\vec{b},\vec{\tau},E_T,\phi), \quad (5)$$

where $\vec{\tau}$ is the impact parameter of the hard parton-parton collision, $T_{AA}(b)=\int d^2\tau T_A(\vec{\tau})T_A(\vec{b}-\vec{\tau})$ is the nuclear thickness function, $T_A(\tau)=\int_{-\infty}^{\infty}dz'\rho_A(\tau,z')$, is given by the integral over longitudinal coordinate z' of the nuclear density $\rho_A(\vec{r})$, ϕ is the azimuthal angle between the quark trajectory and reaction plane.

The nuclear suppression factor $S_{Q\bar{q}}(\vec{b},\vec{\tau},E_T,\phi)$ in Eq. (5) is the survival probability of the $Q\bar{q}$ dipole produced in the hard collision with starting transverse separation r_1, and propagating through the medium without inelastic collisions. It has the following form:

$$S_{Q\bar{q}}(\vec{b},\vec{\tau},E_T,\phi) = \frac{\left|\int_0^1 d\alpha\int d^2r_1 d^2r_2 \Psi_h^\dagger(\vec{r}_2,\alpha)G_{Q\bar{q}}(\vec{b},\vec{\tau},E_T,\phi|L_1,\vec{r}_1;L_2,\vec{r}_2)\Psi_{in}(\vec{r}_1,\alpha)\right|^2}{\left|\int_0^1 d\alpha\int d^2r_1 d^2r_2 \Psi_h^\dagger(\vec{r}_2,\alpha)\Psi_{in}(\vec{r}_1,\alpha)\right|^2}. \quad (6)$$

It is subject to color transparency effects; the smaller is the dipole, the higher is its chance to survive in the medium. The most effective way of calculation of the factor $S_{Q\bar{q}}$ is summing up all trajectories of Q and $\bar{q}$. This leads to the path integral formalism, which gives rise to the factor $G_{Q\bar{q}}(\vec{b},\vec{\tau},E_T,\phi|L_1,\vec{r}_1;L_2,\vec{r}_2)$ in Eq. (6). The Green function $G_{Q\bar{q}}(L_1,\vec{r}_1;L_2,\vec{r}_2)$ describes evolution of a dipole starting from transverse separation $\vec{r}_1$ at the longitudinal coordinate L_1 up to size $\vec{r}_2$ at the longitudinal distance L_2, in accordance with the two-dimensional Schrödinger equation [5,23–26],

$$i\frac{d}{dL_2}G_{Q\bar{q}}(L_1,\vec{r}_1;L_2,\vec{r}_2) = \left[\frac{\mu^2-\Delta_{r_2}}{2E_T\alpha(1-\alpha)} - V_{Q\bar{q}}(L_2,\vec{r}_2)\right]G_{Q\bar{q}}(L_1,\vec{r}_1;L_2,\vec{r}_2), \quad (7)$$

with the boundary conditions

$$G_{Q\bar{q}}(L_1,\vec{r}_1;L_2,\vec{r}_2)\big|_{L_1=L_2} = \delta^{(2)}(\vec{r}_2-\vec{r}_1),$$
$$G_{Q\bar{q}}(L_1,\vec{r}_1;L_2,\vec{r}_2)\big|_{L_1>L_2} = 0. \quad (8)$$

In Eq. (7) $\mu^2=(1-\alpha)m_q^2+\alpha m_Q^2$; $E_T=\sqrt{p_T^2+(m_q+m_Q)^2}$ is the energy of the $Q\bar{q}$ dipole.

The imaginary part of the LF potential $V_{Q\bar{q}}(L_2,\vec{r}_2)$ in Eq. (7) is responsible for absorption of the $Q\bar{q}$ dipole in the medium and can be expressed through the broadening rate $\hat{q}$ (usually called transport coefficient) as follows [5]:

$$\mathrm{Im}V_{Q\bar{q}}(L,\vec{r}) = -\frac{1}{4}\hat{q}(L)r^2. \quad (9)$$

It varies with transverse coordinates and time. We rely on the popular model from Ref. [27],

$$\hat{q}(t,\vec{b},\vec{\tau}) = \frac{\hat{q}_0 t_0}{t}\frac{n_{\rm part}(\vec{b},\vec{\tau}+t\vec{p}_T/p_T)}{n_{\rm part}(0,0)}\Theta(t-t_0), \quad (10)$$

where $\hat{q}$ is proportional to the number of participants $n_{\rm part}$ depending on the transverse coordinate $\vec{\tau}$ and impact parameter $\vec{b}$ of the collision. Its maximal value $\hat{q}_0$ is reached for the central collision at $b=\tau=0$ and at $t=t_0$, which is the timescale for medium formation, $t_0\sim 1$ fm. The value of $\hat{q}_0$ is difficult to predict reliably, so it is the fitted parameter in the analysis of data. The falling time dependence is associated with longitudinal expansion of the medium. It is related to the path length of the dipole as $L = t\sqrt{1-(m_q+m_Q)^2/E_T^2}$.

The real part of the light-front potential $V_{Q\bar{q}}$ in Eq. (7) describes the nonperturbative interaction between Q and $\bar{q}$ in the dipole as was discussed in Refs. [24,28]. Here we treat the $Q\bar{q}$ system as free noninteracting partons, like in Ref. [5], i.e., assuming maximal effects of absorption. We checked that the real part of potential does not affect much the dipole evolution during the initial perturbative stage of its development.

The dependence of the hadron wave function $\Psi_h(\vec{r},\alpha)$ in Eq. (6) on the transverse $Q\bar{q}$ dipole separation r and LF momentum fraction α is taken according to the prescription for the Lorentz boost from the S-wave state in the hadronic rest frame to the LF frame used in Refs. [29–31],

$$\Psi_h(\vec{r},\alpha) = N\frac{4\alpha(1-\alpha)}{R_h^2} \times \exp\left[-\frac{2\alpha(1-\alpha)r^2}{R_h^2} - \frac{(1-2\alpha)^2\mu^2 R_h^2}{8\alpha(1-\alpha)}\right], \quad (11)$$

where $R_h^2 = 8/3\langle r_{ch}^2\rangle_h$, and the wave function squared is normalized to unity, $\int d^2r d\alpha |\psi_h(\vec{r},\alpha)|^2 = 1$.

A high-p_T $Q\bar{q}$ dipole is produced with a small initial size, controlled by the hard scale of the process, $r \sim 1/\bar{Q} \sim 1/E_T$. Therefore, we take in Eq. (6) the initial dipole size distribution function in the form,

$$\Psi_{in}(r) = \exp\left[-\frac{1}{2}E_T^2 r^2\right]. \quad (12)$$

Due to color transparency the survival probability of a dipole propagating through the medium rises when the dipole size shrinks. As function of p_T the initial dipole separation, $r_0 \sim 1/E_T$, becomes smaller, and the dipole size expands quickly, proportionally to the path length. At longer distances, however, Lorentz time dilation slows down the dipole expansion. The dipole size expansion at the early stage is so fast that the initial dipole very small size r_0 is quickly ‘forgotten’ and is not important anymore at longer path length [5,6],

$$\langle r^2(t)\rangle = \frac{2t}{\alpha(1-\alpha)E_T} + r_0^2. \quad (13)$$

This naturally explains the rising p_T dependence of $R_{AA}(p_T)$ clearly seen in data.

Notice that Eq. (13) presents an oversimplified description of the dipole evolution, which allows to understand a qualitative features of the dipole expansion. In what follows we rely on the accurate quantum-mechanical description based on the path-integral technique.

We performed calculations with constituent quark masses $m_q = 0.3$ GeV and $m_s = 0.5$ GeV. The results for the nuclear modification factor $R_{AA}(p_T)$ are compared

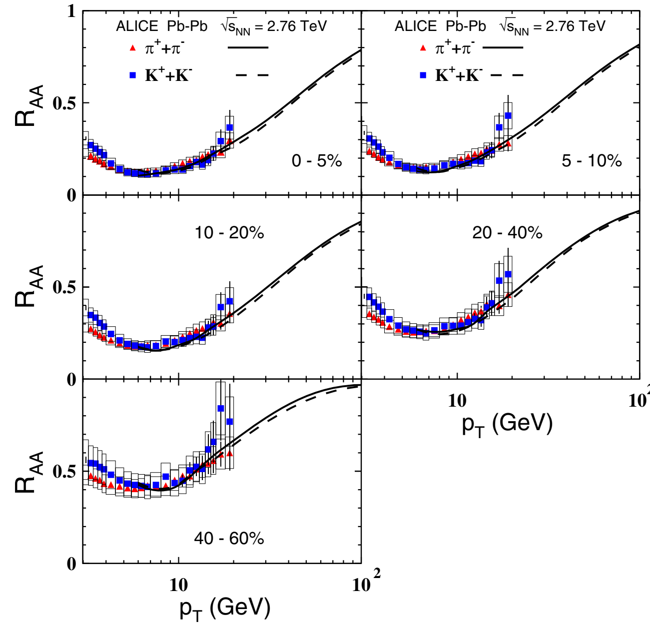

FIG. 2. Model predictions for the suppression factor $R_{AA}(p_T)$ in inclusive production of pions (solid lines) and kaons (dashed lines) at different centralities in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Data for R_{AA} are from the ALICE experiment [2].

with data on production of pions and kaons at the collision energy $\sqrt{s_{NN}} = 2.76$ TeV and at different centralities in Fig. 2. As mentioned above, the rate of broadening, parameter $\hat{q}_0$, could not be predicted reliably because of poorly known nonperturbative dynamics. So it was treated as a free parameter and adjusted to data at $\hat{q}_0 = 2.0\ \mathrm{GeV}^2/\mathrm{fm}$ [5]. This value of the maximal broadening rate is consistent with $\hat{q}_0 = 1.7$–$2.2\ \mathrm{GeV}^2/\mathrm{fm}$ extracted in Ref. [32] analyzing LHC data on hadron suppression in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using various parametrizations for the next-to-leading-order (NLO) parton fragmentation function. We assume that $\hat{q}_0$ is the same for pions and kaons, only the mean radii are different. For heavy flavors the values of $\hat{q}_0$ turn out to be quite less (see below).

With the same value of $\hat{q}_0$ for light quarks we also describe well data for the magnitude of suppression for charged light hadrons $h^\pm$ produced in central HICs at the collision energy $\sqrt{s_{NN}} = 5.02$ TeV, depicted in Fig. 3.

One can see from Figs. 2 and 3 that pions, kaons, and charged hadrons (combination of pions, kaons, and protons with a dominant weight of pions) are suppressed similarly, which is not a big surprise due to similarity of the color transparency effects for all particles, controlled by the formation length. The latter is the path length required for the dipole to expand up to hadronic radius,

$$L_f \approx \frac{1}{8}R_h^2\sqrt{p_T^2 + 4m_q^2} = \frac{1}{3}\langle r_{ch}^2\rangle_h\sqrt{p_T^2 + 4m_q^2}. \quad (14)$$

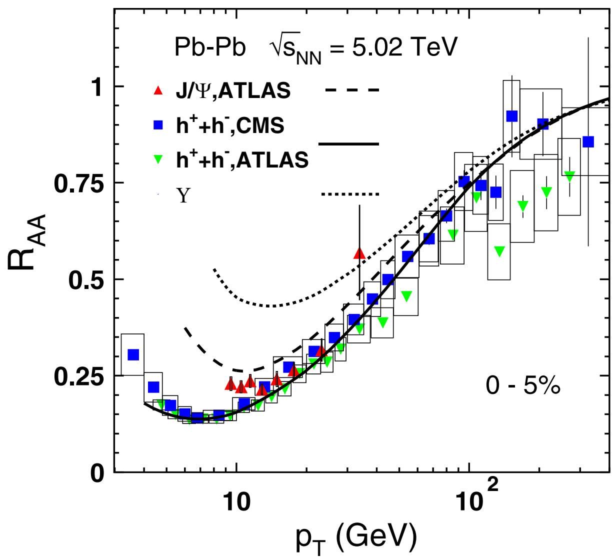

FIG. 3. Model predictions for the suppression factor $R_{AA}(p_T)$ in inclusive production of charged hadrons (solid line), prompt J/Ψ (dashed line) and Υ (dotted line) at the centrality 0–5% in lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Data for R_{AA} in production of charged hadrons are from the ATLAS [33] and CMS [34] Collaborations. Data for R_{AA} in production of prompt J/Ψ are from the ATLAS [3] measurements.

Here we simplify the dipole evolution, by treating it as a classical expansion. Therefore, the results should be taken with caution, only as semiqualitative estimate.

According to Eq. (14) the color transparency regime becomes effective above the following p_T-values,

$$E_T \approx p_T \gtrsim \frac{3R_A}{\langle r_{ch}^2 \rangle_h} = \frac{8R_A}{R_h^2} = p_T|_{\min}^h. \tag{15}$$

Taking in Eq. (14) $L_f \approx R_A$ with the nuclear radius $R_A \approx 5$ fm, and $\langle r_{ch}^2\rangle_\pi = 0.659^2$ fm^2, $\langle r_{ch}^2\rangle_K = 0.560^2$ fm^2 (see compilations of experimental measurements on https://pdglive.lbl.gov/DataBlock.action?node=S008CR and https://pdglive.lbl.gov/DataBlock.action?node=S010CR), we obtain the following minimum values of p_T for the color transparency regime,

$$p_T|_{\min}^\pi \sim 8 \text{ GeV},$$
$$p_T|_{\min}^K \sim 10 \text{ GeV}. \tag{16}$$

Such an expectation is consistent with the ALICE data and model calculations presented in Fig. 2. We will demonstrate and discussed below that a similar suppression of other large-p_T hadrons is less obvious.

B. Heavy flavored mesons produced in HICs

Mesons with open heavy flavor, such as D- and B-mesons, represent an asymmetric heavy-light systems. The transverse separation of the $Q\bar{q}$ dipole is controlled by the mass of the light quark, $r \sim 1/m_q$, while the longitudinal momentum is nearly entirely carried by the heavy quark. The light $\bar{q}$ carries only a small fraction $\alpha \sim m_q/m_Q$ of the dipole LF momentum. Such a specifics of heavy-light mesons leads to the following key features of their production and final-state interactions:

(i) As far as the heavy quark carries the main fraction of the LF momentum of the meson, the fragmentation function $D_{Q/Q\bar{q}}(z)$ should peak at large z, as is confirmed by data on e^+e^- annihilation [35,36];

(ii) Smallness of the LF momentum fraction $1-z$ indicates at a short radiational path length. i.e., fragmentation of a heavy quark ceases promptly, on a path length much shorter than 1 fm [16–21]. Therefore the early perturbative stage of hadronization and long-range final-state interaction in a nuclear environment factorize and can be treated separately [16–21];

(iii) An asymmetric $Q\bar{q}$ dipole, produced with a small initial separation, expands quickly up to the meson size $\langle r_M^2\rangle$, related to the mean charge radius squared $\langle r_{ch}^2\rangle_M$ of the produced heavy (either D or B) mesons, $\langle r_M^2\rangle = 8/3\langle r_{ch}^2\rangle_M$. The transverse speed of expansion is inverse to the quark mass, i.e., is dominated by the light component of the dipole. At the same time, the Lorentz factor is controlled by the heavy quark mass. Thus, the formation length in the rest frame of the medium reads,

$$L_f \approx \frac{4m_q p_T}{3m_Q}\langle r_{ch}^2\rangle_M, \tag{17}$$

demonstrating thus a significant reduction in comparison with a light-light dipole, Eq. (14);

(iv) A $Q\bar{q}$ dipole, expanded quickly its size up to a large value $\langle r_{ch}^2\rangle_M \approx \langle r_{ch}^2\rangle_\pi$, has a large breakup inelastic cross section, i.e., a very short mean free path, $\lambda_{Q\bar{q}} = 1/\hat{q}\langle r_M^2\rangle \ll 1$ fm, in a dense medium. Nevertheless, a breakup of such a dipole does not produce a dramatic effect, since the heavy quark carrying the main momentum fraction, easily picks up a light $\bar{q}$ and produces a new dipole with about the same momentum. However, after many such breaks on the long path in the medium, the leading heavy quark may lose a substantial part of its momentum. This leads to a positive shift Δz in the fragmentation function $D_{Q/Q\bar{q}}$ resulting in suppression of the production rate.

More details of this process can be found in Refs. [16–21]. The results for the nuclear ratio $R_{AA}(p_T)$ in production of D- and B-mesons are compared with suppression of light charged hadrons in Figs. 4 and 5.

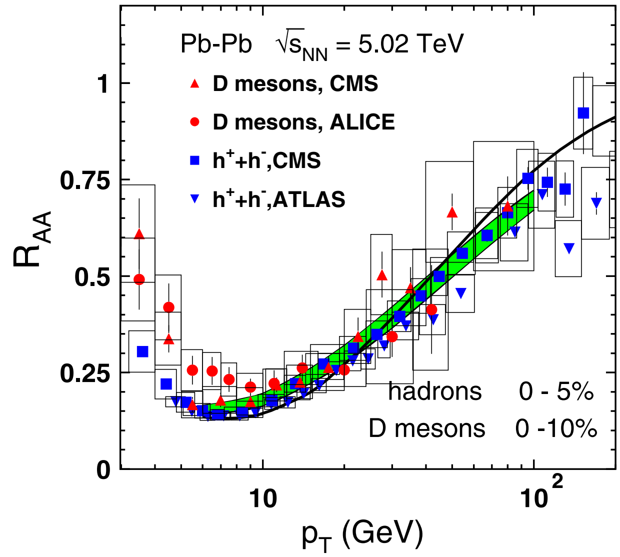

FIG. 4. Comparison of model predictions with data for the suppression factor $R_{AA}(p_T)$ in inclusive production of charged hadrons (solid line) and heavy flavored D mesons (green strip) at the centrality 0–5% and 0–10%, respectively. Data on $R_{PbPb}(p_T)$ at $\sqrt{s_{NN}} = 5.02$ TeV in production of charged hadrons are from the ATLAS [33] and CMS [34] Collaborations. Data for production of D mesons are from the ALICE [37] and CMS [38] experiments.

In the limit of short formation length in comparison with the nuclear radius, $L_f \ll R_A$, no color transparency effects causing the rise of R_{AA} vs p_T are expected. However, the formation length $L_f \propto E_T$ rises with E_T leading so to onset of the color transparency regime. This happens at the following value of p_T,

$$p_T \gtrsim \frac{2m_Q R_A}{m_q \langle r_M^2 \rangle} = p_T|_{\rm min}^M \approx p_T|_{\rm min}^h \cdot \frac{m_Q}{4m_q}. \qquad (18)$$

Setting $R_A \approx 5$ fm, and $\langle r_M^2 \rangle \sim 1/m_q^2$ we obtain the minimum values of p_T for the color transparency regime,

$$p_T|_{\rm min}^D \sim 15 \div 20 \text{ GeV},$$
$$p_T|_{\rm min}^B \sim 45 \div 50 \text{ GeV}. \qquad (19)$$

This estimate is confirmed by more accurate calculations [16,17,20,21] and by data displayed in Figs. 4 and 5. Indeed, the data in Fig. 4 show a steep rise of R_{AA} for D-mesons starting from $p_T \sim 15 \div 20$ GeV. Data on R_{AA} for B-mesons indeed demonstrate a flat behavior up to $p_T \approx 40$ GeV, and we expect onset of the rising $R_{AA}(p_T)$ as for light hadrons at $p_T \gtrsim 50$ GeV in agreement with the above model calculations [21] presented in Fig. 5.

The important feature of our results is a universal suppression for production of different mesons. The corresponding broadening rate parameter (transport coefficient) was found to be $\hat{q}_0^c = 0.45$–0.55 GeV^2/fm for D-mesons, and $\hat{q}_0^b = 0.2$–0.25 GeV^2/fm for B-mesons (shown by strips in Figs. 4 and 5). The value of $\hat{q}_0^c$ for the Large Hadron Collider (LHC) kinematic region is rather consistent with $\hat{q}_0^c = 0.3$–0.5 GeV^2/fm found in our previous works [41,42] analyzing charmonium suppression in gold-gold collisions at Relativistic Heavy Ion Collider (RHIC).

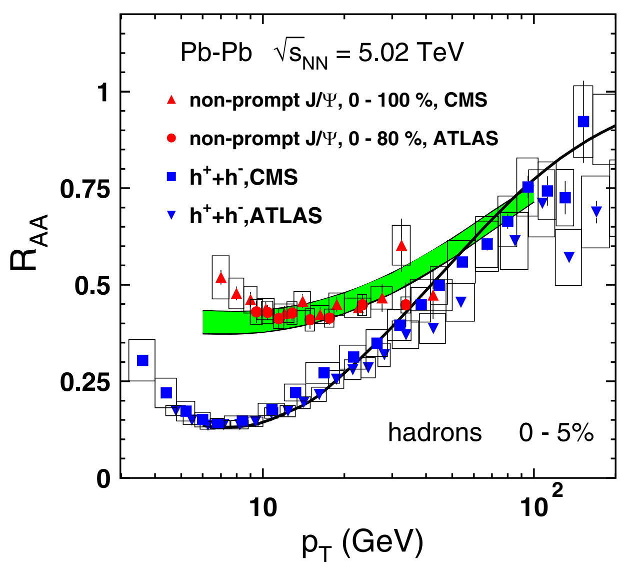

FIG. 5. The same as Fig. 4 but now the suppression factor $R_{AA}(p_T)$ for inclusive production of charged hadrons at the centrality 0–5% is compared to heavy flavored B-mesons produced at all centralities. Data for production of B-mesons are from the ATLAS [39] and CMS [40] experiments.

C. Heavy quarkonia produced in HICs

Here we highlight briefly the similarities and differences in production and final-state interactions of heavy quarkonia (HQ) compared to light and heavy flavored mesons:

(i) As was demonstrated in Sec. II and showed in Fig. 1, the light and heavy quarks radiate differently. The duration of the fragmentation process decreases with the quark mass and the corresponding path length $L_p \ll 1$ fm, similarly as in production of heavy flavored mesons;

(ii) Smallness of the fractional energy radiated by heavy quarks leads to a specific shape of the fragmentation functions (FFs) $c \to J/\Psi$ and $b \to \Upsilon$ consistent with calculations [43] including the NLO corrections. Similar shapes of FFs $c \to D$ and $b \to B$ were predicted in our recent work [21] in a good accord with direct measurements in e^+e^- annihilation [35,36]. The corresponding distributions strongly peak at $z \sim 0.75 \div 0.85$ due to almost the whole momentum of the jet carried by the final heavy flavored mesons and/or quarkonia. On the contrary, the FFs of light quarks to light mesons fall steadily and steeply from small z towards $z = 1$ [44];

(iii) In contrast to heavy flavored mesons, the HQ are produced mainly from the symmetric $Q\bar{Q}$ dipoles with $\alpha \sim 0.5$. The transverse size of the $Q\bar{Q}$ dipole is controlled by the mass of the heavy quark, $r \sim 1/m_Q$, differently from production of heavy flavored mesons. Consequently, expansion of such a dipole in the medium with small initial separation, $r_0 \sim 1/E_T$, up to formation of the final small-sized heavy quarkonia, is much longer. However, it is slowed down due to Lorentz time dilation, so is subject to the effect of color transparency. Therefore, the mechanism of final-state interactions is different from that in production of heavy flavored D- and B-mesons discussed in the previous Sec. III B;

(iv) According to Eq. (14) the quarkonium formation time, controlling the onset of color transparency, is longer for heavier quarks. We expect a hierarchy, $L_f(\Upsilon) < L_f(J/\psi) < L_f(\pi, K, p)$, related to the inequalities between average meson sizes, $\langle r^2_\Upsilon \rangle < \langle r^2_{J/\psi} \rangle < \langle r^2_{\pi,K,p} \rangle$. Consequently, at smaller values of $p_T \lesssim 10 \div 15$ GeV, the in-medium final state interaction in production is controlled by the stage of fast expansion of corresponding dipoles demonstrating a sensitivity to quark masses. It is manifested in Fig. 3 as a hierarchy, $R_{AA}(h^+ + h^-) < R_{AA}(J/\psi) < R_{AA}(\Upsilon)$.

For a more accurate description of the color transparency regime, an alternative to the classical expansion Eq. (14), more appropriate is the quantum-mechanical expression for the formation time,

$$L_f \approx \frac{2p_T}{m'^2_{HQ} - m^2_{HQ}}, \tag{20}$$

where m_{HQ} and m'_{HQ} is the mass of the ground state and next excited state of heavy quarkonia, respectively. Equation (20) is based on the uncertainty principle. One can distinguish between production of these heavy quarkonium states only if the process lasts sufficiently long compared with the inverse difference of corresponding masses. Besides, Eq. (20) includes the Lorentz time dilation in the rest frame of the nucleus. So the full CT regime is reached for sufficiently quarkonium transverse momenta,

$$p_T \gtrsim \frac{1}{2} R_A (m'^2_{HQ} - m^2_{HQ}) = p_T|^{HQ}_{\min} \approx p_T|^{h}_{\min} \cdot \frac{m_Q}{m_q}, \tag{21}$$

giving the following minimum values of p_T for the CT regime,

$$p_T|^{J/\psi}_{\min} \sim 50 \text{ GeV},$$
$$p_T|^{\Upsilon}_{\min} \sim 140 \text{ GeV}. \tag{22}$$

These evaluations are confirmed by our model calculations with results depicted in Fig. 3. Here the data for charmonium production demonstrate that the suppression factor $R_{AA}(p_T)$ is similar to that for light hadrons in correspondence with our predictions. The data for the large-p_T bottomonium production in HICs are plotted for comparison, to show an evidence of universal behavior of the corresponding R_{AA} at large p_T given mainly by the CT effects.

Similarly as in production of D- and B-mesons, we have obtained the model predictions, demonstrating the universal suppression also in production of different heavy quarkonia, adjusting the maximum value of the broadening rate in consistency with Ref. [21], where $\hat{q}^c_0 = 0.45$–0.55 GeV^2/fm for J/ψ-mesons, and $\hat{q}^b_0 = 0.2$–0.25 GeV^2/fm for Υ-mesons.

Another observable, which is sensitive to properties of the medium created after heavy ion collisions, is azimuthal asymmetry of the produced hadrons relative to the reaction plane. It is usually presented in terms of the second moment of the azimuthal angle ϕ distribution, $v_2 \equiv \langle \cos(2\phi) \rangle$, at given impact parameter b,

$$v_2(p_T, b) = \frac{\int d^2\tau T_A(\vec{\tau}) T_A(\vec{b}-\vec{\tau}) \int_0^{2\pi} d\phi \cos(2\phi) S_{Q\bar{q}}(\vec{b}, \vec{\tau}, E_T, \phi)}{\int d^2\tau T_A(\vec{\tau}) T_A(\vec{b}-\vec{\tau}) \int_0^{2\pi} d\phi S_{Q\bar{q}}(\vec{b}, \vec{\tau}, E_T, \phi)}, \tag{23}$$

where the nuclear suppression factor $S_{Q\bar{q}}(\vec{b}, \vec{\tau}, E_T, \phi)$ is defined in Eq. (6). Figures 2–5 demonstrate that our perturbative QCD mechanism of high-p_T meson production is in a good accord with data only at sufficiently large $p_T \gtrsim 6 \div 8$ GeV. Notice that azimuthal asymmetry sometimes is identified with elliptic flow, assuming that the heavy quarks are embedded into the hot medium, which is subject to elliptic flow. However, the asymmetry parameter Eq. (23) does not assume that, but asymmetry is a result of path dependence of the absorption factor $S_{Q\bar{q}}(\vec{b}, \vec{\tau}, E_T, \phi)$.

We expect hierarchy of asymmetry parameters, correlated with the quark masses, $v_2^\Upsilon \lesssim v_2^B < v_2^{J/\psi} < v_2^D \lesssim v_2^K \sim v_2^\pi$, due to a weaker quenching of high-p_T mesons containing heavy quarks. Besides, azimuthal asymmetry parameter $v_2(p_T)$ should gradually decrease with p_T like it was observed for production of high-p_T pions and charged hadrons in HICs at RHIC and the LHC [5,7].

Flavor dependence of v_2 was also studied in Ref. [45] within the quark coalescence model, concluding that $v_2^\pi > v_2^K > v_2^\phi$. Nonetheless, calculations of the azimuthal asymmetry within the light quark sector are beyond the scope of the present paper, and will be done elsewhere.

Scaling properties of azimuthal asymmetry were studied also in Ref. [46] for different centralities, hadronic species and collision energies from RHIC to the LHC. The observed scaling, interpreted as a consequence of induced energy loss, was analyzed for small $p_T < Q_s^A$, where the saturation momentum Q_s^A reaches values of at most about

4 GeV, namely for central Pb-Pb collisions at the LHC. The dynamics of particle production was treated adopting the model of color strings with fusion and percolation. For such small values of p_T one cannot apply our mechanism of the in-medium hadronization presented in this paper. However, extension of the v_2-scaling to larger p_T is questionable due to an interplay of the above mentioned two mechanisms of hadron production. This may lead to a modification of the v_2-scaling law which was discussed in Ref. [46].

IV. CONCLUSIONS

In the present paper we analyzed the nontrivial observation of similar magnitudes of the nuclear suppression factor $R_{AA}(p_T)$ for production of different hadrons at large p_T. The main conclusions are as follows:

(i) In the process of high-p_T meson production with Feynman $x_F = 0$ in HICs one can single out two stages. The first one is accompanied by the gluon radiation and parton energy loss up to color neutralization and ceases shortly after a hard collision. Radiative energy loss at this stage is nearly the same in vacuum and nuclear medium. Remarkably, heavy quarks radiate a much smaller fraction of the initial quark energy compared to light quarks due to the dead-cone effect. This is why heavy flavored mesons usually carry a dominant fraction z of the heavy quark momentum, in consistency with a nonmonotonic shape of z-dependence of the corresponding fragmentation function. In contrast, FFs for light quarks exhibit a monotonically falling z-behavior. The production length L_p of color neutralization, controlling the duration of this hadronization stage, turns out to be very short, $L_p \ll 1 \div 2$ fm for the both light and heavy quarks, and it decreases with p_T.

(ii) The first stage does not produce any sizeable suppression effect, it is quite short and ends up with production of a small size $\sim 1/p_T$ dipole. During subsequent propagation of this dipole throughout the medium it is developing the wave function of the final meson. This may take a long time. The corresponding path length L_f rises with p_T. This stage of meson production is the main source of suppression, related to a chance that the colorless dipole can be broken by inelastic (color-exchange) collisions within the medium.

(iii) At large p_T, the evolution of a small dipole propagating through a medium up to formation of the final meson is slowed down due to Lorentz dilation. If $L_f \gtrsim R_A$, production of various mesons is governed by the color transparency effects, and their attenuation is directly controlled by the p_T-dependent dipole size. This leads to independence of the meson radius, i.e., to universality of the suppression in production of various high-p_T mesons, analyzed in the present paper.

(iv) The condition $L_f \gtrsim R_A$ requires sufficiently high p_T, i.e., imposes the lower limits $p_T|^M_{\rm min}$ defining the range of p_T-values, $p_T \gtrsim p_T|^M_{\rm min}$, for the onset of the color transparency regime. The corresponding $p_T|^M_{\rm min}$ have been evaluated for pions, kaons, heavy quarkonia, as well as for heavy flavored D- and B-mesons taking into account a different dynamics of their production.

(v) Whereas light mesons (pions, kaons) require a small $p_T|^M_{\rm min} \sim 8 \div 10$ GeV for manifestation of universal suppression, heavy quarkonia prefers higher values, $p_T|^{J/\psi}_{\rm min} \approx p_T|^M_{\rm min} \cdot f_c \sim 50$ GeV and $p_T|^{\Upsilon}_{\rm min} \approx p_T|^M_{\rm min} \cdot f_b \sim 140$ GeV, enlarged by factors $f_c \approx m_c/m_q$ and $f_b \approx m_b/m_q$, respectively. On the other hand, the heavy flavored D and B mesons scan the smaller $p_T|^D_{\rm min} \approx p_T|^M_{\rm min} \cdot h_c \sim 15 \div 20$ GeV and $p_T|^B_{\rm min} \approx p_T|^M_{\rm min} \cdot h_b \sim 45 \div 50$ GeV due to their asymmetric heavy-light quark configurations and different mechanism of production leading to smaller factors $h_c \approx m_c/4m_q < f_c$ and $h_b \approx m_b/4m_q < f_b$.

(vi) Our analysis of the universal suppression contains one unavoidable parameter, which is the broadening rate of the quark in the medium. In correspondence with our previous studies, we found its maximal value $\hat{q}_0 \sim 2.0$ GeV^2/fm, 0.45–0.55 GeV^2/fm and 0.20–0.25 GeV^2/fm for the light, c and b quark, respectively. Such a diminution of $\hat{q}_0$ with the quark mass is a clear manifestation of the dead-cone effect, which reduces the broadening.

(vii) Our expectations of the manifestation of universal suppression in production of various high-p_T mesons are consistent with available data, as well as with our model calculations based on the rigorous Green function formalism.

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