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# UNIVERSAL SUPPRESSION OF HIGH-$p_{\rm T}$ HADRONS IN HEAVY-ION COLLISIONS[*]

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Data from the ALICE experiment demonstrate universality of suppression of different hadrons produced with high $p_{\rm T}$ in heavy-ion collisions (HICs) at the Large Hadron Collider (LHC). Moreover, the recent data from ATLAS on production of prompt charmonia at large $p_{\rm T}$ demonstrate a similar attenuation as observed for light hadrons. Such a universality could hardly be explained by the energy-loss mechanism, since the rate of medium induced energy loss strongly correlates with the parton mass. However, the hadronization length has been evaluated to be very short, especially at high $p_{\rm T}$, therefore, attenuation of the high-$p_{\rm T}$ hadrons originates mainly from the possibility to be broken-up by inelastic collisions during propagation through the dense medium. The survival probability is controlled by the effect of color transparency, which makes the attenuation dependent on the dipole size, related mainly to $p_{\rm T}$. This naturally explains the observed universality of hadron suppression. With the same value of the transport coefficient, we predict similar suppression factors $R_{AA}$ for inclusive production of pions, kaons, protons, charmonia and even bottomonia as a function of $p_{\rm T}$ and centrality in good agreement with data.

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## 1. Introduction

The recent data on production of high-$p_{\mathrm{T}}$ pions, kaons and protons in heavy-ion collisions from the ALICE experiment [1] as well as the ATLAS data on prompt $J/\Psi$ [2] show universality of suppression. Such a universal suppression cannot be explained by the models based on the popular scenario (see, *e.g.* [3]), where the observed suppression of the hadron production rate is interpreted in terms of induced energy loss by a parton propagating through the dense medium. Different radiation by light and heavy quarks as well as different mechanisms in production of mesons and baryons should naturally lead to a different magnitudes of suppression. In the present paper, we rely on the alternative scenario, based on the proven shortness of the hadronization length [4–7]. Correspondingly, the observed suppression is related to the small survival probability of the originally produced dipole, propagating in the medium. At sufficiently high $p_{\mathrm{T}}$, the dipole size depends on $p_{\mathrm{T}}$ rather than quark masses, therefore, color transparency makes attenuation of the dipoles flavor-independent. This mechanism explains the observed universality in production of different particles and allows to describe data in a parameter-free way.

## 2. Radiative energy loss in vacuum

One can define two time scales controlling the hadronization process as is illustrated in Fig. 1. As a result of a high-$p_{\mathrm{T}}$ parton–parton scattering, during the first time scale, the parton regenerates its color field, which has been stripped off in a hard reaction. Such a regeneration up to transverse frequencies $k < p_{\mathrm{T}}$ is accompanied by an intensive gluon radiation and energy dissipation either in vacuum or in a medium. Multiple interactions by the quark in the medium induce additional, *usually less intensive*, radiation. The loss of energy ceases at the moment, which is called *the production time (length)*, $t_{\mathrm{p}}$ ($l_{\mathrm{p}}$), when the quark picks up an antiquark neutralizing its color.

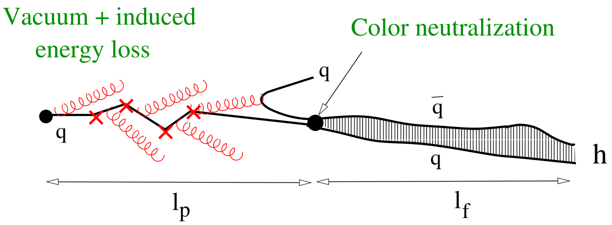

Fig. 1. (Color online) Space-time development of hadronization of a highly virtual quark producing a leading hadron (meson), which carries the main fraction $z$ of the initial quark light-cone momentum.

The production time can be given by the approximate relation (see [4], for example), $t_{\mathrm{p}} \lesssim \frac{E}{\langle|\mathrm{d}E/\mathrm{d}t|\rangle}(1-z)$, where $\langle|\mathrm{d}E/\mathrm{d}t|\rangle$ represents the mean value of the rate of energy loss.

The second stage begins with production of *colorless dipole* (pre-hadron), which does not have either the wave function or hadronic mass $m_h$. It takes *the formation time (length)* $t_{\mathrm{f}}$ ($l_{\mathrm{f}}$) to develop both. The formation time rises with the jet energy $E$ due to the Lorentz boosting factor and reads [4], $t_{\mathrm{f}} = \frac{2zE}{m_{h*}^2 - m_h^2}$. This stage of hadronization can be described within a simplified heuristic consideration [5, 6] or by the path integral method [4].

The amount of energy radiated after the hard collision by the scattered parton over time interval $t$ (path length $L$) was calculated in [4, 7, 8]. It has been shown that gluon radiation is subject to the *dead cone effect* [9], which implies that heavy quarks radiate less energy than the light ones.

Substantial difference between radiation of energy by heavy and light quarks is shown in Fig. 2 [11], which clearly demonstrates that radiation by heavy quarks ceases shortly. In contrast to hadronization pattern of light quarks, which keeps radiating for a long time and lose the most of the initial energy, only a small fraction of the initial heavy-quark energy, $\Delta z = \Delta E_{\mathrm{rad}}/E$, is radiated over a long-time interval.

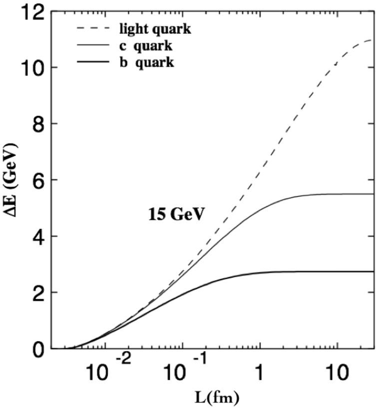

Fig. 2. Fractional radiational vacuum energy loss by a high-$p_{\mathrm{T}}$ light, $c$ and $b$ quark, produced with initial energy $E = \sqrt{p_{\mathrm{T}}^2 + m_q^2} = 15$ GeV.

A small amount of the initial energy radiated by heavy quarks causes that the final $J/\Psi$ and $\Upsilon$ mesons carry almost the whole momentum of the jet. Such an expectation is in accordance with calculations of the fragmentation functions (FFs) $c \to J/\Psi$ and $b \to \Upsilon$ including NLO corrections [10]. The corresponding shape of the FF $c \to J/\Psi$ is shown in Fig. 3 and is similar to that for the FFs $c \to D$ and $b \to B$ measured directly in $e^+e^-$ annihilation [12]. Figure 3 indeed shows that the distribution strongly peaks at $z \sim 0.75 \div 0.80$. A similar behavior was obtained also for the FF $b \to \Upsilon$ [10]. Note that the FFs of light quarks to light mesons are well-known to fall steadily and steeply from small $z$ towards $z = 1$ [13].

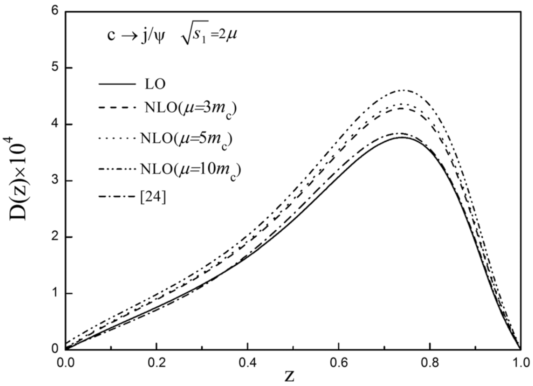

Fig. 3. The $c \to J/\Psi$ fragmentation function calculated in [10].

## 3. Evolution and attenuation of dipoles: path-integral technique

The shortness of $l_{\rm p}$ for light and heavy quarks has been discussed in [4] and [11], respectively. Short $l_{\rm p}$ causes that namely the evolution and attenuation of the produced colorless dipoles in the medium represents the main source of the observed suppression in inclusive production of high-$p_{\rm T}$ hadrons [4].

Assuming production of light mesons and also heavy quarkonia ($J/\Psi$, $\Upsilon$), the corresponding attenuation factor for $\bar{q}q$ dipole can be written as [4]

$$S_{AB}(p_{\rm T}) = \frac{\int_0^{2\pi} \frac{{\rm d}\phi}{2\pi} \left| \int_0^1 {\rm d}\alpha \int {\rm d}^2 r_1 {\rm d}^2 r_2\, \Psi_h^\dagger(\vec{r}_2,\alpha) G_{\bar{q}q}(l_1,\vec{r}_1; l_2,\vec{r}_2) \Psi_{\rm in}(\vec{r}_1,\alpha) \right|^2}{\left| \int_0^1 {\rm d}\alpha \int {\rm d}^2 r_1 {\rm d}^2 r_2\, \Psi_h^\dagger(\vec{r}_2,\alpha) \Psi_{\rm in}(\vec{r}_1,\alpha) \right|^2}\,, \tag{1}$$

where the Green function $G_{\bar{q}q}$ satisfies the two-dimensional Schrödinger equation [4] and describes the evolution and attenuation of a $\bar{q}q$ dipole propagating through an absorptive medium.

The imaginary part of the light-cone (LC) potential in the Schrödinger equation, ${\rm Im}\, V_{\bar{q}q}(\vec{b},\vec{\tau}; l,\vec{r}) = -\frac{1}{4}\, \hat{q}(l,\vec{b},\vec{\tau}\,)\, r^2$ and is responsible for absorption of $\bar{q}q$ dipole in the medium. Here, properties of the medium are described by means of the transport coefficient (TC), $\hat{q}(l,\vec{b},\vec{\tau}\,)$, where $\vec{b}$ and $\vec{\tau}$ are the impact parameters of a hard collision and position of the parton, respectively. For the shape of the TC, we adopted the model from [14], $\hat{q}(t,\vec{b},\vec{\tau}\,) = \frac{\hat{q}_0\,t_0}{t}\,\frac{n_{\rm part}(\vec{b},\vec{\tau}\,)}{n_{\rm part}(0,0)}$, where the parameter $\hat{q}_0$ represents the maximal value of the TC for the medium produced at the initial time $t = t_0$ in a central collision at $b = \tau = 0$. Here, we took the time scale of medium formation, $t_0 = 1$ fm. The value $\hat{q}_0 = 2$ GeV$^2$/fm has been taken from our analysis of data on inclusive production of light hadrons in central HICs [4]. We treat the $\bar{q}q$ system as free noninteracting partons with $\mathrm{Re}\,V_{\bar{q}q} = 0$, like in Ref. [4].

Considering production of baryons, one needs to describe the evolution of a $\bar{q}q$ dipole to a $3q$-system. Introducing the Jacobi coordinates, $\vec{s}_1 = (\vec{x}_1 - \vec{x}_2)/\sqrt{2}$ and $\vec{s}_2 = \sqrt{2/3}[\vec{x}_3 - (\vec{x}_1 + \vec{x}_2)/2]$, where vectors $\vec{x}_i$ denote the position of valence quarks in the proton, the $3q$-nucleon interaction cross section reads [15], $\sigma_{3q}(\vec{\rho}_1,\vec{\rho}_2) = \frac{\sigma_{\bar{q}q}(\rho_1)\,\langle\rho_1^2\rangle + \sigma_{\bar{q}q}(\rho_1)\,\langle\rho_2^2\rangle}{\langle\rho_1^2+\rho_2^2\rangle}$, where $\vec{\rho}_{1,2} = \vec{s}_{1T,2T}$ and $\vec{s}_{1,2} = (\vec{\rho}_{1,2}, s_{1L,2L})$. Then the evolution to the proton state can be treated as the evolution of two independent dipoles for each Jacobi coordinate $\vec{\rho}_1$ and $\vec{\rho}_2$ like for meson production. This leads to the imaginary part of the LC potential, $\mathrm{Im}\,V_{3q}(\vec{b},\vec{\tau};l,\vec{\rho}_1,\vec{\rho}_2) = -\frac{1}{8}\,\hat{q}(l,\vec{b},\vec{\tau}\,)\,(\rho_1^2 + \rho_2^2)$. Consequently, the corresponding $3q$ Green function can be expressed in the factorised form, $G_{3q}(l_1,\vec{\rho}_{1i},\vec{\rho}_{2i};l_2,\vec{\rho}_{1f},\vec{\rho}_{2f}) = G_{\bar{q}q}(l_1,\vec{\rho}_{1i};l_2,\vec{\rho}_{1f})\,G_{\bar{q}q}(l_1,\vec{\rho}_{2i};l_2,\vec{\rho}_{2f})$.

## 4. Comparison with data

The calculations of the nuclear modification factor $R_{AA}(p_{\rm T})$ were performed within the color dipole approach based on the Green function formalism [4]. Predictions for suppression of pions, kaons and protons produced in lead–lead collisions at $\sqrt{s} = 2.76$ TeV and at different centralities are shown by solid, dashed and dotted curves in Fig. 4 *vs.* the last data from the ALICE experiment [1].

Figure 4 demonstrates an universality in suppression of different particles in accordance with our predictions as a direct confirmation of the non-energy loss interpretation of the jet quenching [4, 6, 7] when gluon radiation ceases very shortly after HICs. Very short $l_{\rm p}$ means also that various mechanisms responsible for production of different hadrons do not affect much their production rates in the medium. Such an interpretation differs considerably from the pure energy loss scenario [18, 19], which cannot, in principle, explain such a similar suppression due to a different medium-induced energy loss expected in production of mesons and protons.

Note that at large $p_{\rm T} \geq 15 \div 20$ GeV, we predict a rising $p_{\rm T}$-dependence of $R_{AA}$ following from the reduction of the mean dipole size with $p_{\rm T}$ — the effect of *color transparency* (CT) [4, 5].

Finally, as a further manifestation of universal suppression in production of various hadrons given by CT effects, we show in Fig. 5 model predictions for $R_{AA}(p_\mathrm{T})$ in a good agreement with ATLAS [2, 16] and CMS [17] data.

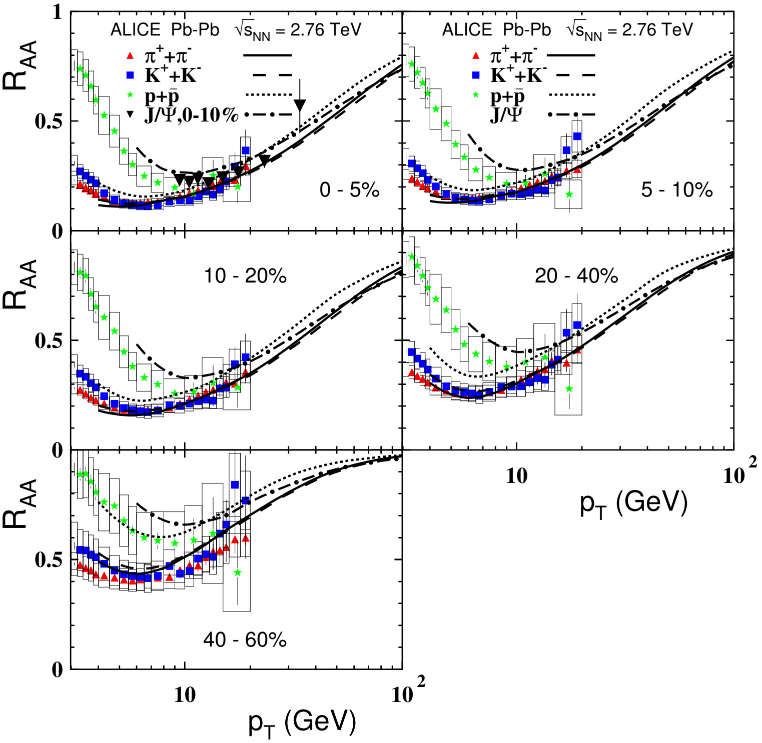

Fig. 4. The suppression factor $R_{AA}$ for inclusive production of pions, kaons, protons and prompt $J/\Psi$ at different centralities in Pb–Pb collisions at $\sqrt{s} = 2.76$ TeV and 5.02 TeV, respectively. Data for $R_{AA}$ are from the ALICE [1] and ATLAS [2] collaborations.

CT effects are controlled by the formation time, $t_\mathrm{f} = \frac{1}{3}\,\langle r^2_\mathrm{ch}\rangle_h\,\sqrt{p^2_\mathrm{T} + m^2_h}$, where $\langle r^2_\mathrm{ch}\rangle_h$ is the mean hadron charge radius squared. Then the same values of $t_\mathrm{f}$ in production of different hadrons should lead to their identical attenuation as is demonstrated in Fig. 5. One can also see from Fig. 5 that an approximate universality in suppression of light hadrons and charmonia (bottomonia) is visible already at much smaller $p_\mathrm{T}$ when $l_\mathrm{f}$ is comparable with a typical size (a few Fermi) of the region where the medium is created.

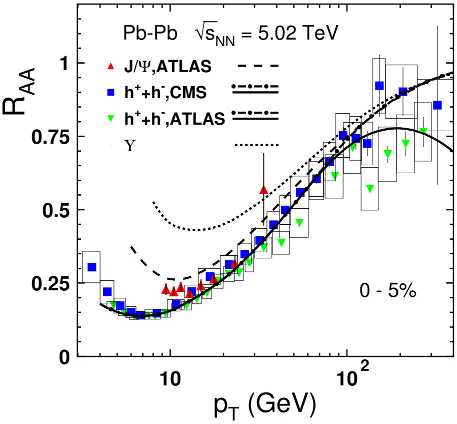

Fig. 5. The suppression factor $R_{AA}$ for inclusive production of charged hadrons, prompt $J/\Psi$ and $\Upsilon$ at the centrality 0–5% in lead–lead collisions at $\sqrt{s} = 5.02$ TeV. Data for $R_{AA}$ in production of charged hadrons are from the ATLAS [16] and CMS [17] collaborations. Data for $R_{AA}$ in production of prompt $J/\Psi$ are from the ATLAS [2] measurements.

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