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Těžké kvarky jako sonda hmoty vytvořené v srážkách těžkých iontů

Heavy quarks as the probe of the medium created in heavy ion collisions

Summary

Production of heavy flavored hadrons from fragmentation of heavy quarks represents an alternative way for study of manifestations and properties of a medium created after heavy ion collisions. The observed strong suppression of heavy flavored hadrons produced with high p_T, is caused by final state interactions with the created dense medium. The space-time pattern of hadronization is controlled by the vacuum radiation by high-p_T heavy quarks and is ceased at a short time scale in accordance with perturbative QCD calculations and LEP measurements of the fragmentation functions. Production of a heavy flavored hadrons in a dense matter lasts a long time scale due to prompt breakup of the hadrons caused by the medium. This fact together with the specific shape of the heavy quark fragmentation functions allow to explain a strong suppression of D and B heavy mesons in a good accord with available data.

Souhrn

Produkce hadronů těžkých vůní z fragmentace těžkých kvarků představuje alternativní způsob zkoumání projevů a vlastností prostředí vytvořeného po srážce těžkých iontů. Pozorované silné potlačení hadronů těžkých vůní produkovaných s velkými p_T je způsobeno jejich interakcemi v konečném stavu s vytvořeným prostředím. Časoprostorový vývoj hadronizace je kontrolován vakuovou radiací produkovanou těžkými kvarky s velkým p_T a skončí počas krátké časové škály v souladu s poruchovými výpočty QCD a s výsledky měření fragmentačních funkcí na urychlovači LEP. Produkce hadronů těžkých vůní v husté materii trvá dlouho v důsledku jejich okamžitých rozpadů způsobených prostředím. Tento fakt, společně se specifickým tvarem fragmentačních funkcí těžkých kvarků, umožňuje vysvětlit silné potlačení těžkých D a B mezonů v dobrém souladu s dostupnými daty.

Klíčová slova:
hadrony těžkých vůní, fragmentační funkce, energetické ztráty ve vakuu, horká a hustá hmota, srážky těžkých iontů

Keywords:
heavy flavored hadrons, fragmentation functions, vacuum energy loss, hot and dense matter, heavy ion collisions

Contents

1 Introduction

The popular scenario explaining the jet quenching is based on induced energy loss during propagation of a parton system in a dense and hot medium created after heavy ion collisions. As a result of a weaker radiation by heavy quarks, i.e. the so called *dead-cone effect*, a much weaker suppression in production of heavy flavored hadrons, compared with light hadrons, was anticipated in [1].

Later, however, measurements revealed similar magnitudes of suppression for heavy and light hadrons in contradiction with models based on energy loss scenario. Here we propose an alternative scenario for production of heavy flavored hadrons from a dense and hot medium. This novel mechanism is able to explain data in a parameter-free way.

2 Hard parton collision

The figure 1 illustrates the high-p_T parton-parton scattering leading to formation of 4 cones of gluon radiation: (i) the color field of the colliding partons is shaken off in forward-backward directions;
(ii) the scattered partons carrying no field up to transverse frequencies $k <$

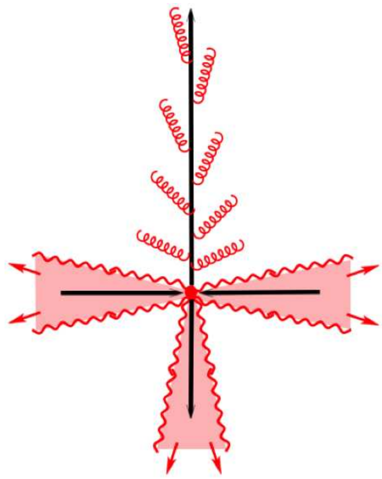

Figure 1: High-p_T parton scattering. The two forward-backward jets are formed by the shaken-off gluon fields. The high-p_T partons regenerate the lost field, radiating gluons. The figure is taken from [2].

p_T, are regenerating the lost components of their field, radiating gluons and forming two high-p_T jets.

The lifetime of the quark-gluon fluctuation can be estimated through the coherence length/time of gluon radiation by a quark of mass m_q and energy E with the following form,

$$l_c = \frac{2E\,x(1-x)}{k^2 + x^2 m_q^2}\,, \tag{1}$$

where x is the fractional light-cone (LC) momentum of the radiated gluon. Note, that first of all are radiated and regenerated gluons with small longitudinal and large transverse momenta.

Assuming high-p_T collisions, the peculiar feature of these jets is that their initial virtuality imposed by p_T is very close to energy $E = \sqrt{p_T^2 + m_q^2}$. For this reason the intensity of radiation by a parton and corresponding dissipation of energy is controlled by the jet energy.

To demonstrate this fact one can evaluate the amount of energy, radiated after the hard collision by the scattered parton over path length L [3],

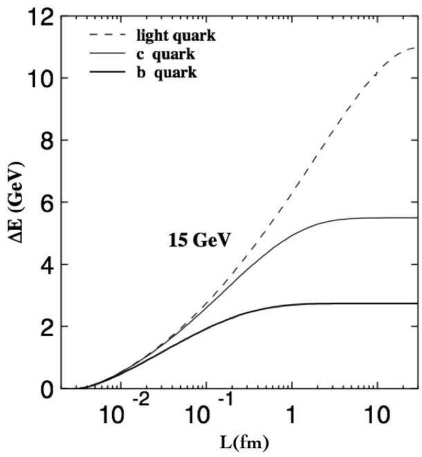

Figure 2: Radiational energy loss of light, c and b quarks having initial energy $E = \sqrt{p_T^2 + m_q^2} = 15\,\text{GeV}$, versus path length. The figure is taken from [2].

$$\Delta E_{rad}(L) = E \int_{\Lambda^2}^{p_T^2} dk^2 \int_0^1 dx\, x\, \frac{dn_g}{dx\, dk^2} \Theta(L - l_c)\,, \qquad (2)$$

where the radiation spectrum reads,

$$\frac{dn_g}{dx\, dk^2} = \frac{2\alpha_s(k^2)}{3\pi\, x}\, \frac{k^2[1 + (1-x)^2]}{[k^2 + x^2 m_q^2]^2}\,. \qquad (3)$$

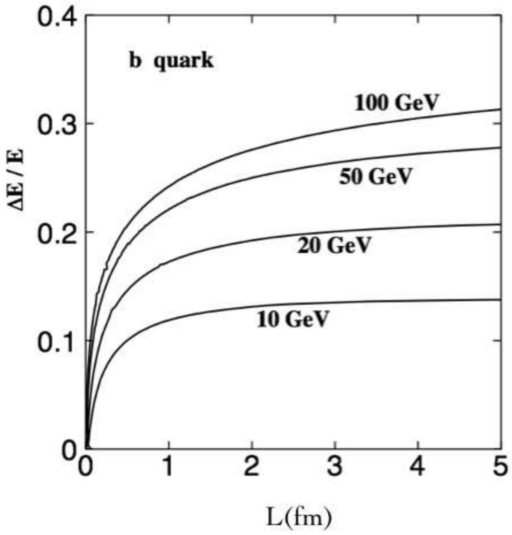

Figure 3: Fractional radiational energy loss by a high-p_T b-quark, produced with different initial energies. The figure is taken from [2].

The figures 2 and 3 show results of calculations for absolute and fractional radiated energy loss, respectively and clearly demonstrates that radiation of heavy quarks ceases shortly. In contrast to hadronization pattern of light quarks, which keeps radiating long time and lose most of the initial energy (see figure 2), only a small fraction of the initial heavy quark energy, $\Delta z = \Delta E_{rad}/E$, is radiated after a long time interval. A small amount of the initial energy radiated by the heavy quark causes that the final D or B mesons carry almost the whole momentum of the jet. Such an expectation is in accordance with the direct measurements of the fragmentation functions

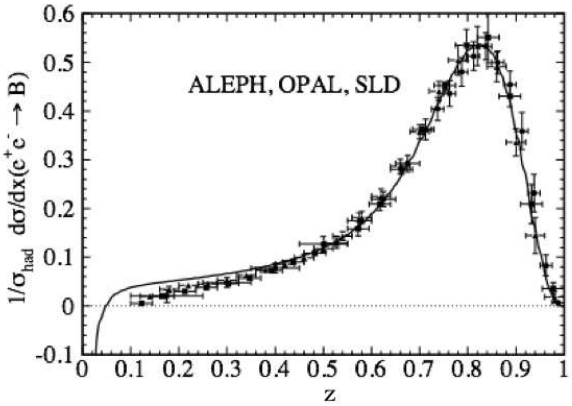

Figure 4: The $b \to B$ fragmentation function, from e^+e^- annihilation. The curve is the DGLAP fit [5]. The figure is taken from [2].

in e^+e^- annihilation [4, 5]. The figure 4 represents the example of the $b \to B$ fragmentation function [5] and indeed shows that the distribution strongly peaks at $z \sim 0.85$. A similar behavior was observed also for the $c \to D$ fragmentation function [4] with the maximum of the distribution at $z \sim 0.65$.

Note that in comparison to heavy quarks the fragmentation functions of light quarks to light mesons are well known to fall steadily and steeply from small z towards $z = 1$ [6].

3 How long does it take to produce heavy mesons ?

If a heavy mesons (or a $Q\bar{q}$ dipole, where Q denotes the heavy c or b quark) is produced at a distance l_p known as the production length, the momentum of a heavy meson equals approximately to the momentum of the Q-quark at this point.

The momentum fraction carried by the light q is very small, $\alpha \approx m_q/m_Q$, i.e. is about 15% and 5% for heavy c and b quark, respectively. We can safely neglect this correction for b quark and consider for illustration production of heavy flavored B mesons in what follows. From the known magnitude of the radiational vacuum energy loss dE/dl one can directly relate the production length distribution $W(l_p)$ to the $b \to B$ fragmentation function $D_{b/B}(z)$,

$$\frac{dW}{dl_p} = \left.\frac{\partial \Delta p_+^b / p_+^b}{\partial l}\right|_{l=l_p} D_{b/B}(z)\,, \tag{4}$$

where the production length probability distribution and the fragmentation function are normalized to unity, $\int_0^\infty dl_p\, dW/dl_p = 1$ and $\int_0^1 dz\, D_{b/B}(z) = 1$ respectively; $z \equiv p_+^B/p_+^b = 1 - \Delta p_+^b(l_p)/p_+^b = 1 - \Delta z(l_p)$; and

$$\Delta p_+^b(l_p) = \int\limits_0^{l_p} dl\, \frac{dp_+^b(l)}{dl}\,. \tag{5}$$

The rate of LC momentum loss is related to energy loss in accordance with $p_+^b = E + \sqrt{E^2 - m_b^2}$. Note that a direct relation between z and l_p follows from the knowledge of fragmentation function $D_{b/B}(z)$ and vacuum energy loss dE/dl.

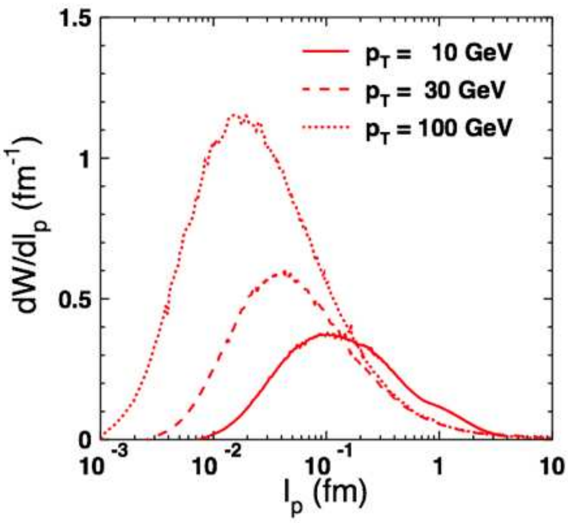

Figure 5: The l_p-distribution of B-mesons produced with different p_T in pp collisions. The figure is taken from [2].

One can extract the production length of B-mesons directly from data for $D_{b/B}(z)$ calculating $\Delta z(L)$ over path length L. Figure 5 shows the l_p dependence of production length distribution dW/dl_p and clearly demonstrates that the mean value of l_p shrinks with rising p_T, like it happens for production of high-p_T light hadrons [7].

Concluding, the fragmentation of a heavy b-quark in vacuum looks like radiational energy loss up to a point $l = l_p$, where b-quark picks up a light $\bar{q}$ forming a colorless $Q\bar{q} = b\bar{q}$ dipole, which performs a direct transition to heavy flavored B meson without loss of the b-quark momentum.

4 Fragmentation in a hot medium

In comparison with vacuum production of B mesons finishing at the path length $l = l_p$, in a dense medium the space-time pattern of B production if totally different. Here the B-meson (or $b\bar{q}$ dipole) can easily breakup interacting with the medium, and release the b-quark. This heavy quark will continue hadronization process and picks-up another light antiquark creating B meson again and so on. Such recreations and breakups of B-mesons will be multiply repeated, until the final production of the detected B-meson, which will survive escaping from the medium. For this specific pattern of heavy b-quark to heavy B-meson hadronization one should understand what happens with this b-quark, while it propagates either as a constituent of a $b\bar{q}$ dipole, or is released and is losing energy to hadronization.

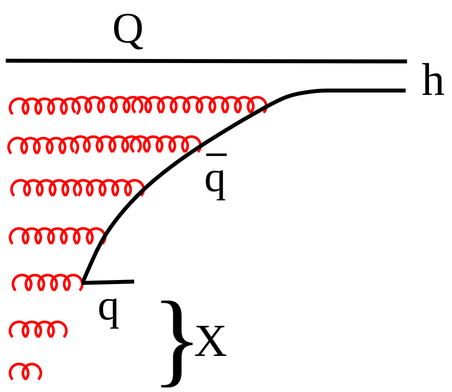

Figure 6: Redistribution of the energy inside a $Q\bar{q}$ dipole by gluon radiation by Q absorbed by $\bar{q}$. The figure is taken from [2].

The process of the color neutralization ceases the radiation by heavy b-quark and is terminated by production of the $b\bar{q}$ dipole, which propagates further without radiation and loss of energy. However, if the b-quark did not finish regeneration of its color field, it keeps radiating inside the dipole. The only difference with the preceding radiation process by a single quark, is that the radiation inside the dipole is reabsorbed by accompanying $\bar{q}$, as is illustrated in figure 6. Thus, the $b\bar{q}$ dipole does not radiate, its energy remains constant, however the b-quark energy decreases and is redistributed inside the dipole, decelerating the b-quark and accelerating the $\bar{q}$.

Figures 2 and 3 clearly demonstrate that perturbative radiation of heavy quarks ceases shortly, within a distance of about 1 fm (for a typical p_T range). However, in accordance with confinement the heavy quark cannot propagate on longer distances like a free particle with a constant energy. For this reason we additionally consider a popular model for the nonperturbative mechanism of energy loss, known as the string model with the rate of energy loss $dE_{str}/dl = -\kappa$, where the string tension in vacuum is $\kappa \approx 1\,\mathrm{GeV}/fm$.

While in vacuum a heavy flavored meson is produced on a very short length scale, $l_p \ll 1\,\mathrm{fm}$, in a hot medium a strong absorption pushes the production point to the dilute medium surface. Therefore, for such a long-lasting hadronization process continuing throughout the whole area occupied by the medium, the non-perturbative energy loss becomes important. However, in a deconfined hot medium no string can be formed. Therefore the magnitude of the string tension, and even its very existence, depends on the medium temperature. We rely on the model [8, 9, 10] based on the lattice simulations for temperature dependence of the string tension, $\kappa(T) = \kappa\,(1 - T/T_c)^{1/3}$, where the critical temperature is fixed at $T_c = 280\,\mathrm{MeV}$.

Thus, the full rate of energy loss comes from both perturbative and non-perturbative mechanisms,

$$\frac{dE}{dl} = \frac{dE_{rad}}{dl} - \kappa(T)\,. \tag{6}$$

After the b-quark has promptly radiated the whole gluon spectrum and decreased its virtuality down to the soft scale, the string becomes the only source of energy loss. As we already mentioned above, the perturbative stage of hadronization ceases at $l_p \lesssim 1$ fm, i.e. very shortly after a hard collision when the b quark picks-up a light $\bar{q}$ that are connected by a string. Then within such non-perturbative stage of the hadronization process the heavy b-quark is decelerated and the light $\bar{q}$ is accelerated with a rate given by the string tension. Such an exchange of energy between b and $\bar{q}$ is similar to what is observed for perturbative radiation. Consequently, one can conclude that the b-quark constantly loses energy with a rate, which does not depend on whether it propagates alone, or as a constituent within a $b\bar{q}$ dipole.

The process of hadronization will finalize only after the last recreation of a B-meson, which escapes from the medium without further breakups. Apparently, due to breakups in a dense medium the final B-meson will have a reduced energy compared with a B-meson produced at $l = l_p$ in vacuum. In other words, with the same starting momentum p^b_+ the final momentum of the B meson coming out of a medium, will be smaller than in vacuum. This causes suppression because of steeply falling p_T distribution of the perturbatively produced b-quarks, and due to the steep fall-off of the b-quark fragmentation function at small z, as is shown in figure 4. Notice that above description of fragmentation and time-dependent energy loss holds for charm quarks as well.

5 Suppression of heavy flavored mesons

The cross section for inclusive production of a B-meson with momentum p_T in proton-proton (pp) collisions reads,

$$\sigma_{pp}(p_T) \equiv \frac{d\sigma(pp \to BX)}{d^2p_T} = \int d^2p^b_+ \, \frac{d\sigma(pp \to QX)}{d^2p^b_+} \, \frac{1}{z} \, D_{b/B}(z)\,, \tag{7}$$

where $p^b_+ = p^b_T + \sqrt{(p^b_T)^2 + m_b^2}$ is the initial LC momentum of the b-quark;

$$z \equiv \frac{(p_T + \sqrt{p_T^2 + M_B^2})}{p^b_+} = 1 - \frac{\Delta p^b_+(l_p)}{p^b_+}\,. \tag{8}$$

Similar relation holds also for heavy ion (AA) collisions, however l_p^{AA}, the production length of the final, last created colorless $Q\bar{q}$ dipole, is longer than in pp collisions, so LC momentum loss Δp^b_+ is larger, and z_{AA} is smaller. Besides, the corresponding cross section for B-meson production additionally contains a suppression factor $S(l_p^{AA})$ representing the survival probability of the $Q\bar{q}$ dipole created at the point l_p^{AA}. Such a dipole has to escape the medium without being broken-up developing the hadronic wave function.

Thus in AA collision the Eq. (7) is modified as,

$$\sigma_{AA}(p_T) \equiv \frac{d\sigma(AA \to BX)}{d^2p_T} = \int d^2p_+^b \frac{d\sigma(pp \to QX)}{d^2p_+^b} \times \frac{1}{z_{AA}} D_{b/B}(z_{AA})\, S(l_p^{AA}), \tag{9}$$

with $z_{AA} = 1 - \Delta p_+^b(l_p^{AA})/p_+^b$.

In comparison with Eq. (7) the additional factor $S(l_p^{AA})$ in (9) is an important player, making the hadronization processes in pp and AA different. If this factor is unity, $S = 1$, then there is no reason to delay production point to a longer distance l_p^{AA} compared with hadronization in vacuum. However, absorption terminates the colorless $b\bar{q}$ dipoles produced "too early", so it pushes the production point to the diluted surface of the hot medium, making the production length long, $l_p^{AA} \gg l_p$, and $z_{AA} \ll z$. This causes a strong suppression of the fragmentation function $D_{b/B}(z_{AA})$ according to figure 4.

Thus, Eq. (9) contains two last factors working in opposite directions and causing suppression of produced B or D mesons:

(i) The fragmentation function $D_{b/B}(z)$, peaking at large z (fig. 4), tends to reduce momentum loss $\Delta p_+^b(l_p^{AA})$, selecting shorter l_p^{AA}.

(ii) However, a shorter l_p^{AA} means a longer path length for further propagation of the colorless $Q\bar{q}$ dipole in the medium, increasing its chance to brake-up.

6 Attenuation of a $Q\bar{q}$ dipole in a hot medium

6.1 The formation time

In order to evaluate the suppression of production of heavy D and B mesons in heavy ion collisions one should understand first of all the corresponding attenuation of a $Q\bar{q}$ dipole. Such a $Q\bar{q}$ pair produced perturbatively with initially small separation, quickly expands. As we already mentioned above the light quark in the $Q\bar{q}$-meson carries a tiny fraction of the momentum, $\alpha \sim m_q/m_Q$. Consequently, even if the produced $b\bar{q}$ dipole has a small initial transverse separation, its size expands with a high speed, enhanced by a factor $1/\alpha$. Within the harmonic oscillator model the formation time of the B-meson wave function (in the medium rest frame) is very short and can be estimated as,

$$t_f^B = \frac{4\alpha(1-\alpha)\sqrt{p_T^2+m_B^2}}{2m_B\omega} \leq \frac{\sqrt{p_T^2+m_B^2}}{2m_B\omega}\,, \tag{10}$$

where $\omega = 300\,\mathrm{MeV}$ is the oscillator frequency, which determines the splitting of the ground state and the first radial excitation. For instance at $p_T = 10\,\mathrm{GeV}$ the B meson is formed on a short distance $l_f^B \leq 0.8\,\mathrm{fm}$, which is an order of magnitude shorter than for light mesons.

In comparison with light hadron production [11] where a small-size dipole with $r^2 \sim 1/p_T^2$ is propagating through the medium, production of heavy flavored mesons is controlled by propagation of a nearly formed large $Q\bar{q}$ dipole. Such a large dipole can be easily broken-up, so its mean free path is quite short. Indeed, the B-meson is nearly as big as a pion, $\langle r_{ch}^2\rangle_B = 0.378\,\mathrm{fm}^2$ [12]. Then the corresponding mean free path of such a meson in a hot medium is very short, $\lambda_B \sim [\hat{q}\,\langle r_T^2\rangle]^{-1}$, where $\langle r_T^2\rangle = 8\langle r_{ch}^2\rangle/3$. Here the so called transport coefficient $\hat{q}$ is the rate of broadening of the quark transverse momentum in the medium. For instance, at $\hat{q} = 1\,\mathrm{GeV}^2/\,\mathrm{fm}$ (compare with [11]) the mean free path $\lambda_B = 0.04\,\mathrm{fm}$, i.e. the b-quark propagates through the hot medium, frequently picking up and losing light antiquark comovers. Meanwhile the b-quark keeps losing energy with a rate, enhanced by medium-induced effects. Eventually the detected B-meson is formed and can survive in the dilute periphery of the medium.

6.2 The suppression factor $S(l_p^{AA})$

Considering hot a dense medium, the finally detected B-meson is produced at $l = l_p^{AA} > l_p$. Depending on the magnitude of formation length (10) one can distinguish different regimes in production of heavy flavored mesons.

In the low energy limit the formation length (10) is very short and one can use the eikonal Glauber approximation,

$$S(l_p^{AA}) = \exp\left[-\frac{\langle r_B^2\rangle}{2}\int\limits_{l_p^{AA}}^{\infty} dl\,\hat{q}(l)\right]\,, \tag{11}$$

where $\langle r_B^2\rangle \equiv \langle r_T^2\rangle_B = 8\,\langle r_{ch}^2\rangle_B/3$.

In the high-energy limit, the dipole size is "frozen" by Lorentz time dilation. Then the suppression factor reads,

$$S(l_p^{AA}) = \int d^2r\, d\alpha\, \left|\Psi_B(r,\alpha)\right|^2 \exp\left[-\frac{r^2}{2}\int\limits_{l_p^{AA}}^{\infty} dl\, \hat{q}(l)\right] , \tag{12}$$

where $\Psi_B(r, \alpha)$ is the LC wave function of the B-meson.

The general description interpolating between these two limits is based on the path-integral technique [13], summing all paths of the Q and $\bar{q}$. The corresponding expression for the suppression factor has the following form,

$$S(l_1, l_2) \propto \left|\int\limits_0^1 d\alpha \int d^2r_1 d^2r_2\, \Psi_M^\dagger(r_2,\alpha)\, G_{Q\bar{q}}(l_1,\vec{r}_1,\alpha;l_2,\vec{r}_2,\alpha)\, \Psi_{in}(r_1,\alpha)\right|^2 , \tag{13}$$

where in the case under consideration $l_1 = l_p^{AA}$, $l_2 \to \infty$. The initial distribution amplitude $\Psi_{in}(r_1, \alpha)$ is taken in the Gaussian form with mean separation $\langle r_1^2\rangle = \langle r_B^2\rangle$.

The Green function $G_{Q\bar{q}}(l_1, \vec{r}_1, \alpha; l_2, \vec{r}_2, \alpha)$ in (13) describes propagation of the $Q\bar{q}$ dipole between longitudinal coordinates l_1, l_2 with initial and final separations $\vec{r}_1$ and $\vec{r}_2$ respectively. It satisfies the 2-dimensional LC equation,

$$\left[i\frac{d}{dl_2} - \frac{m_{Q\bar{q}}^2 - \Delta_{r_2}}{2\,p_+^b\,\alpha\,(1-\alpha)} - V_{Q\bar{q}}(l_2,\vec{r}_2)\right] G_{Q\bar{q}}(l_1,\vec{r}_1;l_2,\vec{r}_2) = i\delta(l_2-l_1)\,\delta(\vec{r}_2-\vec{r}_1)\,, \tag{14}$$

where the variable $m_{Q\bar{q}}^2(\alpha) = m_Q^2(1-\alpha) + m_q^2\alpha$. The imaginary part of the LC potential, $\mathrm{Im}\,V_{Q\bar{q}}(l,\vec{r}) = -\hat{q}(l)r^2/4$, is responsible for attenuation in a medium. The real part is the phenomenological Cornell-type potential, adjusted to reproduce the masses and decay constants for B and D mesons [14, 12].

7 Comparison with data

Now we are in a position to calculate the suppression factor $R_{AA}(\vec{b})$ of heavy flavored mesons produced with high p_T in a hard process in a collision of nuclei A and A (colliding nuclei can be also different) with relative impact parameter b,

$$R_{AA}(\vec{b}, p_T) = \frac{\int d^2\tau\, T_A(\tau) T_A(\vec{b} - \vec{\tau})\, \sigma_{AA}(p_T, \vec{b}, \vec{\tau})}{T_{AA}(b)\, \sigma_{pp}(p_T)}\,, \tag{15}$$

where $\vec{\tau}$ is the impact parameter of the hard parton-parton collision relative to the center of one of the nuclei; $T_{AA} = \int d^2\tau\, T_A(b) T_A(\vec{b} - \vec{\tau})$; the differential cross sections $\sigma_{pp}(p_T)$ and $\sigma_{AA}(p_T)$ are given by Eq. (7) and by Eqs. (9) and (13), respectively.

The phenomenology presented above in previous Sections does not require to fix any parameters and allows so a parameter-free description of data. However, one parameter is unavoidably present in such kind of analysis. This is the transport coefficient $\hat{q}$, which cannot be predicted reliably, in particular its coordinate and time dependence. Here we employ the popular model from [15],

$$\hat{q}(l, \vec{b}, \vec{\tau}) = \frac{\hat{q}_0\, l_0}{l} \frac{n_{part}(\vec{b}, \vec{\tau})}{n_{part}(0, 0)}\, \Theta(l - l_0)\,, \tag{16}$$

where $n_{part}(\vec{b}, \vec{\tau})$ is the number of participants, and $\hat{q}_0$ is the rate of broadening of a quark propagating in the maximal medium density produced at impact parameter $\tau = 0$ in central collisions ($b = 0$) at the time $t = t_0$ after the collision. The value $\hat{q}_0 \sim 2\, GeV^2/\,\mathrm{fm}$ has been determined from our previous studies [11] of data on quenching of light high-p_T hadrons at LHC energy range. We fixed the medium equilibration time at $t_0 = 1\,\mathrm{fm}$ [11].

The time interval after the hard collision is $t = l/v_{Q\bar{q}}$ where $v_{Q\bar{q}}$ is the speed of the $Q\bar{q}$ dipole,

$$v_{Q\bar{q}} = \sqrt{1 - \frac{(2\, m_{Q\bar{q}})^2}{E^2_{Q\bar{q}}}}\,, \tag{17}$$

where $E_{Q\bar{q}} = \sqrt{p_T^2 + 4\, m^2_{Q\bar{q}}}$.

Different sources of time-dependent medium-induced energy loss were added, including radiative and collisional mechanisms [16]. Medium-induced energy loss is much smaller than the vacuum one, and do not produce a dramatic effect. They are particularly small for heavy flavors.

Model calculations of the nucleus-to-nucleon ratio of the cross sections (the so called nuclear modification factor R_{AA}) for B-meson production are

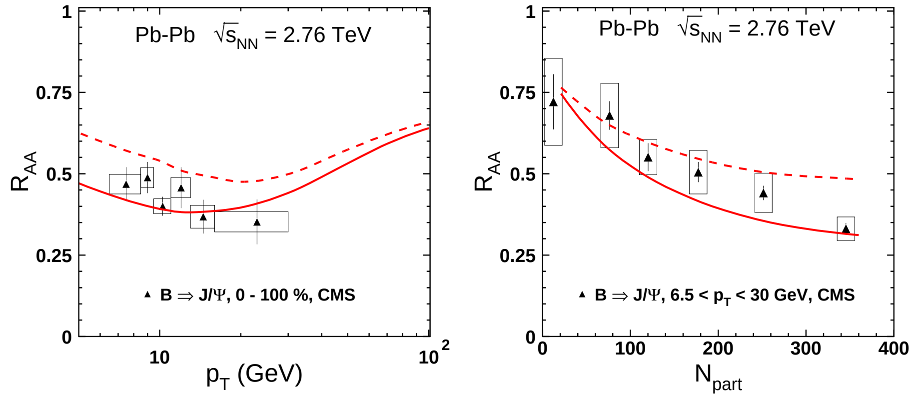

Figure 7: Comparison with CMS data for indirect J/ψ production [17] at $\sqrt{s} = 2.76\,\mathrm{TeV}$. The solid and dashed curves are calculated including and neglecting the induced energy loss, respectively.

compared with data on indirect production of J/ψ, originating from B decays. Such a comparison is performed vs p_T and centrality. The dashed curves in figure 7 correspond to calculations including only pure vacuum energy loss (radiative plus string) and neglecting induced energy loss at c.m. collision energy $\sqrt{s} = 2.76$ TeV. The solid curves represent the full calcula-

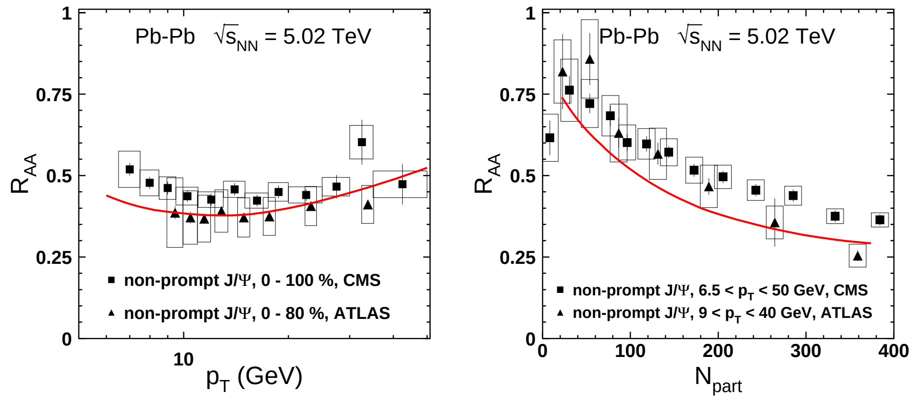

Figure 8: The same as in Fig. 7, but at $\sqrt{s} = 5.02\,\mathrm{TeV}$. Data are from the CMS [19] and ATLAS [18] Collaborations.

tion including also the induced energy loss and are in a reasonable agreement with CMS data [17].

The next figure 8 shows a comparison of our predictions with recent data from the ATLAS [18] and CMS [19] collaborations at c.m. collision energy $\sqrt{s} = 5.02\,\text{TeV}$. The data give an evidence for the lack of rise of R_{AA} at high p_T in a good agreement with our calculations. This is a new result in comparison with production of light hadrons where the nuclear modification factor R_{AA} rises with p_T due to color transparency effects[11] The weak p_T dependence of R_{AA} in production of heavy flavored mesons follows from a short formation time (10) when a small $Q\bar{q}$ dipole quickly expands to a normal meson size.

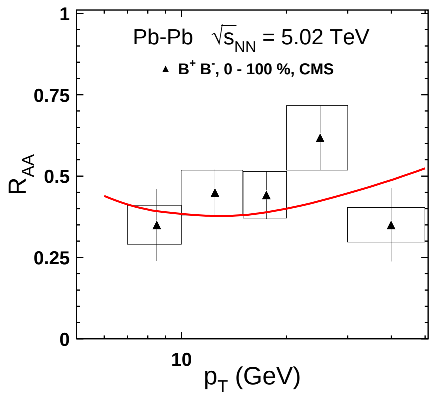

Figure 9: The same as in figure 8, but for direct production of B-mesons at $\sqrt{s} = 5.02\,\text{TeV}$. Data are from [20].

However, the CMS Collaboration recently published new results on direct $B^{\pm}$-meson production at c.m. collision energy $\sqrt{s} = 5.02\,\text{TeV}$. The corresponding comparison with our predictions is depicted in Fig. 9. This new data give a further evidence for the lack of rise of $R_{AA}(p_T)$ at high p_T in correspondence with data on production of $B^{\pm}$-mesons from indirect production of J/Ψ investigated by the ATLAS and CMS Collaborations [18, 19] and presented on the left panel of Fig. 8.

The approach developed here can also be applied to production of D-mesons. The results are compared with data in figures 10 and 11 vs p_T and centrality.

Notice that c-quarks radiate in vacuum much more energy than b-quarks,

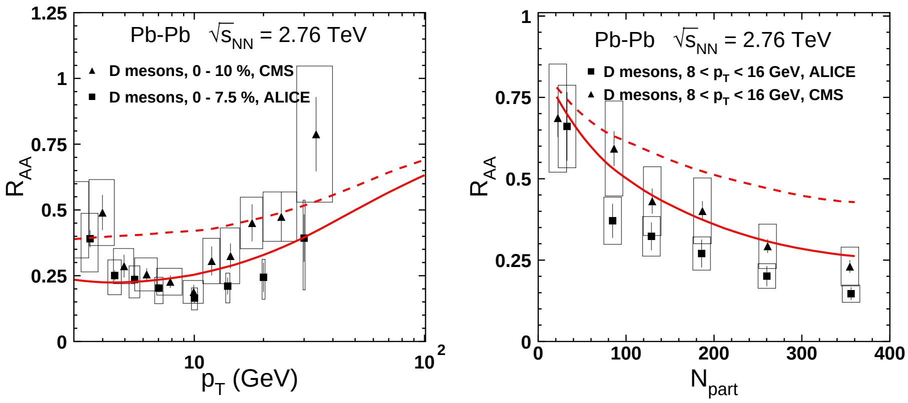

Figure 10: The same as in figure 7, but for D-mesons at $\sqrt{s} = 2.76\,\text{TeV}$. Data are from [21, 22, 23] and [24, 25].

while the effects of absorption of $c\bar{q}$ and $b\bar{q}$ dipoles in the medium are similar. Therefore, D-mesons are suppressed in AA collisions more than B-mesons.

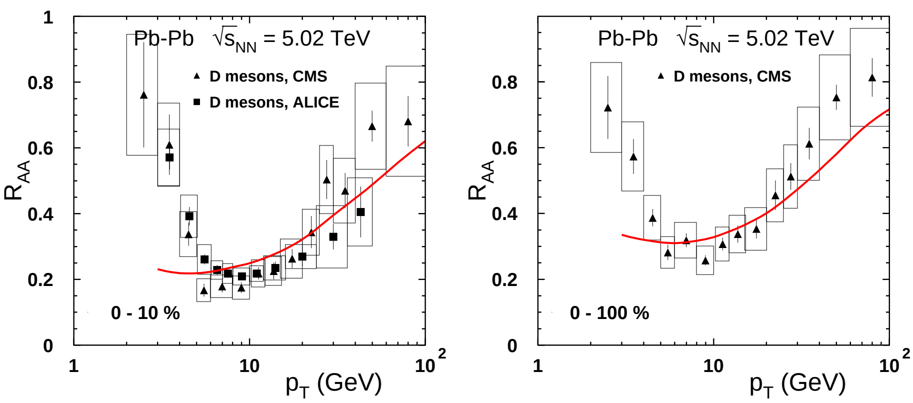

Figure 11: The same as in figure 10, but at $\sqrt{s} = 5.02\,\text{TeV}$ for centralities 0-80% and minimum bias events. Data are from CMS [26] and and ALICE [27] measurements

8 Summary

In comparison with production of light hadrons, we demonstrate that the production of heavy flavored mesons in heavy ion collisions shows new non-trivial features:

- During the first stage of hadronization succeeding high-p_T partonic collisions the heavy and light quarks radiate differently. Heavy quarks radiate a significantly smaller fraction of the initial energy regenerating their stripped-off color field much faster than light ones.

- This leads to a specific shape of the fragmentation functions for heavy-quark jets. Differently from light flavors, the heavy quark fragmentation functions strongly peak at large fractional momentum $z \sim 0.8 \div 0.9$, i.e. the produced heavy-light meson, B or D, carry the main fraction of the jet momentum. This is a clear evidence of a short production time of heavy-light mesons.

- The second stage of hadronization is controlled by the propagation of colorless dipoles in the medium. Whereas in large-p_T production of light hadrons a small $\bar{q}q$ dipole can survive in the medium due to color transparency, in heavy flavor production a $Q\bar{q}$ dipole promptly expands to a large size. Such a big dipole has no chance to survive intact in a hot medium. Multiple breakups and recreations of $\bar{q}Q$ dipoles increase energy loss preceding the final production of heavy flavored meson pushing the production point to the dilute medium surface. This is different from the scenario of high-p_T production of light $\bar{q}q$ mesons [11].

- Model predictions in a parameter-free way are in a good agreement with data for production of high-p_T B and D mesons. The maximal value of the transport coefficient $\hat{q}_0 \sim 2\ \mathrm{GeV}^2/\,\mathrm{fm}$ and agrees well with results of our previous analyses [11].

- We have disregarded so far the small initial state suppression of heavy flavors due to higher twist heavy dipole attenuation and leading twist shadowing [28]. Inclusion of these effect will lead to a small decrease of the values of $\hat{q}_0$ extracted from the analysis.

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nuclear shadowing in DIS
leading twist gluon shadowing contribution to nuclear suppression
hadronization in nuclear medium
propagation of partons in nuclear matter
nuclear broadening in inclusive hadron production off nuclei
nuclear suppression of hadrons in heavy-ion collisions
nuclear suppression at large Feynman x
production of heavy flavored hadrons in interactions off nuclei
Cronin effect in hadron-nucleus interactions
diffractive electroproduction of vector mesons
color transparency and coherence length effets

Education

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◦ H index: 15
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◦ taught courses: Applied quantum chromodynamics at high energies - for doctoral studies

Selected journal papers

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