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Novel mechanism for suppression of heavy flavored mesons in heavy ion collisions

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Abstract. Production of heavy flavored hadrons from fragmentation of heavy quarks represents an alternative probe for a medium created after heavy ion collisions. We demonstrate that observed strong suppression of heavy flavored D and B mesons, produced with high transverse momenta p_T , is caused by final state interactions with such a medium. The space-time pattern of hadronization of a highly virtual heavy quark is controlled predominantly by intensive gluon radiation, which is ceased at a short time scale in accordance with perturbative QCD calculations and LEP measurements of the fragmentation functions. However, production of heavy flavored hadrons lasts a long time due to prompt multiple breakups of produced colorless (pre)hadrons in the medium. This fact together with the specific shape of heavy quark fragmentation function, peaked at large z , allows to explain the observed strong suppression of D and B mesons in a good accord with data.

1. Introduction

The popular scenario (see e.g. [1]) explaining the jet quenching relies on the unjustified assumption of a long production time t_p of a colorless dipole, which is then developing the hadron wave function. This scenario is based on induced energy loss by a parton during propagation in a medium. In comparison to light hadrons a weaker radiation by heavy quarks, i.e. the so called *dead-cone effect*, should lead to a much weaker suppression in production of heavy flavored hadrons [2] in contradiction with data from Large Hadron Collider (LHC). In the present paper we propose an alternative scenario for production of heavy flavored hadrons. This novel mechanism is able to explain data in a parameter-free way.

2. Radiative energy loss in vacuum

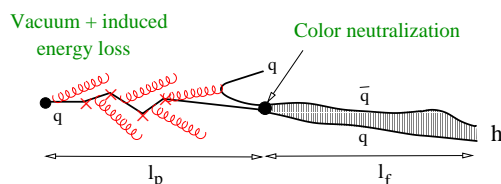


Figure 1. (color online) Space-time development of hadronization of a highly virtual quark producing a leading hadron (meson), which carries the main fraction z of the initial quark light-cone momentum.

One can define two time scales controlling the hadronization process as is illustrated in Fig. 1. As a results of a high- p_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 $k < p_T$ 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*, t_p , when the quark picks up an antiquark neutralizing its color. The production time can be given by approximate relation, $t_p \lesssim \frac{E}{\langle |dE/dt| \rangle} (1 - z)$, where $\langle |dE/dt| \rangle$ represents the mean value of the rate of energy loss and the factor $1 - z$ comes from the energy conservation: a hadron with a large $z \rightarrow 1$ requires a stopping of energy loss and has to be produced immediately after a hard collision.

The second stage begins with production of *colorless dipole* (prehadron), which does not have either the wave function or hadronic mass. It takes *the formation time* t_f to develop both. The formation time rises with the jet energy E due to Lorentz boosting factor and reads, $t_f = \frac{2zE}{m_{h^*}^2 - m_h^2}$, where the denominator follows from the uncertainty principle: it takes a proper time $t_f^* = 1/(m_{h^*} - m_h)$ to resolve between the ground state with hadronic mass m_h and the first radial excitation with m_{h^*} . This stage of hadronization can be described within a simplified heuristic consideration [3, 4] or by the path integral method [5, 6].

The amount of energy, radiated after the hard collision by the scattered parton over time interval t , was calculated in [7, 8, 5]. It has been shown that gluon radiation is subject to the *dead cone effect* [2], which implies that heavy quarks radiate less energy than the light ones.

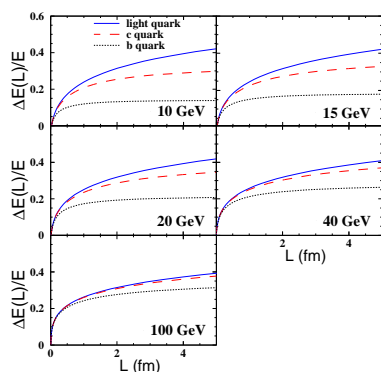


Figure 2. Fractional radiational vacuum energy loss by a high- p_T light, c and b -quark, produced with different initial energies.

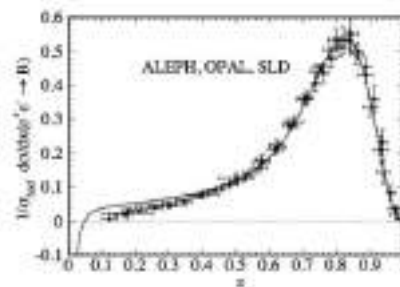


Figure 3. The $b \rightarrow B$ fragmentation function, from e^+e^- annihilation. The curve is the DGLAP fit [10].

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

A small amount of the initial energy radiated by heavy quarks causes that the final D or B mesons carry almost the whole momentum of the jet. Such an expectation is in accordance with direct measurements of the fragmentation functions (FFs) $c \rightarrow D$ and $b \rightarrow B$ in e^+e^- annihilation [9, 10]. The Fig. 3 illustrates the example of the $b \rightarrow B$ FF and indeed shows that the distribution strongly peaks at $z \sim 0.85$. A similar behavior was observed also for the $c \rightarrow D$ FF [9]. Note that the FFs of light quarks to light mesons are well known to fall steadily and steeply from small z towards $z = 1$ [11].

3. Fragmentation in a hot medium

The suppression in production of heavy D and B mesons in HICs is caused by the attenuation of a heavy-light $\bar{q}Q$ dipole during the second stage of hadronization. The dipole evolution with initially small separation is different in production of light and heavy flavored mesons. Whereas in light mesons the q or \bar{q} carries almost the same fraction of the meson momentum $\alpha \sim 0.5$, in the B meson the light q or \bar{q} carries a tiny momentum fraction, $\alpha \sim m_q/m_b \approx 0.05$. Consequently, the $\bar{q}b$ dipole expands its transverse size faster, enhanced by a factor $\sim 1/\alpha$.

The corresponding formation time of the B meson wave function can be estimated within the harmonic oscillator approximation, $t_f^B = \frac{\sqrt{p_T^2 + m_B^2}}{2m_B\omega}$, where $\omega = 0.3$ GeV is the oscillatory frequency. Consequently, for instance, at $p_T = 10$ GeV the B meson is formed on a short distance ~ 0.8 fm, which is an order of magnitude shorter than for light mesons.

In comparison to light hadron production [5] 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 $\bar{q}Q$ dipole. Such a large dipole can be easily broken-up, so its mean free path in a hot medium is quite short, $\lambda_B \sim [\hat{q} \langle r_T^2 \rangle]^{-1}$, where $\langle r_T^2 \rangle = 8\langle r_{ch}^2 \rangle/3$. For instance, taking the B -meson radius $\langle r_{ch}^2 \rangle_B = 0.378 \text{ fm}^2$ [12] and the transport coefficient $\hat{q} = 1 \text{ GeV}^2/\text{fm}$ [5], then the mean free path $\lambda_B = 0.04 \text{ fm}$, 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.

As was demonstrated in Fig. 2, perturbative radiation by heavy quarks ceases shortly. However, in accordance with confinement 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 $\kappa \approx 1 \text{ GeV}/\text{fm}$. In the medium we rely on the model [13, 14, 15] 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 $T_c = 280 \text{ MeV}$. Thus, the full rate of energy loss comes from both perturbative and nonperturbative mechanisms $\frac{dE}{dl} = \frac{dE_{rad}}{dl} - \kappa(T)$.

4. Suppression of heavy flavored mesons

In pp collisions the corresponding cross section for inclusive production of a B -meson with momentum p_T has the form [16],

$$\sigma_{pp}(p_T) \equiv \frac{d\sigma(pp \rightarrow BX)}{d^2p_T} = \int d^2p_+^b \frac{d\sigma(pp \rightarrow QX)}{d^2p_+^b} \frac{1}{z} D_{b/B}(z), \quad (1)$$

where p_+^b is the initial LC momentum of the b -quark.

In AA collisions a high- p_T b -quark produced in a dense medium propagates over a longer distance $l_p^{AA} > l_p$ up to the medium surface, where the final B -meson can survive. The b -quark keeps losing energy over all this path and the produced colorless B -meson has so the reduced fractional momentum $z_{AA} < z$, which is suppressed by the FF (see Fig. 3). Thus in AA collision the Eq. (1) is modified as [16],

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

Here the suppression factor $S(l_p^{AA})$ represents the survival probability of the $\bar{q}Q$ dipole created at the point l_p^{AA} and was calculated using the path-integral technique [17], summing all paths of the Q and \bar{q} . The calculational details can be found in [5, 16].

5. Comparison with data

We calculated the suppression factor $R_{AA}(\vec{b})$ at relative impact parameter b , $R_{AA}(\vec{b}, p_T) = \frac{\int d^2\tau T_A(\tau)T_A(\vec{b}-\vec{\tau})\sigma_{AA}(p_T, \vec{b}, \vec{\tau})}{T_{AA}(b)\sigma_{pp}(p_T)}$, where $\vec{\tau}$ is the impact parameter of the hard parton-parton collision relative to the center of one of the nuclei; $T_{AA} = \int d^2\tau T_A(b)T_A(\vec{b}-\vec{\tau})$; and differential cross sections $\sigma_{pp}(p_T)$ and $\sigma_{AA}(p_T)$ are given by Eqs. (1) and (2), respectively.

The phenomenology presented above allows a parameter-free description of data except of the transport coefficient \hat{q} , for which we employ the popular model from [18], $\hat{q}(l) \equiv \hat{q}(l, \vec{b}, \vec{\tau}) = \frac{\hat{q}_0 l_0}{l} \frac{n_{part}(\vec{b}, \vec{\tau})}{n_{part}(0,0)} \Theta(l - l_0)$, where $n_{part}(\vec{b}, \vec{\tau})$ is the number of participants. The variable \hat{q}_0 is the rate of broadening of a quark propagating in the maximal medium density produced at $\tau = 0$ and at the time $t = t_0$ after the collision. Its value $\hat{q}_0 \sim 2 \text{ GeV}^2/\text{fm}$ has been taken from our previous studies [5]. We fixed the medium equilibration time at $t_0 = 1 \text{ fm}$ [5].

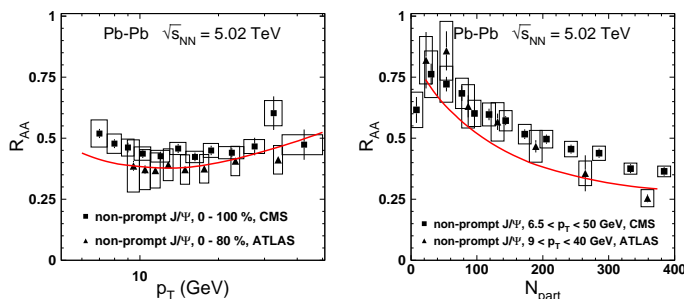


Figure 4. Comparison with ATLAS [19] and CMS [20] data for non-prompt J/Ψ production at c.m. collision energy $\sqrt{s} = 5.02 \text{ TeV}$.

In Fig. 4 the model calculations of the nuclear modification factor R_{AA} are compared with data on production of non-prompt J/Ψ , originating from B decays. Such a comparison is performed vs p_T and centrality. One can see a fair agreement of model predictions with recent data from ATLAS [19] and CMS [20] collaborations at c.m. collision energy $\sqrt{s} = 5.02 \text{ TeV}$.

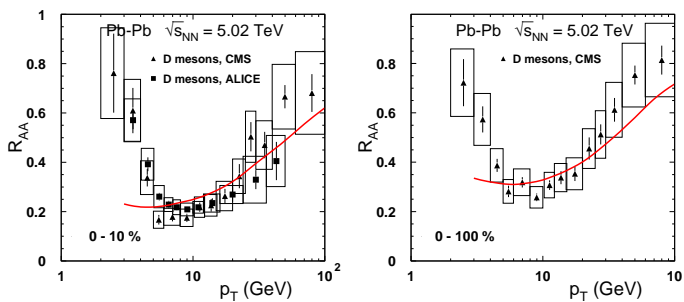


Figure 5. Comparison with data on $R_{AA}(p_T)$ for production of D mesons at $\sqrt{s} = 5.02 \text{ TeV}$ and at centralities 0-10% and 0-100%. Data are from CMS [21] and ALICE [22] measurements.

The approach developed here can also be applied to production of D -mesons. The results are compared with data in Fig. 5 vs p_T . Notice that c -quarks radiate in vacuum much more energy than b -quarks, while the effects of absorption of $\bar{q}c$ and $\bar{q}b$ dipoles in the medium are similar. Therefore, D -mesons are suppressed in AA collisions more than B -mesons.

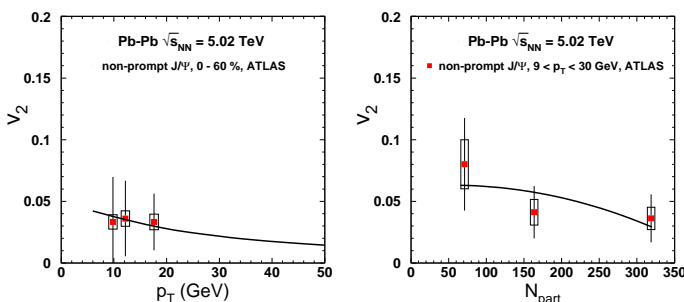


Figure 6. Azimuthal asymmetry v_2 vs p_T and centrality for production of non-prompt J/Ψ at $\sqrt{s} = 5.02 \text{ TeV}$. Data are from the ATLAS experiment [23].

Finally, in Fig. 6 we predict a weak p_T - and centrality- dependence of the azimuthal asymmetry, $v_2 \equiv \langle \cos(2\phi) \rangle$, in a good agreement with the last ATLAS data [23].

6. Summary

In comparison to light hadrons, we demonstrate that the production of heavy flavored mesons in heavy ion collisions shows new nontrivial 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.

This leads to a specific shape of the FFs for heavy-quark jets. Differently from light flavors, the heavy quark FFs strongly peak at large fractional momentum z , i.e. the produced heavy-light meson, B or D , carry the main fraction of the jet momentum as a clear evidence of a short production time.

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 light-light $\bar{q}q$ dipole can survive in the medium due to color transparency, in heavy flavor production a heavy-light $\bar{q}Q$ dipole promptly expands to a large size. This leads to much lower survival probability. Multiple breakups and recreations of $\bar{q}Q$ dipoles increase energy loss prior to the final production of heavy flavored mesons pushing the production point to the dilute medium surface. This is different from the scenario for high- p_T production of light $\bar{q}q$ mesons [5].

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 $\hat{q}_0 \sim 2 \text{ GeV}^2/\text{fm}$ and agrees well with results of our previous analyses [5].

Acknowledgments

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