

## Energy loss of $B$ and $D$ mesons in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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We present the calculations of collisional and radiative energy loss of  $B$  and  $D$  mesons in the medium produced in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The nuclear modification factor  $R_{AA}$  of  $B$  and  $D$  mesons including shadowing and energy loss are calculated and compared with the measured data. While the  $D$  meson  $R_{AA}$  can be described in terms of the radiative energy loss alone, both the collisional as well as radiative energy loss are required to explain the  $B$  meson measurements.

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## 1. Introduction

The heavy ion collisions at ultra relativistic energy create matter with high energy density required to form Quark Gluon Plasma (QGP). Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) are designed to create and explore QGP. Many measurements at RHIC and LHC already point to the formation of QGP [1]. The heavy quarks (charm and bottom) are produced in hard partonic interactions in heavy ion collisions and their initial momentum distribution can be calculated from pQCD [2]. While traversing the hot/dense medium formed in the collisions, these quarks lose energy either due to the elastic collisions with the plasma constituents or by radiating a gluon or both. There are several formulations to calculate collisional [3, 4, 5, 6, 7] as well as radiative energy loss [8, 9, 10, 11]. For a review of many of these formalism see Ref. [12]. At high parton energies, the radiative energy loss becomes much larger than the collisional energy loss but at lower energies, these two processes can contribute equally with the collisional energy loss being the dominant for small values of the parton energy [13].

In this work, we calculate the collisional energy loss of heavy quark using Bjorken formalism [6, 7] and Peigne and Peshier (PP) formalism [5]. We calculate the radiative energy loss of heavy quarks using reaction operator formalism DGLV (Djordjevic, Gyulassy, Levai and Vitev) [10, 11, 14] and using generalized dead cone approach [15, 16]. We calculate the nuclear modification factor including shadowing and energy loss for  $B$  and  $D$  mesons and compare with ALICE and CMS data.

## 2. Heavy Quark Production

The production cross sections of  $c\bar{c}$  and  $b\bar{b}$  pairs are calculated to NLO in pQCD using the CT10 parton densities [17]. We use the same set of parameters as that of Ref. [18] which are obtained by fitting the energy dependence of open heavy flavor production to the measured total cross sections. The mass of charm quark is taken as 1.29 GeV and the mass of bottom quark is taken as 4.7 GeV. The central EPS09 NLO parameter set [19] is used to calculate the modifications of the parton distribution functions (nPDF) in heavy ion collisions, referred as shadowing effects.

For the fragmentation of heavy quarks into mesons, Peterson fragmentation function is used [20].

$$D_Q(z) = \frac{N}{z \left[ 1 - \frac{1}{z} - \frac{\epsilon_Q}{(1-z)} \right]^2}. \quad (2.1)$$

Here  $z = p_T^H/p_T^Q$  and  $N$  is the normalization constant which is fixed by summing over all hadrons containing heavy quarks ,

$$\sum \int dz D_Q(z) = 1. \quad (2.2)$$

For charm quark :  $\epsilon_c=0.016$  and  $N = 0.2478$  .

For bottom quark :  $\epsilon_b=0.0012$  and  $N = 0.05181$  .

The distribution peaks at

$$z_{\max} = \frac{(\epsilon_Q + 2) - \sqrt{\epsilon_Q (\epsilon_Q + 4)}}{2}. \quad (2.3)$$

### 3. Collisional Energy Loss

In Peigne and Peshier Formalism, the QCD calculation of the rate of energy loss of heavy quark per unit distance ( $dE/dx$ ) in QGP is given by Braaten and Thoma [3]. Their formalism is an extension of QED calculation of  $dE/dx$  for a muon [4] which assumes that the momentum exchange  $q \ll E$ . Such an assumption is not valid in the domain when the energy of the heavy quark  $E \gg M^2/T$ , where  $M$  is the mass of the heavy quark. Peigne and Peshier [5] extended this calculation which is valid in the domain  $E \gg M^2/T$  to give the expression for  $dE/dx$  as

$$\frac{dE}{dx} = \frac{4\pi\alpha_s^2 T^2}{3} \left[ \left(1 + \frac{N_f}{6}\right) \log\left(\frac{ET}{\mu_g^2}\right) + \frac{2}{9} \log\frac{ET}{M^2} + c(N_f) \right], \quad (3.1)$$

where  $T$  is the temperature of QGP medium,  $E$  is the energy of heavy quark,  $N_f (= 3)$  is the active flavours,  $\alpha_s (= 0.3)$  is the fine structure splitting constant and  $c(N_f) = 0.146N_f + 0.05$ . The thermal gluon mass can be written as  $m_g = \mu_g/\sqrt{2}$  where  $\mu_g = \sqrt{4\pi\alpha_s T^2 \left(1 + \frac{N_f}{6}\right)}$  is the Debye screening mass.

The expression of Bjorken formalism to calculate the collisional energy loss of heavy quark is given in Ref. [6, 7]

### 4. Radiative Energy Loss

The rate of radiative energy loss of a heavy quark with energy  $E$  due to the inelastic scattering with the medium is calculated as

$$\frac{dE}{dx} = \frac{\langle \omega \rangle}{\lambda}, \quad (4.1)$$

where  $\langle \omega \rangle$  is the mean energy of the emitted gluons and  $\lambda$  is the mean free path length.  $\langle \omega \rangle$  is calculated from generalised dead cone  $\mathcal{D}$  as

$$\langle \omega \rangle = \frac{d\omega \int \mathcal{D} d\eta}{\frac{1}{\omega} d\omega \int \mathcal{D} d\eta}, \quad \mathcal{D} = \left(1 + \frac{M^2}{s} e^{2\eta}\right)^{-2} \quad \text{and} \quad \eta = -\ln \tan\left(\frac{\theta}{2}\right). \quad (4.2)$$

Here  $s (= 2E^2 + 2E\sqrt{E^2 - M^2} - M^2)$  is mandalstam variable and  $\theta$  is the emission angle.  $\lambda$  is calculated as [15, 16]

$$\frac{1}{\lambda} = \rho_{QGP} \sigma_{2 \rightarrow 3}. \quad (4.3)$$

Here  $\sigma_{2 \rightarrow 3}$  for the process  $2 \rightarrow 3$  is calculated as [21]

$$\sigma_{2 \rightarrow 3} = 4 C_A \alpha_s^3 \int \frac{1}{q_\perp^2} dq_\perp^2 \int \frac{1}{\omega} d\omega \int \mathcal{D} d\eta. \quad (4.4)$$

Here  $C_A = 3$  and  $q_\perp$  is the transverse momentum of the exchanged gluon.

Using Eqs. (4.1), (4.2), (4.3) and (4.4) and assigning the limits of  $q^2$ ,  $\omega$  and  $\eta$  we get

$$\frac{dE}{dx} = 24 \alpha_s^3 \rho_{QGP} \int_{q_\perp^2|_{\min}}^{q_\perp^2|_{\max}} \frac{1}{q_\perp^2} dq_\perp^2 \int_{\omega_{\min}}^{\omega_{\max}} d\omega \int_{\eta_{\min}}^{\eta_{\max}} \mathcal{D} d\eta. \quad (4.5)$$

Limits are given in Ref.[15, 16].

Equation (4.5) is solved to get the following result which we call present result

$$\frac{dE}{dx} = 24 \alpha_s^3 \rho_{QGP} \frac{1}{\mu_g} (1 - \beta_1) \left( \sqrt{\frac{1}{(1 - \beta_1)} \log\left(\frac{1}{\beta_1}\right)} - 1 \right) \mathcal{F}(\delta) . \quad (4.6)$$

Here

$$\mathcal{F}(\delta) = 2\delta - \frac{1}{2} \log\left(\frac{1 + \frac{M^2}{s} e^{2\delta}}{1 + \frac{M^2}{s} e^{-2\delta}}\right) - \left(\frac{\frac{M^2}{s} \sinh(2\delta)}{1 + 2 \frac{M^2}{s} \cosh(2\delta) + \frac{M^4}{s^2}}\right) , \quad (4.7)$$

$$\delta = \frac{1}{2} \log\left[\frac{1}{(1 - \beta_1)} \log\left(\frac{1}{\beta_1}\right) \left(1 + \sqrt{1 - \frac{(1 - \beta_1)}{\log\left(\frac{1}{\beta_1}\right)}}\right)^2\right] , \quad (4.8)$$

$$\beta_1 = \mu_g^2 / (C E T) , \quad (4.9)$$

$$C = \frac{3}{2} - \frac{M^2}{4 E T} + \frac{M^4}{48 E^2 T^2 \beta_0} \log\left[\frac{M^2 + 6 E T (1 + \beta_0)}{M^2 + 6 E T (1 - \beta_0)}\right] , \quad (4.10)$$

$$\beta_0 = \sqrt{1 - \frac{M^2}{E^2}} . \quad (4.11)$$

$\rho_{QGP}$  is density of QGP medium.

The expression of DGLV formalism to calculate the radiative energy loss of heavy quark is given in Ref.[14].

## 5. Evolution Model

The evolution of the system for each centrality bin is governed by an isentropic cylindrical expansion with prescription given in Ref. [22]. The entropy conservation condition  $s(T)V(\tau) = s(T_0)V(\tau_0)$  and equation of state obtained by Lattice QCD along with hadronic resonance are used to obtain temperature as a function of proper time [23]. The transverse size  $R$  for a given centrality with number of participant  $N_{part}$  is obtained as  $R(N_{part}) = R_A \sqrt{2 A/N_{part}}$ , where  $R_A$  is radius of the nucleus. The initial entropy density  $s(\tau_0)$  is

$$s(\tau_0) = \frac{a_m}{V(\tau_0)} \left(\frac{dN}{d\eta}\right) . \quad (5.1)$$

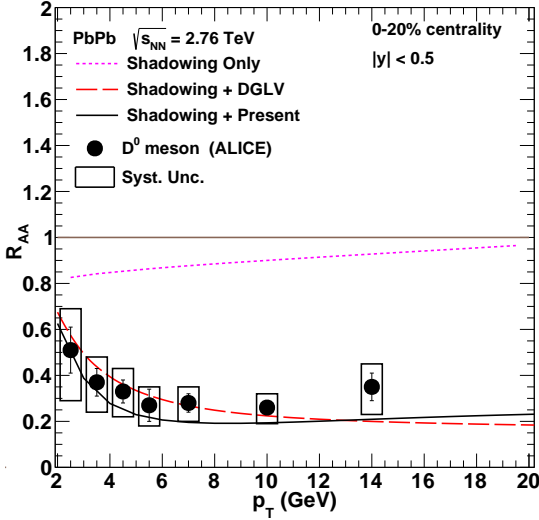
Here  $a_m = 5$  is a constant which relates the total entropy with the multiplicity [24]. The initial volume  $V(\tau_0) = \pi [R(N_{part})]^2 \tau_0$  and measured values of  $dN/d\eta$  for LHC [25] are used for a given centrality. The calculated average path length ( $L$ ) for 0-20 % centrality is 5.62 fm and for 0-100 % centrality is 4.3 fm.

## 6. Results and Discussions

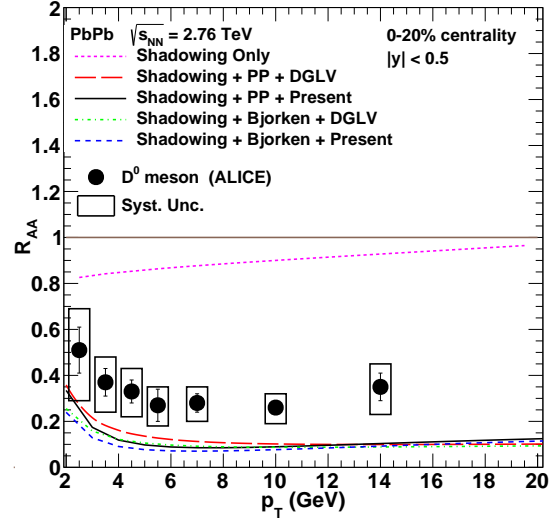
Figure 1 shows the nuclear modification factor  $R_{AA}$  of  $D^0$  mesons as a function of transverse momentum using Radiative energy loss (DGLV and Present) and shadowing in PbPb collision at

$\sqrt{s_{NN}}=2.76$  TeV. The data is from ALICE measurements of  $D^0$  mesons [26]. The radiative energy loss by both DGLV and present calculations explain the data.

Figure 2 shows the nuclear modification factor  $R_{AA}$  of  $D^0$  mesons as a function of transverse momentum using energy loss (PP+DGLV and PP+Present) and shadowing in PbPb collision at  $\sqrt{s_{NN}}=2.76$  TeV. The data is from ALICE measurements of  $D^0$  mesons [26]. We observe that DGLV+PP, DGLV+Bjorken, Present+PP and Present+Bjorken calculations overestimate the measured suppression of  $D$  meson.



**Figure 1:** Nuclear modification factor  $R_{AA}$  of  $D^0$  mesons as a function of transverse momentum using Radiative energy loss (DGLV and Present) and shadowing in PbPb collision at  $\sqrt{s_{NN}}=2.76$  TeV. The data is from ALICE measurements of  $D^0$  mesons [26].

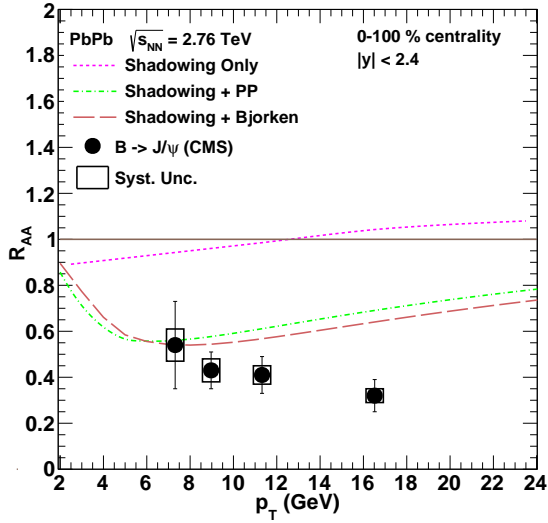


**Figure 2:** Nuclear modification factor  $R_{AA}$  of  $D^0$  mesons as a function of transverse momentum using energy loss (PP+DGLV and PP+Present) and shadowing in PbPb collision at  $\sqrt{s_{NN}}=2.76$  TeV. The data is from ALICE measurements of  $D^0$  mesons [26].

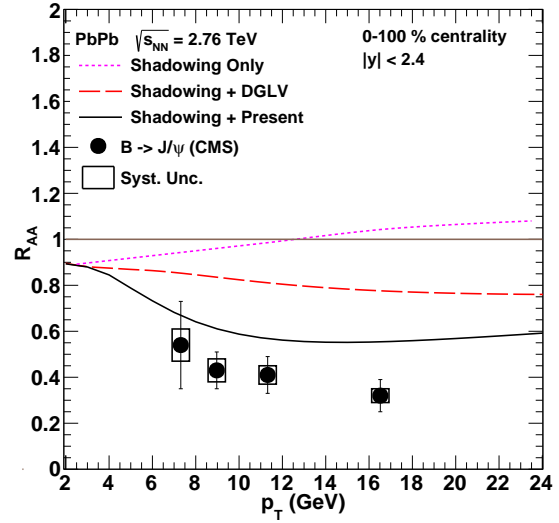
Figure 3 shows the nuclear modification factor  $R_{AA}$  of inclusive  $J/\psi$  coming from  $B$  mesons as a function of transverse momentum using collisional energy loss (PP and Bjorken) and shadowing in PbPb collision at  $\sqrt{s_{NN}}=2.76$  TeV. The data is from CMS measurements of  $J/\psi$  mesons from  $B$  decay [27]. We observe that the collisional energy loss (PP and Bjorken) calculations underestimate the suppression of  $B$  meson.

Figure 4 shows the nuclear modification factor  $R_{AA}$  of inclusive  $J/\psi$  coming from  $B$  mesons as a function of transverse momentum using radiative energy loss (DGLV and Present) and shadowing in PbPb collision at  $\sqrt{s_{NN}}=2.76$  TeV. The data is from CMS measurements of  $J/\psi$  mesons from  $B$  decay [27]. We observe that radiative energy loss (DGLV and Present) calculations underestimate the suppression of  $B$  meson.

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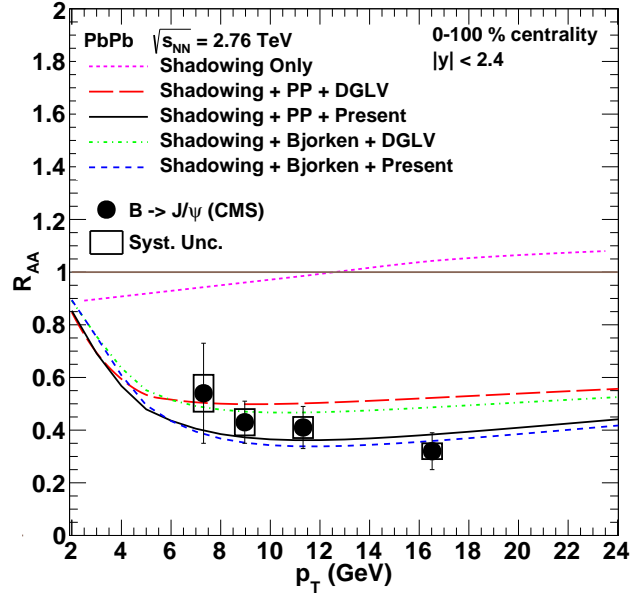
measured suppression of  $B$  meson. Present+PP and Present+Bjorken produce more suppression than the DGLV+PP but are consistent with the data.

## 7. conclusion

We study the energy loss of heavy quark due to elastic collisions and gluon radiation in hot/dense medium. Results of radiative energy loss are obtained from two different formalisms have been compared. Similarly the results of collisional energy loss obtained from two different formalisms have been compared. The  $D$  meson suppression in LHC PbPb collisions can be described in terms of radiative energy loss alone but, both the collisional and radiative energy loss are required to explain the  $B$  meson suppression.

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**Figure 5:** Nuclear modification factor  $R_{AA}$  of inclusive  $J/\psi$  coming from  $B$  mesons as a function of transverse momentum using energy loss (PP+DGLV and PP+Present) and shadowing in PbPb collision at  $\sqrt{s_{NN}}=2.76$  TeV. The data is from CMS measurements of  $J/\psi$  mesons from  $B$  decay [27].

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