Heavy Flavour Production and Propagation

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In this talk, I discuss production of heavy quarks in heavy-ion collisons, their thermalisation, different energy-loss formalisms based on pQCD including their theoretical foundation, limitations and kinematic domain of applicability and some of the important observables for quark-gluon plasma.

1. Introduction

The advent of the ultrarelativistic nucleus nucleus collisions at higher and higher energies highlights heavy quarks as a useful probe [1] for the Quark-Gluon Plasma (QGP). Heavy quarks defined for the purposes of this talk are the charm (c) and bottom (b) quarks. They are usually produced in pairs ($Q\bar{Q}$) from the fusion of gluons ($gg \to Q\bar{Q}$) or light quarks ($q\bar{q} \to Q\bar{Q}$), mainly during initial fusion of partons and also from QGP, if the initial temperature is high enough. Because of their large masses ($M_c = 1.27^{+0.07}_{-0.09}$ GeV/c^2 and $M_b = 4.19^{+0.18}_{-0.06}$ GeV/c^2), there is no production of heavy quarks at later times in the QGP and none in the hadronic matter [2, 3]. Thus, the total number of heavy quarks gets frozen very early in the history of collision, which makes them an excellent probe of QGP, as one is left with the task of determining the distribution, whose details may reflect development in the plasma.

After their production heavy quarks are expected to be present in the QGP and the subsequent hadron gas throughout their evolution. The important question is that how much do heavy quark thermalise in heavy-ion collisions [4]. The possibility of heavy quarks actually thermalising in the medium provides an opportunity to utilise them as probes for the transport coefficients of the QCD medium [2, 3]. Also after their production they will propagate through the medium and will lose energy [5–13] in the process of scattering with the quarks and gluons and also by radiation of gluons. They may fragment into heavy mesons by combining with light quarks/antiquarks, which are in great abundance in the plasma. These mesons may further decay through leptonic channels [1]. Thus the final spectra for mesons/leptons would contain information about the energy loss suffered by the heavy quarks/antiquarks.

2. Heavy Quark Production in pp collisions

Since heavy quarks are primarily produced through parton hard scattering, the production cross-section may be calculated using pQCD. At leading order pQCD, heavy quarks in pp collisions are mainly produced by fusion of gluons ($gg \to Q\overline{Q}$) or light quarks ($q\overline{q} \to Q\overline{Q}$) [14]. The cross-section for the production of heavy quarks from pp collisions at leading order can be expressed as [14, 15]:

$$\frac{d\sigma}{dy_1\, dy_2\, dp_T} = 2x_1x_2p_T \sum_{ij} \Big[f_i^{(1)}(x_1,Q^2) f_j^{(2)}(x_2,Q^2)\hat{\sigma}_{ij} + f_j^{(1)}(x_1,Q^2) f_i^{(2)}(x_2,Q^2)\hat{\sigma}_{ij} \Big] /(1+\delta_{ij}), \quad (1)$$

where i and j are the interacting partons, $f_i^{(1)}$ and $f_j^{(2)}$ are the partonic structure functions and x_1 and x_2 are the fractional momenta of the interacting hadrons carried by the partons i and j. The short range subprocesses for the heavy quark production, $\hat{\sigma} = d\sigma/dt$ are de-

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fined as:

$$\frac{d\sigma}{dt} = \frac{1}{16\pi s^2}\,|\mathcal{M}|^2, \tag{2}$$

where $|\mathcal{M}|^2$ for the processes $gg{\rightarrow}Q\bar{Q}$ and $q\bar{q}{\rightarrow}\ Q\bar{Q}$ can be obtained from Ref. [14]. The running coupling constant α_s at leading order is

$$\alpha_s = \frac{12\pi}{(33-2N_f)\ln{(Q^2/\Lambda^2)}}, \tag{3}$$

where $N_f = 3$ is the number of active flavours and $\Lambda = \Lambda_{\rm QCD}$. The p_T distribution of production of heavy quarks at leading order supplemented with a K-factor ≈ 2.5 is taken as the baseline for the calculation of the nuclear suppression factor, R_{AA} [16]. Effect of prefactor K is diluted during computation of nuclear modification factor due to its identical effects on both initial and final distributions profiles. Furthermore, the K-factor, if equal for c and b quarks, has not only a diluted effect but can actually be neglected in the ratios. The shadowing effect is considered using EKS98 parameterization [17] for nucleon structure functions and here we use the CTEQ4M [18] set for nucleon structure function. We use Peterson fragmentation function [19] with parameter $\epsilon_c = 0.06$ and $\epsilon_b = 0.006$ for fragmentation of c quarks into D mesons and b quarks into B mesons, respectively.

All the calculations are done assuming the mean intrinsic transverse momentum of the partons to be zero. We also note one can consider next-to-leading-order (NLO) or fixed-order-next-to-leading-log (FONLL) levels. The NLO includes contributions of the strong coupling α_s^2 and α_s^3, while FONLL calculations include contribution of those orders along with logarithm contributions of the form $\alpha_s^n \log^{n-1}(p_T/M_Q)$ and $\alpha_s^n \log^n(p_T/M_Q)$ resummed to all order in n (where p_T is the transverse momentum of heavy quark).

3. Proagation and Energy Loss of Heavy Quarks

The charm quarks will be produced on a time scale of $1/2Mc \sim 0.07$ fm/c, which would be as low as 0.02 fm/c for bottom quarks. Immediately upon their production, these heavy quarks will propagate through the deconfined matter (QGP) and start losing energy. There are two contributions to the energy-loss of a heavy quark in the QGP: one caused by elastic collisions with the light partons of the QGP and the other by radiation of the decelerated color charge, i.e., bremsstrahlung of gluons. The energy loss encountered by an energetic-parton in a QCD medium reveals the dynamical properties of that medium and presently is a field of high interest in view of jet quenching of high energy partons; both light and heavy. Naively, one imagines that the amount of quenching for heavy flavours jet should be smaller than that of light flavours due to the large mass of heavy quarks. However, the single electron data at RHIC [1] exhibit almost a similar suppression for heavy flavored hadrons compared to that for light hadrons.

A. Collisional Energy Loss and Thermalization of Heavy Quarks

There is an extensive body of literature on the collisional energy-loss of energetic quarks considering elastic collisions with the quarks and gluons $Qg \rightarrow Qg$ and $Qq \rightarrow Qq$, of the dense medium [5, 7, 9, 10]. A complete leading order result for the collisional energy-loss of heavy quarks has been found using the hard thermal loop resummation technique.

The importance of the collisional energy-loss contribution and the possibility of heavy quark thermalisation provides an important information for the transport coefficients of QGP. To this end, one can calculate the transport (drag and diffusion) coefficients in the perturbative QGP by relating them to the collisional energy loss and momentum broadening. These transport properties can be used to formulate a Fokker-Planck or, equivalently, Langevin equation. Exploiting this one can study the phenomenology of heavy quark transport in QGP [2–4], using a boost invariant hydrodynamical model. A comparision to data would thus yield information on the interaction between heavy quarks with the medium (QGP).

B. Dead-Cone and Radiative Energy Loss

Among the interactions that a charged particle undergoes, as it traverses a dense matter, inelastic (i.e. radiative) scattering [6, 8, 10, 11, 13] is undoubtedly the most important and interesting one. A number of different energy loss models has also been formulated in the literature (for review see Refs [20, 21]). The basic differences among the different models are the various constraints (*e.g.*, kinematic cuts, large angle radiation etc.) implemented to make the calculations manageable. We define the rate of radiative energy loss of a parton with energy E, due to inelastic scatterings with the medium partons in a very canonical [22].

Due to the mass effect, a suppression, known as 'dead cone' effect, in the soft gluon emission off a heavy quark was predicted in comparison to that from a light quark. This resulted in a reduction of heavy quark energy loss induced by the medium [8], which is limited only to the forward direction.

In a very recent works [23] the probability of gluon emission off a heavy quark has been generalised by relaxing some of the constraints, *e*.g., the gluon emission angle and the scaled mass of the heavy quark with its energy, which were imposed in earlier calculations [8]. It resulted in a very compact and elegant expression for the gluon radiation spectrum off a heavy quark (*e*.g., $Qq \to Qqg$) as [23]

$$\frac{dn_g}{d\eta dk_\perp^2} = \frac{C_A\alpha_s}{\pi}\frac{1}{k_\perp^2}\mathcal{D} \ , \tag{4}$$

where the transverse momentum of the emitted massless gluon is related to its energy by $k_\perp = \omega\sin\theta$, and the rapidity, $\eta = -\ln[\tan(\theta/2)]$, is related to the emission angle, and the generalised dead cone is given by

$$\mathcal{D} = \left(1 + \frac{M^2}{s\tan^2(\frac{\theta}{2})}\right)^{-2} . \tag{5}$$

Now, the Mandelstam variable s is given as, $s = 2E^2 + 2E\sqrt{E^2 - M^2} - M^2$, with E and M, respectively, the energy and mass of the heavy quark. C_A is the Casimir factor for adjoint representation and α_s is the strong coupling constant. In the small angle limit, $\theta \ll \theta_0 (= M/E) \ll 1$, the dead cone in (5) reduces to that in Ref. [8] as $(1 + \theta_0^2/\theta^2)^{-2}$ whereas for massless case it becomes unity and (4) reduces to the Gunion-Bertsch formula [24, 25]. The gluon spectrum for the process, $Qg \to Qgg$, can also be found in Ref. [23].

In Fig. 1, a Monte Carlo simulation of the above suppression factor (5) (*i*.e., the scaled gluon emission spectrum off a heavy quark with that of light quark) is displayed. It reveals a forward-backward asymmetry which encompasses the fact that the gluon emission off a heavy quark is as strong as that of light quark at the large angles (backward direction) whereas it is suppressed due to nonzero quark mass at the small angles (forward direction). However, if the energy of the heavy quark is large compared to its mass, the effect of dead cone diminishes, both heavy and light quark are expected to lose energy almost similarly. This result can have important consequences for a better understanding of heavy flavour energy loss in the context of heavy-ion collisions at RHIC and LHC.

Now, we obtain [22] the rate of radiative energy loss of a parton with energy E, due to inelastic scatterings with the medium partons in a very canonical way as

$$\frac{dE}{dx} = \frac{\langle\omega\rangle}{\langle\lambda\rangle}, \tag{6}$$

where $\langle\omega\rangle$ and $\langle\lambda\rangle$ are the mean energy of emitted gluons and the mean free path of the traversing quark, respectively. Among the set of variables $[k_\perp, \eta, \omega]$ in (4) any two together are sufficient to completely describe an emitted gluon. For convenience we now change the variable duo from $[k_\perp, \eta]$ to $[\omega, \eta]$ as

$$\frac{dn_g}{d\eta dk_\perp} \Rightarrow \frac{dn_g}{d\eta d\omega} \ . \tag{7}$$

It is now easy to find mean energy of the emitted soft gluons from the spectrum as

$$\begin{aligned}\langle\omega\rangle &= \left(\int \frac{dn_g}{d\eta d\omega}\omega \, d\eta d\omega\right) / \left(\int \frac{dn_g}{d\eta d\omega} \, d\eta d\omega\right) \\ &= \left(\int d\omega \int \mathcal{D} d\eta\right) / \left(\int \frac{1}{\omega} \, d\omega \int \mathcal{D} \, d\eta\right).\end{aligned}$$

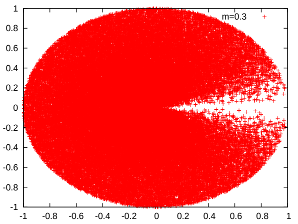

FIG. 1: (color online) A Monte Carlo simulation for the suppression factor in (5) in the full domain of gluon emission angle, θ, off a heavy quark for the scaled mass $m = \frac{M}{\sqrt{s}} = 0.3$. This actually represents a two dimensional view of the scaled gluon emission probability off a heavy quark with that of a light quark as given in (4). We consider the direction of propagation of a heavy quark is from left to right along the horizontal axis and collide with medium partons at the origin of a circle of unit radius. This simulation has been performed by throwing points at random directions within the full domain of θ but with a probabilistic weight $\mathcal{D}(\theta)$, which would then correspond to a point randomly on the selected θ-line as a '*red plus*' inside the circle of unit radius. The shade with red pluses represents the soft gluon emission zone whereas the conical white zone in the forward direction indicates a dead cone for gluon emission due to the mass effect.

Other important quantity in (6) is the mean free path $\langle\lambda\rangle$, which is the average distance covered by the traversing quark between two successive collision, *followed by a soft gluon radiation*. The magnitude of mean free path depends on the characteristics of the system in which the energetic particle is traversing, and it is defined as

$$\langle\lambda\rangle \;=\; 1/(\sigma_{2\to 3}\; \rho_{\rm qgp}) \;, \qquad (8)$$

where $\sigma_{2\to 3}\rho_{\rm qgp} = \rho_q \sigma_{Qq(\bar{q})\to Qq(\bar{q})g} + \rho_g \sigma_{Qg\to Qgg}$, $\sigma_{2\to 3}$ is the cross section of relevant $2 \to 3$ processes and $\rho_{\rm qgp}$ is the density of QGP medium which acts as a background containing target partons, for the high energetic projectile quark. We also note that the Landau-Pomeranchuk-Migdal (LPM) interference correction may be marginal, based on formation time of the emitted gluon and kinematical restrictions.

4. Initial Conditions and Evolution of the Medium

As the heavy quarks are expected to lose most of their energy during the earliest time after the formation of QGP, we can safely neglect the transverse expansion of the plasma while discussing the heavy quark energy loss.

We consider a heavy quark, which is being produced at a point $(r,\, \Phi)$ in a central collision and moves at an angle ϕ with respect to $\hat{r}$ in the transverse plane. If R be the radius of the colliding nuclei, the path length covered by the heavy quark would vary from 0 to $2R$, before it exits the QGP. The distance covered by the heavy quark inside the plasma in a central collision, L, is given by [26]:

$$L(\phi,\, r) = \sqrt{R^2 \,-\, r^2 \sin^2\phi} \,-\, r\cos\phi. \qquad (9)$$

We can estimate the average distance traveled by the heavy quarks in the plasma as:

$$\langle L\rangle = \frac{\int_0^R r\, dr \int_0^{2\pi} L(\phi,\, r) T_{AA}(r, b=0)\, d\,\phi}{\int_0^R r\, dr \int_0^{2\pi} T_{AA}(r, b=0)\, d\,\phi}, \qquad (10)$$

where $T_{AA}(r,b \;=\; 0)$ is the nuclear overlap function. We estimate $\langle L\rangle$ as 5.78 fm for central Au+Au collisions and 6.14 fm for central Pb+Pb collisions.

The temperature of the plasma at a time τ, assuming a chemically equilibrated plasma can be expressed as [10]

$$T\,(\tau) = \left(\frac{\pi^2}{1.202}\, \frac{\rho\,(\tau)}{(9\, N_f + 16)}\right)^{\frac{1}{3}}, \qquad (11)$$

where the gluon density at time τ is given by [10]:

$$\rho_g\,(\tau) = \frac{1}{\pi\, R^2\, \tau}\, \frac{dN_g}{dy}. \qquad (12)$$

Here we consider only the gluon density as the heavy quarks lose most of their energy in interaction with gluons. We also add that the gluon multiplicity is taken as 3/2 times the number of charged hadrons and the initial temperature is obtained using (11), assuming an initial time.

We take $(\frac{dN_g}{dy}) \approx 1125$ for Au+Au collisions at 200 AGeV [27], ≈ 2855 for Pb+Pb collisions at 2.76 ATeV[28] and ≈ 4050 for Pb+Pb collisions at 5.5 ATeV [29]. We assume that the heavy quark having rapidity in the central region moves along the fluid of identical rapidity. This kind of approximation has been used earlier in literature [30–32].

5. Results and Discussion

In Fig. 2 a comparison of average radiative energy loss of an energetic quark traversing in a deconfined quark matter produced in Pb-Pb collision at 2.76A TeV in the present calculation with Djordjevic, Gyulassy, Levai and Vitev (DGLV) formalism in Refs. [10, 11]. As can be seen both light and heavy quarks in the present formalism, within the gluon emission spectrum of $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(1/k_\perp^2)$ as given in (4), lose energy in a similar fashion for $E \geq 10$ GeV since the effect of mass is small compared to the energy. However, it is slightly less than that of a light quark for $E \leq 10$ GeV, due to the dead cone suppression at small angles. In addition the results from the present calculation differ from that of DGLV [10, 11] one. These differences arise mainly because of the proper kinematic cuts for gluon emission as well as the method used to obtain energy loss. The various cuts in the present as well as in DGLV formalism are in close proximity except the gluon emission in DGLV is constrained only to the forward emission angles [20], $\theta \leq \pi/2$, whereas in the present calculation [22] the full range of θ is taken care off through the variable η.

In Figs.3, we have displayed average energy loss of a charm quark in a deconfined quark matter, respectively, at 200 AGeV Au-Au collision at RHIC. We find that at RHIC energies the average energy loss of a charm quark in our formalism is higher than that of the DGLV formalism for the considered energy range, $(0 < E < 50)$ GeV, of the charm quark. As seen the average energy loss of charm quark is larger in the present formalism only in the domain, $(0 < E < 15)$ GeV, of the charm quark and beyond which it is less compared to the DGLV formalism. The difference, in fact, increases as energy of the quark increases.

In Fig. 4 we display a comparison of collisional energy loss of charm quark as calcu-

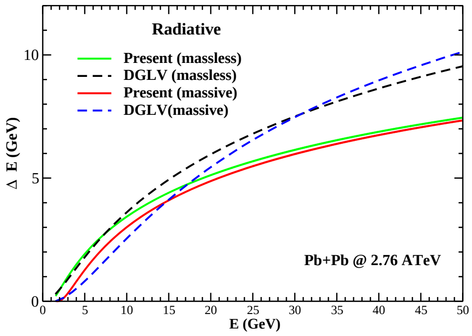

FIG. 2: (color online): Comparison of average energy loss for light quark and charm quark with mass 1.5 GeV in a deconfined quark matter produced in Pb-Pb collision at 2.76 ATeV in the present and DGLV [10] formalisms. For both cases the characteristics of the deconfined matter are treated in the same footing, *i.e.*, the strong coupling $\alpha_s = 0.3$ and the average path length, $\langle L \rangle \approx 6.14$ fm, traversed by an energetic quark in a deconfined medium produced in such collisions.

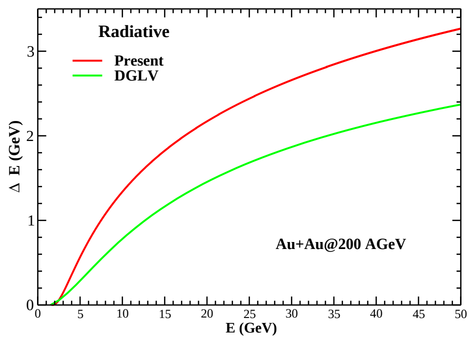

FIG. 3: (color online): Same as Fig. 2 but only for charm quark in Au-Au collision at 200 AGeV with $\langle L \rangle = 5.78$ fm.

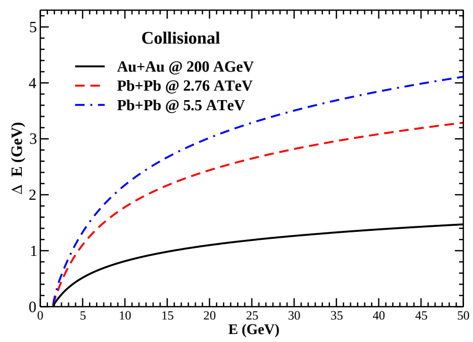

FIG. 4: (color online): Collisional energy loss of charm quark [9] in Pb-Pb collision at 2.76 ATeV and 5.5 ATeV at LHC, and 200 AGeV at RHIC energies.

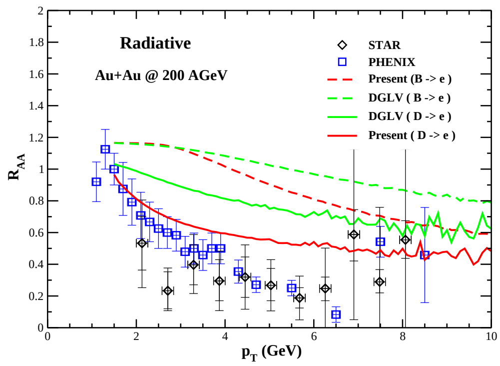

FIG. 6: (color online): R_{AA} with only radiative energy loss for non-photonic single electron from the decay of individual D mesons and B mesons in Au-Au collision at 200 AGeV. The data are from Ref. [1]. Both systematic and statistical error bars are shown for STAR data whereas only systematic error bars are displayed for PHENIX data.

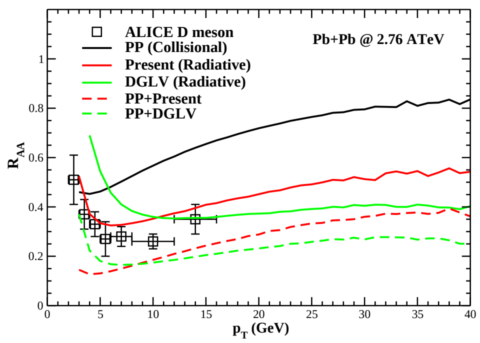

FIG. 5: (color online): Nuclear modification factor R_{AA} for D mesons with both collisional and radiative energy loss in Pb-Pb collision at 2.76 ATeV. The data are from Ref. [33] but only the systematic error bars are shown here.

lated by Peigne and Peshier (PP) in Ref. [9] for RHIC and LHC energies. As seen the collisional energy loss increases with the increase in centre of mass energy of the colliding ions.

In Fig. 5 the nuclear suppression factor, R_{AA}, for D meson is displayed considering both radiative and collisional energy loss and compared with the ALICE data [33] at 2.76 ATeV. As can be seen the differences in radiative energy loss between the present and DGLV formalism discussed in Fig. 2 for 2.76 ATeV in Pb-Pb collisions is clearly reflected in Fig. 5. For the present calculation it is manifested in gradual increase of R_{AA} of D meson [33] for transverse momentum, $p_\perp > 5$ GeV whereas in DGLV case it remains almost constant. The suppression factor obtained in the present formalism with radiative energy loss is in close agreement with the most recent data from ALICE collaboration at 2.76 ATeV [33]. On the other hand the inclusion of the collision contribution is found to suppress R_{AA} further in both cases. As found the data suggest that the collisional contribution may be small. Nonetheless, more data in the high $p_\perp$ domain is necessary to know the actual trend of the energy loss of charm quark and will finally constrain the various energy loss and jet quenching model in the literature. We also expect a similar rise in light hadrons for high $p_\perp$ since both light and heavy quark lose energy in a similar fashion as shown in Fig. 2. However, we note that the ALICE data on R_{AA} for inclusive charge hadrons [34] at 2.76 ATeV in Pb-Pb collision

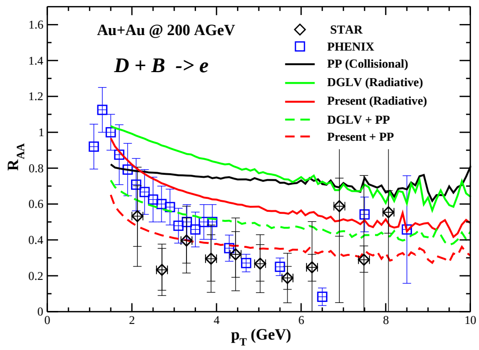

FIG. 7: (color online): R_{AA} with collisional and radiative energy-loss for non-photonic single electron from the combined decay of both D and B mesons in Au-Au collision at 200 AGeV.The data are from Ref. [1]. Both systematic and statistical error bars are shown for STAR data whereas only systematic error bars are displayed for PHENIX data.

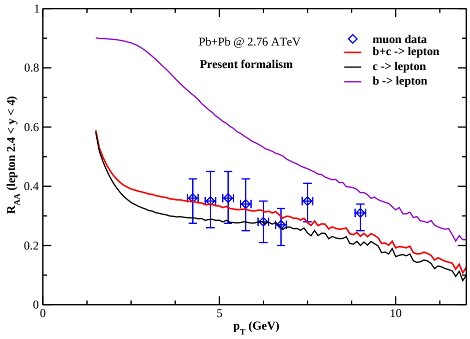

FIG. 8: (color online): R_{AA} with collisional and radiative energy-loss for muon from the combined decay of both D and B mesons in Pb-Pb collision at 2.76 ATeV at different for forward rapidity. The data are from Ref. [35].

has also shown a similar increasing trend as $p_\perp$ increases. It is natural to believe that such data is completely dominated by the contribution from light hadrons.

In Fig. 6 the nuclear suppression factors for individual decay of D and B mesons to non-photonic single electron is displayed considering only the radiative energy loss for RHIC energy at 200 AGeV. As expected the contribution from the B decay is small compared to that of D decay. In Fig. 7 the total contribution of single electron from D and B decay is shown considering both radiative and collisional energy loss. It is found that the contributions of the collisional energy loss is important at RHIC energy.

In Fig. 8, we dispalyed R_{AA} for muons at forward rapidity in PB-PB collisions at 2.76 ATeV that agrees well with the data [35].

6. Conclusion

In this talk the heavy quarks production in heavy-ion collisions and their propagation through the dense matter created in such collisions are reviewed. Some relevant quantities are also discussed and compared with RHIC and LHC data.

Acknowledgments

The works presented here are done in collaboration with R. Abir, C. Greiner, U. Jamil, M. Martinez, D. K. Srivastava and J. Uphoff.

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