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# Study of Charm and Bottom Quark Production, Propagation, Energy Loss and associated Nuclear Modification Factor as a Signature of Quark Gluon Plasma

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## ABSTRACT

The aim of this research work is to calculate the Nuclear Modification Factor ( $R_{AA}$ ) for heavy quarks for most central nucleus-nucleus collisions at mid rapidity at different centre of collision energy.

We consider 2.76 ATeV and 5.5 ATeV LHC energies and 200 AGeV RHIC energy for which the initial distribution for production of charm and bottoms quarks are obtained using the FONLL (Fixed Order Next to Leading Logarithm) calculation. We calculate the radiative energy loss by using the AJMS treatment and the collisional energy loss considering the Bjorken treatment and Peigne and Peshier treatment for both charm and bottom quarks. Finally we look for the  $R_{AA}$  for both heavy quarks at different energies considering the radiative and collisional energy loss of heavy quarks and compare the results.

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## INTRODUCTION

Right after the Big Bang, the universe was at an extremely high energy density condition where a mixture of elementary particles was there which no longer experience any force and free to move on their own near the speed of light over an extended region. This mixture was of quarks and gluons (together known as Partons) and hence this new state of matter was named as Quark-Gluon Plasma (QGP). To understand precisely the evolution and characteristics of the very early Universe, powerful accelerators (LHC & RHIC) were made to carry out some experiments in order to recreate similar conditions as that of the earlier time. These accelerators make collisions between the projectile ion and the target ion by accelerating the projectile ion near the speed of light (Ref. [1]). In these collisions the protons and neutrons in the two nuclei smash into each other with very high energies. This results in the formation of an extremely tiny fireball within which everything melts and turns to quark-gluon plasma. The primary goal to create the QGP under such circumstances is to investigate the QGP's properties, such as the temperature, order of

the phase transition and the transport properties (Ref. [1]) etc which could give new perceptions in the early universe. One way to study the properties of the QGP is to use the jets as a hard probe (Ref. [2]) of the created medium.

We measure how the jets are changing as they interact with the quarks and gluons during their flight through the medium in order to probe the QGP. When the collision occurs, partons of the projectile nucleus interact with nucleons of the target nucleus and as a result large momentum transfer takes place (Ref. [1]). Such kind of scatterings is named as hard scattering. Thus large transverse momenta would be gained by the final partons. Eventually these partons will hadronize and form a cluster of hadrons which is commonly known as jets. These jet productions can be calculated by using Perturbative Quantum Chromodynamics (pQCD) (Ref. [3]). Thus, we can gain knowledge about the QGP medium by studying the modification of the jets during their journey throughout the medium.

In our studies we need to calculate the average energy loss experienced by the heavy quarks by interacting with quarks and gluons while passing through the QGP medium and find out the Nuclear Modification Factor ( $R_{AA}$ ) due to the energy loss.

### **OBJECTIVE**

The primary aim of the experiments in LHC and RHIC is to understand the properties of nuclear or hadronic matter at extreme conditions. A prediction was made by using the Bjorken (Ref. [4]) formula for energy densities (Ref. [5, 6]) of the collisions inside the colliders which was found to be larger than the energy densities in which QGP was expected to be formed. Also at RHIC (Ref. [7]), the maximum temperature that could be attained was much larger than the value of the critical temperature for a transition to the QGP.

From the fusion of gluons or light quarks at the initial situation, heavy quarks are formed. The pairs (jets) thus produced will carry a large energy. They will traverse the QGP medium colliding with the quarks and gluons and hence exchange of both momentum and color will take place. In the journey of these jets through the QGP medium may lose energy either by collision or they will radiate gluons and will end up becoming a charm or bottom meson or baryons. These heavy quarks probing the medium are a very good signature of QGP (Ref. [8]). Finally the final spectra of open quarks/hadrons carry the information about the evolution of the QGP.

The concern in exploring the energy loss of heavy quarks was prompted by the correlated charm or bottom decay gives to the thermal dileptons (Ref. [9]) which was considered as one of the prime signature of the QGP formation. It was figured out by Shuryak, Lin, Kampfer and Mustafa (Ref. [10, 11]) that the correlated charm and bottom decay

could be suppressed if the energy loss suffered by heavy quarks before they form D or B mesons was accounted for. With time numerous attempts were fabricated to determine the energy loss of heavy quarks as they emanate through the QGP.

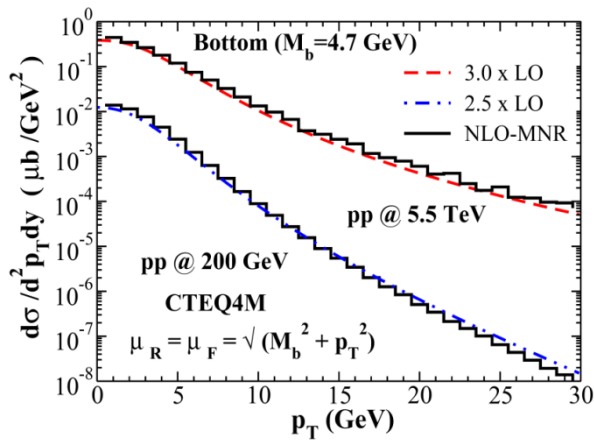
These calculations were done both in RHIC and LHC energies for a comparative study which can give vital trials on a wide range of theories, which deals with the loss of energy, posed by heavy quarks as they disseminate through QGP.

### **MATERIALS AND METHODS**

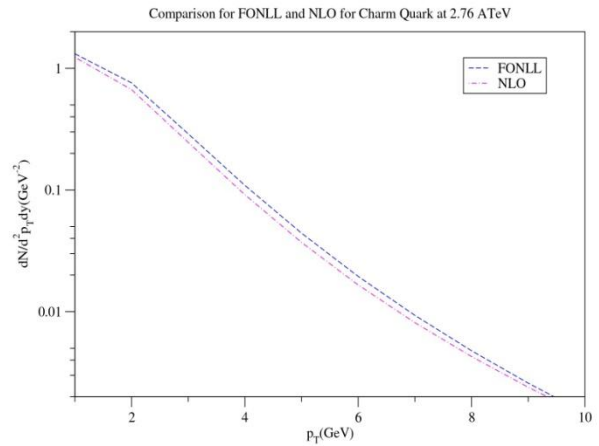
#### **Comparison between NLO and FONLL Results**

The initial distribution for the production of heavy quarks were calculated in (Ref. [14]) by using the lowest order pQCD for pp collision and the same were compared with the results of NLO - pQCD calculation developed by Mangano Nason Ridolfi (MNR-NLO) (Ref. [12]). These calculations were carried out by neglecting the intrinsic transverse momentum of the partons. It has been seen that the results for LO in pQCD comes to an agreement with MNR-NLO results if the results for LO have been supplemented with a K-Factor  $\approx 2.5$ , as shown in the fig.1(a) (Ref. [14]).

In our calculation we preferred to use the FONLL calculation (Ref. [13],[27]) in which one matches fixed next-to-leading order (NLO) QCD with all order resummation to next-to-leading log (NLL) accuracy in the limit where the transverse momentum of a heavy quark is much higher than its mass. It has been used extensively nowadays to predict the heavy quarks production data at LHC and RHIC. It shows a satisfactory agreement between the theory and data. A comparison between NLO and FONLL treatments for the charm quark at 2.76 ATeV has been shown in the fig.1(b).



(a)



(b)

fig.1

**Initial Distribution of Production of Heavy Quarks by FONLL**

As mentioned above, the heavy quark production from the fusion of partons in A-A collision has been obtained by using the Fixed Order Next to Leading Logarithm (FONLL) calculation. The comparison of the initial  $p_T$  distribution for the production of charm and bottom quarks at 2.76ATeV and 5.5ATeV is represented in the fig.2. Also the initial production of charm quark at

different LHC and RHIC energies (2.76ATeV, 5.5ATeV, 8ATeV, 200 AGeV) has been shown in fig 3. The structure function which we are using is CTEQ6.6. As we expected, suppressed production of bottom quark has been observed at the low  $p_T$  region. But with the increase in  $p_T$ , the production of bottom quarks gradually starts rising over charm quark. And for charm quark at different energies, it is seen that the larger the value of the initial energy, the more is the production of the heavy quark.

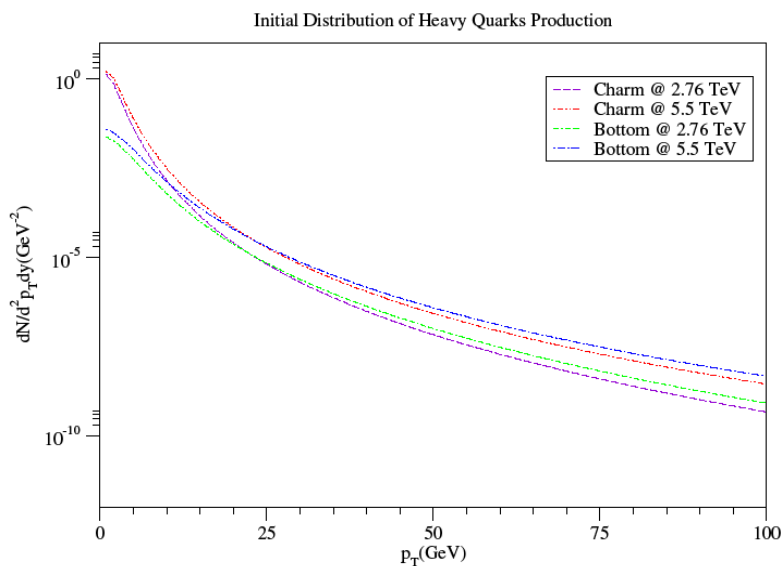


fig.2

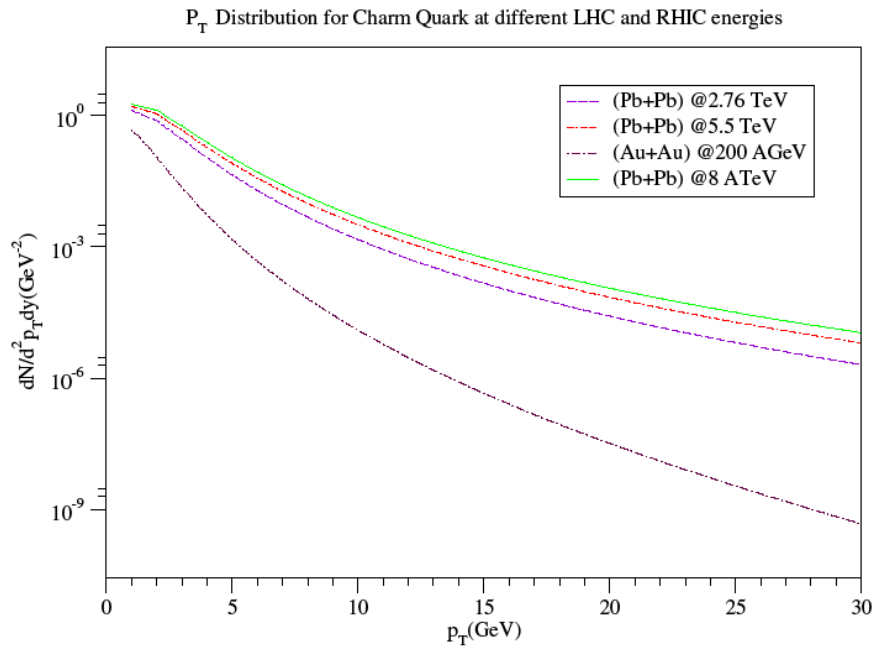


fig.3

### The Initial Conditions and the Evolution of Plasma

After the collision takes place, the heavy quarks formed at the initial state travels through QGP. They lose their energy by colliding with quarks and gluons and also by radiating gluons throughout their journey. The energy lose depends upon three fundamental factors which are the path length of the heavy quarks in the plasma, the temperature evolution of the plasma and the energy and mass of the heavy quarks (Ref. [14]).

To move along, some assumptions has been made in order to simplify our calculation. It is assumed that most of the energy of the heavy quark will be lost during the period when the temperature of the QGP remains very high i.e. within the earliest time after the formation of the QGP. For this earliest period, the transverse expansion of the QGP is being neglected. A Gaussian rapidity density distribution (Ref. [15]) has been considered for the production of particles and also it is made sure that this distribution

will be intently followed by the initial rapidity distribution of quarks and gluons.

Hence an assumption is made to calculate the rapidity distribution of gluons as given below-

$$\frac{dN_g}{dy} = \left(\frac{dN_g}{dy}\right)_0 \exp(-y^2/2\sigma^2)$$

(1)

Here in our calculations we are considering  $\sigma \approx 3$  and  $\sigma \approx 4$  for Au+Au and Pb+Pb collisions respectively.

The Bjorken cooling is assumed to work locally at different rapidities, and we consider the passage of a heavy quark having the rapidity  $y$  in a fluid having identical fluid rapidity. This approximation, which corresponds to assuming a boost-invariant expansion along with a local fluid approximation, has been used earlier in the literature [1].

We consider the case of production of heavy quark at a point  $(r, \Phi)$  where  $\Phi$  is the angle at

which the quark is travelling with respect to  $\hat{r}$  in a most central collision that is the rapidity  $y$  will be zero in our case. In general, the distance covered by the heavy quark before it exits the QGP will vary from 0 to  $2R$ , where  $R$  is the radius of the colliding

$$L(\Phi, r) = \sqrt{R^2 - r^2 \sin^2 \Phi} - r \cos \Phi \quad (2)$$

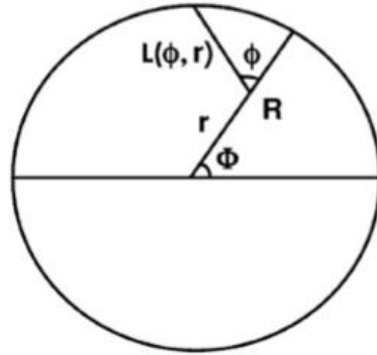


Fig.4: distance  $L$  covered by a heavy quark passing through QGP

Hence, an estimation has been made for the average path length (Ref. [14]) covered by the heavy quark before it leaves the QGP and according to this we can give the expression as-

$$\langle L \rangle = \frac{\int_0^R r dr \int_0^{2\pi} L(\Phi, r) T_{AA}(r, b=0) d\Phi}{\int_0^R r dr \int_0^{2\pi} T_{AA}(r, b=0) d\Phi} \quad (3)$$

We got the values of  $\langle L \rangle$  as 6.14fm for Pb+Pb collisions in LHC and as 5.78fm for Au+Au collisions in RHIC. In equation (3)  $T_{AA}(r, b = 0)$  is the nuclear overlap function which gives the probability of heavy quark production.

While moving through the QGP medium, the heavy quark loses maximum of its energy by gluon interaction. Hence it will be enough to take into account only the gluon distribution. The gluon density (Ref. [17]) at time  $\tau$  can be given as-

$$\rho(\tau) = \frac{1}{\pi R^2 \tau} \frac{dN_g}{dy} \quad (4)$$

nuclei. The equation for the total distance  $L$  (fig 4) which will be covered by the produced heavy quark while travelling through the plasma (Ref. [16]) can be given as

We are taking  $\frac{dN_g}{dy} \approx 1125$  for Au+Au collision in RHIC at 200 AGeV (Ref. [19]),  $\approx 2855$  for Pb+Pb collision in LHC at 2.76 ATeV (Ref. [18]) and  $\approx 4050$  for Pb+Pb in LHC at 5.5 ATeV (Ref. [20]). Assuming a chemically equilibrated plasma, the corresponding temperature is (Ref. [17])-

$$T(\tau) = \left( \frac{\pi^2}{1.202} \frac{\rho(\tau)}{9N_f + 16} \right)^{1/3} \quad (5)$$

We assume that the initial time for the formation of QGP is  $\tau_0 = 0.2$  fm/c. Hence we can consider the values for  $T_0$  at  $y = 0$  as 377 MeV for RHIC and as 555 MeV for LHC. The Bjorken's cooling law,  $T^3 \tau = \text{constant}$ , allow us to know that the QGP will cool down to the critical temperature  $T_c \approx 160$  MeV at  $\tau_c \approx 2.6$  fm/c in RHIC and 8 fm/c in LHC.

#### **Mechanism for Energy Loss of Heavy Quarks**

As mentioned before, the heavy quarks loss energy via collisions and radiating gluons. Various formalisms were introduced for the calculation of collisional and radiative energy loss of heavy

quarks. For the collisional energy loss, Bjorken has treated the case of light quarks to be similar to that of a charged particle passing through a medium and losing energy by ionizing the medium. It was adapted by Braaten and Thoma (BT) (Ref. [21]) to use in the case of heavy quarks. To obtain the collisional energy loss of a heavy quark, BT also reconstruct the expression for the energy loss experienced by muons as it passes through the QED plasma. Results obtained by these mechanisms are valid only for the collisions where the momentum transfer  $q$  is much less than energy of heavy quark ( $q \ll E$ ). This was further modified by Peigne and Peshier (PP) (Ref. [22]). They added the  $u$ -channel which strongly suits for the large energies.

In case of the radiative energy loss also, a number of formalisms were introduced. Djordjevic, Gyulassy, Levai and Vitev (DGLV) (Ref. [23]) developed a treatment using opacity expansion to calculate the radiative energy loss. Another treatment was put forwarded by Armesto, Salgado and Wiedemann (ASW) (Ref. [25]) using the path integral formalism for medium-induced gluon radiations of massive quarks. There was one more formalism introduced by Xiang, Ding, Zhou and Rohrich (XDZR) (Ref [26]) where they used the light cone-path integral approach.

In our work we are using the Bjorken formalism and the Peshier formalism in order to calculate the collisional energy loss suffered by the heavy quarks. In case of the radiative energy loss, we are adapting the formalism which was developed by Abir, Jamil, Mustafa and Srivastava (AJMS) (Ref. [24]) to calculate the energy loss of the heavy quarks.

### **Nuclear Modification Factor ( $R_{AA}$ )**

The expression for the Nuclear Modification Factor ( $R_{AA}$ ) for heavy quarks can be give as-

$$R_{AA}(b) = \frac{dN^{AA}/d^2P_T dy}{T_{AA}(b)d\sigma^{NN}/d^2P_T dy} \quad (6)$$

Where  $b$  is the impact parameter and  $T_{AA}$  is the nuclear overlap function for  $b$ . We used  $T_{AA} \approx 290 \text{ fm}^{-2}$  for Pb+Pb collision in LHC and  $\approx 280 \text{ fm}^{-2}$  for Au+Au collision in RHIC at  $b = 0$  (Ref. [14]).

Here in our project, we will look for the  $R_{AA}$  with two different situations. At first we will consider the energy loss only for the radiation of gluons. Then we will consider the energy loss both for radiation and collision.

## **RESULTS AND DISCUSSION**

### **Results for Energy Loss of Heavy Quarks**

#### **1. Radiative Energy Loss:**

We have used the AJMS treatment to compare the radiative energy loss between charm and bottom quarks for Pb+Pb collision at LHC at 2.76 ATeV and 5.5 ATeV (fig.5). We have plotted the transverse energy loss ( $\Delta E_T$ ) for bottom and charm quarks as a function of the transverse energy  $E_T \left( \sqrt{P_T^2 + M^2} \right)$ . Further we have compared the radiative energy loss between Pb+Pb collision at 2.76 ATeV in LHC and Au+Au collision at 200AGeV in RHIC (fig.6). It is seen that the energy loss for the charm quark is greater than that of the bottom quark in LHC energies and the energy loss for the Au+Au in RHIC is much lesser than the energy loss for Pb+Pb collision in LHC.

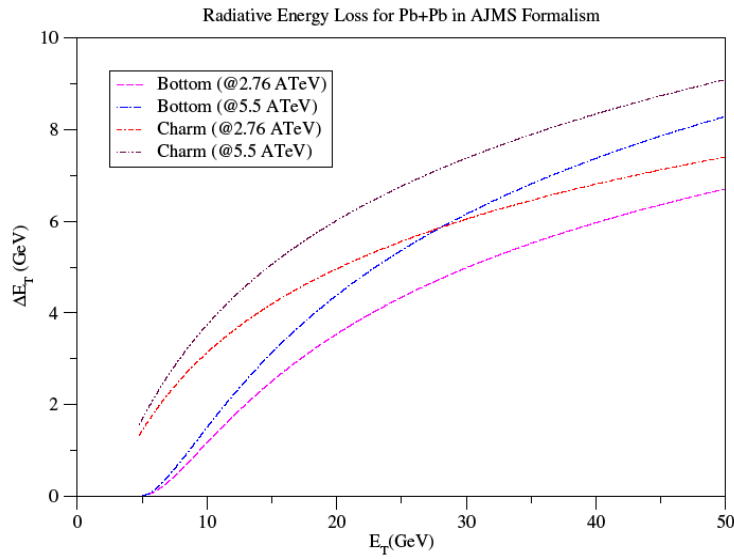


fig.5

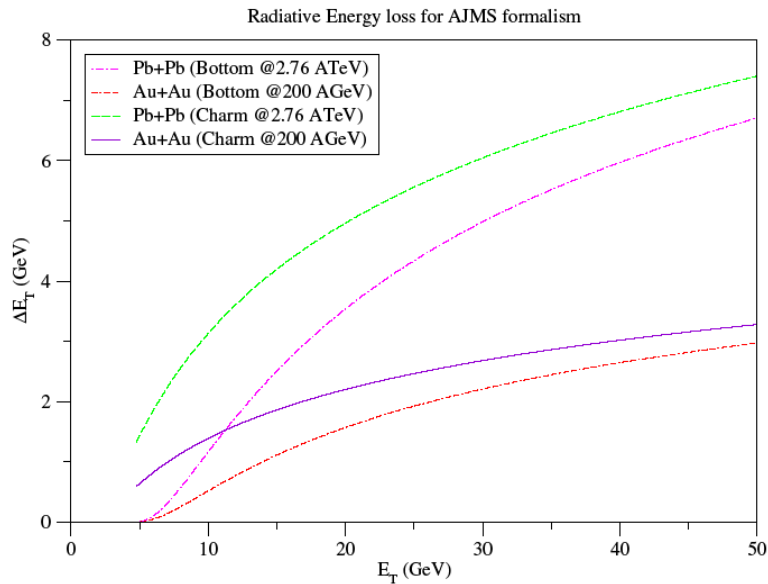


fig.6

## 2. Collisional Energy Loss:

For the calculation of the collisional energy loss, we have considered the Bjorken and Peshier formalisms to compare the energy loss between the charm and bottom quark with different energies. We have plotted the transverse energy loss of charm and bottom quark at 200 AGeV for Au+Au collision in RHIC (fig. 7), 2.76 ATeV and 5.5 ATeV for Pb+Pb collision in LHC (fig. 8 and 9).

We have got to see various amazing characteristics of the energy loss for different quarks with different formalisms. It shows that the collisional energy loss for the charm quark is much higher than that of the bottom quark in both formalisms at different energies. This is happening due to the mass difference as the bottom quark is much heavier than the charm quark which results into low collisional energy loss of the bottom quark.

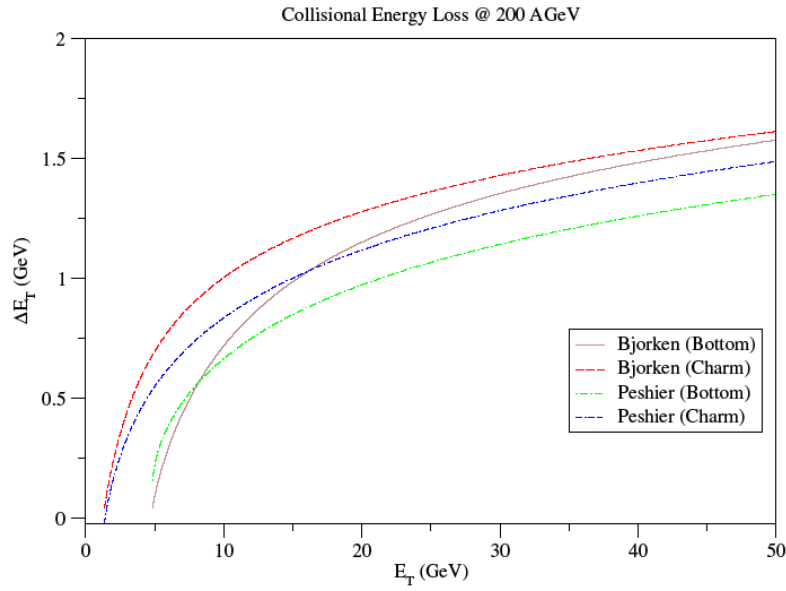


fig.7

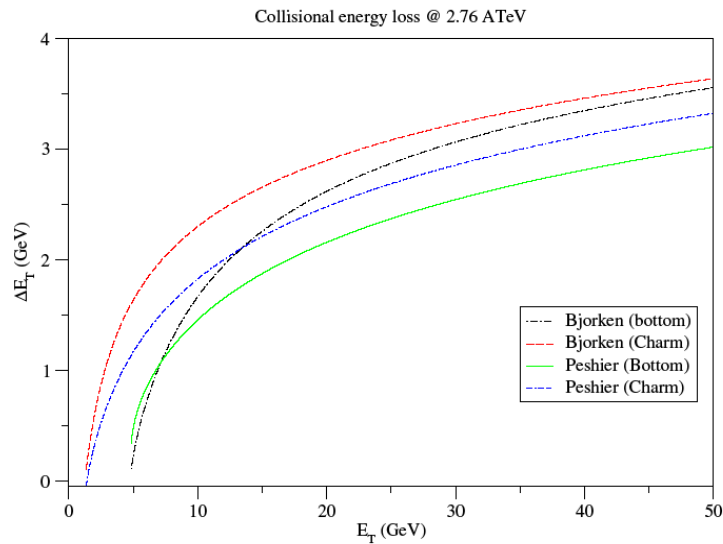


fig.8

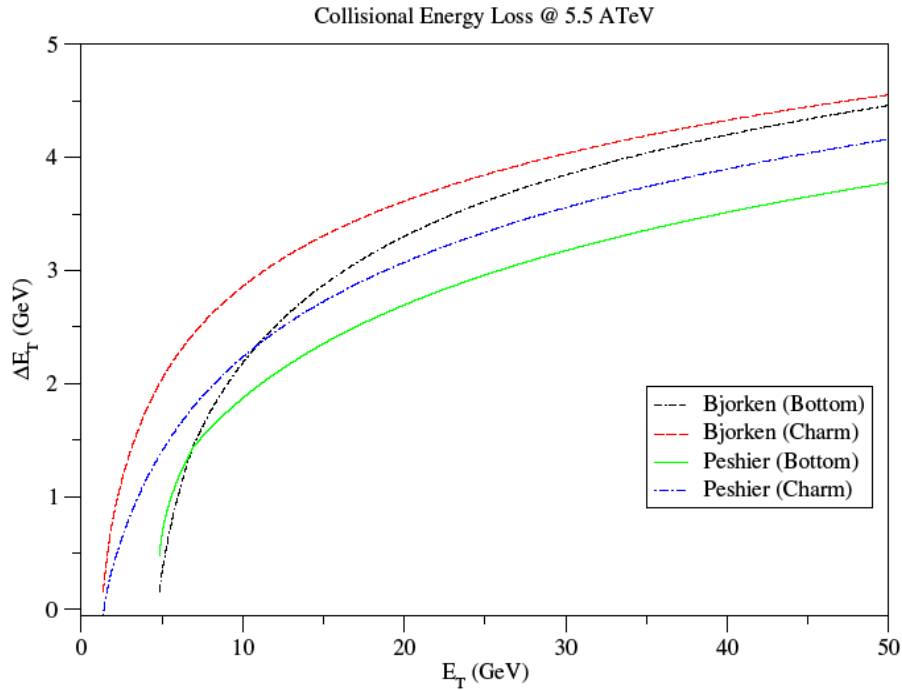


fig.9

### Results for $R_{AA}$ of Heavy Quarks

Here we will take a large number of particles and we will consider that these particles will follow the initial distribution that we have calculated earlier for the production of the heavy quarks. Now these particles will lose their energy through radiation and collision during their movement in the QGP medium. This energy loss will cause a change in their transverse momentum and because of which there will be a change in the distribution. We shall name this newly obtained distribution as the final distribution for the heavy quarks. In the final distribution the transverse momentum is going to decrease since the energy of the heavy quarks is decreasing. The heavy quarks which have initially showed up in the region of high transverse momenta will now going to appear in a low transverse momenta region. And thus we will get a final distribution. Now if we take the ratio of

the final distribution and initial distribution, then this will give us the Nuclear Modification Factor ( $R_{AA}$ ).

The below plots shows the nature of the nuclear modification factor against transverse momentum after the energy loss of the heavy quarks takes place. In fig.10 we have plotted the transverse momentum ( $P_T$ ) versus nuclear modification factor ( $R_{AA}$ ) graph at 2.76 ATeV for bottom quark considering only the radiative energy loss at first and then considering both collisional and radiative energy loss. Here in case of the collisional energy loss we are considering the Bjorken formalism. It is seen that if we consider only the radiative energy loss, the heavy quark suffers a little suppression in the nuclear modification factor in the low transverse momentum region. When we consider both collisional and radiative energy loss, we can see from the graph that the heavy quark suffers even more suppression in the lower transverse momentum region.

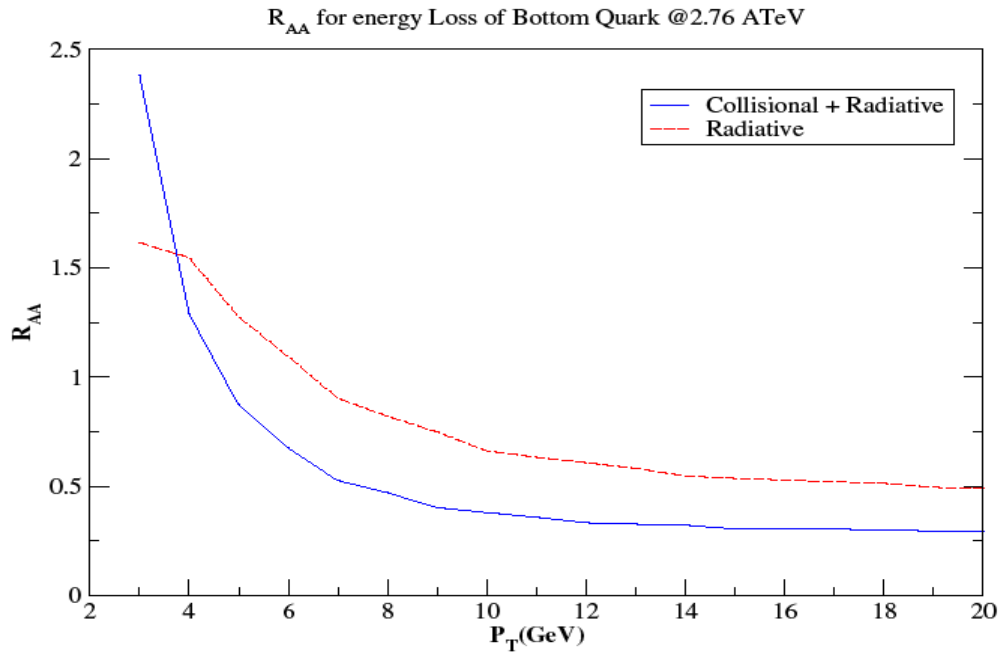


fig.10:  $R_{AA}$  vs. transverse momentum for bottom quark

In fig.11 we have considered both radiative and collisional energy loss for charm quark at energies 2.76 ATeV, 5.5 ATeV, 200 AGeV. From the graph it is visible that for higher energies, the heavy quark suffers more suppression in nuclear

modification factor at lower transverse momentum region compared to that of the lower energies. In the low transverse momentum region, the modification factor falls rapidly and then gradually starts rising in the high transverse momentum region.

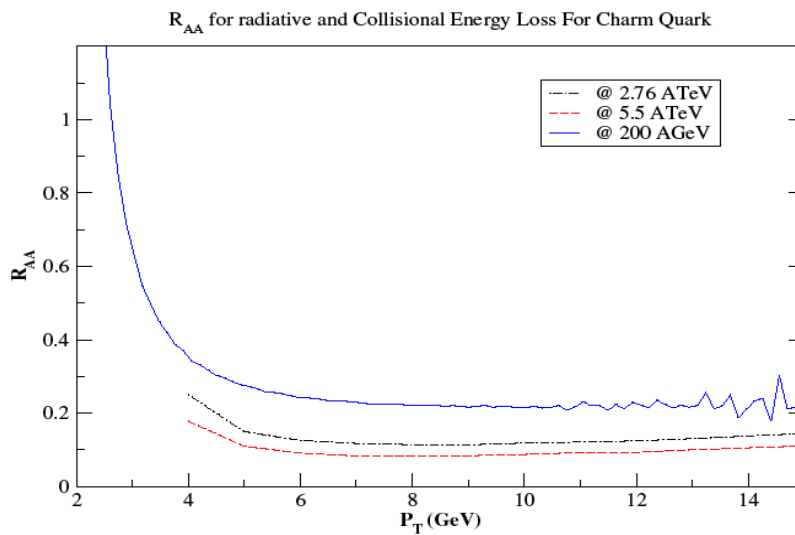


fig.11:  $R_{AA}$  vs. transverse momentum for charm quark

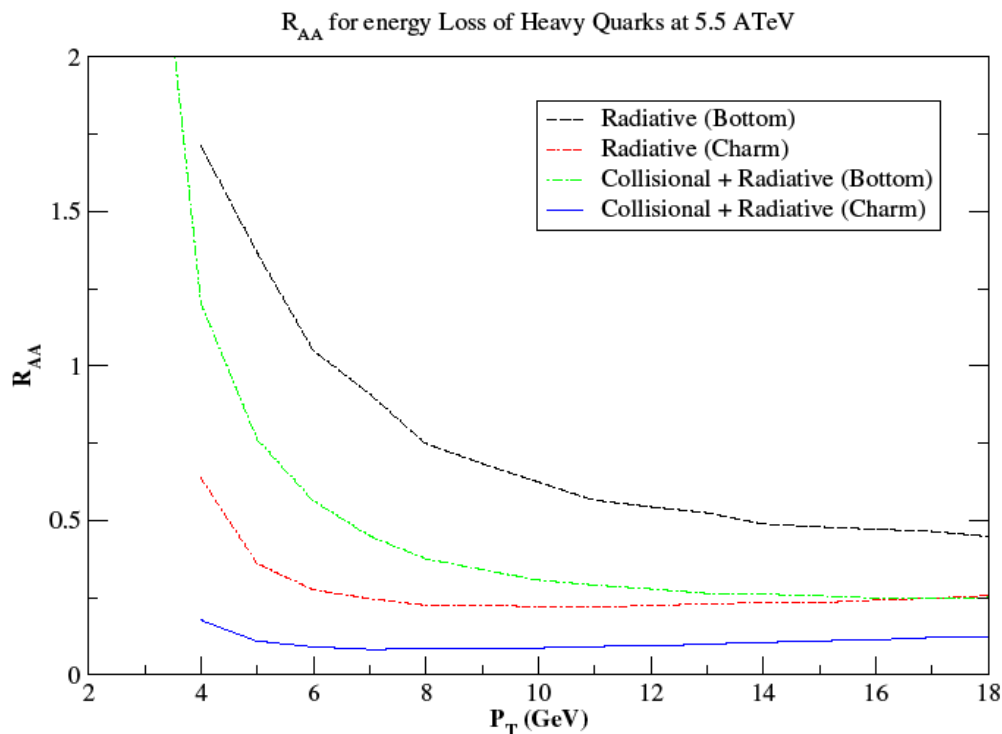


fig.12:  $R_{AA}$  vs. transverse momentum for bottom and charm quark

In fig.12 we have plotted the outcomes for both charm and bottom quarks at 5.5 ATeV considering only radiative energy loss and then both collisional and radiative energy loss together. We can see that in both cases of the energy loss, the suppression of the nuclear modification factor for the charm quark is much higher than that of the bottom quark. We can see, in the energy loss calculations of both collisional and radiative, the bottom quark loses energy lesser than that of the charm quark. And therefore lower suppression in the modification factor has been seen for the bottom quark.

#### **FUTURE SCOPE**

The work done in this minor research work is some initial study to observe and understand the Nuclear Modification Factor which is an important signature of QGP. In this work, we have considered very simple approach for the expansion of the plasma. A more realistic approach for the evolution

and expansion of the plasma can be developed for better predictions. It will be interesting to predict Nuclear Modification Factor of heavy mesons as well as semi-leptonic decay and elliptic flow of heavy quarks. Behaviour of heavy quarks in Non Central collisions will also carry lots of information of the expansion of the plasma. These are few points which can be planned for some research work in near future.

#### **CONCLUSION**

In this project work, our aim was to obtain the nuclear modification factor at different LHC and RHIC energies. At first we have taken the initial distribution for the production of bottom and charm quarks at 200 AGeV, 2.76 ATeV, and 5.5 ATeV with the help of the FONLL calculation.

Next we have calculated the radiative and collisional energy loss for both the quarks at different energies. To calculate this energy loss we

have adapted the AJMS treatment for radiative energy loss and the Bjorken formalism and Peshier formalism for the collisional energy loss.

Finally we have obtained the nuclear modification factors and plotted graphs between the nuclear modification factor and the transverse momentum to see the distinctions between  $R_{AA}$  for energy loss of charm and bottom quarks at different energies.

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