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HEAVY QUARKS AS A SIGNATURE OF QUARK GLUON PLASMA

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ABSTRACT

Heavy quarks produced in the initial stage of Relativistic Heavy Ion Collisions would traverse the Quark Gluon Plasma and loose energy by colliding with quarks and gluons and also by radiating gluons. After their production, they may get fragmented into heavy mesons by picking up light quarks/antiquarks and in turn may decay through leptonic channels. These leptons would carry information of the initial stage of heavy ion collisions and also the evolution of the plasma.

In this work, we present the nuclear modification factor, R_{AA} of Heavy Quarks at mid rapidity for most central Pb+Pb collisions at 2.76 ATeV and 5.02 ATeV at Large Hadron Collider experiment and also compare R_{AA} at these collisional energies. The transverse momentum distribution of heavy quarks produced from the initial fusion of partons is obtained from Fixed Order Next to Leading Logarithmic approach. We consider both the radiative and collision energy losses along with a boost-invariant expansion of the plasma for the prediction of R_{AA}.

INTRODUCTION

Under the influence of extremely high energy densities the particles inside a nucleus gets free from the attractive nature of the strong force and creates a state of matter which is known as the Quark Gluon Plasma (QGP) .The elementary particles that makes up the nucleus (Protons and neutrons, together which are known as Partons) are known as quarks and gluons. Gluons are the force carrier of the strong nuclear force, responsible for the binding of partons in to nucleus. On the other hand quarks are the elementary particles which create hadrons. As it is highly evident that the early universe was filled with these matters (QGP) at the high energy densities, hence by replicating those high energy density conditions and studying the Quark gluon plasma under those circumstances can be extremely helpful to understand the early universe better. The study of QGP can be done by the heavy ion collision experiments. The Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) are designed to obtain new and new information and explore various properties about QGP. In order to reach the energy densities where QGP can be formed, these colliders use heavy nuclei and accelerate them to near the speed of light. When the collision occurs the particles inside nuclei gets to the state of QGP. There are various means through which the study of QGP can be carried out. These signatures of QGP can help us understand the properties of QGP and the early state of the universe. Some such signatures are hadrons which are consisting of light quarks coming from the ion collision, photons and dileptons, energy loss of a passing hard jet etc.

To probe the QGP formed we use the heavy quarks created in the collision. Heavy quarks are produced mainly from pre-thermal stage of interaction among partons when temperature is considerably high and while at the later times their production is limited owing to their large masses. Because of their large masses, they move slowly through the partonic wind, which consist mainly of gluons and lighter quarks and thus heavy quarks loose energy as well as momentum and also the direction of their motion may not change substantially from these interactions. This will make them a valuable probe for the reaction plane dependent properties of the quark-gluon-plasma (QGP). Since heavy quarks are formed mainly at pre-thermal period, hence they are alien to the bulk of the systems and can be used as a probe for the medium.

OBJECTIVE

The facilities like LHC and RHIC are dedicated to explore the properties and existence of QGP. The energy densities [(l.Arsene, 2005), (S, 2003), (B, 2005), (K, 2001)] which are expected in these collisions happening inside the facilities using the Bjorken [(D, 1983)] formula is larger than the energy density within which the QGP is expected to be formed. On the other hand the experimental data from RHIC [(D d. D., 2006)] shows that the critical temperature for the transition to QCD is much higher than the results obtained from the lattice QCD formalism. The observation like large elliptical flow [(S A. S., 2003), (S E. , 2003), (C, 2003), (C, Azimuthal Anisotropy of , 2002), (C, Identified Particle Elliptic Flow in , 2001) , (Huovinen P, 2001), (Teaney D, 2001)] jet quenching [(Wang, 2001), (Gyulassy M, 2001), (Adcox, 2001), (J, 2003)] makes a strong case for existence of the QGP.

The initial fusion of gluons or light quark can produce the heavy quarks. The pair production can be treated by using Perturbative Quantum Chromodynamics (pQCD) due to their large mass. These quarks will move through the QGP while colliding with the gluons and quarks and radiating gluons and will appear as a charm or bottom mesons or baryons. Hence these particles will carry the information about the energy loss of the heavy quarks which can be gathered by studying the final spectra of the hadrons. As discussed earlier, the fact that heavy quarks has very high mass makes it a perfect candidate of probe. Due to its mass the production of these particles are limited compared to the light quarks and gluons. Also the charm and bottom hadrons stands out in the background compared to the light hadrons and can be track back to understand the QGP.

The interest in the study of the energy loss of the heavy quarks were ignited because thermal depletion, which was considered as one of the major signature for existence of QGP [(V S. , 1978), (Kajantie K, 1986), (L, 1993), (Kajantie, 1985), (K. Kajantie, 1986), (Dinesh Kumar Srivastava, 1996)]. It was pointed out by Shuryak [(Shuryak.E, 1997), (Ziwei Lin, 1998)] Kampfer [(K.Gallmeistera, 1998)] and Mustafa [(Munshi Golam Mustafa, 1998)] that the correlated charm and bottom decay could be suppressed if the energy loss suffered by the heavy quarks before they form D and B mesons was accounted for. Several attempts have been carried out since then to calculate the energy loss of the heavy quarks as they move through the QGP.

The RHIC have been doing many experiments to put these results through test which indicates clear evidences of energy loss of the heavy quarks. Compared to RHIC the energy reached in the LHC is much higher, which allows the researchers to study the results in much wider rapidity. Thus RHIC and LHC can perform some valuable tests on various theories that which deal with the energy loss of heavy quark while propagating through QGP.

The main objectives of this project work is to predict the nuclear suppression of heavy flavours at different centre of mass energies of heavy ion collisions. These studies will show the uniqueness of heavy flavour as a probe to QGP in relativistic heavy ion collisions.

THEORY

2.1: PRODUCTION OF HEAVY QUARKS IN PP COLLISION

The fusion of gluons or light quark is the reason for the production of heavy quarks in the pp collision. In the lowest order pQCD, the cross-section for the production of heavy quark for pp collision is given by [(B.L.Combridge, 1979), (E. Eichten, 1984)]

$$\frac{d\sigma}{dy_1\, dy_2\, dp_T} = 2x_2\, p_T \sum_{ij}[\, f_i^{(1)}(x_1, Q^2) f_j^{(2)}\left(x_{2,} Q^2\right)\hat{\sigma}(\hat{s}, \hat{t}, \hat{u})$$

$$+f_i^{(2)}(x_2, Q^2)\hat{\sigma}\, f_j^{(1)}(x_2, Q^2)(\hat{s}, \hat{t}, \hat{u})]/(1+\delta_{ij}). \qquad (1)$$

Here in (1), i and j are interacting partons, $f_i^{(1)}$ and $f_j^{(2)}$ are the partonic structure function and x_1 , x_2 are the fractional momentum of the interacting hadrons carried by the partons i and j. The relation between P_T and x_1 , x_2 with their respective rapididies can be written as

$$x_1 = \frac{M_T}{\sqrt{s}}(e^{y_1} + e^{y_2}), \quad x_2 = \frac{M_T}{\sqrt{s}}(e^{-y_1} + e^{-y_2}) \qquad (2)$$

Here M_T is the transverse mass $\sqrt{M_T + P_T^2}$, of the heavy quark produced . The function $\hat{\sigma} = \frac{d\sigma}{dt}$ can be defined as

$$\frac{d\sigma}{dt} = \frac{1}{16\pi\hat{s}^2}|\mathcal{M}|^2 \qquad (3)$$

The term $|\mathcal{M}|^2$ for heavy quark production are written in terms of the mandelstan variables which are $\hat{s}, \hat{t}\ and\ \hat{u}$.

For the process gg → $Q\bar{Q}$

$$|\mathcal{M}|^2_{(gg\to Q\bar{Q})} = \pi^2\alpha_s^2\left[\frac{12}{\hat{s}^2}\left(M^2-\hat{t}\right)\left(M^2-\hat{u}\right)+\frac{8}{3}\frac{\left(M^2-\hat{t}\right)\left(M^2-\hat{u}\right)-2M^2\left(M^2+\hat{t}\right)}{\left(M^2-\hat{t}\right)^2}\right.$$
$$+\frac{8}{3}\frac{\left(M^2-\hat{t}\right)\left(M^2-\hat{u}\right)-2M^2\left(M^2+\hat{u}\right)}{\left(M^2-\hat{u}\right)^2}-\frac{2M^2\left(\hat{s}-4M^2\right)}{3\left(M^2-\hat{t}\right)\left(M^2-\hat{u}\right)}$$
$$\left.-6\frac{\left(M^2-\hat{t}\right)\left(M^2-\hat{u}\right)+M^2(\hat{u}-\hat{t})}{\hat{s}\left(M^2-\hat{t}\right)}-6\frac{\left(M^2-\hat{t}\right)\left(M^2-\hat{u}\right)+M^2(\hat{t}-\hat{u})}{\hat{s}\left(M^2-\hat{u}\right)}\right]$$

And for qq→ $Q\bar{Q}$

$$|\mathcal{M}|^2_{(qq\to Q\bar{Q})} = \frac{64\pi^2\alpha_s^2}{9}\left[\frac{\left(M^2-\hat{t}\right)^2+\left(M^2-\hat{u}\right)^2+2M^2\hat{s}}{\hat{s}^2}\right].$$

Here

$\alpha_s = \frac{12\pi}{(33-2N_f)\ln(Q^2/\Lambda^2)}$, is the running coupling constant at lower order

Where the value of N_f = 3, which is the number of flavours that is active and Λ=Λ_{QCD} .The factorization and normalization scales used in this calculation is, $Q^2 = m_T^2$. To understand the results on variation on these scales the readers are requested to go through[(Vogt, 2003)]. The comparison of these LO pQCD calculations with NLO (next to leading order) pQCD calculations developed by Mangano, Nason and Ridolfi. [(Michelangelo L.Mangano, 1992)] are beautifully shown in the paper by Umme Jamil and D. K. Srivastava [Umme Jamil, 2010].

Through out our calculations, the p_T distribution of heavy quarks produced from the initial fusion of partons in nucleus-nucleus collisions at LHC energy is obtained by Fixed Order Next to Leading Logarithm (FONLL) calculation. We use CTEQ 6.6 structure function set. The comparisons of p_T distributions of initial productions of charm and bottom quarks at 2.76 AteV and 5.02 AteV, calculated with the help of FONLL calculations, are presented in Fig. 1. As expected, it is seen that at low p_T production of charm quarks is much more than bottom quarks, however with the increase of p_T gradually production of bottom quarks starts dominating.

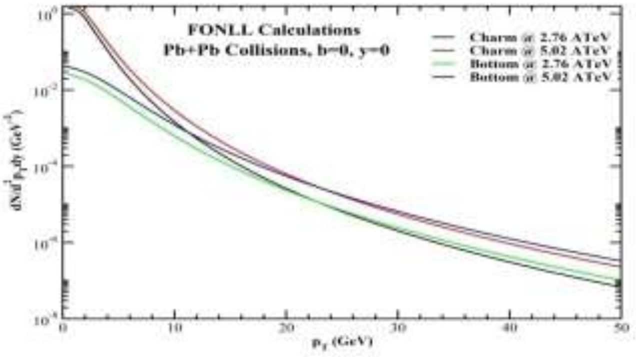


Fig 1: The initial distribution of production of heavy quarks.

2.2: THE EVOLUTION OF PLASMA

We study the energy loss suffered by both charm and bottom quarks with help of different formalisms to predict the nuclear modification factor R_{AA} for heavy quarks at different centre of collision energies of heavy ion collisions at LHC. The transverse momentum (p_T) distribution of D and B meson should be almost similar to that of the charm and bottom quarks respectively as the mass of the heavy quarks are large enough. We use a local fluid approximation [(R. Vogt, 1994), (S. Gavin, Lepton production from charm decay in nuclear collisions at √s=200 GeV and 5.5 TeV per nucleon, 1996)] to work in the medium when the rapidity of the heavy quarks same as the rapidity of the fluid.

While moving through QGP during the initial state of heavy ion collision, the heavy quarks losses energy by colliding with quarks and gluons, and radiating gluons. The energy loss of the particles will depend upon the factors, namely, the path length of the heavy quark, the temperature evolution of the QGP and also upon the mass and energy of the heavy quark.

A few simplifying assumption has been made in order to proceed. It is assumed most of the energy loss of the heavy quark will occur during the time when temperature of the QGP is still very high, which is the earliest times of the QGP formation. And the transverse expansion of the plasma can be ignored in the earliest times of the QGP formation. The distribution of particles produced are assumed to follow the Gaussian rapidity energy distribution and also the initial rapidity distribution is followed closely by the gluons and quarks is similar to the distribution mentioned above.

Thus, the rapidity density distribution of gluons are taken as [(R. Vogt, 1994)].

$$\frac{\mathrm{d}N_g}{\mathrm{d}y} = \left(\frac{\mathrm{d}N_g}{\mathrm{d}y}\right)_0 \exp\left(-y^2/2\sigma^2\right)$$

We use $\left(\frac{\mathrm{d}N_g}{\mathrm{d}y}\right)_0 \approx 3300$ and $\sigma = 4$ for Pb+Pb collision at 5.02 ATeV and $\left(\frac{\mathrm{d}N_g}{\mathrm{d}y}\right)_0 \approx 2800$ at 2.76 ATeV.

The heavy quarks losses maximum energy via gluon interaction and hence it is sufficient to take account of only the gluon distribution. The gluon density at time τ can be expressed as [(Simon Wicks, 2007)]

$$\rho(\tau) = \frac{1}{\pi R^2 \tau}\frac{\mathrm{d}N_g}{\mathrm{d}y}$$

Considering the plasma is at chemical equilibrium, the temperature corresponding to time, τ is [(Simon Wicks, 2007)]

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

Let's considering a production of heavy quarks in a central collision at (r,ϕ) point, which is in the transverse plane with respect to r̂, moving with an angle ϕ . The distance in general these heavy quarks moves through the QGP varies from 2R to R. R is the radius of the colliding nuclei. The distance covered by the heavy quark in the plasma, L (see the figure 2) is given by [(Müller, 2003)]

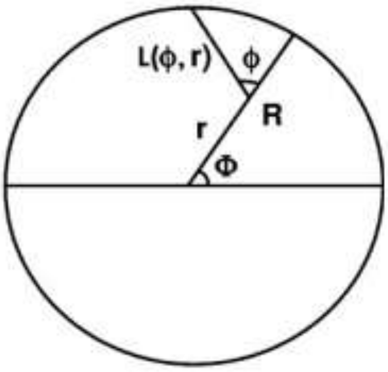


Fig 2: The distance L covered by a heavy quark while passing through QGP

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

The average distance can be estimated as

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

In this equation, $T_{AA}\,(r, b = 0)$ is the nuclear overlap function, which deals with the probability of production of the heavy quarks in hard binary collision. $\langle L \rangle$ =6.14 fm in case of Pb+Pb collision.

We assume that around $\tau_0 \approx 0.2\, fm/c$ the QGP is formed and calculate the corresponding temperature T_0 at y=0 as around 550 MeV for LHC. Some detailed research acknowledges the fact that the initial temperature can be lower as well. However we assume the plasma cools and expands at an approximate temperature, which is at $\tau =< L >_{eff}/2$. We take the Bjorken cooling law $T^3\tau = constant,$ which leads to the result that, the plasma would cool down to the transition temperature or the critical temperature at LHC is $T_C \approx 170\ MeV\ at\ \tau_c \approx$ 8 fm/c at LHC.

If we take the quark velocity as, $v_T = P_T/M_T$, the time taken for the quarks to cross the plasma is $\tau_L =< L >/v_T$. Now if $\tau_c \geq \tau_L$, for the entire duration of $\tau_o - \tau_L$ the quark will be inside the QGP but if $\tau_c \leq \tau_L$, the quarks will be inside the QGP only for the duration in which it will cover the distance $v_T \times \tau_c$. Another approximation is used where we assume that the expansion and cooling of the plasma takes place only in one temperature i.e at $\tau =< L >_{eff}$, where $< L >_{eff}=$ min $[< L >, v_T \times \tau_c]$, this ia very commonly used approximation [Jamil Umme, 2010, (Simon Wicks, 2007)]

2.3: ENERGY LOSS OF THE HEAVY QUARKS:

As it was already mentioned before that there are two ways for the quarks to lose energy inside the QGP, i.e either by collisions or by gluon emission. There exists multiple theoretical mechanism which we can use to estimate the energy loss both via collisions and emission for the quarks, however we are going to use the formalisms discussed below

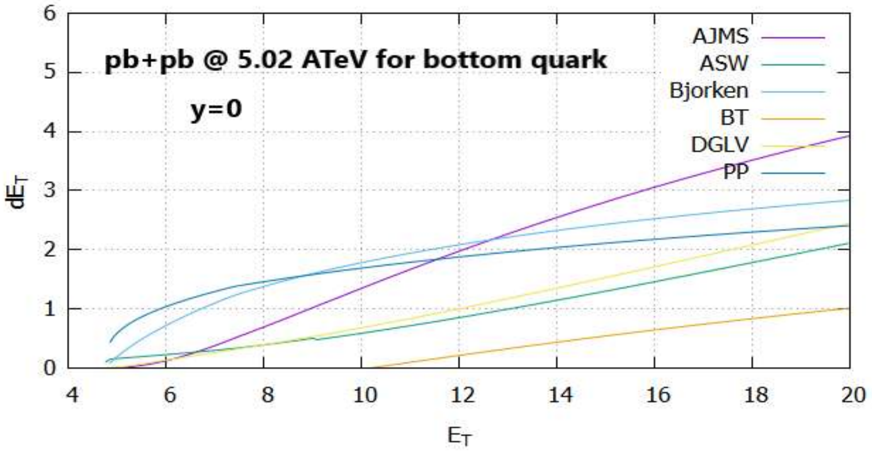
Bjorken [(Bjorken, 1982)] has considered that the energy loss via collision for heavy quarks as analogous to the energy loss of a charge particle via ionization as they move through a medium. Braaten and Thoma [(Thoma, 1991)] was inspired by Bjorken's expression for mass less quark and used it for heavy quarks, we will refer to this mechanism as Bjorken . The energy loss for muons inside QGP was also modified by BT and used to obtain the heavy quark energy loss while moving through QGP via collisions. The results from these formalisms are applicable only if the momentum transfer $q \leq E$, here E is the energy of the heavy quark. This formalism was however improved by Peigne and Peshier (PP) [(Peshier, 2008)]

The treatment known as Djordjovic,Gyulassy,levai and Vitev (DGLV) [(Magdalena Djordjevic, 2004)] will be used in order to understand the radiative energy loss and also the treatment of Armesto, Salgado and widemann (ASW) [(Néstor Armesto, 2004)] which was derived via path integral formalism for medium induced gluon radiations of massive quarks and also the AJMS treatment is used [Abir et. al, 2012]

RESULTS AND DISCUSSION

ENERGY LOSS RESULTS:

We use various formalism to calculate the loss of transverse energy for heavy quark at y=0. We plot a graph between the transverse energy loss (ΔE_T) and transverse energy for both bottom and charm quark at 5.02 ATeV and 2.76 ATeV for pb+pb collision



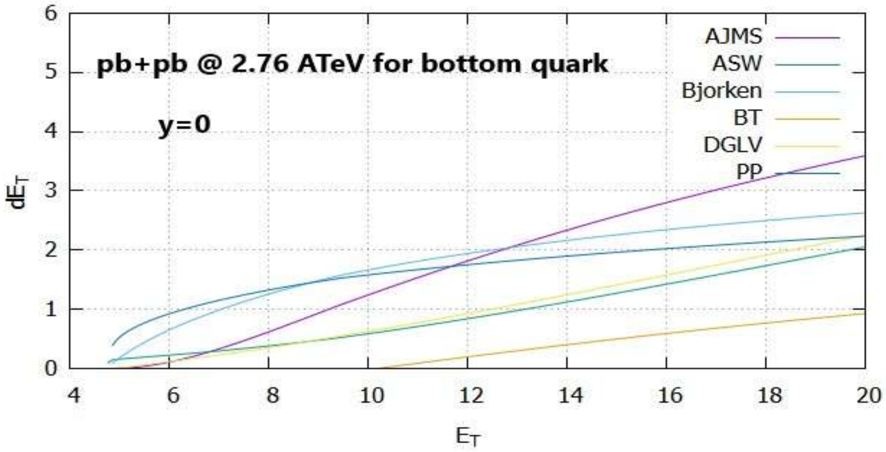
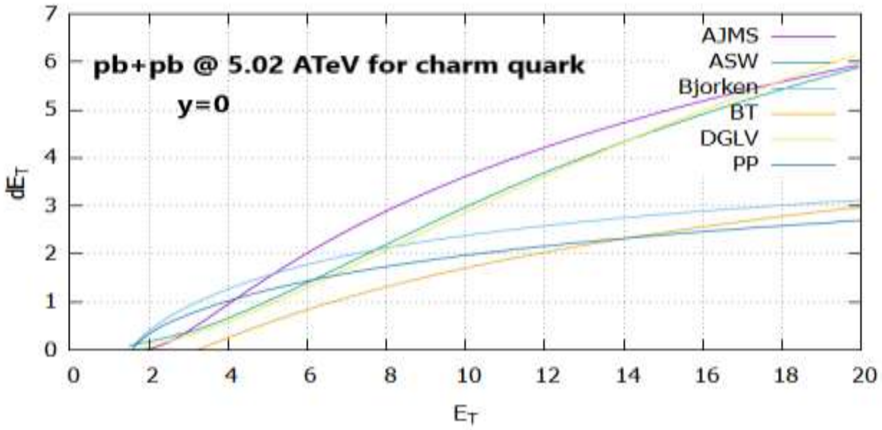


Fig:3: Collisional and rAdiative energy loss for bottom quarks while passing through QGP



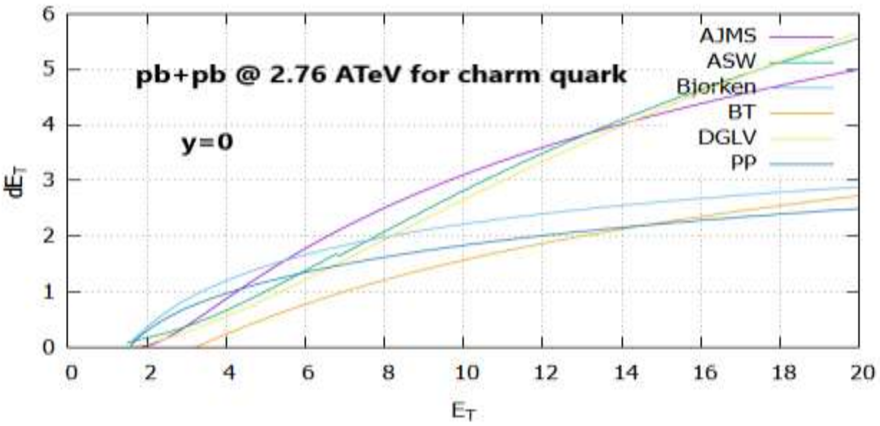


Fig 4: same for charm quark

We learn several things about the nature of the energy loss obtained by different formalism while analyzing the graph we have produced. We see that for collisional energy loss, at both the energies the formalisms give comparable energy loss. However BT formalism gives smaller energy loss because of assumptions taken while formulating. The energy loss of the bottom quark is low compared to charm quark in both collisional and radiative energy loss which is caused by the mass of bottom quark which is larger than the charm quark which leads to low collisional energy loss. In case of the radiative energy loss we see that DGLV and ASW both are almost similar with each other for charm quarks and in case of bottom quark these two formalism gives energy loss comparable to that of collisional energy loss

In case of the AJMS energy loss we see it is the largest radiative energy loss in case of the bottom quark however in case of the charm quark we see that the ASW and DGLV both of the energy loss is almost comparable to that of AJMS.

A comparison plot between two different energies for PP (for collision) and AJMS (for radiative) energy loss formalism would be more meaningful which have been plotted bellow.

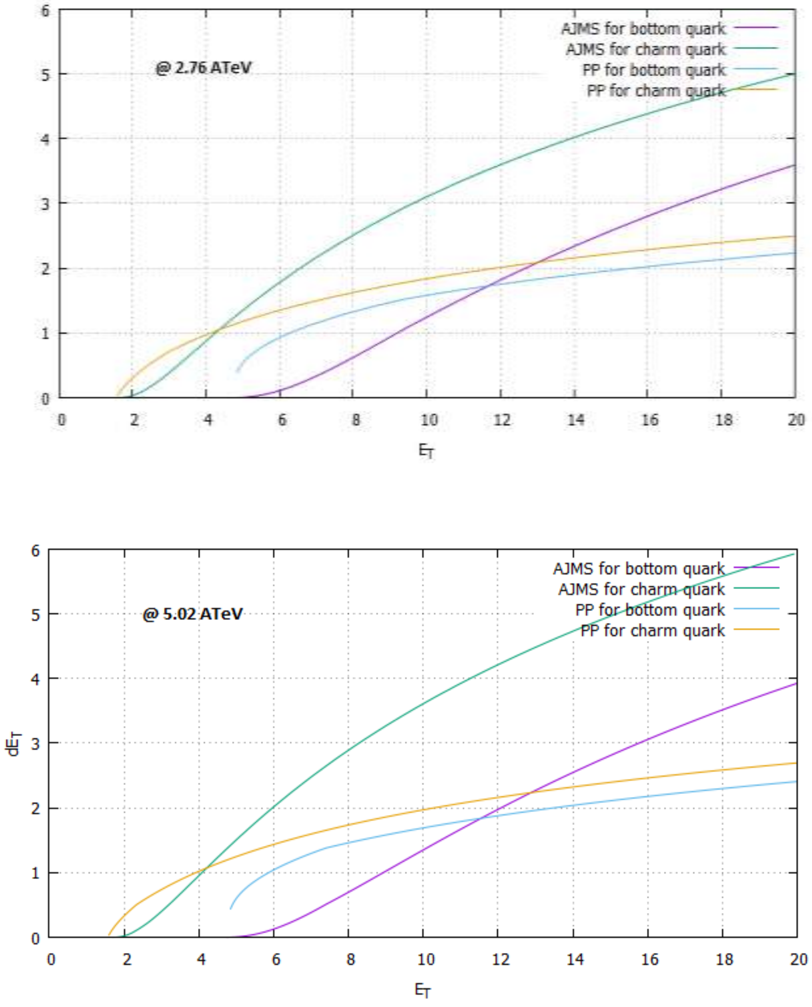


Fig 5: energy comparison for AJMS and PP formalism at both the energies

R_{AA} FOR HEAVY QUARKS:

As we have obtained the initial distribution for the heavy quarks that is produced in the collision, now we will consider a large number of particles following the same initial distribution, these particles will now lose energy via collision and radiation as they move through the QGP. The energy loss would correspond to a change in the transverse momentum of the particle which will result in a change in the distribution. We will call this new distribution the final distribution for the heavy quarks. As energy decreases while moving through the QGP, the transverse momentum in the final distribution will also decrease, means initially heavy quarks which appeared in a high transverse momentum region will now appear in the lower transverse energy region and hence will give us a new distribution. By taking the ration between the initial and distribution and final distribution we get the nuclear modification factor. This calculation is carried out by performing a Monte Carlo Calculation.

We can see the graph between nuclear modification factor and transverse momentum below for both the energies to understand it better while taking one of the formalism into account from both collisional and radiative energy loss. In this case we are taking the AJMS and PP energy loss into account at y=0.

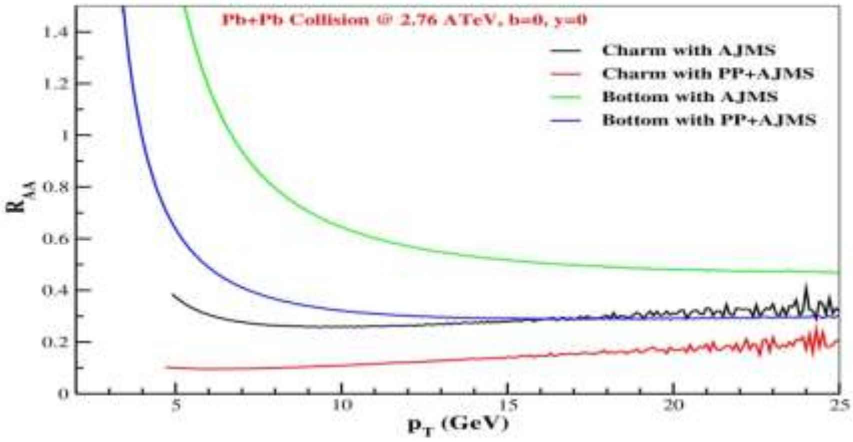


Fig 6 : Raa vs transverse momentum at 2.76 ATeV

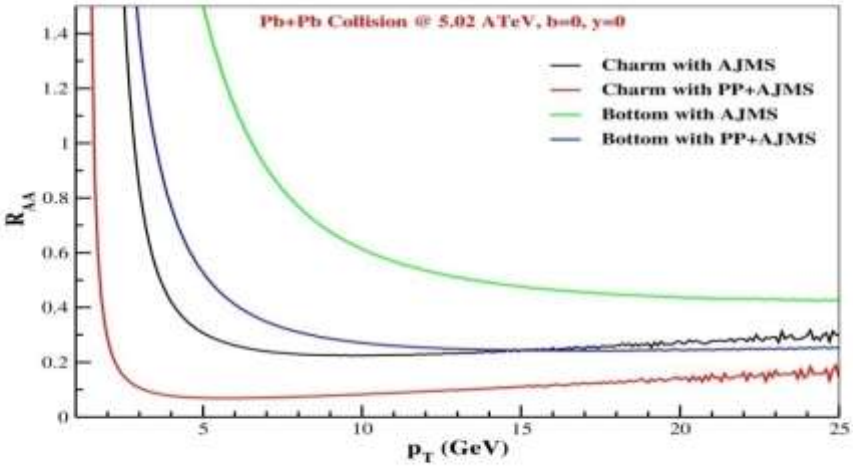


Fig 7 : Raa vs transverse momentum at 5.02 ATeV

The graphs gives the behavior of nuclear suppression factor with transverse momentum after the heavy quarks suffers collisional and radiative energy loss, in this case we have taken into account the AJMS and PP energy loss. We see (fig 6) that at energy 2.76 ATeV when we consider only AJMS energy loss the charm quarks suffers suppression in the nuclear modification factor in the lower transverse energy region and as the momentum increases we see a little enhancement in the nuclear modification factor. When we add both AJMS and PP energy loss for the charm quark, the suppression in the lower momentum region increases more as we can see in the graph. We can see the similar behavior at 5.02 ATeV energy (fig 7) as well, the modification factor decreases rapidly in the low momentum region and starts increasing a little in the high momentum region.

In case of the bottom quark even though the pattern for change in nuclear modification factor with transverse energy is same, we can see (fig 7) that in the both the energies suppression of the modification factor is a bit low compared to that of charm quark for both AJMS energy loss and AJMS+PP . That is because the fact that bottom quark losses less energy both via collision and radiation compared to charm quark as we can see at the results of the energy loss. Let us see the a graph between nuclear suppression factor and transverse energy for both the quarks together while considering both AJMS and PP energy loss (fig 8)

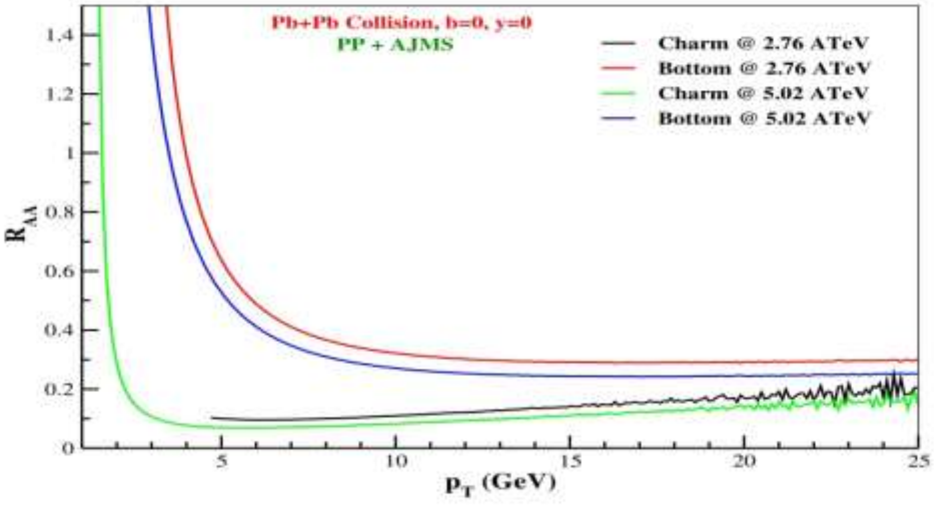


Fig 7 : Raa vs transverse momentum at at both the energies with AJMS+PP

CONCLUSION

Our attempt was to find the nuclear modification factor at 5.02 ATeV and 2.76 ATeV while using charm and bottom quark as our probe. In the first step we obtained the initial distribution for the production of charm and bottom quark in the heavy ion collision, which allowed us to check the usefulness of the pQCD to obtain the NLO results.

We also used different energy loss formalism to obtain the energy loss suffered by the heavy quarks, while they move through the QGP. We obtained both collisional and radiative energy loss for these quarks at two different energies with help of which we obtained nuclear modification factor and plot a graph between the nuclear modification factor with transverse momentum for both the heavy quarks while taking AJMS and PP energy loss formalisms into account.

This work can be extended further to get the R_{AA} of heavy mesons and also for single electron decayed from heavy mesons and compared with the experimental data available. As we know that the experimentally in RHIC and LHC, R_{AA} can be measured only for heavy mesons and semi leptons, not for bare quarks. With the ground work done in this project, one can easily predict R_{AA} of heavy mesons/single electron and compare it with experimental data. It will be interesting to look at the prediction for the energies of proposed Future Circular Collider Experiments with our simple theoretical model.

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