R_{AA} of Charm quarks at RHIC and LHC

Umme Jamil[a*], and Dinesh K. Srivastava[a]

[a]Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700064.

The nuclear modification factor R_{AA} of charm quarks produced from the initial fusion of nucleus nucleus collisions at RHIC and LHC energies is estimated. We consider the effect of energy loss of the charm quarks while passing through the QGP and also the gluon shadowing effect for the calculation of R_{AA} at different rapidities.

1. Introduction

Charm quarks produced at the initial time of relativistic heavy ion collisions are expected to be an efficient probe for the Quark Gluon Plasma. Charm quark is produced from the initial fusion of gluons or light quarks at a time, $1/2M_Q$, which is much less than 0.1 fm/c, i.e., much before the formation of QGP and there will be negligible production of charm quarks at later times.

After production, charm quarks will pass through the QGP, where they will collide with quarks and gluons and radiate gluons. Thus they will loose energy before they fragment in to charm mesons or baryons. These hadrons would carry information on the energy loss suffered by the charm quarks.

As the temperature expected to achieve at LHC is much more than that at RHIC, the various treatments for energy loss suffered by charm quark, available in the literature, can be put to a rigorous test by studying the energy loss of charm quark at RHIC and LHC energies at different rapidities. We study these effects in terms of the nuclear modification factor R_{AA} for charm quark.

First we study the charm quark production in LO pQCD and compare our results with a NLO pQCD calculation. Then we estimate the average energy loss suffered by charm quarks of a given energy using various mechanisms discussed in the literature considering the same initial conditions. Finally we find the average change in the p_T spectra of charm quark using a Monte Carlo calculation and get R_{AA} as a function of p_T for different rapidities.

2. Charm quark production in pp collisions

The cross-section for the charm quark production from pp collisions at LO is [1,2]:

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

where, i and j are the interacting partons, $f_i^{(1)}$ and $f_j^{(2)}$ are the partonic structure functions. The fractional momentum x_1 or x_2 can be expressed in terms of p_T and the rapidities:

$$x_{1,2} = \frac{m_T}{\sqrt{s}}\,(e^{\pm y_1} + e^{\pm y_2}), \quad (2)$$

where m_T is the transverse mass, $\sqrt{M^2 + p_T^2}$, of the produced charm quark. Charm quark in pp collisions is mainly produced by fusion of gluons or light quarks, at LO pQCD [1]. With the inclusion of the NLO processes, the flavour excitation process, $qQ \rightarrow qQ$ and $gQ \rightarrow gQ$, is known to be suppressed [3]. So, we take the short range subprocesses $\hat{\sigma} = d\sigma/dt$ for the fusion of gluons and light quarks [1] only. The factorization and renormalization scales are taken as $Q = m_T$.

---

[*] One of us, UJ, gratefully acknowledges the financial support provided by CR Perugia, Italy to attend the conference BEACH2010. She would also like to thank the Department of Science and Technology, Govt. of India for providing the International travel support.

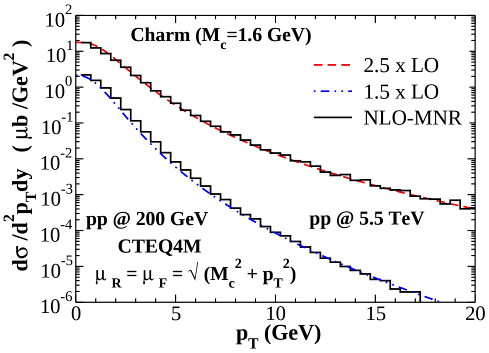

Figure 1. Our LO pQCD results compared with the NLO-MNR calculation for charm quark ($M_c = 1.6\,\text{GeV}$) at $y = 0$.

We also calculate the differential cross section for charm quark in pp collision at NLO in pQCD using the treatment developed by Mangano, Nason, and Ridolfi (MNR-NLO) [4]. Throughout the calculations we neglect the intrinsic transverse momentum of the partons. We introduce nuclear shadowing effect using EKS 98 parameterization [5] for nucleon structure functions. We take CTEQ4M [6] structure function set for nucleons. In Fig. 1 we present our results for p_T distribution obtained by using LO pQCD for pp collision at midrapidity for charm quarks at RHIC and LHC energies. We compare these results with the results obtained by using NLO-MNR treatment. These comparisons suggest a K factor of ≈ 1.5 - 2.5 for our LO calculations for agreement with NLO results.

3. Energy Loss formalisms

For the collisional energy loss mechanisms we consider Bjorken formalism, Braaten and Thoma (BT) formalism and Peigne and Peshier (PP) formalism. Bjorken [7] estimated the collisional energy loss of light quarks analogous to the loss of energy of a charged particle by ionising the medium through which it passes. The expression of Bjorken for light quarks was adapted and modified by BT to the case of heavy quarks [8]. We shall label this mechanism as Bjorken. BT [8] also modified the expression for the collisional energy loss suffered by muons while traversing QED plasma, to obtain that for a heavy quark as it passes through the QGP. These results are valid for collisions where the momentum transfer q << E, where E is the energy of the heavy quark. PP [9] improved this treatment by including the u-channel, which becomes important for large energies.

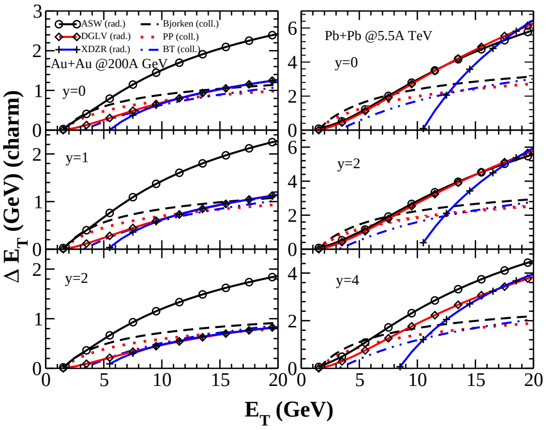

Figure 2. Collisional (dotted lines) and radiative (solid lines) energy loss suffered by a charm quark while passing through the QGP

For the calculation of radiative energy loss, we consider the formalism of Djordjevic, Gyulassy, Levai, and Vitev (DGLV) [10] using opacity expansion, the formalism of Armesto, Salgado, and Wiedemann (ASW) [11] using path integral formalism for medium-induced gluon radiations off massive quarks, and the formalism of Xiang, Ding, Zhou, and Rohrich (XDZR) [12] using light cone path integral approach.

4. The Initial conditions

As the charm quark is expected to be produced at the earliest times after the formation of QGP, we can neglect the transverse expansion of the plasma. Here, We assume a gaussian rapidity density distribution for the particles produced as [13]:

$$\frac{dN_g}{dy} = \left(\frac{dN_g}{dy}\right)_0 \ \exp\ \left(-y^2/2\sigma^2\right). \qquad (3)$$

We take $(\frac{dN_g}{dy})_0 \approx 900$ and $\sigma = 3$ for Au+Au collisions at RHIC [14] and$(\frac{dN_g}{dy})_0 \approx 3300$ and $\sigma = 4$ for Pb+Pb collisions at LHC [15].

The Bjorken cooling is then assumed to work locally at different rapidities, and we consider the passage of a heavy quark having rapidity y in a fluid having an identical fluid rapidity. This approximation has been used earlier in literature [13].

We consider a heavy quark produced in a central collision, at the point (r, Φ), and moving at an angle ϕ with respect to $\hat{\mathrm{r}}$ in the transverse plane. The distance covered by the heavy quark in the plasma, L, is given by [16]:

$$L(\phi,\, \mathrm{r}) = \sqrt{\mathrm{R}^2 - \mathrm{r}^2 \sin^2\phi} - \mathrm{r}\cos\phi. \qquad (4)$$

where R is the radius of the colliding nuclei. We find the average distance, $\langle \mathrm{L} \rangle$ as 5.78 fm for Au+Au collisions at RHIC and 6.14 fm for Pb+Pb collisions at LHC.

The rapidity dependence of temperature [10], assuming a chemically equilibrated plasma is given by

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

where

$$\rho\,(\tau) = \frac{1}{\pi\,\mathrm{R}^2\,\tau}\,\frac{dN_g}{dy}. \qquad (6)$$

We assume that the QGP is formed at $\tau_0 = 0.2$ fm/c. The velocity of the charm quark, $v_T = p_T/m_T$. So, the time taken by the charm quark to cross the plasma, $\tau_L = \langle \mathrm{L} \rangle / v_T$. Now, If $\tau_c \geq \tau_L$, the charm quark would remain inside the plasma from τ_0 to τ_L. But, if $\tau_c < \tau_L$, the charm quark would remain inside the plasma only while covering the distance $v_T \times \tau_c$. We further approximate the expanding and cooling plasma with one at a temperature of T at $\tau = \langle \mathrm{L} \rangle_{\mathrm{eff}}/2$, where $\langle \mathrm{L} \rangle_{\mathrm{eff}} = \min\,[\langle \mathrm{L} \rangle,\, v_T \times \tau_c]$. Such a procedure can be found in the literature [10].

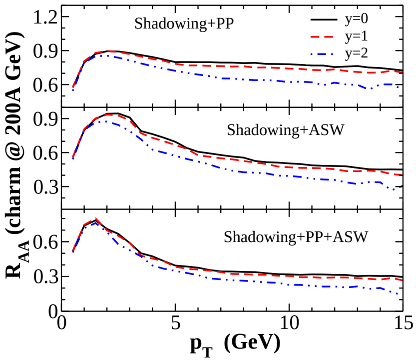

Figure 3. R_{AA} of charm quark considering both the nuclear shadowing effect and the energy loss at more forward rapidities at RHIC energy.

5. Results and discussions

We compare the results for transverse energy loss for a charm quark using different energy loss treatments, discussed earlier, for several rapidities. We plot the transverse energy loss of charm quark, ΔE_T as a function of transverse energy E_T ($\sqrt{p_T^2 + M^2}$) in Fig. 2 at RHIC and LHC energies.

We observe that the collisional energy loss for charm quarks at RHIC and LHC energies is only marginally dependent on the rapidity where as the radiative energy loss shows a complex behaviour. It should be noted that in our procedure, the change in rapidity means the change in temperature. So, we can see that collisional energy loss show a weaker dependence on the temperature and also on the average path length traversed by the charm quark. Among the radiative energy loss formalisms, we see that the ASW formalism shows largest degradation in the energy at all rapidities for higher E_T range. The DGLV and the XDZR formalisms show almost similar results at RHIC energies whereas at LHC energy, the ASW and DGLV formalisms give nearly identical results at y=0 and y=2 but the corresponding value at y=4 differs, which, we expect, is due the complex dependency of the ASW formalism on $\langle \mathrm{L} \rangle_{\mathrm{eff}}$.

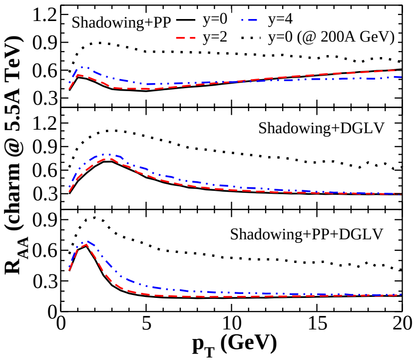

Figure 4. R_{AA} of charm quark considering both the nuclear shadowing effect and the energy loss at more forward rapidities at LHC energy.

The R_{AA} for charm quark can be expressed as:

$$R_{AA}(b) = \frac{dN^{AA}/d^2p_T\,dy}{T_{AA}(b)\,d\,\sigma^{NN}/d^2p_T\,dy}, \tag{7}$$

We get $T_{AA}\approx$ 280 fm^{-2} for Au+Au collisions at RHIC and $\approx$ 290 fm^{-2} for Pb+Pb collisions at LHC, for b = 0 fm.

In Figs. 3 and 4 we discuss our results for R_{AA} with the additional inclusion of collisional and radiative energy losses at RHIC and LHC energies. Here we will consider collisional energy loss using the PP formalism and the radiative energy loss using ASW or DGLV formalism.

In Fig. 3, R_{AA} first increses approximately from 0.5 to 0.8 at $p_T \approx 2$ GeV and then again drops to 0.3. R_{AA} remains constant at 0.3 for the p_T range 5-15 GeV.

In Fig. 4, we can see that the p_T distribution of R_{AA} at LHC energy behaves in the same manner as that for RHIC. It first rises to a value of 0.6 and then drops to 0.2 at $p_T \approx 5$ GeV and remains constant at that value for the p_T range 5-20 GeV. From these p_T distribution of R_{AA}, we can see that in contradiction to the decrease of energy loss at more forward rapidities, the total nuclear suppression increases with forward rapidity. This is due to the complex behaviour of the nuclear shadowing effect at more forward rapidities. Along with the p_T distribution of R_{AA} at LHC, the result of R_{AA} at RHIC at $y = 0$ is also presented and it shows a substantial suppression of charm quark R_{AA} while going from RHIC to LHC energy. For more details please see [17].

We can say that the description for energy loss for one quark mass, one incident energy or one rapidity may not be sufficient to pointout the most reliable energy loss formalism. These studies can be improved by using more realistic 3+1 dimensional hydrodynamics. Also, one should carry out calculations for non central collisions.

REFERENCES

1. B. L. Combridge, *Nucl. Phys. B* 151 (1979) 429.
2. E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, *Rev. of Mod. Phys.* 56 (1984) 579.
3. Z. Lin and M. Gyulassy, *Phys. Rev. C* 51 (1995) 2177.
4. M. L. Mangano, P. Nason, and G. Ridolfi, *Nucl. Phys. B* 373 (1992) 295.
5. K. J. Eskola, V. J. Kolhinen, and C. A. Salgado *Eur. Phys. J. C* 9 (1999) 61.
6. H. L. Lai *et al.*, *Phys. Rev. D* 55 (1997) 1280.
7. J. D. Bjorken, FERMILAB-PUB-82/059-THY (1982).
8. E. Braaten and M. H. Thoma, *Phys. Rev. D* 44 (1991) R2625.
9. S. Peigne and A. Peshier, *Phys. Rev. D* 77 (2008) 114017.
10. S. Wicks, W. Horowitz, M. Djordjevic, and M. Gyulassy, *Nucl. Phys. A* 784 (2007) 426.
11. N. Armesto, C. A. Salgado, and U. A. Wiedemann, *Phys. Rev. D* 69 (2004) 114003.
12. W. C. Xiang, H. T. Ding, D. C. Zhou, and D. Rohrich, *Eur. Phys. J. A* 25 (2005) 75.
13. S. Gavin, P. L. McGaughey, P. V. Ruuskanen, and R. Vogt, *Phys. Rev. C* 54 (1996) 2606.
14. I. G. Bearden *et al.*, *Phys. Rev. Lett.* 88 (2002) 202301.
15. D. Kharzeev, E. Levin, and M. Nardi, *Nucl. Phys. A* 747 (2005) 609.
16. B. Müller, *Phys. Rev. C* 67 (2003) 061901.
17. U. Jamil and D. K. Srivastava, *J. Phys. G* 37 (2010) 085106.