Effect of quark gluon plasma on charm quark produced in relativistic heavy ion collision

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Abstract. Charm quarks are produced mainly in the pre-equilibrium stage of heavy ion collision and serve as excellent probes entering the thermalized medium. They come out with altogether different momenta and energies and fragments into D-mesons and decay into non-photonic electrons which are observed experimentally. Here we present the effect of QGP on charm quark production using two different models: first one based on Wang-Huang-Sarcevic model of multiple scattering of partons and the second one is based on Parton Cascade Model with Boltzmann transport equation used for charm quark evolution in QGP.

1. Introduction

Charm quarks are produced mostly in the early period after heavy ion collision when quarks and gluons with high momenta interact with momentum transfer $Q^2 > 2m_c$ (mass of charm). Thus charm production rate may be controlled using perturbative QCD techniques. Also, being produced small in number as compared to massless gluons and light quarks, they remain separated from the bulk properties of the deconfined system and may serve as the probes to quark gluon plasma.

2. Production of charm and its energy loss in quark gluon plasma

At first let us discuss briefly production of charm quarks:

2.1. charm quarks production

The differential cross-section for $c\bar{c}$ production in proton-proton collision can be shown to be

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

where i and j are the interacting partons and f_i and f_j are the partonic structure functions, and x_1 and x_2 are the momentum fractions of the parent nucleons carried by the interacting partons [1].

$$\frac{d\sigma}{d\hat{t}} = \frac{|M|^2}{16\pi\hat{s}^2} \tag{2}$$

where the invariant amplitude $|M|^2$ is given by [2].

For heavy ion collisions the p_T spectrum for heavy quark production is given by

$$\frac{dN}{d^2p_T dy} = T_{AA}(b)\frac{d\sigma}{d^2p_T dy} \tag{3}$$

where for collisions at different centrality, $T_{AA}(b)$ can be calculated using Glauber formalism. We account for higher order corrections by taking a constant K-factor ≈ 2.5

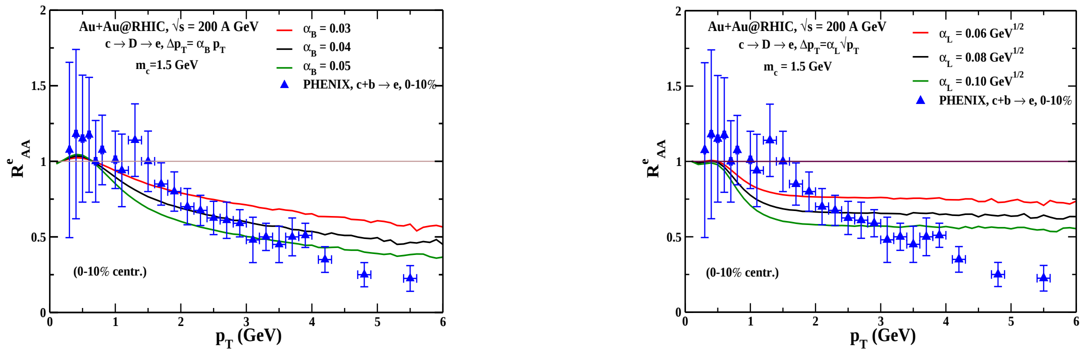

Figure 1. $R_{AA}(p_T)$ of single non-photonic electron at RHIC energy of $\sqrt{s} = 200$ A GeV.

2.2. Energy Loss of charm

The medium effect on charm p_T spectrum has been obtained using two different models. The first one deals with energy loss of charm via momentum loss per collision through multiple collisions of charm with medium partons. The calculations are partly inspired by Wang-Huang-Sarcevic model of multiple scattering of jet partons with medium partons [3]. The momentum loss per collision for 'i^{th}' charm is defined by

$$\Delta p_i = \alpha(p_i)^{\beta}\,, \alpha = \alpha_L(\beta = 0.5)\,, \text{and}\, \alpha_B(\beta = 1.0) \tag{4}$$

The no. of collisions for given charm momentum is calculated using Poisson distribution. Finally nuclear modification factor, '$R_{AA}(p_T)$' and azimuthal anisotropy, '$v_2(p_T)$' have been calculated for single non-photonic electrons and D mesons and results compared with recent data from RHIC and LHC experiments.

The second model used for charm evolution is Parton Cascade Model [4]. One of its implementation commonly called VNI/BMS-box mode has been utilized. The calculations are based on Microscopic Boltzman transport equation given by

$$p^{\mu}\frac{\partial F_k(x,\vec{p})}{\partial x^{\mu}} = \sum_{processes:i} C_i[F], \tag{5}$$

where $F_k(x,\vec{p})$ is the single particle phase space distribution and the collision term on r.h.s. is a non-linear functional of phase space distribution terms inside an integral.

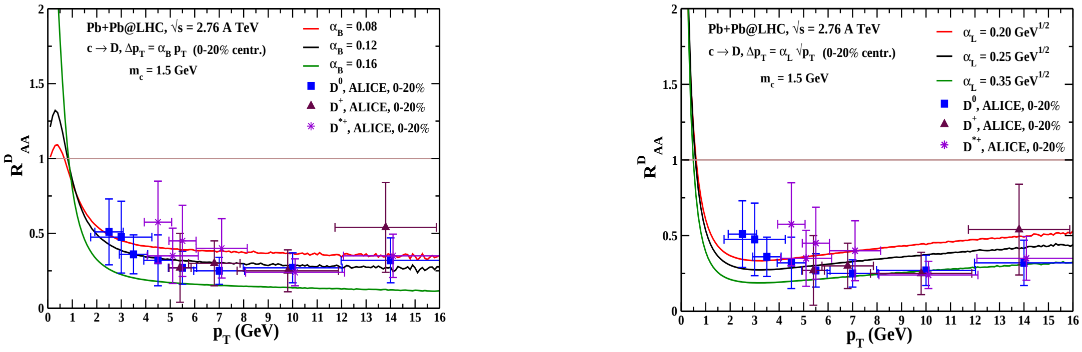

Figure 2. $R_{AA}(p_T)$ of D mesons at LHC energy of $\sqrt{s} = 2.76$ A TeV

We have included the matrix elements for all $2 \rightarrow 2$ binary elastic scattering processes for charm interaction with gluons or light quarks(u, d, s) and $2 \rightarrow n$ process for radiative (brehmsstrahlung) corrections after each scattering. The elastic processes included are

$$\begin{aligned} cg &\rightarrow cg, \\ cq(\bar{q}) &\rightarrow cq(\bar{q}). \end{aligned} \tag{6}$$

The corresponding differential scattering cross section is defined to be,

$$\frac{d\hat{\sigma}}{dQ^2} = \frac{1}{16\pi(\hat{s} - M_c^2)^2} \sum |\mathcal{M}|^2. \tag{7}$$

The invariant transition amplitude, $|M|^2$ for elastic scattering which can be calculated or obtained from [5].

In our calculations, radiative corrections are included in form of time-like branching of the probe charm into a final charm and a shower of radiated partons. In time-like branching the probe charm after each scattering may split into a daughter charm with different momentum and a gluon. Together with this, we have also included coherent emission of gluons commonly called Landau-Pomeranchuk-Migdal(LPM) effect in our radiative energy loss formalism.

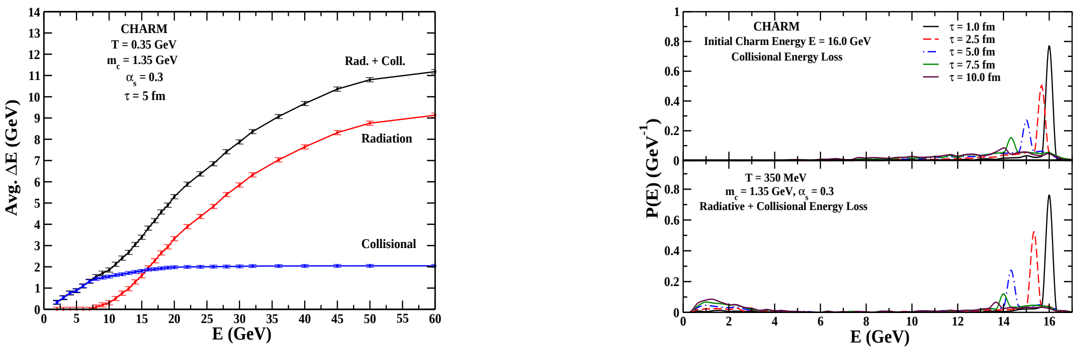

Figure 3. (left)Average energy loss of different energy charms, (right) energy profile of a 16.0 GeV charm at different time.

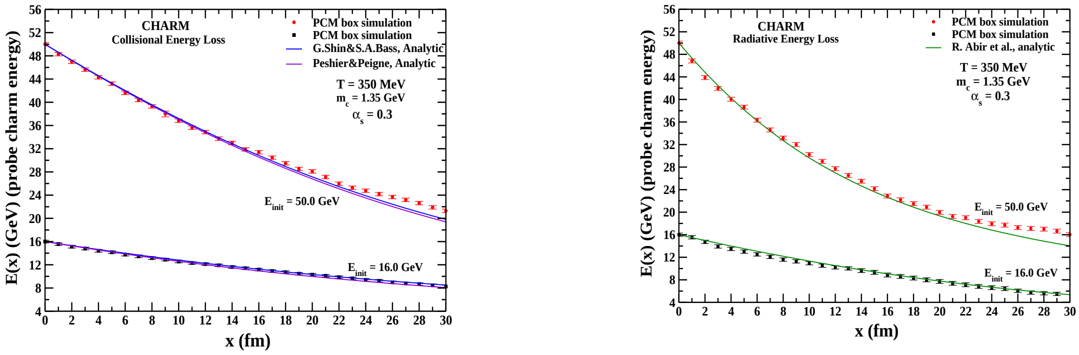

Figure 4. Energy of probe charm with distance traveled for collisional loss(left) only and radiative energy loss(right) only

3. Results

From the model calculation of multiple scattering of charm in QGP, we have obtained R_{AA} and v_2 of charm at both LHC and RHIC collision energies, for two different mechanisms for momentum loss per collision. Our calculations for $\alpha = \alpha_B(\beta = 1.0)$ explains the experimental data mostly in lower and mid-p_T region for both RHIC and LHC temperatures. However, the other mechanism of $\alpha = \alpha_L(\beta = 0.5)$ seems to explain the data for higher charm momentum, p_T region where the $R_A A$ data for D-mesons and non-photonic electrons seem to rise just like lighter mesons, see Fig. 1 and, Fig. 2. v_2 results from our calculations however do not match experimental data well enough at RHIC but it clearly shows different trend between two mechanisms we have included in our calculations.

From the second model of PCM-VNI/BMS, we have calculated average energy loss of charms of different energies(E_c). The collisional loss seems to dominate below E_c $<$16.0 GeV while radiative loss takes over and dominates beyond E_c $\geq$16.0 GeV. We also showed energy profile of a 16.0 GeV charm tracked through different evolution time. The collisional loss shows a shift in the peak with a long tail-like structure unlike results for charm quarks,from recent calculations with Langevin equation(+ hydrodynamical background) under similar conditions, Fig. 3. In last two plots, Fig. 4 we have shown probe charm energy evolution for different distances it travels in QGP at a fixed temperature of 350 MeV. We used, two different initial charm energy of 16.0 and 50.0 GeVs respectively and studied the evolution of energy for collisional loss radiative loss, separately. The PCM simulation results are compared with some of the recent analytical calculation of charm quark energy loss per unit length it travels in QGP [6].

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