Medium Modification of Charm Production in Relativistic Heavy Ion Collisions due to Pre-equilibrium Dynamics of Partons at $\sqrt{s_{NN}} = 0.2–5.02$ TeV

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We study the production dynamics of charm quarks in the parton cascade model for relativistic heavy ion collisions at RHIC and LHC energies. The model is eminently suited for a study of the pre-equilibrium dynamics of charm quarks at modest transverse momenta. The treatment is motivated by QCD parton picture and describes the dynamics of an ultra-relativistic heavy-ion collision in terms of cascading partons which undergo scattering and multiplication while propagating. We find considerable suppression of charm quarks production in $AA$ collisions compared to those for $pp$ collisions at the same $\sqrt{s_{NN}}$ scaled by number of collisions. This may be important for an accurate determination of energy loss suffered by charm quarks while traversing the thermalized quark gluon plasma.

I. INTRODUCTION

The existence of Quark Gluon Plasma (QGP), a deconfined strongly interacting matter, which was predicted by lattice Quantum Chromo Dynamics calculations (see, e.g. Ref. [1] for a recent review), is now routinely produced in relativistic heavy ion collisions at BNL Relativistic Heavy Ion Collider and CERN Large Hadron Collider. It is believed to have filled the early universe till a few micro-seconds after the Big Bang. The study of QGP has remained one of the most rewarding disciplines of modern nuclear physics for more than three decades.

The observation of large elliptic flow of hadrons [2, 3] and jet-quenching [4, 5], because of the energy loss of high energy partons in the hot and dense medium, are the most prominent early signatures of the formation of QGP in these collisions. Additional confirmation has been provided by detection of thermal radiation of photons forming these collisions [6, 7]. The unexpected surprises have been provided by the parton recombination as a mechanism of hadronization [8] and the very low viscosity (see e.g., Ref. [9, 10]).

Coming years will explore its properties to a great deal of accuracy and once the Facility for Anti-proton and Ion Research, Darmstadt (FAIR) and the Nuclotron-based Ion Collider Facility, Dubna (NICA) start working, the next frontier of this fascinating field, namely QGP at high baryon density and low temperatures, which perhaps forms the core of large neutron stars [11, 12], will be open for exploration. The Future Circular Collider (FCC) will provide an opportunity to study $pp$ and $AA$ collisions at unprecedented high centre of mass energies [13, 14].

Charm quarks have emerged as a valuable probe of the evolution dynamics of quark gluon plasma. This was realized quite early in the literature. The large mass of charm quarks ensures that they are produced only in processes involving a sufficiently large $Q^2$. This makes these interactions amenable to perturbative QCD calculations. The later interactions conserve charm and the hadrons containing charm are easily identified. More than three decades ago, Svetistky [14] obtained the drag and diffusion coefficients for them by considering that they execute a Brownian motion in the QGP. A first estimate of the radiative energy loss of heavy quarks was also obtained by authors of Ref. [15] using some simplifying assumptions. These early studies have been brought to a very high degree of sophistication by now. The energy loss suffered by heavy quarks due to scatterings and radiation of gluons have been estimated and its consequences have been explored in detail (see, e.g. [16–38]). The temperature dependence of the drag coefficient has also been calculated using lattice QCD [39–41]. A phenomenological extension of Wang, Huang, Sarcevic model [42, 43] was used by authors of Ref. [44] to extract energy loss of charm quarks in the quark gluon plasma and their azimuthal correlations [45] and a comparative study of different energy loss mechanisms for heavy quarks at central and forward rapidities was performed by authors of Ref. [46].

However, all the above studies mostly start with the assumption of a thermally and chemically equilibrated plasma at some formation time $\tau_0 \approx 0.2–1.0$ fm/$c$. The assumption of chemical equilibration has been relaxed in some studies for determination of the drag and diffusion [19]. The consequences of this relaxation for interactions [47–48] following their initial production in prompt collisions [49] have also been studied. The drag and diffusion coefficients for heavy quarks for the pre-equilibrium phase have been studied by replacing the distributions of quarks and gluons by Colour Gluon Condensate model inspired distributions [50].

The thermalization of heavy quarks by assuming that they perform Brownian motion in a thermal bath of gluons was studied quite some time ago [51]. Heavy quark thermalization and flow has been studied in considerable detail within a partonic transport model BAMPS (Boltzmann Approach of Multi Parton Scatterings) by the authors of Ref. [52, 53], where the initial distribution of charm quarks was sampled from PYTHIA.
The parton cascade model proposed by Geiger and Muller \cite{54} has been refined by Bass, Muller, and Srivastava \cite{55} with improved implementation of the dynamics of the collision with several interesting insights and results. It was further extended to implement the production of heavy quarks \cite{56}. A box-mode implementation was shown to provide an accurate description of energy loss suffered by charm quarks in QGP at a given temperature due to collisions and radiations \cite{57}.

Recently it was employed to study the transport dynamics of parton interactions in $pp$ collisions at the LHC energies \cite{58}. These studies are of interest because of the QGP like features observed in high multiplicity events of these collisions. The studies reported in Refs. \cite{56, 58} were performed by neglecting the Landau Pomeranchuk Migdal (LPM) effect, which results in enhanced parton multiplication.

Authors of Ref. \cite{59} have reported results for charm production in $pp$ collisions with the accounting of LPM effect. Their results indicate that $pp$ collisions at the higher LHC energies may lead to formation of a dense medium. This, in turn triggers a suppression of radiations (and parton multiplication) due to the LPM effect. However, it was reported that, even after these suppressions, multiple scatterings occur among the partons and the transverse momentum distribution of charm quark is rather sensitive to such scatterings. These calculations also provided a reasonably good description of the charm distribution measured at LHC energies. The bottom quarks, on the other hand, due to their very large mass are not likely to be produced in multiple scatterings after the initial collisions and were not affected by this suppression \cite{60}, at least for $pp$ collisions.

These considerations presage a considerable influence of LPM effect in $AA$ collisions. We aim to study this pre-equilibrium dynamics for charm production in $AA$ collisions, in the present work.

We briefly discuss the details of our formulation in the next section, give our results in Sec. III, and conclusions in Sec. IV.

II. FORMULATION

First of all, let us state the limited objective of our work in a little more detail. We realize that charm quarks, after their initial production in hard partonic scatterings will be a witness to the emergence of a thermally and possibly chemically equilibrated QGP followed by its expansion and cooling. These will see the beginning of the flow and hadronization. The heavy mesons containing charm quarks may also undergo scatterings during the hadronic phase. Thus these are valuable chroniclers of the system.

As mentioned earlier, the drag, diffusion, energy loss and flow experienced by them need to be understood in quantitative detail so that we can use them to determine the properties of the medium precisely. We realize that the charm quarks will experience a considerable turmoil, before the thermally and chemically equilibrated plasma sets in at some formation time $\tau_0$ of the order of 0.2–1.0 fm/$c$. This suggests that we understand their dynamics before the system enters the so-called QGP phase, as some amount of medium modification of their momentum distribution could already happen by then. In absence of

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{fig1.png}
\caption{(Colour on-line) The $p_T$ distribution of charm quarks at the end of the pre-equilibrium phase for nucleus-nucleus collisions (for $b = 0$ fm) and $pp$ collisions scaled by the number of collisions, at the same $\sqrt{s_{NN}}$ for $y = 0$. Results are given for Au+Au collisions at 200 AGeV (upper panel), Pb+Pb collisions at 2.76 ATeV (middle panel) and 5.02 ATeV (lower panel).}
\end{figure}
this the medium modification already sustained during the pre-equilibrium phase will have to be, per-force, accounted by adjusting the values for drag, diffusion and radiative energy loss during the QGP phase and later.

The parton cascade model \cite{54,52} is eminently suited for this study for the following reasons. It starts from experimentally measured parton distribution functions and proceeds to pursue a Monte Carlo implementation of the Boltzmann equation to study the time evolution of the parton density, due to semi-hard perturbative Quantum Chromo Dynamics (pQCD) interactions including scatterings and radiations within a leading log approximation \cite{61}. The $2 \rightarrow 2$ scatterings among massless partons use the well-known matrix elements (see, e.g. \cite{62}) at leading order pQCD. The singularities present in the matrix elements are regularized by introducing a transverse momentum cut-off ($\rho_T^{\text{cut-off}}$) fixed at 2 GeV in the present work.

The radiation processes ($g \rightarrow gg$ and $q \rightarrow qg$) are, in turn, regularized by introducing a virtuality cut-off, $\mu_0^2 = \sqrt{m_i^2 + \mu_0^2}$, where $m_i$ is the current mass of quark (zero for gluons) and $\mu_0$ is taken as 1 GeV. This is implemented using the well tested procedure implemented in PYTHIA \cite{63}. It has been reported earlier that the introduction of the LPM effect minimizes the dependence of the results on the precise value of $\mu_0$ \cite{59,62}.

The matrix elements for the $gg \rightarrow Q\bar{Q}$ and $q\bar{q} \rightarrow Q\bar{Q}$ processes do not have a singularity and the minimum $Q^2$ for them is $4M_Q^2$, which for charm quarks is more than 7 GeV$^2$ and amenable to calculations using pQCD. The $qQ \rightarrow gQ$ and $qQ \rightarrow gQ$ processes will require a $\rho_T^{\text{cut-off}}$ to avoid becoming singular, and it is taken as 2.0 GeV as before. The matrix elements for these are taken from Combridge \cite{64}. For more details, the readers are referred to earlier publications \cite{60}.

The scatterings among partons and radiation of gluons will lead to a rapid formation of a dense partonic medium for $AA$ collisions, even though the PCM involves only those partons which participate in the collisions leading to momentum transfers larger than $\rho_T^{\text{cut-off}}$ and are radiated only their till virtuality of the mother parton drop to $\mu_0^2$ (see above). This would necessitate introduction of LPM effect. We have already noted its importance for $pp$ collisions \cite{59}.

We have implemented the LPM effect by assigning a formation time $\tau$ to the radiated particle:

$$\tau = \frac{\omega}{k_T^2},$$

where $\omega$ is its energy and $k_T$ is its transverse momentum with respect to the emitter. We further implement a scheme such that during the formation time, the radiated particle does not interact. The emitter, though continues to interact and if that happens, the radiated particle is removed from the list of participants and is thus excluded from later evolution of the system \cite{65} (see \cite{59}, for more detail).

These aspects are incorporated in the Monte Carlo implementation of the parton cascade model, VNI/BMS which we use for the results given in the following. Before proceeding, we insist that PCM does not include the soft scatterings which lead to flow etc. We have already mentioned that a good description of charm production at LHC energies, using this procedure, was reported earlier \cite{54}.

### III. RESULTS

We have calculated production of charm quarks for $Au + Au$ collisions at 200 AGeV and for $Pb + Pb$ collisions at 2.76 ATeV and 5.02 ATeV for zero impact parameter. Results for $pp$ collisions at the same centre of mass energy have also been included for a comparison and for estimating the medium modification factor $R_{AA}$, such that

$$R_{AA}(p_T) = \frac{dN_{AA}/d^2p_T dy}{N_{coll} \times dN_{pp}/d^2p_T dy}$$

where $N_{coll}$ is the number of binary nucleon-nucleon collisions for the given centrality.

We shall also use the ratio of $p_T$ and $y$ integrated results to denote the possible deviation of the production of charm quarks from the $N_{coll}$ values for $pp$ interactions:

$$R = \frac{N_{AA}}{N_{coll} \times N_{pp}}$$

We expect the final results for the medium modification to deviate substantially from what is reported here, which is only due to pre-equilibrium dynamics of the system.

Charm will be conserved during the later evolution of the system. Thus, a rich structure should emerge for the final modification, once the energy loss suffered by the charm quarks and the consequence of the collective flow is accounted for as they traverse the quark gluon plasma. The depletion of charm quark at larger momenta should be accompanied by an enhancement at lower momenta. This enhancement may depend strongly on the transverse momentum as the $p_T$ spectrum falls rapidly with increase in $p_T$. Further, as charm quarks participate in the collective expansion of the medium, their flow would lead to a depletion of charm having very low momenta which would result in an enhancement at intermediate momenta.

In Fig.1 we plot the $p_T$ distribution of charm quarks for central $AA$ collisions at $y = 0$ along with the same for $pp$ collisions at the corresponding $\sqrt{s_{NN}}$ scaled by the number of collisions as appropriate for production mechanisms involving hard interactions. We notice a $p_T$ dependent suppression of charm production in $AA$ collisions, increasing with the centre of mass energy of the collisions.

The $p_T$ integrated rapidity distributions shown in Fig.2 brings this fact even more clearly. It additionally
The medium modification of total charm production $R$, is shown in Fig. 3 as a function of centre of mass energy per nucleon. We note that the suppression increases with $\sqrt{s_{NN}}$ and tends to saturate at LHC energies. We are not sure that the importance of this has been sufficiently emphasized in literature.

Let us discuss this in a little more detail. The experimentally measured $R_{AA}$ at 200 AGeV [66], 2.76 ATeV [68], and 5.02 ATeV [69] for the central rapidity is always less than one. We know that the charm production during the thermally equilibrated phase is rather negligible. This trend should persist at larger rapidities.

The authors of Ref. [58] reported emergence of LPM effect already in $pp$ collisions, signalling the formation of a dense medium. As stated earlier, it was found that even with this suppression of scatterings and parton multiplications, there was multiple parton scatterings beyond the primary-primary collisions followed by fragmentations which provided a reasonable explanation to the experimental data. In $AA$ collisions the LPM effect should be quite strong. This will result in a large scale suppression of partonic collisions as parton multiplication is arrested due to the delayed fragmentaions of off-shell partons following scatterings. This should then lead to an overall suppression of charm production beyond that expected from a straightforward scaling of results of $pp$ collisions by the number of collisions, seen here. It is also expected that this effect would get stronger as the centre of mass energy rises. We recall that this was not seen in calculations performed with the neglect of the LPM effect [56], where $R_{AA} \geq 1$ was seen for low $p_T$ (recall also that the $p_T$ distributions drop rapidly with increasing $p_T$). This implies that in the absence of LPM effect, the parton multiplications and multiple scatterings would lead to a charm production in $AA$ collisions well beyond that obtained from a scaling of the corresponding results.
FIG. 4: The medium modification of charm production due to the pre-equilibrium dynamics for Au+Au collisions at 200 AGeV (upper panel), Pb+Pb collisions at 2.76 ATeV (middle panel) and 5.02 ATeV (lower panel) along with experimental data by STAR [66, 67], ALICE [68] and CMS [69] Collaborations respectively.

for pp collisions. We have verified that it is indeed so, for all the three energies considered here.

This has one interesting and important consequence. While the final $R_{AA}$ will result from a rich interplay of collective flow and energy loss of the charm quarks, its value at lower $p_T$ would already be quite smaller than unity. An effort to attribute this entire suppression due to energy loss during the QGP phase alone would necessarily require a larger value for $dE/dx$.

We give our results for medium modification of charm production at $y = 0$ for most central collisions in Fig. 4. We emphasize that we neither intend nor expect to explain the experimental $R_{AA}$. These are shown only to denote how this rich input of medium modification of charm phase space distribution due the pre-equilibrium dynamics, has to provide the platform for the launch of their journey through the hydrodynamic evolution of the system. During this period they will be subjected to the collective flow and further energy loss.

We do note one interesting and possibly valuable result of these studies. The distribution of charm quarks having large $p_T \geq 6$ GeV or so does not seem to be affected strongly by the pre-equilibrium dynamics discussed here.

Thus we feel that a charm distribution whose momenta are sampled from those for pp collisions and the points of production distributed according to the nuclear thickness function $T_{AA}(x, y)$ is not quite adequate as in input for study of charm propagation during the QGP phase of the system produced in relativistic collision of nuclei.

IV. SUMMARY AND DISCUSSION

We have calculated the dynamics of production of charm quark using parton cascade model, which should provide a reasonable description of the parton dynamics, albeit limited to, $p_T \geq p_T^{cut-off}$ and a reasonably modest virtuality $\geq \mu_0$ defined earlier during the pre-equilibrium phase. The LPM effect provides a rich structure to the so-called medium modification factor for charm quarks, defined as a ratio of the results for $AA$ collisions divided by the results for pp collisions (at the same $\sqrt{s_{NN}}$) scaled by number of collisions. We noticed an over all suppression of charm production, which we attribute to the LPM effect.

The medium modification factor as a function of $p_T$ shows a rich structure which evolves with energy, deviating (suppression) from unity by about 10% at low $p_T$ and approaching unity as intermediate $p_T$ at $\sqrt{s_{NN}} = 200$ GeV. This deviation (suppression) is seen to rise to about 40% at LHC energies. An interesting result, seems to be the supression of large $p_T$ charm at 2.76 TeV, but not at 5.02 TeV, which we are unable to understand.

Realizing that this should form input to the calculations using hydrodynamics and with collisional and radiative energy loss of charm quarks to determine $dE/dx$, we expect some interesting deviations with those with the neglect of these suppressions.

A future study, which is under way, will use more modern structure functions, (we have used GRV HO in these preliminary studies) and account for straight forward corrections like nuclear shadowing, which will further suppress the production of charm quarks beyond what is reported here. The results for the phase space distribution of charm quarks at the end of the pre-
equilibrium phase will then be used as inputs to hydrodynamics based calculations, as indicated above.

In brief, we see that the pre-equilibrium dynamics of parton scattering and fragmentation along with LPM effect provides a rich structure to the production of charm quarks. We suggest that this effect should be taken into account to get a precise value for the energy loss suffered by charm quarks and the modification of their $p_T$ distributions due to the flow.

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[1] C. Ratti, Rept. Prog. Phys. 81, no. 8, 084301 (2018) doi:10.1088/1361-6633/aabbb7 [arXiv:1804.07810 [hep-lat]], and references therein.
[2] C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 90, 032301 (2003) doi:10.1103/PhysRevLett.90.032301 [nucl-ex/0206006].
[3] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 152301 (2003) doi:10.1103/PhysRevLett.91.152301 [nucl-ex/030513].
[4] K. Adcox et al. [PHENIX Collaboration], Phys. Rev. Lett. 88, 022301 (2002) doi:10.1103/PhysRevLett.88.022301 [nucl-ex/0109003].
[5] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 91, 172302 (2003) doi:10.1103/PhysRevLett.91.172302 [nucl-ex/0305015].
[6] M. M. Aggarwal et al. [WA98 Collaboration], Phys. Rev. Lett. 85, 3595 (2000) doi:10.1103/PhysRevLett.85.3595 [nucl-ex/0006008].
[7] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 104, 132301 (2010) doi:10.1103/PhysRevLett.104.132301 [arXiv:0804.4168 [nucl-ex]].
[8] J. Adam et al. [ALICE Collaboration], Phys. Lett. B 754, 235 (2016) doi:10.1016/j.physletb.2016.01.020 [arXiv:1509.07321 [nucl-ex]].
[9] R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003) doi:10.1103/PhysRevLett.90.202303 [nucl-th/0301087].
[10] H. Song and U. W. Heinz, Phys. Rev. C 77, 064901 (2008) doi:10.1103/PhysRevC.77.064901 [arXiv:0712.3715 [nucl-th]].
[11] M. Luzum and P. Romatschke, Phys. Rev. C 78, 034915 (2008) doi:10.1103/PhysRevC.78.034915, 10.1103/PhysRevC.79.039903 [arXiv:0804.4015 [nucl-th]].
[12] H. Song, S. A. Bass, U. Heinz, T. Hirano and C. Shen, Phys. Rev. Lett. 106, 192301 (2011) doi:10.1103/PhysRevLett.106.192301, 10.1103/PhysRevLett.109.139904 [arXiv:1011.2783 [nucl-th]].
[13] E. Annala, T. Gorda, A. Kurkela, J. Ntil and A. Vuorinen, [arXiv:1903.09121 [astro-ph.HE]], and references there-in.
[14] A. Dainese et al., CERN Yellow Rep., no. 3, 635 (2017) doi:10.23731/CYRM-2017-003.635 [arXiv:1605.01389 [hep-ph]].
[15] N. Armesto, A. Dainese, D. d’Enterria, S. Masiocchi, C. Roland, C. A. Salgado, M. van Leeuwen and U. A. Wiedemann, Nucl. Phys. A 956, 854 (2016) doi:10.1016/j.nuclphysa.2016.02.051 [arXiv:1601.02963 [hep-ph]].
[16] N. Armesto, A. Dainese, D. d’Enterria, S. Masiocchi, C. Roland, C. A. Salgado, M. van Leeuwen and U. A. Wiedemann, Nucl. Phys. A 931, 1163 (2014) doi:10.1016/j.nuclphysa.2014.09.067 [arXiv:1407.7640 [nucl-ex]].
[17] B. Svetitsky, Phys. Rev. D 37, 2484 (1988). doi:10.1103/PhysRevD.37.2484.
[18] M. G. Mustafa, D. Pal, D. K. Srivastava and M. Thoma, Phys. Lett. B 428, 294 (1998) doi:10.1016/S0370-2693(98)00429-8, 10.1016/S0370-2693(98)01134-4 [nucl-th/9711059].
[19] M. Golam Mustafa, D. Pal and D. Kumar Srivastava, Phys. Rev. C 57, 889 (1998) doi:10.1103/PhysRevC.57.889 [nucl-th/9706001].
[20] H. van Hees and R. Rapp, Phys. Rev. C 71, 034907 (2005) doi:10.1103/PhysRevC.71.034907 [nucl-th/0412155].
[21] G. D. Moore and D. Teaney, Phys. Rev. C 71, 064904 (2005) doi:10.1103/PhysRevC.71.064904 [hep-ph/0412346].
[22] H. van Hees, V. Greco and R. Rapp, Phys. Rev. C 73 (2006) 034913 doi:10.1103/PhysRevC.73.034913 [nucl-th/0508055].
[23] S. Peigne and A. Peshier, Phys. Rev. D 77 (2008) 114017 doi:10.1103/PhysRevD.77.114017 [arXiv:0802.4364 [hep-ph]].
[24] P. B. Gossiaux and J. Aichelin, Phys. Rev. C 78, 014904 (2008) doi:10.1103/PhysRevC.78.014904 [arXiv:0802.2525 [hep-ph]].
[25] P. B. Gossiaux, R. Bierkandt and J. Aichelin, Phys. Rev. C 79, 044906 (2009) doi:10.1103/PhysRevC.79.044906 [arXiv:0901.0946 [hep-ph]].
[26] M. He, R. J. Fries and R. Rapp, Phys. Rev. C 86, 014903 (2012) doi:10.1103/PhysRevC.86.014903 [arXiv:1106.6006 [nucl-th]].
[27] S. Cao and S. A. Bass, Phys. Rev. C 84, 064902 (2011) doi:10.1103/PhysRevC.84.064902 [arXiv:1108.5101 [nucl-th]].
[28] R. Abir, U. Jamil, M. G. Mustafa and D. K. Srivastava, Phys. Lett. B 715, 183 (2012) doi:10.1016/j.physletb.2012.07.044 [arXiv:1203.5221 [hep-ph]].
[29] A. Meistrenko, A. Peshier, J. Uphoff and C. Greiner, Nucl. Phys. A 901, 51 (2013) doi:10.1016/j.nuclphysa.2013.02.012 [arXiv:1204.2397 [hep-ph]].
[30] W. M. Alberico, A. Beraudo, A. De Pace, A. Molinari, M. Monteno, M. Nardi, F. Prino and M. Sitta, Eur. Phys. J.
[69] A. M. Sirunyan et al. [CMS Collaboration], Phys. Lett. B 782, 474 (2018) doi:10.1016/j.physletb.2018.05.074 [arXiv:1708.04962 [nucl-ex]].

[70] M. Gluck, E. Reya and A. Vogt, Z. Phys. C 67, 433 (1995). doi:10.1007/BF01624586