OPEN HEAVY FLAVOR AT RHIC AND LHC IN A PARTONIC TRANSPORT MODEL*

Jan Uphoff[a], Oliver Fochler[a], Zhe Xu[b], Carsten Greiner[a]

[a]Institut für Theoretische Physik
Johann Wolfgang Goethe-Universität Frankfurt
Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany
[b]Physics Department, Tsinghua University, Beijing 100084, China

(Received December 12, 2011)

Heavy quarks are a unique probe to study the medium produced in ultra-relativistic heavy ion collisions. Within the partonic transport model *Boltzmann Approach to Multi-parton Scatterings* (BAMPS) the production, energy loss and elliptic flow of heavy quarks are investigated in $3+1$ dimensional simulations of the quark-gluon plasma evolution. With only binary interactions between heavy quarks and particles from the medium calculated within perturbative QCD, the results on elliptic flow and the nuclear modification factor are not compatible with experimental data from RHIC and LHC. However, if the binary cross section is multiplied with $K = 4$ both the elliptic flow and the nuclear modification factor are simultaneously described at RHIC and also LHC. Furthermore, preliminary results are presented that the implementation of radiative processes leads to a stronger suppression which agrees well with the measured nuclear modification factor at RHIC without the need of any K factor.

DOI:10.5506/APhysPolBSupp.5.555
PACS numbers: 25.75.–q, 25.75.Bh, 25.75.Cj, 12.38.Mh

1. Introduction

Several evidences [1] show that in ultra-relativistic heavy ion collisions a unique state of matter is produced. This medium consists only of deconfined quarks and gluons and is, therefore, called quark-gluon plasma. Since the plasma itself cannot be seen directly, its properties must be revealed by measuring particles produced after hadronization of the deconfined medium. Due to these indirect and complex measurements, many open questions about the properties of the produced medium remain.

* Presented at the Conference "Strangeness in Quark Matter 2011", Kraków, Poland, September 18–24, 2011.

Heavy quarks, that is, in this context, charm and bottom quarks, are a perfect probe to tackle many of the open questions. They are well calibrated in a sense that they are produced entirely in the early stage of the heavy ion collision due to their large mass [2] and are also tagged during hadronization due to flavor conservation. Charm (bottom) quarks hadronize to D (B) mesons, which are, however, difficult to measure. Therefore, at RHIC one measures electrons stemming from the meson decays, which can also reveal much information about heavy quarks. However, as a disadvantage it cannot be distinguished between electrons from charm and bottom quarks. Nevertheless, at LHC for the first time it is possible to reconstruct D mesons and, therefore, receive information only about charm quarks with — in principle — no bottom contribution.

The heavy flavor electron data from RHIC [3,4] and the heavy flavor electron, muon and D meson data from LHC [5,6] show that the suppression of heavy quarks is comparable to that of light quarks. From the theory perspective it was thought that radiative processes involving heavy quarks are suppressed due to the dead cone effect [7, 8], which would imply a smaller suppression for massive particles. Elliptic flow v_2 measurements of particles associated with open heavy flavor also show that heavy quarks interact strongly with the other particles of the medium. Whether these observations can be explained by collisional or radiative energy loss or other effects is currently in debate [9, 10].

The paper is organized as the following. After a short introduction to our model BAMPS, we compare in Sec. 3 the results on the elliptic flow and nuclear modification factor to experimental data from RHIC and LHC. How this picture is altered by introducing radiative collisions of heavy quarks in addition to binary interactions is shown in Sec. 4, followed by a short summary.

2. Partonic transport model BAMPS

For the simulation of the QGP we use the partonic transport model *Boltzmann Approach to Multi-parton Scatterings* (BAMPS) [11], which describes the full space-time evolution of the QGP by solving the Boltzmann equation for on-shell partons and pQCD interactions. The following processes are implemented for gluons (g) and heavy quarks (Q): $gg \to gg$, $gg \to ggg$, $ggg \to gg$, $gg \to Q\bar{Q}$, $Q\bar{Q} \to gg$, $gQ \to gQ$ and $g\bar{Q} \to g\bar{Q}$. Details of the model and the employed cross sections can be found in [2, 10, 11]. In Sec. 4 we will also discuss some preliminary results including the radiative process $gQ \to gQg$.

3. Elliptic flow and suppression of heavy quarks

The elliptic flow v_2 and the nuclear modification factor R_{AA} of heavy quarks are important observables. Figure 1 compares our results to the heavy flavor electron data from Ref. [4]. In BAMPS the hadronization of charm (bottom) quarks to D (B) mesons is carried out with Peterson fragmentation [10, 12] and their decay to electrons is performed by PYTHIA [13]. Since the binary pQCD cross sections are too small even with running coupling and improved Debye screening [10, 14], those cross sections have been multiplied by a factor $K = 4$ to be compatible with the data. Remarkably, both v_2 and R_{AA} of heavy quarks can be simultaneously described with $K = 4$. It has, of course, to be shown that currently missing contributions such as radiative processes can account for this additional factor. In Sec. 4, we will present a first attempt in this direction by considering the additional process $gQ \to gQg$.

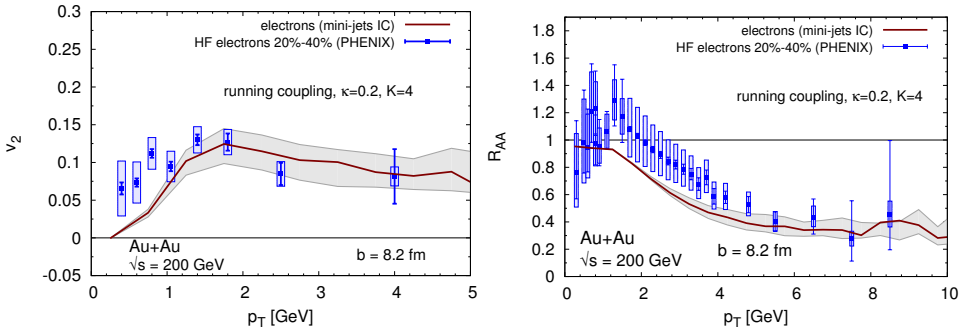

Fig. 1. Elliptic flow v_2 (left) and nuclear modification factor R_{AA} (right) of heavy flavor electrons for Au + Au collisions at RHIC with an impact parameter of $b = 8.2$ fm together with data [4]. The cross section of $gQ \to gQ$ is multiplied by the factor $K = 4$.

At LHC for the first time it is possible to reconstruct D mesons and, therefore, distinguish between charm and bottom quarks. In Fig. 2, our results on D mesons [15] is compared to data from ALICE. For the same parameters, that describe the RHIC data, a good agreement is also found at LHC. In addition, muon data from charm and bottom quarks at forward rapidity is also well described, as is shown in the left-hand side of Fig. 3.

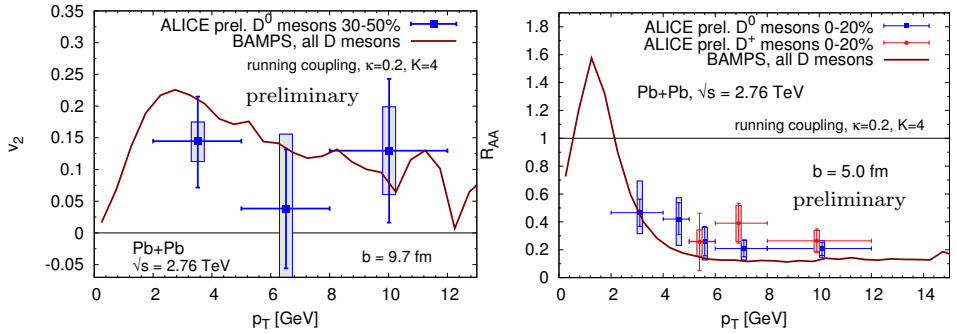

Fig. 2. Preliminary BAMPS results on elliptic flow v_2 (left) and nuclear modification factor R_{AA} (right) of D mesons at Pb + Pb collisions at LHC with an impact parameter b together with data [6, 16]. The cross section of $gQ \to gQ$ is multiplied with the factor $K = 4$.

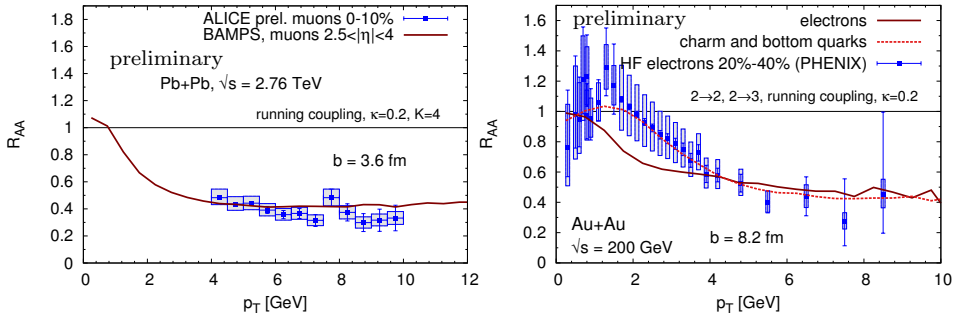

Fig. 3. Preliminary results obtained with BAMPS. Left: R_{AA} of muons at LHC with data [5]. For heavy quarks only binary collisions are switched on, which are multiplied with $K = 4$. Right: R_{AA} of heavy flavor electrons at RHIC (*cf.* r.h.s of Fig. 1). In addition to binary collisions, radiative processes are included. No K factor is employed.

4. Radiative processes

We calculated the Gunion–Bertsch [17] matrix element for heavy quark scattering with a light quark within QCD to be [18]

$$\left|\overline{\mathcal{M}}_{qQ\to qQg}\right|^2 = 12g^2\left|\overline{\mathcal{M}}_{qQ\to qQ}\right|^2\left[\frac{\boldsymbol{k}_\perp}{k_\perp^2+x^2M^2}+\frac{\boldsymbol{q}_\perp-\boldsymbol{k}_\perp}{(\boldsymbol{q}_\perp-\boldsymbol{k}_\perp)^2+x^2M^2}\right]^2 . \quad (1)$$

This is in accordance with the result obtained with scalar QCD [19] as well as the result in Feynman gauge [8] in the appropriate limit. Within the employed approximations (*cf.* Ref. [17]) the matrix element of the process $gQ \to gQg$ only differs by a color factor.

In the right panel of Fig. 3, the R_{AA} of heavy flavor electrons at RHIC is shown, which is obtained with both binary and radiative processes for heavy quarks without any artificial K factor.

The curve is in good agreement with the data, in particular for large transverse momentum p_{T}, where Peterson fragmentation works best. For smaller p_{T} coalescence might play an important role.

5. Summary

A full space-time simulation of the quark-gluon plasma phase in heavy ion collision is presented. The elliptic flow and nuclear modification factor of heavy quarks cannot be explained by binary collisions which are calculated with pQCD, even if a running coupling and improved Debye screening is employed. To be compatible with experimental data at RHIC and LHC a $K = 4$ factor is needed, which reflects that higher order contributions are currently missing in our model. First preliminary calculations with radiative contributions to heavy quark scatterings, however, look very promising since no artificial K factor is needed anymore to be compatible with R_{AA} data at RHIC. In the future, we will investigate the impact of the implementation of the radiative processes on heavy flavor phenomenology in more detail.

J.U. would like to thank P. Gossiaux and J. Aichelin for insightful discussions. The BAMPS simulations were performed at the Center for Scientific Computing of the Goethe University Frankfurt. This work was supported by the Helmholtz International Center for FAIR within the framework of the LOEWE program launched by the State of Hesse.

REFERENCES

[1] J. Adams *et al.* [STAR Collaboration], *Nucl. Phys.* **A757**, 102 (2005) [arXiv:nucl-ex/0501009]; K. Adcox *et al.* [PHENIX Collaboration], *Nucl. Phys.* **A757**, 184 (2005) [arXiv:nucl-ex/0410003].

[2] J. Uphoff, O. Fochler, Z. Xu, C. Greiner, *Phys. Rev.* **C82**, 044906 (2010) [arXiv:1003.4200 [hep-ph]].

[3] B.I. Abelev *et al.* [STAR Collaboration], *Phys. Rev. Lett.* **98**, 192301 (2007) [arXiv:nucl-ex/0607012]; A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **98**, 172301 (2007) [arXiv:nucl-ex/0611018].

[4] A. Adare *et al.* [PHENIX Collaboration], *Phys.Rev.* **C84**, 044905 (2011) [arXiv:1005.1627 [nucl-ex]].

[5] S. Masciocchi [ALICE Collaboration], *J. Phys. G* **38**, 124069 (2011) [arXiv:1109.6436 [nucl-ex]].

[6] A. Rossi [ALICE Collaboration], *J. Phys. G* **38**, 124139 (2011) [arXiv:1106.5931 [hep-ex]].

[7] Y.L. Dokshitzer, D.E. Kharzeev, *Phys. Lett.* **B519**, 199 (2001) [arXiv:hep-ph/0106202].

[8] R. Abir *et al.*, arXiv:1109.5539 [hep-ph].

[9] N. Armesto *et al.*, *Phys. Lett.* **B637**, 362 (2006) [arXiv:hep-ph/0511257]; H. van Hees, V. Greco, R. Rapp, *Phys. Rev.* **C73**, 034913 (2006) [arXiv:nucl-th/0508055]; G.D. Moore, D. Teaney, *Phys. Rev.* **C71**, 064904 (2005) [arXiv:hep-ph/0412346]; M.G. Mustafa, *Phys. Rev.* **C72**, 014905 (2005) [arXiv:hep-ph/0412402]; S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, *Nucl. Phys.* **A784**, 426 (2007) [arXiv:nucl-th/0512076]; A. Adil, I. Vitev, *Phys. Lett.* **B649**, 139 (2007) [arXiv:hep-ph/0611109]; S. Peigne, A. Peshier, *Phys. Rev.* **D77**, 114017 (2008) [arXiv:0802.4364 [hep-ph]]; P.B. Gossiaux, J. Aichelin, *Phys. Rev.* **C78**, 014904 (2008) [arXiv:0802.2525 [hep-ph]]; W. Alberico *et al.*, *Eur. Phys. J.* **C71**, 1666 (2011) [arXiv:1101.6008 [hep-ph]]; S. Cao, S.A. Bass, *Phys. Rev.* **C84**, 064902 (2011) [arXiv:1108.5101 [nucl-th]]; C. Young, B. Schenke, S. Jeon, C. Gale, arXiv:1111.0647 [nucl-th].

[10] J. Uphoff, O. Fochler, Z. Xu, C. Greiner, *Phys. Rev.* **C84**, 024908 (2011) [arXiv:1104.2295 [hep-ph]].

[11] Z. Xu, C. Greiner, *Phys. Rev.* **C71**, 064901 (2005) [arXiv:hep-ph/0406278v2]; *Phys. Rev.* **C76**, 024911 (2007) [arXiv:hep-ph/0703233].

[12] C. Peterson, D. Schlatter, I. Schmitt, P.M. Zerwas, *Phys. Rev.* **D27**, 105 (1983).

[13] T. Sjostrand, S. Mrenna, P.Z. Skands, *Comput. Phys. Commun.* **178**, 852 (2008) [arXiv:0710.3820 [hep-ph]].

[14] J. Uphoff, O. Fochler, Z. Xu, C. Greiner, *J. Phys.: Conf. Ser.* **230**, 012004 (2010) [arXiv:1004.4091 [hep-ph]]; *J. Phys.: Conf. Ser.* **270**, 012028 (2010) [arXiv:1008.1995 [hep-ph]]; *Nucl. Phys.* **A855**, 444 (2011) [arXiv:1011.6183 [hep-ph]]; J. Uphoff, *et al.*, *PoS* **BORMIO2011**, 032 (2011) [arXiv:1104.2437 [hep-ph]].

[15] O. Fochler, J. Uphoff, Z. Xu, C. Greiner, *J. Phys. G* **38**, 124152 (2011) [arXiv:1107.0130 [hep-ph]].

[16] C. Bianchin [ALICE Collaboration], *Acta Phys. Pol. B Proc. Suppl.* **5**, 335 (2012), this issue [arXiv:1111.6886 [hep-ex]].

[17] J. Gunion, G. Bertsch, *Phys. Rev.* **D25**, 746 (1982).

[18] J. Uphoff, O. Fochler, Z. Xu, C. Greiner, 2011, in preparation.

[19] P. Gossiaux, J. Aichelin, T. Gousset, V. Guiho, *J. Phys. G* **37**, 094019 (2010) [arXiv:1001.4166 [hep-ph]].