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Open heavy flavor in Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV within a transport model

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ABSTRACT

The space–time evolution of open heavy flavor is studied in Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV using the partonic transport model *Boltzmann Approach to MultiParton Scatterings* (BAMPS). An updated version of BAMPS is presented which allows interactions among all partons: gluons, light quarks and heavy quarks. Heavy quarks, in particular, interact with the rest of the medium via binary scatterings with a running coupling and a Debye screening which is matched by comparing to hard thermal loop calculations. The lack of radiative processes in the heavy flavor sector is accounted for by scaling the binary cross section with a phenomenological factor $K = 3.5$, which describes well the elliptic flow v_2 and nuclear modification factor R_{AA} at RHIC. Within this framework we calculate in a comprehensive study the v_2 and R_{AA} of all interesting open heavy flavor particles at the LHC: electrons, muons, D mesons, and non-prompt J/ψ from B mesons. We compare to experimental data, where it is already available, or make predictions. To do this accurately next-to-leading order initial heavy quark distributions are employed which agree well with proton–proton data of heavy flavor at $\sqrt{s} = 7$ TeV.

1. Introduction

In ultra-relativistic heavy ion collisions at the BNL RHIC and CERN LHC the energy deposited in the collision zone is large enough to produce a medium that consists of deconfined quarks and gluons [1–3]. This state of matter, the quark gluon plasma (QGP), has remarkable properties such as collective behavior, a small viscosity to entropy ratio, and a large density that leads to quenching of jets.

Open heavy flavor particles such as D and B mesons, which consists of one heavy quark and one light quark, are an exciting probe to study the QGP. Their heavy constituents, namely charm and bottom quarks, are created at a very early stage of the heavy ion collision due to their large mass [4]. Consequently, they travel for a long time through the QGP, collide with other medium particles, lose energy, and participate in the collective behavior.

Measurements of heavy flavor electrons from the decay of D and B mesons at RHIC [5–7] indicate that the elliptic flow v_2 and nuclear modification factor R_{AA} of open heavy flavor is on the same order as for light particles. This is in contrast to the expectations drawn from the dead cone effect [8,9], that gluon radiation off heavy quarks is suppressed at small angles compared to light quarks. The reason for the rather large elliptic flow and suppression of heavy flavor is currently under investigation [10–22].

At the LHC, for the first time, it is possible to distinguish between charm and bottom quarks. In addition to looking at heavy flavor electrons or muons from both D and B mesons, ALICE can reconstruct D mesons directly [23]. In addition, CMS presented data for non-prompt J/ψ [24] which stem from the decay of B mesons.

In the present Letter we present our calculations of the elliptic flow and nuclear modification factor of D mesons and non-prompt J/ψ, obtained with the transport model *Boltzmann Approach to MultiParton Scatterings* (BAMPS). In addition, we show results of heavy flavor muons at forward rapidity as well as electrons at mid-rapidity and compare them to experimental data.

2. Open heavy flavor in BAMPS

In this section we briefly review the features of our model, the parton cascade *Boltzmann Approach to MultiParton Scatterings* (BAMPS). More details concerning the model itself and the implementation of heavy flavor can be found in Ref. [25,26] and [4,21], respectively.

BAMPS is a 3 + 1 dimensional partonic transport model that solves the Boltzmann equation

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$$\left(\frac{\partial}{\partial t} + \frac{\mathbf{p}_i}{E_i}\frac{\partial}{\partial \mathbf{r}}\right) f_i(\mathbf{r}, \mathbf{p}_i, t) = \mathcal{C}_i^{2\to 2} + \mathcal{C}_i^{2\leftrightarrow 3} + \cdots, \tag{1}$$

for on-shell partons. Implemented processes on the light parton sector are all $2 \to 2$ and $2 \leftrightarrow 3$ processes. In contrast to previous publications [21,27–29] where we only took gluons (g) and heavy quarks (Q) into account, in the present calculation light quarks (q) are explicitly included. All cross sections are calculated in leading order pQCD. Light partons interact among each other via binary collisions and radiative $2 \leftrightarrow 3$ processes, which are taken in the Gunion–Bertsch limit [30].

For heavy quarks, currently only the elastic collisions

$$\begin{aligned} gg &\leftrightarrow Q\bar{Q} \\ q\bar{q} &\leftrightarrow Q\bar{Q} \\ gQ &\to gQ \\ qQ &\to qQ \end{aligned} \tag{2}$$

are implemented. The inclusion of radiative processes is underway and planned for the near future.

In this Letter we focus on the heavy flavor sector. For BAMPS results of light partons we refer to Refs. [25,26,29,31–36].

The cross sections for the processes from (2) are calculated in leading order pQCD for a finite heavy quark mass [37]. Since the matrix elements of the t channel of those elastic heavy quark scattering with a light parton are divergent, they are screened with a screening mass, which is determined from comparison to hard thermal loop (HTL) calculations. By comparing the energy loss of a heavy quark in a static medium calculated within HTL and the same quantity calculated from the leading order pQCD cross section with a screening mass $\mu^2 = \kappa m_D^2$, one can obtain the prefactor κ analytically to be [19,21,38]

$$\kappa = \frac{1}{2e} \approx 0.184 \approx 0.2. \tag{3}$$

The Debye mass m_D^2 is calculated in BAMPS from the non-equilibrium distribution functions f of gluons and light quarks via [25]

$$m_D^2 = \pi \alpha_s \nu_g \int \frac{d^3p}{(2\pi)^3} \frac{1}{p}(N_c f_g + n_f f_q), \tag{4}$$

where $N_c = 3$ denotes the number of colors, $\nu_g = 16$ is the gluon degeneracy, and $n_f = 3$ the number of active light flavors. As a note, in equilibrium and with Boltzmann statistics the Debye mass is given by $m_{D,\mathrm{eq}}^2 = \frac{8\alpha_s}{\pi}(N_c + n_f)T^2$. The Debye mass prefactor κ was determined for an arbitrary number of light quark degrees of freedom n_f and is thus easily applied to the t channel of heavy quark interactions with light quarks.

Furthermore, instead of just assuming a constant value for the coupling α_s we employ the running coupling for all heavy flavor processes [19,21,38,39],

$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0} \begin{cases} L_-^{-1}, & Q^2 < 0 \\ \frac{1}{2} - \pi^{-1}\arctan(L_+/\pi), & Q^2 > 0 \end{cases} \tag{5}$$

with $\beta_0 = 11 - \frac{2}{3}n_f$ and $L_\pm = \ln(\pm Q^2/\Lambda^2)$ with $\Lambda = 200$ MeV. For consistency a running coupling is also used in calculating the Debye mass from Eq. (4).

After the energy density in the surrounding of a heavy quark in BAMPS has dropped below 0.6 GeV/fm^3 it is fragmented to a D or B meson. This is done according to the Peterson fragmentation function [40]

$$D_{H/Q}(z) = \frac{N}{z(1 - \frac{1}{z} - \frac{\epsilon_Q}{1-z})^2}. \tag{6}$$

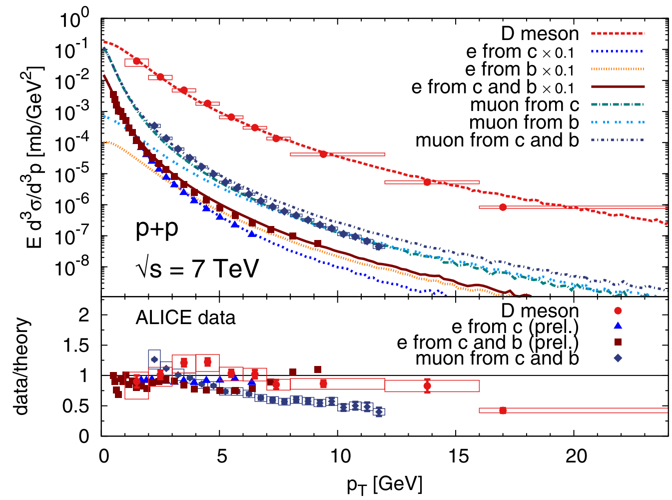

Fig. 1. Differential invariant cross section of D mesons with $|y| < 0.5$ and heavy flavor electrons with $|y| < 0.8$ at mid-rapidity and muons at forward rapidity $2.5 < y < 4$ as a function of transverse momentum for proton–proton collisions with $\sqrt{s} = 7$ TeV simulated with MC@NLO. For comparison experimental data [45–47] with the same kinematic cuts is also shown. In the upper plot the electron curves and the corresponding data points have been scaled with the factor 0.1 to distinguish them from the muon curves. Since the data of electrons is preliminary, we do not have access to the errors and plot those data points without any errors as obtained from Ref. [46].

N is a normalization constant, $z = |\vec{p}_H|/|\vec{p}_Q|$ the ratio of the meson and quark momenta, and $\epsilon_Q = 0.05$ (0.005) for charm (bottom) quarks. The D mesons can then directly be compared to the experimental data. To yield non-prompt J/ψ we carry out the decay of B mesons with PYTHIA [41,42] by switching on the relevant decay channels. PYTHIA is also used to perform the decay of D and B mesons to electrons and muons which can then be compared to experimental data.

Especially for the LHC, where charm and bottom can be separated, it is important to have the correct reference for the initial heavy quark distribution. To generate the initial heavy quark spectrum for the BAMPS simulation of the heavy ion collision we employ the next-to-leading order (NLO) event generator MC@NLO [43,44]. The factorization and renormalization scales, μ_F and μ_R, respectively, are in principle arbitrary when considering all orders of the cross section. However, for the leading order cross section uncertainties due to neglecting higher order terms can be reduced if the two scales are of the order of the relevant scale $\sqrt{p_T^2 + M^2}$, p_T^2 being the transverse momentum and M the mass of the produced heavy quarks. The exact value of the scale is fixed by giving a good agreement with the experimental data which results in $\mu_F = \mu_R = 1\sqrt{p_T^2 + M_c^2}$ for charm ($M_c = 1.3$ GeV) and $\mu_F = \mu_R = 0.4\sqrt{p_T^2 + M_b^2}$ for bottom quarks ($M_b = 4.6$ GeV).

In Fig. 1 the invariant differential cross sections of D mesons, heavy flavor electrons and muons are compared to experimental data from ALICE at $\sqrt{s} = 7$ TeV. The D mesons and heavy flavor electrons at mid-rapidity are well described by MC@NLO. At forward rapidity, however, the slope of the muons at larger p_T is slightly different. Such a disagreement has also been observed by CMS in a more detailed study of inclusive bottom jets in Ref. [48] by comparing MC@NLO to data for larger p_T and various rapidities. Nevertheless, we checked that the muon R_{AA} is not very sensitive to the exact slope in this p_T range.

To obtain the initial heavy quark distribution as an input for BAMPS we run MC@NLO with the same parameters for a center