Heavy quark transport at RHIC and LHC

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Abstract. We calculate the heavy quark evolution in heavy ion collisions and show results for the elliptic flow $v_2$ as well as the nuclear modification factor $R_{AA}$ at RHIC and LHC energies. For the calculation we implement a Langevin approach for the transport of heavy quarks in the UrQMD (hydrodynamics + Boltzmann) hybrid model. As drag and diffusion coefficients we use a Resonance approach for elastic heavy-quark scattering and assume a decoupling temperature of the charm quarks from the hot medium of 130 MeV. At RHIC energies we use a coalescence approach at the decoupling temperature for the hadronization of the heavy quarks to $D$-mesons and $B$-mesons and a sub-following decay to heavy-flavor electrons using PYTHIA. At LHC we use an additional fragmentation mechanism to account for the higher transverse momenta reached at higher collision energies.

1. Introduction

Heavy quarks are an ideal probe for the QGP. They are produced in the primordial hard collisions of the nuclear reaction and therefore probe the created medium during its entire evolution process. When the system cools down they hadronize, and their decay products can finally be detected. Therefore, heavy-quark observables provide new insights into the interaction processes within the hot and dense medium. Two of the most interesting observables are the elliptic flow, $v_2$, and the nuclear modification factor, $R_{AA}$, of open-heavy-flavor mesons and their decay products. The measured large elliptic flow, $v_2$, of open-heavy-flavor mesons and the electrons from heavy-flavor decays underline that heavy quarks take part in the collective motion of the bulk medium, consisting of light quarks and gluons. The nuclear modification factor shows a large suppression of the open-heavy-flavor particles’ spectra at high transverse momenta ($p_T$) compared to the findings in pp collisions. This also supports a high degree of thermalization of the heavy quarks with the bulk medium.

In this letter we explore the medium modification of heavy-flavor $p_T$ spectra, using a hybrid model, consisting of the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model \cite{1,2} and a full (3+1)-dimensional ideal hydrodynamical model \cite{3,4} to simulate the bulk medium. The heavy-quark propagation in the medium is described by a relativistic Langevin approach \cite{5}. Similar studies have recently been performed in a thermal fireball model with a combined
coalescence-fragmentation approach [6, 7, 8, 9, 10, 11, 5], in an ideal hydrodynamics model with a lattice-QCD EoS [12, 13], in a model from Kolb and Heinz [14], in the BAMPS model [15, 16], the MARTINI model [17] as well as in further studies and model comparisons [18, 19, 20, 21, 22].

2. Description of the model

The UrQMD hybrid model has been developed to combine the advantages of transport theory and (ideal) fluid dynamics [23]. It uses initial conditions, generated by the UrQMD model [24, 25], for a full (3+1) dimensional ideal fluid dynamical evolution, including the explicit propagation of the baryon current. After a Cooper-Frye transition back to the transport description, the freeze out of the system is treated dynamically within the UrQMD approach. The hybrid model has been successfully applied to describe particle yields and transverse dynamics from AGS to LHC energies [23, 26, 27, 28, 29] and is therefore a reliable model for the flowing background medium.

The diffusion of a “heavy particles” in a medium consisting of “light particles” can be described with help of a Fokker-Planck equation [31, 32, 18, 31, 32, 33, 37, 6, 35, 36] as an approximation of the collision term of the corresponding Boltzmann equation. It can be mapped into an equivalent stochastic Langevin equation, suitable for numerical simulations.

The drag and diffusion coefficients for the heavy-quark propagation within this framework are taken from a Resonance approach [33], where the existence of D-mesons and B-mesons in the QGP phase is assumed, as well as a $T$-Matrix approach [6] in which quark-antiquark potentials are used for the calculation of the coefficients in the QGP.

The initial production of charm quarks in our approach is based on a Glauber approach. For the realization of the initial collision dynamics we use the UrQMD model. We perform a first UrQMD run excluding interactions between the colliding nuclei and save the nucleon-nucleon collision space-time coordinates. These coordinates are used in a second, full UrQMD run as possible production coordinates for the charm quarks.

As momentum distribution for the initially produced charm quarks at $\sqrt{s_{NN}} = 200$ GeV we use

$$\frac{dN}{2\pi p_T dp_T} = \frac{C \cdot (1 + A_1 \cdot p_T^2)^2}{(1 + A_2 \cdot p_T^2)^A_3},$$

with $A_1 = 2.0/\text{GeV}^2$, $A_2 = 0.1471/\text{GeV}^2$ and $A_3 = 21.0$ and for bottom quarks

$$\frac{dN}{2\pi p_T dp_T} = \frac{C}{(1 + A_1 \cdot p_T^2)^A_2},$$

with $A_1 = 0.0173/\text{GeV}^2$ and $A_2 = 5.04$. These distributions are taken from [37, 6]. The $p_T$ distribution for charm quarks at 2.76 TeV is obtained from a fit to PYTHIA calculations.

$$\frac{dN}{2\pi p_T dp_T} = \frac{C}{(1 + A_1 \cdot p_T^2)^A_2},$$

with the coefficients $A_1 = 0.379/\text{GeV}^2$ and $A_2 = 5.881$. $C$ is an arbitrary normalization constant with the unit 1/GeV$^2$.

Starting with these distributions as initial conditions we propagate the heavy quarks at each hydro-timestep. We use the UrQMD/hydro’s cell velocities, the cell temperature, the size of the time-step, and the $\gamma$-factor for the calculation of the momentum transfer, propagating all quarks independently. Our approach provides us only with the heavy-quark distributions. Since heavy quarks cannot be measured directly in experiments we include a hadronization mechanism for D-mesons and B-mesons, via the use of a quark-coalescence mechanism. To implement this coalescence we perform our Langevin calculation until the decoupling temperature is reached. Subsequently we add the momenta of light quarks to those of the heavy quarks.
3. Results
First we performed our calculations in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in a centrality range of 20%-40%. To compare our results to the single-electron spectra measured by PHENIX we use PYTHIA for the decay of the heavy quarks to heavy-flavor electrons and apply a rapidity cut of $|y| < 0.35$. Fig. 1 (left) shows our results for the elliptic flow $v_2$. For a decoupling temperature of 130 MeV we obtain a reasonable agreement with the experimental data except for low $p_T$ bins. Here a depletion effect can be seen. In case of a developed elliptic flow particles in $x$ direction have a higher velocity than in $y$ direction. Consequently there is a depletion of particles with high $v_x$ in the low $p_T$ region and thus a smaller elliptic flow. This effect is more important for heavier particles and a larger radial flow [38, 39].

In Fig. 1 (right) the nuclear modification factor $R_{AA}$ for the heavy-flavor decay electrons is depicted.

![Figure 1](image1)

Figure 1. (Color online) Elliptic flow $v_2$ (left) and nuclear modification factor $R_{AA}$ (right) of electrons from heavy quark decays in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using a coalescence mechanism. We use a rapidity cut of $|y| < 0.35$. For a decoupling temperature of 130 MeV we get a reasonable agreement to data [40]. Also here we obtain a good agreement with the data, especially in case of using the T-Matrix coefficients or a low decoupling temperature.

Now we performed the same calculations, but in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in a centrality range of 30%-50%. The analysis is done in a rapidity cut of $|y| < 0.35$ in line with the ALICE data. Here we made use of the coalescence mechanism with a decoupling temperature of 130 MeV only since we achieved the best results using this configuration at RHIC energies. In the ALICE experiment D-mesons are measured. Therefore we do not need to perform the decay to electrons this time. Fig. 2 (left) depicts our results for the elliptic flow compared to ALICE measurements. Additionally, apart from the calculation using the coalescence mechanism, also a calculation using a fragmentation mechanism is shown, since fragmentation might get more important at higher $p_T$ bins, as measured at LHC. As fragmentation mechanism we used the Peterson fragmentation [42].

$$D_Q^H(z) = \frac{N}{z[1 - ((1/z) - \epsilon_Q/(1-z))]}.$$  

Here $N$ is a normalization constant, $z$ the relative-momentum fraction obtained in the fragmentation of the charm quarks and $\epsilon_Q = 0.05$. Both $v_2$ calculations are in agreement with the ALICE data set. Using the fragmentation function a sharper rise of the elliptic flow at low $p_T$ is reached, while at medium $p_T$ the flow using the coalescence approach is stronger. At high $p_T$ both hadronization mechanisms lead to similar results.
Figure 2. (Color online) Left: Flow $v_2$ of D-mesons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to data from the ALICE experiment. (Talk by Z. Conesa del Valle at QM 2012, data not published yet.) A rapidity cut of $|y| < 0.35$ is employed. Right: $R_{AA}$ of D-mesons in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV compared to experimental data from ALICE [41]. A rapidity cut of $|y| < 0.35$ is employed.

A complementary view on the drag and diffusion coefficients is provided by the nuclear suppression factor $R_{AA}$. Figure 2 (right) shows the calculated nuclear modification factor $R_{AA}$ of D-mesons compared to the experimental ALICE measurements [41]. In line with the experimental data the simulation is done for a more central bin of $\sigma/\sigma_0 = 0\%-20\%$. In case of the coalescence approach we find a maximum of the $R_{AA}$ at about 2 GeV followed by a sharp decline to an $R_{AA}$ of about 0.2 at high $p_T$. The “peak-like” structure of the $R_{AA}$ is due to the coalescence of low $p_T$ heavy quarks that are pushed to higher $p_T$ due to the transverse momentum of the light quarks. The fragmentation approach leads to a different result at low $p_T$. A very sharp $R_{AA}$ drop-off from low to high $p_T$ is seen. At high $p_T$ the two approaches nearly converge. Concerning the difference of the results using the fragmentation and coalescence mechanism new $v_2$ and $R_{AA}$ measurements, especially at low $p_T$, would be very helpful to draw conclusions on the hadronization mechanism at LHC.

To summarize, we presented in this letter our results on the medium modification of heavy quarks at RHIC and LHC energies using the nuclear modification factor $R_{AA}$ and the elliptic flow $v_2$ as observables. At RHIC energies we compared different sets for drag and diffusion coefficients and obtained the best agreement to experimental measurements if using a Resonance model with a decoupling temperature of 130 MeV. At LHC we compared a coalescence approach and a fragmentation approach as hadronization mechanism using the Resonance model at a decoupling temperature of 130 MeV. Both approaches describe the elliptic flow $v_2$ in pretty good agreement with the experimental data while for the $R_{AA}$ a major disagreement between our models at low $p_T$ can be seen that needs to be resolved by new measurements.

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