

# Charm quark transport in Pb+Pb reactions at $\sqrt{s_{NN}} = 2.76$ TeV from a (3+1) dimensional hybrid approach

Thomas Lang<sup>1,2</sup>, Hendrik van Hees<sup>1,2</sup>, Jan Steinheimer<sup>3</sup>, and Marcus Bleicher<sup>1,2</sup>

<sup>1</sup> *Frankfurt Institute for Advanced Studies (FIAS),  
Ruth-Moufang-Str. 1, 60438 Frankfurt am Main, Germany*

<sup>2</sup> *Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität,  
Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany and*

<sup>3</sup> *Lawrence Berkeley National Laboratory,  
1 Cyclotron Road, Berkeley, CA 94720, USA  
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## Abstract

We implement a Langevin approach for the transport of charm quarks in the UrQMD (hydrodynamics + Boltzmann) hybrid model. Due to the inclusion of event-by-event fluctuations and a full (3+1) dimensional hydrodynamic evolution, this approach provides a more realistic model for the evolution of the matter produced in heavy ion collisions as compared to simple homogeneous fireball expansions usually employed. 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. A coalescence approach at the decoupling temperature for the hadronization of the charm quarks to D-mesons is also included. We present calculations of the nuclear modification factor  $R_{AA}$  as well as the elliptic flow  $v_2$  in Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The comparison to ALICE measurements shows a very good agreement with our calculations.

## I. INTRODUCTION

One major goal of high-energy heavy-ion physics is to recreate the phase of deconfined matter, where quarks and gluons move quasi free (the Quark Gluon Plasma, QGP) as it might have existed a few microseconds after the Big Bang. Various experimental facilities have been built to explore the properties of this QGP experimentally, while on the theory side a multitude of (potential) signatures and properties of the QGP have been predicted [1–3].

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 like “non-photonic” single electrons. The measured large elliptic flow,  $v_2$ , of open-heavy-flavor mesons and the “non-photonic single electrons or muons” from their decay 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. A quantitative analysis of the degree of thermalization of heavy-quark degrees of freedom in terms of the underlying microscopic scattering processes thus leads to an understanding of the mechanisms underlying the large coupling strength of the QGP and the corresponding transport properties.

In this letter, we explore the medium modification of heavy-flavor transverse momentum ( $p_T$ ) spectra. In contrast to previous studies, see e.g. [4–22], we perform the simulation based on a hybrid model, consisting of the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) and a (3+1) dimensional hydrodynamical model to simulate the bulk medium. This approach includes event-by-event initial-state fluctuations and a full (3+1)-dimensional hydrodynamics. The heavy-quark propagation in the medium is described within a relativistic Langevin approach.

## II. 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, 26–29] and is therefore a reliable model for the flowing background medium.

The equation of state we use for our calculations includes quark and gluonic degrees of freedom coupled to a hadronic parity-doublet model [30]. It includes a smooth crossover at low baryon densities between an interacting hadronic system and a quark gluon plasma. The thermal properties of the EoS are in agreement with lattice QCD results at vanishing baryon density, and the EoS therefore is well suited for our investigation at LHC energies.

The diffusion of a “heavy particle” in a medium consisting of “light particles” can be described with help of a Fokker-Planck equation [9, 17, 21, 31–35] 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. In the relativistic realm such a Langevin process

reads

$$\begin{aligned} dx_j &= \frac{p_j}{E} dt, \\ dp_j &= -\Gamma p_j dt + \sqrt{dt} C_{jk} \rho_k. \end{aligned} \quad (1)$$

Here  $E = \sqrt{m^2 + \mathbf{p}^2}$ , and  $\Gamma$  is the drag or friction coefficient. The covariance matrix,  $C_{jk}$ , of the fluctuating force is related with the diffusion coefficients. Both coefficients are dependent on  $(t, \mathbf{x}, \mathbf{p})$  and are defined in the (local) rest frame of the fluid. The  $\rho_k$  are Gaussian-normal distributed random variables, i.e., its distribution function reads

$$P(\boldsymbol{\rho}) = \left(\frac{1}{2\pi}\right)^{3/2} \exp\left(-\frac{\boldsymbol{\rho}^2}{2}\right). \quad (2)$$

The fluctuating force thus obeys

$$\langle F_j^{(\text{fl})}(t) \rangle = 0, \quad \langle F_j^{(\text{fl})}(t) F_k^{(\text{fl})}(t') \rangle = C_{jl} C_{kl} \delta(t - t'). \quad (3)$$

It is important to note that with these specifications the random process is not yet uniquely determined since one has to specify, at which argument of the momentum the covariance matrix  $C_{jk}$  has to be taken to define the stochastic time integral in (1). Thus, we set

$$C_{jk} = C_{jk}(t, \mathbf{x}, \mathbf{p} + \xi d\mathbf{p}). \quad (4)$$

For  $\xi = 0$ ,  $\xi = 1/2$ , and  $\xi = 1$  the corresponding Langevin processes are called the pre-point Ito, the mid-point Stratonovic-Fisk, and the post-point Ito (or Hänggi-Klimontovich) realization.

The drag and diffusion coefficients for the heavy-quark propagation within this framework are taken from a resonance approach [33].

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.

The momentum distribution for the initially produced charm quarks serves as the starting point of our calculations. The  $p_T$  distribution is obtained from a fit to PYTHIA calculations. The fitting function for charm quarks with 2.76 TeV is:

$$\frac{dN}{d^2p_T} = A_1 \frac{1}{(1 + A_1 \cdot (p_T^2)^2)^{A_3}} \quad (5)$$

with the coefficients  $A_1 = 0.136$ ,  $A_2 = 2.055$  and  $A_3 = 2.862$ . Starting with this distribution as initial condition, at each UrQMD/hydro time-step we perform an Ito-postpoint time-step, as described in Sec. I. We use the UrQMD/hydro's cell velocities, 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 charm-quark distribution. Since charm quarks cannot be measured directly in experiments we include a hadronization mechanism for D-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 charm quarks. On average the velocity of light quarks can be approximated by the flow-velocity vector of the local hydro cell. The mass of the light quarks is assumed to be 369 MeV so that the D-Meson mass becomes 1.869 GeV when adding the masses of the light quarks and the charm quarks (1.5 GeV).

### III. ELLIPTIC FLOW $v_2$ AND NUCLEAR MODIFICATION FACTOR $R_{AA}$

We have performed our calculations 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.

Fig. 1 depicts our results for the elliptic flow compared to ALICE measurements. The D-Meson

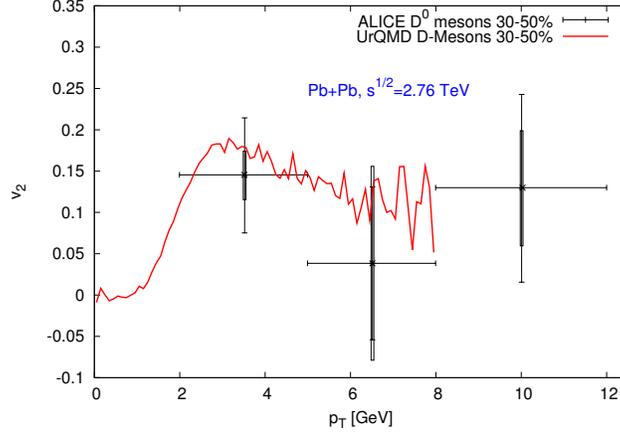


FIG. 1. Flow  $v_2$  of D-Mesons in Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV compared to data from the ALICE experiment [36]. A rapidity cut of  $|y| < 0.35$  is employed.

$v_2$  exhibits a strong increase and reaches a maximum at about  $p_T = 3$  GeV with  $v_2 \sim 15\%$ . Considering the error bars the agreement between the measurements and our calculation is quite satisfactory.

A complementary view on the drag and diffusion coefficients is provided by the nuclear suppression factor  $R_{AA}$ . Figure 2 shows the calculated nuclear modification factor  $R_{AA}$  of D-Mesons at LHC. Here we compare to two data sets available, for  $D^0$  and  $D^+$  mesons. In line with the experimental data the simulation is done for a more central bin of  $\sigma/\sigma_{to} = 0\%-20\%$ .

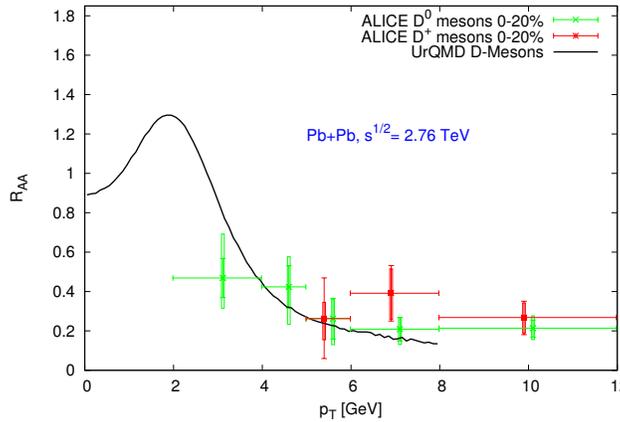


FIG. 2.  $R_{AA}$  of D-Mesons in Pb Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV compared to preliminary data from ALICE [37]. A rapidity cut of  $|y| < 0.35$  is employed.

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  $p_T$ . Especially at low  $p_T$  new measurements would be helpful to conduct a more detailed comparison to the model prediction.

In summary we can conclude that our description of the medium modification of charm quarks at LHC energies for both the elliptic flow  $v_2$  and the nuclear modification factor  $R_{AA}$  is compatible with the experimental measurements of ALICE.

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