# Heavy Quark Dynamics toward thermalization: $R_{\rm AA}, v_1, v_2, v_3$

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**Abstract.** We describe the propagation of Heavy quarks (HQs) in the quark-gluon plasma (QGP) within a relativistic Boltzmann transport (RBT) approach. The interaction between heavy quarks and light quarks is described within quasi-particle approach which is able to catch the main features of non-perturbative interaction as the increasing of the interaction in the region of low temperature near $T_C$. In our calculations the hadronization of charm quarks in $D$ mesons is described by mean of an hybrid model of coalescence plus fragmentation. We show that the coalescence play a key role to get a good description of the experimental data for the nuclear suppression factor $R_{\rm AA}$ and the elliptic flow $v_2(p_T)$ at both RHIC and LHC energies. Moreover, we show some recent results on the direct flow $v_1$ and triangular flow $v_3$ of D meson.

## 1 Introduction

Charm and bottom quarks are produced at the early stages of a Heavy Ion Collision (HIC) and due to their large masses they are expected to thermalize slower in the QGP. Therefore they represent an ideal probe to study the whole evolution of the QGP. Furthermore, because they are produced out-of-equilibrium they are expected to conserve memory of the history of the plasma evolution. The nuclear suppression factor $R_{\rm AA}$, which is the ratio between the spectra of heavy flavor hadrons measured in nucleus-nucleus, and the elliptic flow $v_2(p_T)$ which is a measure of the anisotropies in momentum space are the two key observables in heavy flavor sector. Experimental measurements at both RHIC and LHC energies have shown a small value of their $R_{\rm AA}$ and the large values of $v_2(p_T)$ which are almost comparable to those of light hadrons. Several theoretical efforts within different models have been made to study and describe simultaneously the small $R_{\rm AA}$ and large $v_2$ measured in experiments [1–6] Recently this analysis has been extended to the study of different harmonics showing that also a direct flow $v_1$ and triangular flow $v_3(p_T)$ of D meson is non vanishing [7, 8].

## 2 Transport equation for charm quarks in the QGP

We the describe the evolution of the charm quark by solving the RBT equations. In our model the charm quarks scatter in a bulk medium of quarks and gluons as described by the following set of eq.s

$$\begin{aligned} p^{\mu}\partial_{\mu} f_Q(x,p) &= C[f_q, f_g, f_Q](x,p) \\ p^{\mu}_k \partial_{\mu} f_k(x,p) &= C[f_q, f_g](x_q,p_q) \qquad k = q, g \end{aligned}$$

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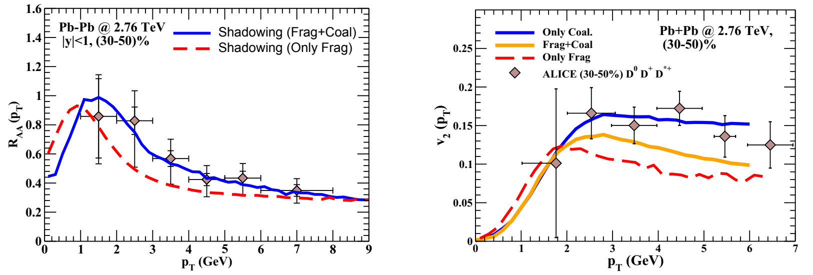


**Figure 1.** Left and middle panel: D meson $R_{\rm AA}$ and $v_2$ respectively in $Pb + Pb$ collisions at $\sqrt{s_{\rm NN}} = 2.76\, TeV$ and centrality $30 - 50\%$ compared to ALICE data. Experimental data has been taken from Ref.s [17, 18].

$f_k(x, p)$ indicates the on-shell phase space one-body distribution function of the $k$ parton (quark or gluon) while $C[f_q, f_g, f_Q](x, p)$ is the relativistic Boltzmann-like collision integral. In our calculations, the phase-space distribution function of the bulk medium (quarks and gluons) enters in the evolution equation for charm quarks as an external quantities with $C[f_q, f_g, f_Q]$ and the evolution of $f_q$ and $f_g$ have been assumed to be independent of $f_Q(x, p)$. The evolution of the bulk of quark and gluons is given by the solution of the other two transport equations where the $C[f_q, f_g]$ is tuned to keep fixed the $\eta/s$ ratio, for a detailed discussion see ref.s [9–11]. We have considered a bulk with massive quarks and gluons that provide a softening of the equation of state with a decreasing speed of sound when the cross over region is approached. Within this approach we describe the evolution of a system that dynamically has approximatively the lQCD equation of state [12, 13]. The quarks and gluons masses are given by the QPM [13]. The hadronization process plays a crucial role in determining the final spectra, $R_{\rm AA}(p_T)$ and $v_2(p_T)$ in comparison to the experimental data. In our calculations we have considered a hybrid model of coalescence plus fragmentation. For a detailed discussion of the hadronization model see [14]. We simulate $Pb + Pb$ collisions at $\sqrt{s_{\rm NN}} = 2.76\, TeV$. The initial conditions for the bulk in the $r$-space are given by the standard Glauber condition assuming boost invariance along the longitudinal direction. In momentum space we use a Boltzmann-Juttner distribution function up to a transverse momentum $p_T = 2$ GeV while at larger momenta mini-jet distributions as calculated by pQCD at NLO order in [15]. The initial temperature at the center of the fireball is fixed to $T_0 = 490\, MeV$ and the initial time for the simulations is $\tau_0 \simeq 1/T_0 = 0.3\, fm/c$. In the $r$-space charm quarks are distributed according to $N_{coll}$ while in the $p$-space the charm quarks are distributed according to the Fixed Order + Next-to-Leading Log (FONLL) calculations, taken from Ref. [16]. In the calculation shown in this paper the dynamical evolution of the bulk is constrained by an $\eta/s = 1/(4\pi)$.

## 3 Results

In the first part of this section we show the comparison of the results for the nuclear modification factor $R_{\rm AA}$ and for the elliptic flow $v_2$ with the experimental data. In the second part we discuss the recent results about the direct flow $v_1$ and triangular flow $v_3(p_T)$ of D meson. In Fig. 1 it is shown the comparison of our results for the $R_{\rm AA}(p_T)$ with the experimental data for $Pb + Pb$ collisions at $\sqrt{s_{\rm NN}} = 2.76\, TeV$ for $30 - 50\%$ centrality. We observe comparing dashed that the effect of the coalescence is to increase the $R_{\rm AA}$ for momenta larger than 1 GeV. This is due to the hadronization mechanism because a D mesons from coalescence, which is composed by one light quark and a charm

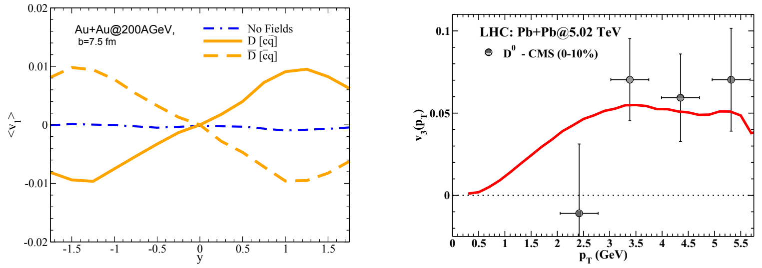


**Figure 2.** Left panel: Directed flow $v_1$ as a function of the rapidity for $Au + Au$ at $\sqrt{s_{NN}} = 200\,GeV$ for D and anti-D meson. Right panel: $v_3(p_T)$ for $Pb + Pb$ at $\sqrt{s_{NN}} = 5.02\,TeV$ for $(0 - 10)\%$ centrality (data from[19]).

quark, it get a larger momentum respect to the D mesons obtained from fragmentation. On the other hand at larger momenta, fragmentation becomes anyway the dominant mechanism of hadronization. In the right panel of Fig. 1, we show the corresponding results for the final $v_2(p_T)$ of D mesons. We show explicitly the different contributions to the $v_2(p_T)$ played by only coalescence (blue solid line) and only fragmentation (red dashed line). As shown, the $v_2$ developed via only coalescence is larger than the $v_2$ developed due to fragmentation. This is due mainly to the fact that the D meson is the result of the coalescence of a light quark with a charm quark therefore the final D mesons anisotropy in momentum space reflects both the heavy quark and light quark anisotropies in momentum space and it can even lead to an increase of about a factor two at $p_T > 2\,$GeV. While, when coalescence plus fragmentation mechanism is included for the hadronization, the $v_2$ of the D-mesons increases with respect to the $v_2$ of D meson by about a 30%, see solid orange line. The extracted diffusion coefficient $2\pi D_s$ is in agreement with the data and within the present systematic uncertainties to the lattice QCD calculation for a detailed discussion see [14]. It has been shown that very strong electric and magnetic fields created at early times of uRHICs can affect the charm quarks dynamics [8]. Due to the collision geometry the magnetic field created at early times is dominated by the component along the y axis. The main effect of the magnetic field is the induction of a current in the xz plane while at the same time the electric field is created and it is directed in the x direction. The combined effect of the fields is a current in the xy plane and the effect of which is to generate a finite directed flow $v_1$. In Fig.2 it is shown the final $v_1$ of the D mesons as a function of the rapidity for $Au + Au$ at $\sqrt{s_{NN}} = 200\,GeV$ at $b = 7.5\,fm$. In these calculations we have considered for the electromagnetic field the same space-time solution obtained in Ref. [20]. As shown the $v_1$ at forward rapidity is positive for the D meson and negative for anti D meson which means that the displacement induced by the Faraday current has a stronger effect compared to the Hall drift of the magnetic field. Recently, we have developed an event-by-event transport approach for the bulk in order to study the role of finite $\eta/s$ on the anisotropic flows $v_n(p_T)$, for details see [10]. In the right panel of Fig.2 we present the $v_3(p_T)$ of D mesons for central collisions for $Pb + Pb$ at $\sqrt{s_{NN}} = 5.02\,TeV$. In our calculation we have used a transport approach to model the soft sector on an event-by-event basis and describe the flow harmonics. Our event-by-event analysis consists of 1000 events for each centrality class. As shown we get a finite $v_3(p_T)$ which is a linearly increasing function at intermediate $p_T$ and as shown we get a good agreement with recent experimental results of CMS collaboration [19]. Notice that the results shown have been obtained including only the hadronization by fragmentation the inclusion of the coalescence will give an enhancement of the final anisotropic flows $v_n$.

## 4 Conclusions

We have studied the charm quark propagation in QGP at LHC energies within a relativistic Boltzmann transport approach. The interaction between charm quarks and light quarks of the bulk is described within quasi-particle model. This model is able to catch the main features of non-perturbative interaction and it is possible to describe the evolution of bulk that reproduce the lattice QCD equation of state. Our calculations give a good description for D meson $R_{\rm AA}$ and $v_2$ both at LHC energies within the experimental uncertainties. In general, we found that the non-perturbative behavior described by the QPM enhances the charm quark bulk interaction near $T_c$ which is essentially the ingredient for the build-up of a large $v_2$. Moreover, we observe that the effect of the hadronization by coalescence is to increase the $R_{\rm AA}$ and $v_2(p_T)$ for $p_T > 1\,GeV$. We have also studied the charm quark dynamics in the presence of electromagnetic field. We have found that the effect of the initial electromagnetic fields on the charm quarks is to develop a sizable directed flow $v_1$ which could be measurable at experiments. This suggest that the heavy quark $v_1$ could be a significant probe to characterize the initial electromagnetic field produced in the HICs.

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