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Open heavy flavor dynamics in heavy ion collisions: R_{AA}, v_1, v_2, v_3

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We study the propagation of charm quarks in the quark-gluon plasma (QGP) by means of a relativistic Boltzmann transport (RBT) approach. We have take into account for non-perturbative interaction between heavy quarks and light quarks by mean a quasi-particle approach. Such a model 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. The hadronization of charm quarks in D mesons is described by mean of an hybrid model of fragmentation plus coalescence. We show that the resulting charm in-medium evolution is able to correctly predict simultaneously the experimental data for the nuclear suppression factor R_{AA} and the elliptic flow $v_2(p_T)$at both RHIC and LHC energies at different centralities.

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1. Introduction

Heavy quarks (HQs) mainly charm and bottom quarks represent an ideal probe to study the properties of hot and dense QCD matter created at ultra-Relativistic Heavy Ion Collisions. They 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 Quark-Gluon Plasma (QGP). Therefore HQ can probe the whole evolution of the QGP and moreover because they are produced out-of-equilibrium they are expected to conserve memory of the history of the plasma evolution. The two key observables in HQ sector are the nuclear suppression factor R_{AA} which is the ratio between the spectra of heavy flavor hadrons measured in nucleus-nucleus collisions with the same spectra in proton-proton collisions and the elliptic flow $v_2(p_T)$ which is a measure of the anisotropies in momentum space. Experimental measurements at both RHIC and LHC energies have shown many interesting observations of heavy flavor hadrons such as the small values of their R_{AA} and the large values of $v_2(p_T)$ which are almost comparable to those of light hadrons. Several theoretical efforts have been made to study the R_{AA} and the v_2 measured in experiments within different models [1, 2, 3, 4, 5, 6] Besides the well studied elliptic flow it has been shown recently that also the triangular flow $v_3(p_T)$ of D mesons is non vanishing [7].

2. Transport equation for charm quarks in the QGP

The evolution of the charm quark distribution function is given by solving the RBT equations where the charm quarks scatters in a bulk medium of quarks and gluons by the following eq.s

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

with $f_k(x,p)$ we indicate the on-shell phase space one-body distribution function of the k parton and with $\mathscr{C}[f_q, f_g, f_Q](x,p)$ the relativistic Boltzmann-like collision integral. The phase-space distribution function of the bulk medium that consists of quarks and gluons enters in the evolution equation for charm quarks as an external quantities in $\mathscr{C}[f_q, f_g, f_Q]$. We assume that the evolution of f_q and f_g are independent of $f_Q(x,p)$ therefore we discard collisions between heavy quarks. The evolution of the bulk of quark and gluons is given by the solution of the other two transport equations where the $\mathscr{C}[f_q, f_g]$ is tuned to a fixed $\eta/s(T)$, see ref.s [8, 9]. In our calculations we have employed 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 that describe the evolution of a system that dynamically has approximately the lQCD equation of state [10]. Hadronization dynamics plays an important role in determining the final spectra and therefore the final $R_{AA}(p_T)$ and $v_2(p_T)$. In the result shown in this paper we have considered a hybrid model of coalescence plus fragmentation. For a detailed discussion of the hadronization model see [11]. For $Pb+Pb$ collisions at $\sqrt{s} = 2.76\,TeV$, the initial conditions for the bulk in the r-space are given by the standard Glauber condition assuming boost invariance along the longitudinal direction, while in the p-space we use a Boltzmann-Juttner distribution function up to a transverse momentum $p_T = 2$ GeV and at larger momenta mini-jet distributions as calculated by pQCD at NLO order in [12]. The initial maximum temperature at the center of the fireball is $T_0 = 490\,MeV$ and the initial time

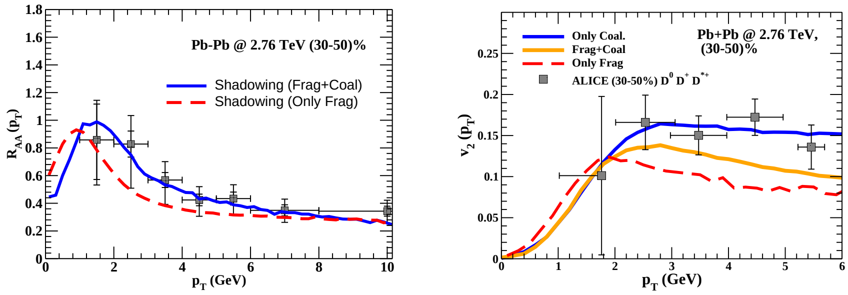

Figure 1: Left and middle panel: D meson R_{AA} and v_2 respectively in $Pb+Pb$ collisions at $\sqrt{s} = 2.76\,$ATev and centrality $30-50\%$ compared to ALICE data. Experimental data has been taken from Ref.s [15, 16].

for the simulations is $\tau_0 \simeq 1/T_0 = 0.3\,fm/c$. In our calculation quarks and gluons are massive in order to reproduce the lattice QCD equation of state according the QPM [13]. In the r-space HQ 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. [14]. Finally, 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_{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 of D meson. In the left panel of Fig. 1, we compare our results for the $R_{AA}(p_T)$ with the experimental data for $Pb+Pb$ collisions at $\sqrt{s} = 2.76\,$ATeV for centralities $30-50\%$. We observe comparing dashed lines with solid lines that the coalescence implies an increasing of the R_{AA} for momenta larger than $1\,$GeV. This is due to the hadronization mechanism which implies that a D mesons from coalescence of one light quark and a charm quark get a larger momentum respect to the D mesons obtained from fragmentation. At larger momenta, fragmentation becomes anyway the dominant mechanism of hadronization. In the right panel of Fig. 1, we compare our results for the $v_2(p_T)$ with the the experimental data. In particular we show explicitly the different contributions played by coalescence and fragmentation. The dashed red line refer to the v_2 for D mesons obtained considering only the fragmentation as hadronization mechanism while the solid blue line is the v_2 for D mesons obtained only via coalescence. 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 therefore the D mesons anisotropy in momentum space reflect both the heavy quark and light quark anisotropies in momentum space and it can even lead to an increase of about a factor of two at $p_T > 2\,$GeV. Finally, if 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 in Fig. 1. The coalescence play a key role to get a good description of the experimental data and moreover 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 [11]. Since HQs are produced at the very early stage they are good probes that can

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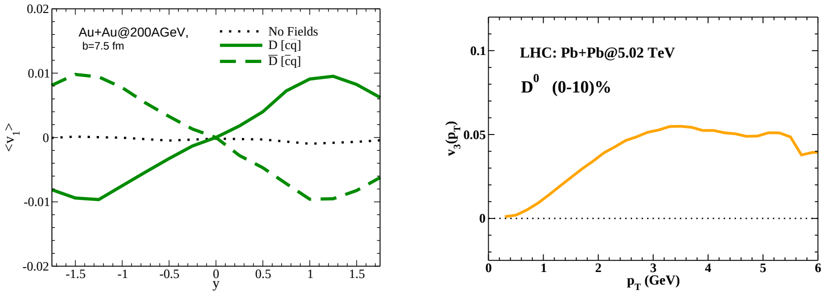

Figure 2: Left panel: Directed flow v_1 as a function of the rapidity for $Au+Au$ at $\sqrt{s} = 200\,GeV$ for D and anti-D meson. Right panel: triangular flow $v_3(p_T)$ for $Pb+Pb$ at $\sqrt{s} = 5.02\,TeV$ for $(0-10)\%$ centrality.

keep information of the early stages of HICs. Recently it has been recognized that very strong electric and magnetic fields created at early times of uRHICs can affect the charm quarks dynamics [17]. The magnetic field is dominated by the component along the y axis, so its main effect is the induction of a current in the xz plane while at the same time the electric field 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 fine directed flow v_1. In Fig.2 it is shown the final v_1 of the D mesons for $Au+Au$ at $\sqrt{s} = 200\,AGeV$ at $b = 7.5\,fm$ these results have been obtained employing for the Electromagnetic field the same space-time solution developed in Ref. [18]. As shown the v_1 at forward rapidity is positive for the D meson (with the charm) 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 η/s on the anisotropic flows $v_n(p_T)$ [9]. Therefore the transport approach is used to model the soft sector on an event-by-event basis and describe the flow harmonics. In Fig.2 (right panel) it is shown the p_T-dependence of the triangular flow $v_3(p_T)$ of D mesons for central collisions. As shown we get a finite $v_3(p_T)$ which is a linearly increasing function at intermediate p_T. Notice that the results shown have been obtained including only the hadronization by fragmentation the inclusion of the coalescence will increase 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 charm quark and the bulk interaction has been taken into account within a QPM which is able to reproduce the lattice QCD equation of state. The hadronization of charm quarks has been described by means of a hybrid model of coalescence plus fragmentation. We have studied the R_{AA} and v_2 of D meson. Our calculations give a good description for D meson R_{AA} and v_2 both at LHC energies within the experimental uncertainties. We found that the non-perturbative behavior described by the QPM enhances the charm quark bulk interaction near T_c with respect to a mere decrease of the drag coefficient γ with $1/T^2$ which is essentially the ingredient for the build-up of a large v_2. Moreover the hybrid model of hadronization by fragmentation plus coalescence help to increase both the R_{AA} and v_2 close to the recent experimental data. We have also studied the charm quark dynamics in the presence of electromagnetic field. We found that heavy quarks develop a sizable directed flow v_1 which could be measurable at experiments and suggesting the heavy quark v_1 as a significant probe to characterize the initial electromagnetic field.

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