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Charm and Bottom quarks dynamics in heavy-ion collisions: R_{AA}, anisotropic flows v_n and their correlations to the bulk.

Maria Lucia Sambataro[1,2,*], *Salvatore* Plumari[1,2], *Yifeng* Sun[2], *Vincenzo* Minissale[1,2], and *Vincenzo* Greco[1,2]

[1]Department of Physics and Astronomy 'E. Majorana', University of Catania, Via S. Sofia 64, 1-95123 Catania, Italy
[2]Laboratori Nazionali del Sud, INFN-LNS, Via S. Sofia 62, I-95123 Catania, Italy

Abstract. We describe the propagation of heavy quarks (HQs), charm and bottom, in the quark-gluon plasma (QGP) by means of a full Boltzmann transport approach including event-by-event fluctuations within a coalescence plus fragmentation hadronization. The non-perturbative dynamics of the interaction between HQs and plasma particles have been taken into account through a Quasi-Particle Model (QPM). We show that the resulting charm in-medium evolution is able to correctly predict simultaneously not only the experimental data for the average D-mesons $R_{AA}(p_T)$ and $v_{2,3}(p_T)$ at LHC energies but also the extension of the analysis to the event-shape engineeering tecnique that classify events according to magnitude of the second-order harmonic reduced flow vector q_2. In the same scheme we show predictions for $R_{AA}(p_T)$ of electrons from semi-leptonic B-mesons decays at top LHC energies. Our results entail a determination of D_s which is consistent with the lattice QCD calculations.

1 Introduction

Heavy quarks (HQs), namely charm and bottom, are excellent probes of the system created in a ultra-Relativistic Heavy Ion Collision (uRHIC). They are produced out-of-equilibrium in the early stage of the collisions by pQCD process and being $M_{HQ} >> T$, they are expected to thermalize slower in the Quark-Gluon Plasma (QGP) with respect to their light counterparts so that they can conserve memory of the history of the plasma evolution. One of the main observable in HQs sector that it has been also extensively used as a probe of QGP, is the nuclear suppression factor R_{AA} which is defined as the ratio between the spectra of heavy flavor hadrons measured in nucleus-nucleus collisions with the same spectra in proton-proton collisions [1, 2]. Another set of key observables are the anisotropic flows that are characterized by the magnitude of the coefficient v_n in the free expansion of the azimutal particle distribution[3, 4]. For a smooth matter distribution, all odd v_n coefficients are zero by symmetry but the event-by-event fluctuation in initial state entail the presence of non-zero odd harmonic coefficients, i.e. triangular flow v_3 that is an asimmetry triangularly shaped. Therefore, due to event by event fluctuations, collisions belonging to the same centrality class can give rise to systems with different initial eccentricity and hence different flow harmonics

*e-mail: sambataro@lns.infn.it

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for the final hadron distributions. We have developed an event-by-event transport approach that incorporates initial state fluctuations to study the collective flows in Pb + Pb collisions and the correlations between initial geometry and final collective flows [5, 6]. This issue can also be addressed to the Event-Shape-Engineering (ESE) tecnique consisting in selecting events in the same centrality class with different average elliptic anisotropy of final-state particles, selected according to the magnitude of the second-order harmonic reduced flow vector $q_2 = |\vec{Q}_2|/\sqrt{M}$ where $Q_2 = \sum_{j=1}^{M} e^{ij\phi_j}$ and M is the multiplicity of charged particles [7, 8]. This tecnique is adopted to study the correlation between the flow coefficients of heavy quark mesons and soft hadrons. Within this approach, we study the $v_n(p_T)$ of D mesons making a comparisons with the available experimental data and we extend our transport approach to study the bottom dynamics showing the comparison between our results on $R_{AA}(p_T)$ of electrons from semileptonic B-mesons decay and the available ALICE experimental data.

2 Transport equation for charm and bottom quarks in the QGP

In our approach, we describe both the bulk and HQs evolution by solving relativistic Boltzmann equations developed to perform studies of the dynamics of heavy-ion collisions [9–12]:

$$\begin{aligned} \{p_k^{\mu}\partial_{\mu} + m^*(x)\partial_{\mu}m^*(x)\partial_p^{\mu}\}f_k(x,p_k) &= C[f_q,f_g](x,p_k) \\ p^{\mu}\partial_{\mu}f_Q(x,p) &= C[f_q,f_g,f_Q](x,p) \end{aligned} \tag{1}$$

where $f_k(x,p)$ is the on-shell phase space one-body distribution function of the k parton and $C[f_q,f_g,f_Q](x,p)$ is the relativistic Boltzmann-like collision integral. In order to take into account the non-perturbative effects in HQs scattering, we evaluate $C[f_q,f_g,f_Q](x,p)$ within a quasi-particle model (QPM) approach in which the interaction is encoded in the quasi-particle masses that behave like massive constituents of free gas plus a background field interaction. It has been shown that QPM can reproduce the lQCD equation of state: pressure, energy density and interaction measure $T^{\mu}_{\mu} = \epsilon - 3P$ [13, 14] . In our model the collision integral $C[f_q,f_g](x,p_k)$ is gauged to viscous hydrodynamics allowing to construct a relativistic transport approach at fixed $\eta/s \approx 0.1$. For more details see Ref.s [5, 15]. For Pb + Pb collisions at $\sqrt{s} = 5.02 TeV$, the initial conditions of plasma particles in the r-space are given by a Monte-Carlo Glauber model in order to take into account the initial event-by-event fluctuations while we distrubute light partons in p-space using a Boltzmann-Juttner distribution up to $p_T = 2\ GeV$ and we include mini-jet production distributed at larger momenta according pQCD calculation at NLO [16]. Regarding HQs distribution in p-space, we use the Fixed Order + Next-to-Leading Log (FONLL) calculations [17]. Finally, in this paper we have considered a hybrid model of coalescence plus fragmentation hadronization [18] in order to determine the final D meson and B meson spectra and therefore the final $R_{AA}(p_T)$ and $v_n(p_T)$.

3 Results

We discuss now the comparison of the results for the D-meson elliptic flow $v_2(p_T)$, also evaluated in ESE selection, and triagular flow $v_3(p_T)$ with the available ALICE experimental data. In the left panel of Fig.1, we show our results for the D meson $v_{2,3}(p_T)$ at mid-rapidity for Pb + Pb collisions at $\sqrt{s} = 5.02\ TeV$ at 0-10% centrality class. Within our approach we find a finite $v_2(p_T)$ (red solid line) and $v_3(p_T)$ (green dashed line) of D mesons that are qualitatively in agreement with the experimental data. In the right panel of Fig.1, the $v_2(p_T)$ of D mesons at midrapidity for different q_2 selections is shown as function of p_T.

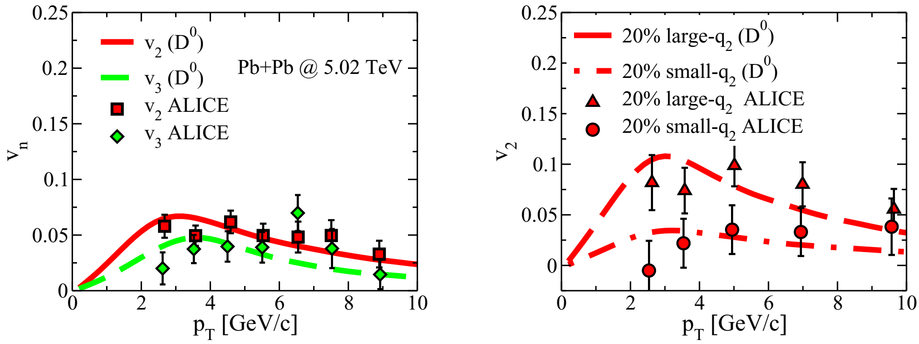

Figure 1. Left panel: D meson $v_2(p_T)$(red solid line) and $v_3(p_T)$(green dashed line) as function of p_T at $0-10\%$ centrality class for Pb + Pb $\sqrt{s} = 5.02\ TeV$. Right panel: D meson $v_2(p_T)$ at large (red dashed line) and small (red dot-dashed line) q_2 selection as function of p_T in the same centrality class. Experimental data have been taken from Ref.s [7, 8].

As shown in the right panel of Fig.1, the 20% large q_2 selection gives an elliptic flow that is larger with respect to the unbiased one (red solid line in the left panel of Fig.1). As one should expect, a large q_2 selection corresponds to a fireball with an initial larger eccentricity ϵ_2 that produces, after the fireball expansion, a corresponding larger final elliptic flow. In a similar way a small q_2 selection corresponds to smaller initial ϵ_2 and smaller final v_2. Our results show a significant difference of v_2 in the two q_2 selections of about 50% in agreement with the ALICE experimental data. Notice that the space diffusion coefficient $2\pi T D_s$ extracted with our approach is in satisfying agreement with the lQCD data within the present systematic uncertainties, for more details see Ref. [19]. In the same scheme of boltzmann transport approach with hybrid coalescence plus fragmentation approach for the hadronization process, we extend this analysis to bottom quark dynamics. Notice that the results shown in this section have been obtained with an interaction between bottom quarks and bulk that is the same to the one of charm quarks which gives a spacial diffusion coefficient in agreement with lQCD data.

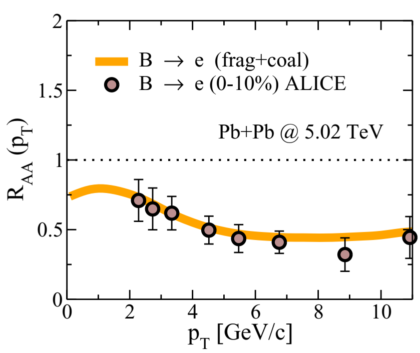

Figure 2. Nuclear modification factor $R_{AA}(p_T)$ of electrons from semi-leptonic B-mesons decays at $0-10\%$ centrality class for Pb + Pb at $\sqrt{s} = 5.02\ TeV$. Experimental data have been taken from Ref. [20].

In the Fig.2 we show the comparison between our result for $R_{AA}(p_T)$ of electrons from semi-leptonic B-mesons decays at $0-10\%$ centrality class and the available ALICE experimental data for Pb + Pb at $\sqrt{s} = 5.02\ TeV$. In order to obtain the electrons spectra we have implemented in our code the decay channel of $B \to e$ taking into account the semileptonic decay matrix weigthed by the different branching ratios of the decay. As shown in Fig. 2, our result are in good agreement with the ALICE experimetal data suggesting a strong coupling with collectively expanding fireball for bottom quark.

4 Conclusions

We have studied the charm and bottom quark propagation in QGP at LHC energies within a relativistic Boltzmann transport approach including non-perturbative effects of interaction by means of QPM approach. The hadronization process has been described by means of a hybrid model of coalescence plus fragmentation. We have studied the D meson $v_2(p_T)$ and $v_3(p_T)$ and the D meson $v_2(p_T)$ evaluated with the ESE technique. Our results show that with our approach we can simultaneously reproduce the elliptic flow of D mesons for different q_2 selections within the current experimental uncertainties. The same transport approach has been applied in order to study the bottom quark dynamics showing an $R_{AA}(p_T)$ in agreement with experimental data. The spatial diffusion coefficient D_s of charm and bottom quarks extracted from D and B mesons $R_{AA}(p_T)$ is in good agreement with the lQCD data within the still large uncertainties.

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