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Charm and bottom quarks dynamics in heavy-ion collisions: Anisotropic flows v_n and their correlations with Event-Shape Engineering technique

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Summary. — We describe the propagation of heavy quarks (HQs), namely charm and bottom, in the quark-gluon plasma within an event-by-event full Boltzmann transport approach followed by a coalescence plus fragmentation hadronization. We discuss the extension to high-order anisotropic flows ($v_n(p_T)$) also evaluated within the Event-Shape Engineering technique which consists in selecting events in the same centrality class but characterized by different geometry in the initial state. In this context, we show prediction of correlations between different D-meson flow harmonics at LHC energies. In the same scheme, we extend our approach to study bottom quark dynamics: we find that QPM approach is able to correctly predict the first available data on R_{AA} and v_2 of single-electron from B decays. Within this approach we extract the space-diffusion coefficient D_s of heavy quarks, in particular discussing the comparison of our results with the lQCD calculation evaluated in the infinite mass limit. We find that our results in this limit are in good agreement with the recent lQCD data.

1. – Introduction

In the study of Quark-Gluon Plasma (QGP), charm and bottom quarks can be considered excellent probes to experience the full evolution of the system created in ultra-Relativistic Heavy Ion Collision (uRHIC), [1, 2]. Heavy quarks (HQs) are produced out-of-equilibrium in the early stage of the collisions by pQCD process and their large mass leads to a thermalization time, at least for charm, comparable to the lifetime of the QGP itself [1, 3]. In this context, there are two main observables that have been also extensively used as a probe of QGP: the nuclear suppression factor R_{AA} [4-6] and the elliptic flow v_2 [7, 8]. In particular, the R_{AA} give a quantitative estimation of HQ-bulk interaction being defined as the ratio between the spectra of heavy flavor hadrons measured in nucleus-nucleus collisions with the same spectra in proton-proton collisions. On the other hand, the v_2 investigates the participation of HQs in the collective motion giving a measure of the anisotropy in the particle angular distribution. The elliptic flow v_2 is the second coefficient of the final azimuthal particle distribution and it is the dominant contribution in non-central collisions. The other different n-order harmonics v_n give us information on the final anisotropy of the system being related to the initial spatial eccentricities ϵ_n. We have developed an event-by-event transport approach with hybrid coalescence plus fragmentation approach that incorporates initial state fluctuations to study the anisotropic flows in Pb + Pb collisions. In particular, we have studied the correlations between initial geometry and final collective flows [9] with the Event-Shape-Engineering (ESE) technique consisting in selecting events in the same centrality class but characterized by different average elliptic anisotropy of final-state particles. These events are 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 [10]. This technique is adopted to study the correlation between the flow coefficients of both heavy quark mesons and soft hadrons fixing the centrality class while varying the q_2. Lately, we have also extended our approach to study the main observables in the bottom quark sector, providing some prediction also for centralities in which experimental data are not yet available [11]. In this context, we discuss our results for the spatial diffusion coefficient D_s of HQs: the extension of the study to the bottom quark allows to investigate the mass dependence of the interaction toward the infinite mass limit assumed in the main lQCD calculations. Indeed, in order to have a proper comparison to the lQCD calculations, we show the D_s coefficient for a fictitious super heavy quark staying in the limit fulfilled by lQCD data.

2. – Transport equation for heavy quarks in the QGP

In order to study both the bulk and HQs evolution in the QGP, we solve relativistic Boltzmann equations described by [12-15]:

$$\{p_k^\mu \partial_\mu + m^*(x)\partial_\mu m^*(x)\partial_p^\mu\} f_k(x, p_k) = C[f_q, f_g](x, p_k) \tag{1a}$$

$$p^\mu \partial_\mu f_Q(x, p) = C[f_q, f_g, f_Q](x, p) \tag{1b}$$

where $C[f_q, f_g, f_Q](x, p)$ is the relativistic Boltzmann-like collision integral with $f_k(x, p)$ describing the on-shell phase space one-body distribution function of the k parton. Furthermore, we evaluate the collision integral $C[f_q, f_g, f_Q](x, p)$ within a quasi-particle model (QPM) approach in order to take into account the non-perturbative effects of bulk-HQs scattering. Within this approach which encoded the interaction in the quasi-particle masses, we can reproduce the lQCD equation of state: pressure, energy density and interaction measure $T^\mu_\mu = \epsilon - 3P$ [16]. The collision integral $C[f_q, f_g](x, p_k)$ is also gauged to viscous hydrodynamics in order to construct a relativistic transport approach at fixed $\eta/s \approx 0.1$. For more details see refs. [17, 18]. The initial conditions of plasma particles in our calculations for Pb + Pb collisions at $\sqrt{s} = 5.02 TeV$ in the r-space are described using a Monte-Carlo Glauber model allowing to include the initial event-by-event fluctuations. Furthermore, the momentum distributions of light partons are described using a Boltzmann-Juttner distribution up to $p_T = 2\ GeV$ including also mini-jet production distributed at $p_T > 2\ GeV$ according pQCD calculation at NLO [19]. Meanwhile, HQs distribution in p-space are described by the Fixed Order + Next-to-Leading Log (FONLL) calculations [20]. Finally, we consider a hybrid model of coalescence plus fragmentation hadronization [21] in order to determine the final D meson and B meson spectra and $v_n(p_T)$.

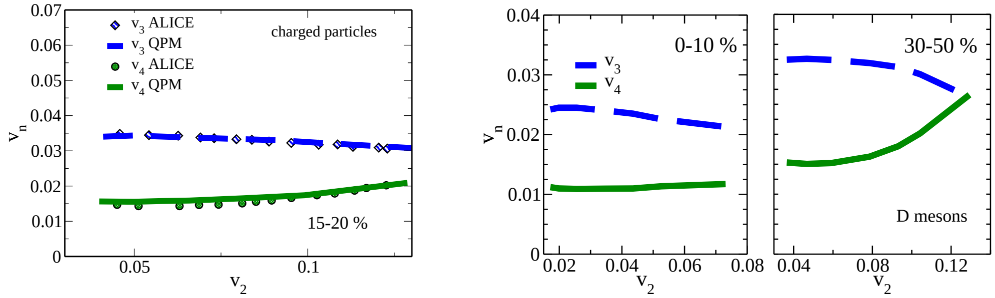

Fig. 1. – Correlations between v_n and v_m ($n = 2, m = 3, 4$) for charged particles in $PbPb$ collisions at $\sqrt{s_{NN}} = 2.76\ ATeV$ in comparison to ALICE experimental data [22] (left panel) and for D mesons in $PbPb$ collisions at $\sqrt{s_{NN}} = 5.02\ ATeV$ in different centrality classes (right panels).

3. – Results

In this section, we firstly discuss the correlations between different order anisotropic flows $v_n - v_m$ for both charged particles and D mesons evaluated with ESE technique. In the second part, we show the extension of our model to study the bottom quark dynamics.

In fig. 1 the correlations between v_2 and v_3 (blue dashed line), v_2 and v_4 (green solid line) for both charged particles and D mesons in $PbPb$ collisions for different centrality classes are shown. The results for charged particle are also shown in comparison with the experimental data from ALICE collaboration [22]. As shown in ref. [9], the response of the system in term of anisotropic flows v_n to the initial spatial eccentricities ϵ_n is essentially linear for the second and third harmonics, meaning that v_2 and v_3 are very well correlated with the second and third order eccentricities in the initial state for small values of η/s [23-25]. In particular, our calculations for charged particles show an anti-correlations $v_2 - v_3$ and a non linear correlation $v_2 - v_4$ both related to the initial correlations between $\epsilon_2 - \epsilon_{3,4}$. In particular, v_4 can be parametrized as the quadrature sum of one component proportional to v_2^2 (as $v_2 \propto \epsilon_2$) that comes from the non-linear hydrodynamics response of the medium and another component which should be independent of v_2. Our results for charged particles are in good agreement with the experimental data suggesting that our approach may capture the initial spatial fluctuations of the bulk matter. In the same scheme, we give prediction in fig. 1 (right panel) for the v_n-v_m correlations of D mesons in $PbPb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV in most central $0 - 10\%$ and semi-peripheral $30 - 50\%$ centrality classes. As for the light quark sector, we predict an anti-correlation between v_2-v_3 and a non linear, quadratic correlation between v_2-v_4. This similar behaviour between light and heavy flavours can be explained because of the strong correlation coefficient between the heavy and light quarks v_2 ($C \approx 0.95$), almost flat and independent of impact parameter, previously discussed in ref. [26]. In the last part of this section, we discuss the extension of the Boltzmann transport approach with hybrid coalescence plus fragmentation approach to study the bottom quark dynamics. We find that QPM approach is able to correctly predict the first available data on $R_{AA}(p_T)$ of single-electron from semi-leptonic B decays shown in the left panel of fig. 2. More details can be found in ref. [11] where we also show our results for elliptic flow $v_2(p_T)$ at top LHC energies and, in particular, predictions for both $v_2(p_T)$ and $v_3(p_T)$ at centralities where data are not yet available.

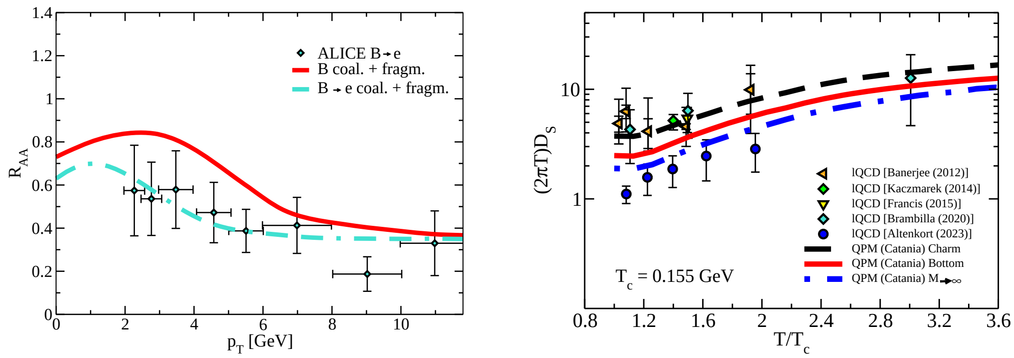

Fig. 2. – (left panel) Nuclear modification factor $R_{AA}(p_T)$ for B mesons and electrons from B mesons decay in $PbPb$ collisions at $\sqrt{s_{NN}} = 5.02\ ATeV$ for $0-10\%$ centrality class. The data for electrons by ALICE collaboration are taken from ref. [27]. (right panel) Spatial diffusion coefficient $(2\pi T)D_s$ for charm, bottom and infinite mass limit for HQs. The lQCD data are taken from refs. [28-32].

Starting from the R_{AA} and v_2, we have extrapolated the spatial diffusion coefficient D_s of both charm and bottom quark that we compare to lQCD calculation in the right panel of fig. 2. Furthermore, we have also evaluated the D_s coefficient for a fictitious super-heavy quark ($M_Q \approx 15\ GeV$) staying in the limit in which the thermalization time scales as M/T, a limit which is not yet reached in the charm mass scale and fulfilled in the bottom mass scale with a discrepancy of about 20%. We stress that this calculation is necessary in order to have a consistent comparison with the lQCD calculations which are evaluated in the infinite mass limit for heavy quarks. In the right panel of fig. 2, we show that the D_s in this limit (blue dot-dashed curve) is in good agreement to the new lQCD calculations which are the more pertinent one to compare to because they include dynamical fermions differently from previous calculations (until 2020) which are for a quenched medium. For more details about the D_s in the infinite mass limit, see ref. [11].

4. – Conclusions

We have discussed the HQs propagation in the QGP at top LHC energies within a relativistic event-by-event Boltzmann transport approach including non-perturbative effects of interaction by means of QPM. Furthermore, the hadronization process has been described by means of a hybrid coalescence plus fragmentation approach. We have studied both the $v_2(p_T)$ and $v_3(p_T)$ of D mesons and we have also discussed our prediction for correlation between $v_2 - v_{3,4}$ of these particles evaluated within the ESE technique. Our results show a similar correlation between different order harmonics in charm sector wrt to charged particles. The same transport approach has been applied in order to study the bottom quark dynamics showing an $R_{AA}(p_T)$ for electrons from B meson decay in agreement with the available experimental data by ALICE collaboration. The spatial diffusion coefficient D_s of charm and bottom quarks have been extracted from both D and B mesons $R_{AA}(p_T)$ and $v_2(p_T)$, further discussing the mass dependence of D_s in QPM in order to have a proper comparison to lQCD data evaluated in the infinite mass limit. We find that our calculation of D_s for a super-heavy quark staying in this limit is in agreement with the recent lQCD calculation which include dynamical fermions.

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