Heavy-flavor anisotropic flow at RHIC and LHC energies within a full transport approach

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Abstract. The propagation of heavy quarks (HQs) in the quark-gluon plasma (QGP) is described by means of a full Boltzmann transport approach. The non-perturbative dynamics and the interaction between HQs and the bulk is taken into account by means of a Quasi-Particle Model. Including the intense electromagnetic and vortical fields, we discuss their impact on the directed flow of neutral D mesons at RHIC energy, clarifying the role of this observable in giving information on QGP transport properties. We also show a novel study of the correlations between different flow coefficients of D mesons and soft hadrons at LHC energy within a coalescence plus fragmentation hadronization scheme and including event-by-event initial state fluctuations. This investigations can put further constraints on HQ transport coefficients towards a solid determination in comparison to the lattice QCD calculations.

1 Introduction

Heavy quarks (HQs), namely charm and bottom quarks, are excellent probes of the dynamical evolution of ultra-Relativistic Heavy Ion Collisions (uRHICs). Being produced in hard binary processes in the early off-equilibrium stage, their formation time is very small compared to that of light quarks. Due to the large masses, their thermalization time is comparable or larger than the lifetime of the Quark-Gluon Plasma (QGP). Hence, the HQs witness and keep a better memory of both initial stage and QGP evolution. Key observables of the HQ final states, such as D mesons, are the anisotropic flow coefficients v_n that characterize the azimuthal particle distribution in momentum space. The first coefficient, the directed flow v_1, is a collective sidewards deflection of particles on the event plane with respect to the beam axis; the v_1 of neutral D-meson has proven to give important evidences of the non-perturbative dynamics, the longitudinal bulk matter asymmetry and the electromagnetic (EM) fields [1–5]. Among the observables connected to higher-order flow coefficients, the Symmetric Cumulant (SC) [6] gives important evidences of the event-by-event fluctuations coming from the random nucleon positions as well as of the correlations between different-order flow anisotropies.

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2 Heavy quark transport approach

We describe the QGP and HQ evolution in relativistic heavy-ion collisions by solving the relativistic Boltzmann transport equations [7–11]:

$$\left[p_\mu \partial_x^\mu + q_j F_{\mu\nu}(x) p^\nu \partial_p^\mu\right] f_j(x,p) \quad = \quad C[f_j, f_k](x,p) \tag{1}$$

$$\left[p_\mu \partial_x^\mu + q_Q F_{\mu\nu}(x) p^\nu \partial_p^\mu\right] f_Q(x,p) \quad = \quad C[f_j, f_k, f_Q](x,p) \tag{2}$$

where $f_{j,k}(x,p)$ and $f_Q(x,p)$ are the phase-space one-body distribution function of, respectively, the light parton $j,k = g, q, \overline{q}$ (gluon, quark or antiquark) and the HQ $Q = c, \overline{c}$ (charm or anticharm); $F_{\mu\nu}$ is the electromagnetic strength tensor and $C = C_{22}$ is the relativistic collision integral that accounts for $2 \to 2$ scattering processes. In the collision integral of Eq. 1 the total cross section is determined in order to have a fixed value of the viscosity over entropy ratio, $\eta/s = 1/(4\pi)$, during the QGP evolution [9]. In Eqs. (2) we neglect collisions between HQs and describe the HQ interaction with the QGP medium by means of scattering matrices calculated at Leading-Order in pQCD but accounting for the non-perturbative effects by means of the Quasi-Particle Model (QPM) [10, 12] in which quarks and gluons are dressed with thermal masses that allow to reproduce lattice QCD thermodynamics [13]. When the fireball temperature goes below the quark-hadron transition temperature, $T_c = 155$ MeV, the charm quarks are hadronized to D-meson by means of a coalescence plus fragmentation model [14]. For the calculation of the directed flow we adopt a non boost-invariant initial condition for the bulk medium in the coordinate space able to describe the onset of vorticity in the fireball caused by the angular momentum of the colliding nuclear system. This is obtained by means of an asymmetric initial distribution of the QGP density in the $x - \eta_s$ plane that gives rise to a tilted fireball on the reaction plane [5]. For the calculations of the higher flow harmonics we assume longitudinal boost invariance and employ a Monte-Carlo Glauber model in order to take into account the initial event-by-event fluctuations. In momentum space the initial conditions for the bulk medium are given by a Boltzmann-Jüttner distribution function up to transverse momentum $p_T = 2$ GeV while at larger momenta we adopt mini-jet distributions as calculated by pQCD at NLO order in [15]. The charm quark and antiquark distributions are initialized in coordinate space in accordance with the number of binary nucleon-nucleon collisions. In momentum space we use charm quark production calculated at the Fixed Order + Next-to-Leading Log (FONLL) [16] [10]. The EM fields appearing in Eqs. (1) and (2) are computed with the method of Ref. [1, 17], where the QGP electrical conductivity σ_{el} is assumed constant in order to have analytic solutions of the Maxwell equations.

3 Results and discussion

The initial QGP density asymmetry is translated to the final azimuthal asymmetry of final hadrons measured by the charged particle v_1 shown in the left panel of Fig. 1. We show results for two values of the parameter η_m, which determines the degree of tilt of the fireball and, consequently, the directed flow magnitude. In the right panel of Fig. 1 we show our result for the v_1 of D mesons in comparison to the STAR data [19]. The values of the combined v_1 of D^0 and $\overline{D}^0$ mesons in the central rapidity range $|y| < 1$ are about 20-30 times larger than those of charged particle shown in left panel. This is a result of the shift in the transverse profiles of the tilted QGP fireball and the symmetrically-distributed HQ emission points from initial hard scatterings [2]. This shift leads to a pressure push of the bulk medium on the HQs, which is however effective only because the HQ interaction in QGP is largely non-perturbative, corresponding to a very small space diffusion coefficient $2\pi T D_s$ of charm quarks in satisfying agreement with the lattice QCD data; this generate an amplification of the D-meson v_1. While

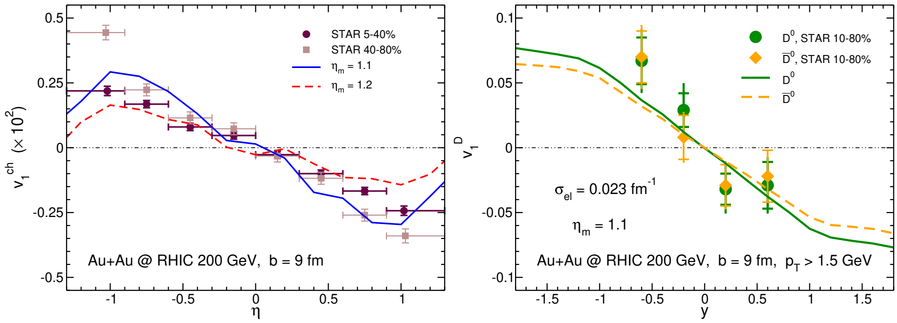

Figure 1. (Pseudo)rapidity dependence of the directed flow of charged particles (left) and D mesons (right) in Au+Au collisions at RHIC energy $\sqrt{s_{NN}}$ = 200 GeV with impact parameter b = 9 fm. The experimental data are from the STAR Collaboration [18, 19]. Figures from Ref. [5].

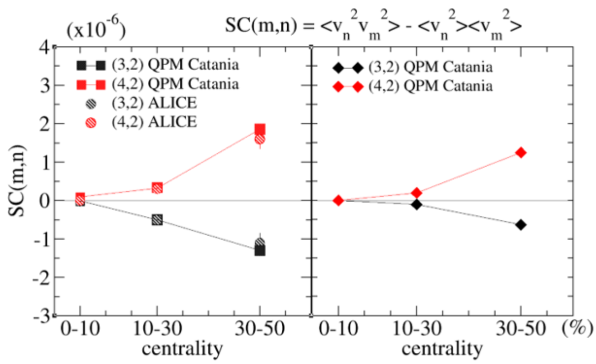

Figure 2. Centrality dependence of the Symmetric Cumulant Correlator for charged particles (left) and D mesons (right) with $|\eta| < 0.8$ and $0.5 < p_T < 5.0$ GeV in $PbPb$ collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The circles in the left panel are the ALICE experimental data [22]. Figure from Ref. [23].

the v_1 magnitude is associated with the HQ diffusion coefficient, the v_1 splitting is connected to the electric conductivity of the QGP medium. In simulations without the EM fields the two lines of the v_1 of D^0 and $\overline{D}^0$ lie one on top of each other; we see clearly from Fig. 1 (right) that a splitting of the two curves is generated when the EM fields are considered, in agreement with Refs. [1, 3]. In this calculation we assume that D^0 and $\overline{D}^0$ are produced only by fragmentation of c and $\overline{c}$ quarks respectively, thus the v_1 of neutral D mesons is driven by the v_1 of charm quarks and antiquarks. Our result indicates that the total effect coming from B_y and E_x which push positively and negatively charged particles in opposite directions is slightly dominated by the electric field, consistently also with studies on the light sector in large [17, 20] and small [21] systems at top RHIC energy.

The event-by-event transport approach allows to analyse higher-order v_n through the SC correlator that is defined as $SC(m,n) =< v_n^2 v_m^2 > - < v_n^2 >< v_m^2 >$, where the brackets indicate average over all events for a given centrality class. The SC correlator vanishes for fixed values of v_n and v_m over all events as well as when event-by-event fluctuations of v_n and v_m are uncorrelated. Therefore, a nonzero SC indicates that the event-by-event fluctuations of v_n and v_m are correlated. In Fig. 2 we show $SC(4,2)$ (red lines) and $SC(3,2)$ (black lines) for charged particles (left panel) and D mesons (right panel). The result for charged particles is in good agreement with the experimental data from the ALICE Collaboration [22]. The $SC(4,2)$ is positive, indicating that for a given centrality interval, events with larger v_2 have on average larger v_4. On the other hand, the $SC(3,2)$ is negative indicating an anti-correlation between v_2 and v_3 at fixed centrality. This confirm what was observed within the event-shape selected v_n–v_m correlations [23] and extend a previous study on the heavy-light flavor correlations of anisotropic flows [24]. The predictions for the SC correlators of D mesons indicate a weaker but similar behaviour with the centrality with respect to light hadrons. In both panels we observe that $SC(4,2)$ and $SC(3,2)$ decrease considerably in magnitude from peripheral to central events. This large decrease does not imply that the correlations between these harmonics becomes negligible for centrality class smaller then $(0-10)\%$, but occurs since $SC \sim v_n^2 v_m^2$ and for very central events the flow coefficients (especially v_2) become quite small.

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