

Event-by-event heavy-flavour dynamics: Estimating the spatial diffusion coefficient D_s from charm to the infinite mass limit

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Abstract. Quasi-Particle Model (QPM) has been developed to study charm quark dynamics in ultra-relativistic heavy-ion collisions with good description of D mesons $R_{AA}(p_T)$ and $v_{2,3}(p_T)$ and leading to the evaluation of the spatial diffusion coefficient $D_s(T)$. With an event-by-event full Boltzmann transport approach followed by a hybrid hadronization via coalescence plus fragmentation, we show $R_{AA}(p_T), v_2(p_T)$ down to $p_T \rightarrow 0$ for D and B mesons. We find that QPM approach is able to correctly predict first available data on $R_{AA}(p_T)$ and $v_2(p_T)$ of single-electron from B mesons decays measured by ALICE. A significant breaking of the expected scaling of the thermalization time τ_{th} with M_Q/T is found. Charm quark $D_s(T)$ is about 50% larger than the asymptotic value for $M_Q \rightarrow \infty$, while the bottom $D_s(T)$ is only 20% higher. In the infinite mass limit the $D_s(T)$ is consistent with recent lQCD calculations with dynamical quarks.

1 Introduction

Charm and bottom quarks, Heavy quarks (HQs), are considered excellent probes for the system created during an ultra-Relativistic Heavy Ion Collision (uRHIC). The production of these quarks happens in the early stages of the collisions, and can be described by out-of-equilibrium pQCD process. Because their masses are large, i.e. $M_{HQ} \gg T$, they are expected to have a slow thermalization in the Quark-Gluon Plasma (QGP) with respect to the bulk components, because of this features they can preserve information about their evolution throughout the plasma history. A main observable is the nuclear suppression factor R_{AA} which is defined as the ratio between AA and pp hadron spectra [1, 2]. Another set of key observables are the anisotropic flows that are characterized by the magnitude of the coefficient v_n in the Fourier expansion of the azimuthal particle distribution [3, 4]. The odd v_n coefficients, are expected to be zero starting from symmetry considerations, but, in more realistic situations, the event-by-event fluctuations in the initial states lead to non-zero odd harmonic coefficients. As a consequence of the event by event fluctuations, collisions that are classified as collision with the same centrality can have different initial eccentricity and hence different flow harmonics for the final hadron distributions. We have developed an event-by-event transport approach with initial state fluctuations that allow us to study the collective flows in $PbPb$ collisions and the correlations between initial geometry and final collective flows [5, 6]. In order

to explore these correlations we have used an Event-Shape-Engineering (ESE) technique, that select events which have different average elliptic anisotropy in the same centrality class. This can be performed selecting the final particles 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]. Within this approach, we study the $v_n(p_T)$ of D mesons making a comparisons with the available experimental data. Then we extend our standard transport approach to study the bottom dynamics, we show the comparison between our $R_{AA}(p_T)$ results of electrons from semileptonic B-mesons decay and the available ALICE experimental data.

2 Transport equation in QGP

Solving relativistic Boltzmann equations the evolution of both bulk and HQs quarks is [9–12]:

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

where $f_k(x, p)$ is the phase space one-body distribution function of the k parton and $C[f_q, f_g, f_Q](x, p)$ is the relativistic collision integral. The non-perturbative effects in HQs scattering are modeled with a quasi-particle model (QPM) approach, where the interaction affects the quasi-particle, via their mass, that behave like a massive constituent of free gas plus a background field interaction. Starting from this approach the collision integral $C[f_q, f_g, f_Q](x, p)$. The bulk collision integral $C[f_q, f_g](x, p_k)$ is gauged to viscous hydrodynamics, giving the possibility to construct a relativistic transport that reproduce a fixed $\eta/s \approx [5, 15]$. The QPM approach used is able to reproduce thermodynamics quantities such as pressure, energy density and interaction measure $T_\mu^\mu = \epsilon - 3P$, and the lQCD equation of state [13, 14]. The simulation for $PbPb$ collisions at $\sqrt{s} = 5.02 TeV$ starts with plasma particles that are distributed in the coordinate space following a Monte-Carlo Glauber model, with this choice we can employ the initial event-by-event fluctuations. The momentum distribution that we consider for light partons is a Boltzmann-Juttner distribution, for momenta up to $p_T = 2 GeV$, above this momentum we include mini-jet production distributed according to pQCD calculation at NLO [16]. For HQs we use FONLL distributions in momentum space [17]. For what concerns the hadronization of quarks, we use an hybrid model based on the coalescence and fragmentation processes [18] that determines the final particle spectra and, consequently, $R_{AA}(p_T)$ and $v_n(p_T)$. A quantitative information on HQ interaction is obtained via the spatial diffusion coefficient D_s , that measures the space dispersion. It can be evaluated also in lQCD in the zero momentum limit. The relation between this quantity and the thermalization time is given by $\tau_{th}(p \rightarrow 0) = M_{HQ}(2\pi T D_s)/2\pi T^2$, furthermore $\tau_{th} \equiv 1/\gamma(p \rightarrow 0)$, where γ is the drag coefficient. In our QPM approach we can evaluate the drag coefficient starting from the scattering matrices [10]

3 Results

In the left panel of Fig.1, we show our results for the D meson anisotropic flows, in $PbPb$ collisions at $\sqrt{s} = 5.02 TeV$ for the 0-10% centrality class at mid-rapidity. With our approach we find that $v_2(p_T)$ (orange solid line) and $v_3(p_T)$ (green dot-dashed line) of D mesons are qualitatively in agreement with the available ALICE experimental data [7, 8]. In the right panel of Fig.1 are shown the D mesons $v_2(p_T)$ when different selection of q_2 are performed. It can be seen that increasing the q_2 there is a corresponding increase of v_2 . In particular the selection with the 20% large q_2 gives an elliptic flow that is enhanced compared to the D meson v_2 without any selection (orange solid line in the left panel). At the same time

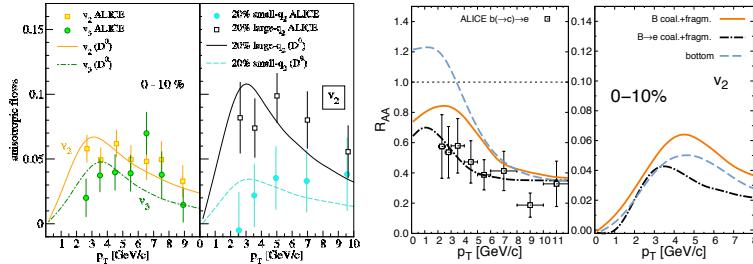


Figure 1. [Left Figure]: D meson $v_2(p_T)$ (orange solid) and $v_3(p_T)$ (green dot-dashed line) Right panel: D meson $v_2(p_T)$ at large (black solid) and small (turquoise dashed) q_2 selection in the same centrality class. Exp. data from [7, 8]. [Right Figure]: (Left panel) $R_{AA}(p_T)$ (Right panel) $v_2(p_T)$ for bottom, B mesons and electrons from B meson decay at 0 – 10% centrality class for $PbPb$ $\sqrt{s} = 5.02$ TeV.[20].

the 20% small q_2 shows an elliptic flow suppression w.r.t. the unbiased one. This result agrees with what can be expected considering that a large (or small) q_2 selection corresponds to a larger (or smaller) initial fireball eccentricity ϵ_2 , that is commuted, after the fireball expansion, to a corresponding larger (or smaller) final elliptic flow. The model is able to reproduce the experimental data and shows a significant difference in the two q_2 selections with a difference of about 50%. We have extend to bottom quark the same approach of Boltzmann transport equation with an hadronization via coalescence plus fragmentation, with the same interaction between bottom quarks and bulk as the charm quarks one. The results, at LHC energies, for the nuclear modification factor $R_{AA}(p_T)$ and $v_2(p_T)$ of bottom quark, B mesons and electrons from B meson decay are shown in Fig.1(Right) in comparison with the available ALICE experimental data for $PbPb$ at $\sqrt{s} = 5.02$ TeV at 0 – 10% centrality class [20, 21]. In order to obtain the electrons spectra we have implemented in our code the decay channel of $B \rightarrow e$ taking into account the semi-leptonic decay matrix weighted by the different branching ratios of the decay. As shown in Fig.1(Right), our result are in good agreement with the ALICE experimental data suggesting a strong coupling with collectively expanding fireball for bottom quark. In Fig.2 are shown the extracted $2\pi TD_s$ for charm and bottom that is in agreement with the lQCD data [22–25]. We have plot by red dot-dashed line also the spatial diffusion coefficient in the infinite mass limit. The $2\pi TD_s(T)$, in the large mass limit, is quite close to the new lQCD data (orange triangles [26]), which are obtained performing calculations in 2+1 flavours QCD with dynamical fermions, differently from the other lQCD data that are obtained in the quenched approximations.

4 Conclusions

We have studied the charm and bottom quark propagation in QGP at LHC energies with a relativistic Boltzmann transport approach including non-perturbative effects of interaction by means of QPM approach. We have studied the D meson $v_2(p_T)$ 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. The same transport approach has been applied in order to study the bottom quark dynamics showing $R_{AA}(p_T)$ and v_2 , for electron coming from B decay, that are in agreement with experimental data. With a QPM approach the spatial diffusion coefficient D_s of charm and bottom quarks extracted from D and B mesons $R_{AA}(p_T)$ and the one obtained once the mass scale dependence is taken into account is in agreement with the most recent lQCD calculations that include dynamical fermions [26]. The HQ thermalization

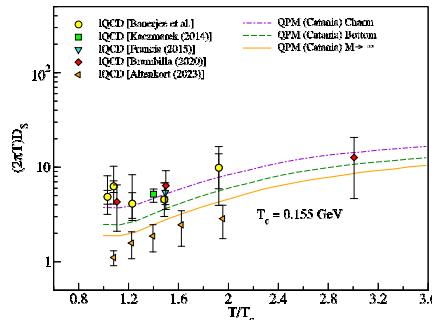


Figure 2. Spatial diffusion coefficient $D_s(T)$ for charm quark (solid black line), bottom quark (dashed green line) and in the infinite mass limit (orange solid line) compared to the lQCD expectations [22–26].

time evaluation in uRHICs directly from lQCD $2\pi T D_s(T)$ discarding the mass dependence can be underestimated, in particular for charm quarks.

References

- [1] B.I. Abelev, *et al.*, Phys. Rev. Lett. **98**, 192301 (2007)
- [2] J. Adam, *et al.*, JHEP **03**, 081 (2016)
- [3] A. Adare, *et al.*, Phys. Rev. Lett. **98**, 172301 (2007)
- [4] B.B. Abelev, *et al.*, Phys. Rev. C**90**(3), 034904 (2014)
- [5] S. Plumari, *et al.*, Phys.Rev.C **92** (2015) 5, 054902
- [6] S. Plumari, *et al.*, Phys.Lett.B **805** (2020) 135460
- [7] S. Acharya *et al.* (ALICE), Phys.Lett.B **813**, 136054 (2021)
- [8] S. Acharya *et al.* (ALICE), JHEP **02**, 150 (2019)
- [9] S. K. Das, F. Scardina, S. Plumari, and V. Greco, Phys. Lett. B **747**, 260 (2015)
- [10] M. L. Sambataro, S. Plumari, V. Greco, Eur.Phys.J.C **80** (2020) 12, 1140
- [11] M. Ruggieri *et al.*, Phys. Rev. C **92**, 064904 (2015)
- [12] A. Gabbana *et al.*, Phys.Rev.C **101** (2020) 6, 064904
- [13] S. Plumari, *et al* Phys. Rev. D **84**, 094004 (2011)
- [14] S. Borsanyi *et al.*, JHEP **1011**, 077 (2010)
- [15] M. Ruggieri, F. Scardina, S. Plumari and V. Greco, Phys.Rev. C**89**, 054914 (2014)
- [16] V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003)
- [17] M. Cacciari, *et al.*, JHEP **10** 137 (2012)
- [18] S. Plumari,*et al.* Eur.Phys.J.C **78** (2018) 4, 348
- [19] F. Scardina, *et al.* Phys.Rev.C **96** (2017) 4, 044905
- [20] R. Arnaldi, Hard Probes Conference, online (2020)
- [21] M. L. Sambataro, *et al.*, Phys. Lett. B **849** (2024), 138480
- [22] D. Banerjee, S. Datta, R. Gavai and P. Majumdar, Phys. Rev. D **85** (2012), 014510
- [23] O. Kaczmarek, Nucl. Phys. A **931** (2014), 633–637
- [24] A. Francis,*et al.* Phys. Rev. D **92** (2015) no.11, 116003
- [25] N. Brambilla,*et al.* Phys. Rev. D **102** (2020) no.7, 074503
- [26] L. Altenkort *et al.* [HotQCD], Phys. Rev. Lett. **130** (2023) no.23, 231902