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Heavy-quark dynamics in heavy-ion collisions

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Abstract. The dynamics of partons and hadrons in ultra-relativistic nucleus-nucleus collisions are analyzed within the Parton-Hadron-String Dynamics (PHSD) transport approach, which is based on a dynamical quasiparticle model (DQPM) for the partonic phase including a dynamical hadronization scheme while reproducing lattice QCD results in thermodynamic equilibrium for the equation-of-state as well as transport coefficients like shear and bulk viscosities, the electric conductivity or the charm diffusion coefficient of the hot QCD medium. In this contribution, we report on recent results on the charm dynamics and elliptic flow in Au+Au collisions at RHIC and Pb+Pb collisions at the LHC.

1. Introduction

The dynamics of the early universe in terms of the 'Big Bang' may be studied experimentally by ultra-relativistic nucleus-nucleus collisions at Relativistic-Heavy-Ion-Collider (RHIC) or Large-Hadron-Collider (LHC) energies in terms of 'tiny bangs' in the laboratory. With sufficiently strong parton interactions, the medium in the collision zone can be expected to achieve local equilibrium after some initial delay and exhibit approximately hydrodynamic flow [1, 2]. In these collisions a new state of strongly interacting matter is created, being characterized by a very low shear viscosity η to entropy density s ratio, η/s, close to a nearly perfect fluid [3]. Lattice QCD (lQCD) calculations [4] indicate that a crossover region between hadron and quark-gluon matter should have been reached in these experiments.

Since the hot and dense matter produced in relativistic heavy-ion collisions appears only for a couple of fm/c, it is a big challenge for experiments to investigate its properties. Heavy-flavor mesons are considered to be promising probes in this respect since the production of heavy flavor requires a large energy-momentum transfer. Thus it takes place early in the heavy-ion collisions, and - due to the large energy-momentum transfer - should be described by perturbative quantum chromodynamics (pQCD). The produced heavy flavor then interacts with the hot dense matter (of partonic or hadronic nature) by exchanging energy and momentum. As a result, the ratio of the measured number of heavy flavors in heavy-ion collisions to the expected number in the absence of nuclear or partonic matter, which is the definition of R_{AA}, is suppressed at high transverse momentum, and the elliptic flow of heavy flavor is generated by the interactions in noncentral heavy-ion collisions [5, 6]. Although it had been expected that the R_{AA} of heavy flavor is less suppressed and its elliptic flow is smaller as compared to the corresponding quantities for light hadrons, the experimental data show that the suppression of heavy-flavor hadrons at high transverse momentum and its elliptic flow v_2 are comparable to those of light hadrons [5, 6]. This is a puzzle for heavy-flavor production and dynamics in relativistic heavy-ion collisions [7].

Since the heavy-flavor interactions are closely related to the dynamics of the partonic or hadronic degrees-of-freedom due to their mutual interactions, a proper description of the relativistic heavy-ion collisions and their bulk dynamics is necessary. In this contribution, we report about results from the parton-hadron-string dynamics (PHSD) approach [8], which has been successfully applied to p+A and Au+Au (Pb+Pb) collisions from SPS to LHC energies with respect to single-particle spectra, collective flows and electromagnetic observables [9].

2. Charm and bottom dynamics in PHSD

In the PHSD the charm and bottom quark pairs are produced through initial hard nucleon-nucleon scattering in relativistic heavy-ion collisions. We employ the PYTHIA event generator [10] to produce the heavy-quark pairs and modify slightly their transverse momentum and rapidity such that they are similar to those from the FONLL calculations [11]. The corrections employed at RHIC and LHC energies can be found in Refs. [12, 13, 14]. Accordingly, our tuned PYTHIA generator gives very similar charm and bottom distributions as those from FONLL calculations [11, 15], which fixes the input from pQCD in our approach.

The produced charm and bottom quarks in hard nucleon-nucleon interactions are hadronized in p+p collisions by emitting soft gluons, which is denoted by 'fragmentation' (cf. Ref. [12] for details). The excited $D^*(B^*)$ mesons first decay into $D(B)+\pi$ or $D(B)+\gamma$, and finally the $D-$ and $B-$mesons produce single electrons through the semileptonic decay [16]. In case of heavy-ion collisions, the shadowing effect is incorporated in the PHSD by employing the EPS09 package from Ref. [17] as in most of the related approaches [7]. The details of the implementation are given in Ref. [13].

In PHSD the baryon-baryon and baryon-meson collisions at high-energy produce strings, which above the critical energy density ($\sim$ 0.5 GeV/fm^3) melt into quarks and antiquarks with masses determined by the temperature-dependent spectral functions from the dynamical quasiparticle model (DQPM) [18], which has been fitted to thermodynamical quantities from lattice QCD. Massive gluons are formed through flavor-neutral quark and antiquark fusion in line with the DQPM. The heavy quarks and antiquarks produced in early hard collisions interact with the dressed lighter off-shell partons in the partonic phase. The cross sections for the heavy-quark scattering with massive off-shell partons have been calculated by considering explicitly the mass spectra of the final state particles in Ref. [19, 20]. The elastic scattering of heavy quarks in the QGP is treated in the PHSD by including the non-perturbative effects of the strongly interacting quark-gluon plasma (sQGP) constituents, i.e. the temperature-dependent coupling $g(T/T_c)$ as well as the effective propagators with broad spectral functions (imaginary parts) from the DQPM [18]. We note that heavy flavor interactions in the QGP – as described by the DQPM charm scattering cross sections – differ substantially from the pQCD scenario, however, the spacial diffusion constant for charm quarks $D_s(T)$ is consistent with the lQCD data [13, 21].

The heavy-quark hadronization in heavy-ion collisions is realized via 'dynamical coalescence' in competition to fragmentation. Here 'dynamical coalescence' means that the probability to find a coalescence partner is defined by Monte Carlo in the vicinity of the critical energy density $0.4 \leq \epsilon \leq 0.75$ GeV/fm^3 as explained in Ref. [13].

After the hadronization of heavy quarks and their subsequent decay into D, D^*, B and B^* mesons, the final stage of the evolution concerns the interaction of these states with the hadrons conforming the expanding bulk medium. A realistic description of the hadron-hadron scattering —potentially affected by resonant interactions— includes collisions with the states $\pi, K, \bar{K}, \eta, N, \bar{N}, \Delta$, and $\bar{\Delta}$. Such a description of their interactions has been developed in

Refs. [22, 23, 24] using effective field theory. The resulting cross sections are implemented in the PHSD.

3. Results for heavy-ion reactions

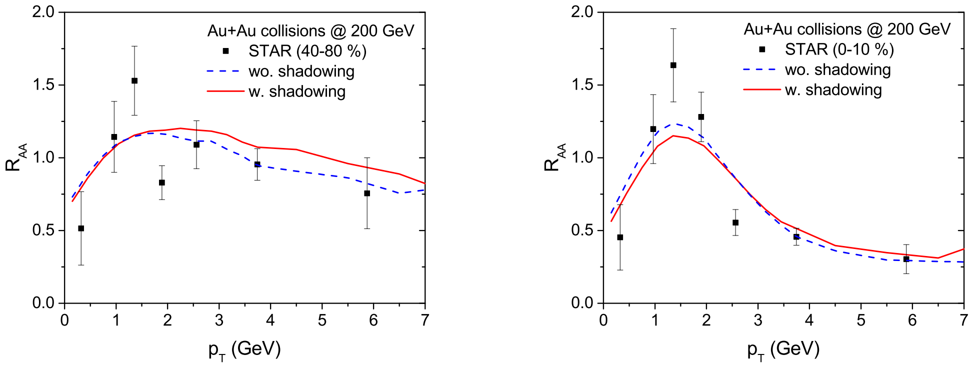

Figure 1. $R_{\rm AA}$ of $D-$mesons with (solid) and without (dashed) shadowing effect in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV for different centralities in comparison to the experimental data from the STAR collaboration [25].

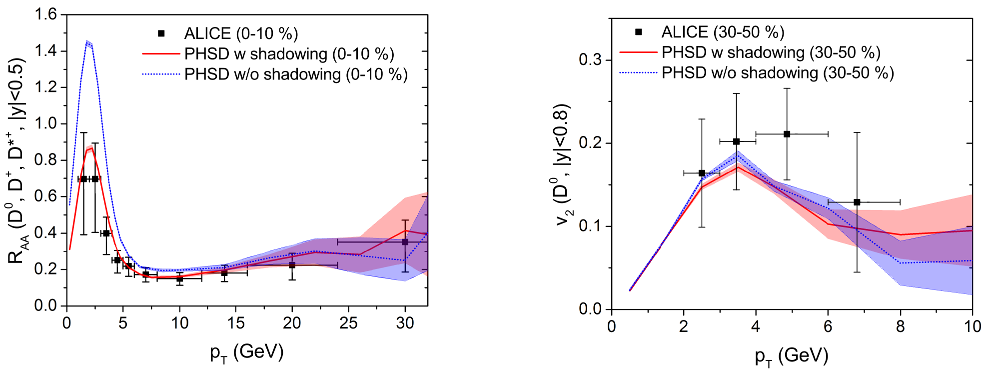

Figure 2. (left) The ratio $R_{\rm AA}$ of D^0, D^+, and D^{*+} mesons within $|y| < 0.5$ as a function of $p_{\rm T}$ in 0-10 % central Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV compared with the experimental data from the ALICE collaboration [26]. The solid and dotted lines are, respectively, $R_{\rm AA}$ with and without (anti-)shadowing. (right) The elliptic flow v_2 of D^0 mesons within $|y| < 0.8$ in 30-50 % central Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV compared with the experimental data from the ALICE collaboration [27].

Since the heavy flavor strongly interacts with the expanding matter in A+A reactions, it is also accelerated outwards. Such effects of the medium on the heavy-flavor dynamics are expressed in terms of the nuclear modification factor defined as [13]

$$R_{\rm AA}({\rm p_T}) \equiv \frac{dN_{\rm AA}/d{\rm p_T}}{N_{\rm binary}^{\rm AA} \times dN_{\rm pp}/d{\rm p_T}}, \tag{1}$$

where $N_{\rm AA}$ and $N_{\rm pp}$ are, respectively, the number of particles produced in heavy-ion collisions and that in p+p collisions, and $N_{\rm binary}^{\rm AA}$ is the number of binary nucleon-nucleon collisions in the heavy-ion collision for the centrality class considered. Furthermore, in noncentral heavy-ion collisions the produced matter expands anisotropically due to the different pressure gradients in plane and out-of plane. If the heavy flavor interacts strongly with the nuclear matter, then it also follows this anisotropic motion to some extend. The dominant anisotropic flow is expressed in terms of the elliptic flow $v_2 = \langle (p_x^2 - p_y^2)/(p_x^2 + p_y^2) \rangle$ which is the dominant observable to quantify the collectivity of the reaction [13].

In Fig. 1 we show the $R_{\rm AA}$ of $D-$mesons in different centrality classes with (solid) and without (dashed) shadowing effect in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV in comparison to the experimental data from the STAR collaboration [25]. The shadowing effect decreases the charm production by ∼8 % in central reactions. We note that the elliptic flow v_2 of D^0 mesons is enhanced by hadronic scattering by up to 30% at higher $p_{\rm T}$ [12].

Figure 2 (left) shows the ratio $R_{\rm AA}$ of D^0, D^+, and D^{*+} mesons within the rapidity range $|y| < 0.5$ as a function of $p_{\rm T}$ in 0-10 % central Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The solid and dotted lines are, respectively, the $R_{\rm AA}$ of D mesons with and without (anti-)shadowing. We can see that the $R_{\rm AA}$ of D mesons decreases especially at small transverse momentum due to shadowing. When including shadowing our results are in a good agreement with the experimental data from the ALICE collaboration [26]. Figure 2 (right) shows the elliptic flow v_2 of D^0 mesons within the rapidity range $|y| < 0.8$ in 30-50 % central Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV in comparison to the data from the ALICE collaboration [27]. The (anti-)shadowing effect slightly decreases the elliptic flow, because it reduces the production of low-$p_{\rm T}$ charm which more easily follows the bulk flow. We recall that so far it has been a challenge for theoretical models to reproduce the experimental data and to explain simultaneously the large energy loss of charm quarks ($R_{\rm AA}$) and the strong collectivity (v_2) [7]. According to the studies performed above the microscopic PHSD approach appears to be quite in line with the experimental observations for charm quarks at top RHIC and LHC energies.

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