Particle Production in Nuclear Collisions: Hadronization and QCD

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Abstract. We discuss recent progress made in the description of light and heavy quark observables, regarding the properties of the quark gluon plasma which is produced in relativistic nuclear collisions. In particular we highlight the effects of the hadronic phase on the QCD hadronization temperature and the modifications of charm quark properties in the dense plasma and hadronic phase.

1. Introduction

The production and the properties of strange and charmed hadrons was always considered a useful probe for the hot and dense systems produced in relativistic nuclear collisions [1, 2]. In this paper we will present recent progress made in the description of light and heavy quark observables, and how they can be used to shed light on the properties of QCD.

2. Strangeness production and the hadronization curve

The determination of the hadronization temperature of QCD, by an experimental observable, is one of the goals of high energy nuclear physics. It has been conjectured [3] that experimentally measured hadron multiplicities represent such an observable: they depend on the temperature at, or close to QGP hadronization. Statistical approaches are able to reproduce the measured hadronic yields, both in elementary [4] and in relativistic nucleus-nucleus collisions [5]. This has led to the formulation of the Statistical Hadronization Model (SHM), which assumes that hadrons are emitted from the fireball in chemical equilibrium. One can take advantage of this phenomenon to obtain the position of the parton-hadron coexistence line of QCD matter in the (T, μ_{B}) plane.

A recent outcome from LHC heavy-ion data has been the relatively low p/π ratio measured by the ALICE experiment in central Pb+Pb collisions [6] at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, compared to the expectation from the SHM [7]. A similar result was obtained earlier by the SPS experiment NA49 [8]. This has been interpreted [9, 10, 11, 12] as an evidence of post-hadronization baryon-antibaryon annihilation. An alternative explanation has been put forward in ref. [13]. Recently, the ALICE experiment at the LHC has provided [14] a set of measurements of hadronic multiplicities also as a function of centrality. The improved accuracy and the increased total

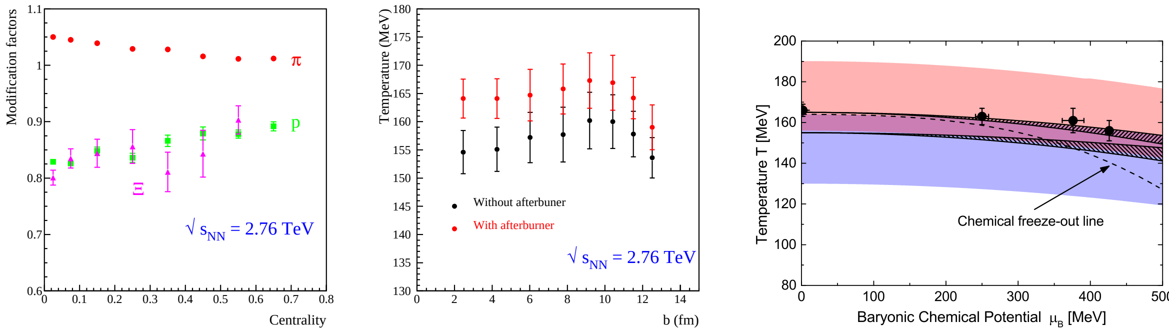

Figure 1. Left: Modification factors for π^+, proton, and Ξ^- as a function of centrality at $\sqrt{s_{\rm NN}} = 2.76$ TeV calculated with UrQMD. Middle: Temperature as a function of the impact parameter b (central values corresponding to centralities measured by ALICE). Black dots: chemical freeze-out temperature. Red dots: LCEP (see text) temperature obtained by including UrQMD modification factors. Right: Predictions from lattice-QCD calculations on the curvature of the crossover line (in T and μ): the upper solid line is the critical temperature defined through strange quark susceptibility, the lower one defined through the chiral condensate) [21, 22] and the colored areas represent the widths of the crossover transitions. The dashed line is the chemical freeze-out line [23], while the reconstructed original chemical equilibrium points in this work are shown as closed circles.

multiplicity with respect to lower beam energy, allows us to identify a dependence of $T_{\rm chem}$ on centrality.

We have analyzed the multiplicities measured by the ALICE experiment [14] to determine the chemical freeze-out parameters with fits to the usual SHM (described in ref. [15]) predictions and to the same formula corrected for the *modification factors*, namely the ratios between the particle yields with hadronic rescattering and the same yields without it. The modification factors have been estimated with a hybrid version of the UrQMD code [16, 17] taking into account hadronic rescatterings after hadron generation according to local thermodynamical equilibrium (Cooper-Frye formula). The modification factors for π^+, proton, and Ξ^- are shown in fig. 1 (left) as a function of the collision centrality. Note that the survival factors get closer to one for peripheral collisions.

The results of the fit including corrections for hadronic rescattering are shown in the middle frame of figure 1. The theoretical yields are calculated multiplying the output from SHM with the modification factors shown in the left part of figure 1 [18]. Therefore, the fitted temperature pertains to the source at its latest chemical equilibrium point (LCEP, see ref. [19]), before hadronic collisions set in.

The fit quality improves after the implementation of hadronic phase corrections. The fitted temperature rises by several MeV, as shown in fig. 1 (middle), in agreement with our previous findings [19]. Furthermore, the LCEP temperature is less centrality dependent than the plain chemical freeze-out temperature, which supports the idea of a universal hadronization temperature [15, 20].

Figure 1 (right) finally shows the resulting new chemical freeze out curve, for central collisions at several beam energies, when the effects of the hadronic final state is taken into account properly, compared with the curvature of the lattice QCD pseudo critical line. One can observe a correspondence of the two lines over a wide range in T and μ_B.

3. Charm Quark transport

Charm quarks are an ideal probe for the QGP. They are produced, in hard processes, early in the collision and therefore probe the medium during its entire evolution. When the system dilutes they hadronize, and their decay products can be detected. The two most interesting observables are the nuclear modification factor, R_{AA}, and the elliptic flow, v_2. Experimentally, the nuclear modification factor shows a large suppression of the open heavy-flavor meson spectra at high transverse momenta (p_T) compared to the findings in pp collisions. The measured large elliptic flow, v_2, of open heavy-flavor mesons indicates that charm quarks take part in the collective expansion of the bulk medium.

We explore the modification of heavy-flavor p_T spectra, using a hybrid model, consisting of the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [16] and a full (3+1)-dimensional ideal hydrodynamical model [24, 25] to simulate the medium expansion. A more detailed description of the hybrid model including parameter tests and results can be found in [17]. The heavy-quark propagation in the medium is modeled by a relativistic Langevin approach [26] which describes the diffusion of a "heavy particle" in a medium consisting of "light particles". One approximates the collision term of the corresponding Boltzmann equation, which can be mapped into an equivalent stochastic (relativistic) Langevin equation:

$$\mathrm{d}x_j = \frac{p_j}{E}\mathrm{d}t \quad \text{and} \quad \mathrm{d}p_j = -\mathit{\Gamma} p_j \mathrm{d}t + \sqrt{\mathrm{d}t}\, C_{jk}\rho_k. \tag{1}$$

Here $\mathrm{d}t$ is the time step in the Langevin calculation, $\mathrm{d}x_j$ and $\mathrm{d}p_j$ are the coordinate and momentum changes in each time-step, $E = \sqrt{m^2 + \boldsymbol{p}^2}$, and Γ is the drag or friction coefficient. The covariance matrix, C_{jk}, of the fluctuating force is related to the diffusion coefficients. Both Γ and C_{jk} dependent on $(t, \boldsymbol{x}, \boldsymbol{p})$ and are defined in the (local) rest-frame of the fluid. The ρ_k are Gaussian-normal distributed random variables. For the production of open charm D mesons we us a quark coalescence approach. To implement this coalescence we perform the Langevin calculation until a decoupling temperature is reached. Subsequently we coalesce a light quark with a heavy quark. As the light quarks constitute the medium propagated by hydrodynamics, the average velocities of the light quarks are approximated by the local flow-velocities of the medium. The mass of the light quarks is assumed to be 370 MeV so that the D-meson mass becomes 1.87 GeV when the masses of the light quarks and the charm quarks (1.5 GeV) are added.

The decay to electrons is calculated using PYTHIA to compare to experimental measurements from the PHENIX collaboration. Fig. 2 (left) shows our results for v_2. The high elliptic flow is due to the momentum kick of the light quarks in the recombination process, which provides additional flow from the medium. For a decoupling temperature of 130 MeV we obtain a reasonable agreement with the experimental data.

In Fig. 2 (right) the nuclear modification factor for non-photonic single electrons is depicted. Also here we obtain a good agreement with the data, especially at moderate $p_T \sim 2\,\mathrm{GeV}$. The coalescence mechanism pushes the heavy quarks to higher p_T. As seen before, we obtain the best agreement to data for rather low decoupling temperatures.

In conclusion we observe that the coalescence mechanism is required to describe experimental data with our Langevin model. Only with the coalescence model one is able to describe both R_{AA} and v_2 consistently in the present model. Within our study we find the best agreement to experimental data using a low decoupling temperature of 130 MeV. This emphasizes the need to study effects of hadronic rescattering on the D-meson properties, as the effective degrees of freedom at such low temperatures should be hadrons.

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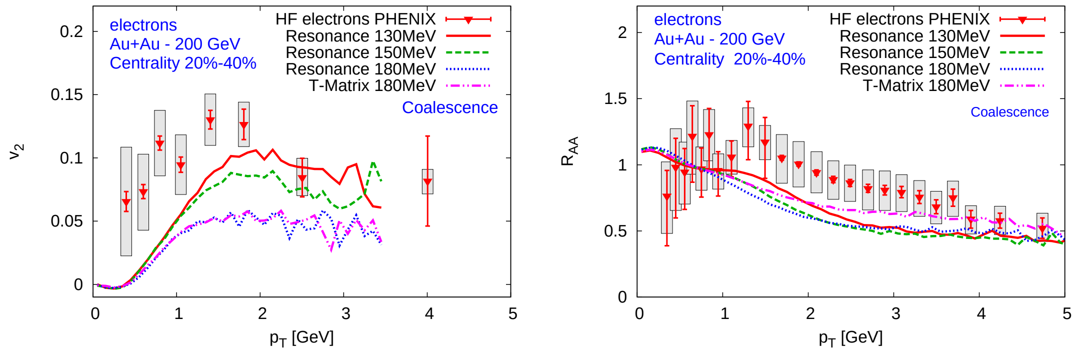

Figure 2. Elliptic flow v_2 (left) and nuclear modification factor R_{AA} (right) of electrons from heavy quark decays in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using a coalescence mechanism. We use a rapidity cut of $|y| < 0.35$. For a decoupling temperature of 130 MeV we obtain a reasonable agreement to data [27].

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