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Production, diffusion and energy loss of heavy quarks in the early stage of high energy nuclear collisions

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In ultrarelativistic nuclear collisions heavy quarks, charm and beauty, are produced almost immediately after the collision between the two colliding objects takes place. In fact, their production (proper) time can be estimated as $\tau_{\text{form}} \approx 1/2m$ where m is the mass of the heavy quarks: this gives $\tau_{\text{form}} \approx 0.06$ fm/c for charm and $\tau_{\text{form}} \approx 0.02$ fm/c for beauty. Consequently, charm and beauty can probe the entire evolution of the system produced by the collision, including the very early stage in which the strong, coherent gluon fields, called the Glasma, dominate the dynamics. The early stage is then followed by the quark-gluon plasma stage, and finally by hadronization. We briefly review the recent developments on the diffusion and the energy loss of charm and beauty in ultrarelativistic heavy ion collisions, with particular emphasis on those in the early stage and on the estimate of the spatial diffusion coefficient of heavy quarks in the quark-gluon plasma.

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1. Introduction

In ultrarelativistic nuclear collisions, namely proton-nucleus (pA) and nucleus-nucleus (AA) collisions at relativistic energies, charm, c, and beauty, b, quarks are produced almost immediately after the collision between the two colliding objects takes place. Indeed, their production proper time, τ_{form}, can be estimated as $\tau_{\text{form}} \approx 1/2m$ where m is the mass of the heavy quarks: this gives $\tau_{\text{form}} \approx 0.06$ fm/c for charm and $\tau_{\text{form}} \approx 0.02$ fm/c for beauty. Consequently, c and b can probe the entire evolution of the system produced by the collision, see [1] for a review as well as references therein. Evolution of c and b includes also the diffusion in the very early stage of the collision, in which the strong, coherent gluon fields, called the Glasma, dominate the dynamics. The early stage is then followed by the quark-gluon plasma (QGP) stage, and finally by the hadronization.

In this talk, we briefly review the recent developments obtained by us on the evolution of HQs in the early stage of pA and AA collisions, as well as on that in the QGP stage. Regarding the evolution in the early stage, after a short introduction to the problem we focus on the relativistic kinetic theory description of HQs, which includes their interaction with the strong initial gluon fields. We then discuss some results on the application of relativistic kinetic theory, improved by a quasi-particle model (QPM), to the propagation of HQs in the QGP stage, discussing the predictions on the nuclear modification factor and the elliptic flow of heavy mesons as well as on the spatial diffusion coefficient of the heavy quarks in the quark-gluon plasma phase.

2. Heavy quarks in the early stage

For nuclear collisions at high energies we adopt the description based on the effective theory of the color glass condensate (CGC) [2–4], see [5] for a review as well as references therein. According to the CGC picture, the collision of the two colliding objects can be viewed as that of two thin sheets of colored glass. The interaction of these sheets during the collision leads to the formation of two sets of effective color charges, one on each sheet, which are connected by filaments of dense gluon fields. These fields are characterized by a large occupation number and are thus classical in nature; moreover, each of this filament contains, at the leading order in the strong coupling, longitudinal color-electric and color-magnetic fields. These fields form in the entire interaction region of the two colliding objects and are known as the Glasma [6]. Within the CGC picture, the Glasma serves as the initial condition for the system created in high energy nuclear collisions. In the simplest implementation, which is the one we adopted in our works, the sources of the fields in the two colored glasses, $\rho_a(\boldsymbol{x}_T)$, are assumed to be gaussian random variables with zero mean and with fluctuations characterized as

$$\langle \rho_a(\boldsymbol{x}_T)\rho_b(\boldsymbol{y}_T)\rangle = (g\mu)^2\delta^{ab}\delta^{(2)}(\boldsymbol{x}_T - \boldsymbol{y}_T), \tag{1}$$

where $\boldsymbol{x}_T$, $\boldsymbol{y}_T$ denote coordinates in the transverse plane, $a, b = 1, \ldots, N_c^2 - 1$ are adjoint color indices, g is the strong gauge coupling and μ denotes the density of color carriers in the transverse plane. The fluctuations (1) are linked to one energy scale, $g\mu$, which is of the order of the main energy scale in this model, namely the saturation scale, Q_s, that corresponds to the scale below which the non-linear QCD effects, in particular the gluon recombination, are important. $Q_s = O(1\ \text{GeV})$

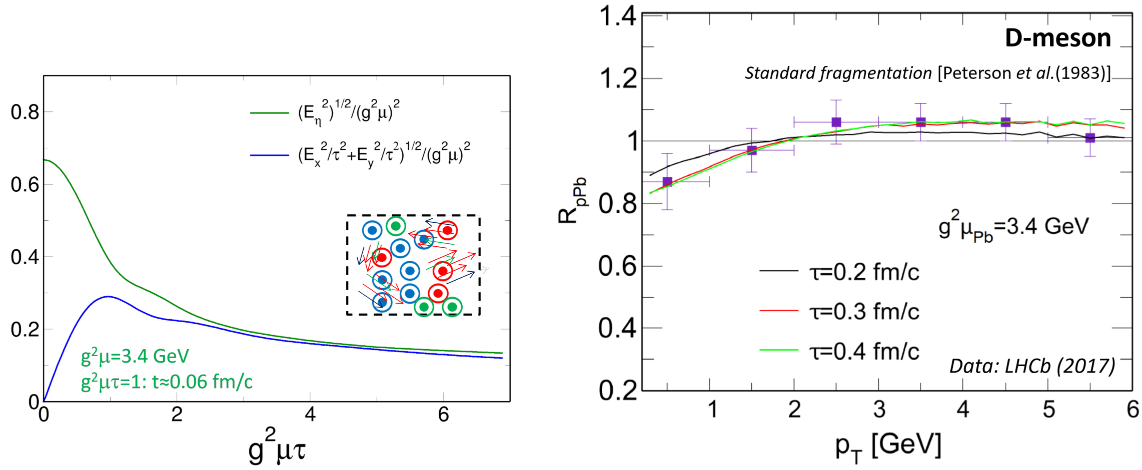

Figure 1: Left panel: averaged components of the color-electric field in the early stage of ultrarelativistic nuclear collisions, taking the Glasma as the initial condition. Right panel: R_{pPb} of $D-$mesons versus p_T, computed within the relativistic kinetic theory coupled to the evolving Glasma fields. Adapted from [12, 13]. Standard fragmentation [24] was used to convert c into $D-$mesons. Experimental data were taken from [**?**].

for large nuclei in collisions at the RHIC and the LHC energies. The Glasma then evolves according to the classical Yang-Mills (CYM) equations, see [11] for details.

In the left panel of Fig. 1 we plot the averaged components of the color-electric field, obtained taking the Glasma as the initial condition and then evolving this by means of the CYM equations. Results for the color-magnetic fields are similar. We notice that initially the fields consist of the longitudinal component only; however, this configuration is unstable, indeed transverse fields form immediately. In the proper time range $g^2\mu\tau \approx 1$ the longitudinal and the transverse fields are of the same magnitude; their amplitude then decreases as a result of the longitudinal expansion of the system. The transverse fields are relevant for the transverse momentum diffusion of HQs in the early stage, see below.

Heavy quarks are produced by hard QCD scatterings during the collision process. We adopted the fixed-order-next-to-leading-log production scheme which leads to the initial spectrum [7–10]

$$\left.\frac{dN}{d^2p_T}\right|_{\mathrm{prompt}} = \frac{x_0}{(1+x_3 p_T^{x_1})^{x_2}}; \tag{2}$$

numerical values of the parameters can be found in [11]. After initialization, HQs are evolved according to relativistic kinetic theory by means of the Wong equations, that are [11, 14–16]

$$\frac{dx_i}{dt} = \frac{p_i}{E}, \quad E\frac{dp_i}{dt} = gQ_a F^a_{i\nu}p^\nu, \quad E\frac{dQ_a}{dt} = -gQ_c\varepsilon^{cba}\boldsymbol{A}_b\cdot\boldsymbol{p}. \tag{3}$$

Here, $E = \sqrt{\boldsymbol{p}^2+m^2}$ is the relativistic kinetic energy of the HQs; $F^a_{\mu\nu}$ and $\boldsymbol{A}_b$ denote the field strength tensor and the gluon field in the evolving Glasma fields. Hence, Eqs. (3) describe the evolution of the HQs in the early stage. Q_a denotes the color charge of HQs. The evolution of HQs in the early stage is dominated by diffusion [11], as a result of the high energy density of the gluon fields combined with the short lifetime of the early stage and the equilibration time of the HQs, which was estimated in [11] to be of the order of a dozen of fm/c. Moreover, the diffusion of HQs in this stage is characterized by the non-linear evolution of the momentum broadening, $\sigma_p \equiv \langle p - \langle p \rangle \rangle^2$, with time, as a result of the diffusion inside coherent domains (color filaments) of the Glasma [11, 14]. The diffusion coefficient in the early stage is in agreement with the one computed within perturbative QCD [17]. For different approaches see [18–21] and references therein. For potential implications on the elliptic flow see [22], while for anisotropic angular momentum fluctuations see [23].

In the right panel of Fig. 1 we plot the nuclear modification factor, R_{pPb}, in a p-Pb collision at the LHC energy, computed in [12, 13]. This result was obtained assuming the initialization (2) and considering the evolution in the Glasma fields according to the scheme descrived above, then adopting a standard fragmentation scenario for converting c quarks into $D-$mesons [24]. We notice that qualitatively, and to some extent also quantitatively, R_{pPb} obtained within the theoretical framework is in fair agreement with the experimental data.

3. Heavy quarks in the QGP stage

Next, we turn to the evolution of HQs in the QGP phase. This was described by relativistic transport theory at a fixed η/s, where η represents the shear viscosity of the QGP and s its entropy density. The collision integrals for the light quarks and the gluons, as well as that for the HQs, are computed within a quasi-particle model with masses obtained by fitting the QCD equation of state [25]. Within this approach one can obtain a good description of R_{AA} and v_2 of heavy mesons at the RHIC and the LHC energies [26]. Moreover, it is possible to compute the thermalization time of HQs in the QGP, or equivalently, the spatial diffusion coefficient, which turns out to be in fairly good agreement with the latest Lattice-QCD data, see [27] and references therein.

4. Conclusions

We presented our recent results on the production, the diffusion and the energy loss of HQs in the ultrarelativistic nuclear collisions. We focused on the evolution of HQs in the early stage, which we described via a diffusion-dominated motion in the strong gluon fields of the Glasma. We then mentioned results about the propagation of HQs in the QGP phase, obtained within an approach based on relativistic kinetic theory coupled to a quasi-particle model. Within this approach it is possible to have a good description of R_{AA} and v_2 and the RHIC and the LHC energy, as well as an estimate of the thermalization time of HQs in the QGP, which is equivalent to the estimate of the spatial diffusion coefficient, D_s: this turns out to be in a fair agreement with the latest Lattice-QCD results.

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