Heavy quark dynamics in QCD matter

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Abstract. Simultaneous description of heavy quark nuclear modification factor R_{AA} and the elliptic flow v_2 is a top challenge for all the existing models. We highlight how the temperature dependence of the energy loss/transport coefficients is responsible for addressing a large part of such a puzzle along with the full solution of the Boltzmann collision integral for the momentum evolution of heavy quarks in the medium. We consider four different models to evaluate the temperature dependence of drag coefficients of the heavy quark in the QGP. We have also highlighted the heavy quark dynamics in the presence of an external electromagnetic field which induces a sizable heavy quark directed flow, $v_1(y)$, that can be measurable at LHC.

1. Introduction

Ongoing experimental efforts at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) aim at creating and characterizing the properties of quark gluon plasma (QGP). The open heavy flavor mesons (mesons which contain one heavy quark, mainly c and b) constitute a novel probe of the QGP properties, because they are produced in the early stage of the heavy-ion collisions and they are the witness of the entire space-time evolution of the QGP.

The two main experimental observables related to the heavy quark dynamics in the QGP are: (i) the nuclear modification factor, R_{AA} [1, 2] which is the ratio of the p_T spectra of heavy flavored mesons (D and B) produced in nucleus + nucleus collisions to those produced in proton + proton collisions scaled with the number of binary collisions and (ii) the elliptic flow, $v_2 = \langle cos(2\phi_p) \rangle$ [2], which is a measure of the anisotropy in the azimuthal distribution of particle production. Several theoretical efforts have been made to study the R_{AA} and the v_2 measured in experiments within different models [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16] (see also for heavy baryons [17]). However all the approaches show some difficulties to describe both the R_{AA} and v_2 simultaneously.

2. Results

To achieve a simultaneous description of R_{AA} and v_2, we need to focus on the time evolution of R_{AA} and v_2 to understand how they develop during the expansion of the QGP. As shown in Ref. [18], the R_{AA} develops mostly at the very early stage of the QGP evolution within 3-4 fm/c, while the v_2 can be transferred to the heavy quarks only at later stages when the fireball has reached temperatures (T) close to the critical temperature. This indicates a more liquid-like behavior of the quark-gluon plasma and the T-dependence of the drag coefficient plays a significance role for a simultaneous description of R_{AA} and v_2 as they are sensitive to the two

different stages of the QGP evolution (T_i and T_c). To investigate the influence of the temperature dependence of the drag (and diffusion) coefficients on heavy quark observables, four different models have been used to calculate the drag and diffusion coefficients.

Model-I (pQCD): In this case, the elastic collisions of heavy quarks with the bulk consisting of light quarks, light anti-quarks and gluons have been considered within the framework of pQCD having temperature dependence of the coupling [19]:

$$g^{-2}(T) = 2\beta_0 ln\left(\frac{2\pi T}{a\,T_c}\right) + \frac{\beta_1}{\beta_0} ln\left[ln\left(\frac{2\pi T}{a\,T_c}\right)\right] \tag{1}$$

where $\beta_0 = (11 - 2N_f/3)/16\pi^2$, $\beta_1 = (102 - 38N_f/3)/(16\pi^2)^2$ and $a = 1.3$. N_f is the number of flavor and T_C is the transition temperature.

Model-II (AdS/CFT): In this second case, we consider the drag force from the gauge/string duality i.e. AdS/CFT [23], $\Gamma = C\frac{T_{QCD}^2}{M_{HQ}}$, where $C = 2.1 \pm 0.5$ and M_{HQ} the diffusion coefficient deduced from fluctuation-dissipation [24].

Model-III (QPM): In this case, we employ a quasi-particle model (QPM) [25, 26] with T-dependent quasi-particle masses, $m_q = 1/3g^2T^2$, $m_g = 3/4g^2T^2$, along with a T-dependent background field known as the bag constant which is tuned to match the thermodynamics of the lattice QCD. Such a fit leads to the coupling, $g^2(T) = \frac{48\pi^2}{[(11N_c - 2N_f)ln[\lambda(\frac{T}{T_c} - \frac{T_s}{T_c})]^2}$, where λ=2.6 and T/T_s=0.57.

Model-IV ($\alpha_{QPM}(T), m_q = m_g = 0$): In this fourth case, we consider a model where the light quarks and gluons are massless but the coupling is taken from the QPM model discussed above. This case is merely a way to obtain a drag coefficient increasing toward T_c.

This fourth case has been considered to have a drag coefficient whose T dependence is similar to that in the T-matrix approach [4, 27].

In Fig 1, we have shown the variation of the drag coefficients obtained within the four different models discussed above. Our methodology is to reproduce the R_{AA} measured experimentally within all the four models, hence, these are the rescaled drag coefficients.
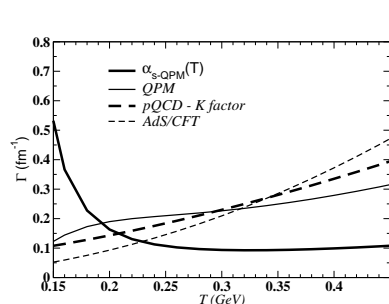

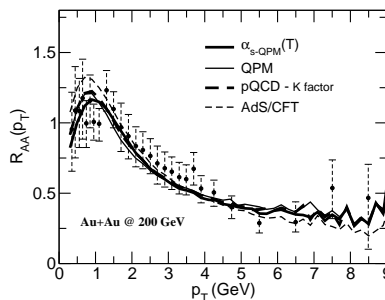**Figure 1.** Drag coefficients as a function of temperature.

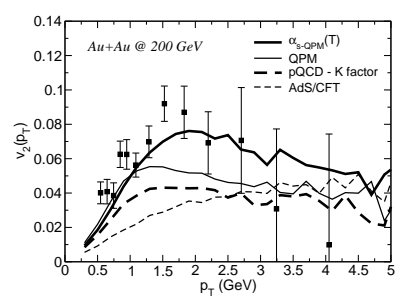**Figure 2.** R_{AA} as a function of p_T for the minimum bias Au+Au collisions.

Figure 3. v_2 as a function of p_T for the minimum bias Au+Au collisions.

We have solved the Langevin dynamics to study the heavy quark momentum evolution in QGP starting from charm quark production in $p + p$ collision [22] as the initial charm quark distributions in the momentum space. To simulate the heavy quark dynamics in QGP, we need the bulk evolution. We are using the transport bulk which can reproduce the gross features of the bulk, i.e. the spectra and elliptic flow. For the $Au + Au$ collisions at the highest RHIC energy, we simulate the QGP evolution with the initial temperature at the center of the fireball

$T_i = 340$ MeV and the initial time $\tau_i = 0.6$ fm/c. For the details of the fireball evolution, we refer to our early works [20, 21].

In Fig 2, we have shown the variation of R_{AA} as a function of p_T for the four different models at RHIC energy. The v_2 for the same R_{AA} has been plotted in Fig 3 for all the four models. The experimental data on non-photonic electrons are taken from ref. [2]. It has been observed that for the same R_{AA}, the v_2 build-up can be quite different depending on the T-dependence of the drag coefficient in the model. The larger the drag coefficient at T_c, the larger the v_2 [8]. Similar effect has also been found in the light quark sector [28, 29]. This suggests that the correct temperature dependence of the drag coefficient has a vital role for a simultaneous reproduction of heavy quark R_{AA} and v_2. The heavy quark observables are also sensitive to the hadronic rescattering [18, 31], to the pre-equilibrium phase [32] as well as to the time evolution equation i.e. whether it follows the Langevin or Boltzmann equation [11]. In particular, the solution of the full two-body collision integral shows that the anisotropic flows are larger with respect to those predicted by a Langevin dynamics. For details we refer to our earlier works [11].

Recently it has been recognized that a very strong magnetic field [33, 34, 35] is created at early times in heavy-ion collisions. Since heavy quarks are produced at the very early stage of evolution due to their large masses, their dynamics can be affected by such a strong magnetic field [37, 38]. The $\vec{B}$ field generated in non-central heavy-ion collisions is dominated by the component along the $\vec{y}$ axis, so its main effect is the induction of a current in the xz plane. For the calculation of the electromagnetic field generated in ultra-relativistic heavy-ion collisions, we refer to the space-time solution developed in Ref. [36]. In Fig.4 we show the time dependence of the magnetic field B_y and electric field E_x at finite space rapidity $\eta = 1.5$ in a $Pb + Pb$ collision with $\sqrt{s} = 2.76$ ATeV at $b = 9.5$ fm for a medium of $\sigma_{el} = 0.023$ fm^{-1}. The impact of the electromagnetic field has been taken into account through the Lorentz force as the external force in the Langevin equation. For details we refer to Ref. [39].

The Magnetic field introduces an anisotropy which eventually leads to a substantial directed flow, $v_1 = \langle p_x/p_T \rangle$, that is measurable experimentally. In Fig. 5 we show the resulting directed flow v_1 as a function of rapidity for charm (black solid line) and anti-charm quarks (dashed line). We find a substantial v_1 at finite rapidity with a peak at $y \simeq 1.75$. The flow is negative for positive charged particle (charm) at forward rapidity which means that the magnetic field dominates over the displacement induced by the Faraday current associated with the time dependence of the magnetic field. This is a non-trivial result and depends not only on the absolute magnitude of the magnetic field but also on the strength of heavy-light quark interaction. If we artificially increase the drag coefficient by a factor 5 to achieve a thermalization of the charm quarks similar to that of the light quarks, this will lead to a much smaller $v_1(y)$.
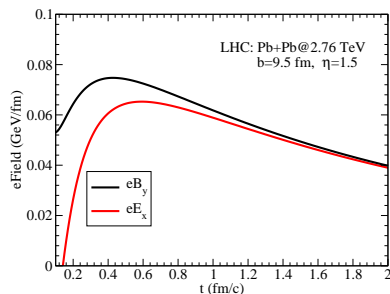
Figure 4. Time evolution of the magnetic field eB_y and the electric field eE_x in the forward rapidity region.
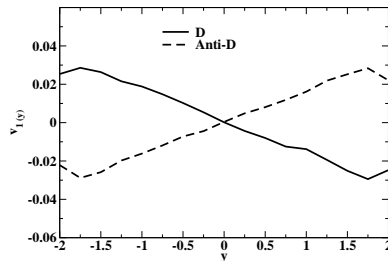
Figure 5. Directed flow v_1 as a function of the rapidity in $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ ATeV with $b = 9.5$ fm for D meson $[c\bar{q}]$ (solid line) and anti-D meson $[\bar{c}q]$ (dashed line).

3. Summary and outlook

In summary, we have shown how the v_2 build-up for the same R_{AA} depends on the T-dependence of the drag coefficient which is the key for a simultaneous description of heavy quark R_{AA} and v_2. The larger the drag coefficient at T_c, the larger the v_2. We have also studied the heavy quark dynamics in the presence of an external electromagnetic field. Heavy quarks develop a sizable directed flow (v_1) which could be measurable experimentally. The present study suggests that the heavy quark v_1 can be considered a sensitive probe to the creation and characterization of the magnetic field in the heavy-ion collisions

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