Heavy quark dynamics in the QGP: $R_{AA}$ and $v_2$ from RHIC to LHC

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Abstract

We study the stochastic dynamics of $c$ and $b$ quarks in the hot plasma produced in nucleus-nucleus collisions at RHIC and LHC, providing results for the nuclear modification factor $R_{AA}$ and the elliptic flow coefficient $v_2$ of the single-electron spectra arising from their semi-leptonic decays. The initial $Qar{Q}$ pairs are generated using the POWHEG code, implementing pQCD at NLO. For the propagation in the plasma we develop a relativistic Langevin equation (solved in a medium described by hydrodynamics) whose transport coefficients are evaluated through a first-principle calculation. Finally, at $T_c$, the heavy quarks are made hadronize and decay into electrons: the resulting spectra are then compared with RHIC results. Predictions for LHC are also attempted.

Keywords: Quark Gluon Plasma, heavy quarks, Langevin equation, transport coefficients

1. Introduction

Heavy quarks, produced in initial hard processes, allow to perform a “tomography” of the medium created in the relativistic heavy-ion collisions at RHIC and (soon) at LHC. The modification of their spectra provides information on the properties (encoded into few transport coefficients) of the matter (hopefully a thermalized Quark Gluon Plasma) crossed before hadronizing and giving rise to experimental signals: so far, the electrons from their semi-leptonic decays. We employ an approach based on the relativistic Langevin equation, assuming that medium-modifications of the initial heavy-quark spectrum arise from the effects of many independent random collisions. As a final outcome we provide results for the $R_{AA}$ and $v_2$ of non-photonic electrons from heavy-flavor decays measured at RHIC and attempt predictions for LHC. Further results can be found in Refs. [1, 2]. For similar studies see Refs. [3, 4, 5, 6, 7].

2. The relativistic Langevin equation

The usual Langevin equation can be generalized to the relativistic case [12], providing a tool to study the propagation of $c$ and $b$ quarks in the QGP. The variation of the heavy-quark momentum in the time-interval $\Delta t$

$$\frac{\Delta \vec{p}}{\Delta t} = -\eta_0(p) \vec{p} + \xi(t),$$

is given by the sum of a deterministic friction term and a stochastic noise term $\xi(t)$, which is completely determined by its two-point temporal correlator

$$\langle \xi(t) \xi(t') \rangle = b^j(p) \delta(t-t'), \quad \text{with} \quad b^j(p) \equiv \kappa_T(p) \vec{p}^j + \kappa_L(p) (\delta^j - \vec{p}^j).$$

The latter involves the transport coefficients $\kappa_T(p) \equiv \frac{1}{2} \frac{\langle \Delta \vec{p}_T^2 \rangle }{\Delta \vec{p}^2}$ and $\kappa_L(p) \equiv \frac{\langle \Delta \vec{p}_L^2 \rangle }{\Delta \vec{p}^2}$, representing the average transverse and longitudinal squared-momentum acquired per unit time by the heavy quark due to the collisions suffered in the...
medium. Finally, as in the non-relativistic case, the friction coefficient $\eta_D(p)$ is fixed in order to insure the approach to thermal equilibrium. In the Ito discretization $[8]$ of Eq. (1) one has:

$$
\eta_D^{\text{Ito}}(p) = \frac{\kappa_L(p)}{2\pi T} - \frac{1}{E^2} \left[ (1 - y^2) \frac{\partial \kappa_L(p)}{\partial y^2} + \frac{d - 2}{2} \frac{\kappa_L(p) - \kappa_T(p)}{y^2} \right].
$$

Eq. (3) has then to be solved in the evolving medium produced in the heavy-ion collisions and described by ideal/viscous hydrodynamics. For this purpose the output of two independent hydro codes $[9, 10, 11]$ are exploited. Details on the employed procedure can be found in Refs. $[1, 2]$.

3. Evaluation of the transport coefficients

The transport coefficients $\kappa_T/L$ are evaluated according to the procedure presented in Refs. $[1, 2]$. Following Ref. $[13]$ we introduce an intermediate cutoff $|t^*| \sim m_D^2$ $(t \equiv (p^2 - T^2)^2)$ separating hard and soft scatterings. The contribution of hard collisions ($|t| > |t^*|$) is evaluated through a kinetic QCD calculation of the processes $Q(p)q_{t^*} \rightarrow Q(p')q_{t^*}$ and $Q(p)g \rightarrow Q(p')g$ $[14]$. On the other hand in soft collisions ($|t| < |t^*|$) the exchanged gluon feels the presence of the plasma. A resummation of medium effects is thus required and this is provided by the Hard Thermal Loop approximation. The final result is given by the sum of the two contributions $\kappa_T/L(p) = \kappa_{T/H}^{\text{hard}}(p) + \kappa_{T/L}^{\text{soft}}(p)$ and its explicit expression can be found in Ref. $[11]$. In Fig. 1 we display the behavior of the transport coefficients of $c$ and $b$ quarks. The sensitivity to the value of the intermediate cutoff $|t^*|$ is quite small, hence supporting the validity of the approach.

4. Numerical results: single-electron spectra at RHIC and LHC

For each explored case we generated an initial sample of $45 \cdot 10^6$ $c\bar{c}$ and $b\bar{b}$ pairs, using the POWHEG code $[15]$ with CTEQ6M PDFs. In the $AA$ case we introduced nuclear effects in the PDFs according to the EPS09 scheme $[16]$; the quarks were then distributed in the transverse plane according to the nuclear overlap function $dN/dx_{\perp} \sim T_{AB}(x, y) \equiv T_A(x+b/2, y)T_B(x-b/2, y)$. At the proper-time $\tau \equiv t^2 - z^2 = \tau_0$ we started following the Langevin dynamics of the quarks until hadronization. The latter was modeled using Peterson fragmentation functions $[17]$, with branching fractions into the different hadrons taken from Refs. $[18, 19]$. Finally each hadron was forced to decay into electrons with PYTHIA $[20]$, using updated decay tables $[21]$. The $e$-spectra from $c$ and $b$ were then combined with a weight accounting for the respective total production cross-section and for the branching ratios of the various processes

![Figure 1: The transport coefficients $\kappa_T/L$ of $c$ and $b$ quarks after summing the soft and hard contributions. The dependence on the cutoff $|t^*|$ is mild. The coupling $g$ was evaluated at the "central value" of our systematic scan $\mu = 1.5\pi T$.](image)
Table 1: Initialization for RHIC and LHC: the \( c\bar{c} \) and \( b\bar{b} \) production cross section given by POWHEG and the explored hydro scenarios.

|          | \( \sqrt{s_{NN}} \) (GeV) | \( \sigma_{c\bar{c}} \) (\( \mu b \)) | \( \sigma_{b\bar{b}} \) (\( \mu b \)) | Hydro code | \( \tau_0 \) (fm/c) | \( s_0 \) (fm\(^{-3}\)) | \( T_0 \) (MeV) |
|----------|-----------------|-----------------|-----------------|------------|-----------------|-----------------|-----------------|
| p-p      | 200             | 254.14          | 1.769           | ideal      | 0.6             | 110             | 357             |
| Au-Au    | 236.11          | 2.033           |                 | viscous    | 1.0             | 83.8            | 333             |
|          | 5.5             | 3.0146          | 0.1872          | viscous    | 0.1             | 1840            | 854             |
| Pb-Pb    | 2.2877          | 0.1686          |                 | viscous    | 1.0             | 184             | 420             |

Figure 2: The electron \( R_{AA} \) for minimum bias Au-Au collisions (corresponding to an impact parameter \( b=8.44 \) fm) at \( \sqrt{s_{NN}} = 200 \) GeV compared with PHENIX results [22]. The sensitivity to the scale \( \mu = \pi T - 2\pi T \) is displayed. The high-momentum region \( (p_T > \sim 4 \) GeV/c) is better reproduced with the intermediate coupling. Ideal (left panel) and viscous (right panel) hydro scenarios provide similar results.

Figure 3: The electron \( R_{AA} \) and \( v_2 \) for minimum bias Pb-Pb collisions \( (b=8.58 \) fm) at LHC for the two hydro scenarios considered.

leading to electrons in the final state. We first address the RHIC case. The parameters characterizing the “initial state” are given in Table 1. In Fig. 2 our results for the electron \( R_{AA} \) in minimum-bias collisions are displayed and compared with PHENIX data [22]. The dependence on the hydro scenario is quite small. The major uncertainty comes from the scale at which one evaluates the coupling \( g \): for that we explore the range \( \mu = \pi T - 2\pi T \). The high-
momentum region ($p_T \gtrsim 4$ GeV/c) is better reproduced evaluating $\alpha_s$ at the scale $1.5\pi T$ ($\alpha_s = 0.32$ at $T = 300$ MeV). Hadronization via coalescence \cite{4}, so far ignored, could improve the agreement at lower $p_T$. Results for $v_2$ can be found in Ref. \cite{2}. We address now the LHC case, described by the parameters in Table 1. Notice the dramatic effect of the nPDFs on the $c\bar{c}$ production. Our findings for $R_{AA}$ and $v_2$ are shown in Fig. 3 While the $b$-spectrum is simply suppressed at high-$p_T$, the charm – beside a stronger quenching – also displays a sizable flow. Finally in Fig. 4 we provide a comparison of our results for the inclusive ($c+b$) single-electron spectra for RHIC and LHC conditions. In the last case the larger initial temperature entails a stronger quenching and a more pronounced elliptic flow. The effect would be even stronger in the absence of initial state effects, responsible for a larger $\sigma_{b\bar{b}}/\sigma_{c\bar{c}}$ at LHC with respect to RHIC.

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Figure 4: The electron $R_{AA}$ and $v_2$ for minimum bias collisions at RHIC (Au-Au at $\sqrt{s_{NN}} = 200$ GeV) and LHC (Pb-Pb at $\sqrt{s_{NN}} = 5.5$ TeV).