Heavy-flavor dynamics in nucleus–nucleus collisions: from RHIC to LHC

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Abstract. The stochastic dynamics of \(c\) and \(b\) quarks in the fireball created in nucleus–nucleus collisions at RHIC and LHC is studied employing a relativistic Langevin equation, based on a picture of multiple uncorrelated random collisions with the medium. Heavy-quark transport coefficients are evaluated within a pQCD approach, with a proper HTL resummation of medium effects for soft scatterings. The Langevin equation is embedded in a multi-step setup developed to study heavy-flavor observables in \(pp\) and \(AA\) collisions, starting from a NLO pQCD calculation of initial heavy-quark yields, complemented in the nuclear case by shadowing corrections, \(k_T\)-broadening and nuclear geometry effects. Then, only for \(AA\) collisions, the Langevin equation is solved numerically in a background medium described by relativistic hydrodynamics. Finally, the propagated heavy quarks are made hadronize and decay into electrons. Results for the nuclear modification factor \(R_{AA}\) of heavy-flavor hadrons and electrons from their semi-leptonic decays are provided, both for RHIC and LHC beam energies.

Heavy-flavor electron spectra, measured in Au–Au collisions at \(\sqrt{s_{NN}} = 200\) GeV by PHENIX \([1, 2]\) and STAR \([3]\) experiments at RHIC, have displayed a large suppression with respect to \(pp\) collisions, comparable in amount to the one observed for charged hadrons. Models considering medium-induced gluon radiation \([4, 5]\) as the dominant energy loss mechanism for heavy quarks propagating in QGP come up against difficulties in reproducing such results.

These findings gave a great boost to calculations taking in consideration the role of collisional energy loss \([6, 7]\). In some models the heavy-quark propagation in QGP is described through a Langevin stochastic equation \([8, 9, 10]\), assuming that heavy-quark spectrum modifications arise from the cumulated effect of many uncorrelated random collisions with the medium.
In our approach we use a relativistic Langevin equation \([11]\), describing the time evolution of the heavy-quark momentum:

\[
\frac{\Delta p^i}{\Delta t} = -\eta_D(p)p^i + \xi^i(t)
\]

that involves a deterministic friction term and a stochastic noise term \(\xi^i(t)\), completely determined by its two-point temporal correlator:

\[
\langle \xi^i(t)\xi^j(t') \rangle = b^j(p)\delta(t-t') \quad \text{with} \quad b^j(p) \equiv \kappa_L(p)p^j + \kappa_T(p)(\delta^j - \bar{p}^j\bar{p}^i)
\]

The latter involves the transport coefficients \(\kappa_T(p)\equiv \frac{1}{2} \langle \Delta p_T^2 \rangle\) and \(\kappa_L(p)\equiv \frac{\langle \Delta p_L^2 \rangle}{\Delta t}\), which are evaluated according to the procedure presented in \([12]\). We introduce an intermediate cutoff \(|t|^* \sim m_D^2 (t \equiv (P'-P)^2)\) to separate hard and soft scatterings. The contribution of hard collisions \((|t| > |t|^*)\) is evaluated through a pQCD calculation of the processes \(Q(P)q_{i/\bar{i}} \to Q(P')q_{i/\bar{i}}\) and \(Q(P)g \to Q(P')g\). On the other hand for soft collisions \((|t| < |t|^*)\) a resummation of medium effects is provided by the Hard Thermal Loop approximation, with \(\alpha_s(\mu)\) evaluated at a scale \(\mu \propto T\). The final result \([12]\) is given by \(\kappa_T/L(p) = \kappa_{T/L}^{\text{hard}}(p) + \kappa_{T/L}^{\text{soft}}(p)\). According to the scale \(\mu\) at which \(\alpha_s(\mu)\) is evaluated to calculate \(\kappa_{T/L}^{\text{hard}}\), we devised two different sets of calculations, referred to in the following as HTL1 (for \(T \propto T\)) and HTL2 (for \(\mu = |t|\)).

The Langevin simulation tool is embedded in a full setup to calculate heavy-flavor observables in pp and AA collisions, divided into the following independent steps \([12]\):

(i) A sample of \(c\) and \(b\) quarks is generated using POWHEG \([13]\), a code which implements pQCD at NLO accuracy, with CTEQ6M PDFs as input. For AA collisions, EPS09 nuclear corrections to PDFs are employed \([14]\); then, heavy quarks are distributed in the transverse plane according to the nuclear overlap function \(T_{AB}(x,y) \equiv T_A(x+b/2,y)T_B(x-b/2,y)\) corresponding to the selected impact parameter \(b\); a \(p_T\)-broadening correction to heavy-quark momenta is also included.

(ii) At a given proper-time \(\tau_0\) an iterative procedure is started, only for AA collisions, to follow the stochastic evolution of the heavy quarks in the plasma until hadronization: the Langevin transport coefficients are evaluated at each step according to the local 4-velocity and temperature \(T(x)\) of the expanding background medium, as provided by hydrodynamic codes: both ideal and viscous fluid scenarios were tested \([15, 16, 17]\).

(iii) Heavy quarks are made fragment into hadron species, sampled according to \(c\) and \(b\) branching fractions taken from Refs. \([18, 19]\), while their momenta are sampled from a Peterson fragmentation function \([20]\, with \(\epsilon = 0.04\) and 0.005 for \(c\) and \(b\) respectively. Finally, each heavy-quark hadron is forced to decay into electrons with PYTHIA \([21]\), using updated tables of branching ratios based on Ref. \([19]\).

The effects of the Langevin evolution of \(c\) and \(b\) quarks in AA collisions resulting from our calculations are studied through the nuclear modification factor \(R_{AA}(p_T) \equiv \left( \frac{dN/dp_T}{dN/dp_T} \right)^{AA}/\left\langle N \right\rangle_{\text{coll}}(dN/dp_T)^{pp}\) and the elliptic flow coefficient \(v_2(p_T) \equiv \langle \cos(2\phi) \rangle_{p_T}\) of
Figure 1. (left) $R_{AA}(p_T)$ of heavy-flavor electrons in minimum-bias Au–Au collisions at RHIC ($0 - 92\%$ of the inelastic cross section); (right) $R_{AA}$ obtained by integrating the electron yields over the indicated momentum ranges, as a function of $N_{\text{part}}$. In both panels our predictions (with HTL1 calculation) are compared to PHENIX data [2].

final-state heavy-quark hadrons or decay-electrons. Here we will display only results obtained using viscous hydrodynamics for some representative values of the input parameters ($\tau_0$ and the QCD scale $\mu$), among those fully explored in [12].

In Fig. 1 our findings for the $R_{AA}$ of heavy-flavor electrons in Au–Au collisions at RHIC ($\sqrt{s_{NN}} = 200$ GeV), obtained with the calculation HTL1 by assuming viscous hydrodynamics, $\tau_0 = 1$ fm/c and $\mu = 3\pi T/2$, are compared to PHENIX [2] data. In the left panel we observe a general agreement of $R_{AA}(p_T)$ with the PHENIX results on a minimum-bias data sample ($0 - 92\%$ of the inelastic cross section) for $p_T \gtrsim 3$ GeV/c. In the right panel, displaying the $R_{AA}$ obtained by integrating the electron yields above a given $p_T$ and plotted versus $N_{\text{part}}$, the centrality dependence of the PHENIX data is shown to be nicely reproduced, except for the most-peripheral centrality bin. We do not show here the results obtained for the heavy-flavor electron $v_2(p_T)$ [12], that appear to underestimate the PHENIX minimum-bias data. However, a more detailed treatment of hadronization, including also the coalescence mechanism, should enhance both $v_2$ and $R_{AA}$ at $p_T \lesssim 3$ GeV/c.

In Fig. 2 we show our predictions for the $R_{AA}(p_T)$ of heavy-flavor electrons (left panel) and of $D$, $B$ mesons (right panel) in Pb–Pb collisions at LHC ($\sqrt{s_{NN}} = 2.76$ TeV), calculated by selecting the $0 - 10\%$ most-central events, under the hypothesis of viscous hydrodynamics and for two different choices (HTL1 or HTL2) of the $\mu$ scale in the calculation of $\kappa^{\text{hard}}_{T/L}$. General features of the $R_{AA}$ of heavy-flavor electrons appear similar to those observed at RHIC at the same centrality [12], with a stronger suppression of both charm and bottom contributions. However, results obtained with the calculation HTL2 display a weaker quenching for $p_T > 3$ GeV/c. As regards $D$ and $B$ suppression, slighter differences between HTL1 and HTL2 are observed, and at higher $p_T$.

The main goal of our study was to deliver a weak-coupling calculation to be used
as a benchmark for advanced studies or less conventional scenarios. The capability to accommodate the electron spectra observed at RHIC for $p_T \gtrsim 3$ GeV/$c$ strengthens the hypothesis that heavy-quark collisional energy loss must be taken into proper account. Moreover, we will soon be able to test our predictions against first data with Pb–Pb collisions delivered by LHC experiments [22] [23] [24].

References
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