

Heavy quark energy loss and angular de-correlation in a quark-gluon plasma matter

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Abstract. We study heavy quark energy loss in a hot and dense nuclear matter in the framework of Langevin equation coupled to a (2+1)-dimensional hydrodynamic model. The classical Langevin framework is modified such that both quasi-elastic scattering and gluon radiation are incorporated. We provide good description of D meson suppression measured by the ALICE collaboration. We further investigate the angular correlation function of $c\bar{c}$ pairs, and find that it can be potentially employed to distinguish different energy loss mechanisms of heavy quarks inside QGP.

1. Introduction

It is now generally accepted that a deconfined state of QCD matter, the *strongly interacting quark-gluon plasma* (sQGP), is created during relativistic heavy-ion collisions at RHIC and LHC. Such hot and dense matter displays properties similar to a nearly perfect fluid and has been successfully described by hydrodynamic models. Among various probes of QGP properties, heavy quarks are of great interest because their high- p_T suppression and elliptic flow are revealed as significant as the light flavors in spite of their large mass [1, 2, 3]. Therefore, it is crucial to explore how heavy quarks interact with and lose energy inside such QGP matter.

Between the two energy loss mechanisms of heavy quark – gluon radiation and quasi-elastic scattering with background particles, the latter is usually considered to be dominant at low energies because the radiation phase space is restricted by the “dead-cone effect” [4]. In the limit of multiple scatterings where the momentum transfer during each interaction is small, such scatterings inside a thermalized medium can be described by the Langevin equation [5, 6]. This framework has provided good descriptions of heavy flavor suppression and elliptic flow measured at RHIC. However, when extending to the LHC energies, our previous study [7] indicated that the radiative energy loss should no longer be ignored since heavy quarks also become ultra-relativistic. We modify the classical Langevin approach such that gluon radiation is also incorporated. The momentum distribution of the radiated gluons is simulated using the Higher-Twist calculation [8, 9]. Within this improved approach, we find our calculation of D meson suppression consistent with the LHC data [2].

Another interesting quantity for exploring the energy loss of hard probes is the two particle correlations [10, 11]. In this work, we study the angular correlation function of $c\bar{c}$ pairs after they traverse the medium and find that it is sensitive to different energy loss mechanisms. If future measurements are able to provide related observations, we may acquire better understanding about how heavy quarks lose energy inside hot QGP.



2. Methodology

The heavy quark motion inside QGP is governed by the following modified Langevin equation:

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g. \quad (1)$$

The first two terms on the right are the drag force and the thermal random force from the classical Langevin equation for Brownian motion, and the third term $\vec{f}_g = -d\vec{p}_g/dt$ is introduced for the force exerted on the heavy quark due to gluon radiation. The probability of gluon radiation during each time interval Δt is determined by the average number of gluons:

$$P_{\text{rad}}(t, \Delta t) = \langle N_g(t, \Delta t) \rangle = \Delta t \int dx dk_{\perp}^2 \frac{dN_g}{dx dk_{\perp}^2 dt}, \quad (2)$$

where k_{\perp} is the transverse momentum of the radiated gluon, and x is the ratio between the gluon energy and the heavy quark energy. If a gluon is emitted, its energy and momentum is sampled according to the distribution from the Higher-Twist calculation [8, 9]:

$$\frac{dN_g}{dx dk_{\perp}^2 dt} = \frac{2\alpha_s(k_{\perp})}{\pi} P(x) \frac{\hat{q}}{k_{\perp}^4} \sin^2 \left(\frac{t - t_i}{2\tau_f} \right) \left(\frac{k_{\perp}^2}{k_{\perp}^2 + x^2 M^2} \right)^4. \quad (3)$$

With the assumption that the interaction during each scattering is small, the fluctuation-dissipation relation between the drag and the thermal force still holds $-\eta_D(p) = \kappa/(2TE)$, where κ is the momentum space diffusion coefficient defined in $\langle \xi^i(t) \xi^j(t') \rangle = \kappa \delta^{ij} \delta(t - t')$. Note that such Einstein relation between gluon radiation and absorption has not been included yet due to the lack of the latter process. However, we set a lower limit of the gluon energy at $\omega_0 = \pi T$ – the balance point between gluon emission and absorption, above which the classical Langevin equation is modified by gluon radiation. Below ω_0 , the heavy quark motion is dominated by quasi-elastic scatterings whose detail balance is well defined. These assumptions guarantee the equilibrium of heavy quarks after a sufficiently long time of evolution. Different transport coefficients are related via $D = 2T^2/\kappa$ and $\hat{q} = 2\kappa C_A/C_F$, where D is the spatial diffusion coefficient of heavy quark and \hat{q} is the gluon transport coefficient.

We use this modified Langevin equation to simulate the heavy quark evolution. The QGP is generated with a (2+1)D viscous hydrodynamic model, which was developed by Song [12, 13] and has recently been modified by Qiu and Shen for increased numerical stability [14]. We here employ the code version and parameter tunings for Pb+Pb collisions at LHC energies that were previously used in Ref. [14]. The MC-Glauber initialization is adopted for the hydrodynamic calculation if not otherwise emphasized. Our heavy quarks are initialized with the MC-Glauber model for the position space and a leading-order pQCD calculation for the momentum space, and are fragmented to heavy mesons via Pythia 6.4 after they traverse the medium.

3. Results

In Fig.1, we compare the D meson suppression between different energy loss mechanisms and the recent LHC data [2]. The heavy quark transport coefficient is set at $D = 6/(2\pi T)$. One observes that collisional energy loss dominates the low p_T region while gluon radiation dominates the high p_T region. The combination of the two mechanisms provides a good description of the D meson R_{AA} . The slight deviation at low p_T (below 2 GeV/c) may originate from lacking the corrections of cold nuclear matter effect and the recombination mechanism of heavy flavor hadronization in our current calculation, which will be incorporated in the future effort.

Figure 2 compares v_2 with experimental observation. Our calculation seems to underestimate the D meson v_2 , but various uncertainties still exist. For instance, as shown by Fig.3, if the

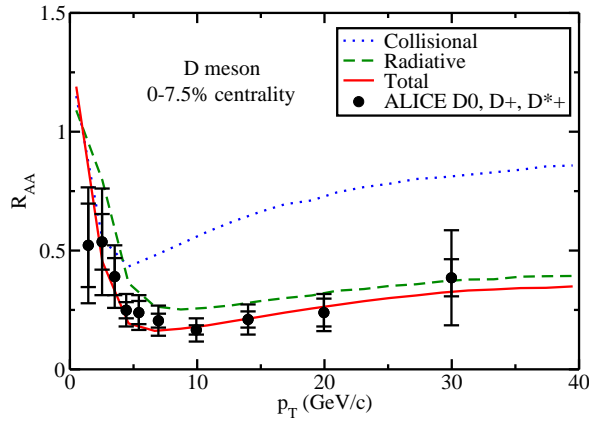


Figure 1. (Color online) Comparison of D meson R_{AA} between different heavy quark energy loss mechanisms and ALICE data.

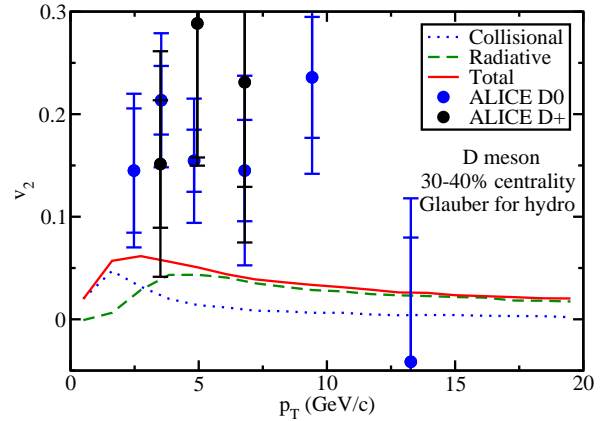


Figure 2. (Color online) Comparison of D meson v_2 between different heavy quark energy loss mechanisms and ALICE data.

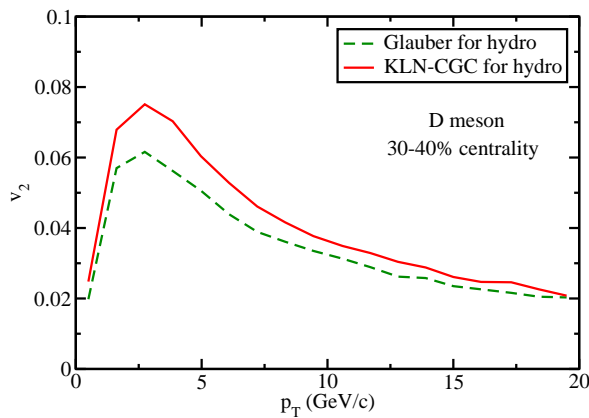


Figure 3. (Color online) Influence of the initial conditions of the hydrodynamic model on D meson v_2 .

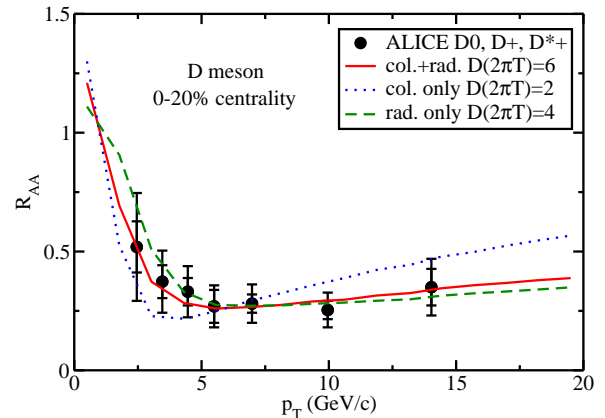


Figure 4. (Color online) Fitting D meson R_{AA} with different energy loss mechanisms by tuning the transport coefficient.

initial condition for the hydrodynamic calculation is altered from MC-Glauber to KLN-CGC, we obtain larger eccentricity of the QGP profile and therefore a larger D meson v_2 by around 30%, while the overall suppression is not significantly influenced.

Figures 4 and 5 demonstrate how the $c\bar{c}$ de-correlation behavior may help distinguish between different energy loss mechanisms. For simplicity, in this initial study, we assume back-to-back initial production of $c\bar{c}$ pairs¹. By tuning the values of transport coefficient for each energy loss mechanism alone, we are able to obtain a reasonable fit to the data (Fig.4), however, different mechanisms lead to significantly different final state $c\bar{c}$ angular correlation (Fig.5(a)). With only collisional energy loss, the correlation function is almost flat between 0 and π , indicating the thermalization of charm quarks after they traverse QGP. On the contrary, the angular correlation distribution still peaks around π for the case of only gluon radiation, implying $c\bar{c}$ pairs strongly correlated after traversing the medium. This can be understood from the small angle dominance for the gluon radiation. Though such correlation functions are model dependent, they may

¹ Higher order contributions to heavy quark production include gluon splitting into a $c\bar{c}$ pair, contributing to small angle correlation. We shall study these in a forthcoming work.

provide deeper insight of the energy loss mechanism if a comparison can be made between theory and experiment. Last but not least, the thermalization behavior strongly depends on the momentum scale [15]. Figure 5(b) shows the result when a 2 GeV/c low p_T cut is applied.

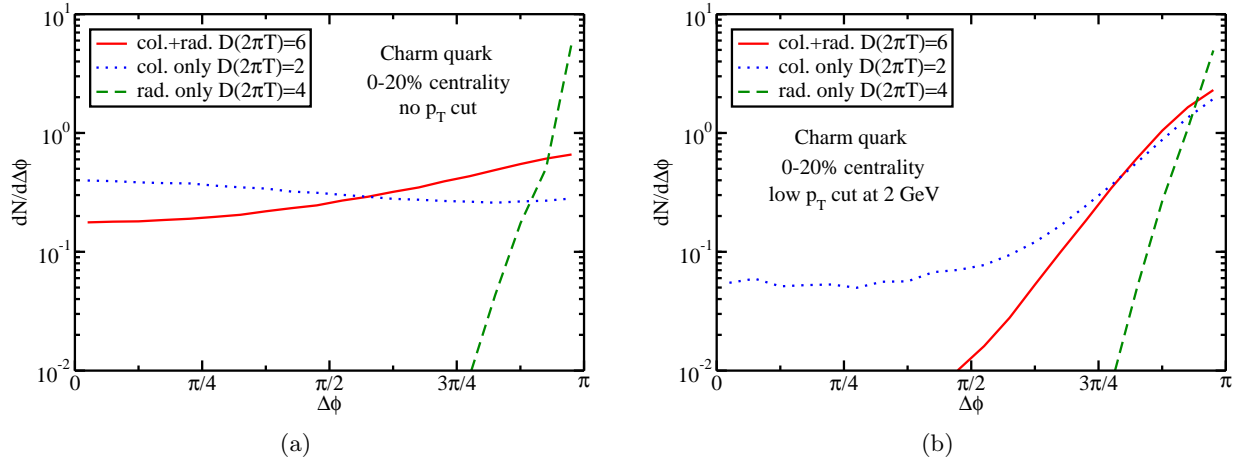


Figure 5. (Color online) Comparison of final state $c\bar{c}$ pair angular correlation functions between different energy loss mechanisms, (a) without momentum cut and (b) with 2 GeV/c low p_T cut.

4. Summary

We have studied heavy quark evolution inside a QGP medium in the framework of a Langevin equation. The classical Langevin approach has been modified such that both collisional and radiative energy loss are incorporated. Our calculation reveals a significant effect of the medium-induced gluon radiation on the heavy quark energy loss at LHC energies, and provides a good description of the D meson suppression measured by the ALICE collaboration. We have briefly discussed the $c\bar{c}$ pair angular correlation function, which may serve as an additional measurable quantity to help distinguish different energy loss mechanisms.

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