The Influence of Initial State Fluctuations on Heavy Quark Energy Loss in Relativistic Heavy-ion Collisions

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We study the effects of initial state fluctuations on the dynamical evolution of heavy quarks inside a quark-gluon plasma created in relativistic heavy-ion collisions. The evolution of heavy quarks in QGP matter is described utilizing a modified Langevin equation that incorporates the contributions from both quasi-elastic scatterings and medium-induced gluon radiation. The spacetime evolution of the fireball medium is simulated with a (2+1)-dimensional viscous hydrodynamic model. We compare the results from smooth and fluctuating initial conditions and find that heavy quarks tend to lose more energy inside a medium with local fluctuations. The possibility of using hard probes to infer the information of initial states of heavy-ion collisions is discussed.

I. INTRODUCTION

High energy heavy-ion collisions at the Relativistic Heavy-ion Collider (RHIC) and the Large Hadron Collider (LHC) provide unique opportunities to study QCD matter at extreme temperatures and densities. It is now well established that a highly excited and color deconfined quark-gluon plasma (QGP) may be created in these energetic nucleus-nucleus collisions. The dynamical evolution of the bulk matter has been successfully described by models utilizing relativistic hydrodynamic simulation [1], in particular the strong collective flow behaviors exhibited by the soft hadrons formed out of the expanding QGP fireball [2, 3]. Recently there has been significant effort in studying initial state fluctuations in heavy-ion collisions, such as the fluctuations of nucleon positions and color charges inside initial colliding nuclei [5]. Some of the most interesting consequences of initial state fluctuations include nonzero anisotropy in ultra-central collisions and the presence of odd-order harmonic geometry and flow [6–15]. The elliptic, triangular and other higher-order harmonic flows have been measured at RHIC and the LHC [16–18]. These measurements have triggered great interest in studying the origin of the initial state fluctuations, and how they affect the dynamical evolution of the fireball and manifest in the final state particle flow and correlations [1, 7, 9, 12, 13, 19–22]. One of the purposes of these studies is to obtain a quantitative extraction of transport properties such as the shear viscosity of the QGP matter produced in high energy nucleus-nucleus collisions.

Interestingly, the initial conditions especially the geometry of the heavy-ion collisions still remain one of the major uncertainties in the extraction of a precise value for QGP shear viscosity [23–25]. Various fluctuations such as the initial transverse flow and longitudinal fluctuations [21, 20] may introduce more uncertainties in our understanding of the initial states. The purpose of this work is to investigate the effect of fluctuating initial conditions on the dynamics of heavy quark in medium and whether it is possible to infer information on the initial state fluctuations in heavy-ion collisions from heavy flavor observables.

Heavy quarks, due to their large masses, are mainly produced via initial hard scatterings, and thus provide a valuable tool to probe the spacetime profile and transport properties of the QGP fireball. Previous studies have shown that low-\(p_T\) heavy quarks provide direct measure of the thermal properties of the medium, while at large \(p_T\) heavy flavor quarks may provide a reference to investigate the medium modification of high-energy jets [27, 28]. At intermediate \(p_T\), heavy quarks and mesons may provide rich information for our understanding of fragmentation-versus-coalescence mechanisms for hadron formation [29–33]. From the experimental side, RHIC and LHC have observed significant suppression at high \(p_T\) and strong elliptic flow for heavy flavor mesons and heavy flavor decay electrons [34–37]. Various transport models have been developed to study the in-medium evolution of heavy quarks, such as the Boltzmann-based parton cascade model (BAMPS) [38], the linearized Boltzmann model coupled to a hydrodynamic medium [39, 40], and the Langevin evolution of heavy quark inside the QGP medium [32, 33, 11, 47].

In studying heavy quark evolution and energy loss in realistic hydrodynamic QGP matter, smooth initial conditions have been utilized for hydrodynamical evolution in most literatures. The influence of the initial state fluctuations on heavy quarks has not yet been studied. There have been similar studies of the effect of the initial state fluctuations in the context of high \(p_T\) light flavor jets [48–50], but no unified conclusion has been reached yet. For instance, Ref. [45] used a (1+1)-dimensional Bjorken hydrodynamic background and found that the fluctuation in the spatial distribution of the initial hard scatterings significantly reduced the suppression of jet production. In Ref. [50] it is found that with the in-
clusion of the transverse expansion of the medium, i.e., using a (2+1)-dimensional hydrodynamic model, jet energy loss will be enhanced when the initial state fluctuation is incorporated. However, using a (2+1)-dimensional medium for peripheral collisions, Ref. [49] showed a decrease of quenching when the initial state fluctuations are included.

In this work, we investigate the influence of the initial state fluctuations on heavy quark evolution inside the QGP matter. We simulate the dynamical evolution of heavy quarks using our modified Langevin equation developed in our previous work [33] that includes both collisional and radiative energy loss mechanisms. The QGP medium is simulated with a (2+1)-dimensional viscous hydrodynamic model which has been tuned to describe the bulk matter observables. We do not aim for a direct comparison with experimental data in this work, but focus on exploring how heavy quark evolution and energy loss are affected by the presence of the initial state fluctuations. One may refer to Ref. [33] for a detailed comparison to experimental data using smooth initial conditions. We will discuss about the possibility of utilizing heavy quarks to probe the granularity of local fluctuations inside QGP and to narrow down our knowledge of the initial states of the QGP fireball.

The paper is organized as follows. In Sec II, we briefly introduce our Langevin approach for simulating the dynamical evolution of heavy quarks inside QGP. In Sec III we study how the energy loss of heavy quark is affected by the size and the number of local fluctuations (hot spots) using a static medium. In Sec IV we study the influence of the initial state fluctuations on heavy quark quenching using a realistic hydrodynamic medium. The summary and discussion will be presented in Sec V.

II. HEAVY QUARK EVOLUTION INSIDE QGP

In the limit of multiple scatterings, the in-medium evolution of heavy quarks can be treated as Brownian motion and is usually described using the Langevin approach. Apart from the collisional energy loss resulting from quasi-elastic scatterings, heavy quarks may also lose energy through medium-induced gluon radiation. To include both contributions, we use the modified Langevin equation developed in our previous work [33]:

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

The first two terms on the right-hand side represent the drag force and the thermal random force. The last term $\vec{f}_g = -d\vec{p}_g/dt$ is introduced to describe the recoil force exerted on heavy quarks due to gluon radiation, where $\vec{p}_g$ denotes the momentum of radiated gluons.

In our simulation, we determine the probability of gluon radiation during a time interval $\Delta t$ using the average number of radiated gluons:

$$P_{\text{rad}}(t, \Delta t) = \langle N_g(t, \Delta t) \rangle = \Delta t \int d\vec{k}_g \frac{dN_g}{d\vec{k}_g^2 dt},$$  \hspace{1cm} (2)

We choose sufficiently small time steps $\Delta t$ to ensure that this probability is smaller than one in a single evolution time step. Here the medium-induced gluon emission spectrum is taken from the higher-twist energy loss formalism [31, 53]:

$$\frac{dN_g}{d\vec{k}_g^2 dt} = \frac{2\alpha_s P(x)\hat{q}}{\pi k_\perp^4} \sin^2 \left( \frac{t - t_f}{2\tau_f} \right) \left( \frac{k_\perp^2}{k_\perp^2 + x^2 M^2} \right)^4,$$  \hspace{1cm} (3)

where $k_\perp$ is the transverse momentum of the radiated gluon, and $x$ is the fractional energy taken away by the radiated gluon. Additionally, $\alpha_s$ is the strong coupling constant, $P(x)$ is the parton splitting function and $\hat{q}$ is the gluon transport coefficient. The gluon formation time is defined as $\tau_f = 2E x(1 - x)/(k_\perp^2 + x^2 M^2)$, in which $E$ and $M$ are the energy and mass of heavy quarks. At a given time step, Eq. (2) is utilized to determine the probability of gluon formation. If a gluon is radiated, its energy and momentum is then sampled using the Monte-Carlo (MC) method according to the gluon spectrum given by Eq (3).

With the requirement that heavy quarks approach thermal equilibrium after sufficiently long time of in-medium evolution, the fluctuation-dissipation relation between the drag and the thermal force may be obtained $-\eta_D(p) = \kappa/(2TE)$, where $\kappa$ is the momentum space diffusion coefficient defined as $\langle \xi(t)\xi(t') \rangle = \kappa \delta^{\delta}(t - t')$. Note that such Einstein relation between gluon radiation and absorption has not been included in this work due to the absence of the latter process. We may mimic this detailed balance effect by introducing a lower cut-off for the radiated gluon energy $\omega = \pi T$, which is considered as the balance point between gluon emission and absorption. Above $\omega_0$, the classical Langevin equation is modified by gluon radiation and quasi-elastic scatterings. Below the cut-off, the heavy quark motion is entirely governed by quasi-elastic scatterings whose detailed balance is well defined. In this work, we relate different transport coefficients via $D = 2T^2/\kappa$ and $\hat{q} = 2\kappa C_A/C_F$, where $D$ is the spatial diffusion coefficient of heavy quarks. With the above setup, there is only one free parameter in our Langevin framework. Throughout our calculation below, the spatial diffusion coefficient of heavy quarks is chosen as $D = 6/(2\pi T)$, which is equivalent to $\hat{q}$ around 3 GeV$^2$/fm at a temperature of 400 MeV. Such setup has been shown to provide the best $p_T$ spectra of $D$ meson $R_{AA}$ in 2.76 TeV central Pb-Pb collisions [33]. We note that the value of jet transport coefficient used here is comparable to many other studies on light flavor jet quenching [54, 55].

Using our modified Langevin framework, we may simulate the heavy quark evolution inside a QGP matter produced in relativistic heavy-ion collisions. For the spacetime evolution of the QGP fireballs, a (2+1)-dimensional
viscous hydrodynamic model is used \cite{56,57}. Here we employ the code version and parameter tunings taken from Ref. \cite{58}. A MC-Glauber model is adopted to generate the positions of participant nucleons and binary collisions, providing both the initial conditions of hydrodynamics and the spatial distribution of initial heavy quarks. The initial momentum spectra of heavy quarks is obtained from a leading-order perturbative QCD calculation. The hydrodynamic model provides the spacetime evolution of the local temperature and collective flow of the QGP medium. For every Langevin time step, we first boost the heavy quark into the rest frame of the fluid cell, and the energy and momentum of the heavy quark are updated according to the above Langevin algorithm before it is boosted back to the global center-of-mass frame.

In our simulation, heavy quarks are assumed to stream freely prior to hydrodynamics’ starting time $\tau_0 = 0.6$ fm/c. The possible energy loss during the pre-equilibrium stage is neglected; it is expected to be small due to its short period of time compared to the much longer history of the fireball evolution. Once they enter a fluid cell whose local temperature is below 165 MeV, heavy quarks are treated as free-streaming again. To isolate the effects of the initial state fluctuations on heavy quark energy loss, we do not include the hadronization process and the subsequent interaction between heavy mesons and hadron gas in this work. One may refer to our previous work \cite{33} for more information about the hadronization process of heavy quarks to their respective mesonic bound states.

III. EFFECTS OF FLUCTUATIONS ON HEAVY QUARKS: A STATIC MEDIUM CASE

In this section, we investigate the influence of the local temperature fluctuations (or hot spots) on heavy quark energy loss in a static QGP medium. We will look at two different aspects of density fluctuations: the size and the number of local fluctuations. To mimic the effect of the realistic (2+1)-dimensional boost invariant hydrodynamic medium which we will use in the next section, the static medium is chosen to be two dimensional, i.e., the hot spots are in fact hot tubes in this case.

For the first scenario, we generate one cylindrical medium (hot tube) with a constant temperature. As demonstrated by the cartoon inside Fig. 1 we vary its size and study how the energy loss of charm quarks is affected. When varying the size, the total energy contained inside the tube is kept fixed. The temperature of the medium is set as 200 MeV when the tube radius is $R = 5$ fm and will increase as the radius decreases. Each charm quark is initialized with 50 GeV and placed at the center of the cylinder. We calculate the average energy loss of charm quarks as they exit the hot tube medium, and the results are shown in Fig. 1. We also compare the results using different energy loss mechanisms of heavy quarks: collisional energy loss only, radiative only and the combined loss. In the plot we multiply the results from quasi-elastic scatterings by a factor of 4 for a better resolution. From the figure, we observe that the energy loss of charm quarks is not very sensitive to the size of the hot tube (with the total deposited energy unchanged).

To study the effect of the number of local density fluctuations on the heavy quark energy loss, we generate $N$ hot tubes with the same radius $R = 0.5$ fm. As displayed by the cartoon inside Fig. 2 they are lined up along charm quarks’ initial propagation direction. The initial charm quark energy is set as 50 GeV (placed at the edge of the first hot tube) and the temperature of the medium is set as 500 MeV when there is only one hot tube. Again, when changing the number of hot tubes, the total energy deposited in the medium (sum of the $N$ hot tubes) is fixed. The result for such scenario is shown in Fig. 2. We see that the energy loss of charm quarks is quite sensitive to the number of hot tubes.

The above results can be easily understood with the following argument. One may assume the power law dependence for heavy quark energy loss on the medium...
In our energy loss model, \( \alpha \) and \( \beta \) denote power law dependence of heavy quarks on the path length and the medium temperature. Since we fix the total amount of energy contained in the medium, i.e., \( \epsilon V = \text{Const.} \), one may obtain the dependence on the size and the number of hot tubes as:

\[
\Delta E \propto N^{\alpha - \beta /4} R^{\alpha - \beta d /4}.
\]

(5)

In our energy loss model, \( \alpha = 1 \) and \( \beta = 2 \) are good approximations for the collisional energy loss and one may roughly use \( 1 < \alpha < 2 \) (say taking \( \alpha = 3/2 \) in the following analysis), and \( \beta = 3 \) for the radiative energy loss.

When there is only one hot tube \( N = 1 \) (the first scenario), Eq. (3) is reduced to \( \Delta E \propto R^{\alpha - \beta d /4} \). Thus for a 2-dimensional system, this indicates that the total energy loss of heavy quark is not very sensitive to the size \( R \) of the hot tubes. This is consistent with Fig. 1. We have also checked that for a 1-dimensional system, the total energy loss of heavy quarks decreases when confining the same amount energy in a smaller region, but the energy loss increases for a 3-dimensional system.

Similarly, one may fix the the size \( R \) of hot tubes in Eq. (3) to isolate the influence of the number of hot tubes: \( \Delta E \propto N^{\alpha - \beta /4} \). One can see that the total energy loss does not depend on the dimension of the system, but increases significantly with the number of hot tubes for both collisional and radiative energy loss. This is consistent with the finding shown in Fig. 2.

One may combine the above two scenarios, i.e., changing the size and number of hot spots/tubes simultaneously. This is very similar to the change from a large and smooth medium to fluctuating medium consisting of several hot (and cold) regions as demonstrated by the cartoon inside Fig. 3. The total energy contained in these two different media are the same. To simplify the study, we split a large smooth tube medium into \( N \) hot tubes with smaller sizes, which are lined up adjacent to each other along the direction of the initial momentum of our charm quarks (\( E_{\text{init}} = 50 \text{ GeV} \)). Another \( N \) cold tubes (vacuum here) are also placed between every two hot tubes to mimic the realistic distribution of local density fluctuations. The sizes of the smaller tubes are chosen such that the total length \( 4N R \) traversed by heavy quarks is fixed as the diameter of the original smooth medium with a radius of 5 fm and temperature of 200 MeV. The results for a 2-dimensional system are shown in Fig. 3. One observes that the energy loss of charm quarks increases when the original smooth medium is splitted into more hot and cold tubes, i.e., the more fluctuations the medium has, the stronger energy loss the charm quarks experience.

To sum up for this section, we find that the energy loss of charm quarks in a 2-dimensional system does not have much dependence on the size of the local fluctuations, but is quite sensitive to the number of local fluctuations in the medium. Heavy quarks tend to lose more energy in a fluctuating medium than in a smooth one when the total energies contained in the medium are the same. Although the above results are obtained using a static medium, it provides an intuition to explain the results for a realistic hydrodynamic medium presented in the next section. We also note that our finding is based on the path length and temperature dependence of heavy quark energy loss in our model, i.e., the values of \( \alpha \) and \( \beta \) in Eq. (3).

IV. HEAVY QUARKS IN EVENT-BY-EVENT HYDRODYNAMIC MEDIUM

In the previous section, we have studied the response of heavy quark energy loss to the temperature fluctuations in a static QGP medium. In this section, we perform the investigation for a realistic expanding medium in which both temperature fluctuations and flow (fluctuations) are present. Here, we utilize a (2+1)-dimensional viscous hydrodynamic model as described in Sec II to simulate the dynamical evolution of the hot QGP produced in Pb-Pb collisions at the LHC. The initial conditions for the hydrodynamical evolution are obtained from the Monte-Carlo Glauber model.

In Fig. 4, we compare the initial entropy density distribution in the transverse plane from a typical event [Fig. 4(a)] and the one after averaging over 100,000 events for 0-7.5% Pb-Pb collisions at 2.76 TeV at the LHC [Fig. 4(b)]. We note that in Fig. 4(b) the initial profiles of all the events have been rotated to the same second-order participant plane before performing the event average of the entropy density. One can clearly see the presence of

![Cylindrical hot tubes (2D)](image-url)
hot and cold regions in the QGP fireball for fluctuating initial conditions.

In Fig. 4 we show the nuclear modification factor $R_{AA}$ of charm quarks after their traveling through the QGP medium created in 2.76 TeV Pb-Pb collisions. We compare the results from smooth initial conditions and from an event-by-event calculation for three different centralities. One can read from Fig. 5(a)–5(c) that the event-by-event calculations give larger suppression for heavy quarks at high $p_T$, i.e., the initial state fluctuations lead to larger energy loss for heavy quarks. This is consistent with the finding for the static medium case in the previous section. As a consequence, slightly smaller suppression is observed for low $p_T$ charm quarks.

As has been mentioned, there exist temperature fluctuations and flow (fluctuations) in a realistic medium. To remove and investigate the effect of the medium flow on heavy quark evolution, one may solve the Langevin equation Eq. (1) in the global center-of-mass frame instead of the local rest frame of the fluid cell. In this way, the evolution of heavy quarks is solely affected by the temperature distribution and fluctuations of the medium. One
can see that the effect of the medium flow is to boost low $p_T$ charm quarks into medium $p_T$ regime and form the bump structure for the nuclear modification factor $R_{AA}$. This bump feature disappears when the flow is turned off in the calculation.

The above observation can be seen more clearly in the subfigures inside Fig. 5(a) - 5(c) where we show the ratios between the final state $p_T$ spectra of charm quarks from the event-by-event calculations and those from the smooth cases. For the central collisions [Fig. 5(a)], we obtain about 12% more quenching at high $p_T$ for the fluctuating initial condition as compared to the smooth initial condition. This could result in a 10%-15% difference in the extraction of the gluon transport coefficient $\hat{q}$ inside QGP. For more peripheral collisions, the effect of initial state fluctuations on heavy quark energy loss is less; the quenching increases about 7% when switching from the smooth to the fluctuating initial condition in 40%-50% Pb-Pb collisions [Fig. 5(c)].

V. SUMMARY

In this work, we have studied the impact of initial state fluctuations on heavy quark evolution and energy loss in relativistic heavy-ion collisions. The in-medium evolution of heavy quarks is described using a modified Langevin equation that simultaneously incorporates collisional and radiative energy loss components. We have investigated the effect of local fluctuations for both static and realistic expanding QGP media. For realistic medium, we have utilized a (2+1)-dimensional viscous hydrodynamic model to simulate the spacetime evolution of the QGP fireball. The initial conditions for hydrodynamics are obtained from a MC-Glauber model, for both smooth and fluctuating cases.

We have studied the effects of temperature fluctuations on heavy quark energy loss in terms of the sizes and the number of local fluctuations (hot spots). We found that the total energy loss of heavy quarks is not very sensitive to the sizes of local fluctuations in a 2-dimensional system, but the energy loss increases significantly with the increasing number of hot spots. And our simulation in a realistic QGP medium have demonstrated that fluctuating initial conditions may bring around 10% more suppression for inclusive charm quark production at high $p_T$ in relativistic nucleus-nucleus collisions. The effect of initial state fluctuations on heavy quark energy loss tends to diminish for more peripheral collisions.

Our study constitutes an important contribution to the quantitative understanding of heavy quark dynamics in relativistic heavy-ion collisions with initial state fluctuations. Although we utilize heavy quarks in our study to probe the effects of the fluctuations, many of our results should apply to light flavor partons as well. Our results suggest that jet modification might be utilized to probe the fluctuations of QGP medium, such as the degree of inhomogeneity or the number of hot spots. We further note that the sensitivity of heavy quark energy loss to hot spot number might be enhanced when one uses the correlation measurements or triggered observables; we leave such study to a future effort. The study along such direction may potentially provide more constraints on modeling initial states, thus helping our quantitative understanding of the transport properties of the hot and dense QGP produced in high energy heavy-ion collisions.

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