D mesons in non-central heavy-ion collisions: fluctuating vs. averaged initial conditions

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Abstract

The suppression of *D* mesons in non-central heavy-ion collisions is investigated. The anisotropy in collisions at finite impact parameter leads to an ordering of all-angle, in- and out-of-plane nuclear modification factors due to the different in-medium path lengths. Within our MC@sHQ+EPOS model of heavy-quark propagation in the QGP we demonstrate that fluctuating initial conditions lead to an effective reduction of the energy loss of heavy quarks, which is seen in a larger nuclear modification factor at intermediate and high transverse momenta. The elliptic flow at small transverse momenta is reduced.

Keywords:

1. Introduction

Heavy-quark observables like the nuclear modification factor R_{AA} and the elliptic flow v_2 are measured in ultra-relativistic heavy-ion collisions at RHIC [1] and the LHC [2–4]. The results indicate a substantial medium modification of the spectra: a suppression at high transverse momentum p_T and partial thermalization with the QGP medium at low p_T . Many theoretical approaches describing the energy loss via elastic scatterings [5], gluon bremsstrahlung [6] or a mixture of both processes exist. For some of these approaches, it is necessary to rescale these interaction cross sections or the diffusion coefficient and to couple to a background fluid dynamical medium of light partons in order to reproduce the experimental data within numerical simulations [7–11]. It remains, however, a challenge to describe R_{AA} and v_2 within a single setup.

In order to discriminate between the various models it becomes therefore necessary to improve the description of the fluid dynamical evolution, explore the potential of new heavy-quark observables, such as azimuthal correlations [12, 13], and to study the centrality and mass dependence of these observables. In this work, we present the coupled MC@sHQ+EPOS model and study the R_{AA} in non-central heavy-ion collisions as all-angle, in- and out-of-plane observables. In particular, we discuss the influence of fluctuating versus smooth initial conditions. This latter aspect was studied in the frame-work of (light-hadron) jet physics [14–16], but only recently attracted attention in the context of heavy-quark observables [17], where contrary to the present work it is found that the energy loss of heavy quarks is enhanced in a medium with local fluctuations.

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Figure 1. The in- and out-of-plane R_{AA} of D mesons in the 30 – 50 % centrality class in comparison to the all-angle R_{AA} for the purely collisional (left) and the collisional+radiative (right) interaction mechanism for fluctuating initial conditions.

2. MC@shQ + EPOS

Recently, we presented first results from our Monte-Carlo heavy quark propagation, MC@shQ, coupled to the state-of-the-art fluid dynamical evolution of the QGP from EPOS initial conditions [11–13]. Three main stages of the coupled evolution are described: 1) initialization at the nucleon-nucleon collision points, thus inside the initial hot spots, according to the FONLL momentum distribution [18], 2) propagation through the medium by Monte-Carlo sampling of the Boltzmann equation, and 3) hadronization at $T = 155$ MeV according to coalescence and fragmentation.

The cross sections in the Boltzmann equation are either given by purely elastic scatterings off the gluons and light quarks, drawn from the thermal medium, or include radiative corrections. Both interaction scenarios are investigated in the present work. The respective scattering rates are rescaled by a K -factor in order to reproduce the high- p_T R_{AA} data for D mesons measured by ALICE [3] in central collisions. All other heavy-quark observables, like the elliptic flow and azimuthal correlations and their centrality or mass dependence, are calculated with the same K -factor. With $K = 0.8$ for the collisional+radiative interaction mechanism we are rather close to the generic case of $K = 1.0$.

It had been shown that different description of the background medium can lead to large uncertainties in the R_{AA} of D mesons [19]. It is, therefore, important to use a model for the light hadron sector, which compares successfully to experimental data. The EPOS model is capable of describing transverse momentum spectra, flow harmonics and correlation patterns like the ridge in Au+Au collisions at RHIC and Pb+Pb and p+Pb collisions at the LHC [20].

In principle, the EPOS fluctuating initial conditions allow us to study heavy quark observables in an event-by-event setup. For the numerical simulation, however, we run N^{HQ} events per EPOS event in order to be more efficient in computing power. The particular choice of N^{HQ} will be discussed in this work.

We note here, that the current version of MC@shQ+EPOS does not include shadowing, which is expected to suppress the initial heavy quark momentum spectrum at low p_T as compared to the proton-proton reference and thus reduces the low- p_T R_{AA} even in the absence of the QGP. Shadowing will be included in the next version.

3. Results

The R_{AA} of D mesons in 30 – 50% most central heavy-ion collisions at $\sqrt{s} = 2.76$ TeV is determined in the full azimuth over all angles and separately in in-plane and out-of-plane directions. The in-plane R_{AA} is defined for D mesons with $\Delta\phi \in [-\pi/4, \pi/4]$ and $[3\pi/4, 5\pi/4]$, where $\Delta\phi$ is the azimuthal angle with respect to the participant plane. The out-of-plane R_{AA} is defined accordingly with $\Delta\phi \in [\pi/4, 3\pi/4]$ and $[5\pi/4, 7\pi/4]$. Due to the initial spatial anisotropy high- p_T heavy quarks which initially go in-plane traverse less QGP matter than those initially going out-of-plane. In Fig. 1 we observe the expected ordering of the suppression for $1 \text{ GeV} < p_T < 20 \text{ GeV}$. Both interaction scenarios give very similar R_{AA} over the shown p_T range. They saturate toward high p_T , where the R_{AA} in the collisional+radiative scenario is slightly below the one in the purely collisional interaction. At $p_T < 7 \text{ GeV}$ the

Figure 2. Initial energy density for 30 – 50% most central events in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV. The left plot shows the average over the initial conditions of 100 events. The right plot is the energy density of one random event.

peak in the R_{AA} for the collisional+radiative interaction seems to be broader than in the purely collisional scenario accumulating the heavy quarks which originate from higher p_T and lost a sufficient amount of energy. Due to the lack of shadowing and the strong radial flow in the EPOS environment our calculations for the R_{AA} are above the data for the lower p_T in the 0 – 20% most central collisions. We expect this issue to persist also in the non-central collisions investigated here.

We have the possibility to study the heavy-quark propagation in a fluid dynamical environment, which is subsequent to either (event-by-event) fluctuating or (event-) averaged initial conditions. In fig. 2 we show the energy density profiles at midrapidity ($\eta = 0$) for initial conditions, which are averaged over 1000 EPOS initial stages of Pb+Pb collisions in the 30-50% centrality class (left), and for one random event in the same centrality class (right). In both cases the x-axis is aligned with the angle of the participant plane. The elliptic initial anisotropy is well observed for the averaged initial conditions, which produce a smooth profile. In the initial conditions for a single event, however, one sees denser/hotter spots as well as more dilute/colder spots. The peak energy density in the hot spots is much higher than the averaged values.

The following two aspects are crucial for investigating the energy loss in a fluctuating medium. 1) The correlation of the production points of the heavy quarks and the initial hot spots, which leads locally to an enhanced energy loss as compared to a scenario with averaged initial conditions. 2) The dependence of heavy-quark energy loss on the energy density of the medium is less than linear. In order to elaborate on this last point, one can look at a medium with local fluctuations $\varepsilon(x) = \varepsilon_0 + \delta\varepsilon(x)$ around an averaged energy density $\langle \varepsilon(x) \rangle = \varepsilon_0$. The local energy loss is related to the temperature by $dE/dx \propto T^\beta$ with β ranging from ≈ 1 for collisional energy loss with running α_s to $\beta \approx 2$ for radiative LPM [21], and $\varepsilon \propto T^n$, with $n \approx 4$. Thus

$$\frac{dE}{dx} \propto \varepsilon^{\beta/n} \quad \text{with} \quad \frac{\beta}{n} < 1. \quad (1)$$

A Taylor expansion around ε_0 gives an averaged energy loss of

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{dE(\varepsilon_0)}{d\varepsilon} \times \left[1 - \frac{\beta/n(1-\beta/n)}{2} \frac{\langle (\delta\varepsilon)^2 \rangle}{\varepsilon_0^2} + \dots \right]. \quad (2)$$

We see that due to the negative curvature of dE/dx as a function of the energy density ($\beta/n < 1$), the effective energy loss of the heavy quarks in a fluctuating medium is reduced compared to the energy loss in an averaged medium.

In our numerical simulations for an expanding medium we see that this second effect, where the fluctuations in the medium reduce the energy loss, dominates. In Fig. 3 we present results for the R_{AA} (left) and the v_2 (right) for the scenario of collisional plus radiative energy loss. The factor $K = 0.8$ is tuned to reproduce the R_{AA} for higher p_T in central collisions in the case of fluctuating initial conditions. Since we are interested in the mere influence of the initial conditions we do not recalibrate the K -factor for energy loss in the case of averaged initial conditions. In the

Figure 3. The R_{AA} (left) and the v_2 (right) compared for fluctuating and averaged initial conditions. Figure 4. The azimuthal correlation function of $D\bar{D}$ -pairs in two p_T -trigger classes compared for fluctuating and averaged initial conditions.

R_{AA} (left) one observes a smaller quenching in the fluctuating case for all transverse momenta $p_T > 3$ GeV. In central collisions we expect to find the same ordering: larger quenching for averaged than for fluctuating initial conditions.

The result for the R_{AA} is largely independent of the number N^{HQ} of MC@shQ events, which we run per EPOS fluid dynamical event, and results converge quickly with the number N^{EPOS} of EPOS fluid dynamical events, when the overall statistics $N^{HQ} \times N^{EPOS}$ is high enough. In the present study, $N^{HQ} = 10^4$.

In fig. 3 (right) we show the v_2 results for the same evolution scenarios obtained from correlations of the heavy quarks with the participant plane. At low momenta $p_T \lesssim 5$ GeV we find that the averaged initial conditions lead to a larger v_2 than the fluctuating initial conditions. The hot and dense spots in the initial energy density are themselves rather spherical, which reduces the spatial anisotropy. Local pressure gradients in these regions produce an azimuthally isotropic expansion. This reduces the overall elliptic flow. At larger p_T the elliptic flow is built significantly from energy loss along the different path lengths in- and out-of-plane. Here a more detailed study of these contributions with enhanced statistics is mandatory.

For the elliptic flow results to converge one needs to run a sufficiently large number of EPOS fluid dynamical events N^{EPOS} . Due to computational limitations, this can be achieved by running $N^{HQ} \leq 10^4$ heavy quark events per one EPOS fluid dynamical event. For the study of the elliptic flow only initial fluctuations are taken into account. The event-by-event fluctuations of the final event plane in comparison to the initial participant plane are not considered here. It is not expected that shadowing affects the v_2 .

Finally in fig. 4, we show the azimuthal correlations of $D\bar{D}$ -pairs, which are initially correlated back to back. These observables do not show any sensitivity to whether the initial conditions are smooth or fluctuating.

4. Conclusions

Within our coupled model, MC@HQ+EPOS, we studied charm quark propagation in non-central heavy-ion collisions at the LHC. We found the expected ordering of all-angle, in- and out-of-plane R_{AA} . Analysing the R_{AA} , we found that a fluid dynamical expansion from fluctuating initial conditions leads to a reduced effective energy loss as compared to the equivalent case with averaged initial conditions. The quantitative difference between these two scenarios is, however, much smaller than the resolution which can be expected in the experimental data. Our results are qualitatively different from the ones found in [17]. This shows that different implementation of the energy loss of heavy quarks, of the background fluid dynamical medium and the coupling between these two sectors might put different emphasis on the influence of the initial production points of the heavy quarks or of the fluctuations in the medium during the evolution, as we discussed. It would additionally be interesting to investigate if the different path length dependence of energy loss mechanisms probes the fluctuations in a medium differently. We found that while the elliptic flow at low momenta is reduced in a fluctuating medium it deserves a more detailed further analysis at higher momenta. This is left for when our model is improved to include the consistent initialization of the charm quarks within the EPOS multiple scattering approach and a viscous fluid dynamical evolution.

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