DD̄ Correlations as a Sensitive Probe for Thermalization in High-Energy Nuclear Collisions

K. Schweda[1], X. Zhu[2,3,4], M. Bleicher[2], S.L. Huang[5], H. Stöcker[2,3], N. Xu[5], P. Zhuang[4]

[1] *Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany*
[2] *Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität,*
Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany
[3] *Frankfurt Institute for Advanced Studies (FIAS), Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany*
[4] *Physics Department, Tsinghua University, Beijing 100084, China and*
[5] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

We propose to measure azimuthal correlations of heavy-flavor hadrons to address the status of thermalization at the partonic stage of light quarks and gluons in high-energy nuclear collisions. In particular, we show that hadronic interactions at the late stage cannot significantly disturb the initial back-to-back azimuthal correlations of DD̄ pairs. Thus, a decrease or the complete absence of these initial correlations does indicate frequent interactions of heavy-flavor quarks and also light partons in the partonic stage, which are essential for the early thermalization of light partons.

Keywords: High-energy nuclear collisions, quark-gluon plasma, heavy-flavor quarks, thermalization.

I. INTRODUCTION

Lattice QCD calculations, at vanishing or finite net-baryon density, predict a cross-over transition from the deconfined thermalized partonic matter (the Quark Gluon Plasma, QGP) to hadronic matter at a critical temperature $T_c \approx 150$–180 MeV [1].

Measurements of hadron yields in the intermediate and high transverse momentum (p_T) region indicate that dense matter is produced in Au+Au collisions at RHIC [2, 3]. The experimentally observed large amount of elliptic flow of multi-strange hadrons [4], such as the ϕ meson and the Ω baryon, suggest that collective motion develops in the early partonic stage of the matter produced in these collisions. A crucial issue to be addressed next is the thermalization status of this partonic matter.

Heavy-flavor (c, b) quarks are particularly excellent tools [5, 6, 7] to study the thermalization of the initially created matter. As shown in Fig. 1, their large masses are almost exclusively generated through their coupling to the Higgs field in the electro-weak sector, while masses of light quarks (u, d, s) are dominated by spontaneous breaking of chiral symmetry in QCD. This means that in a QGP, where chiral symmetry might be restored, light quarks are left with their bare current masses while heavy-flavor quarks remain heavy. Due to their large masses ($\gg \Lambda_{QCD}$), the heavy quarks can only be pair-created in early stage pQCD processes. Furthermore, their production cross sections in nuclear collisions are found to scale with the number of binary nucleon-nucleon collisions [8, 9]. In the subsequent evolution of the medium, the number of heavy quarks is conserved because the typical temperature of the medium is much smaller than the heavy quark (c, b) masses, resulting in negligible secondary pair production. In addition, the heavy quarks live much longer than the lifetime of the formed high-density medium, decaying well outside. These heavy quarks (c, b) can participate in collective motion or even kinetically equilibrate if, and only if, interactions at the partonic level occur at high frequency. The idea of statistical hadronization of kinetically equilibrated charm quarks [10] even predicted significant changes in hidden charm hadron production [11]. Hence, heavy-flavor quarks are an ideal probe to study early dynamics in high-energy nuclear collisions. Recent STAR and PHENIX
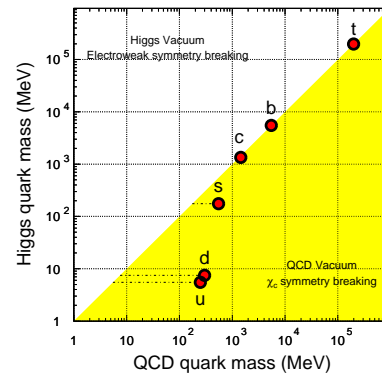

FIG. 1: (Color online) Quark masses in the QCD vacuum and the Higgs vacuum. A large fraction of the light quark masses is due to the chiral symmetry breaking in the QCD vacuum. The numerical values were taken from Ref. [12].

results on elliptic flow and nuclear modification factors of non-photonic electrons indicate that charm quarks might indeed participate in the collective motion of the matter produced in Au+Au collisions at RHIC. To explain the data, a large drag diffusion coefficient in the Langevin equation, describing the propagation of charm quarks in the medium, is found to be necessary [13]. Two- and three-body interactions [14, 15] of heavy-quarks and resonant rescattering [16] in the partonic stage seem to become important. These investigations suggest that heavy-quarks actively participate in the partonic stage.

In this paper, we study the change of azimuthal correlations of D and D̄ meson pairs as a sensitive indicator of frequent occurrences of partonic scattering. Since heavy-flavor quarks are pair-created by initial scattering processes, such as $gg \rightarrow c\bar{c}$, each quark-antiquark pair is correlated in relative azimuth $\Delta\phi$ due to momentum conservation. In elementary col-

lisions, these correlations survive the fragmentation process to a large extent and hence are observable in the distribution of the relative azimuth of pairs of D and D̄ mesons [17]. We evaluate by how much these correlations should be affected by the early QGP stage and by the hadronic scattering processes in the late hadronic stage.

II. RESULTS AND DISCUSSIONS

To explore how the QCD medium generated in central ultra-relativistic nucleus-nucleus collisions influences the correlations of D and D̄ meson pairs, we employ a non-relativistic Langevin approach which describes the random walk of charm quarks in a QGP as was first described in Refs. [5, 6, 7]. Here, both the drag coefficient γ and the momentum-space diffusion coefficient α depend on the *local* temperature, T with a momentum-independent $\gamma(T) = aT^2$. We chose $a = 2 \cdot 10^{-6}$ (fm/c)$^{-1}$ MeV^{-2}. Details of our calculations can be found in [18].

In order to isolate the effects purely due to parton-parton re-scattering in the outlined medium, we generated c and c̄ quarks with the same p_T and zero longitudinal momentum back-to-back, i.e. with $\Delta\phi = \pi$ at a time of the order of $1/m_c \simeq 0.1$ fm/c, and used a delta function for fragmenting the charm quark into a charmed hadron at the hadronization stage. The radius r where each pair is created is randomly generated from a distribution reflecting the number of binary nucleon-nucleon collisions taking place at that radius, $p(r)\mathrm{d}r \propto (R^2 - r^2)2\pi r\,\mathrm{d}r$. The angular distribution of the initially produced charm quarks in the transverse plane is isotropic.

The evolution of the charm momenta with the Langevin equation is stopped when T reaches the critical temperature $T_c = 165$ MeV or when the charm quark leaves the QGP volume. Furthermore, to get a first estimation of the QGP effect on the charm quark pairs azimuthal correlation, we omit the possible contribution of the mixed phase. Figure 2 (a) shows the results for the D meson (charm quark) pairs angular correlations for different initial charm quark p_T values, for $T_0 = 300$ MeV and $\tau_0 = 0.5$ fm/c (typical values for RHIC collisions). We see that the fastest charm quarks (represented by the $p_T = 3$ GeV/c) are able to escape from the QGP without suffering significant medium effects, while the slower quarks (see the $p_T = 0.5$ GeV/c black line) have their pair azimuthal correlation almost completely smeared out by the interactions in the medium.

Figure 2 (b) shows the corresponding results for $T_0 = 700$ MeV and $\tau_0 = 0.2$ fm/c, values representative of LHC energies. Here, the interactions of the charm quarks with the medium are so frequent that only the most energetic charm quarks preserve part of their initial angular correlation; low p_T pairs can even be completely stopped by the medium. Because the c and the c̄ quarks of a given pair are created together, in the same space point, the pair has a higher escape probability if both quarks escape the medium from the side of the fireball where the thickness is smaller. Thus, the $\Delta\phi$ distribution is shifted towards smaller values.

Presently, reliable numbers on the drag coefficient do not exist [16, 19]. The dependence on the drag coefficient is shown in Figs. 2 (c) and (d) for the cc̄ angular correlations for energetic c quarks: $p_T = 3$ and 10 GeV/c for $T_0 = 300$ and 700 MeV, respectively. These correlations vanish when a is increased by around a factor of five in the first case and by around a factor of two in the latter one, with respect to values from pQCD-calculations.
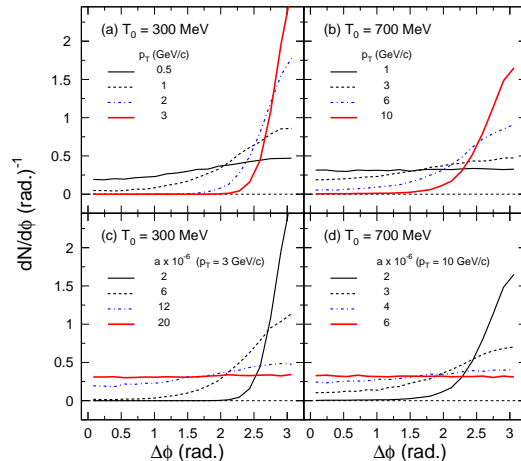

FIG. 2: (Color online) Correlations in relative azimuth $\Delta\phi$ of DD̄ pairs from Langevin calculations with $T_0 = 300$ MeV (RHIC) and 700 MeV (LHC). The upper part shows the dependence of the correlations on the initial p_T of the c quark; the lower part shows the drag coefficient dependence.

We have demonstrated that initial correlations of cc̄ pair correlations are clearly affected by the formed QCD medium, and sensitive to its temperature and drag coefficient. The question is to what extent hadronic interaction can modify these initial correlations. In the following, we apply the microscopic hadronic transport approach UrQMD v. 2.2 [20, 21]. A phase transition to a QGP state is *not* incorporated into the model dynamics. In the latest version of the model, PYTHIA (v. 6.139) was integrated to describe the energetic primary elementary collisions [22]. Measured particle yields and spectra are well reproduced by this approach [22].

In this model, D mesons stem from the early-stage high-energy nucleon-nucleon collisions, calculated with PYTHIA. For their propagation in the hadronic medium, we consider elastic scattering of D mesons with all other hadrons. The hadronic scattering cross-section for D mesons is generally considered to be small [23] and we take 2 mb in our calculation. The results of the UrQMD calculations are shown in Fig. 3 (a), for minimum bias Au+Au reactions at $\sqrt{s_{\rm NN}} = 200$ GeV. To better illustrate the *change* in the angular correlations of the DD̄ pairs, we show the ratio between the final distribution, affected by the evolution with UrQMD, and the initial one, directly obtained from PYTHIA. In case hadronic interactions do not modify the correlations, this ratio is unity.

For this specific analysis, all DD̄ pairs were selected, irrespective of the p_T of the D mesons. Fig. 3 (a) shows our

results assuming a forward peaked scattering cross section, $\propto \exp(7 \cos\theta)$, where θ is the scattering angle in the center of mass system of the decaying resonance. Even for a large cross section of 20 mb, the $D\bar{D}$ pair correlations are barely affected by hadronic interactions.

On the other hand, intermediate resonances formation (essentially $D+\pi \leftrightarrow D^*$), might result in isotropic emission, i.e. the correlation might be completely destroyed by a single scattering process. Only when assuming the unlikely case of a large cross section of 20 mb with fully isotropic emission, the $D\bar{D}$ pair correlations are significantly modified, see Fig. 3 (b). We also find that most scatterings occur at relatively early times, when the hadron density is high. At RHIC energies, the (pure) hadronic stage is presumably shorter than assumed in the present calculations.

Hence, we conclude that hadronic interactions are unlikely to significantly modify $D\bar{D}$ pair correlations. A change in these angular correlation must be dominated by frequent parton-parton scatterings occurring in the QGP phase.
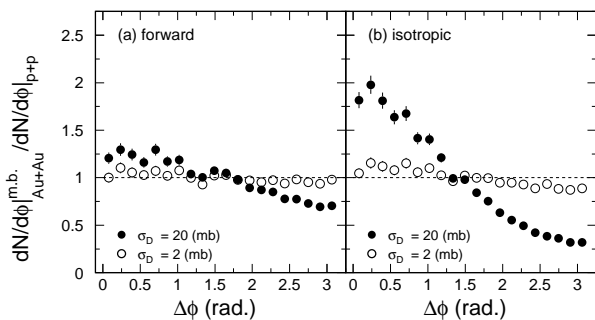

FIG. 3: Ratios between the $\Delta\phi$ distributions of $D\bar{D}$ pairs produced in minimum bias Au+Au reactions at $\sqrt{s_{NN}} = 200$ GeV, before and after hadronic rescattering, using forward (left panel) and isotropic (right panel) angular distributions.

The calculations reported above show that heavy-flavor correlations provide a sensitive tool to directly access the status of equilibration of the partonic medium. A similar picture emerges from the observation and suppression of back-to-back correlations of unidentified high p_T hadrons (jets). Both features originate from the propagation of partons (heavy quarks or jets) in the medium. However, D mesons (and B mesons) have the advantage that they can still be identified, even if they lose a significant fraction of their energy and get kinetically equilibrated.

III.   CONCLUSION AND OUTLOOK

In summary, we argue that the observation of broadened angular correlations of heavy-flavor hadron pairs in high-energy heavy-ion collisions would be an indication of thermalization at the partonic stage (among light quarks and gluons). We have seen that hadronic interactions at a late stage in the collision evolution cannot significantly disturb the azimuthal correlations of $D\bar{D}$ pairs. Thus, a visible decrease or the complete absence of such correlations, would indicate frequent interactions of heavy-flavor quarks and other light partons in the partonic stage, implying early thermalization of light quarks in nucleus-nucleus collisions at RHIC and LHC.

These measurements require good statistics of events in which *both* D mesons are cleanly reconstructed. A complete reconstruction of the D mesons (i.e. of *all* their decay products) in full azimuth is essential to preserve the kinematic information and to optimize the acceptance for detecting correlated D meson pairs. Solid experimental measurements in pp and light-ion collisions, at the same energy, are crucial for detailed studies of changes in these azimuthal correlations, and should be performed as a function of p_T. Proposed upgrades of STAR [24] and PHENIX at RHIC and the ALICE detector [25] at LHC with micro-vertex capabilities and direct open charm reconstruction should make these measurements possible.

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