$D\overline{D}$ Correlations as a sensitive probe for thermalization in high-energy nuclear collisions

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(Dated: April 20, 2006)

We propose to measure 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, shown on the example of azimuthal correlations of $D\overline{D}$ pairs. We show that hadronic interactions at the late stage can not disturb these correlations significantly. Thus, a decrease or the complete absence of these initial correlations indicates frequent interactions of heavy-flavor quarks in the partonic stage. Therefore, early thermalization of light quarks is likely to be reached.

PACS numbers: 25.75.-q

Introduction

Lattice QCD calculations, at vanishing or finite net-baryon density, predict a cross-over transition from the deconfined thermalized partonic matter 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 has been produced in Au+Au collisions at RHIC [2, 3]. The experimentally observed large amount of elliptic flow of multi-strange hadrons [4], i.e. the ϕ meson and the Ω baryon, suggest that this collective motion has been already developed at the early partonic stage. A crucial issue to be addressed for the discovery of the Quark-Gluon-Plasma (QGP) is to probe the status of thermalization in the early partonic stage.

Especially heavy-flavor (c, b) quarks are excellent tools 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 electroweak 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 obtain 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. And their production cross sections in nuclear collisions are found to scale with the number of binary collsions [5, 6]. In the subsequent evolution of the medium, their numbers are conserved because the typical temperature of the medium is much less than the heavy (c, b) quark masses resulting in negligible new pair production. In addition, heavy quarks do not decay weakly during the short time of the evolution of the medium, i.e. they decay outside of the medium. These heavy (c, b) quarks can participate in collective motion or even kinetically equilibrate only when interactions at the partonic level occur at high frequency. The idea of statistical hadronization of kinetically equilibrated charm quarks [7] even predicted significant changes in hidden charm hadron production [8]. Hence, heavy-flavor quarks are an ideal probe to study early dynamics in high-energy collisions.

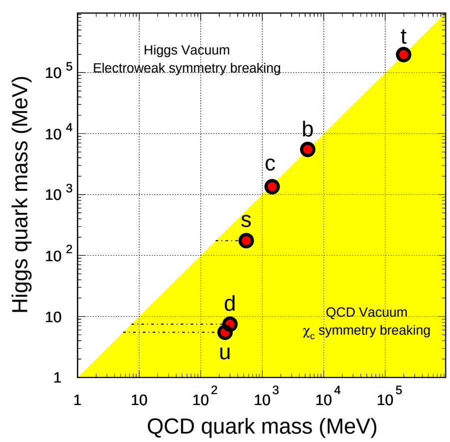

FIG. 1: (Color online) Quark masses in QCD vacuum and Higgs vacuum. A large fraction of the light quark masses is due to the chiral symmetry breaking in the QCD vacuum. The numbers on quark masses have been taken from Ref. [9].

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Recent results from non-photonic electrons on elliptic flow and nuclear modification factors from STAR and PHENIX and yields of directly reconstructed D mesons indicate that charm quarks do indeed participate in the collective motion 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 [10]. Two- and three-body interactions [11, 12] of heavy-quarks and resonant rescattering [13] in the partonic stage 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 pairs of D and $\overline{\mathrm{D}}$ mesons as a sensitive indicator of frequent occurrences of partonic scattering. Since heavy-flavor quarks are pair-created by initial scattering processes, e.g. $gg \to c\bar{c}$, each quark-antiquark pair is correlated in relative azimuth $\Delta\phi$ due to momentum conservation. In elementary collisions, these correlations survive the fragmentation process to a large extent and hence are observable in the final state hadron distribution, i.e. in the distribution of relative azimuth of pairs of D and $\overline{\mathrm{D}}$ mesons. We quantitatively address the question by how much these correlations are affected by the early QGP stage and the hadronic scattering processes in the late hadronic stage.

Results and Discussions

We start by reviewing the D and $\overline{\mathrm{D}}$ angular correlations in pp collisions. The Monte Carlo generator PYTHIA [14] — which includes the lowest order pQCD heavy quark production ($gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$) — reproduces well the experimentally observed correlations of D mesons, measured at fixed target energies [15]. Fig. 2 shows results for such correlations predicted by default PYTHIA (v. 6.139) generator for pp collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. The $\Delta\phi$ distribution is peaked at 180°, especially for high p_{T} D mesons, with the D mesons being oriented back-to-back as one would expect within a pair stemming from a hard scattering of partons. The deviation from $\Delta\phi = \pi$ for lower p_{T} D mesons is due to NLO diagrams and non-perturbative effects, such as the intrinsic k_{T} and fragmentation.

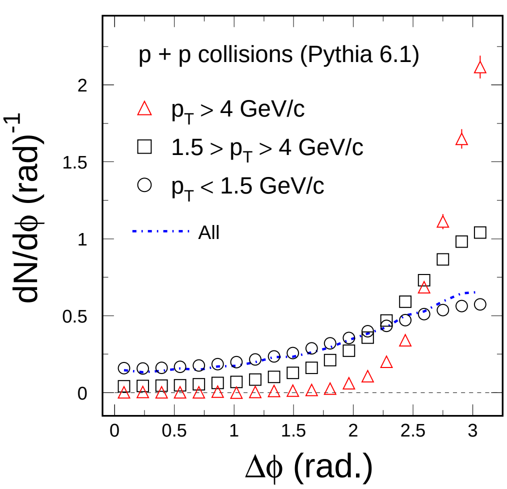

FIG. 2: (Color online) Correlations in relative azimuth, $\Delta\phi$, of $D\overline{D}$ pairs from pp collisions at $\sqrt{s} = 200$ GeV as predicted by PYTHIA (v. 6.139) for different p_{T} ranges.

To explore how the QCD medium generated in central relativistic nucleus-nucleus collisions influences the correlations of D and $\overline{\mathrm{D}}$, we employ a non-relativistic Langevin approach which describes the random walk of charm quarks in a QGP and was first described in Refs. [16, 17, 18],

$$\frac{d\vec{p}}{dt} = -\gamma(T)\vec{p} + \vec{\eta}, \qquad (1)$$

where η is a Gaussian noise variable, normalized such that $\langle \eta_i(t)\eta_j(t')\rangle = \alpha(T)\delta_{ij}\delta(t-t')$. Both the drag coefficient γ and the momentum-space diffusion coefficient α depend on the *local* temperature. We use the same parameterization for γ as in Ref. [16], $\gamma(T) = aT^2$, with $a = 2 \cdot 10^{-6}$ fm^{-1} MeV^{-2} and also neglect the momentum dependence of γ. γ and α are related by the fluctuation-dissipation relation in equilibrium, $\langle p_i^2 \rangle = \alpha/2\gamma$. As in Ref. [16], the α is calculated from the above equation with $\langle p_i^2 \rangle = 1.33 m_c T$, with a charm quark mass $m_{\mathrm{c}} = 1.5$ GeV/c^2.

For simplicity, the initial conditions for the central heavy nucleus (Au or Pb) collisions are the same as in Ref. [16]. We assume a plasma in thermal equilibrium occupying a cylinder of fixed radius R, equal to the radius of the colliding nuclei ($R = 7$ fm in the present calculations). After the full formation of the plasma at the initial time τ_0, the plasma evolves according to Bjorken's hydrodynamics, i.e. $T = T_0(\tau_0/\tau)^{1/3}$. Before the time τ_0, the plasma is changing rapidly and is not fully equilibrated. However, as in Ref. [16], we assume that the plasma is in equilibrium at $T = T_0$ before τ_0. The charmed quark then diffuses in the same way as it does after τ_0. In order to show the pure effect of parton-parton re-scattering in the outlined medium, we generate the charm quarks back-to-back, i.e. $\Delta\phi = \pi$ at the time on the order of $1/m_c \simeq 0.1$ fm/c, and use a delta function for fragmenting the charm quark into a charmed hadron at the hadronization stage. The radius r where the pairs are created is taken from a distribution proportional to 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 quark in the transverse plane is isotropic.

The evolution of the charm momenta with the Langevin equation is stopped when T reaches the critical temperature $T_{\mathrm{c}} = 165$ MeV or when the charm quark leaves the QGP volume. As a first estimation of the QGP effect on the charm quark azimuthal correlation, we, furthermore, neglect the possible contribution of the mixed phase. Fig. 3 (a) shows the results for the D meson (charm quark) angular correlations at different initial charm quark p_{T} for typical RHIC temperature $T_0 = 300$ MeV at $\tau_0 = 0.5$ fm/c. As one can see, for the charm quark pairs with $p_{\mathrm{T}} = 0.5$ GeV/c, the initial angular correlation is almost completely smeared out. While for pairs with $p_{\mathrm{T}} = 3$ GeV/c, the azimuthal correlation is mostly preserved.

Fig. 3 (b) shows the results for $T_0 = 700$ MeV at $\tau_0 = 0.2$ fm/c as expected at LHC. Here, the interactions of charm quarks with the medium are so frequent that even initially high transverse momentum charm pairs can not preserve their angular correlations — low p_{T} pairs are even completely stopped by the medium. Because the $c\bar{c}$ pairs are created at the same position in the fireball, there is a higher probability to escape from the fireball to the same side of the medium where the medium thickness is smaller. Thus, the distribution is shifted towards $\Delta\phi = 0$. Presently, there is only longitudinal flow in the used hydrodynamical model. However, we expect that the strong radial flow further enhances the same side correlations in the case of fully kinetically thermalized charm pairs. Because the pairs are created at the same position in the medium, they will be pushed in the same direction by the radial flow. This mechanism is also regarded as a source of the so-called non-flow effect in the measurement of collective flow [20].

The above results are obtained with a drag coefficient estimated with perturbative QCD [19]. As shown in Ref. [13], non-perturbative contributions that arise from quasi-hadronic bound states in the QGP might be more important. The presence of these resonances at moderate QGP temperature would result in a much larger drag coefficient. Since exact values of the drag coefficient from lattice QCD calculations do not exist, we show the sensitivity of our calculations when varying the parameter a within reasonable values. Figs. 3 (c) and (d) show the drag coefficient dependence of the $c\bar{c}$ angular correlations for $p_T = 3$ GeV/c at $T_0 = 300$ MeV and $p_T = 10$ GeV/c at $T_0 = 700$ MeV, respectively. For $T_0 = 300$ MeV and for $p_T = 3$ GeV/c, the $c\bar{c}$ angular correlations are washed out when a is more than 5 times larger. For $T_0 = 700$ MeV the angular correlations of $p_T = 10$ GeV/c $c\bar{c}$ pairs already vanish completely when a is twice the pQCD value.

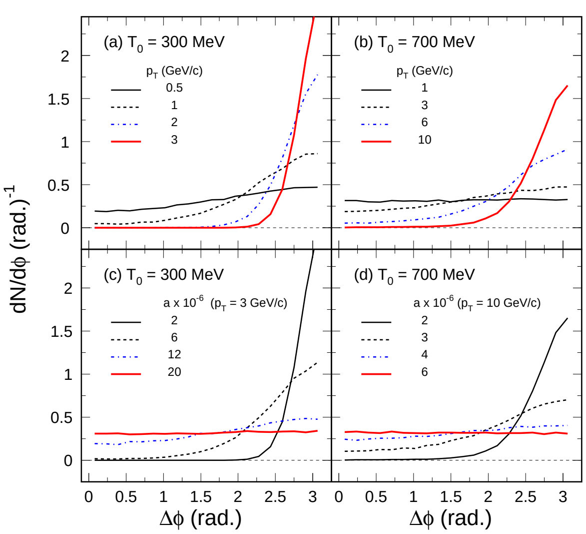

FIG. 3: (Color online) Correlations in relative azimuth $\Delta\phi$ of $D\bar{D}$ pairs from Langevin calculations with $T_0 = 300$ MeV (RHIC) and 700 MeV (LHC). The upper part shows the p_T dependence of the correlations; the lower part shows the drag coefficient dependence.

While the initial correlations of $c\bar{c}$ pairs are clearly affected by the assumed early hot QCD medium and sensitive to its temperature and the drag coefficient, it is important to study whether the loss of correlations can be mimicked by *hadronic* interactions. Therefore, we further investigate by how much the $c\bar{c}$ correlations deteriorate due to hadronic scattering in the late stage of high-energy nuclear collisions. For this purpose, we employ the microscopic hadronic transport approach UrQMD v2.2 [21, 22].

This microscopic transport approach is based on the covariant propagation of constituent quarks and diquarks accompanied by mesonic and baryonic degrees of freedom. It simulates multiple interactions of in-going and newly produced particles, the excitation and fragmentation of color strings and the formation and decay of hadronic resonances. 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 [23]. The yields and spectra of the populated particles are well reproduced in this latest version [23].

In this model, D mesons stem from the very early stage high-energy nucleon-nucleon collisions which are 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 small [24] and we take 2 mb in our calculation. To obtain an upper bound, a large cross section, 20 mb, is also studied. There is an important factor that can affect the $D\bar{D}$ correlations, namely the final state angular distribution of the elastic scattering between D mesons and other hadrons. The strongest effects on the charm correlations is obtained from an isotropic angular distribution in the scattering process. This distribution is motivated by the idea of the formation of intermediate resonances (essentially $D+\pi \leftrightarrow D^*$). For comparison also a forward peaked distribution has been studied. In the forward distribution, the distribution of the cosine of the scattering angle θ in the center of mass system of the decaying resonance, $p(\cos\theta) \propto \exp(7\cos\theta)$.

The results of the UrQMD calculations are shown in Fig. 4. To demonstrate the change in the angular correlations of $D\bar{D}$ pairs, we show the ratio of the final angular correlation after the evolution with UrQMD and the initial distribution from PYTHIA (see Fig. 2). In this analysis, all $D\bar{D}$ pairs were selected, i.e. there is no trigger on a certain p_T range of the D mesons. As one can see in Fig. 4 (a), i.e. in the forward scattering case, the correlation in relative azimuthal angle in Au+Au reactions at $\sqrt{s_{NN}}$=200 GeV is barely changed when compared to the same energy pp collisions, even if the cross section is 20 mb. In Fig. 4 (b), for the isotropic scattering case, the correlation is almost not changed when the cross section is 2 mb either. Only a drastic increase of the hadronic cross section of D mesons to an unrealistically large value of 20 mb results in the $D\bar{D}$ correlations to be completely washed out.

We also find that most scatterings happen at very early times, when the hadron density is very high. More realistically one expects that at the highest energy at RHIC, the (pure) hadronic stage is even shorter than assumed in the present simulation. Hence, the hadron density is expected to be so low that the hadronic stage will not alter the $D\bar{D}$ correlations. Thus, a change of the $D\bar{D}$ angular correlations in heavy-ion collisions would most likely be attributed to frequent parton-parton scattering and, hence, to the existance of a QGP state.

The above calculations, show that heavy-flavor correlations

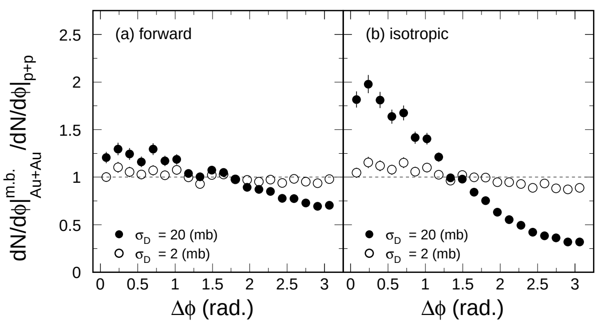

FIG. 4: Ratios of the correlations after hadronic rescattering in relative azimuthal angle $\Delta\phi$ of $D\overline{D}$ pairs from minimum bias Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV to that from PYTHIA (in Fig. 2). The left part is for the case of forward scattering, and the right part is for isotropic scattering.

provide a sensitive tool to directly access the status of equilibration in the medium. A similar picture emerges from the observation and suppression of back-to-back correlations of unidentified high p_T hadrons (jets). Both of them originate from the propagation of partons (heavy quarks or jets) in the medium. However, we have to stress that if heavy quarks lose their energies in the medium and even get kinetically equilibrated, they can still be identified, which is not true in the case of jets. So, in the case of heavy quark correlations, we are actually focusing on the constituents of the medium itself!

Conclusions and Outlook

We propose to measure the change of correlations of heavy-flavor hadrons as an indicator of thermalization at the partonic stage (among light quarks and gluons) in high-energy nuclear collisions. On the example of azimuthal correlations of $D\overline{D}$ pairs, we have demonstrated that hadronic interactions at the late stage can not disturb these correlations significantly. Thus, a decrease or the complete absence of these initially existing correlations clearly indicates frequent interactions of heavy-flavor quarks in the partonic stage. If observed, this would imply an early thermalization of light quarks which would be the main scattering centers. These measurements require good statistics of events in which *both* D mesons are reconstructed at small background. A full reconstruction of D mesons (i.e. of *all* their decay products) in full azimuth is essential to preserve the kinematic information and optimize the acceptance for detecting correlated D meson pairs. We, furthermore, stress that an experimental reference from pp collisions at the same energy is indispensable for detailed studies of changes in these azimuthal correlations. The proposed detector upgrades at RHIC of STAR and PHENIX with their micro-vertex capabilities [25] and direct open charm reconstruction will make these measurements possible.

Acknowledgements One of the authors (H.K.W.) would like to thank C. Lourenço for valuable discussions. This work has been supported by GSI and BMBF, in part by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. After finishing this work, P.-B. Gossiaux informed us about his similar unpublished studies.

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