$D\overline{D}$ momentum correlations versus relative azimuth as a sensitive probe for thermalization

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Abstract

In high-energy nuclear collisions at LHC, where a QGP might be created, the degree of thermalization at the partonic level is a key issue. Due to their large mass, heavy quarks are a powerful tool to probe thermalization. We propose to measure azimuthal correlations of heavy-quark hadrons and their decay products. Changes or even the complete absence of these initially existing azimuthal correlations in $Pb-Pb$ collisions might indicate thermalization at the partonic level. We present studies with PYTHIA for $p-p$ collisions at 14 TeV using the two-particle transverse momentum correlator $\langle\overline{\Delta}p_{t,1}\overline{\Delta}p_{t,2}\rangle$ as a sensitive measure of potential changes in these azimuthal correlations. Contributions from transverse radial flow are estimated.

1 Introduction

Ultra-relativistic heavy ion collisions offer the unique opportunity to probe highly excited (dense) nuclear matter under controlled laboratory conditions. The compelling driving force for such studies is the expectation that at high enough temperature and/or density hadrons dissolve into a new form of elementary particle matter, the Quark Gluon Plasma (QGP), where quarks and gluons are deconfined. An essential difference between elementary particle collisions and nuclear collisions is the development of collective motion in the latter. The collective flow of all hadrons, especially the multistrange hadrons ϕ and Ω, has been experimentally measured [1] at RHIC and suggest that collective motion develops in the early partonic stage. Presently, the degree of thermalization at the parton level is a crucial issue.

The observables related to heavy-quark hadrons are of particular interest in the study of thermalization [2]. Heavy quarks remain massive in a QGP and can only be pair-created in the early stage of the collisions contrary to light quarks which obtain their small bare masses in the deconfined phase when chiral symmetry is partially restored. 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 thresholds for thermal heavy quark (c, b) production. These heavy quarks participate in collective motion provided their interactions at the partonic level occur at high frequency. Thus, collective motion of heavy-quark hadrons will be a useful tool for studying the early thermalization of light quarks in high-energy nuclear collisions.

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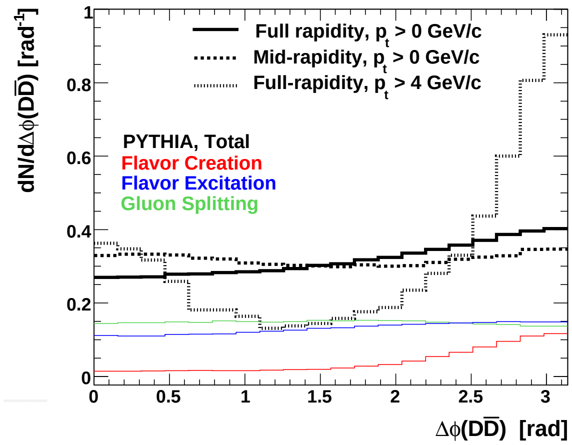


Fig. 1: (Colour online) Distribution in relative azimuth $\Delta\phi$ of $D\overline{D}$ pairs from $p-p$ collisions at $\sqrt{s}$ = 14 TeV as calculated by PYTHIA (v. 6.406), at full rapidity (solid line), and mid-rapidity (dashed line). Contributions from flavor creation, flavor excitation and gluon splitting to the full rapidity distribution are also shown as well as the $p_t > 4$ GeV/c range (dotted line).

1.1 $D\overline{D}$ angular correlations

Since heavy quarks are pair-created by initial hard scattering processes, 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 distribution of D and $\overline{D}$ mesons. The observation of broadened angular correlations of heavy-quark hadron pairs in high-energy heavy-ion collisions would be an indication of thermalization at the partonic stage (among light quarks and gluons) since the hadronic interactions at a late stage in the collision evolution cannot significantly disturb the azimuthal correlation of $D\overline{D}$ pairs [3]. As a result, a visible decrease or the complete absence of such correlations, would indicate frequent interactions of heavy quarks and other light partons in the partonic stage in nucleus-nucleus collisions at RHIC and LHC energies.

Concerning $p-p$ collisions, the Monte Carlo event generator PYTHIA [4] reproduces well the experimentally observed correlations of D mesons, measured at fixed target energies [5]. Fig. 1 shows the calculated correlation for $p-p$ collisions at LHC energies ($\sqrt{s}$ = 14 TeV) where the PYTHIA (v. 6.406) parameters were tuned to reproduce the NLO predictions [6, 7] (with the option MSEL=1). The calculations at leading order (LO) which contain only flavor creation processes ($q\overline{q} \to Q\overline{Q}$, $gg \to Q\overline{Q}$) lead to back-to-back $D\overline{D}$ pairs. Next-to-leading order (NLO) contributions like flavor excitation ($qQ \to qQ, gQ \to gQ$) and gluon splitting ($g \to Q\overline{Q}$) which become dominant at high energy, do not show explicit angular correlation leading to a strongly suppressed back-to-back correlation. At mid-rapidity, the $D\overline{D}$ correlation in $p-p$ collisions at LHC energies has a rather flat angular distribution [8]. Thus, the measurement of these correlations and their modifications in $Pb-Pb$ collisions is challenging. We introduce the two-particle transverse momentum correlator as a sensitive measure of heavy-quark correlations.

2 Employing the two-particle transverse momentum correlator

The strong transverse momentum dependence of the $D\overline{D}$ correlation leads to a $\Delta\phi$ distribution peaked at 180^{o} for high p_t D mesons, as one would expect for back-to-back pairs stemming from hard scatterings of partons (Fig. 1). For this purpose, an additional measure is introduced. The occurence of non-statistical fluctuations of the event-by-event mean transverse momentum M_{pt} goes along with correlations among the transverse momenta of particles. Such correlations can be calculated employing the two-particle transverse momentum correlator [9, 10] for D and $\overline{D}$ respectively.

$$\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle^{(D\overline{D})} = \frac{1}{\sum_{k=1}^{n_{\rm ev}} N_k^{\rm pairs}} . C_k \tag{1}$$

where C_k is the p_t convariance:

$$C_k = \sum_{i=1}^{N_k} \sum_{j=1}^{N_k} (p_{ti} - \overline{p_t}^{(D)})(p_{tj} - \overline{p_t}^{(\overline{D})}) \tag{2}$$

where p_{ti} and p_{tj} are the p_t for i^{th} and j^{th} track in an event of D and $\overline{D}$ respectively, $\overline{p_t}$ is the inclusive mean transverse momentum of all tracks from all events of D and $\overline{D}$, $\sum_{k=1}^{n_{\rm ev}} N_k^{\rm pairs}$ the total number of $D\overline{D}$ pairs and n_{ev} the total number of $p-p$ collisions. It is also possible

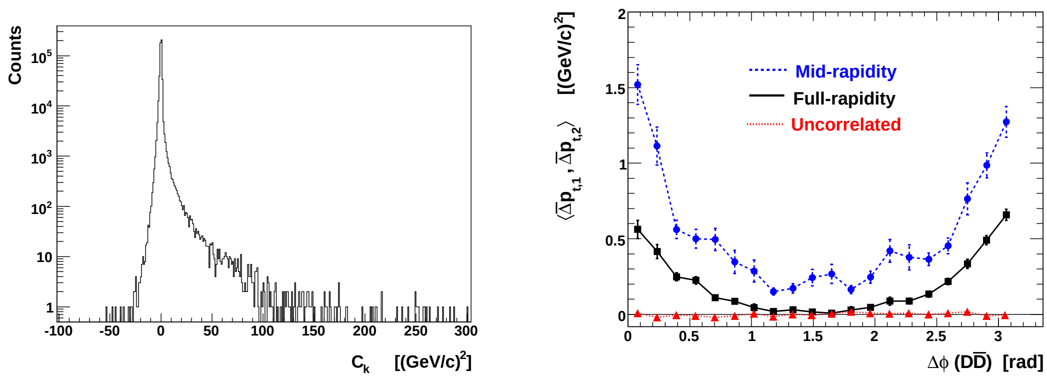


Fig. 2: (Colour online) Distribution of the p_t convariance C_k for $D\overline{D}$ pairs from $p-p$ collisions at $\sqrt{s}$ = 14 TeV as calculated by PYTHIA (v. 6.406) (left panel) and their momentum correlator $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ as a function of $\Delta\phi$ at full rapidity, mid-rapidity and for background using the mixed event method (right panel).

to study the scale dependence of p_t correlations in azimuthal space by calculating the correlator in bins of the azimuthal separation $\Delta\phi$ of particle pairs. For the case of independent particle emission from a single parent distribution, $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ vanishes. Fig. 2 (left panel) shows the distribution of the p_t convariance C_k for $D\overline{D}$ pairs. The mean of this distribution reveals a strong correlation with $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle = 0.199 \pm 0.006$ GeV^2/c^2, which corresponds to the normalized dynamical fluctuation Σ_{pt} [11] of $\sim 30\%$ in $\overline{p_t}$. This is a strong correlation when compared to $\sim 1\%$ that was measured for unidentified charged particles in central collisions at SPS and RHIC [11–13]. The $D\overline{D}$ momentum correlator $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ as a function of relative azimuth angle $\Delta\phi$ is shown in Fig. 2 (right panel). Using particles from different $p-p$ collisions, which are physically uncorrelated (mixed event method), results in a value of $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ consistent with zero, as expected. Applying the correlator to $D\overline{D}$ mesons from the same $p-p$ collision, a rich structure is observed. At full rapidity, the most pronounced features are a strong peak at

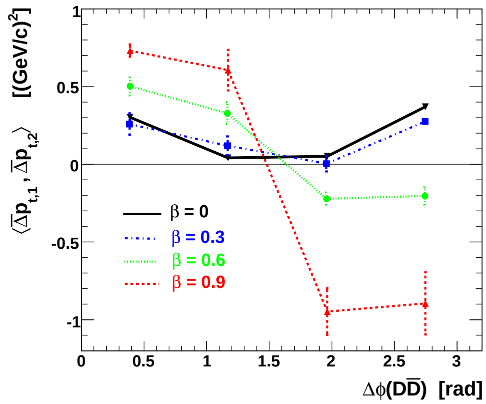


Fig. 3: (Colour online) The momentum correlator $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ of $D\overline{D}$ pairs from $p - p$ collisions at $\sqrt{s}$ = 14 TeV as calculated by PYTHIA (v. 6.406), as a function of their relative azimuth $\Delta\phi$ at full rapidity for various collective flow velocities β.

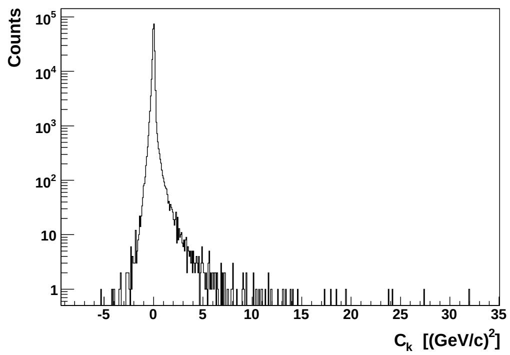
small angles due to gluon splitting, while flavor creation of $c\bar{c}$-quark pairs results in a peak of similar magnitude at large angles. At mid-rapidity the signal is even enhanced, due to the harder p_t spectrum of $D\overline{D}$ meson-pairs.

Our tests show that a realistic amount of elliptic flow does not change these correlations. Concerning the radial flow contribution, it is assumed that the expansion produces an additional momentum $p_{t,f} = \gamma m \beta$, where γ is the Lorentz factor, β is the profile velocity and m is the mass of the D meson. By adding this radial flow component [14] vectorially to the momentum vector produced by PYTHIA, we evaluate the $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ as a function of $\Delta\phi$. As it is shown in Fig. 3, strong radial flow will further increase the same side momentum correlations of $D\overline{D}$ pairs and might lead to strong anti-correlations at large angles.

As we have shown, the initial correlations of $c\bar{c}$ pairs survive the fragmentation process. However, direct reconstruction of D mesons from topological decays suffer from small efficencies resulting in low statistics. Therefore, we investigated semileptonic decays of D mesons and performed an analogous analysis. Our results indicate that dileptons from $D\overline{D}$ decay preserve the original $D\overline{D}$ angular p_t correlation to a large extent. Fig. 4 shows the momentum correlator $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ of e^+e^- pairs from $D\overline{D}$ decay, as a function of of their relative azimuth $\Delta\phi$ at full rapidity, where the away-side peak at large angles is sizeable (right panel). The correlation is given by $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle = 0.007 \pm 0.001$ GeV^2/c^2, which corresponds to the normalized dynamical fluctuation Σ_{pt} of $\sim 12\%$.

3 Conclusions and outlook

In summary, the $D\overline{D}$ momentum correlations versus relative azimuth in $p - p$ collisions at $\sqrt{s}$ = 14 TeV were investigated. The two-particle transverse momentum correlator $\langle \overline{\Delta} p_{t,1} \overline{\Delta} p_{t,2} \rangle$ is a sensitive measure to carefully address these correlations. Our measure has a high sensitivity leading to strong $D\overline{D}$ back-to-back correlation and helps to identify and disentangle different contributions to the observed correlation pattern. We demonstrated that the correlation of generated $c\bar{c}$ pairs survives the fragmentation process and even semileptonic decay to electrons (positrons) to a large extent. Thus, measurements of these correlations seem feasible with the upcoming collisions from LHC.



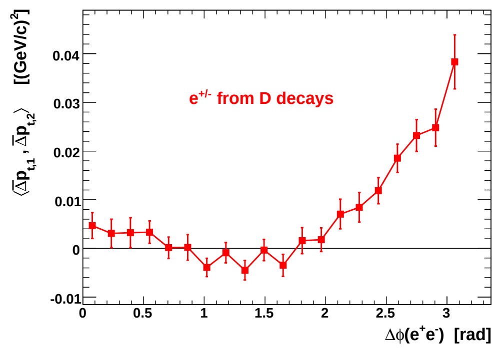


Fig. 4: (Colour online) Distribution of the p_t convariance C_k for e^+e^- pairs from $D\overline{D}$ decays from $p-p$ collisions at $\sqrt{s}$ = 14 TeV as calculated by PYTHIA (v. 6.406) (left panel) and their momentum correlator $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ as a function of $\Delta\phi$ at full rapidity (right panel).

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