Heavy-quark azimuthal momentum correlations as a sensitive probe of thermalization

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High-energy nuclear collisions offer the unique opportunity to probe highly excited nuclear matter in the laboratory. Due to their large mass, heavy quarks and their possible participation in the collective flow of the QCD-medium constitute a powerful probe for thermalization. We present studies with PYTHIA for \textit{pp} collisions at the top LHC energy of $\sqrt{s} = 14$ TeV applying the two-particle transverse momentum correlator $\langle \Delta \p_{T,1}, \Delta \p_{T,2} \rangle$ to pairs of heavy-quark hadrons and their semi-leptonic decay products as a function of their relative azimuth. Modifications or even the complete absence of initially existing correlations in Pb+Pb collisions might indicate thermalization at the partonic level.

I. INTRODUCTION

In high-energy nuclear collisions the degree of thermalization at the partonic level is a key issue. Due to their large mass, heavy quarks and their possible participation in the collective flow of the QCD-medium constitute a powerful probe for thermalization. We present studies with PYTHIA for \textit{pp} collisions at the top LHC energy of $\sqrt{s} = 14$ TeV applying the two-particle transverse momentum correlator $\langle \Delta \p_{T,1}, \Delta \p_{T,2} \rangle$ to pairs of heavy-quark hadrons and their semi-leptonic decay products as a function of their relative azimuth. Modifications or even the complete absence of initially existing correlations in Pb+Pb collisions might indicate thermalization at the partonic level.

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quarks ($Q, \bar{Q}$). Next-to-leading order (NLO) contributions such as flavor excitation ($gQ \rightarrow qQ, gQ \rightarrow gQ$) and gluon splitting ($g \rightarrow Q\bar{Q}$) have a strong dependence on the center-of-mass energy and become dominant at LHC. It was noted in [13] that these higher-order processes do not show pronounced features in azimuth and weaken or destroy the azimuthal correlation between charmed hadrons. By choosing momentum cuts, a somewhat enhanced correlation was extracted [15].

With these processes expected to dominate at LHC energies, sensitivity to heavy quark thermalization might be lost. We investigate whether the $p_t$ correlator as a more sensitive measure of correlations would again provide sensitivity to thermalization. We introduce the two-particle transverse momentum correlator as a sensitive measure of heavy-quark correlations. This method has the following advantages:

(i) The correlator is sensitive to non-statistical fluctuations, thus carving out any physical correlation.

(ii) In case of physically uncorrelated candidate–pairs (e.g. background), the extracted value for the correlator vanishes, thus providing a reliable baseline.

(iii) A localization of the observed correlations in transverse momentum space may help to obtain further insight into the origin of the observed correlations in relative azimuth.

II. EMPLOYING THE TWO-PARTICLE TRANSVERSE MOMENTUM CORRELATOR

We studied two-particle correlations of $D\bar{D}$–pairs in the ($\chi(p_t)_1, \chi(p_t)_2$)-plane, with the cumulative variable $\chi(p_t)$ defined as $\chi(p_t) = \int_0^{p_t} \rho(p'_t)dp'_t,$

$$\chi(p_t) = \int_0^{p_t} \rho(p'_t)dp'_t.$$  \hspace{1cm} (1)

Here, $\rho(p'_t)$ is the inclusive $p_t$ distribution, normalized to unity, which is obtained from all $D\bar{D}$–pairs used in the analysis. For the study of two-particle $p_t$ correlations, the $\chi(p_t)$-values of $D\bar{D}$–pairs ($\chi(p_t)_1, \chi(p_t)_2$) are filled into two-dimensional arrays. In Fig. 1) the two-particle correlation function $dM/ d\chi_1 d\chi_2$ is shown for different values of the azimuthal separation $\Delta \phi = \phi_D - \phi_{\bar{D}}$ of the $D\bar{D}$–pair. For small values in $\Delta \phi$ we observe a strong positive correlation at $\chi_1 \approx \chi_2 \approx 1$. This correlation is most pronounced in the high $p_t$-region related to gluon splitting processes. At large values of $\Delta \phi \approx 180^\circ$, a substantial positive correlation in the high $p_t$-region comes from flavor creation processes.

The occurrence of non-statistical fluctuations of the event-by-event mean transverse momentum $M_{p_t}$ goes along with correlations among the transverse momenta of particle pairs [13]. Such correlations were successfully extracted from experimental data employing the two-particle transverse momentum correlator [14–23]. For the study of $p_t$ correlations

![FIG. 1: (Color online) Two-particle correlations as function of ($\chi(p_t)_1, \chi(p_t)_2$) of 500k $D\bar{D}$ pairs in different regions of $\Delta \phi$ integrated over full rapidity for $pp$ collisions at $\sqrt{s} = 14$ TeV as calculated using PYTHIA (v. 6.406).](image-url)
between particles of different charge sign like $D$ and $\bar{D}$ mesons, the correlator is calculated in the following way:

$$\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle^{(D\bar{D})} = \frac{1}{\sum_{k=1}^{n_{ev}} N_{D}^{k} N_{\bar{D}}^{k}} \sum_{k=1}^{n_{ev}} N_{D}^{k} \sum_{t=1}^{N_{D}^{k}} \sum_{j=1}^{N_{\bar{D}}^{k}} (p_{ti} - \bar{p}_{t}(D))(p_{tj} - \bar{p}_{t}(\bar{D}))$$

where $p_{ti}$ and $p_{tj}$ are the transverse momentum of the $i^{th}$ and $j^{th}$ $D$– and $\bar{D}$–meson. Here, the index $i$ runs over all particles, while the index $j$ runs over all anti–particles created in a single $pp$ collision. The inclusive mean transverse momentum is averaged over all $D$ and $\bar{D}$–mesons, respectively, and is denoted by $\bar{p}_{t}$. The total number of $D\bar{D}$ pairs summed over the number of $pp$ collisions is given by $\sum_{k=1}^{n_{ev}} N_{D}^{k} N_{\bar{D}}^{k}$, with $N_{D}$ and $N_{\bar{D}}$ the number of $D$ and $\bar{D}$ mesons created in a single $pp$ collision. Note that in the present studies we generated one $D\bar{D}$ pair per $pp$ collision, $N_{D}^{k} = N_{\bar{D}}^{k} = 1$. In total, we generated $2M$ ($500k$) $pp$ collisions with a $D\bar{D}$ ($B\bar{B}$) pair.

We studied $p_{t}$ correlations and their dependence on azimuthal separation by calculating the correlator in bins of $\Delta \phi$. In case of independent particle emission, the correlator $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ vanishes. The $D\bar{D}$ momentum correlator $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ from our simulations of $pp$ collisions at $\sqrt{s} = 14$ TeV is shown in the left panel of Fig. 2 as a function of $\Delta \phi$. The error bars reflect the statistical uncertainties from our finite data sample. The correlator has a pronounced forward-backward peaked structure. We observe an enhancement at small azimuth from gluon splitting processes, while flavor creation of $c\bar{c}$–quark pairs leads to an enhanced correlation at backward angles. We have checked that flavor excitation processes, involving a larger number of gluons, lead to a rather flat distribution. Also, our studies show that the correlations are even stronger at mid-rapidity when compared to full rapidity which can be attributed to the harder particle spectrum at mid-rapidity. Integrating the correlator over all azimuth and full rapidity, we get $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle = 0.199 \pm 0.006$ GeV$/c^{2}$.

In order to account for a possible change in the single particle spectrum when comparing different collision systems or energies, the normalized dynamical fluctuation

$$\Sigma_{pt} = \text{sgn}(\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle) \frac{\sqrt{|\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle|}}{\bar{p}_{t}}$$

has been introduced as a dimensionless measure [20].

Our result for $D\bar{D}$ mesons as given above amounts to $\Sigma_{pt} \approx 28\%$ with $\bar{p}_{t}(D) = 1.58$ GeV$/c$. This represents a large value implying a strong correlation when compared to e.g. $\Sigma_{pt} \approx 1\%$ observed for unidentified charged particles in central collisions at SPS and RHIC [21,22]. To mimic combinatorial background which is always present in the experiment, we applied the correlator to $D$– and $\bar{D}$– mesons from different $pp$ collisions, which are physically uncorrelated. This results in a value of $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ consistent with zero (see Fig. 2). Therefore the correlator allows for a clear distinction between the case were correlations are present (different from zero) or absent (equal to zero) going beyond the method described in [10,13].

FIG. 2: (Color online) Distribution of the momentum correlator $\langle \Delta p_{t,1}, \Delta p_{t,2} \rangle$ of $500k$ $D\bar{D}$ pairs (left panel) and $500k$ $B\bar{B}$ pairs (right panel) as a function of relative azimuth $\Delta \phi$ at mid-rapidity (circles), for full rapidity (squares) and for background using the mixed event method (triangles) for $pp$ collisions at $\sqrt{s} = 14$ TeV as calculated using PYTHIA (v. 6.406). The lines connect the points.
The $B\bar{B}$ momentum correlator is shown in the right panel of Fig. 2 and has a structure similar to the one for $D\bar{D}$ pairs. Integrating the correlator over all azimuth and full rapidity, we get $(\Delta p_{t,1}, \Delta p_{t,2}) = 2.73 \pm 0.05 \text{ GeV}/c^2$ which corresponds to the normalized fluctuation $\Sigma_{pt} \approx 31\%$ with $p_{t}^{B} = 5.27 \text{ GeV}/c$. This demonstrates that by applying the momentum correlator to pairs of heavy quarks in $pp$ collisions at LHC energies, strong correlations are predicted which should be experimentally observable. When only considering $D\bar{D}$ production yields as a function of relative azimuth, a weaker dependency is predicted [15].

At LHC energies, the production of $D$–mesons is dominated by gluon splitting and flavor excitation processes while the contribution from flavor creation is about 10% at low momentum and increases up to 20% at larger momentum [24]. On the other hand, the production of $B$–mesons is dominated by flavor creation and flavor excitation with a small contribution below 10% from gluon splitting and an overall weak dependence on transverse momentum [24].

As shown above, the initial correlations of $c\bar{c}$–quark pairs survive the fragmentation process into hadrons to a large extent. However experimentally, full kinematic reconstruction of $D$–mesons from topological decays suffer from small branching ratios and rather small reconstructing efficiencies resulting in low statistics, especially when pairs of $D$–mesons are considered where these factors enter quadratically. In minimum bias $pp$ collisions at $\sqrt{s} = 14$ TeV, roughly 28 (2) out of 1000 collisions create a charmed (beauty) meson such as $D^0$, $D^+$ or $D_s^+$ ($B^0$, $B^+$ or $B_s^0$) at mid-rapidity $|y| < 1$. The branching ratio in the golden channel $D^0 \rightarrow K^- + \pi^+$ amounts to 3.83% with additional penalty factors due to the detector acceptance for the decay particles and topological reconstruction of the secondary decay vertex. Overall we estimate the number of fully reconstructed $D^0 - \bar{D}^0$ pairs in 10$^8$ minimum bias $pp$ collisions, which is equivalent to one year of ALICE data taking, to be in the order of 10. This is obviously too low to study $p_t$ correlations.

As an alternative, we considered electrons (positrons) from semi-leptonic decays of charm and beauty hadrons with an average branching ratio to electrons of 10% and 11%, respectively.

The left panel of Fig. 3 shows the momentum correlator versus relative azimuth for $D - e^-$–pairs (triangles), with the electron stemming from the semi- leptonic decay of one of the $D$–mesons and for $e^+ - e^-$–pairs (squares) where both $D$–mesons decayed into an electron. The right panel shows the correlator for $e^+ e^-$–pairs from semi-leptonic decays of $B\bar{B}$–mesons pairs. The correlations at small values of $\Delta \phi$ do not survive the semi-leptonic decay while at backward angles around $\Delta \phi \approx 180^\circ$, we still observe a strong correlation. We checked that this is due to the decay kinematics with gluon splitting processes dominating at forward angles resulting in a softer distribution of the heavy-quark hadron. At backward angles flavor creation processes dominate leading to a significantly harder spectrum.

Integrating the correlator over all azimuth and full rapidity, we extract $(\Delta p_{t,1}, \Delta p_{t,2}) = 0.007 \pm 0.001 \text{ GeV}/c^2$ (0.10 ± 0.01 GeV$^2$/c$^2$) for $e^+ e^-$–pairs from charm (bottom) decays corresponding to the normalized dynamical fluctuation $\Sigma_{pt} \approx 17\% (18\%)$ with $p_{t} = 0.50 \text{ GeV}/c$ (1.73 GeV/c). This clearly indicates that the initial correlations among a heavy quark and its corresponding anti–quark even survive semi-leptonic decays into electrons (positrons) to a large extent. With the predicted charm production in full rapidity of 0.16 per minimum bias $pp$ collision at $\sqrt{s} = 14$ TeV [13], we estimate the number of electron-positron pairs in the ALICE central barrel ($|y| < 0.9, p_t > 0.2 \text{ GeV}/c$) from heavy-quark decays within one nominal year of ALICE running to be more than 100k. Thus, an experimental observation of heavy-quark momentum correlation at the LHC should be possible.

The heavy-quark transverse momentum depends on the relative contributions from different QCD-process. Furthermore, experimentally it has been observed that the average transverse momentum is monotonically rising with the charged-particle multiplicity in $pp$ collisions [22, 26]. We studied the normalized dynamical fluctuation $\Sigma_{pt}$ of $D\bar{D}$–pairs in several multiplicity regions in $pp$ collisions at the top LHC energy as shown in Fig. 4. Higher multiplicity collisions result in stronger correlations due to the increase of the mean transverse momentum from $p_{t} = 1.53 \text{ GeV}/c$...
at multiplicities $\langle N_{ch}\rangle \approx 25$ to $p_t = 3.46$ GeV/$c$ at $\langle N_{ch}\rangle \approx 42$. In addition, the contribution from flavor creation to the production of $D$-mesons increases up to 18% in high multiplicity events compared with 12% in low multiplicity events leading to enhanced correlations at large relative azimuth $\Delta \phi$. Thus, the highest multiplicities at LHC energies might be a good case to experimentally establish the existence of these correlations for heavy quarks. The results on the heavy-quark correlator discussed above are our prediction for $pp$ collisions at the top LHC energy and serve as a baseline for the case that no thermalization sets in as is expected for such a small collision system. Further, our calculations show that higher multiplicity $pp$ collisions result in stronger correlations.

Finally, we consider the relative pseudo-rapidity $\Delta \eta$ of $D\bar{D}$ pairs and show the correlator as a function of $\Delta \phi$ and $\Delta \eta$ (see Fig. 5). Gluon splitting processes lead to correlations at small values of $\Delta \phi$ and $\Delta \eta$. On the other hand, flavor creation results in correlations at large values of $\Delta \phi$ extending over a large range in $\Delta \eta$. In Pb+Pb collisions, the development of strong transverse flow would lead to a broadening of the away-side momentum correlation and an enhancement at small relative azimuth of $D\bar{D}$ pairs [27, 28]. To experimentally disentangle these different contributions, an analysis in ranges of pseudo-rapidity, e.g. $|\Delta \eta| < 0.5$ to study gluon splitting processes and effects of collective flow versus $|\Delta \eta| \geq 0.5$ where flavor creation dominates, might help. Further, a comparison of experimental heavy-quark correlations from Pb+Pb collisions to results from microscopic transport calculations would provide an independent way to extract effective heavy-quark scattering rates in the QCD-medium [28].

III. CONCLUSIONS AND OUTLOOK

In summary, we have presented a sensitive method to see azimuthal correlations of heavy-quarks in $pp$ collisions at LHC energies. We applied the momentum correlator to pairs of heavy-quark hadrons and their semi-leptonic decay products as a precise and normalized measure. At LHC energies, the production of charm quarks is expected to be dominated by gluon splitting processes resulting in forward correlations with an increasing contribution of backward-peaked pair creation at larger momentum. A stronger correlation is expected in high-multiplicity $pp$ collisions. A modification or disappearance of these momentum correlations in Pb+Pb collisions as compared to $pp$ collisions will be explored as a sensitive probe of thermalization.
FIG. 5: (Color online) The momentum correlator of 2 million \(DD\)-pairs as a function of \(\Delta \phi\) and \(\Delta \eta\) from \(pp\) collisions at \(\sqrt{s} = 14\) TeV as calculated using PYTHIA (v. 6.406).

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