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Long-range and short-range dihadron angular correlations in central PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$

The CMS Collaboration[*]

Abstract

First measurements of dihadron correlations for charged particles are presented for central PbPb collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV over a broad range in relative pseudorapidity ($\Delta\eta$) and the full range of relative azimuthal angle ($\Delta\phi$). The data were collected with the CMS detector, at the LHC. A broadening of the away-side ($\Delta\phi \approx \pi$) azimuthal correlation is observed at all $\Delta\eta$, as compared to the measurements in pp collisions. Furthermore, long-range dihadron correlations in $\Delta\eta$ are observed for particles with similar ϕ values. This phenomenon, also known as the "ridge", persists up to at least $|\Delta\eta| = 4$. For particles with transverse momenta (p_{T}) of 2–4 GeV/c, the ridge is found to be most prominent when these particles are correlated with particles of $p_{\mathrm{T}} = 2$–$6\,\mathrm{GeV}/c$, and to be much reduced when paired with particles of $p_{\mathrm{T}} = 10$–$12\,\mathrm{GeV}/c$.

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[*] See Appendix A for the list of collaboration members

1 Introduction

Measurements of dihadron azimuthal correlations [1–7] have provided a powerful tool to study the properties of the strongly interacting medium created in ultrarelativistic nuclear collisions [8–11]. An early indication of strong jet-medium interactions at RHIC was the absence of high-transverse-momentum (high-p_{T}) back-to-back particle pairs in dihadron correlation measurements [1] and the corresponding enhancement of low-p_{T} hadrons recoiling from a high-p_{T} leading, or "trigger", particle [3]. The recent observations of the suppression of high-p_{T} charged hadrons [12] and of asymmetric energies of reconstructed jets [13, 14] in PbPb collisions at the Large Hadron Collider (LHC) provide further evidence of jet quenching, suggesting a large energy loss for partons traversing the produced medium.

At RHIC, extending dihadron azimuthal correlation measurements to larger relative pseudorapidities resulted in the discovery of a ridge-shaped correlation in central AuAu collisions between particles with small relative azimuthal angles ($|\Delta\phi| \approx 0$), out to very large relative pseudorapidity ($|\Delta\eta|$) [2, 6]. Although the "ridge" has been qualitatively described by several different models [15–26], its origin is still not well understood. Some models attribute the ridge to jet-medium interactions, while others attribute it to the medium itself. The ridge has been observed for particles with transverse momenta from several hundred MeV/c to a few GeV/c. However, the character of the ridge for even higher-p_{T} particles, as well as its dependence on collision energy, is still poorly understood from the RHIC results [2]. Recently, a striking ridge structure has also been observed in very high multiplicity proton-proton (pp) collisions at a center-of-mass energy of 7 TeV at the LHC by the Compact Muon Solenoid (CMS) Collaboration [27], posing new challenges to the understanding of these long-range correlations.

This paper presents the first measurement of dihadron correlations for charged particles produced in the most central (0–5% centrality) PbPb collisions at a nucleon-nucleon center-of-mass energy ($\sqrt{s_{_{NN}}}$) of 2.76 TeV over a large phase space. The results are presented in terms of the associated hadron yields as a function of pseudorapidity and azimuthal angle relative to trigger particles in different transverse momentum intervals. Traditionally, trigger particles have been utilized to represent the direction of the leading hadron in a jet, and were required to have a higher momentum than all the other associated particles in the jet [2, 6]. However, as shown in Ref. [27], important information can also be obtained by studying the correlation of hadron pairs from the same p_{T} interval, which is particularly useful when addressing the properties of the medium itself. The current analysis employs both approaches. This measurement provides a unique examination of the ridge in the most central PbPb collisions at the highest energies reached so far in the laboratory over a wide range in transverse momentum (2–12 GeV/c) and up to large relative pseudorapidity ($|\Delta\eta| \approx 4$), imposing further quantitative constraints on the possible origin of the ridge.

Details of event readout and analysis for extracting the correlation functions are described in Section 2, the physics results found using the correlations are described in Section 3, and a summary is given in Section 4.

2 Data and Analysis

The analysis reported in this paper is based on PbPb collisions at $\sqrt{s_{_{NN}}}$ = 2.76 TeV collected during the LHC heavy-ion run in November and December 2010 with the CMS detector. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the field volume are the inner tracker, the crystal electromagnetic calorimeter, and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The nearly 4π solid-angle acceptance of the CMS detector is ideally suited for studies of both short- and long-range particle correlations. A detailed description of the CMS detector can be found in Ref. [28]. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the counterclockwise beam direction. The detector subsystem primarily used for the present analysis is the inner tracker that reconstructs the trajectories of charged particles with $p_{\mathrm{T}} > 100\,\mathrm{MeV}/c$, covering the pseudorapidity region $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the beam direction. The inner tracker consists of 1440 silicon pixel and 15 148 silicon strip detector modules immersed in the 3.8 T axial magnetic field of the superconducting solenoid.

The event readout of the CMS detector for PbPb collisions is triggered by coincident signals in forward detectors located on both sides of the nominal collision point. In particular, minimum bias PbPb data are recorded based on coincident signals in the beam scintillator counters (BSC, $3.23 < |\eta| < 4.65$) or in the steel/quartz-fiber Cherenkov forward hadron calorimeters (HF, $2.9 < |\eta| < 5.2$) from both ends of the detector. In order to suppress events due to noise, cosmic rays, double-firing triggers, and beam backgrounds, the minimum bias trigger used in this analysis is required to be in coincidence with bunches colliding in the interaction region. The trigger has an acceptance of $(97 \pm 3)\%$ for hadronic inelastic PbPb collisions [14].

Events are selected offline by requiring in addition at least three hits in the HF calorimeters at both ends of CMS, with at least 3 GeV of energy in each cluster, and the presence of a reconstructed primary vertex containing at least two tracks. These criteria further reduce background from single-beam interactions (e.g., beam gas and beam halo), cosmic muons, and large-impact-parameter, ultra-peripheral collisions that lead to the electromagnetic breakup of one or both of the Pb nuclei [29]. The reconstructed primary vertex is required to be located within 15 cm of the nominal collision point along the beam axis and within a radius of 0.02 cm relative to the average vertex position in the transverse plane.

This analysis is based on a data sample of PbPb collisions corresponding to an integrated luminosity of approximately 3.12 $\mu\mathrm{b}^{-1}$ [30, 31], which contains 24.1 million minimum bias collisions after all event selections are applied.

The energy released in the collisions is related to the centrality of heavy-ion interactions, i.e., the geometrical overlap of the incoming nuclei. In CMS, centrality is classified according to percentiles of the distribution of the energy deposited in the HF calorimeters. The centrality class used in this analysis corresponds to the 0–5% most central PbPb collisions, a total of 1.2 million events. More details on the centrality determination can be found in Refs. [14, 32].

A reconstructed track is considered as a primary-track candidate if the significance of the separation along the beam axis between the track and the primary vertex, $d_z/\sigma(d_z)$, and the significance of the impact parameter relative to the primary vertex transverse to the beam, $d_{xy}/\sigma(d_{xy})$, are each less than 3. In order to remove tracks with potentially poorly reconstructed momentum values, the relative uncertainty of the momentum measurement, $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}$, is required to be less than 5.0%. Requiring at least 12 hits on each track helps to reject misidentified tracks. Systematic uncertainties related to the track selections have been evaluated as discussed below.

Trigger particles are defined as all charged particles originating from the primary vertex, with $|\eta| < 2.4$ and in a specified $p_{\mathrm{T}}^{\mathrm{trig}}$ range. The number of trigger particles in the event is denoted by N_{trig}, which can be more than one per event. Hadron pairs are formed by associating with every trigger particle the remaining charged particles with $|\eta| < 2.4$ and in a specified $p_{\mathrm{T}}^{\mathrm{assoc}}$

range. The per-trigger-particle associated yield distribution is then defined by:

$$\frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}, \tag{1}$$

where $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ of the pair, respectively. The signal distribution, $S(\Delta\eta,\Delta\phi)$, is the measured per-trigger-particle distribution of same-event pairs, i.e.,

$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{same}}}{d\Delta\eta d\Delta\phi}. \tag{2}$$

The mixed-event background distribution,

$$B(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{mix}}}{d\Delta\eta d\Delta\phi}, \tag{3}$$

is constructed by pairing the trigger particles in each event with the associated particles from 10 different random events, excluding the original event. The symbol N^{mix} denotes the number of pairs taken from the mixed event. The background distribution is used to account for random combinatorial background and pair-acceptance effects. The normalization factor $B(0,0)$ is the value of $B(\Delta\eta,\Delta\phi)$ at $\Delta\eta = 0$ and $\Delta\phi = 0$ (with a bin width of 0.3 in $\Delta\eta$ and $\pi/16$ in $\Delta\phi$), representing the mixed-event associated yield for both particles of the pair going in approximately the same direction, thus having full pair acceptance. Therefore, the ratio $B(0,0)/B(\Delta\eta,\Delta\phi)$ is the pair-acceptance correction factor used to derive the corrected per-trigger-particle associated yield distribution. Equation (1) is calculated in 2 cm wide bins of the vertex position (z_{vtx}) along the beam direction and averaged over the range $|z_{\text{vtx}}| < 15$ cm. To maximize the statistical precision, the absolute values of $\Delta\eta$ and $\Delta\phi$ are used to fill one quadrant of the $(\Delta\eta,\Delta\phi)$ histograms, with the other three quadrants filled (only for illustration purposes) by reflection. Therefore, the resulting distributions are symmetric about $(\Delta\eta,\Delta\phi) = (0,0)$ by construction.

Each reconstructed track is weighted by the inverse of the efficiency factor, $\varepsilon_{\text{trk}}(\eta, p_{\text{T}})$, as a function of the track's pseudorapidity and transverse momentum. The efficiency weighting factor accounts for the detector acceptance $A(\eta, p_{\text{T}})$, the reconstruction efficiency $E(\eta, p_{\text{T}})$, and the fraction of misidentified tracks, $F(\eta, p_{\text{T}})$,

$$\varepsilon_{\text{trk}}(\eta, p_{\text{T}}) = \frac{AE}{1-F}. \tag{4}$$

Studies with simulated Monte Carlo (MC) events show that the combined geometrical acceptance and reconstruction efficiency for the primary-track reconstruction reaches about 60% for the 0–5% most central PbPb collisions at $p_{\text{T}} > 2\,\text{GeV}/c$ over the full CMS tracker acceptance ($|\eta| < 2.4$) and 65% for $|\eta| < 1.0$. The fraction of misidentified tracks is about 1–2% for $|\eta| < 1.0$, but increases to 10% at $|\eta| \approx 2.4$. The weighting changes the overall scale but not the shape of the associated yield distribution, which depends on the ratio of the signal to background distributions.

A closure test of the track-weighting procedure is performed on HYDJET [33] (version 1.6) MC events. The efficiency-weighted associated yield distribution from reconstructed tracks is found to agree with the generator-level correlation function to within 3.3%. In addition, systematic checks of the tracking efficiency, in which simulated MC tracks are embedded into data events, give results consistent with pure HYDJET simulations to within 5.0%. The tracking efficiency also depends on the vertex z position of the event. However, this dependence is negligible in this analysis, and its effects are taken into account in the systematic uncertainty by comparing the efficiency-corrected correlation functions for two different z_{vtx} ranges, $|z_{\mathrm{vtx}}| < 15\,\mathrm{cm}$ and $|z_{\mathrm{vtx}}| < 5\,\mathrm{cm}$, which are found to differ by less than 2.2%. Additional uncertainties due to track quality cuts are examined by loosening or tightening the track selections described previously, and the final results are found to be insensitive to the selections to within 2.0%. An independent analysis, using a somewhat different but well-established methodology [34, 35] in constructing the mixed-event background is performed as a cross-check, where 10 trigger particles from different events are selected first and combined to form a single event, and then correlated with particles from another event. It yields results within 2.9–3.6% of the default values (3.6% for $|\Delta\eta| < 1$ and 2.9% for $2 < |\Delta\eta| < 4$), with a slight dependence on $\Delta\eta$ and $\Delta\phi$. The other four sources of systematic uncertainty are largely independent of $\Delta\eta$ and $\Delta\phi$.

Table 1 summarizes the different systematic sources, whose corresponding uncertainties are added in quadrature becoming the quoted systematic uncertainties of the per-trigger-particle associated yield.

Table 1: Summary of systematic uncertainties.

Source	Systematic uncertainty of the per-trigger-particle associated yield (%)
Tracking weighting closure test	3.3
Tracking efficiency	5.0
Vertex dependence	2.2
Track selection dependence	2.0
Construction of the mixed-event background	2.9–3.6
Total	7.3–7.6

3 Results

The measured per-trigger-particle associated yield distribution of charged hadrons as a function of $|\Delta\eta|$ and $|\Delta\phi|$ in the 0–5% most central PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76\,\mathrm{TeV}$ is shown in Fig. 1a for trigger particles with $4 < p_{\mathrm{T}}^{\mathrm{trig}} < 6\,\mathrm{GeV}/c$ and associated particles with $2 < p_{\mathrm{T}}^{\mathrm{assoc}} < 4\,\mathrm{GeV}/c$. To understand the effects of the hot, dense medium produced in the collisions, this distribution can be compared to that from a PYTHIA8 MC simulation [36] (version 8.135) of pp collisions at $\sqrt{s} = 2.76\,\mathrm{TeV}$, shown in Fig. 1b. This transverse momentum range, one of several studied later in this paper, is chosen for this figure since it illustrates the differences between correlations from PbPb data and PYTHIA8 pp MC events most clearly. The main features of the simulated pp MC distribution are a narrow jet-fragmentation peak at $(\Delta\eta, \Delta\phi) \approx (0, 0)$ and a back-to-back jet structure at $|\Delta\phi| = \pi$, but extended in $\Delta\eta$. In the 0–5% most central PbPb collisions, particle correlations are significantly modified, as shown in Fig. 1a. The away-side pairs ($\Delta\phi \approx \pi$) exhibit a correlation with similar amplitude compared to PYTHIA8, although the structure in PbPb data is much broader in both $\Delta\phi$ and $\Delta\eta$ so that it appears almost flat. On the near side ($\Delta\phi \approx 0$), besides the common jet-like particle production in both pp and PbPb at $(\Delta\eta, \Delta\phi) \approx (0, 0)$ due to jet fragmentation, a clear and significant ridge-like structure is observed in PbPb at $\Delta\phi \approx 0$, which extends all the way to the limit of the measurement of

$|\Delta\eta| = 4$.

In relativistic heavy-ion collisions, the anisotropic hydrodynamic expansion of the produced medium is one possible source of long-range azimuthal correlations, driven by the event-by-event initial anisotropy of the collision zone [7, 37]. For non-central collisions, these correlations are dominated by the second-order Fourier component of the $|\Delta\phi|$ distribution, usually called elliptic flow or v_2. Measurements of dihadron correlations at RHIC have frequently attempted to subtract or factorize the elliptic flow contribution based on direct v_2 measurements, in order to reveal other features of particle correlations that may provide insight into the interactions between the jets and the medium. However, recent theoretical developments indicate that the interplay between initial-state fluctuations and the subsequent hydrodynamic expansion gives rise to additional Fourier components in the azimuthal particle correlations [25, 26, 38–42]. These components need to be treated on equal footing with the elliptic flow component. In particular for the 0–5% most central PbPb collisions, the elliptic flow contribution to the azimuthal correlations is not expected to be dominant [43]. Therefore, the original unsubtracted correlation functions are presented in this paper, containing the full information necessary for the comparison with theoretical calculations.

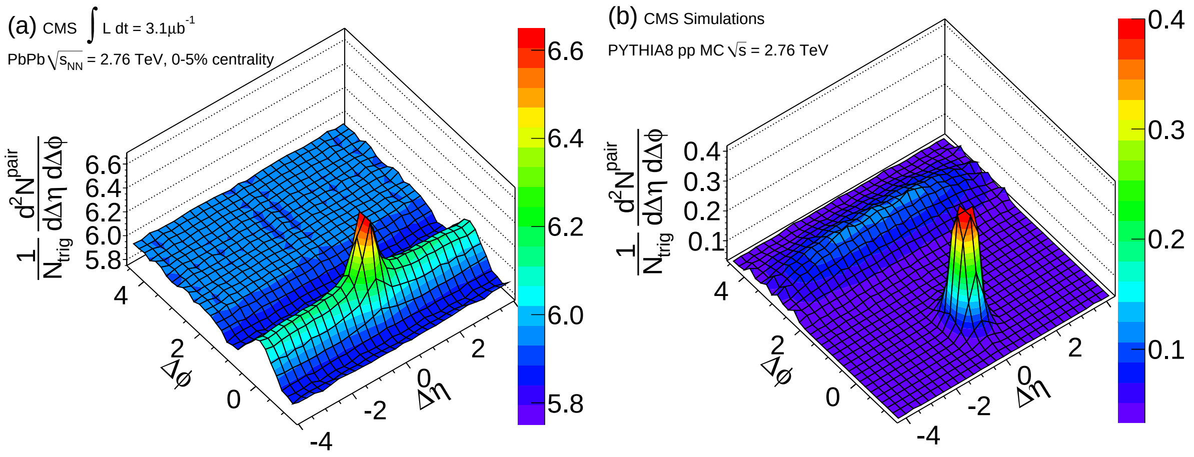

Figure 1: Two-dimensional (2-D) per-trigger-particle associated yield of charged hadrons as a function of $|\Delta\eta|$ and $|\Delta\phi|$ for $4 < p_{\mathrm{T}}^{\mathrm{trig}} < 6\,\mathrm{GeV}/c$ and $2 < p_{\mathrm{T}}^{\mathrm{assoc}} < 4\,\mathrm{GeV}/c$ from (a) 0–5% most central PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$, and (b) PYTHIA8 pp MC simulation at $\sqrt{s} = 2.76\,\mathrm{TeV}$.

3.1 Associated Yield Distributions versus $\Delta\phi$

To quantitatively examine the features of short-range and long-range azimuthal correlations, one dimensional (1-D) $\Delta\phi$ correlation functions are calculated by averaging the 2-D distributions over a limited region in $\Delta\eta$ from $\Delta\eta_{\mathrm{min}}$ to $\Delta\eta_{\mathrm{max}}$:

$$\frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{d\Delta\phi} = \frac{1}{\Delta\eta_{\mathrm{max}} - \Delta\eta_{\mathrm{min}}}\int_{\Delta\eta_{\mathrm{min}}}^{\Delta\eta_{\mathrm{max}}} \frac{1}{N_{\mathrm{trig}}}\frac{d^2N^{\mathrm{pair}}}{d\Delta\eta d\Delta\phi} d\Delta\eta. \tag{5}$$

The results of extracting the 1-D $\Delta\phi$ correlations for the 0–5% most central PbPb collisions are shown in Figs. 2 and 3. The associated yield per trigger particle in the range of $2 < p_{\mathrm{T}}^{\mathrm{assoc}} < 4\,\mathrm{GeV}/c$ is extracted for five different $p_{\mathrm{T}}^{\mathrm{trig}}$ intervals (2–4, 4–6, 6–8, 8–10, and 10–12 GeV/c) and two ranges in $\Delta\eta$. Figure 2 gives the short-range pseudorapidity result, i.e., averaged over the region $|\Delta\eta| < 1$. Figure 3 shows the same comparison for long-range correlations, i.e., averaged over the region $2 < |\Delta\eta| < 4$. A comparison to PYTHIA8 pp MC events at $\sqrt{s} = 2.76\,\text{TeV}$ is also shown, with a constant added to match the PbPb results at $\Delta\phi = 1$ in order to facilitate the comparison. In this projection, only the range $0 < \Delta\phi < \pi$ is shown, as the $\Delta\phi$ correlation function is symmetric around $\Delta\phi = 0$ by construction.

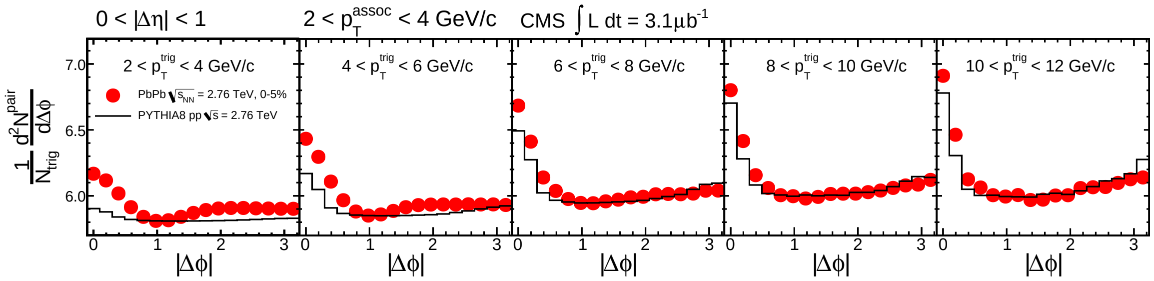

Figure 2: Short-range ($|\Delta\eta| < 1$) per-trigger-particle associated yields of charged hadrons as a function of $|\Delta\phi|$ from the 0–5% most central PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$, requiring $2 < p_T^{\text{assoc}} < 4\,\text{GeV}/c$, for five different intervals of p_T^{trig}. The PYTHIA8 pp MC results (solid histograms) are also shown, shifted up by a constant value to match the PbPb data at $\Delta\phi = 1$ for ease of comparison. The error bars are statistical only and are too small to be visible in most of the panels. The systematic uncertainty of 7.6% for all data points is not shown in the plots.

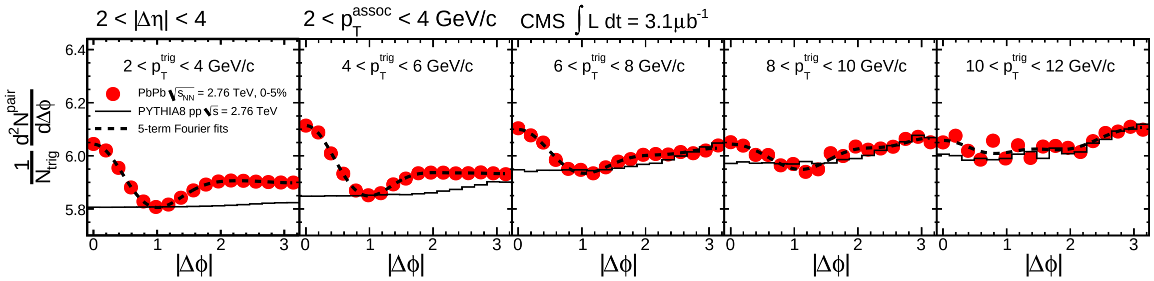

Figure 3: Long-range ($2 < |\Delta\eta| < 4$) per-trigger-particle associated yields of charged hadrons as a function of $|\Delta\phi|$ under the same conditions as in Fig. 2. The systematic uncertainty of 7.3% for all data points is not shown in the plots. Dashed lines show the fits by the first five terms in the Fourier series, as discussed in Section 3.3.

The panels of Figs. 2 and 3 show a modification of the away-side associated yield for $|\Delta\phi| > \pi/2$ in central PbPb collisions that is not present in the PYTHIA8 pp MC simulation. This modification is most pronounced for lower p_T^{trig} values and is characterized by a similarly broad distribution as seen in lower-energy RHIC measurements, where it was attributed to jet quenching and related phenomena [3, 5]. The near-side associated yield in PbPb data includes the contributions from both the jet-like peak and the ridge structure seen in Fig. 1a. Thus, it is not directly comparable to PYTHIA8 pp MC events, where the ridge component is absent. A more quantitative comparison of the jet-like component between PbPb data and PYTHIA8 pp MC events will be discussed below.

For azimuthal correlations at large values of $\Delta\eta$ (Fig. 3), a clear maximum at $\Delta\phi \approx 0$ is observed, which corresponds to the ridge structure seen in the 2-D distribution of Fig. 1a. This feature of the long-range azimuthal correlation function is not present in the PYTHIA8 pp MC simulation for any $p_{\mathrm{T}}^{\mathrm{trig}}$ bin. In PbPb, the height of the ridge structure decreases as $p_{\mathrm{T}}^{\mathrm{trig}}$ increases (Fig. 3) and has largely vanished for $p_{\mathrm{T}}^{\mathrm{trig}} \approx$ 10–12 GeV/c. The diminishing height of the ridge with increasing $p_{\mathrm{T}}^{\mathrm{trig}}$ was not evident from previous measurements at RHIC in AuAu collisions presumably because of lack of events at high p_{T}.

3.2 Integrated Associated Yield

The strengths of the jet peak and ridge on the near side, as well as their dependences on $\Delta\eta$ and $p_{\mathrm{T}}^{\mathrm{trig}}$, can be quantified by the integrated associated yields. In the presence of multiple sources of correlations, the correlation of interest is commonly estimated using an implementation of the zero-yield-at-minimum (ZYAM) method [17]. However, as mentioned previously, the possible contribution of elliptic flow is not taken into account as it is not the dominant effect for the most central PbPb collisions considered here. The ZYAM method is implemented as follows. A second-order polynomial is fitted to the $|\Delta\phi|$ distributions in the region $0.5 < |\Delta\phi| < 1.5$. The location of the minimum of the polynomial in this region is denoted as $\Delta\phi_{\mathrm{ZYAM}}$. Using the position of the minimum, the associated yield is then calculated as the integral of the $|\Delta\phi|$ distribution minus its value at $\Delta\phi_{\mathrm{ZYAM}}$ between $|\Delta\phi| = 0$ and $\Delta\phi_{\mathrm{ZYAM}}$. The uncertainty on the minimum level obtained by the ZYAM procedure, combined with the uncertainty arising from the choice of fit range in $|\Delta\phi|$, results in an uncertainty on the absolute associated yield that is constant with a value of 0.012 over all $\Delta\eta$ and $p_{\mathrm{T}}^{\mathrm{trig}}$ bins.

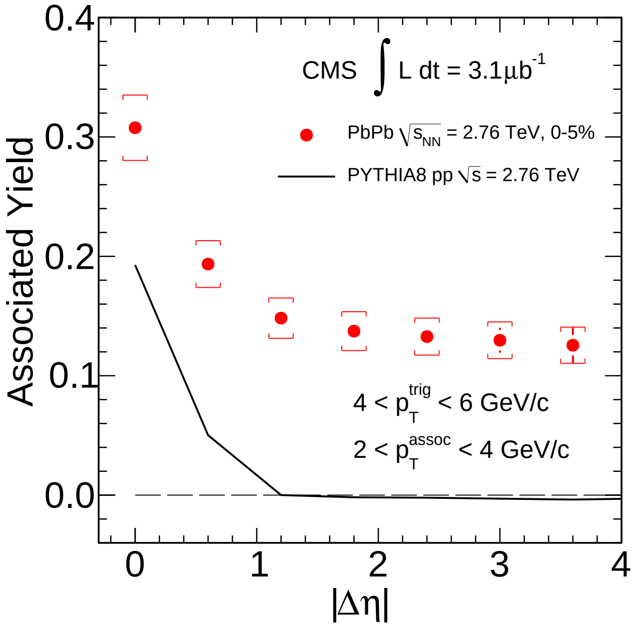

Figure 4: Integrated near-side ($|\Delta\phi| < \Delta\phi_{\mathrm{ZYAM}}$) associated yield for $4 < p_{\mathrm{T}}^{\mathrm{trig}} < 6$ GeV/c and $2 < p_{\mathrm{T}}^{\mathrm{assoc}} < 4$ GeV/c, above the minimum level found by the ZYAM procedure, as a function of $|\Delta\eta|$ for the 0–5% most central PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The error bars correspond to statistical uncertainties, while the brackets denote the systematic uncertainties. The solid line shows the prediction from the PYTHIA8 simulation of pp collisions at $\sqrt{s}$ = 2.76 TeV.

The ZYAM procedure enables the direct extraction of integrated yields of the $\Delta\phi$-projected distributions in a well-defined manner. Figure 4 shows the resulting near-side associated yield

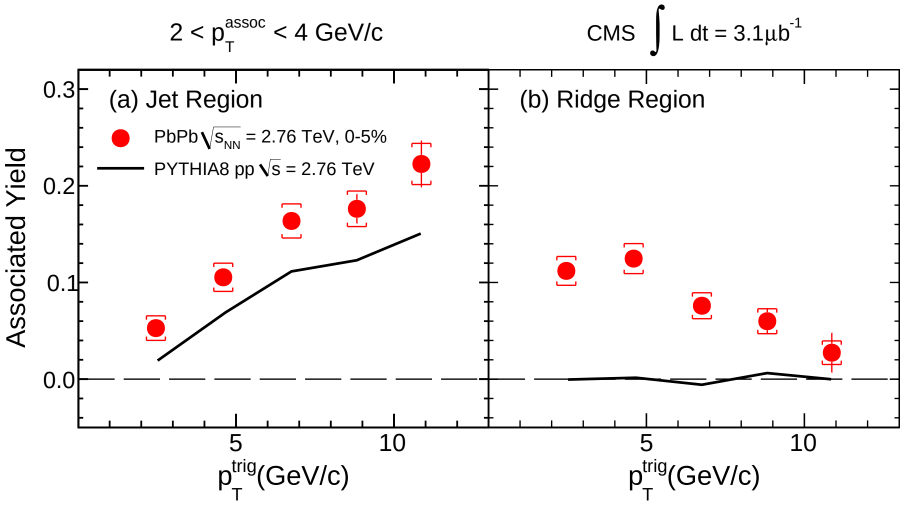

Figure 5: Integrated near-side ($|\Delta\phi| < \Delta\phi_{\mathrm{ZYAM}}$) associated yield above the minimum level found by the ZYAM procedure for (a) the short-range jet region ($|\Delta\eta| < 1$) and (b) the long-range ridge region ($2 < |\Delta\eta| < 4$), as a function of p_T^{trig} in the 0–5% most central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with $2 < p_T^{\mathrm{assoc}} < 4$ GeV/c. The error bars correspond to statistical uncertainties, while the brackets around the data points denote the systematic uncertainties. The solid line shows the prediction from the PYTHIA8 simulation of pp collisions at $\sqrt{s} = 2.76$ TeV.

as a function of $|\Delta\eta|$ (in slices of 0.6 units) in both the central PbPb collisions and PYTHIA8 pp MC. The near-side associated yield for PYTHIA8 pp shows a strong peak at $|\Delta\eta| = 0$, which corresponds to the expected correlations within jets. This near-side peak diminishes rapidly with increasing $|\Delta\eta|$. The PbPb data also exhibit a jet-like correlation peak in the yield for small $|\Delta\eta|$, but in contrast, the PbPb data clearly show that the ridge extends to the highest $|\Delta\eta|$ values measured.

Figure 5 presents the integrated associated yield for the jet region ($|\Delta\eta| < 1$) and the ridge region ($2 < |\Delta\eta| < 4$) with $2 < p_T^{\mathrm{assoc}} < 4$ GeV/c, as a function of p_T^{trig} in the 0–5% most central PbPb collisions. The ridge-region yield is defined as the integral of the near side in long-range $\Delta\phi$ azimuthal correlation functions (Fig. 3), while the jet-region yield is determined by the difference between the short- and long-range near-side integral, as the ridge is found to be approximately constant in $\Delta\eta$ (Fig. 4). While the jet-region yield shows an increase with p_T^{trig} due to the increasing jet transverse energy, the ridge-region yield is most prominent for $2 < p_T^{\mathrm{trig}} < 6$ GeV/c and tends to drop to almost zero when p_T^{trig} reaches 10–12 GeV/c. The bars in Fig. 5 correspond to the statistical uncertainties, while the brackets around the data points denote the systematic uncertainties, which are dominated by the tracking performance, as discussed earlier. Results from the PYTHIA8 pp MC simulation, displayed as solid lines in Fig. 5, are consistent with zero for all p_T^{trig} bins in the ridge region and have qualitatively the same trend with p_T^{trig} in the jet region as the data. It has been seen from previous studies that the ridge is absent in both minimum bias pp data and PYTHIA8 MC simulations. However, the PYTHIA8 program does not fully describe the jet-like correlations observed in pp collisions at

$\sqrt{s} = 7\,\text{TeV}$ [27]. A quantitative comparison of the correlations in PbPb and pp collisions will therefore be deferred until pp results at $\sqrt{s} = 2.76\,\text{TeV}$ become available.

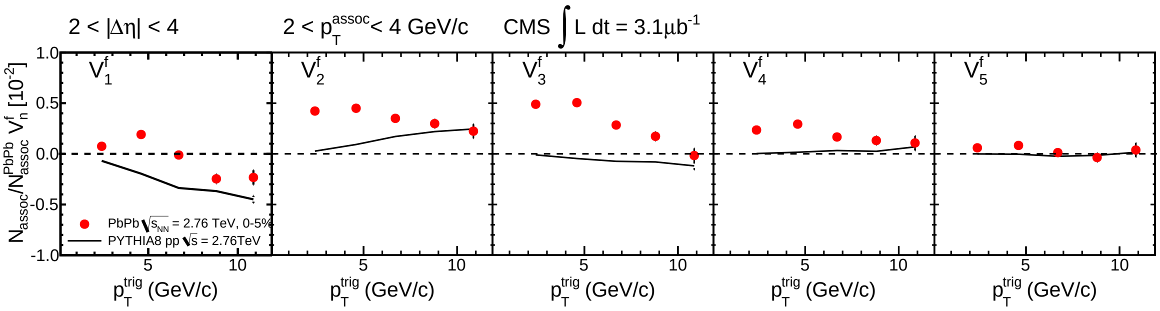

Figure 6: Fourier coefficients, V_1^{f}, V_2^{f}, V_3^{f}, V_4^{f}, and V_5^{f}, extracted as functions of $p_{\text{T}}^{\text{trig}}$ for $2 < p_{\text{T}}^{\text{assoc}} < 4\,\text{GeV}/c$ for the 0–5% most central PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$. The error bars represent statistical uncertainties only. The solid lines show the predictions from the PYTHIA8 simulation of pp collisions at $\sqrt{s} = 2.76\,\text{TeV}$.

3.3 Fourier Decomposition of $\Delta\phi$ Distributions

Motivated by recent theoretical developments in understanding the long-range ridge effect in the context of higher-order hydrodynamic flow induced by initial geometric fluctuations, such as the "triangular flow" effect [26, 38–42], an alternative way of quantifying the observed long-range correlations is investigated in this paper. The 1-D $\Delta\phi$-projected distribution for $2 < |\Delta\eta| < 4$ is decomposed in a Fourier series as

$$\frac{1}{N_{\text{trig}}}\frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi}\left\{1 + \sum_{n=1}^{\infty} 2V_n^{\text{f}} \cos(n\Delta\phi)\right\}, \tag{6}$$

where N_{assoc} represents the total number of hadron pairs per trigger particle for a given $|\Delta\eta|$ range and $(p_{\text{T}}^{\text{trig}}, p_{\text{T}}^{\text{assoc}})$ bin. The 1-D $\Delta\phi$ projections displayed in Fig. 3 are fitted by the first five terms in the Fourier series, the resulting fits being shown as the dashed lines in Fig. 3. The data are well described by the fits. Figure 6 presents the first five Fourier coefficients from the fit as functions of $p_{\text{T}}^{\text{trig}}$ for $2 < p_{\text{T}}^{\text{assoc}} < 4\,\text{GeV}/c$ for the 0–5% most central PbPb collisions and for the PYTHIA8 pp MC simulation. The PYTHIA8 results are scaled by the ratio of $N_{\text{assoc}}^{\text{PYTHIA8}}/N_{\text{assoc}}^{\text{PbPb}}$ in order to remove the trivial effect of the multiplicity dependence. The error bars are statistical only, while the systematic uncertainties are found to be negligible because the Fourier coefficients characterize the overall shape of the correlation functions, and thus are not sensitive to the absolute scale. The coefficients from the fit are also found to be largely independent of each other (correlation coefficients typical below 5%).

All the Fourier coefficients found from fitting the PbPb data show a similar dependence on $p_{\text{T}}^{\text{trig}}$ except for the V_1^{f} term, which contains an additional negative contribution that grows toward higher $p_{\text{T}}^{\text{trig}}$. This negative V_1^{f} component is consistent with a contribution from momentum conservation or back-to-back dijets [44]. If the observed correlation is purely driven by the single-particle azimuthal anisotropy arising from the hydrodynamic expansion of the medium [45], the extracted V_n^{f} components would be related to the flow coefficients v_n (i.e., v_2 for anisotropic elliptic flow) via $V_n^{\text{f}} \sim v_n^{\text{trig}} \times v_n^{\text{assoc}}$, where v_n^{trig} and v_n^{assoc} are the flow coefficients for the trigger and associated particles [26]. The flow coefficients, and especially the higher-order terms, are sensitive to the initial conditions and viscosity of the hot, dense medium [38, 46]. This Fourier analysis serves as an alternative way of quantifying the azimuthal correlation functions in heavy-ion collisions and potentially provides new insights in understanding the origin of the ridge effect in these collisions. Analysis of larger data samples in terms of $p_{\mathrm{T}}^{\mathrm{trig}}$ and $p_{\mathrm{T}}^{\mathrm{assoc}}$, as well as centrality, would allow a more detailed comparison to theoretical calculations of hydrodynamics, for which the Fourier components provide a concise description of the data.

4 Summary

The CMS detector at the LHC has been used to measure angular correlations between charged particles in $\Delta\eta$ and $\Delta\phi$ up to $|\Delta\eta| \approx 4$ and over the full range of $\Delta\phi$ in the 0–5% most central PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$. This is the first study of long-range azimuthal correlations over a large difference in pseudorapidity in PbPb interactions at the LHC energy. The extracted 2-D associated yield distributions show a variety of characteristic features in heavy-ion collisions that are not present in minimum bias pp interactions. Short- and long-range azimuthal correlations have been studied as a function of the transverse momentum of the trigger particles. The observed long-range ridge-like structure for approximately equal azimuthal angles ($\Delta\phi \approx 0$) is most evident in the intermediate transverse momentum range, $2 < p_{\mathrm{T}}^{\mathrm{trig}} < 6\,\mathrm{GeV}/c$, and decreases to almost zero for $p_{\mathrm{T}}^{\mathrm{trig}}$ above 10–12 GeV/c. A qualitatively similar dependence of the ridge on transverse momentum has also been observed in high-multiplicity pp events, indicating a potentially similar physical origin of the effect. A Fourier decomposition of the 1-D $\Delta\phi$-projected correlation functions in the ridge region ($2 < |\Delta\eta| < 4$) has been presented. This alternative way of quantifying the correlation data provides valuable information to test a wide range of theoretical models, including recent hydrodynamic calculations of higher-order Fourier components. The very broad solid-angle coverage of the CMS detector and the statistical accuracy of the sample analyzed in this paper provide significantly improved observations of short- and long-range particle correlations over previously available measurements.

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