EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PH-EP-2012-359
09 December 2012

Long-range angular correlations on the near and away side in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

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December 1, 2012
DRAFT v0.90 $Revision: 631 $

Abstract

Angular correlations between charged trigger and associated particles are measured by the ALICE detector in p–Pb collisions at a nucleon–nucleon centre-of-mass energy of 5.02 TeV for transverse momentum ranges within $0.5 < p_{\mathrm{T,assoc}} < p_{\mathrm{T,trig}} < 4$ GeV/c. The correlations are measured over two units of pseudorapidity and full azimuthal angle in different intervals of event multiplicity, and expressed as associated yield per trigger particle. Two long-range ridge-like structures, one on the near side and one on the away side, are observed when the per-trigger yield obtained in low-multiplicity events is subtracted from the one in high-multiplicity events. The excess on the near-side is qualitatively similar to the one recently reported by the CMS collaboration, while the excess on the away-side is observed for the first time. The two-ridge structure projected onto azimuthal angle is quantified with the second and third Fourier coefficients as well as by near-side and away-side yields and widths. The yields on the near side and on the away side are equal within the uncertainties for all studied event multiplicity and p_{T} bins, and the widths show no significant evolution with event multiplicity or p_{T}. These findings suggest that the near-side ridge is accompanied by an essentially identical away-side ridge.

*See Appendix A for the list of collaboration members

1 Introduction

Two-particle correlations are a powerful tool to explore the mechanism of particle production in collisions of hadrons and nuclei at high energy. Such studies involve measuring the distributions of relative angles $\Delta\varphi$ and $\Delta\eta$ between pairs of particles: a "trigger" particle in a certain transverse momentum $p_{\mathrm{T,trig}}$ interval and an "associated" particle in a $p_{\mathrm{T,assoc}}$ interval, where $\Delta\varphi$ and $\Delta\eta$ are the differences in azimuthal angle φ and pseudorapidity η between the two particles.

In proton–proton (pp) collisions, the correlation at ($\Delta\varphi \approx 0$, $\Delta\eta \approx 0$) for $p_{\mathrm{T,trig}} > 2\,\mathrm{GeV}/c$ is dominated by the "near-side" jet peak, where trigger and associated particles originate from a fragmenting parton, and at $\Delta\varphi \approx \pi$ by the recoil or "away-side" jet [1]. The away-side structure is elongated along $\Delta\eta$ due to the longitudinal momentum distribution of partons in the colliding protons. In nucleus–nucleus collisions, the jet-related correlations are modified and additional structures emerge, which persist over a long range in $\Delta\eta$ on the near side and on the away side [2–14]. The shape of these distributions when decomposed into a Fourier series defined by v_n coefficients [15] is found to be dominated by contributions from terms with $n = 2$ and $n = 3$ [6, 7, 9–14]. The v_n coefficients are sensitive to the geometry of the initial state of the colliding nuclei [16, 17] and can be related to the transport properties of the strongly-interacting de-confined matter via hydrodynamic models [18–20].

Recently, measurements in pp collisions at a centre-of-mass energy $\sqrt{s} = 7\,\mathrm{TeV}$ [21] and in proton–lead (p–Pb) collisions at a nucleon–nucleon centre-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [22] have revealed long-range ($2 < |\Delta\eta| < 4$) near-side ($\Delta\varphi \approx 0$) correlations in events with significantly higher-than-average particle multiplicity. Various mechanisms have been proposed to explain the origin of these ridge-like correlations in high-multiplicity pp and p–Pb events. These mechanisms include colour connections forming along the longitudinal direction [23–25], jet-medium induced [26] and multi-parton [27, 28] interactions, and collective effects arising in the high-density system possibly formed in these collisions [29–34].

Preliminary results from two-particle correlations in $\sqrt{s_{\mathrm{NN}}} = 0.2\,\mathrm{GeV}$ d–Au collisions [35] show a strong suppression of the away-side yield at forward rapidity in central collisions. This modification has been interpreted in the framework of "Colour Glass Condensate" models [36] as a saturation effect caused by nonlinear gluon interactions in the high-density regime at small longitudinal parton momentum fraction x. Similar effects may arise at midrapidity in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, where the parton distributions are probed down to $x < 10^{-3}$, which is comparable to the relevant range of x at forward rapidity ($y \sim 3$) at $\sqrt{s_{\mathrm{NN}}} = 0.2\,\mathrm{TeV}$.

This letter presents results extracted from two-particle correlation measurements in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, recorded with the ALICE detector [37] at the Large Hadron Collider (LHC). The correlations are measured over two units of pseudorapidity and full azimuthal angle as a function of charged-particle multiplicity, and expressed as associated yield per trigger particle. Sections 2 and 3 describe the experimental setup, and the event and track selection, respectively. Details on the definition of the correlation and the per-trigger-particle associated yield are given in Sect. 4. The results of the analysis are discussed in Sect. 5 and a summary is given in Sect. 6.

2 Experimental setup

Collisions of proton and lead beams were provided by the LHC during a short pilot run performed in September 2012. The beam energies were 4 TeV for the proton beam and 1.58 TeV per nucleon for the lead beam, resulting in collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The nucleon–nucleon centre-of-mass system moved with respect to the ALICE laboratory system with a rapidity of -0.465, i.e., in the direction of the proton beam. The pseudorapidity in the laboratory system is denoted with η throughout this letter. Results from pp collisions at $\sqrt{s} = 2.76$ and 7 TeV are shown in comparison to the p–Pb results.

A detailed description of the ALICE detector can be found in Ref. [37]. The main subsystems used in the present analysis are the Inner Tracking System (ITS) and the Time Projection Chamber (TPC), which are operated inside a solenoidal magnetic field of 0.5 T. The ITS consists of six layers of silicon detectors: from the innermost to the outermost, two layers of Silicon Pixel Detector (SPD) with an acceptance of $|\eta| < 1.4$, two layers of Silicon Drift Detector (SDD) with $|\eta| < 0.9$ and two layers of Silicon Strip Detector with $|\eta| < 0.97$. The TPC provides an acceptance of $|\eta| < 0.9$ for tracks which reach the outer radius of the TPC and up to $|\eta| < 1.5$ for tracks with reduced track length. The VZERO detector, two arrays of 32 scintillator tiles each, covering the full azimuth within $2.8 < \eta < 5.1$ (VZERO-A) and $-3.7 < \eta < -1.7$ (VZERO-C), was used for triggering, event selection and event characterization, namely the definition of event classes corresponding to different particle-multiplicity ranges. In p–Pb collisions, the trigger required a signal in either VZERO-A or VZERO-C. In addition, two neutron Zero Degree Calorimeters (ZDCs) located at $+112.5$ m (ZNA) and -112.5 m (ZNC) from the interaction point are used in the event selection. The energy deposited in the ZNA, which for the beam setup of the pilot run originates from neutrons of the Pb nucleus, served as an alternative approach in defining the event-multiplicity classes. In pp collisions, the trigger required a signal in either SPD, VZERO-A or VZERO-C [38].

3 Event and track selection

The present analysis of the p–Pb data is based on the event selection described in Ref. [39]. The events are selected by requiring a signal in both VZERO-A and VZERO-C. From the data collected, 1.7×10^6 events pass the event selection criteria and are used for this analysis. For the analysis of the pp collisions, the event selection described in Ref. [38] has been used, yielding 31×10^6 and 85×10^6 events at $\sqrt{s} = 2.76$ and 7 TeV, respectively.

The primary-vertex position is determined with tracks reconstructed in the ITS and TPC as described in Ref. [40]. The vertex reconstruction algorithm is fully efficient for events with at least one reconstructed track within $|\eta| < 1.4$. An event is accepted if the coordinate of the reconstructed vertex along the beam direction ($z_{\rm vtx}$) is within ± 10 cm from the detector centre.

The analysis uses tracks reconstructed in the ITS and TPC with $0.5 < p_{\rm T} < 4$ GeV/c and in a fiducial region $|\eta| < 1.2$. As a first step in the track selection, cuts on the number of space points and the quality of the track fit in the TPC are applied. Tracks are further required to have a distance of closest approach to the reconstructed vertex smaller than 2.4 cm and 3.2 cm in the transverse and the longitudinal direction, respectively. In order to avoid an azimuthally-dependent tracking efficiency due to inactive SPD modules, two classes of tracks are combined [41]. The first class consists of tracks, which have at least one hit in the SPD. The tracks from the second

class do not have any SPD hit associated, but the position of the reconstructed primary vertex is used in the fit of the tracks. In the study of systematic uncertainties an alternative track selection [42] is used, where a tighter p_{T}-dependent cut on the distance of closest approach to the reconstructed vertex is applied. Further, the selection for the tracks in the second class is changed to tracks, which have a hit in the first layer of the SDD. This modified selection has a less uniform azimuthal acceptance, but includes a smaller number of secondary particles from interactions in the detector material or weak decays.

The efficiency and purity of the primary charged-particle selection are estimated from a Monte Carlo (MC) simulation using the DPMJET event generator [43] (for p–Pb) and the PYTHIA 6.4 event generator [44] with the tune Perugia-0 [45] (for pp) with particle transport through the detector using GEANT3 [46]. In p–Pb collisions, the combined efficiency and acceptance for the track reconstruction in $|\eta| < 0.9$ is about 82% at $p_{\mathrm{T}} = 0.5$–$1\,\mathrm{GeV}/c$, and decreases to about 79% at $p_{\mathrm{T}} = 4\,\mathrm{GeV}/c$. It reduces to about 50% at $|\eta| \approx 1.2$ and is independent of the event multiplicity. The remaining contamination from secondary particles due to interactions in the detector material or weak decays decreases from about 2% to 1% in the p_{T} range from 0.5 to $4\,\mathrm{GeV}/c$. The contribution from fake tracks is negligible. These fractions are similar in the analysis of pp collisions.

In order to study the multiplicity dependence of the two-particle correlations the selected event sample is divided into four event classes. These classes are defined fractions of the analyzed event sample, based on cuts on the total charge deposited in the VZERO detector (V0M), and denoted “60–100%", “40–60%", “20–40%", “0–20%" from the lowest to the highest multiplicity in the following. Table 1 shows the event-classes definitions and the corresponding mean charged-particle multiplicity densities ($\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$) within $|\eta| < 0.5$. These are obtained using the method presented in Ref. [39], and are corrected for vertex reconstruction efficiency, acceptance and tracking efficiency as well as contamination by secondary particles. Also shown are the mean numbers of primary charged particles with $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}/c$ within the pseudorapidity range $|\eta| < 1.2$. These are measured by applying the track selection described above and are corrected for the detector acceptance, track-reconstruction efficiency and contamination.

Event class	V0M range (a.u.)	$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle\|_{\|\eta\|<0.5}$ $p_{\mathrm{T}} > 0\,\mathrm{GeV}/c$	$\langle N_{\mathrm{trk}} \rangle\|_{\|\eta\|<1.2}$ $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}/c$
60–100%	< 138	6.7 ± 0.2	6.4 ± 0.2
40–60%	138–216	16.2 ± 0.4	16.9 ± 0.6
20–40%	216–318	23.7 ± 0.5	26.1 ± 0.9
0–20%	> 318	34.9 ± 0.5	42.5 ± 1.5

Table 1: Definition of the event classes as fractions of the analyzed event sample and their corresponding $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ within $|\eta| < 0.5$ and the mean numbers of charged particles within $|\eta| < 1.2$ and $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}/c$. The given uncertainties are systematic while the statistical uncertainties are negligible.

4 Analysis

For a given event class, the two-particle correlation between pairs of trigger and associated charged particles is measured as a function of the azimuthal difference $\Delta\varphi$ (defined within $-\pi/2$ and $3\pi/2$) and pseudorapidity difference $\Delta\eta$. The correlation is expressed in terms of the associated yield per trigger particle for different intervals of trigger and associated transverse momentum, $p_{\mathrm{T,trig}}$ and $p_{\mathrm{T,assoc}}$, respectively, and $p_{\mathrm{T,assoc}} < p_{\mathrm{T,trig}}$. The associated yield per

trigger particle is defined as

$$\frac{1}{N_{\rm trig}}\frac{{\rm d}^2N_{\rm assoc}}{{\rm d}\Delta\eta{\rm d}\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)} \quad (1)$$

where $N_{\rm trig}$ is the total number of trigger particles in the event class and $p_{\rm T,trig}$ interval. The signal distribution $S(\Delta\eta,\Delta\varphi) = 1/N_{\rm trig}{\rm d}^2N_{\rm same}/{\rm d}\Delta\eta{\rm d}\Delta\varphi$ is the associated yield per trigger particle for particle pairs from the same event. In a given event class and $p_{\rm T}$ interval, the sum over the events is performed separately for $N_{\rm trig}$ and ${\rm d}^2N_{\rm same}/{\rm d}\Delta\eta{\rm d}\Delta\varphi$ before their ratio is computed. Note, that this definition is different from the one used in Ref. [22], where $S(\Delta\eta,\Delta\varphi)$ is calculated per event and then averaged. The method used in this letter does not induce an inherent multiplicity dependence in the pair yields, which is important for the subtraction method discussed in the next Section. The background distribution $B(\Delta\eta,\Delta\varphi) = \alpha\ {\rm d}^2N_{\rm mixed}/{\rm d}\Delta\eta{\rm d}\Delta\varphi$ corrects for pair acceptance and pair efficiency. It is constructed by correlating the trigger particles in one event with the associated particles from other events in the same event class and within the same 2 cm wide $z_{\rm vtx}$ interval (each event is mixed with 5–20 events). The factor α is chosen to normalize the background distribution such that it is unity for pairs where both particles are going into approximately the same direction (i.e. $\Delta\varphi \approx 0, \Delta\eta \approx 0$). To account for different pair acceptance and pair efficiency as a function of $z_{\rm vtx}$, the yield defined by Eq. 1 is constructed for each $z_{\rm vtx}$ interval. The final per-trigger yield is obtained by calculating the weighted average of the $z_{\rm vtx}$ intervals.

When constructing the signal and background distributions, the trigger and associated particles are required to be separated by $|\Delta\varphi^*_{\rm min}| > 0.02$ and $|\Delta\eta| > 0.02$, where $\Delta\varphi^*_{\rm min}$ is the minimal azimuthal distance at the same radius between the two tracks within the active detector volume after accounting for the bending due to the magnetic field. This procedure is applied to avoid a bias due to the reduced efficiency for pairs with small opening angles and leads to an increase in the associated near-side peak yield of 0.4–0.8% depending on $p_{\rm T}$. Further, particle pairs are removed which are likely to stem from a γ-conversion, or a K^0_s or Λ decay, by a cut on the invariant mass of the pair (the electron, pion, or pion/proton mass is assumed, respectively). The effect on the peak yields is less than 2%.

In the signal as well as in the background distribution, each trigger and each associated particle is weighted with a correction factor accounting for detector acceptance, reconstruction efficiency and contamination by secondary particles. These corrections are applied as a function of η, $p_{\rm T}$ and $z_{\rm vtx}$. Applying the correction factors extracted from DPMJET simulations to events simulated with HIJING [47] leads to associated peak yields that agree within 4% with the MC truth. This difference between the two-dimensional corrected per-trigger yield and input per-trigger yield is used in the estimate of the systematic uncertainties. Uncertainties due to track-quality cuts are evaluated by comparing the results of two different track selections, see Sect. 3. The associated yields are found to be insensitive to these track selections within 5%. Further systematic uncertainties related to specific observables are mentioned below.

5 Results

The associated yield per trigger particle in $\Delta\varphi$ and $\Delta\eta$ is shown in Fig. 1 for pairs of charged particles with $2 < p_{\rm T,trig} < 4$ GeV/c and $1 < p_{\rm T,assoc} < 2$ GeV/c in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV in the 60–100% (left) and 0–20% (right) event classes. In the 60–100% class, the visible features are the correlation peak near $(\Delta\varphi \approx 0, \Delta\eta \approx 0)$ for pairs of particles originating from the

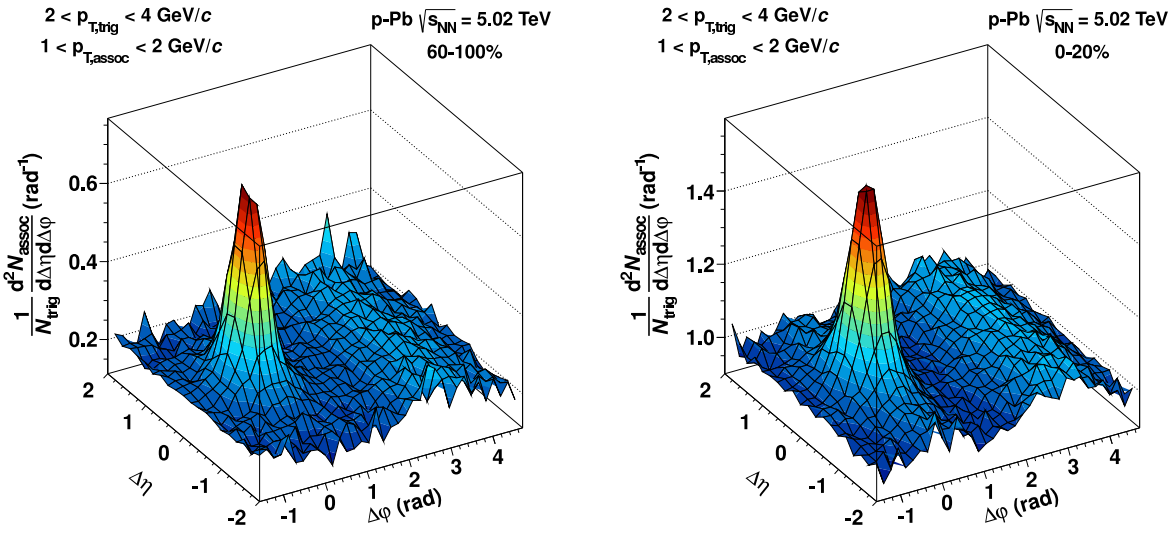

Fig. 1: The associated yield per trigger particle in $\Delta\varphi$ and $\Delta\eta$ for pairs of charged particles with $2 < p_{\mathrm{T,trig}} < 4\,\mathrm{GeV}/c$ and $1 < p_{\mathrm{T,assoc}} < 2\,\mathrm{GeV}/c$ in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV for the 60–100% (left) and 0–20% (right) event classes.

same jet, and the elongated structure at $\Delta\varphi \approx \pi$ for pairs of particles from jets back-to-back in azimuth. These are very similar to those observed in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV. The same features are visible in the 0–20% class. However, both the yields on the near side ($|\Delta\varphi| < \pi/2$) and the away side ($\pi/2 < \Delta\varphi < 3\pi/2$) are higher. [1] This is illustrated in Fig. 2, where the projections on $\Delta\varphi$ averaged over $|\Delta\eta| < 1.8$ are compared for different event classes and to pp collisions at 2.76 and 7 TeV. In order to facilitate the comparison, the yield at $\Delta\varphi = 1.3$ has been simply subtracted for each distribution. It is seen that the per-trigger yields in $\Delta\varphi$ on the near side and on the away side are similar for low-multiplicity p–Pb collisions and for pp collisions at $\sqrt{s} = 7$ TeV, and increases with increasing multiplicity in p–Pb collisions.

To quantify the change from low to high multiplicity event classes, we subtract the per-trigger yield of the lowest (60–100%) from that of the higher multiplicity classes. The resulting distribution in $\Delta\varphi$ and $\Delta\eta$ for the 0–20% event class is shown in Fig. 3 left. A distinct excess structure in the correlation is observed, which forms two ridges, one on the near side and one on the away side. The ridge on the near-side is qualitatively similar to the one recently reported by the CMS collaboration [22]. Note, however that a quantitative comparison would not be meaningful due to the different definition of the per-trigger yield and the different detector acceptance and event-class definition.

On the near side, there is a peak around ($\Delta\varphi \approx 0$, $\Delta\eta \approx 0$) indicating a small change of the near-side jet yield as a function of multiplicity. The integral of this peak above the ridge within $|\Delta\eta| < 0.5$ corresponds to about 5–25% of the unsubtracted near-side peak yield, depending on p_{T}. In order to avoid a bias on the associated yields due to the multiplicity selection and to prevent that this remaining peak contributes to the ridge yields calculated below, the region $|\Delta\eta| < 0.8$ on the near side is excluded when performing projections onto $\Delta\varphi$. The effect of this incomplete subtraction, which if jet-related might also be present on the away side, on the extracted observables is discussed further below.

[1] These definitions of near-side ($|\Delta\varphi| < \pi/2$) and away-side ($\pi/2 < \Delta\varphi < 3\pi/2$) are used throughout the letter.

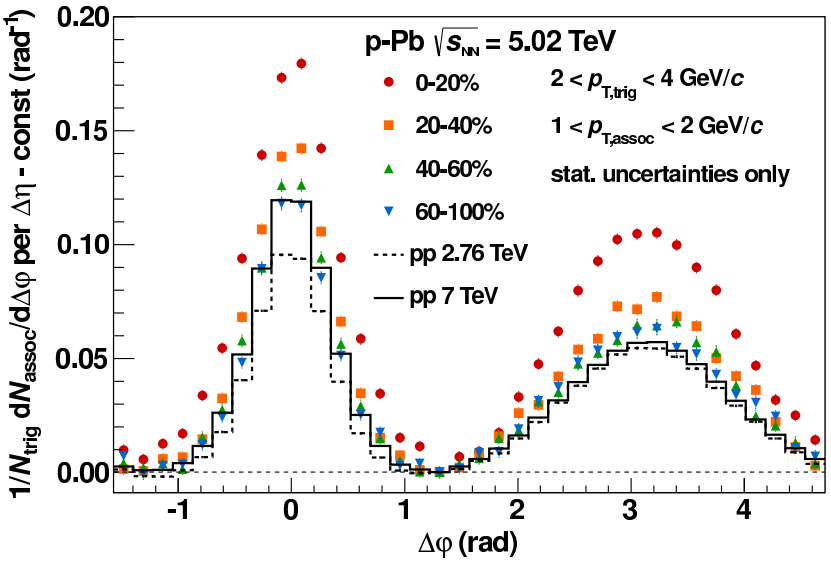

Fig. 2: Associated yield per trigger particle as a function of $\Delta\varphi$ averaged over $|\Delta\eta| < 1.8$ for pairs of charged particles with $2 < p_{\mathrm{T,trig}} < 4$ GeV/c and $1 < p_{\mathrm{T,assoc}} < 2$ GeV/c in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV for different event classes, compared to pp collisions at 2.76 and 7 TeV. The yield between the peaks (determined at $\Delta\varphi \approx 1.3$) has been subtracted in each case. Only statistical uncertainties are shown; systematic uncertainties are less than 0.01 (absolute) per bin.

The top right panel in Fig. 3 shows the projection of Fig. 3 left to $\Delta\eta$ averaged over different $\Delta\varphi$ intervals. The near-side and away-side distributions are flat apart from the discussed small peak around $\Delta\eta = 0$. The bottom right panel shows the projection to $\Delta\varphi$, where a modulation is observed. For comparison, the subtracted associated yield for HIJING simulated events shifted to the baseline of the data is also shown, where no significant modulation remains. To quantify the near-side and away-side excess structures, the following functional form

$$1/N_{\mathrm{trig}}\mathrm{d}N_{\mathrm{assoc}}/\mathrm{d}\Delta\varphi = a_0 + 2\,a_2\cos(2\Delta\varphi) + 2\,a_3\cos(3\Delta\varphi) \tag{2}$$

is fit to the data in multiplicity and p_{T} intervals. The fit has a χ^2/ndf of 1–1.5 in the different p_{T} and multiplicity intervals, indicating that the data are well described by the fits. An example for the fit with and without the $a_3\cos(3\Delta\varphi)$ term is shown in the bottom right panel of Fig. 3. The fit parameters a_2 and a_3 are a measure of the absolute modulation in the subtracted per-trigger yield and characterize a modulation relative to the baseline b in the higher multiplicity class assuming that such a modulation is not present in the 60–100% event class. This assumption has been checked by subtracting the yields obtained in $\sqrt{s} = 2.76$ and 7 TeV pp collisions from the yields obtained for the 60–100% p–Pb event class and verifying that in both cases no significant signal remains. Therefore, the Fourier coefficients v_n of the corresponding single-particle distribution, commonly used in the analysis of particle correlations in nucleus–nucleus collisions [15], can be obtained in bins where the $p_{\mathrm{T,trig}}$ and $p_{\mathrm{T,assoc}}$ intervals are identical using

$$v_n = \sqrt{a_n/b}. \tag{3}$$

The baseline b is evaluated in the higher-multiplicity class in the region $|\Delta\varphi - \pi/2| < 0.2$, corrected for the fact that it is obtained in the minimum of Eq. 2. A potential bias due to the above-mentioned incomplete near-side peak subtraction on v_2 and v_3 is evaluated in the following way: a) the size of the near-side exclusion region is changed from $|\Delta\eta| < 0.8$ to

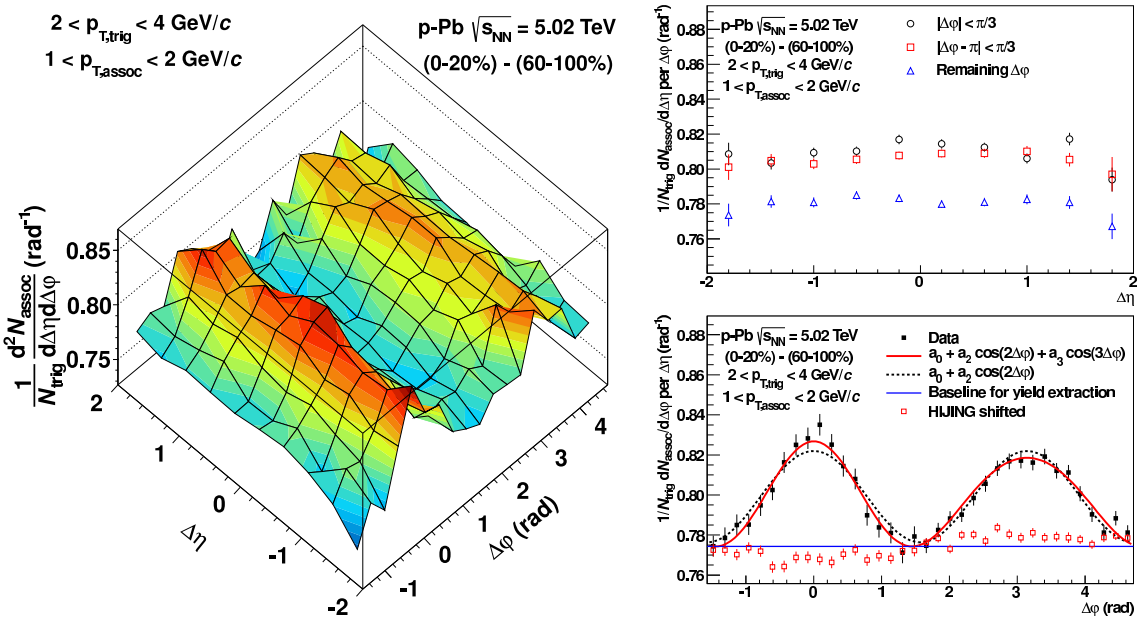

Fig. 3: Left: Associated yield per trigger particle in $\Delta\varphi$ and $\Delta\eta$ for pairs of charged particles with $2 < p_{\mathrm{T,trig}} < 4$ GeV/c and $1 < p_{\mathrm{T,assoc}} < 2$ GeV/c in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV for the 0–20% multiplicity class, after subtraction of the associated yield obtained in the 60–100% event class. Top right: The associated per-trigger yield after subtraction (as shown on the left) projected onto $\Delta\eta$ averaged over $|\Delta\varphi| < \pi/3$ (black circles), $|\Delta\varphi - \pi| < \pi/3$ (red squares), and the remaining area (blue triangles, $\Delta\varphi < -\pi/3$, $\pi/3 < \Delta\varphi < 2\pi/3$ and $\Delta\varphi > 4\pi/3$). Bottom right: as above but projected onto $\Delta\varphi$ averaged over $0.8 < |\Delta\eta| < 1.8$ on the near side and $|\Delta\eta| < 1.8$ on the away side. Superimposed are fits containing a $\cos(2\Delta\varphi)$ shape alone (black dashed line) and a combination of $\cos(2\Delta\varphi)$ and $\cos(3\Delta\varphi)$ shapes (red solid line). The blue horizontal line shows the baseline obtained from the latter fit which is used for the yield calculation. For comparison, the subtracted associated yield applying the same procedure on HIJING shifted to the same baseline is also shown. The figure shows only statistical uncertainties. Systematic uncertainties are mostly correlated and affect the baseline. Uncorrelated uncertainties are less than 1%.

$|\Delta\eta| < 1.2$; b) the residual near-side peak above the ridge is also removed from the away side accounting for the general p_{T} -dependent difference of near-side and away-side jet yields due to the kinematic contraints and the detector acceptance, which is evaluated using the lowest multiplicity class; and c) the lower multiplicity class is scaled before the subtraction such that no residual near-side peak above the ridge remains. The resulting differences in v_2 (up to 15%) and v_3 coefficients (up to 40%) when applying these approaches have been added to the systematic uncertainties.

The coefficients v_2 and v_3 are shown in the left panel of Fig. 4 for different event classes. The coefficient v_2 increases with increasing p_{T}, and shows only a small dependence on multiplicity. In the 0–20% event class, v_2 increases from 0.06 ± 0.01 for $0.5 < p_{\mathrm{T}} < 1$ GeV/c to 0.12 ± 0.02 for $2 < p_{\mathrm{T}} < 4$ GeV/c, while v_3 is about 0.03 and shows, within large errors, an increasing trend with p_{T}. Reference [33] gives predictions for two-particle correlations arising from collective flow in p–Pb collisions at the LHC in the framework of a hydrodynamical model. The values for v_2 and v_3 coefficients, as well as the p_{T} and the multiplicity dependences, are in qualitative agreement with the presented results.

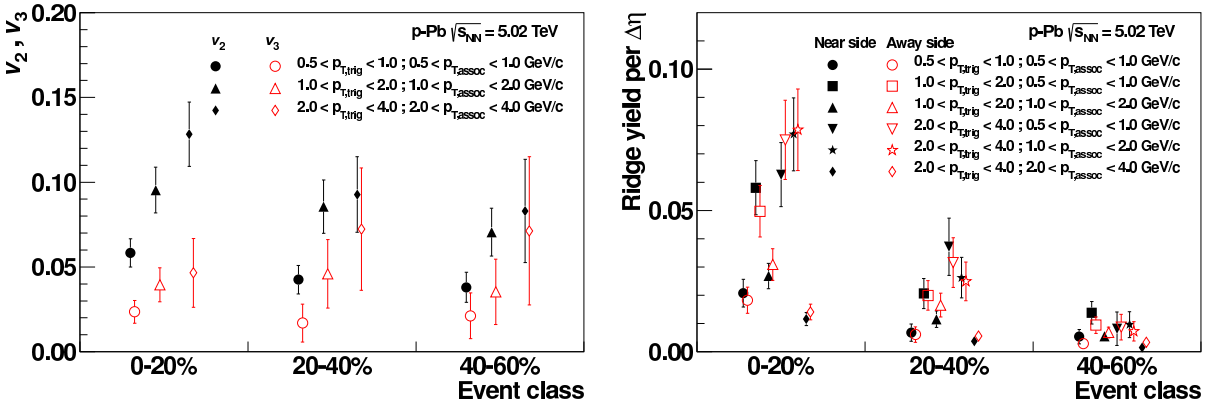

Fig. 4: Left: v_2 (black closed symbols) and v_3 (red open symbols) for different multiplicity classes and overlapping $p_{\mathrm{T,assoc}}$ and $p_{\mathrm{T,trig}}$ intervals. Right: Near-side (black closed symbols) and away-side (red open symbols) ridge yields per unit of $\Delta\eta$ for different $p_{\mathrm{T,trig}}$ and $p_{\mathrm{T,assoc}}$ bins as a function of the multiplicity class. The error bars show statistical and systematic uncertainties added in quadrature. In both panels the points are slightly displaced horizontally for visibility.

To extract information on the yields and widths of the excess distributions in Fig. 3 (bottom right), a constant baseline assuming zero yield at the minimum of the fit function (Eq. 2) is subtracted. The remaining yield is integrated on the near side and on the away side. Alternatively, a baseline evaluated from the minimum of a parabolic function fitted within $|\Delta\varphi - \pi/2| < 1$ is used; the difference on the extracted yields is added to the systematic uncertainties. The uncertainty imposed by the residual near-side jet peak on the yield is evaluated in the same way as for the v_n coefficients. The near-side and away-side ridge yields are shown in the right panel of Fig. 4 for different event classes and for different combinations of $p_{\mathrm{T,trig}}$ and $p_{\mathrm{T,assoc}}$ intervals. The near-side and away-side yields range from 0 to 0.08 per unit of $\Delta\eta$ depending on multiplicity class and p_{T} interval. It is remarkable that the near-side and away-side yields always agree within uncertainties for a given sample despite the fact that the absolute values change substantially with event class and p_{T} interval. Such a tight correlation between the yields is non-trivial and suggests a common underlying physical origin for the near-side and the away-side ridges.

From the baseline-subtracted per-trigger yields the square root of the variance, σ, within $|\Delta\varphi| < \pi/2$ and $\pi/2 < \Delta\varphi < 3\pi/2$ for the near-side and away-side region, respectively, is calculated. The extracted widths on the near side and the away side agree with each other within 20% and vary between 0.5 and 0.7. There is no significant p_{T} dependence suggesting that the observed ridge is not of jet origin.

The analysis has been repeated using the forward ZNA detector instead of the VZERO for the definition of the event classes. Unlike in nucleus–nucleus collisions, the correlation between forward energy measured in the ZNA and particle density at central rapidities is very weak in proton–nucleus collisions. Therefore, event classes defined as fixed fractions of the signal distribution in the ZNA select different events, with different mean particle multiplicity at midrapidity, than the samples selected with the same fractions in the VZERO detector. While the event classes selected with the ZNA span a much smaller range in central multiplicity density, they also minimize any autocorrelation between multiplicity selections and, for example, jet activity. With the ZNA selection, we find qualitatively consistent results compared to the VZERO selection, in particular an essentially symmetric excess correlation structure in the difference between low-multiplicity and high-multiplicity ZNA selected events, but also v_n coefficients

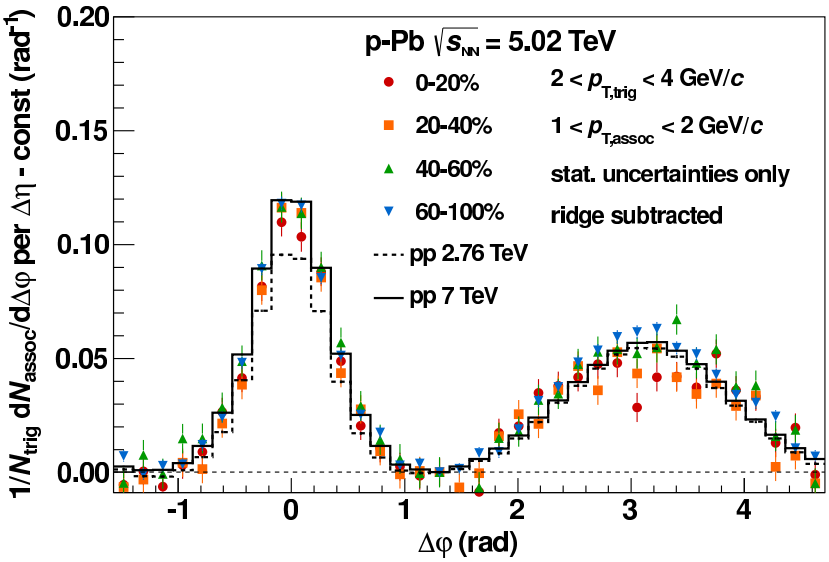

Fig. 5: Associated yield per trigger particle as a function of $\Delta\varphi$ averaged over $|\Delta\eta| < 1.8$ for pairs of charged particles with $2 < p_{\mathrm{T,trig}} < 4\,\mathrm{GeV}/c$ and $1 < p_{\mathrm{T,assoc}} < 2\,\mathrm{GeV}/c$ in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV for different event classes, compared to pp collisions at $\sqrt{s} = 2.76$ and 7 TeV. For the event classes 0–20%, 20–40% and 40–60% the long-range contribution on the near-side $1.2 < |\Delta\eta| < 1.8$ and $|\Delta\varphi| < \pi/2$ has been subtracted from both the near side and the away side as described in the text. Subsequently, the yield between the peaks (determined at $\Delta\varphi \approx 1.3$) has been subtracted in each case. Only statistical uncertainties are shown; systematic uncertainties are less than 0.01 (absolute) per bin.

and σ widths which are similar within uncertainties. However, both the ridge yields and mean charged-particle multiplicity density at midrapidity are different between the VZERO and ZNA event classes. Nevertheless, within the uncertainties, both follow a common linear trend as a function of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle\,|_{|\eta|<0.5}$.

So far it has been seen that the assumption of an unmodified jet shape in different multiplicity classes in p–Pb collisions resulted in the emergence of almost identical ridge-like excess structures on the near side and away side, most pronounced in high-multiplicity events. An alternative way is to start with the assumption that there are identical ridge structures on the near side and away side, and to study whether this assumption leaves any room for multiplicity dependent modifications of the jet shape, in particular on the away side. To this end, a symmetric ridge structure is subtracted on near side and away side from the $\Delta\varphi$ projection of the associated yield per trigger averaged over $|\Delta\eta| < 1.8$. The near-side ridge structure is determined in the same event class within $1.2 < |\Delta\eta| < 1.8$, while the ridge on the away side is constructed by mirroring this near-side structure at $\Delta\varphi = \pi/2$. The ridge-subtracted results in the interval $2 < p_{\mathrm{T,trig}} < 4\,\mathrm{GeV}/c$ and $1 < p_{\mathrm{T,assoc}} < 2\,\mathrm{GeV}/c$ for the 0–20%, 20–40% and 40–60% event classes are shown in Fig. 5 compared to the unsubtracted 60–100% event class and to pp collisions. The remaining yields in all event classes are in agreement with each other and with pp collisions, indicating that the observed correlations are indeed consistent with a symmetric ridge and with no further significant modification of the jet structure at midrapidity in high-multiplicity p–Pb collisions at the LHC, in contrast to what was seen at forward rapidity in $\sqrt{s_{\mathrm{NN}}} = 0.2$ TeV d–Au collisions at RHIC [35].

6 Summary

Results from angular correlations between charged trigger and associated particles in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02\,\text{TeV}$ are presented for transverse momentum ranges within $0.5 < p_{\rm T,assoc} < p_{\rm T,trig} < 4\,\text{GeV}/c$. Associated yields per trigger particle are measured over two units of pseudorapidity and full azimuthal angle in different multiplicity classes. The yields projected onto $\Delta\varphi$ are increasing with event multiplicity and rise to values higher than those observed in pp collisions at § = 2.76 and 7 TeV. The difference between the yields per trigger particle in high-multiplicity and low-multiplicity events exhibits two long-range (up to $|\Delta\eta| \sim 2$) ridge-like, nearly identical excess structures on the near-side ($\Delta\varphi \approx 0$) and away-side ($\Delta\varphi \approx \pi$) quantified by their yields and widths. The excess on the near side is ualitatively similar to the one recently reported by the CMS collaboration in $2 < |\Delta\eta| < 4$ [22]. The excess on the away side is reported here for the first time. The event multiplicity and $p_{\rm T}$ dependences of the near-side and away-side ridge yields are in good agreement, while their width shows no significant dependence on multiplicity or $p_{\rm T}$. The extracted v_2 and v_3 coefficients are in qualitative agreement with a hydrodynamical model calculation [34]. After subtracting the near-side ridge from the near side and away side symmetrically, the correlation shape in $\Delta\varphi$ becomes independent of multiplicity and similar to those of pp collisions at 7 TeV. There is no evidence for further significant structures in two-particle correlations at midrapidity in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02\,\text{TeV}$.

Acknowledgements

The ALICE collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex.
The ALICE collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector:
State Committee of Science, Calouste Gulbenkian Foundation from Lisbon and Swiss Fonds Kidagan, Armenia;
Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP);
National Natural Science Foundation of China (NSFC), the Chinese Ministry of Education (CMOE) and the Ministry of Science and Technology of China (MSTC);
Ministry of Education and Youth of the Czech Republic;
Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation;
The European Research Council under the European Community's Seventh Framework Programme;
Helsinki Institute of Physics and the Academy of Finland;
French CNRS-IN2P3, the 'Region Pays de Loire', 'Region Alsace', 'Region Auvergne' and CEA, France;
German BMBF and the Helmholtz Association;
General Secretariat for Research and Technology, Ministry of Development, Greece;
Hungarian OTKA and National Office for Research and Technology (NKTH);
Department of Atomic Energy and Department of Science and Technology of the Government

of India;
Istituto Nazionale di Fisica Nucleare (INFN) of Italy;
MEXT Grant-in-Aid for Specially Promoted Research, Japan;
Joint Institute for Nuclear Research, Dubna;
National Research Foundation of Korea (NRF);
CONACYT, DGAPA, México, ALFA-EC and the HELEN Program (High-Energy physics Latin-American–European Network);
Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands;
Research Council of Norway (NFR);
Polish Ministry of Science and Higher Education;
National Authority for Scientific Research - NASR (Autoritatea Naţională pentru Cercetare Ştiinţifică - ANCS);
Ministry of Education and Science of Russian Federation, International Science and Technology Center, Russian Academy of Sciences, Russian Federal Agency of Atomic Energy, Russian Federal Agency for Science and Innovations and CERN-INTAS;
Ministry of Education of Slovakia;
Department of Science and Technology, South Africa;
CIEMAT, EELA, Ministerio de Educación y Ciencia of Spain, Xunta de Galicia (Consellería de Educación), CEADEN, Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency);
Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW);
Ukraine Ministry of Education and Science;
United Kingdom Science and Technology Facilities Council (STFC);
The United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio.

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