EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2013-029
Submitted to: Physics Letters B

Measurement with the ATLAS detector of multi-particle azimuthal correlations in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$

The ATLAS Collaboration

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1. Introduction

Recent observations of ridge-like structures in the two-particle correlation functions measured in proton-lead (p+Pb) collisions at 5.02 TeV [1–3] have led to differing theoretical explanations. These structures have been attributed either to mechanisms that emphasize initial-state effects, such as the saturation of parton distributions in the Pb-nucleus [4–7], or to final-state effects, such as jet–medium interactions [8], interactions induced by multiple partons [9–12], and collective anisotropic flow [13–18].

The collective flow of particles produced in nuclear collisions, which manifests itself as a significant anisotropy in the plane perpendicular to the beam direction, has been extensively studied in heavy-ion experiments at the LHC [19–24] and RHIC (for a review see Refs. [25, 26]). In p+Pb collisions the small size of the produced system compared to the mean free path of the interacting constituents might have been expected to generate weaker collective flow, if any, compared to heavy-ion collisions.

However, two-particle correlation studies performed recently on data from p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV revealed the presence of a "ridge", a structure extended in the relative pseudorapidity, $\Delta\eta$, while narrow in the relative azimuthal angle, $\Delta\phi$, on both the near-side ($\Delta\phi \sim 0$) [1] and away-side ($\Delta\phi \sim \pi$) [2, 3]. Furthermore, it was shown in Refs. [2, 3] that, after subtracting the component due to momentum conservation, the $\Delta\phi$ distribution in high-multiplicity interactions exhibits a predominantly $\cos(2\Delta\phi)$ shape, resembling the elliptic flow modulation of the $\Delta\phi$ distributions in Pb+Pb collisions.

The final-state anisotropy is usually characterized by the coefficients, v_n, of a Fourier decomposition of the event-by-event azimuthal angle distribution of produced particles [25, 27]:

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle, \tag{1}$$

where ϕ is the azimuthal angle of the particle, Ψ_n is the event-plane angle for the n-th harmonic, and the outer brackets denote an average over charged particles in an event. In non-central heavy-ion collisions, the large and dominating v_2 coefficient is associated mainly with the elliptic shape of the nuclear overlap, and Ψ_2 defines the direction which nominally points in the direction of the classical impact parameter. In practice, initial-state fluctuations can blur the relationship between Ψ_2 and the impact parameter direction in nucleus-nucleus collisions. In contrast, Ψ_2 in proton-nucleus would be unrelated to the impact parameter and determined by the initial-state fluctuations. In nucleus-nucleus collisions, the v_2 coefficient in central collisions and the other v_n coefficients in all collisions are related to various geometric configurations arising from fluctuations of the nucleon positions in the overlap region [28].

In this Letter, a direct measurement of the second-order anisotropy parameter, v_2, is presented for p+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The cumulant method [29–32] is applied to derive v_2 using two- and four-particle cumulants. The cumulant method has been developed to characterize true multi-particle correlations related to the collective expansion of the system, while suppressing correlations from resonance decays, Bose–Einstein correlations and jet production. Emphasis is placed on the estimate of v_2, $v_2\{4\}$, obtained from the four-particle cumulants which are expected to be free from the effects of short-range two-particle correlations, e.g. from resonance decays, unlike the two-particle cumulants, used to estimate $v_2\{2\}$.

The measurements of multi-particle cumulants presented in this Letter should provide further constraints on the origin of long-range correlations observed in p+Pb collisions.

2. Event and track selections

The p+Pb data sample was collected during a short run in September 2012, when the LHC delivered p+Pb collisions at the nucleon–nucleon centre-of-mass energy $\sqrt{s_{\rm NN}} = 5.02$ TeV with the centre-of-mass frame shifted by -0.47 in rapidity relative to the nominal ATLAS coordinate frame[1].

The measurements were performed using the ATLAS detector [33]. The inner detector (ID) was used for measuring trajectories and momenta of charged particles for $|\eta| < 2.5$ with the silicon pixel detector and silicon microstrip detectors (SCT), and a transition radiation tracker, all placed in a 2 T axial magnetic field. For event triggering, two sets of Minimum Bias Trigger Scintillators (MBTS), located symmetrically in front of the endcap calorimeters, at $z = \pm 3.6$ m and covering the pseudorapidity range $2.1 < |\eta| < 3.9$, were used. The trigger used to select minimum-bias p+Pb collisions requires a signal in at least two MBTS counters. This trigger is fully efficient for events with more than four reconstructed tracks with $p_{\rm T} > 0.1$ GeV. The forward calorimeters (FCal), consisting of two symmetric systems with tungsten and copper absorbers and liquid argon as the active material, cover $3.1 < |\eta| < 4.9$ and are used to characterize the overall event activity.

The event selection follows the same requirements as used in the recent two-particle correlation analysis [3]. Events are required to have a reconstructed vertex with its z position within ± 150 mm of the nominal interaction point. Beam–gas and photonuclear interactions are suppressed by requiring at least one hit in a MBTS counter on each side of the interaction point and at most a 10 ns difference between times measured on the two sides to eliminate through-going particles. To eliminate multiple p+Pb collisions (about 2% of collision events have more than one reconstructed vertex), the events with two reconstructed vertices that are separated in z by more than 15 mm are rejected. In addition, for the cumulant analysis presented here, it is required that the number of reconstructed tracks per event, passing the track selections as described below, is greater than three. With all the above selections, the analysed sample consists of about 1.9×10^6 events.

Charged particle tracks are reconstructed in the ID using the standard algorithm optimized for p+p minimum-bias measurements [34]. Tracks are required to have at least six hits in the SCT detector and at least one hit in the pixel detector. A hit in the first pixel layer is also required when the track crosses an active pixel module in that layer. Additional requirements are imposed on the transverse (d_0) and longitudinal ($z_0 \sin\theta$) impact parameters measured with respect to the primary vertex. These are: $|d_0|$ and $|z_0 \sin\theta|$ must be smaller than 1.5 mm and must satisfy $|d_0/\sigma_{d_0}| < 3$ and $|z_0 \sin\theta/\sigma_z| < 3$, where σ_{d_0} and σ_z are uncertainties on the transverse and longitudinal impact parameters, respectively, as obtained from the covariance matrix of

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. For the p+Pb collisions, the incident Pb beam travelled in the $+z$ direction. The pseudorapidity is defined in laboratory coordinates in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Transverse momentum and energy are defined as $p_{\rm T} = p\sin\theta$ and $E_{\rm T} = E\sin\theta$, respectively.

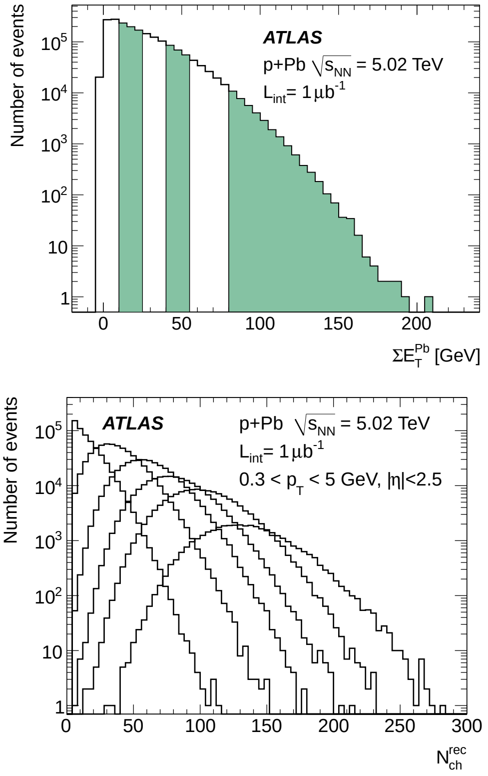

Fig. 1: Upper plot: the $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ distribution with the six activity intervals indicated. Lower plot: the distribution of $N_{\mathrm{ch}}^{\mathrm{rec}}$ for each activity interval. The leftmost distribution corresponds to the interval with the lowest $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$, etc.

the track fit. The analysis is restricted to charged particles with $0.3 < p_{\mathrm{T}} < 5.0$ GeV and $|\eta| < 2.5$.

The tracking efficiency is evaluated using HIJING-generated [35] p+Pb events that are fully simulated in the detector using GEANT4 [36, 37], and processed through the same reconstruction software as the data. The efficiency for charged hadrons is found to depend only weakly on the event multiplicity and on p_{T} for transverse momenta above 0.5 GeV. An efficiency of about 82% is observed at mid-rapidity, $|\eta| < 1$, decreasing to about 68% at $|\eta| > 2$. For low-p_{T} tracks, between 0.3 GeV and 0.5 GeV, the efficiency ranges from 74% at $\eta = 0$ to about 50% for $|\eta| > 2$. The number of reconstructed charged particle tracks, not corrected for tracking efficiency, is denoted by $N_{\mathrm{ch}}^{\mathrm{rec}}$.

The analysis is performed in different intervals of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$, the sum of transverse energy measured in the FCal with $3.1 < \eta < 4.9$ in the direction of the Pb beam with no correction for the difference in response to electrons and hadrons. The distribution of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ for events passing all selection criteria is shown in Fig. 1. These events are divided into six $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ intervals to study the variation of v_2 with overall event activity, as indicated in Fig. 1 and shown in Table 1. Event "activity" is characterized by $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$: the most active events are those with the largest $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$. The distribution of $N_{\mathrm{ch}}^{\mathrm{rec}}$ for each activity interval is shown in the lower plot of Fig. 1.

$\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ range [GeV]	$\langle \Sigma E_{\mathrm{T}}^{\mathrm{Pb}} \rangle$ [GeV]	range in fraction of events [%]	$\langle N_{\mathrm{ch}}^{\mathrm{rec}} \rangle$ (RMS)
> 80	93.7	0–1.9	134 (31)
55–80	64.8	1.9–9.1	102 (26)
40–55	46.7	9.1–20.0	80 (23)
25–40	31.9	20.0–39.3	60 (20)
10–25	16.9	39.3–70.4	37 (17)
< 10	4.9	70.4–100	16 (11)

Table 1: Characterization of activity intervals as selected by $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$. In the last column, the mean and RMS of the number of reconstructed charged particles with $|\eta| < 2.5$ and $0.3 < p_{\mathrm{T}} < 5$ GeV, $N_{\mathrm{ch}}^{\mathrm{rec}}$, is given for each activity interval.

3. Data analysis

The cumulant method involves the calculation of $2k$-particle azimuthal correlations, $corr_n\{2k\}$, and cumulants, $c_n\{2k\}$, where $k = 1, 2$ for the analysis presented in this paper. The two- and four-particle correlations are defined as $corr_n\{2\} = \langle \mathrm{e}^{in(\phi_1 - \phi_2)} \rangle$ and $corr_n\{4\} = \langle \mathrm{e}^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle$, respectively, where the angle brackets denote the average in a single event over all pairs and all combinations of four particles. After averaging over events, the two-particle cumulant is obtained as $c_n\{2\} = \langle corr_n\{2\} \rangle$, and the four-particle cumulant $c_n\{4\} = \langle corr_n\{4\} \rangle - 2 \cdot \langle corr_n\{2\} \rangle^2$. Thus the effect of two-particle correlations is explicitly removed in the expression for $c_n\{4\}$. Further details are given in Refs. [29, 30, 32].

Direct calculation of multi-particle correlations requires multiple passes over the particles in an event, and requires extensive computing time in high-multiplicity events. To mitigate this, it has been proposed in Ref. [32] to express multi-particle correlations in terms of the moments of the flow vector Q_n, defined as $Q_n = \sum_i \mathrm{e}^{in\phi_i}$, where the index n denotes the flow harmonic and the sum runs over all particles in an event. This analysis is restricted to the second harmonic coefficient, $n = 2$. The method based on the flow-vector moments enables the calculation of multi-particle cumulants in a single pass over the full set of particles in each event.

The cumulant method involves two main steps [29, 30]. In the first step, the so-called “reference” flow harmonic coefficients are calculated using multi-particle cumulants for particles selected inclusively from a broad range in p_{T} and η as:

$$v_2^{\mathrm{ref}}\{2\} = \sqrt{c_2\{2\}}, \tag{2}$$

$$v_2^{\mathrm{ref}}\{4\} = \sqrt[4]{-c_2\{4\}}, \tag{3}$$

where $v_2^{\mathrm{ref}}\{2\}$ ($v_2^{\mathrm{ref}}\{4\}$) denotes the reference estimate of the second-order anisotropy parameter obtained using two-particle, $c_2\{2\}$ (four-particle, $c_2\{4\}$) cumulants.

The flow-vector method is easiest to apply when the detector acceptance is azimuthally uniform [32]. A correction for any azimuthal non-uniformity in the reconstruction of charged particle tracks is obtained from the data [25], based on an η–ϕ map of all reconstructed tracks. For each small ($\delta\eta = 0.1, \delta\phi = 2\pi/64$) bin (labelled i), a weight is calculated as $w_i(\eta, \phi) = \langle N(\delta\eta)\rangle / N_i(\delta\eta, \delta\phi)$, where $\langle N(\delta\eta)\rangle$ is the event-averaged number of tracks in the $\delta\eta$ slice to which this bin belongs, while $N_i(\delta\eta, \delta\phi)$ is the number of tracks in an event within this bin. Using this weight forces the azimuthal angle distribution of reference particles to be uniform in ϕ, but it does not change the η distribution of reconstructed tracks. A weighted Q-vector is evaluated as $Q_n = \sum_i w_i \mathrm{e}^{in\phi_i}$ [32]. From Eqs. (2) and (3) it is clear that the cumulant method can be used to estimate v_2 only when $c_2\{4\}$ is negative and $c_2\{2\}$ positive.

In the second step, the harmonic coefficients are determined as functions of p_{T} and η, in bins in each variable (10 bins of equal width are used in η and 22 bins of varied width in p_{T}). These differential flow harmonics are calculated for “particles of interest” which fall into these small bins. First, the differential cumulants, $d_2\{2\}$ and $d_2\{4\}$, are obtained by correlating every particle of interest with one and three reference particles respectively. The differential second harmonic, $v_2\{2k\}(p_{\mathrm{T}}, \eta)$, where $k = 1, 2$, is then calculated with respect to the reference flow as derived in Refs. [29, 30]:

$$v_2\{2\}(p_{\mathrm{T}}, \eta) = \frac{d_2\{2\}}{\sqrt{c_2\{2\}}}, \tag{4}$$

$$v_2\{4\}(p_{\mathrm{T}}, \eta) = \frac{-d_2\{4\}}{\sqrt[3/4]{-c_2\{4\}}}. \tag{5}$$

The differential v_2 harmonic is then integrated over wider phase-space bins, with each small bin weighted by the appropriate charged particle multiplicity. This is obtained from the reconstructed multiplicity by applying η- and p_{T}-dependent efficiency factors, determined from Monte Carlo (MC) simulation as discussed in the previous section. Due to the small number of events in the data sample, the final results are integrated over the full acceptance in η.

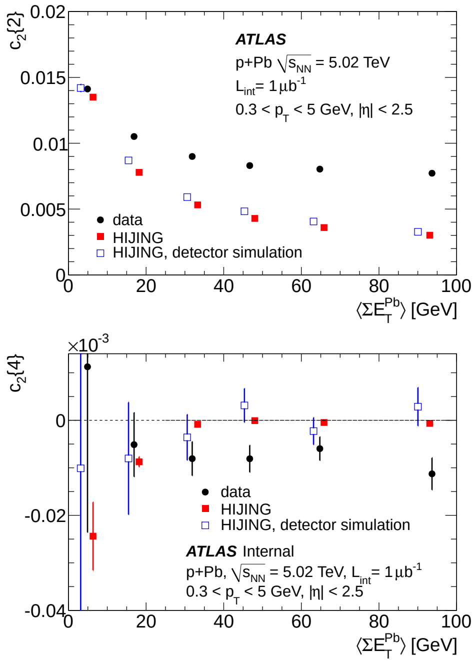

Fig. 2: The two-particle (upper plot) and four-particle (lower plot) cumulants calculated using the reference flow particles as a function of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ for data (circles), the fully simulated HIJING events (open squares) and the large generator-level HIJING sample (filled squares). For clarity, the points for the fully simulated (generated) HIJING events are slightly shifted to the left (right).

Fig. 2 shows the two- and four-particle cumulants, averaged over events in each event-activity class defined in Table 1, as a function of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$. It is observed that four-particle cumulants are negative only in a certain range of event activity. This restricts subsequent analysis to events with $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}} > 25$ GeV, for which the four-particle cumulant in data is found to be less than zero by at least two standard deviations (statistical errors only). It was also checked that for these events $c_2\{4\}$ is unchanged within errors for any high-multiplicity selection. For example, defining N_{20} as the value of $N_{\rm ch}^{\rm rec}$ such that 20% of events have $N_{\rm ch}^{\rm rec} < N_{20}$ (i.e. N_{20} is the 20th percentile), then selecting $N_{\rm ch}^{\rm rec} > N_{20}$ leaves $c_2\{4\}$ unchanged within errors. And for $\Sigma E_{\rm T}^{\rm Pb} > 25$ GeV this holds for any percentile selection.

Fig. 2 also shows the cumulants calculated for 50 million HIJING-generated events, using the true particle information only, as well as for one million fully simulated and reconstructed HIJING events, using the same methods as used for the data. The $\Sigma E_{\rm T}^{\rm Pb}$ obtained from the HIJING sample is rescaled to match that measured in the data. It should be noted that the HIJING Monte Carlo model does not contain any collective flow, and the only correlations are those due to resonance decays, jet production and momentum conservation. The values of $c_2\{2\}$ for HIJING events are smaller than the values obtained from the data, and there is no significant difference between the HIJING results obtained at the generator ("truth") level and at the reconstruction level. For $c_2\{4\}$, the HIJING events at $\Sigma E_{\rm T}^{\rm Pb} \sim 20$ GeV show a negative value comparable to the values seen in the data, indicating that correlations from jets or momentum conservation contribute significantly to $v_2\{4\}$ in events of low multiplicity. For $\Sigma E_{\rm T}^{\rm Pb} > 25$ GeV the generator-level HIJING sample's values for $c_2\{4\}$ are also negative, but the magnitude is much smaller than in the data or in HIJING events with smaller $\Sigma E_{\rm T}^{\rm Pb}$. The size of the fully simulated HIJING event sample is too small to draw a definite conclusion about the sign or magnitude of $c_2\{4\}$.

The systematic uncertainties on $v_2\{2\}$ and $v_2\{4\}$ as a function of $p_{\rm T}$ and $\Sigma E_{\rm T}^{\rm Pb}$ have been evaluated by varying several aspects of the analysis procedure. Azimuthal-angle sine terms in the Fourier expansion should be zero, but a non-zero contribution can arise due to detector biases. It was found that the magnitude of the sine terms relative to the cosine terms is negligible (below 1%) for $v_2\{2\}$ measured as a function of $p_{\rm T}$, as well as for the $p_{\rm T}$-integrated $v_2\{2\}$ and $v_2\{4\}$. In the case of the measurement of the $p_{\rm T}$-dependent $v_2\{4\}$, the systematic uncertainty attributed to the residual sine terms varies between 6% and 14% in the different $\Sigma E_{\rm T}^{\rm Pb}$ intervals. Uncertainties related to the tracking are obtained from the differences between the main results and those using tracking requirements modified to be either more or less restrictive. They are found to be negligible (below 0.2%) for $v_2\{2\}$. For the $p_{\rm T}$-dependent $v_2\{4\}$ they give a contribution of less than 6% to the systematic uncertainty, and less than 1% for the $p_{\rm T}$-integrated $v_2\{4\}$. In addition to varying the track quality requirements, an uncertainty on the $p_{\rm T}$ dependence of the efficiency corrections is also taken into account, and found to be below 1% for the $v_2\{2\}$ and $v_2\{4\}$ measurements. The correction of the azimuthal-angle uniformity is checked by comparing the results to those obtained with all weights, w_i, set equal to one. This change leads to small relative differences, below 1%, for the $v_2\{2\}$ measured as a function of $p_{\rm T}$, as well as for the $p_{\rm T}$-integrated $v_2\{2\}$ and $v_2\{4\}$. Up to 4% differences are observed in the $p_{\rm T}$-dependent $v_2\{4\}$. All individual contributions to the systematic uncertainty are added in quadrature and quoted as the total systematic uncertainty. The total systematic uncertainties are below 1% for the $v_2\{2\}$ measurement. The $v_2\{4\}$ measurement precision is limited by large statistical errors, whereas the systematic uncertainties stay below 15% for $v_2\{4\}(p_{\rm T})$ and below 2% for the $p_{\rm T}$-integrated $v_2\{4\}$.

4. Results

Fig. 3 shows the transverse momentum dependence of $v_2\{2\}$ and $v_2\{4\}$ in four different classes of the event activity, selected according to $\Sigma E_{\rm T}^{\rm Pb}$. A significant second-order harmonic is observed. $v_2\{4\}$ is systematically smaller than $v_2\{2\}$, consistent with the suppression of non-flow effects in $v_2\{4\}$. This difference is most pronounced at high $p_{\rm T}$ and in collisions with low $\Sigma E_{\rm T}^{\rm Pb}$ where jet-like correlations not diluted by the underlying event can contribute significantly. Thus, $v_2\{4\}$ appears to provide a more reliable estimate of the second-order anisotropy parameter of collective flow. As a function of transverse momentum the second-order harmonic, $v_2\{4\}$, increases with $p_{\rm T}$ up to $p_{\rm T} \approx 2$ GeV. Large statistical errors preclude a definite conclusion about the $p_{\rm T}$ dependence of $v_2\{4\}$ at higher transverse momenta.

The shape and magnitude of the $p_{\rm T}$-dependence of $v_2\{4\}$ is found to be similar to that observed in p+Pb collisions using two-particle correlations [2, 3]. The second-order harmonic, v_2, can be extracted from two-particle azimuthal correlations using charged particle pairs with a large pseudorapidity gap to suppress the short-range correlations on the near-side ($\Delta\phi \sim 0$) [3, 22]. However, the two-particle correlation measured this way may still be

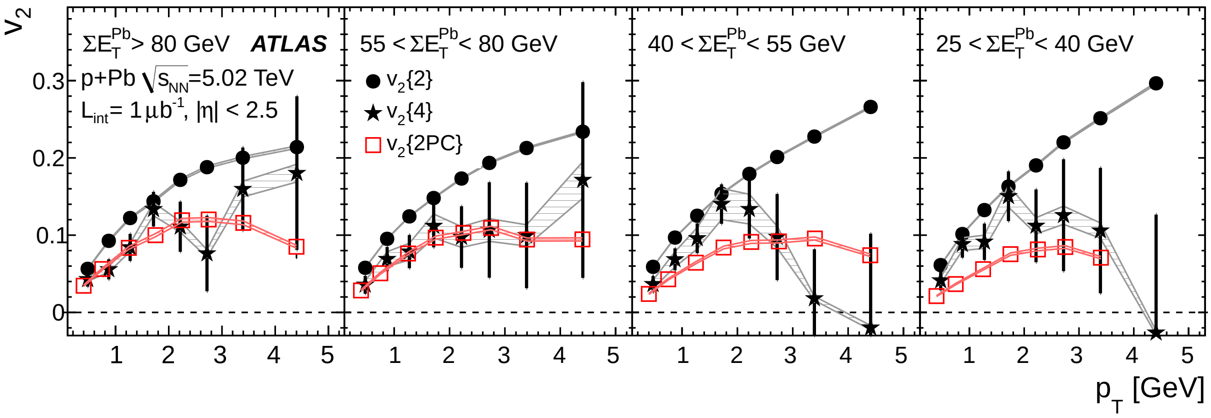

Fig. 3: The second-order harmonic calculated with the two-particle (circles) and four-particle (stars) cumulants as a function of transverse momentum in four different activity intervals. Bars denote statistical errors; systematic uncertainties are shown as shaded bands. The v_2 derived from the Fourier decomposition of two-particle correlations [3] is shown by squares.

affected by the dijet correlations on the away-side ($\Delta\phi \sim \pi$), which can span a large range in $\Delta\eta$. In Ref. [3], the away-side non-flow correlation is estimated using the yield measured in the lowest $\Sigma E_{\rm T}^{\rm Pb}$ collisions and is then subtracted from the higher $\Sigma E_{\rm T}^{\rm Pb}$ collisions. The result of that study, $v_2\{2PC\}$, is shown in Fig. 3 for the four activity intervals with largest $\Sigma E_{\rm T}^{\rm Pb}$, and compared to $v_2\{4\}$. Good agreement is observed between $v_2\{4\}$ and $v_2\{2PC\}$ for collisions with $\Sigma E_{\rm T}^{\rm Pb} > 55$ GeV. For $\Sigma E_{\rm T}^{\rm Pb} < 55$ GeV, the disagreement could be due either to the subtraction procedure used to obtain $v_2\{2PC\}$ or to non-flow effects in $v_2\{4\}$, or to a combination.

The dependence on the collision activity of the second-order harmonic, integrated over $0.3 < p_{\rm T} < 5$ GeV, is shown in Fig. 4. The large magnitude of $v_2\{2\}$ compared to $v_2\{4\}$ suggests a substantial contamination from non-flow correlations. The value of $v_2\{4\}$ is approximately 0.06, with little dependence on the overall event activity for $\Sigma E_{\rm T}^{\rm Pb}$ >25 GeV. The extracted values of $v_2\{4\}$ are also compared to the $v_2\{2PC\}$ values obtained from two-particle correlations. Good agreement is observed at large $\Sigma E_{\rm T}^{\rm Pb}$, while at lower $\Sigma E_{\rm T}^{\rm Pb}$ the $v_2\{2PC\}$ is smaller than $v_2\{4\}$, which may be due to different sensitivity of the two methods to non-flow contributions that become more important in low $\Sigma E_{\rm T}^{\rm Pb}$ collisions. Although $v_2\{4\}$ is constructed to suppress local two-particle correlations, it may still include true multi-particle correlations from jets, which should account for a larger fraction of the correlated particle production in the events with the lowest $\Sigma E_{\rm T}^{\rm Pb}$. If the HIJING results, shown in Fig. 2, were used to correct the measured cumulants for this non-flow contribution, the extracted $v_2\{4\}$ would be decreased by at most 10% for $v_2\{4\}$ shown in Fig. 4. However, this correction is not applied to the final results.

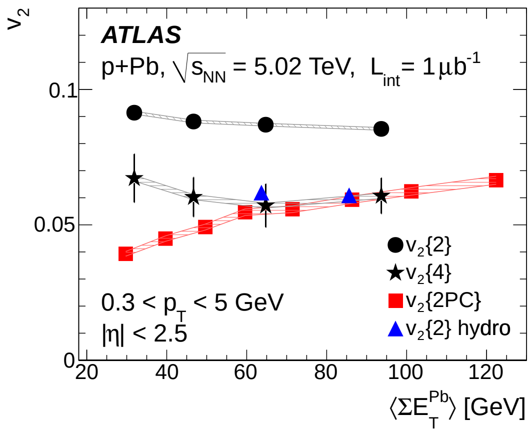

Fig. 4: The second-order harmonic, v_2, integrated over $p_{\rm T}$ and η, calculated with two- and four-particle cumulants (circles and stars, respectively), as a function of $\Sigma E_{\rm T}^{\rm Pb}$. Systematic uncertainties are shown as shaded bands. Also shown is $v_2\{2PC\}$ (squares) and predictions from the hydrodynamic model [18] (triangles) for the same selection of charged particles as in the data.

It is notable that the trend of the $p_{\rm T}$ dependence of both $v_2\{4\}$ and $v_2\{2PC\}$ in p+Pb collisions resembles that observed for v_2 measured with the event-plane method in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [21, 22], although with a magnitude between that observed in the most central and peripheral Pb+Pb collisions. While the trend is found to be nearly independent of the Pb+Pb collision geometry, the magnitude in Pb+Pb events depends on the initial shape of the colliding system, and has been modelled for $p_{\mathrm{T}} < 2$ GeV using viscous hydrodynamics [39–41].

Harmonic flow coefficients in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV have also been predicted using viscous hydrodynamics, with similar initial conditions as the Pb+Pb calculations [18]. The predicted magnitude of the second-order harmonic[2] is compared to the measured $v_2\{4\}$ and $v_2\{2PC\}$ in Fig. 4. It can be seen that the hydrodynamic predictions agree with our measurements over the $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ range where the model predictions are available.

5. Conclusions

ATLAS has measured the second harmonic coefficient in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV using two- and four-particle cumulants. A significant magnitude of v_2 is observed using both two- and four-particle cumulants, although $v_2\{2\}$ is consistently larger than $v_2\{4\}$, indicating a sizeable contribution of non-flow correlations to $v_2\{2\}$. The transverse momentum dependence of $v_2\{4\}$ shows a behaviour similar to that measured in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The magnitude of $v_2\{4\}$ increases with p_{T} up to about 2–3 GeV. As a function of the collision activity, $v_2\{4\}$ remains constant, at the level of about 0.06, for the collisions with $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ >25 GeV, which corresponds to about 40% of the data. The measured $v_2\{4\}$ is found to be consistent with the second harmonic coefficient extracted by the Fourier decomposition of the long-range two-particle correlation function for collisions with $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}} > 55$ GeV. Good agreement is also found with the predictions of a hydrodynamic calculation for p+Pb collisions.

Extending previous results based only on two-particle correlations, the multi-particle cumulant results presented here provide additional evidence for the importance of final-state effects in the highest multiplicity p+Pb reactions. Final-state effects may lead to collective flow similar to that observed in the hot, dense system created in high-energy heavy-ion collisions.

6. Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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[2] We are grateful to the authors of Ref. [18] for providing us with the model predictions for charged particles with η and p_{T} ranges matching those used in the analysis. The model predictions are for two activity intervals corresponding to fractions of events of $0 - 3.4$ % and $3.4 - 7.8$ % which are then translated into the $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ intervals using Fig. 1.

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Shulga[96], M.A. Shupe[7], P. Sicho[125], A. Sidoti[132a], F. Siegert[48], Dj. Sijacki[13a], O. Silbert[172], J. Silva[124a], Y. Silver[153], D. Silverstein[143], S.B. Silverstein[146a], V. Simak[126], O. Simard[5], Lj. Simic[13a], S. Simion[115], E. Simioni[81], B. Simmons[77], R. Simoniello[89a,89b], M. Simonyan[36], P. Sinervo[158], N.B. Sinev[114], V. Sipica[141], G. Siragusa[174], A. Sircar[25], A.N. Sisakyan[64,*], S.Yu. Sivoklokov[97], J. Sjölin[146a,146b], T.B. Sjursen[14], L.A. Skinnari[15], H.P. Skottowe[57], K. Skovpen[107], P. Skubic[111], M. Slater[18], T. Slavicek[126], K. Sliwa[161], V. Smakhtin[172], B.H. Smart[46], L. Smestad[117], S.Yu. Smirnov[96], Y. Smirnov[96], L.N. Smirnova[97,ai], O. Smirnova[79], K.M. Smith[53], M. Smizanska[71], K. Smolek[126], A.A. Snesarev[94], G. Snidero[75], J. Snow[111], S. Snyder[25], R. Sobie[169,j], J. Sodomka[126], A. Soffer[153], D.A. Soh[151,u], C.A. Solans[30], M. Solar[126], J. Solc[126], E.Yu. Soldatov[96], U. Soldevila[167], E. Solfaroli Camillocci[132a,132b], A.A. Solodkov[128], O.V. Solovyanov[128], V. Solovyev[121], N. Soni[1], A. Sood[15], V. Sopko[126], B. Sopko[126], M. Sosebee[8], R. Soualah[164a,164c], P. Soueid[93], A. Soukharev[107], D. South[42], S. Spagnolo[72a,72b], F. Spanò[76], R. Spighi[20a], G. Spigo[30], R. Spiwoks[30], M. Spousta[127,aj], T. Spreitzer[158], B. Spurlock[8], R.D. St. Denis[53], J. Stahlman[120], R. Stamen[58a], E. Stanecka[39], R.W. Stanek[6], C. Stanescu[134a], M. Stanescu-Bellu[42], M.M. Stanitzki[42], S. Stapnes[117], E.A. Starchenko[128], J. Stark[55], P. Staroba[125], P. Starovoitov[42], R. Staszewski[39], A. Staude[98], P. Stavina[144a,*], G. Steele[53], P. Steinbach[44], P. Steinberg[25], I. Stekl[126], B. Stelzer[142], H.J. Stelzer[88], O. Stelzer-Chilton[159a], H. Stenzel[52], S. Stern[99], G.A. Stewart[30], J.A. Stillings[21], M.C. Stockton[85], M. Stoebe[85], K. Stoerig[48], G. Stoicea[26a], S. Stonjek[99], A.R. Stradling[8], A. Straessner[44], J. Strandberg[147], S. Strandberg[146a,146b], A. Strandlie[117], M. Strang[109], E. Strauss[143], M. Strauss[111], P. Strizenec[144b], R. Ströhmer[174], D.M. Strom[114], J.A. Strong[76,*], R. Stroynowski[40], B. Stugu[14], I. Stumer[25,*], J. Stupak[148], P. Sturm[175], N.A. Styles[42], D. Su[143], HS. Subramania[3], R. Subramaniam[25], A. Succurro[12], Y. Sugaya[116], C. Suhr[106], M. Suk[126], V.V. Sulin[94], S. Sultansoy[4c], T. Sumida[67], X. Sun[55], J.E. Sundermann[48], K. Suruliz[139], G. Susinno[37a,37b], M.R. Sutton[149], Y. Suzuki[65], Y. Suzuki[66], M. Svatos[125], S. Swedish[168], M. Swiatlowski[143], I. Sykora[144a], T. Sykora[127], D. Ta[105], K. Tackmann[42], A. Taffard[163], R. Tafirout[159a], N. Taiblum[153], Y. Takahashi[101], H. Takai[25], R. Takashima[68], H. Takeda[66], T. Takeshita[140], Y. Takubo[65], M. Talby[83], A. Talyshev[107,g], J.Y.C. Tam[174], M.C. Tamsett[25], K.G. Tan[86], J. Tanaka[155], R. Tanaka[115], S. Tanaka[131], S. Tanaka[65], A.J. Tanasijczuk[142], K. Tani[66], N. Tannoury[83], S. Tapprogge[81], S. Tarem[152], F. Tarrade[29], G.F. Tartarelli[89a], P. Tas[127], M. Tasevsky[125], T. Tashiro[67], E. Tassi[37a,37b], Y. Tayalati[135d], C. Taylor[77], F.E. Taylor[92], G.N. Taylor[86], W. Taylor[159b], M. Teinturier[115], F.A. Teischinger[30], M. Teixeira Dias Castanheira[75], P. Teixeira-Dias[76], K.K. Temming[48], H. Ten Kate[30], P.K. Teng[151], S. Terada[65], K. Terashi[155], J. Terron[80], M. Testa[47], R.J. Teuscher[158,j], J. Therhaag[21], T. Theveneaux-Pelzer[34], S. Thoma[48], J.P. Thomas[18], E.N. Thompson[35], P.D. Thompson[18], P.D. Thompson[158], A.S. Thompson[53], L.A. Thomsen[36], E. Thomson[120], M. Thomson[28], W.M. Thong[86], R.P. Thun[87,*], F. Tian[35], M.J. Tibbetts[15], T. Tic[125], V.O. Tikhomirov[94], Y.A. Tikhonov[107,g], S. Timoshenko[96], E. Tiouchichine[83], P. Tipton[176], S. Tisserant[83], T. Todorov[5], S. Todorova-Nova[161], B. Toggerson[163], J. Tojo[69], S. Tokár[144a], K. Tokushuku[65], K. Tollefson[88], L. Tomlinson[82], M. Tomoto[101], L. Tompkins[31], K. Toms[103], A. Tonoyan[14], C. Topfel[17], N.D. Topilin[64], E. Torrence[114], H. Torres[78], E. Torró Pastor[167], J. Toth[83,ae], F. Touchard[83], D.R. Tovey[139], H.L. Tran[115], T. Trefzger[174], L. Tremblet[30], A. Tricoli[30], I.M. Trigger[159a], S. Trincaz-Duvoid[78], M.F. Tripiana[70], N. Triplett[25], W. Trischuk[158], B. Trocmé[55], C. Troncon[89a], M. Trottier-McDonald[142], M. Trovatelli[134a,134b], P. True[88], M. Trzebinski[39], A. Trzupek[39], C. Tsarouchas[30], J.C-L. Tseng[118], M. Tsiakiris[105], P.V. Tsiareshka[90], D. Tsionou[136], G. Tsipolitis[10], S. Tsiskaridze[12], V. Tsiskaridze[48], E.G. Tskhadadze[51a], I.I. Tsukerman[95], V. Tsulaia[15], J.-W. Tsung[21], S. Tsuno[65], D. Tsybychev[148], A. Tua[139], A. Tudorache[26a], V. Tudorache[26a], J.M. Tuggle[31], A.N. Tuna[120],

M. Turala[39], D. Turecek[126], I. Turk Cakir[4d], R. Turra[89a,89b], P.M. Tuts[35], A. Tykhonov[74], M. Tylmad[146a,146b], M. Tyndel[129], G. Tzanakos[9], K. Uchida[21], I. Ueda[155], R. Ueno[29], M. Ughetto[83], M. Ugland[14], M. Uhlenbrock[21], F. Ukegawa[160], G. Unal[30], A. Undrus[25], G. Unel[163], F.C. Ungaro[48], Y. Unno[65], D. Urbaniec[35], P. Urquijo[21], G. Usai[8], L. Vacavant[83], V. Vacek[126], B. Vachon[85], S. Vahsen[15], N. Valencic[105], S. Valentinetti[20a,20b], A. Valero[167], L. Valery[34], S. Valkar[127], E. Valladolid Gallego[167], S. Vallecorsa[152], J.A. Valls Ferrer[167], R. Van Berg[120], P.C. Van Der Deijl[105], R. van der Geer[105], H. van der Graaf[105], R. Van Der Leeuw[105], D. van der Ster[30], N. van Eldik[30], P. van Gemmeren[6], J. Van Nieuwkoop[142], I. van Vulpen[105], M. Vanadia[99], W. Vandelli[30], A. Vaniachine[6], P. Vankov[42], F. Vannucci[78], R. Vari[132a], E.W. Varnes[7], T. Varol[84], D. Varouchas[15], A. Vartapetian[8], K.E. Varvell[150], V.I. Vassilakopoulos[56], F. Vazeille[34], T. Vazquez Schroeder[54], F. Veloso[124a], S. Veneziano[132a], A. Ventura[72a,72b], D. Ventura[84], M. Venturi[48], N. Venturi[158], V. Vercesi[119a], M. Verducci[138], W. Verkerke[105], J.C. Vermeulen[105], A. Vest[44], M.C. Vetterli[142,e], I. Vichou[165], T. Vickey[145b,ak], O.E. Vickey Boeriu[145b], G.H.A. Viehhauser[118], S. Viel[168], M. Villa[20a,20b], M. Villaplana Perez[167], E. Vilucchi[47], M.G. Vincter[29], V.B. Vinogradov[64], J. Virzi[15], O. Vitells[172], M. Viti[42], I. Vivarelli[48], F. Vives Vaque[3], S. Vlachos[10], D. Vladoiu[98], M. Vlasak[126], A. Vogel[21], P. Vokac[126], G. Volpi[47], M. Volpi[86], G. Volpini[89a], H. von der Schmitt[99], H. von Radziewski[48], E. von Toerne[21], V. Vorobel[127], M. Vos[167], R. Voss[30], J.H. Vossebeld[73], N. Vranjes[136], M. Vranjes Milosavljevic[105], V. Vrba[125], M. Vreeswijk[105], T. Vu Anh[48], R. Vuillermet[30], I. Vukotic[31], Z. Vykydal[126], W. Wagner[175], P. Wagner[21], H. Wahlen[175], S. Wahrmund[44], J. Wakabayashi[101], S. Walch[87], J. Walder[71], R. Walker[98], W. Walkowiak[141], R. Wall[176], P. Waller[73], B. Walsh[176], C. Wang[45], H. Wang[173], H. Wang[40], J. Wang[151], J. Wang[33a], K. Wang[85], R. Wang[103], S.M. Wang[151], T. Wang[21], X. Wang[176], A. Warburton[85], C.P. Ward[28], D.R. Wardrope[77], M. Warsinsky[48], A. Washbrook[46], C. Wasicki[42], I. Watanabe[66], P.M. Watkins[18], A.T. Watson[18], I.J. Watson[150], M.F. Watson[18], G. Watts[138], S. Watts[82], A.T. Waugh[150], B.M. Waugh[77], M.S. Weber[17], J.S. Webster[31], A.R. Weidberg[118], P. Weigell[99], J. Weingarten[54], C. Weiser[48], P.S. Wells[30], T. Wenaus[25], D. Wendland[16], Z. Weng[151,u], T. Wengler[30], S. Wenig[30], N. Wermes[21], M. Werner[48], P. Werner[30], M. Werth[163], M. Wessels[58a], J. Wetter[161], K. Whalen[29], A. White[8], M.J. White[86], R. White[32b], S. White[122a,122b], S.R. Whitehead[118], D. Whiteson[163], D. Whittington[60], D. Wicke[175], F.J. Wickens[129], W. Wiedenmann[173], M. Wielers[79], P. Wienemann[21], C. Wiglesworth[36], L.A.M. Wiik-Fuchs[21], P.A. Wijeratne[77], A. Wildauer[99], M.A. Wildt[42,r], I. Wilhelm[127], H.G. Wilkens[30], J.Z. Will[98], E. Williams[35], H.H. Williams[120], S. Williams[28], W. Willis[35,*], S. Willocq[84], J.A. Wilson[18], A. Wilson[87], I. Wingerter-Seez[5], S. Winkelmann[48], F. Winklmeier[30], M. Wittgen[143], T. Wittig[43], J. Wittkowski[98], S.J. Wollstadt[81], M.W. Wolter[39], H. Wolters[124a,h], W.C. Wong[41], G. Wooden[87], B.K. Wosiek[39], J. Wotschack[30], M.J. Woudstra[82], K.W. Wozniak[39], K. Wraight[53], M. Wright[53], B. Wrona[73], S.L. Wu[173], X. Wu[49], Y. Wu[87], E. Wulf[35], B.M. Wynne[46], S. Xella[36], M. Xiao[136], S. Xie[48], C. Xu[33b,z], D. Xu[33a], L. Xu[33b], B. Yabsley[150], S. Yacoob[145a,al], M. Yamada[65], H. Yamaguchi[155], Y. Yamaguchi[155], A. Yamamoto[65], K. Yamamoto[63], S. Yamamoto[155], T. Yamamura[155], T. Yamanaka[155], K. Yamauchi[101], T. Yamazaki[155], Y. Yamazaki[66], Z. Yan[22], H. Yang[33e], H. Yang[173], U.K. Yang[82], Y. Yang[109], Z. Yang[146a,146b], S. Yanush[91], L. Yao[33a], Y. Yasu[65], E. Yatsenko[42], K.H. Yau Wong[21], J. Ye[40], S. Ye[25], A.L. Yen[57], E. Yildirim[42], M. Yilmaz[4b], R. Yoosoofmiya[123], K. Yorita[171], R. Yoshida[6], K. Yoshihara[155], C. Young[143], C.J.S. Young[118], S. Youssef[22], D. Yu[25], D.R. Yu[15], J. Yu[8], J. Yu[112], L. Yuan[66], A. Yurkewicz[106], B. Zabinski[39], R. Zaidan[62], A.M. Zaitsev[128], S. Zambito[23], L. Zanello[132a,132b], D. Zanzi[99], A. Zaytsev[25], C. Zeitnitz[175], M. Zeman[126], A. Zemla[39], O. Zenin[128], T. Ženiš[144a], D. Zerwas[115], G. Zevi della Porta[57], D. Zhang[87], H. Zhang[88], J. Zhang[6], L. Zhang[151], X. Zhang[33d], Z. Zhang[115], Z. Zhao[33b], A. Zhemchugov[64], J. Zhong[118], B. Zhou[87], N. Zhou[163], Y. Zhou[151], C.G. Zhu[33d], H. Zhu[42], J. Zhu[87], Y. Zhu[33b], X. Zhuang[33a], V. Zhuravlov[99], A. Zibell[98], D. Zieminska[60], N.I. Zimin[64], C. Zimmermann[81], R. Zimmermann[21], S. Zimmermann[21], S. Zimmermann[48], Z. Zinonos[122a,122b], M. Ziolkowski[141], R. Zitoun[5], L. Živković[35], V.V. Zmouchko[128,*], G. Zobernig[173], A. Zoccoli[20a,20b], M. zur Nedden[16], V. Zutshi[106], L. Zwalinski[30].

[1] School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
[2] Physics Department, SUNY Albany, Albany NY, United States of America
[3] Department of Physics, University of Alberta, Edmonton AB, Canada

[4] (a)Department of Physics, Ankara University, Ankara; (b)Department of Physics, Gazi University, Ankara; (c)Division of Physics, TOBB University of Economics and Technology, Ankara; (d)Turkish Atomic Energy Authority, Ankara, Turkey
[5] LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
[7] Department of Physics, University of Arizona, Tucson AZ, United States of America
[8] Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
[9] Physics Department, University of Athens, Athens, Greece
[10] Physics Department, National Technical University of Athens, Zografou, Greece
[11] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[12] Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
[13] (a)Institute of Physics, University of Belgrade, Belgrade; (b)Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[14] Department for Physics and Technology, University of Bergen, Bergen, Norway
[15] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
[16] Department of Physics, Humboldt University, Berlin, Germany
[17] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[18] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[19] (a)Department of Physics, Bogazici University, Istanbul; (b)Division of Physics, Dogus University, Istanbul; (c)Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
[20] (a)INFN Sezione di Bologna; (b)Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[21] Physikalisches Institut, University of Bonn, Bonn, Germany
[22] Department of Physics, Boston University, Boston MA, United States of America
[23] Department of Physics, Brandeis University, Waltham MA, United States of America
[24] (a)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b)Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c)Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d)Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[25] Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
[26] (a)National Institute of Physics and Nuclear Engineering, Bucharest; (b)University Politehnica Bucharest, Bucharest; (c)West University in Timisoara, Timisoara, Romania
[27] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[28] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[29] Department of Physics, Carleton University, Ottawa ON, Canada
[30] CERN, Geneva, Switzerland
[31] Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
[32] (a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[33] (a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b)Department of Modern Physics, University of Science and Technology of China, Anhui; (c)Department of Physics, Nanjing University, Jiangsu; (d)School of Physics, Shandong University, Shandong; (e)Physics Department, Shanghai Jiao Tong University, Shanghai, China
[34] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
[35] Nevis Laboratory, Columbia University, Irvington NY, United States of America
[36] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[37] (a)INFN Gruppo Collegato di Cosenza; (b)Dipartimento di Fisica, Università della Calabria, Rende, Italy
[38] (a)AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[39] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

[40] Physics Department, Southern Methodist University, Dallas TX, United States of America
[41] Physics Department, University of Texas at Dallas, Richardson TX, United States of America
[42] DESY, Hamburg and Zeuthen, Germany
[43] Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[44] Institut für Kern-und Teilchenphysik, Technical University Dresden, Dresden, Germany
[45] Department of Physics, Duke University, Durham NC, United States of America
[46] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[49] Section de Physique, Université de Genève, Geneva, Switzerland
[50] (a)INFN Sezione di Genova; (b)Dipartimento di Fisica, Università di Genova, Genova, Italy
[51] (a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b)High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[56] Department of Physics, Hampton University, Hampton VA, United States of America
[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
[58] (a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c)ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60] Department of Physics, Indiana University, Bloomington IN, United States of America
[61] Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62] University of Iowa, Iowa City IA, United States of America
[63] Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
[64] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[65] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[66] Graduate School of Science, Kobe University, Kobe, Japan
[67] Faculty of Science, Kyoto University, Kyoto, Japan
[68] Kyoto University of Education, Kyoto, Japan
[69] Department of Physics, Kyushu University, Fukuoka, Japan
[70] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[71] Physics Department, Lancaster University, Lancaster, United Kingdom
[72] (a)INFN Sezione di Lecce; (b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[73] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[74] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[75] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[76] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[77] Department of Physics and Astronomy, University College London, London, United Kingdom
[78] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[79] Fysiska institutionen, Lunds universitet, Lund, Sweden
[80] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[81] Institut für Physik, Universität Mainz, Mainz, Germany
[82] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[83] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[84] Department of Physics, University of Massachusetts, Amherst MA, United States of America
[85] Department of Physics, McGill University, Montreal QC, Canada

[86] School of Physics, University of Melbourne, Victoria, Australia
[87] Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[88] Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[89] (a)INFN Sezione di Milano; (b)Dipartimento di Fisica, Università di Milano, Milano, Italy
[90] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[91] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[92] Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
[93] Group of Particle Physics, University of Montreal, Montreal QC, Canada
[94] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[95] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[96] Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[97] D.V.Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
[98] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[99] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[100] Nagasaki Institute of Applied Science, Nagasaki, Japan
[101] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[102] (a)INFN Sezione di Napoli; (b)Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
[103] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
[104] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[105] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[106] Department of Physics, Northern Illinois University, DeKalb IL, United States of America
[107] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[108] Department of Physics, New York University, New York NY, United States of America
[109] Ohio State University, Columbus OH, United States of America
[110] Faculty of Science, Okayama University, Okayama, Japan
[111] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
[112] Department of Physics, Oklahoma State University, Stillwater OK, United States of America
[113] Palacký University, RCPTM, Olomouc, Czech Republic
[114] Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
[115] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[116] Graduate School of Science, Osaka University, Osaka, Japan
[117] Department of Physics, University of Oslo, Oslo, Norway
[118] Department of Physics, Oxford University, Oxford, United Kingdom
[119] (a)INFN Sezione di Pavia; (b)Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[120] Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
[121] Petersburg Nuclear Physics Institute, Gatchina, Russia
[122] (a)INFN Sezione di Pisa; (b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[123] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
[124] (a)Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; (b)Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
[125] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[126] Czech Technical University in Prague, Praha, Czech Republic
[127] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[128] State Research Center Institute for High Energy Physics, Protvino, Russia

[129] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[130] Physics Department, University of Regina, Regina SK, Canada
[131] Ritsumeikan University, Kusatsu, Shiga, Japan
[132] (a)INFN Sezione di Roma I; (b)Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[133] (a)INFN Sezione di Roma Tor Vergata; (b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134] (a)INFN Sezione di Roma Tre; (b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[135] (a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b)Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d)Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e)Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
[136] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
[137] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
[138] Department of Physics, University of Washington, Seattle WA, United States of America
[139] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[140] Department of Physics, Shinshu University, Nagano, Japan
[141] Fachbereich Physik, Universität Siegen, Siegen, Germany
[142] Department of Physics, Simon Fraser University, Burnaby BC, Canada
[143] SLAC National Accelerator Laboratory, Stanford CA, United States of America
[144] (a)Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[145] (a)Department of Physics, University of Johannesburg, Johannesburg; (b)School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[146] (a)Department of Physics, Stockholm University; (b)The Oskar Klein Centre, Stockholm, Sweden
[147] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[148] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
[149] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150] School of Physics, University of Sydney, Sydney, Australia
[151] Institute of Physics, Academia Sinica, Taipei, Taiwan
[152] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[153] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[154] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[155] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[156] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[157] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[158] Department of Physics, University of Toronto, Toronto ON, Canada
[159] (a)TRIUMF, Vancouver BC; (b)Department of Physics and Astronomy, York University, Toronto ON, Canada
[160] Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[161] Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
[162] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[163] Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
[164] (a)INFN Gruppo Collegato di Udine; (b)ICTP, Trieste; (c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

[165] Department of Physics, University of Illinois, Urbana IL, United States of America
[166] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[168] Department of Physics, University of British Columbia, Vancouver BC, Canada
[169] Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[170] Department of Physics, University of Warwick, Coventry, United Kingdom
[171] Waseda University, Tokyo, Japan
[172] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[173] Department of Physics, University of Wisconsin, Madison WI, United States of America
[174] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[175] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[176] Department of Physics, Yale University, New Haven CT, United States of America
[177] Yerevan Physics Institute, Yerevan, Armenia
[178] Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
[a] Also at Department of Physics, King's College London, London, United Kingdom
[b] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
[c] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
[d] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[e] Also at TRIUMF, Vancouver BC, Canada
[f] Also at Department of Physics, California State University, Fresno CA, United States of America
[g] Also at Novosibirsk State University, Novosibirsk, Russia
[h] Also at Department of Physics, University of Coimbra, Coimbra, Portugal
[i] Also at Università di Napoli Parthenope, Napoli, Italy
[j] Also at Institute of Particle Physics (IPP), Canada
[k] Also at Department of Physics, Middle East Technical University, Ankara, Turkey
[l] Also at Louisiana Tech University, Ruston LA, United States of America
[m] Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[n] Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[o] Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
[p] Also at Department of Physics, University of Cape Town, Cape Town, South Africa
[q] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[r] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
[s] Also at Manhattan College, New York NY, United States of America
[t] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[u] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
[v] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
[w] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[x] Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
[y] Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[z] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
[aa] Also at Section de Physique, Université de Genève, Geneva, Switzerland
[ab] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
[ac] Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
[ad] Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United

States of America
[ae] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
[af] Also at DESY, Hamburg and Zeuthen, Germany
[ag] Also at International School for Advanced Studies (SISSA), Trieste, Italy
[ah] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[ai] Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
[aj] Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America
[ak] Also at Department of Physics, Oxford University, Oxford, United Kingdom
[al] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
* Deceased