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DOI
10.1016/j.physletb.2013.06.057

Publication date
2013

Document Version
Final published version

Published in
Physics Letters B

Link to publication

Citation for published version (APA):

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

ATLAS Collaboration

1. Introduction

Recent observations of ridge-like structures in the two-particle correlation functions measured in proton-lead ($p + \text{Pb}$) collisions at 5.02 TeV [1–3] have led to differing theoretical explanations. These structures have been attributed either to mechanisms that emphasise 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 $p + \text{Pb}$ 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 $p + \text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02$ 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 $\text{Pb} + \text{Pb}$ collisions.

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

$$v_n = \langle \cos(n(\phi - \Psi_n)) \rangle,$$

where $\phi$ is the azimuthal angle of the particle, $\Psi_n$ 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 $\Psi_2$ defines the direction which nominally points in the direction of the classical impact parameter. In practice, initial-state fluctuations can blur the relationship between $\Psi_2$ and the impact parameter direction in nucleus–nucleus collisions. In contrast, $\Psi_2$ in proton–nucleus collisions 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 $p + \text{Pb}$ collisions at
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \). The cumulant method [29–32] is applied to derive \( v_2 \) using two- and four-particle cumulants. The cumulant method has been developed to characterise 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 \( p + \text{Pb} \) collisions.

2. Event and track selections

The \( p + \text{Pb} \) data sample was collected during a short run in September 2012, when the LHC delivered \( p + \text{Pb} \) collisions at the nucleon–nucleon centre-of-mass energy \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) 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 (SCST), 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 \( z = \pm 3.6 \text{ m} \) and covering the pseudorapidity range \( 2.1 < |\eta| < 3.9 \), were used. The trigger used to select minimum-bias \( p + \text{Pb} \) collisions requires a signal in at least two MBTS counters. This trigger is fully efficient for events with more than four reconstructed tracks with \( p_T > 0.1 \text{ GeV} \). 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 characterise 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 \( \pm 150 \text{ mm} \) 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 \( p + \text{Pb} \) 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 \( 1.9 \times 10^6 \) events.

Charged particle tracks are reconstructed in the ID using the standard algorithm optimised 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

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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 \((r, \phi)\) are used in the transverse plane, \( \phi \) being the azimuthal angle around the beam pipe. For the \( p + \text{Pb} \) collisions, the incident \( \text{Pb} \) beam travelled in the \( +z \) direction. The pseudorapidity is defined in laboratory coordinates in terms of the polar angle \( \theta = \eta = -\ln \tanh(\eta/2) \). Transverse momentum and energy are defined as \( p_T = p \sin \theta \) and \( E_T = E \sin \theta \), respectively.

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Fig. 1. Upper plot: the \( \Sigma E_T^{\text{FB}} \) distribution with the six activity intervals indicated. Lower plot: the distribution of \( N_{\text{ch}}^{\text{FB}} \) for each activity interval. The leftmost distribution corresponds to the interval with the lowest \( \Sigma E_T^{\text{FB}} \), etc.
The cumulant method involves the calculation of 2k-particle azimuthal correlations, \( corr_k(2k) \), and cumulants, \( c_n(2k) \), where \( k = 1, 2 \) for the analysis presented in this Letter. The two- and four-particle correlations are defined as \( corr_n(2) = \langle e^{im\delta \eta - i\phi_1} \rangle \) and \( corr_n(4) = \langle e^{i(n\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle \), 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 \( c_0(2) = \langle corr_n(2) \rangle \), and the four-particle cumulant \( c_4(4) = \langle corr_n(4) \rangle - 2 \cdot \langle corr_n(2) \rangle^2 \). Thus the effect of two-particle correlations is explicitly removed in the expression for \( c_0(4) \). 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 \( Q_n = \sum_k e^{i n \phi_k} \), 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 \( \eta \) as:

\[
\begin{align*}
   v_2^{ref}(2) &= \sqrt{c_2(2)}, \\
   v_2^{ref}(4) &= \sqrt{-c_2(4)},
\end{align*}
\]

where \( v_2^{ref}(2) \) (\( v_2^{ref}(4) \)) 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 \( \eta - \phi \) map of all reconstructed tracks. For each small \( (\delta \eta, \delta \phi) = 0.1, 0.1 \) bin (labelled \( l \)), a weight is calculated as \( w_l(\eta, \phi) = \langle N(\delta \eta)/N(\delta \eta, \delta \phi) \rangle \), where \( N(\delta \eta) \) is the event-averaged number of tracks in the \( \delta \eta \) slice to which this bin belongs, while \( N(\delta \eta, \delta \phi) \) 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 \( \phi \), but it does not change the \( \eta \) distribution of reconstructed tracks. A weighted \( Q_\eta \) vector is evaluated as \( Q_\eta = \sum_{l} \frac{w_l^{\text{ref}}}{\sqrt{c_2(4)}} \) [32,38]. 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 \( \eta \), in bins in each variable \( (10 \text{ bins of equal width are used in } \eta \text{ and } 22 \text{ bins of varied width in } p_T) \).
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 \cite{3} is shown by squares.

The systematic uncertainties on \( v_2 \) and \( v_2 \) as a function of \( p_T \) and \( \Sigma E_T^p \) 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 \( v_2 \) measured as a function of \( p_T \), as well as for the \( p_T \)-integrated \( v_2 \) and \( v_2 \). In the case of the measurement of the \( p_T \)-dependent \( v_2 \), the systematic uncertainty attributed to the residual sine terms varies between 6\% and 14\% in the different \( \Sigma E_T^p \) 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 \( v_2 \). For the \( p_T \)-dependent \( v_2 \) they give a contribution of less than 6\% to the systematic uncertainty, and less than 1\% for the \( p_T \)-integrated \( v_2 \). In addition to varying the track quality requirements, an uncertainty on the \( p_T \) dependence of the efficiency corrections is also taken into account, and found to be below 1\% for the \( v_2 \) and \( v_2 \) 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 \( v_2 \) measured as a function of \( p_T \), as well as for the \( p_T \)-integrated \( v_2 \) and \( v_2 \). Up to 4\% differences are observed in the \( p_T \)-dependent \( v_2 \). 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 \( v_2 \) measurement. The \( v_2 \) measurement precision is limited by large statistical errors, whereas the systematic uncertainties stay below 15\% for \( v_2 \) \( (p_T) \) and below 2\% for the \( p_T \)-integrated \( v_2 \).

## 4. Results

Fig. 3 shows the transverse momentum dependence of \( v_2 \) and \( v_2 \) in four different classes of the event activity, selected according to \( \Sigma E_T^p \). A significant second-order harmonic is observed. \( v_2 \) is systematically smaller than \( v_2 \), consistent with the suppression of non-flow effects in \( v_2 \). This difference is most pronounced at high \( p_T \) and in collisions with low \( \Sigma E_T^p \), where jet-like correlations not diluted by the underlying event can contribute significantly. Thus, \( v_2 \) 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, \( v_2 \), increases with \( p_T \) up to \( p_T \approx 2 \) GeV. Large statistical errors preclude a definite conclusion about the \( p_T \) dependence of \( v_2 \) at higher transverse momenta.

The shape and magnitude of the \( p_T \) dependence of \( v_2 \) is found to be similar to that observed in \( p + \text{Pb} \) collisions using two-particle correlations \cite{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 \( (\Delta \phi \sim 0) \) \cite{22}. However, the two-particle correlation measured this way may still be affected by the dijet correlations on the away-side \( (\Delta \phi \sim \pi) \), which can span a large range in \( \Delta \eta \). In Ref. \cite{3}, the away-side non-flow correlation is estimated using the yield measured in the lowest \( \Sigma E_T^p \) collisions and is then subtracted from the higher \( \Sigma E_T^p \) collisions. The result of that study, \( v_2 \), is shown in Fig. 3 for the four activity intervals with largest \( \Sigma E_T^p \), and compared to \( v_2 \). Good agreement is observed between \( v_2 \) and \( v_2 \) for collisions with \( \Sigma E_T^p > 55 \) GeV. For \( \Sigma E_T^p < 55 \) GeV, the disagreement could be due either to the subtraction procedure used to obtain \( v_2 \) or to non-flow effects in \( v_2 \), or to a combination.

The dependence on the collision activity of the second-order harmonic, integrated over \( 0.3 < p_T < 5 \) GeV, is shown in Fig. 4. The large magnitude of \( v_2 \) compared to \( v_2 \) suggests a substantial contamination from non-flow correlations. The value of \( v_2 \) is approximately 0.06, with little dependence on the overall event activity for \( \Sigma E_T^p > 25 \) GeV. The extracted values of \( v_2 \) are also compared to the \( v_2 \) values obtained from two-particle correlations. Good agreement is observed at large \( \Sigma E_T^p \), while at lower \( \Sigma E_T^p \) the \( v_2 \) is smaller than \( v_2 \), which may be due to different sensitivity of the two methods to non-flow contributions.
that become more important in low $\Sigma E_T^{Pb}$ 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 $\Sigma E_T^{Pb}$. 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.

It is notable that the trend of the $p_T$ 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 $\sqrt{s_{NN}} = 2.76$ 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 $p_T < 2$ GeV using viscous hydrodynamics [40–42].

Harmonic flow coefficients in $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ 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 $\Sigma E_T^{Pb}$ range where the model predictions are available.

5. Conclusions

ATLAS has measured the second harmonic coefficient in $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ 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 $\sqrt{s_{NN}} = 2.76$ 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 $\Sigma E_T^{Pb} > 25$ 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 $\Sigma E_T^{Pb} > 55$ 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.

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; DfnR, DSNRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; CSRT and NSRF, Greece; IFI, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNISR, Poland; GRICES and FCT, Portugal; MERSYS (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.

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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