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Measurement of flow harmonics correlations with mean transverse momentum in lead–lead and proton–lead collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV with the ATLAS detector

The ATLAS Collaboration

To assess the properties of the quark–gluon plasma formed in heavy-ion collisions, the ATLAS experiment at the LHC measures a correlation between the mean transverse momentum and the magnitudes of the flow harmonics. The analysis uses data samples of lead–lead and proton–lead collisions obtained at the centre-of-mass energy per nucleon pair of 5.02 TeV, corresponding to total integrated luminosities of 22 $\mu\mathrm{b}^{-1}$ and 28 nb^{-1}, respectively. The measurement is performed using a modified Pearson correlation coefficient with the charged-particle tracks on an event-by-event basis. The modified Pearson correlation coefficients for the 2^{nd}-, 3^{rd}-, and 4^{th}-order harmonics are measured as a function of event centrality quantified as the number of charged particles or the number of nucleons participating in the collision. The measurements are performed for several intervals of the charged-particle transverse momentum. The correlation coefficients for all studied harmonics exhibit a strong centrality evolution in the lead–lead collisions, which only weakly depends on the charged-particle momentum range. In the proton–lead collisions, the modified Pearson correlation coefficient measured for the second harmonics shows only weak centrality dependence. The data is qualitatively described by the predictions based on the hydrodynamical model.

1 Introduction

The large azimuthal anisotropy observed for particles produced in heavy-ion collisions at RHIC [1–4] and the LHC [5–8] is one of the main signatures of the formation of strongly interacting matter called quark–gluon plasma (QGP). A standard picture of an ultrarelativistic heavy-ion collision is that the initial, asymmetric 'almond' shape of the colliding nuclei's overlap region leads to the formation of pressure gradients in the QGP. These pressure gradients transform the initial shape into an azimuthal anisotropy of the final-state particle distributions through a nearly ideal hydrodynamic evolution and subsequent QGP hadronisation process [9]. The azimuthal anisotropy is customarily decomposed into Fourier components with the amplitude of the n^{th} term denoted by v_n and known as a flow harmonic [10]. Theoretical hydrodynamical models successfully describe observed flow phenomena at low particle transverse momenta [11]. The properties of QGP were recently studied with measurements of correlations between flow harmonics of different order [12–16] as well as with analyses of event shapes [16–20]. It is expected that the magnitudes of the azimuthal flow harmonics [6, 7] should be correlated with the mean transverse momentum $[p_{\text{T}}]$ of the particles on an event-by-event basis [21]. In this paper, that correlation is called the v_n–$[p_{\text{T}}]$ correlation. In proton–lead (p+Pb) collisions, the measurements of multi-particle correlations [22] show evidence of collective phenomena. The spectra of identified particles in p+Pb collisions are consistent with a presence of the radial flow [23] while the nuclear modification factor at high p_{T} approaches unity [24]. It is predicted [25] that in p+Pb collisions the v_n–$[p_{\text{T}}]$ correlation could provide constraints on the initial geometry of the particle source, thereby reducing the overall hydrodynamical modelling uncertainty. Simultaneous measurements of v_n–$[p_{\text{T}}]$ correlations in small and large systems may help disentangle the role of initial conditions and subsequent dynamical QGP evolution in final-state particle distributions.

To measure the strength of the v_n–$[p_{\text{T}}]$ correlation, the Pearson correlation coefficient (PCC) R [25] is used where

$$R = \frac{\text{cov}(v_n\{2\}^2, [p_{\text{T}}])}{\sqrt{\text{Var}(v_n\{2\}^2)}\sqrt{\text{Var}([p_{\text{T}}])}}. \tag{1}$$

The term $v_n\{2\}^2$ is the square of the n^{th}-order flow harmonic obtained using the two-particle correlation method [26], $\text{cov}(v_n\{2\}^2, [p_{\text{T}}])$ is the covariance between $v_n\{2\}^2$ and $[p_{\text{T}}]$, and $\text{Var}(v_n\{2\}^2)$ and $\text{Var}([p_{\text{T}}])$ are the variances of the $v_n\{2\}^2$ and $[p_{\text{T}}]$ distributions, respectively. Experimentally, however, the finite event-by-event charged-particle track multiplicity results in an additional broadening of the $v_n\{2\}^2$ and $[p_{\text{T}}]$ distributions due to statistical fluctuations. Thus, the values of the respective variances are increased, especially for $[p_{\text{T}}]$. The magnitude of this broadening depends on the choice of kinematic region and on detector performance, making direct comparisons between experimental results and with theoretical calculations difficult. To overcome this problem, a modified correlation coefficient ρ, less sensitive to the charged-particle multiplicity than R, was suggested in Ref. [25]. To reduce the auto-correlation effects and those due to the finite charged-particle multiplicity in an event, the variances of the $v_n\{2\}^2$ and $[p_{\text{T}}]$ distributions are replaced by corresponding *dynamical* variables, which are more sensitive to intrinsic initial-state fluctuations. The variance of $v_n\{2\}^2$ is replaced by its dynamical counterpart [27]

$$\text{Var}\big(v_n\{2\}^2\big)_{\text{dyn}} = v_n\{2\}^4 - v_n\{4\}^4 = \langle \text{corr}_n\{4\}\rangle - \langle \text{corr}_n\{2\}\rangle^2, \tag{2}$$

where $\text{corr}_n\{2\}$ and $\text{corr}_n\{4\}$ are the values of two- and four-particle correlations [26] and where angular brackets denote that they are averaged over events. These correlations are described in detail in Section 4.

The variance of $[p_{\text{T}}]$ is replaced by the dynamical p_{T} fluctuation magnitude [28, 29] c_k defined as

$$c_k = \left\langle \frac{1}{N_{\text{pair}}} \sum_i \sum_{j\neq i} (p_{\text{T},i} - \langle [p_{\text{T}}]\rangle)(p_{\text{T},j} - \langle [p_{\text{T}}]\rangle) \right\rangle \tag{3}$$

where $\langle[p_{\mathrm{T}}]\rangle$ is the average $[p_{\mathrm{T}}]$ over the all analysed events. The modified PCC ρ is thus defined as

$$\rho = \frac{\mathrm{cov}(v_n\{2\}^2, [p_{\mathrm{T}}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}}\sqrt{c_k}}. \tag{4}$$

It was demonstrated in Ref. [25] that the ρ coefficient calculated using realistic and finite multiplicities provides a reliable estimate of the true value of R found in the limit of infinite multiplicity, whereas the coefficient R, calculated using Eq. (1) for finite multiplicity underestimates the true value.

The ALICE experiment measured [20] that the charged-particle p_{T} spectrum is correlated with the magnitude of the elliptic flow. It is measured to be harder in collisions with the higher second flow harmonics and softer in collisions where the elliptic flow is smaller. The magnitude of spectra modification is observed to increase with p_{T}, starting to be significant at around 1 GeV and reaching a few percent at around 5 GeV. The modification is found to be most significant in the mid-central collisions, decreasing in the most central ones. The ALICE results suggest that the value of the correlation coefficient should be significant in mid-central and central collisions and that its magnitude and centrality dependence should be sensitive to the scale of intrinsic fluctuations of v_2 and p_{T}. Including particles of higher p_{T} in the measurement is expected to result in increased values of the $\rho(v_2\{2\}^2, [p_{\mathrm{T}}])$. The $[p_{\mathrm{T}}]$ correlations with v_2 in peripheral Pb+Pb collisions, v_3 and v_4 in wide centrality range as well as for the v_2 in high multiplicity p+Pb are unexplored by measurements.

This paper reports on the first measurement of the ρ coefficient with the ATLAS detector in Pb+Pb and p+Pb collisions at a centre-of-mass energy per nucleon pair of 5.02 TeV. The Pb+Pb data sample with a total integrated luminosity of 22 $\mu\mathrm{b}^{-1}$ was collected in 2015, and the p+Pb sample with 28 nb^{-1} in 2013.

This paper is organised as follows. Section 2 gives a brief description of the ATLAS detector. Details of the event selection and charged-particle reconstruction are provided in Section 3. Section 4 describes the analysis procedure for calculating the ρ coefficient. Systematic uncertainties are described in Section 5. Results are presented in Section 6, followed by a summary in Section 7.

2 Experimental setup

The ATLAS experiment [30] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π solid angle coverage. The inner detector (ID) covers the pseudorapidity[1] range $|\eta| < 2.5$ and is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. The ID consists of silicon pixel, silicon microstrip (SCT), and straw tube tracking detectors. After the 2013 p+Pb run, an additional pixel silicon layer, the insertable B-layer [31, 32], was installed prior to the 5.02 TeV Pb+Pb data-taking to attain more precise tracking. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The forward calorimeter (FCal) covers $3.2 < |\eta| < 4.9$ and is used for centrality estimation [10]. The minimum-bias trigger scintillators (MBTS) are located on each side of the detector at $z = \pm 3.6$ m and

[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 z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

detect charged particles with $2.07 < |\eta| < 3.86$. The zero-degree calorimeter (ZDC), located in the LHC tunnel and covering $|\eta| > 8.3$, is used for triggering on collision events and pile-up event rejection. It is calibrated to resolve an individual neutron originating from the collision spectators.

A two-level trigger system selects events [33, 34]. The level-1 trigger is implemented in hardware and preselects up to 10^5 events per second for further decisions by the high-level trigger (HLT). The software-based HLT tuned for Pb+Pb collision data selects up to 1000 events per second for recording. This analysis primarily uses charged-particle tracks in the ID, but information from the central calorimeters and the ZDC is also used for triggering, event selection, and analysis.

3 Event and track selection

The Pb+Pb data in this analysis were selected using two mutually exclusive minimum-bias triggers. Events with semi-central and central collisions were selected if the scalar sum of transverse energy in the entire ATLAS calorimeter system exceeded 50 GeV. Peripheral events, i.e. those with large impact parameter of the colliding Pb nuclei, fail the 50 GeV selection and were instead selected by requiring a deposition in the ZDC corresponding to at least one neutron and by requiring at least one track reconstructed in the HLT. Data in this analysis are required to come from periods when the entire detector was functioning normally. The events are required to have a reconstructed vertex within 100 mm of the nominal interaction point. The contribution from events containing more than one inelastic interaction (pile-up) is studied by exploiting correlations between the transverse energy measured in the FCal ($\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$) with the estimated number of neutrons in the ZDC, and with the number of tracks associated with a primary vertex [22, 35]. The distribution of $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ and the distribution of the number of neutrons in events with more than one collision are broader than the corresponding distributions in events with only one collision. Pile-up events are suppressed by rejecting events with abnormally large values of either $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ or the number of neutrons in the ZDC compared with the charged-particle multiplicity in the event. Approximately 0.2% of the events are rejected by these requirements.

The p+Pb data in this analysis were selected using minimum-bias triggers and high-multiplicity triggers (HMT). The minimum-bias trigger required signals in both sides of the MBTS system with a timing difference of less than 10 ns to eliminate non-collision backgrounds. The HMT required the total transverse energy in the calorimeter at level-one and the number of ID track candidates reconstructed in the HLT to be above predefined thresholds. Six combinations of thresholds were used to optimise data-taking during periods with different luminosities. Samples of events collected by these triggers are combined by applying event weights to reproduce the charged-particle multiplicity distribution of the minimum-bias trigger. Further details of the data selection are given in Refs. [22, 36]. The average pile-up probability in the p+Pb dataset is approximately 3% but can be significantly larger in high-multiplicity events. Events with more than one reconstructed vertex are removed from the sample. Similarly to the Pb+Pb dataset, to remove events where the two interaction vertices are too close to resolve as independent ones, the ZDC signal on the Pb fragmentation side is used. The distribution of the number of neutrons, which is broader in events with pile-up than that for the events without pile-up is exploited for that purpose [36]. The fraction of rejected events varies with the event activity and reaches a maximum of 10% for events with the highest multiplicities.

The analysis for both collision systems is performed in narrow bins of event activity defined by the charged-particle multiplicity N_{ch} (described in Section 4), which estimates the collision centrality. In addition, the Pb+Pb results are presented as a function of collision centrality expressed by the average number of

nucleons participating in the collision, N_{part}, to allow comparison with theoretical predictions [37]. The centrality is estimated from the $\Sigma E_{\text{T}}^{\text{FCal}}$ distribution [6, 10] using the Glauber model [38]. The number of events passing the selection requirements is 1.3×10^8 for Pb+Pb within the 0–80% centrality interval. For the p+Pb system, about 0.64×10^8 events enter the analysis.

The charged-particle tracks reconstructed in the ID are required to satisfy selection criteria in order to suppress the contribution of incorrectly reconstructed tracks and secondary products of particle decays. The selection criteria include the requirement that the number of hits in the pixel and SCT detectors should greater than two and eight, respectively, for the Pb+Pb data and greater than one and six for the p+Pb data. The track impact parameters relative to the collision vertex in the transverse direction, $|d_0|$, and longitudinal direction, $|z_0 \sin\theta|$, are required to be less than 1 mm for tracks in the Pb+Pb data sample and less than 1.5 mm in the p+Pb sample. In addition, in p+Pb collisions, the track impact parameter significances must satisfy $|d_0/\sigma_{d_0}| < 3$ and $|z_0 \sin\theta/\sigma_z| < 3$, where σ_{d_0} and σ_z are the uncertainties in d_0 and $z_0 \sin\theta$ determined from the covariance matrix of the track fit. The different selection criteria for Pb+Pb and p+Pb optimise the performance of the track reconstruction in differing running conditions.

Corrections needed due to track reconstruction effects are evaluated using $4{\times}10^6$ Pb+Pb and 10^7 p+Pb minimum-bias Monte Carlo (MC) events generated by the HIJING v1.38b [39] event generator. After the generation, an azimuthal flow is implemented using the afterburner technique [40], and the p_{T} spectrum is reweighted to match the data. Generated events were simulated in the detector by the GEANT 4-based [41] ATLAS detector simulation programs [42] and reconstructed using the same procedures and detector conditions as the data. Track reconstruction corrections are applied to each selected track using weights to account for the tracking efficiency ϵ and the fake-track fraction f. The efficiency is defined as the fraction of primary MC charged particles that are matched to reconstructed tracks, and f is the fraction of tracks that are not matched to primary MC particles or are produced from random combinations of hits in the ID. A similar analysis procedure is described in Refs. [10, 16]. The fake-track fraction and tracking efficiency are determined as functions of the track p_{T} and η and of the track multiplicity in the event. Tracks included in the analysis are weighted with the factor $(1 - f)/\epsilon$. An additional multiplicative weight evaluated from data is applied to the data to correct for detector non-uniformity in the azimuthal angle. These weights are obtained by requiring the tracks to be distributed uniformly in azimuth in all pseudorapidity slices of width 0.1.

In the Pb+Pb data, the contribution of fake tracks is largest in central collisions at the lowest analysed track p_{T} of 0.5 GeV and at the largest $|\eta|$, reaching up to 20%. The fake-track rate is below 1% for tracks with p_{T} above 2 GeV and $|\eta| < 1.5$. The tracking efficiency depends weakly on centrality, and in the most central events it is about 3% less than in more peripheral events. The efficiency increases with the track p_{T} from about 50% at the lowest analysed p_{T} to 70% above 2 GeV. It is highest at mid-rapidity and drops by about 15% for $|\eta| > 1$. For p+Pb collisions, with p_{T} increasing from 0.3 to 1 GeV the efficiency increases from about 75% (60%) to 83% (70%) at $\eta \approx 0$ ($|\eta| > 2$). The p+Pb tracking efficiency is independent of the event's multiplicity for $N_{\text{ch}} \geq 10$, i.e. in the multiplicity range used in the analysis. The fake rate in p+Pb collisions is very low, below 1% (3%) at $\eta \approx 0$ ($|\eta| > 2$).

4 Correlation coefficient ρ

In each event, charged-particle tracks are grouped into three regions of subevents based on their pseudorapidity: region A with $-2.5 < \eta < -0.75$, central region B with $|\eta| < 0.5$ and region C with $0.75 < \eta < 2.5$. The v_n^2 for the $n = 2$–4 harmonics are calculated by correlating charged-particle tracks from subevents A and

C, which are separated in pseudorapidity to suppress non-flow contributions. Tracks in central region B are used to obtain the mean value of the charged-particle transverse momentum in the event, $[p_{\mathrm{T}}]$, defined as

$$[p_{\mathrm{T}}] = \frac{1}{\sum_b w_b} \sum_b w_b p_{\mathrm{T}b}$$

where the summation is over tracks in region B, labelled by index b. The variable c_k (Eq. (3)) is also calculated using tracks from region B. Here, and in following formulas, the weights w include the fake-track fraction, efficiency, and azimuthal non-uniformity corrections, as discussed in Section 3.

The covariance term from the numerator of Eq. (4) is defined as

$$\mathrm{cov}(v_n\{2\}^2, [p_{\mathrm{T}}]) = \mathrm{Re}\Big(\Big\langle \frac{1}{\sum_{a,c} w_a w_c} \sum_{a,c} w_a w_c \mathrm{e}^{\mathrm{i}n\phi_a - \mathrm{i}n\phi_c} ([p_{\mathrm{T}}] - \langle [p_{\mathrm{T}}] \rangle) \Big\rangle\Big), \tag{5}$$

where ϕ is the azimuthal angle and indices a and c span the tracks in regions A and C, respectively.

The two- and four-particle correlations used to define the dynamical variance in Eq. (2), which enters the denominator of Eq. (4), are calculated as in Ref. [26]

$$\langle \mathrm{corr}_n\{2\} \rangle = \mathrm{Re}\Big(\Big\langle \frac{1}{\sum_{a,c} w_a w_c} \sum_{a,c} w_a w_c \mathrm{e}^{\mathrm{i}n\phi_a - \mathrm{i}n\phi_c} \Big\rangle\Big) = \mathrm{Re}\big(\langle q_{n,a} q^*_{n,c} \rangle\big) \tag{6}$$

where the q_a and q_c are the complex flow vectors of subevent A and subevent C, respectively, and the asterisk denotes the complex conjugate. The flow vectors are

$$q_{n,a} = \frac{1}{\sum_a w_a} \sum_a w_a \mathrm{e}^{\mathrm{i}n\phi_a} \qquad \text{and} \qquad q_{n,c} = \frac{1}{\sum_c w_c} \sum_c w_c \mathrm{e}^{\mathrm{i}n\phi_c}.$$

The four-particle correlation is obtained from the expression

$$\langle \mathrm{corr}_n\{4\} \rangle = \mathrm{Re}\Big(\Big\langle \frac{(Q^2_{n,a} - Q_{2n,a})(Q^2_{n,c} - Q_{2n,c})^*}{S_a S_c} \Big\rangle\Big), \tag{7}$$

where for subevent A

$$Q_{n,a} = \sum_a w_a \mathrm{e}^{\mathrm{i}n\phi_a}, \qquad Q_{2n,a} = \sum_a w_a^2 \mathrm{e}^{\mathrm{i}2n\phi_a}, \qquad S_a = \Big(\sum_a w_a\Big)^2 - \sum_a {w_a}^2,$$

and similarly for subevent C. Equation (7) represents the sum $\sum \mathrm{e}^{\mathrm{i}n(\phi_1^a + \phi_2^a - \phi_3^c - \phi_4^c)}$ over all particles from subevents A and C normalised by the number of quadruplets without auto-correlations in each subevent.

The second factor in the denominator of Eq. (4), the mean p_{T} fluctuation in the event class c_k, is defined by Eq. (3) and in this analysis it is calculated as

$$c_k = \Big\langle \frac{1}{(\sum_b w_b)^2 - \sum_b w_b^2} \sum_b \sum_{b' \neq b} w_b (p_{\mathrm{T},b} - \langle [p_{\mathrm{T}}] \rangle) w_{b'} (p_{\mathrm{T},b'} - \langle [p_{\mathrm{T}}] \rangle) \Big\rangle.$$

The summation indices b and b' run over all charged particles in region B.

The correlation coefficient expressed by Eq. (4) is evaluated for the range $0.5 < p_{\mathrm{T}} < 2$ GeV in Pb+Pb collisions and $0.3 < p_{\mathrm{T}} < 2$ GeV in p+Pb collisions. These intervals, called 'main', contain a large number

of soft particles and constitute the main result of the analysis which can be compared with hydrodynamical models. For each system, two additional p_{T} ranges are considered: $0.5 < p_{\mathrm{T}} < 5$ GeV and $1 < p_{\mathrm{T}} < 2$ GeV in the analysis of Pb+Pb collisions, and $0.3 < p_{\mathrm{T}} < 5$ GeV and $0.5 < p_{\mathrm{T}} < 2$ GeV in p+Pb collisions. These ranges facilitate the study of the sensitivity of $\rho(v_n\{2\}^2, [p_{\mathrm{T}}])$ to the high p_{T} part of the particle spectrum and to the lower charged-particle multiplicity from the higher minimum p_{T} value. The charged-particle p_{T} range $0.5 < p_{\mathrm{T}} < 2$ GeV is common to both systems and can be used to compare the $\rho(v_2\{2\}^2, [p_{\mathrm{T}}])$ results from Pb+Pb and p+Pb collisions.

The quantities of interest, i.e. $\mathrm{cov}(v_n\{2\}^2, [p_{\mathrm{T}}])$, $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$, c_k, and $\rho(v_n\{2\}^2, [p_{\mathrm{T}}])$, are determined in bins of reconstructed track multiplicity M_{AC} measured in the combination of regions A and C. This is done to avoid a negative correlation between the multiplicity in subevents A+C and B that occurs if the analysis is binned in multiplicity in the entire ID. Narrow M_{AC} bins are also chosen due to the sensitivity to multiplicity fluctuations of the multi-particle correlations that are used to obtain the $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$ [27]. The events are grouped in fine bins with a width of ten in M_{AC} for $0.5 < p_{\mathrm{T}} < 5$ GeV in the Pb+Pb analysis and $0.3 < p_{\mathrm{T}} < 5$ GeV in the p+Pb analysis. It was cross-checked that the variables of interest obtained with a finer binning in M_{AC} are consistent with the measurement with the nominal binning.

To enable comparisons with the theoretical predictions and with future experimental results, measurements obtained in M_{AC} are presented as a function of the ATLAS ID multiplicity N_{ch} of $0.5 < p_{\mathrm{T}} < 5$ GeV and $|\eta| < 2.5$. They are projected from the M_{AC} values taking into account tracking efficiency and fake-track production as described in the previous section. A similar analysis procedure is described in Ref. [22]. For the N_{part} dependencies in the Pb+Pb system, the results measured in M_{AC} multiplicity intervals are averaged, with weights equal to the probabilities to find any given M_{AC} value in the centrality intervals.

The formulation of the modified PCC $\rho(v_n\{2\}^2, [p_{\mathrm{T}}])$ requires that there should be at least two tracks in each region (A, B, and C). Further, $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$ calculated according to Eq. (6) can be negative at low multiplicities due to statistical fluctuations, which renders Eq. (4) invalid because of the $\sqrt{\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}}$ term. For each M_{AC} bin, p_{T} interval, and harmonic, a criterion is applied that $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$ needs to be positive at a level of at least one standard deviation of its statistical uncertainty. Results presented as a function of N_{ch} are produced only for those M_{AC} intervals. For the N_{part} dependencies in the Pb+Pb system, it is additionally required for each centrality interval that the fraction of rejected events due to this criterion does not exceed 1%.

5 Systematic uncertainties

The systematic uncertainty is estimated by varying individual aspects of the analysis. The systematic uncertainties for the main p_{T} interval are discussed for each collision system. Systematic uncertainties for the other p_{T} intervals behave consistently with the ones for the main p_{T} interval. Since the modified PCC $\rho(v_n\{2\}^2, [p_{\mathrm{T}}])$ is a ratio of quantities which are calculated using tracks, many variations largely cancel out and the resulting systematic uncertainties are small. To suppress the statistical fluctuations and to get more robust estimation of systematic uncertainties, they are averaged over several, wide ranges of the charged-particle multiplicity. For each uncertainty source and for each measurement point, the maximum variation from the baseline measurement is used. The total resulting uncertainty is the sum of the individual contributions combined in quadrature. The following sources of systematic uncertainties are considered.

Track selection. The tracking performance has a relatively small impact on $v_n\{2\}$, but it directly affects the $[p_{\mathrm{T}}]$ and c_k via the admixture of the fake tracks, especially at low p_{T}. To assess the impact on $\rho(v_n\{2\}^2, [p_{\mathrm{T}}])$,

the measurement is repeated with tracks selected with looser and tighter track quality criteria, thus increasing and decreasing the fake-track rate, respectively. The weights used in the evaluation of measured quantities take the modified selection into account. The loose track selection in the Pb+Pb analysis relaxes requirements on the number of pixel and SCT hits to at least one and six, respectively. Additionally, the requirements on the transverse and longitudinal impact parameters of the track are relaxed to 1.5 mm. The tighter selection in the Pb+Pb analysis tightens the requirement on the transverse and longitudinal impact parameters of the track to 0.5 mm. For the p+Pb analysis, the loose selection relaxes the requirements on the transverse and longitudinal impact parameters of the track to 2 mm and on the impact parameter significances to less than 4. In the tight selection, the impact parameter values and their significances must be less than 1 mm and 2, respectively. The largest absolute difference $|\rho(v_n\{2\}^2, [p_\mathrm{T}])^{\mathrm{base}} - \rho(v_n\{2\}^2, [p_\mathrm{T}])^{\mathrm{loose}}|$ or $|\rho(v_n\{2\}^2, [p_\mathrm{T}])^{\mathrm{base}} - \rho(v_n\{2\}^2, [p_\mathrm{T}])^{\mathrm{tight}}|$ is taken as the systematic uncertainty.

Detector material. Since the tracks that are used in the calculation of $\rho(v_n\{2\}^2, [p_\mathrm{T}])$ are weighted by the inverse of the tracking efficiency, a bias in its estimation due to inaccurate modelling of the material in the detector may change the balance between low- and high-p_T tracks in the sums. Based on simulations, the estimated uncertainty in the detector description is obtained [43, 44]. The resulting p_T- and η-dependent uncertainties in the track efficiency of up to 4% are used to determine the systematic uncertainty.

Tracking azimuthal uniformity. In this analysis, the weighting factors w correct for any non-uniformity in the azimuthal angle distribution of reconstructed tracks. The weights are obtained from the data by requiring azimuthal uniformity over the two-dimensional distribution of reconstructed tracks in the η–ϕ plane. The effect of that correction on the result is conservatively estimated by comparing the baseline measurement and the measurement obtained without applying this weight.

Reaction plane asymmetry. The imaginary part associated with the $\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])$ term defined in Eq. (5), and thus the imaginary part associated with $\rho(v_n\{2\}^2, [p_\mathrm{T}])$, referred to as the sine term, quantifies the detector resolution for measuring flow harmonics [6, 27]. In an ideal detector, the sine term should be zero due to symmetry of the collision zone with respect to the reaction plane. Its deviation from zero is considered as an estimate of the systematic uncertainty on the real part, used to measure the variables of interest.

Residual pile-up events. The selection criteria discussed in Section 3 suppress the fraction of pile-up events accepted for analysis to almost zero in central collisions. To estimate the systematic uncertainty related to pile-up, the measurement is conservatively repeated without this event rejection, resulting in at most a 1% difference in the most central events for the $\rho(v_2\{2\}^2, [p_\mathrm{T}])$ coefficient. The p+Pb data were taken with higher pile-up than the Pb+Pb data. To estimate the impact of contamination by residual pile-up events, results were obtained with only the vertex criteria applied. The variation covers the estimated residual pileup fraction in events of the highest track multiplicity [36].

Centrality selection. The minimum-bias trigger is fully efficient for the 0–85% centrality interval. However, the total fraction of inelastic Pb+Pb events selected is known only to 1% accuracy due to trigger inefficiency and possible sample contamination in more peripheral interactions. Centrality selection requirements are altered to account for N_part dependencies of this uncertainty. The centrality selection contributes mainly to uncertainties for peripheral collisions.

Figure 1 shows the magnitude of the systematic uncertainties $\delta\rho(v_n\{2\}^2, [p_\mathrm{T}])$ for n = 2–4 in Pb+Pb collisions as a function of N_ch. In Pb+Pb collisions, the systematic uncertainty of the measured correlation coefficients across different order harmonics and centralities is not dominated by a single source. One of the largest uncertainties comes from restoring the azimuthal uniformity, and dominates for the second and the third harmonics in the most central collisions. A sizeable contribution to the uncertainty for all

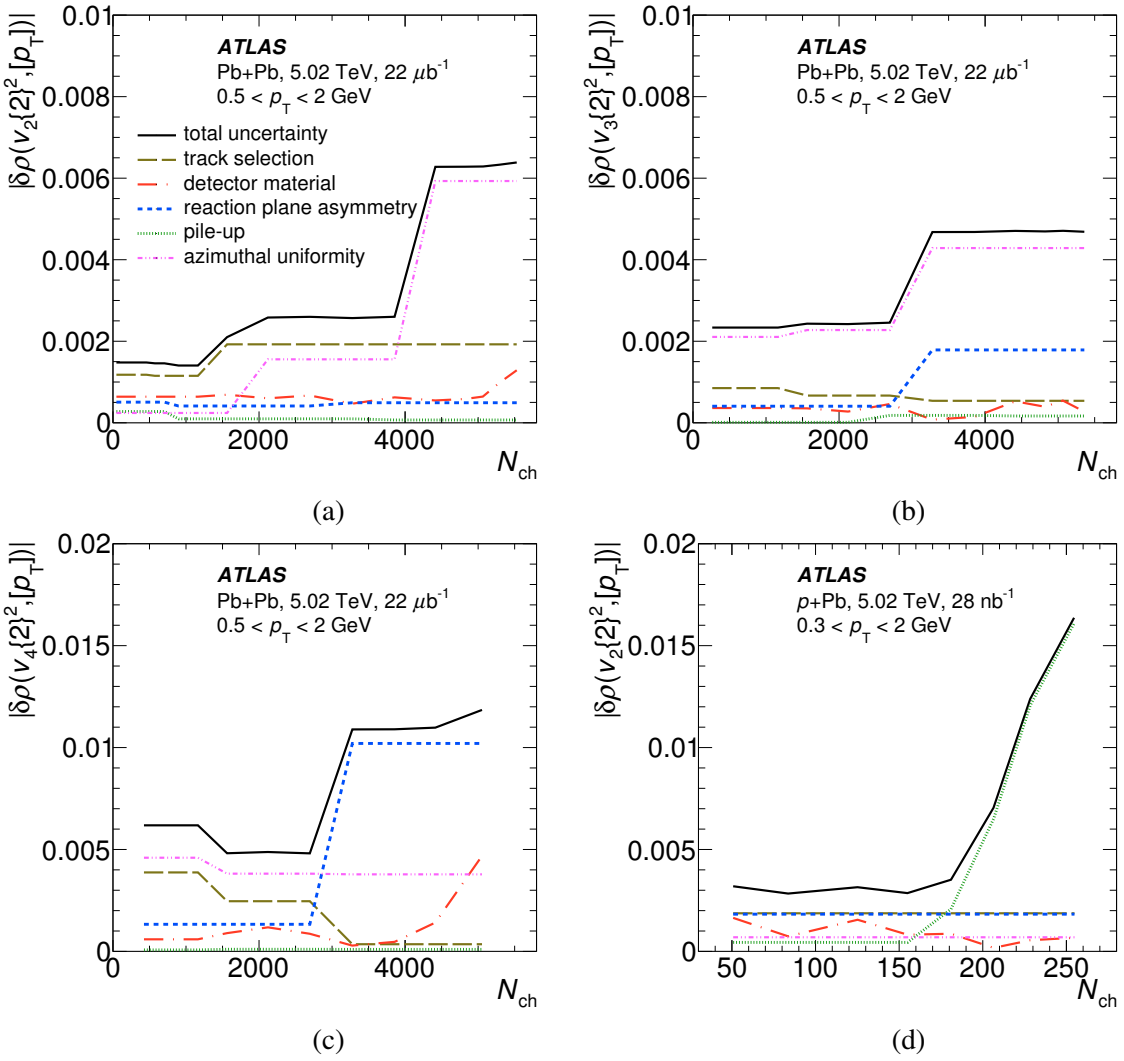

Figure 1: The systematic uncertainty of $\rho(v_n\{2\}^2, [p_{\mathrm{T}}])$ as a function of N_{ch} measured with tracks from main p_{T} intervals for each collision system for the (a) second, (b) third, and (c) fourth harmonics in Pb+Pb collisions, and for (d) $\rho(v_2\{2\}^2, [p_{\mathrm{T}}])$ in p+Pb collisions. The total uncertainty is also shown.

three harmonics in central collisions is due to the reaction plane asymmetry. The residual pile-up in Pb+Pb collisions gives a negligible contribution. Figure 1(d) shows systematic uncertainties for $\rho(v_2\{2\}^2, [p_{\mathrm{T}}])$ coefficients in p+Pb collisions for the main interval of $0.3 < p_{\mathrm{T}} < 2$ GeV as a function of event activity. In p+Pb interactions the largest uncertainty in the most active collisions ($N_{\mathrm{ch}} > 150$) originates from pile-up. Sources of sizeable uncertainties for this collision system are the track selection and the reaction plane asymmetry, while the azimuthal uniformity correction procedure has a marginal impact.

6 Results

6.1 The constituents of the modified PCC

The constituents of the modified PCC include c_k , $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$ and $\mathrm{cov}(v_n\{2\}^2, [p_{\mathrm{T}}])$ and are combined, using Eq. (4), to obtain ρ. Figure 2 shows the dynamical p_{T} fluctuation coefficient c_k as a function of charged-particle multiplicity in Pb+Pb and p+Pb collision systems for tracks in three different p_{T} intervals. A strong decrease of c_k with increasing N_{ch} is observed in all measured results. A similar decrease was observed in Au+Au and Pb+Pb data at lower centre-of-mass energies [28, 29]. For the same N_{ch}, the c_k values differ by an order of magnitude for different p_{T} ranges of tracks used in the analysis. For the intervals with the same lower p_{T} limit, the c_k values are higher for the interval with the larger upper p_{T} limit.

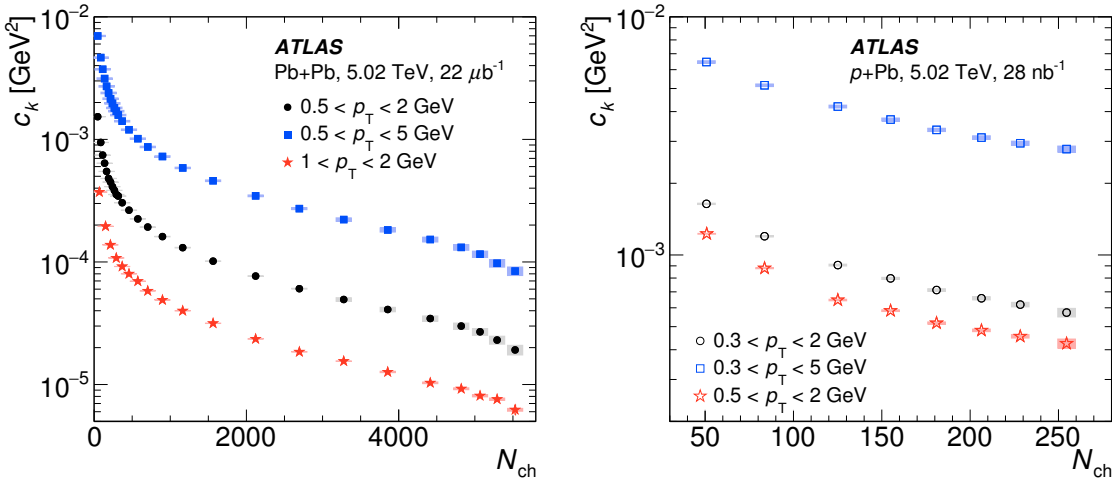

Figure 2: The variable c_k for three p_{T} ranges as a function of the charged-particle multiplicity N_{ch} of (a) Pb+Pb and (b) p+Pb collisions. The statistical and systematic uncertainties are shown as vertical error bars (smaller than symbols) and boxes, respectively.

Figure 3 shows $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$ for n = 2–4 as function of N_{ch} for Pb+Pb collisions. After increasing with N_{ch} for low multiplicities a maximum is reached at N_{ch} approximately 500 or 1000 for n = 2 and n = 3, respectively. At higher N_{ch} values the variances decrease with multiplicity. The dynamical variance for n = 4, measured for $N_{\mathrm{ch}} \gtrapprox 500$, decreases with increasing N_{ch}. The ordering $\mathrm{Var}(v_2\{2\}^2)_{\mathrm{dyn}} > \mathrm{Var}(v_3\{2\}^2)_{\mathrm{dyn}} > \mathrm{Var}(v_4\{2\}^2)_{\mathrm{dyn}}$ and the multiplicity dependence of $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$ are similar to the ordering and centrality dependence of $v_n\{2\}$ measured by ATLAS [10]. Also shown in Figure 3 is $\mathrm{Var}(v_2\{2\}^2)_{\mathrm{dyn}}$ for p+Pb collisions as a function of N_{ch}. The dependence is monotonic, similarly to $v_2\{2\}$ [45]. In both collision systems and for all harmonics, the same ordering of $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$ depending on the p_{T} interval is observed. The largest variances are observed for the p_{T} intervals with an increased lower limit. This is expected as the $v_n\{2\}$ value increases strongly with p_{T} below 3 GeV [10]. Additionally, the interval in which the upper limit on p_{T} is set to 5 GeV integrates the region with the highest values of $v_n\{2\}$ (which occur around 3 GeV) and thus the values of the variance are expected to be larger than that for the main p_{T} range.

In Figure 4, the covariances $\mathrm{cov}(v_n\{2\}^2, [p_{\mathrm{T}}])$ are shown for the 2$^{\mathrm{nd}}$-, 3$^{\mathrm{rd}}$-, and 4$^{\mathrm{th}}$-order harmonics in Pb+Pb collisions and for the second-order harmonics in p+Pb collisions. They are presented as a function

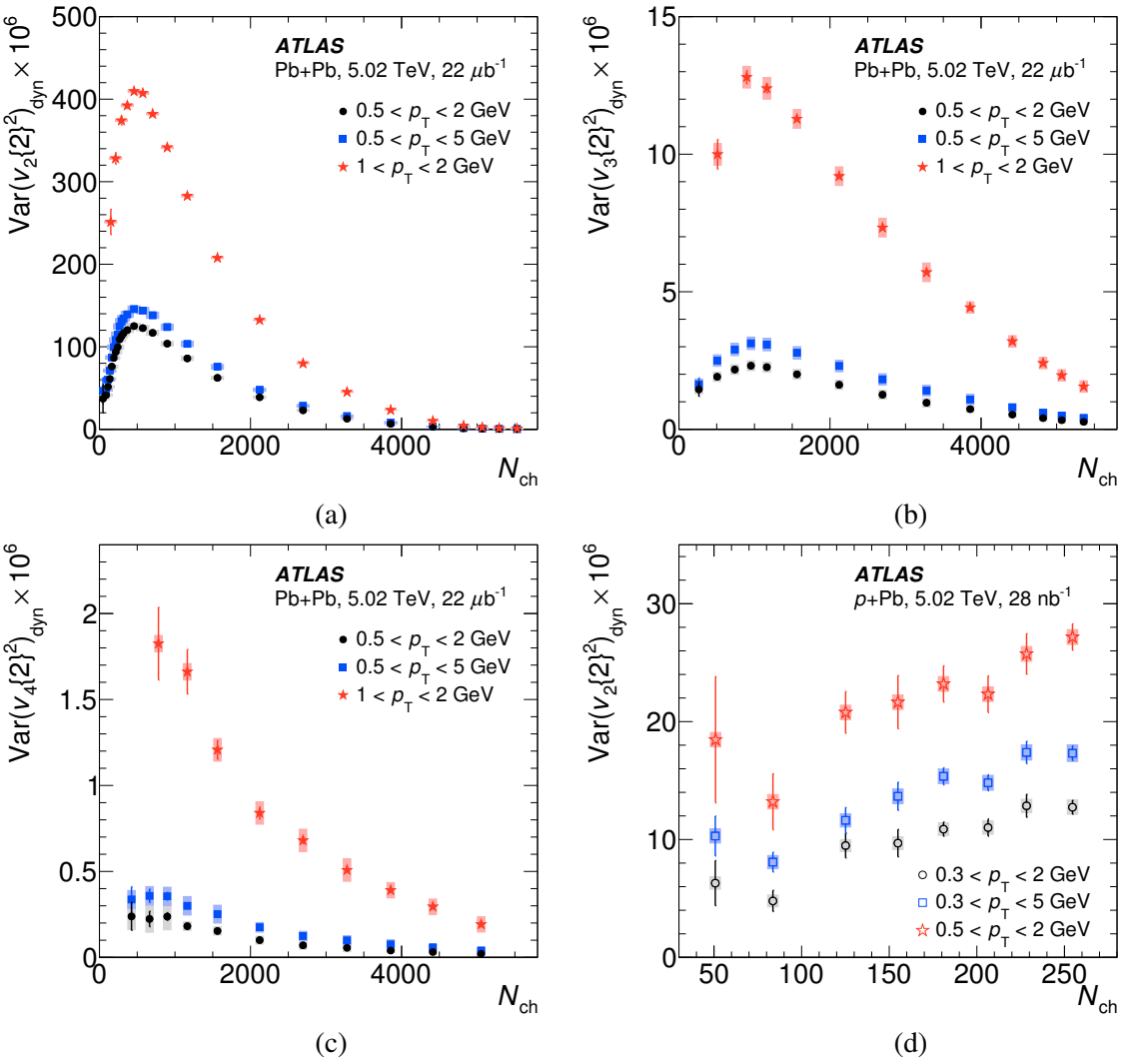

Figure 3: The variance $\mathrm{Var}(v_n\{2\}^2)_{\mathrm{dyn}}$ for n = 2–4 for (a)–(c) Pb+Pb collisions and $\mathrm{Var}(v_2\{2\}^2)_{\mathrm{dyn}}$ for (d) p+Pb collisions for the three p_{T} intervals as a function of charged-particle multiplicity N_{ch}. The statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively.

of N_{ch} for three p_{T} intervals. Significant positive correlations between $v_n\{2\}$ and $[p_{\mathrm{T}}]$ are observed in the Pb+Pb events. The measured covariances depend on the charged-particle multiplicity and the p_{T} range of the charged particles. In Pb+Pb collisions, a strong dependence on the multiplicity is observed for $n = 2$ and 4. The $\mathrm{cov}(v_3\{2\}^2, [p_{\mathrm{T}}])$ depends only weakly on N_{ch}. A negative $\mathrm{cov}(v_2\{2\}^2, [p_{\mathrm{T}}])$ is measured at multiplicities $N_{\mathrm{ch}} < 200$ and a negative $\mathrm{cov}(v_3\{2\}^2, [p_{\mathrm{T}}])$ for $1 < p_{\mathrm{T}} < 2$ GeV below $N_{\mathrm{ch}} < 1800$. The covariances $\mathrm{cov}(v_2\{2\}^2, [p_{\mathrm{T}}])$ in p+Pb events are negative in the entire measured N_{ch} range and show weak N_{ch} dependence. Unlike in Pb+Pb events, the $\mathrm{cov}(v_2\{2\}^2, [p_{\mathrm{T}}])$ in p+Pb events have similar magnitudes for different p_{T} intervals.

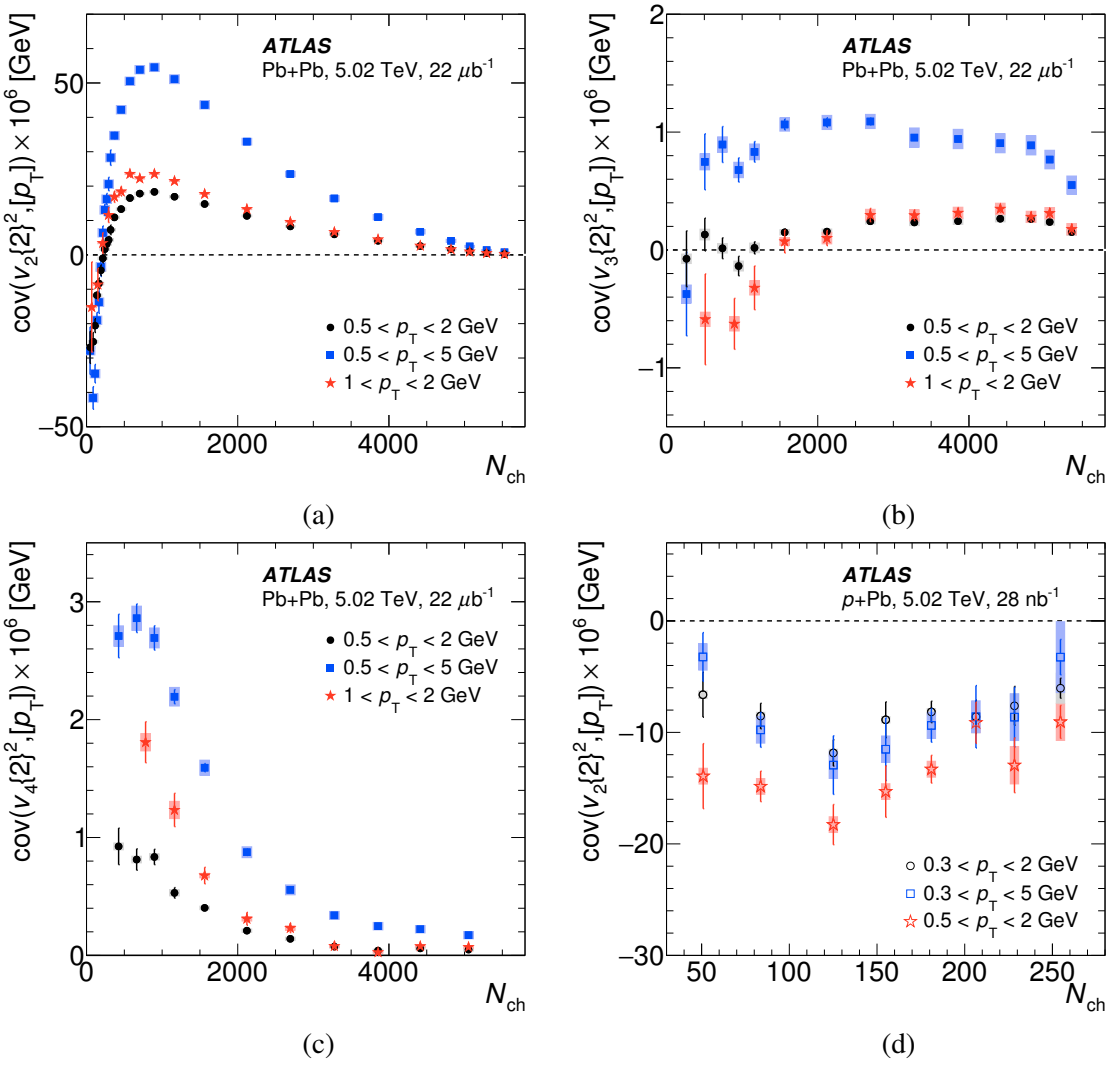

Figure 4: The covariance $\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])$ for n = 2–4 in (a)–(c) Pb+Pb collisions and $\mathrm{cov}(v_2\{2\}^2, [p_\mathrm{T}])$ in (d) p+Pb collisions for three p_T ranges as a function of the charged-particle multiplicity N_ch. The statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively.

6.2 The modified PCC

The modified PCC $\rho(v_n\{2\}^2, [p_\mathrm{T}])$ for n = 2–4 in Pb+Pb collisions and for n = 2 in p+Pb collisions is shown in Figure 5. In Pb+Pb collisions, the behaviour of $\rho(v_2\{2\}^2, [p_\mathrm{T}])$ is similar for all p_T intervals. It starts at negative values for $N_\mathrm{ch} < 200$ and rapidly increases with multiplicity up to ~1500 particles where the increase slows down and reaches the maximum of 0.24–0.3, depending on the p_T interval, at $N_\mathrm{ch} \approx 4500$. At even higher N_ch, the $\rho(v_2\{2\}^2, [p_\mathrm{T}])$ value decreases rapidly. The significant correlation observed for mid-central events suggests a connection between anisotropic and radial [46] flows which might be attributed to stronger hydrodynamic response (larger pressure gradients) to the large initial-state eccentricities [47]. The decrease observed in central collisions, for $N_\mathrm{ch} \gtrsim 5000$, could be related to the increased role of initial-state fluctuations in anisotropic flow [27]. The correlation coefficients calculated with the upper p_T limit of 2 GeV are 10–20% smaller than the values obtained with a p_T limit of 5 GeV.

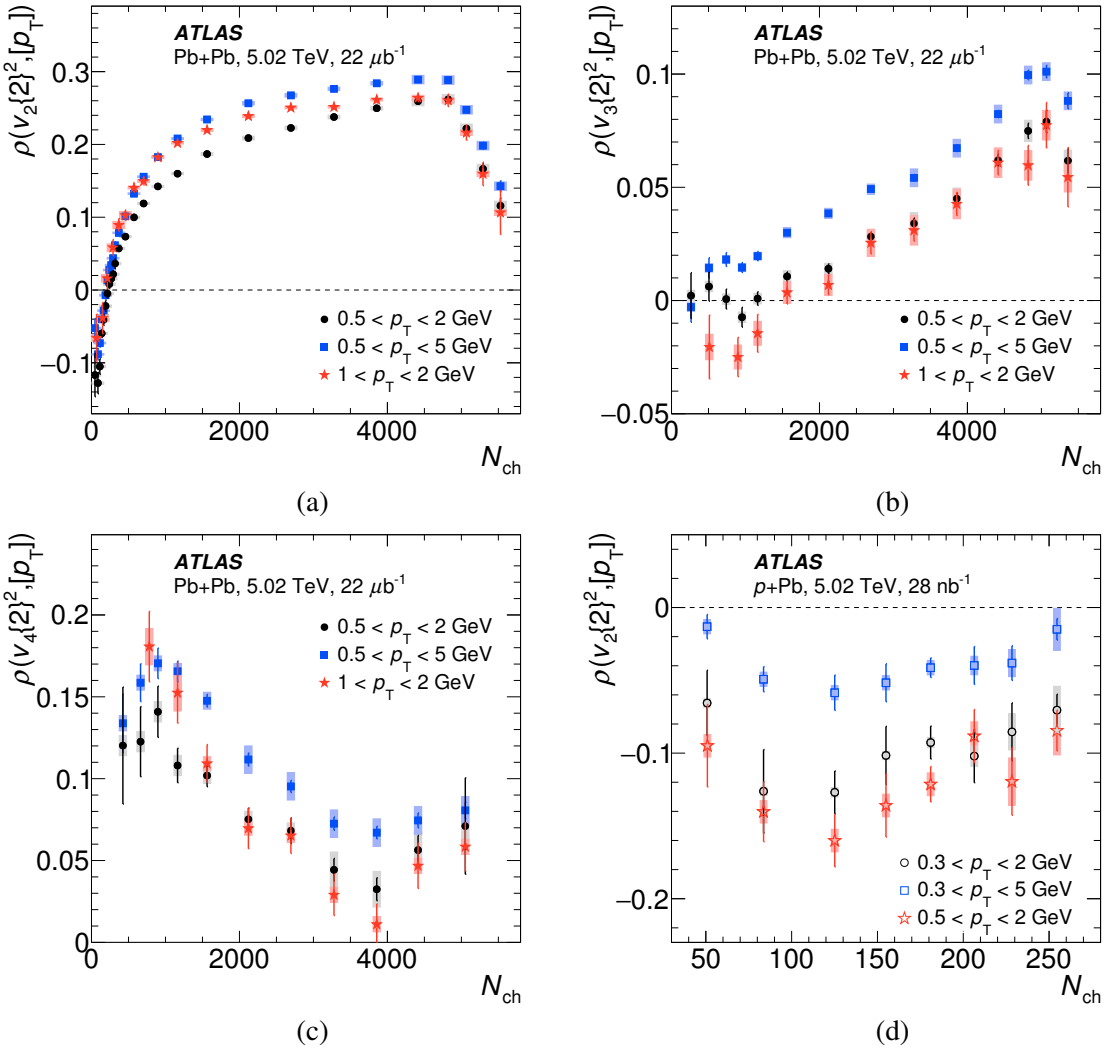

Figure 5: The PCC $\rho(v_n\{2\}^2, [p_T])$ for n = 2–4 in (a)–(c) Pb+Pb collisions and (d) p+Pb collisions as a function of the charged-particle multiplicity N_{ch} for three p_T ranges. The statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively.

The correlation coefficient $\rho(v_3\{2\}^2, [p_T])$ is evaluated in Pb+Pb collisions for the same three p_T ranges. All three curves generally show the increase with N_{ch} in the entire range of the measurement. However, for the main interval of $0.5 < p_T < 2$ GeV, this increase starts at $N_{ch} \sim 1500$, and below it the PCC is consistent with zero. At around the same multiplicity the $1 < p_T < 2$ GeV interval curve crosses zero. Above this value, the curves for the two intervals with the same maximum p_T are consistent with each other and are below the curve for the interval which uses tracks with p_T up to 5 GeV. The magnitudes measured for $\rho(v_3\{2\}^2, [p_T])$ are significantly smaller than those measured for $\rho(v_2\{2\}^2, [p_T])$ and similar to the magnitudes of $\rho(v_4\{2\}^2, [p_T])$. The largest values of $\rho(v_4\{2\}^2, [p_T])$ are observed at $N_{ch} \approx 1000$. For high N_{ch}, $\rho(v_4\{2\}^2, [p_T])$ decreases with N_{ch} up to about $N_{ch} \approx 4000$ and rises slowly at higher values. The decrease for $N_{ch} < 4000$ is expected due to a contribution to v_4 from a non-linear term containing v_2^2, decreasing with increasing centrality [13]. Similarly to the $\rho(v_3\{2\}^2, [p_T])$, the $\rho(v_4\{2\}^2, [p_T])$ correlations measured with the larger upper p_T limit have larger magnitudes. The results for the larger upper p_T

limit show the sensitivity of the $\rho(v_n\{2\}^2, [p_T])$ coefficients to the high p_T part of the particle spectrum contaminated with non-flow correlations from jets. On the other hand, the correlations measured for the intervals with fixed upper p_T limit (2 GeV) and varied lower p_T limits are similar, demonstrating insensitivity of the modified PCC coefficients to a significant change of the event charged-particle multiplicity as expected [25]. The fourth-order correlations are weaker than those for the second-order flow harmonic and for $N_{ch} > 4000$ are comparable to $\rho(v_3\{2\}^2, [p_T])$. The results for all harmonics indicate a change in the trend in events with high N_{ch} around 4500, which suggests a change in the nature of the correlations in those events [47]. In p+Pb collisions, $\rho(v_2\{2\}^2, [p_T])$ exhibits weak N_{ch} dependence and is negative in the whole range of measured N_{ch}. Values for different lower p_T limits are similar, and the $\rho(v_2\{2\}^2, [p_T])$ magnitudes for the larger upper p_T limit are smaller.

6.3 Comparison of p+Pb and Pb+Pb results

Figure 6 shows a comparison of p+Pb and Pb+Pb results shown in Figs. 2–5 for the common p_T interval of $0.5 < p_T <$ GeV. The values of the c_k (Figure 6(a)) are similar for p+Pb and Pb+Pb collisions in this p_T interval, while the behaviour of the dynamical variance $\mathrm{Var}(v_2\{2\}^2)_{dyn}$ (Figure 6(b)) is very different due to the different overlap regions in Pb+Pb and p+Pb collisions. Only a small rise with the multiplicity is observed for p+Pb collisions, which is in agreement with a slow increase of $v_2\{2\}$ with growing event activity [22, 36, 45]. For $N_{ch} \approx 50$, the dynamical variances are comparable between Pb+Pb and p+Pb collisions. The N_{ch} dependence of $\mathrm{cov}(v_2\{2\}^2, [p_T])$ is significantly different for Pb+Pb and p+Pb collisions. A steady rise from negative to positive values with N_{ch} is observed for peripheral Pb+Pb collisions, and approximately constant values are obtained for p+Pb collisions. The N_{ch} dependence of $\rho(v_2\{2\}^2, [p_T])$ is different for the two collision systems. In p+Pb collisions, the modified PCC assumes a value of approximately -0.1 and is constant within uncertainties. For $N_{ch} < 100$ the values of $\rho(v_2\{2\}^2, [p_T])$ are consistent between Pb+Pb and p+Pb collisions. The negative $\rho(v_2\{2\}^2, [p_T])$ coefficients for the small systems in p+Pb and Pb+Pb collisions may suggest a more compact source model [25]. The comparison of the systems underlines the importance of the initial stage in the correlations described by the $\rho(v_2\{2\}^2, [p_T])$ coefficient.

6.4 Comparison to theoretical predictions

To compare the Pb+Pb results with a theoretical prediction in Ref. [25], the $\rho(v_n\{2\}^2, [p_T])$ coefficients for $0.5 < p_T < 2$ GeV are obtained as a function of centrality intervals expressed by N_{part} using the procedure described in Section 4. Figure 7 shows the N_{part} dependence of $\rho(v_n\{2\}^2, [p_T])$ for $n = 2$–4 in Pb+Pb collisions. The N_{part} dependence resemblances the trends observed in Fig. 5, showing the PCC as a function of event activity N_{ch}. The $\rho(v_2\{2\}^2, [p_T])$ increases with collision centrality for $N_{part} < 100$ starting from negative values at $N_{part} < 40$, and the strongest correlations of $\rho(v_2\{2\}^2, [p_T])$ are observed at $N_{part} \approx 320$. The $\rho(v_3\{2\}^2, [p_T])$ correlations are negative or consistent with zero for $N_{part} < 100$, otherwise they are positive. The PCC $\rho(v_4\{2\}^2, [p_T])$ is positive over the full N_{part} range, and the largest values are at $N_{part} \approx 100$. For more central collisions, $\rho(v_4\{2\}^2, [p_T])$ decreases with N_{part} up to about $N_{part} \approx 300$ and rises slowly at higher values. The theoretical predictions of the $\rho(v_n\{2\}^2, [p_T])$ coefficient are based on a model in which the initial conditions were generated with nucleon positions by a MC Glauber model [48]. The initial conditions are evolved using the pressure-driven 3+1D hydrodynamical simulations with viscous effects followed by the statistical particle emission to match multiplicities observed experimentally [37]. The modified Pearson correlation coefficient is then extracted from the final-state particles. The predictions

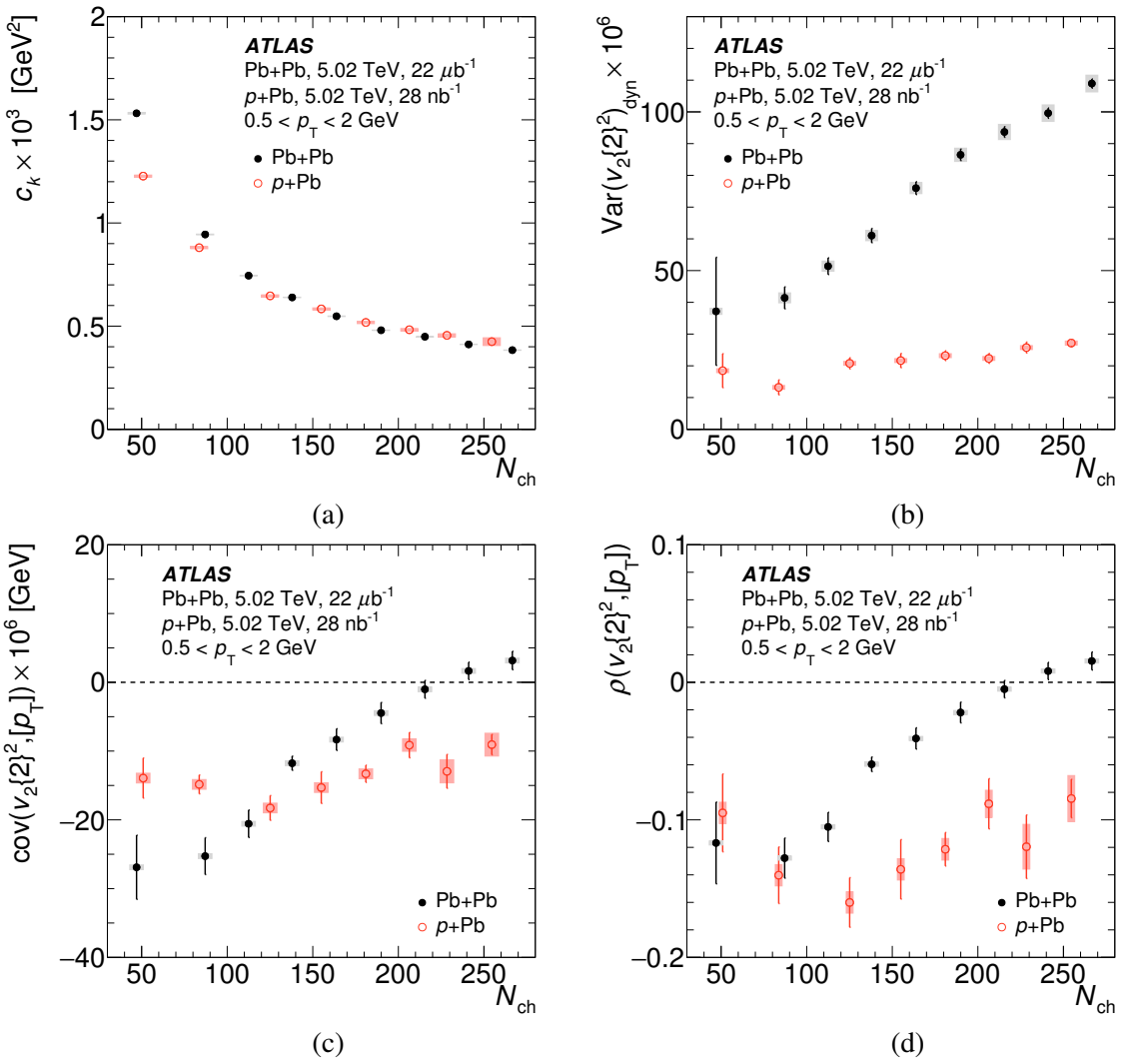

Figure 6: Comparison of (a) c_k, (b) $\mathrm{Var}(v_2\{2\}^2)_{\mathrm{dyn}}$, (c) $\mathrm{cov}(v_2\{2\}^2, [p_{\mathrm{T}}])$, and the (d) $\rho(v_2\{2\}^2, [p_{\mathrm{T}}])$ for the range $0.5 < p_{\mathrm{T}} < 2$ GeV as a function of the charged-particle multiplicity N_{ch}. The statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively.

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for all harmonics are consistent with the data within the large model uncertainties except for the most central collisions where the predictions underestimate the measured $\rho(v_2\{2\}^2, [p_{\mathrm{T}}])$.

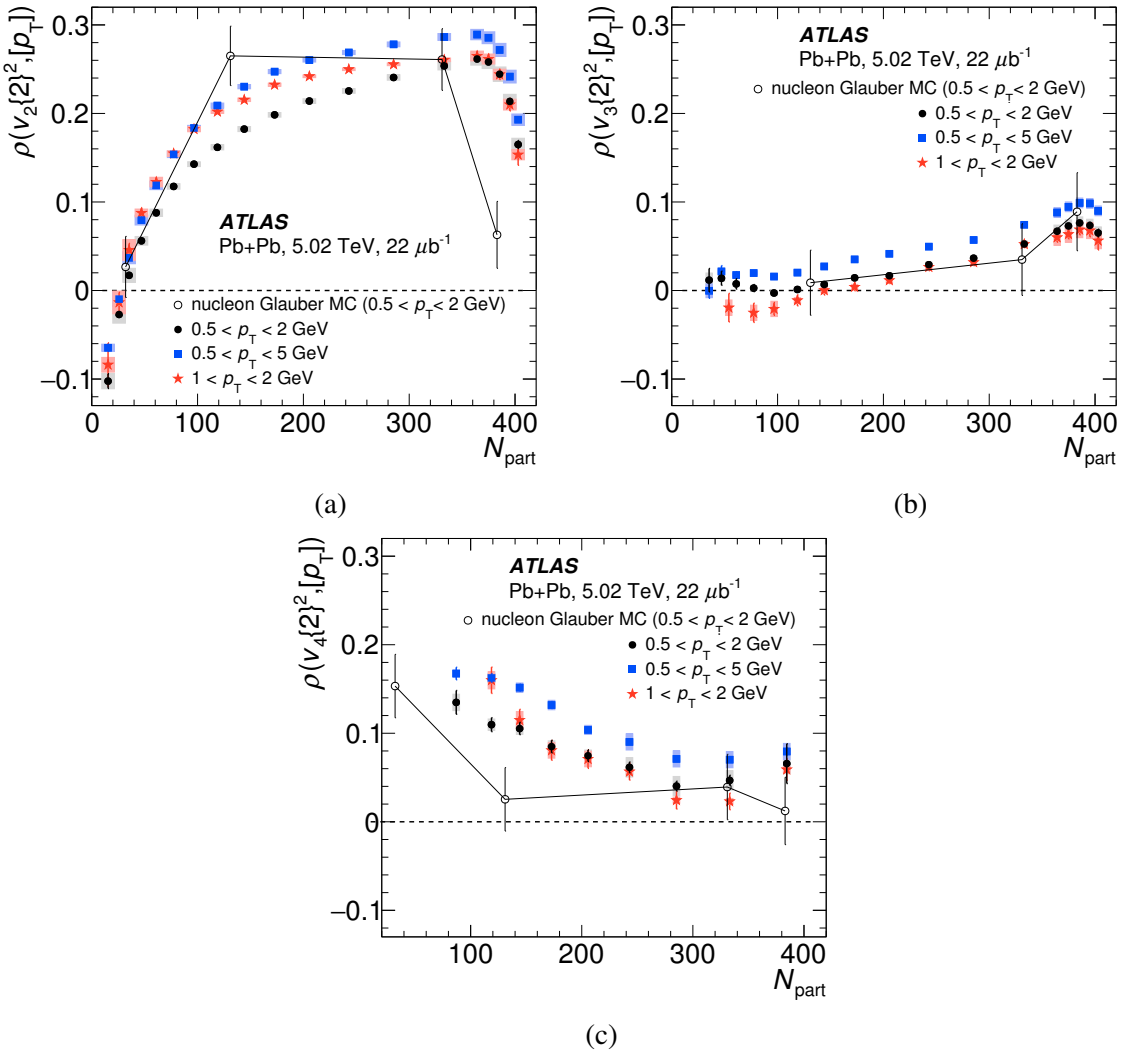

Figure 7: The PCC $\rho(v_n\{2\}^2, [p_T])$ for (a) $n = 2$, (b) $n = 3$, and (c) $n = 4$ in Pb+Pb collisions as a function of N_{part} for three p_T ranges. The statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively. A comparison with model predictions [37] is also shown with a line added to guide the eye.

7 Summary

The first measurement of the modified PCC $\rho(v_n\{2\}^2, [p_T])$ quantifying the correlation between the flow harmonics and the mean transverse momentum is performed by ATLAS experiment at the LHC. The measurement uses 22 μb^{-1} of Pb+Pb data and 28 nb^{-1} of p+Pb data at the same centre-of-mass energy per nucleon pair of 5.02 TeV.

The correlation coefficient for several charged-particle p_T ranges is measured as a function of the number of charged particles N_{ch} and, in Pb+Pb collisions, the average number of nucleons participating in the collision, N_{part}. For the 2^{nd}-, 3^{rd}-, and 4^{th}-order harmonics, the measured quantities exhibit a dependence on the choice of charged-particle p_T range. Measurements with an upper limit of 5 GeV on p_T indicate a stronger correlation than those with an upper limit of 2 GeV. For mid-central and central collisions, when varying the lower p_T limit, consistent values of $\rho(v_3\{2\}^2, [p_T])$ and $\rho(v_4\{2\}^2, [p_T])$ coefficients are obtained,

whereas for the $\rho(v_2\{2\}^2, [p_T])$ coefficient a difference of 10–20% is seen. As a function of event activity, for Pb+Pb collisions, a strong positive correlation $\rho(v_2\{2\}^2, [p_T])$ is observed in mid-central and central collisions while negative values are measured for peripheral events. The correlation $\rho(v_3\{2\}^2, [p_T])$ is found to be weaker, yet non-zero. The values of $\rho(v_4\{2\}^2, [p_T])$ are also positive in the studied centrality range. Non-monotonic behaviour is observed in central Pb+Pb collisions. That trend observed for $\rho(v_2\{2\}^2, [p_T])$ in Pb+Pb collisions is in line with expectations drawn from the ALICE results [20]. In p+Pb collisions, the value of $\rho(v_2\{2\}^2, [p_T])$ is negative and approximately independent of N_{ch}.

The modified PCC is a valuable tool for studying the dynamics of heavy-ion collisions. It provides a reliable estimate of the magnitude of correlations calculated using finite multiplicities. In comparison with existing results, it allows quantitative comparisons between the experimental data and theoretical models. The precise measurements of this observable, presented in this paper, provide useful insights into the interplay of the azimuthal anisotropies (azimuthal flow) and the mean event p_T (radial flow), providing input for a better understanding of QGP dynamics and for constraining the theoretical models. Sizeable positive correlations observed for non-peripheral Pb+Pb collisions support a qualitatively expected scenario in which the azimuthal flow originates from the pressure gradients. The negative correlation in small systems sheds light on the role of the initial conditions in these systems.

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