Measurement of $v_n$ – mean $p_T$ correlations in lead-lead collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with the ATLAS detector

The ATLAS Collaboration

The lead-lead data collected by the ATLAS detector at the LHC provide new opportunities to study dynamic properties of quark-gluon plasma. A tool to study these properties is the recently proposed modified Pearson’s correlation coefficient, $\rho$, that quantifies the correlation between the mean transverse momentum in the event, $[p_T]$, and the square of the flow harmonic magnitude, $v_n^2$. The measurement of $\rho$ for $n=2, 3$ and $4$ is performed using $22 \mu b^{-1}$ of minimum-bias Pb+Pb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV collected with the ATLAS detector at the LHC. To suppress non-flow effects, $v_n^2$ is calculated by correlating charged particles from two sub-events covering opposite pseudorapidity ranges of $0.75 < |\eta| < 2.5$ while $[p_T]$ is evaluated for particles with $|\eta| < 0.5$. Significant (non-zero) values of $\rho$ coefficients for all studied harmonics are obtained. The $\rho$ coefficient as a function of centrality is observed to weakly depend on the transverse momentum range of the selected particles, despite large differences in the mean event transverse momentum and the magnitude of flow harmonics fluctuations. The $\rho$ coefficient for the second order harmonic is found to be negative in peripheral events, have a significant positive value for mid-central events and to drop in the most central events. Measured coefficients are compared to theoretical models.
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 quark-gluon plasma (QGP). The experimental results and theoretical predictions indicate that the magnitude of the anisotropic flow in an event is related to the anisotropy of the initial geometry of the collision zone resulting in anisotropic pressure gradients building up in the QGP. As a result, an enhanced production of particles with higher transverse momentum, $p_T$, is observed in the reaction plane defined by the collision impact parameter vector and the beam axis. The properties of the QGP were recently studied with measurements of correlations between flow harmonics of different order [9–13] as well as the analyses of event shapes [13–17]. Understanding the relationships between the magnitudes of the flow harmonics and other global event characteristics may provide new insight into the properties of the QGP evolution [18]. In particular, it is expected that, on an event-by-event basis, the magnitude of the azimuthal flow harmonics should be correlated with the mean $p_T$, $\langle p_T \rangle$, of the event [19]. In studies published by the ALICE collaboration [17], charged particle spectra are measured in events with small and large azimuthal asymmetry. It is found that the $p_T$ spectra of charged particles are harder (softer) in events with larger (smaller) azimuthal asymmetry compared to the average behaviour.

For a more quantitative approach, Pearson’s $R$ coefficient can be used to measure the strength of the $v_n - [p_T]$ correlation [18]. It is defined as:

$$R = \frac{\text{cov}(v_n[2^2], [p_T])}{\sqrt{\text{Var}(v_n[2^2]) \text{Var}([p_T])}},$$

where the $v_n[2^2]$ is the square of the $n$-th order flow harmonic obtained from two-particle correlations. Experimentally, however, the observed finite charged particle track multiplicity results in an additional broadening of $v_n[2^2]$ and $[p_T]$ distributions and thus in larger values of the two variances, especially of the $[p_T]$. The magnitude of this distortion is determined by a choice of the kinematic region and by the detector performance and thus direct comparison to theoretical calculations is difficult. To overcome this problem, a modified correlation coefficient, $\rho$, which is less sensitive to the event multiplicity than the coefficient $R$, was also suggested in Ref. [18]. In the definition of $\rho$, the variances of the respective univariate $v_n[2^2]$ and $[p_T]$ distributions are substituted by corresponding dynamical variables which eliminate auto-correlation effects and are more directly sensitive to intrinsic initial state fluctuations. The variance $v_n[2^2]$ is substituted by its dynamical counterpart [20]:

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

where $\text{corr}_n[2]$ and $\text{corr}_n[4]$ are two- and four-particle correlations and angular brackets represent averaging over events [21].

The $[p_T]$ variance is replaced by the dynamical $p_T$ fluctuation magnitude [22, 23], $c_k$, defined as:

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

The modified Pearson’s coefficient, $\rho$, is thus defined as:

$$\rho = \frac{\text{cov}(v_n[2^2], [p_T])}{\sqrt{\text{Var}(v_n[2^2])_{\text{dyn}} c_k}}.$$
It was demonstrated in Ref. [18] that the $\rho$ coefficient calculated using realistic, finite multiplicities provides a reliable estimate of the true value of $R$, whereas the coefficient $R$ calculated under the same conditions underestimates the values found in the limit of infinite statistics.

This note reports the first measurement of the $\rho$ coefficient based on the minimum-bias Pb+Pb data sample with the integrated luminosity of 22 $\mu$b$^{-1}$ obtained by the ATLAS experiment in 2015 data taking period at a centre of mass energy per nucleon pair of 5.02 TeV. In order to suppress non-flow effects, the values of $v_n$[2]$^2$ and [$p_T$] are calculated using different sub-events separated in pseudorapidity$^1$.

The note is organised as following. Section 2 gives a brief description of the ATLAS detector. Details on the event selection and charged-particles tracking are provided in Section 3. Section 4 describes the analysis procedure for calculating the $\rho$ 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 [24] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4$\pi$ coverage in solid angle. This analysis uses primarily the Inner Detector (ID), calorimeter and zero-degree calorimeters (ZDC). The ID covers the pseudorapidity range $|\eta| < 2.5$ and is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field. The inner detector consists of silicon pixel, silicon micro-strip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadron (steel/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for both EM and hadronic energy measurements up to $|\eta| = 4.9$. The two-arm forward calorimeter (FCal) that covers 3.2 < $|\eta| < 4.9$ is used for centrality estimation. The ZDC located in the LHC tunnel at $|\eta| > 8.3$ is used for triggering on collision events and pile-up event rejection.

A two-level trigger system is used to select events. The level-one trigger is implemented in hardware to pre-select up to $10^5$ events per second for further decisions to be made by the high-level trigger (HLT). The software-based HLT tuned for Pb+Pb data taking further selects up to 1000 events per second for recording.

3 Event and track selection

The Pb+Pb data sample used in the analysis was collected by two mutually exclusive minimum-bias triggers. Events with semi-central and central collisions were selected if the online estimated total transverse energy in the entire ATLAS calorimeter system exceeded 50 GeV. Alternatively, peripheral collisions were required to deposit signals corresponding to at least one neutron in both arms of the ZDC and to have at least one track reconstructed in the HLT. Additionally, data used in this analysis were required to come from periods when the entire detector was functioning normally. The events are required to have

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

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a reconstructed vertex within 100 mm from 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, $\Sigma_{\text{FCal}}$, the estimated number of neutrons in the ZDC, $N_n$, and the number of tracks associated with a primary vertex, $N_{\text{rec}}$ \cite{25, 26}. Since the distribution of $\Sigma_{\text{FCal}}$ or $N_n$ in events with more than one collision is broader than that for the events with only a single one, pile-up events are suppressed by rejecting events with abnormally large values of $\Sigma_{\text{FCal}}$ or $N_n$ than expected given their $N_{\text{rec}}$ value.

Events are classified according to the collision centrality estimated by $\Sigma_{\text{FCal}}$. Using the Glauber model \cite{27} the average number of nucleons participating in the collision, $N_{\text{part}}$, can be estimated in each centrality interval. These intervals and the corresponding values of $N_{\text{part}}$ are listed in Table 1. After the event selection requirements, approximately 130M events are selected for analysis within the 0-80% centrality interval.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$N_{\text{part}}$</th>
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<tr>
<td>0 – 2%</td>
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<td>118.7 ± 2.6</td>
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<td>40–45%</td>
<td>96.6 ± 2.5</td>
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<tr>
<td>30–35%</td>
<td>144.1 ± 2.7</td>
<td>70–80%</td>
<td>15.4 ± 0.9</td>
</tr>
</tbody>
</table>

Table 1: The $N_{\text{part}}$ values and their uncertainty for the centrality intervals used in the analysis.

The charged-particle tracks reconstructed in the ID are required to pass selection criteria \cite{28} in order to suppress the contribution of incorrectly reconstructed tracks and secondary products of decays. The remaining yields of these are referred to as fake tracks. Corrections for residual fake tracks, finite detector efficiency, and losses due to track selection requirements are based on $4 \times 10^6$ minimum bias Pb+Pb Monte Carlo (MC) events generated by the HIJING v1.38b \cite{29} event generator. Generated events were passed through the Geant 4-based \cite{30} ATLAS detector simulation programs \cite{31} and reconstructed using the same procedure and detector conditions as the data.

Corrections are applied to each track selected for the analysis using weights to account for three effects. The first two are the fake track fraction, $f$, and efficiency, $\epsilon$, obtained as a function of track $p_T$, $\eta$, and collision centrality. They form a weighting factor $w = (1 - f)/\epsilon$ as in Refs. \cite{13, 32}. An additional multiplicative weight, evaluated from data, is applied to correct for detector non-uniformity in the azimuthal angle. These weights are obtained by requirement that the tracks are azimuthally uniformly distributed in each pseudorapidity slice of width 0.1.

The contribution of fake tracks, estimated from the MC simulations, is largest in the central collisions at the lowest analysed $p_T$ and at the largest $|\eta|$. The extreme value that the fake track fraction reaches there is 20%, and it rapidly drops to below 1% for $p_T$ above 2 GeV and $|\eta| < 1.5$. In contrast to the fake track fraction, the tracking efficiency depends weakly on centrality, diminishing in the most central events by about 3% compared to more peripheral events. The efficiency increases with the track $p_T$ from about 50% at the lowest analysed $p_T$ to 70% above 20 GeV. It is highest at mid-rapidity and drops by about 15% for $|\eta| > 1$. 

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4 Correlation coefficient $\rho$

Charged-particle tracks used in the analysis are divided into three sub-events based on their pseudorapidity, defined as: region A with $\eta < -0.75$, central region B with $|\eta| < 0.5$ and region C with $\eta > 0.75$. The $v_n^2$ harmonics are calculated by correlating charged-particle tracks from sub-events A and C which are separated in pseudorapidity to suppress non-flow contributions. Tracks in the central region B are used to obtain the mean value of the charged-particle transverse momentum in the event, $[p_T]$, defined as:

$$[p_T] = \frac{1}{\sum_b w_b} \sum_b w_b p_{Tb}$$

where the summation is performed over tracks in region B, labeled by index $b$. The weights $w_b$ include the fake fraction, efficiency, and azimuthal non-uniformity corrections, as discussed in Section 3.

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

$$\text{cov}(v_n^2, [p_T]) = \left( \frac{1}{\sum_{a,c} w_a w_c} \sum_{a,c} w_a w_c e^{i n \phi_a - i n \phi_c} \right) \left( \frac{1}{\sum_{a,c} w_a w_c} \sum_{a,c} w_a w_c e^{i n \phi_a - i n \phi_c} \right)^*$$

where $\phi$ is the azimuthal angle, and indices $a$ and $c$ are over tracks in regions A and C, respectively.

The dynamical variance, defined in Eq. (2), which enters the denominator of Eq. (4) is calculated using 2- and 4-particle correlations defined in Ref. [21]:

$$\langle \text{corr}_n^2 \rangle = \left( \frac{1}{\sum_{a,c} w_a w_c} \sum_{a,c} w_a w_c e^{i n \phi_a - i n \phi_c} \right)^2$$

where the $q_a$ and $q_c$ are complex flow vectors of sub-event A and sub-event C defined as:

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

The four-particle correlation is obtained from the expression:

$$\langle \text{corr}_n^4 \rangle = \left( \frac{(Q_{n,a}^2 - Q_{2n,a})(Q_{n,c}^2 - Q_{2n,c})}{S_a S_c} \right)^2$$

where for sub-event A:

$$Q_{n,a} = \sum_a w_a e^{i n \phi_a}, \quad Q_{2n,a} = \sum_a w_a^2 e^{i 2n \phi_a}, \quad S_a = \left( \sum_a w_a \right)^2 - \sum_a w_a^2,$$

and similarly for sub-event C.

The second term in the denominator of Eq. (4), the mean $p_T$ fluctuation in the event class [22, 23], is defined by Eq. (3). In the analysis, $c_k$ is calculated using the weights $w_b$ to account for the detector effects as:

$$c_k = \left( \frac{1}{\sum_b w_b^2} \sum_b w_b \left( p_{T,b} - \langle [p_T] \rangle \right) \right) w_{b'} \left( p_{T,b'} - \langle [p_T] \rangle \right)$$

The summation over indices $b$ and $b'$ goes over all charged particles in region B.
Four track $p_T$ ranges, $0.5 < p_T < 5$ GeV, $0.5 < p_T < 2$ GeV, $1 < p_T < 2$ GeV and $1 < p_T < 5$ GeV are studied in the analysis. By using intervals which have the same upper (lower) $p_T$ threshold but a different lower (upper) threshold, the sensitivity of the $\rho$ to the high (low) part of the particle spectrum can be studied. Since binning events according to the charged particle multiplicity in the full ID range would result in negative multiplicity correlation between multiplicities in regions A and C ($M_{AC}$) and those in region B, a different strategy is chosen. A fine binning in $M_{AC}$, calculated using tracks of $p_T$ within the range of $0.5 < p_T < 5$ GeV and a width of 10 tracks per bin is used to obtain the $\text{cov}(\nu_n(2)^2, [p_T])$, $\text{Var}(\nu_n^2)^{\text{dyn}}$ and $c_k$ variables. It was cross-checked that the variables of interest obtained with a finer binning of one or five tracks per bin are consistent with the measurement based on 10 tracks per bin. Due to large statistical fluctuations at low multiplicity, the calculated magnitude of the $\text{Var}(\nu_n^2)^{\text{dyn}}$ can be negative, which is not allowed when calculating $\rho$ due to the presence of $\sqrt{\text{Var}(\nu_n^2)^{\text{dyn}}}$ in Eq. (4). Therefore, in this analysis, the multiplicity range is restricted to the $M_{AC}$ multiplicities such that $\text{Var}(\nu_n^2)^{\text{dyn}}$ and $c_k$ are positive at a level of at least one standard deviation of the statistical uncertainty. The formulation of the modified Pearson’s coefficient $\rho$ also requires that there are at least two tracks in each region (A, B and C). This requirement sets the minimum $M_{AC}$ above which events enter the analysis, and results in the rejection of some events in the peripheral centrality intervals. If the fraction of rejected events exceeds 1%, that centrality interval is not analysed to avoid biasing the results. This limit depends on the harmonic order and on the particle $p_T$ range. The results on $\text{cov}(\nu_n(2)^2, [p_T])$, $\text{Var}(\nu_n^2)^{\text{dyn}}$ and $c_k$, calculated in fine bins of $M_{AC}$, are then combined into wider bins in order to increase the statistical precision of the measurement.

To facilitate comparison with theoretical calculations, transformations from $M_{AC}$ to the number of charged particles, $N_{ch}$, and $N_{\text{part}}$ are performed. For each $M_{AC}$ bin the multiplicity $N_{ch}$ is obtained for the charged particles in the range $0.5 < p_T < 5$ GeV and $|\eta| < 2.5$, corrected for tracking efficiency and fakes. For the $N_{\text{part}}$ dependence, the results measured for each $M_{AC}$ bin are averaged with the weights corresponding to the probability to find any given $M_{AC}$ value in each centrality interval listed in Table 1.

5 Systematic uncertainties

Systematic uncertainties on the correlation coefficients are evaluated by varying individual aspects of the analysis. Since the modified Pearson’s coefficient $\rho$ is a ratio of quantities which are calculated using tracks, many variations largely cancel and the resulting systematic uncertainties are generally small. In order to avoid counting statistical fluctuations as systematic trends, the systematic uncertainties are typically averaged over several centrality classes. For each systematics source and for each measurement point the maximum variation from the baseline measurement is used. Assuming that the different sources of uncertainties are not correlated with each other, the resulting uncertainty is the sum of the individual contributions combined in quadrature.

The following sources of systematic uncertainties are considered:

**Tracking selection.** The tracking performance has only a small influence on the measured $\nu_n$. On the other hand the $[p_T]$ and $c_k$ depend directly on the admixture of the fake tracks at low $p_T$. To assess the impact on $\rho$, the measurement is repeated with tracks selected with looser and tighter track quality criteria, thus increasing and reducing the fake track rate, respectively. The largest difference between the baseline result and the $\rho$ obtained with tighter or looser selections is used as a systematic uncertainty. The effect on $\rho$ in the 20% most central events is at the level of 1%.
**Detector material.** Since the tracks that are used in the calculation of $\rho$ are weighted by the inverse of the efficiency, a bias in its estimation may change the balance between low and high $p_T$ tracks in the sums. The existence of the bias is justified by the imprecise material budget description in the detector simulations [33]. Based on these simulations, the uncertainty due to the detector description is obtained by varying the efficiency up and down according to its uncertainties of about 6% in a $p_T$ and $\eta$ dependent manner. The effect on $\rho$ is at the level of 1% for central collisions.

**Uniformity of the tracking detector performance.** The influence of the weight that is applied to tracks in order to correct for azimuthal non-uniformities is estimated. The estimate is obtained by comparing the baseline measurement and the measurement obtained without applying this weight. For central collisions the magnitude of the differences are found to be about 1% for second harmonics while they are of order of 3-9% for $\rho(v_3(2)^2,[p_T])$ and $\rho(v_4(2)^2,[p_T])$.

**Residual pile-up events.** The pile-up probability during the Pb+Pb data taking is estimated to be about 0.2%. The selection criteria discussed in Sect. 3 suppress the fraction of pile-up events accepted to the analysis almost to zero in central collisions. To estimate the systematics related to pileup, the measurement is conservatively repeated without this event rejection, resulting in at most a 1% difference in the most central events.

**Residual sine term.** The imaginary part of the $\text{cov}(v_n(2)^2,[p_T])$ term, defined in Eq. (6), and thus the imaginary part of $\rho$, referred to as the sine term, quantifies the detector resolution for measuring flow harmonics [20, 34]. In an ideal detector the value of the sine term should be zero. Therefore, its deviation from zero is treated as a systematic uncertainty. This contribution is about 1% for central collisions for $n=2$ and 3, and up to 15% for $n=4$.

**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 cuts are altered to account for this uncertainty. The resulting effect on the measurement of the $\rho$ coefficient reaches 5-25% for $n=2-4$ and is the dominant uncertainty in the peripheral centrality classes.

### 6 Results

Figure 1 shows the values of $c_k$ for the four aforementioned $p_T$ intervals as a function of event multiplicity. For each $p_T$ range, a strong decrease of $c_k$ is observed with increasing $N_{ch}$. For a given $N_{ch}$ bin, $c_k$ values in different $p_T$ ranges differ by up to an order of magnitude. For the same lower $p_T$ threshold, the $c_k$ values from the higher upper $p_T$ threshold are larger, as expected.

Figure 2 shows $\text{Var}(v_n^2)_{dy}^n$ for $n=2, 3, 4$ as function of $N_{ch}$ in the four $p_T$ intervals. After an increase with $N_{ch}$ in the low multiplicity region a maximum is reached and then for higher $N_{ch}$ the variance decreases. The ordering of the variances $\text{Var}(v_2(2)^2)_{dy}^n > \text{Var}(v_3(2)^2)_{dy}^n > \text{Var}(v_4(2)^2)_{dy}^n$ and the multiplicity dependence of $\text{Var}(v_n^2)_{dy}^n$ is similar to the multiplicity dependence of $v_n$ measured by ATLAS [32].

In Fig. 3 the covariances $\text{cov}(v_n(2)^2,[p_T])$ are shown for the three harmonics as a function of $N_{ch}$ for four $p_T$ intervals. Significant (non-zero) values of the covariances indicate positive correlations between the $v_n^2$ and $[p_T]$ values in Pb+Pb events. The measured covariances depend on the event multiplicity and the $p_T$ range of the charged particles. A strong dependence on the multiplicity is observed for $n=2$ and 4. At multiplicities $N_{ch} < 150$ a negative $\text{cov}(v_2(2)^2,[p_T])$ is measured. In contrast to the strong multiplicity
The correlation coefficient $\rho$ towards more central collisions. The significant correlation observed for midcentral events is attributed to the large initial state eccentricities [35]. The strongest correlations with $\rho$ occur at the upper limit of 5 GeV.

The measured $c_k$, $\text{Var}(v_n^2)_{\text{dyn}}$, and covariance values are then combined to form the modified Pearson’s coefficient $\rho(v_n^2, [p_T])$, for $n = 2-4$, that is shown in Fig. 4. For all particle $p_T$ intervals, $\rho(v_2^2, [p_T])$, rapidly increases with collision centrality for $N_{\text{part}} < 100$ starting from negative values at $N_{\text{part}} < 40$. A weaker increasing dependence of the correlation coefficient is observed over the $N_{\text{part}}$ range of 100-350. The strongest correlations with $\rho(v_2^2, [p_T])=0.24-0.30$ is observed at $N_{\text{part}} \sim 320$, and it diminishes towards more central collisions. The significant correlation observed for midcentral events is attributed to stronger hydrodynamic response to the large initial state eccentricities [35]. The correlation coefficient values calculated with the upper $p_T$ limit of 2 GeV are 10-20% smaller than the values obtained with $p_T$ limit of 5 GeV.

The correlation coefficient $\rho(v_3^2, [p_T])$ is also measured for the same $p_T$ intervals. The $\rho(v_3^2, [p_T])$ values, displayed in the middle panel of Fig. 4, are smaller and have a weaker centrality dependence compared to $\rho(v_2^2, [p_T])$. In the 2% most central Pb+Pb collisions, $N_{\text{part}} = 399.0 \pm 1.6$, a hint of
decrease of $\rho(v_3|2^2,[p_T])$ is observed. The $\rho(v_3|2^2,[p_T])$ correlations are positive for all measured centralities except for $N_{\text{part}} < 100$ where they are negative or consistent with 0. The correlations for $p_T$ ranges with the same maximum $p_T$ are consistent with each other for $N_{\text{part}} > 100$ and the values obtained with the higher maximum $p_T$ threshold are larger.

The correlation coefficient $\rho(v_4|2^2,[p_T])$ is also evaluated for the four $p_T$ ranges. Significant positive correlations are observed over the full $N_{\text{part}}$ range used for the measurement but, at moderate and large $N_{\text{part}}$, the fourth order correlations are weaker than those for the elliptic flow. The largest values of $\rho(v_4|2^2,[p_T])$ are observed at low $N_{\text{part}} \approx 100$. For more central collisions $\rho(v_4|2^2,[p_T])$ decreases with $N_{\text{part}}$ up to about $N_{\text{part}} \approx 300$, and rises slowly at higher values. Similarly to the $\rho(v_3|2^2,[p_T])$, the $\rho(v_4|2^2,[p_T])$ correlations with larger upper $p_T$ thresholds have larger magnitudes and also similar to the $n = 3$ case, correlations with lower $p_T$ thresholds are not so different. The magnitude of the $\rho(v_3|2^2,[p_T])$ and $\rho(v_4|2^2,[p_T])$ correlations are similar for $N_{\text{part}} > 270$.

In Fig. 5 predictions for the correlation coefficient $\rho(v_3|2^2,[p_T])$ and $\rho(v_3|2^2,[p_T])$ as a function of $N_{\text{part}}$ for the $p_T$ ranges of $0.5 < p_T < 2$ GeV are compared to the data. The theoretical predictions of the $\rho$ coefficient is based on the nucleon Glauber MC models [36, 37]. Predictions are found to be consistent with the data within the model uncertainties.
Figure 5: Comparison of the nucleon Glauber model predictions for the modified Pearson’s coefficient, $\rho(v_2[2]^2, [p_T])$ (left) $\rho(v_3[2]^2, [p_T])$ (right) for particles of $0.5 < p_T < 2$ GeV [18].

### 7 Summary

The first measurement of the modified Pearson’s correlation coefficient $\rho$ between the flow harmonics and the per-event mean transverse momentum is performed by ATLAS using 22 $\mu$b$^{-1}$ of minimum-bias 5.02 TeV Pb+Pb data. The results presented here establish the modified Pearson’s correlation coefficient as a useful tool to study the dynamics of the hot and dense medium created in the heavy-ion collisions. Significant (non-zero) values of covariances $\text{cov}(v_n[2]^2, [p_T])$, and corresponding modified Pearson’s correlation coefficients, $\rho(v_n[2]^2, [p_T])$, are obtained for $n = 2, 3, 4$. The correlation coefficient is measured as a function of the average number of nucleons participating in the collision, $N_{\text{part}}$, for several charged-particle $p_T$ ranges.

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 entire centrality range studied. The centrality dependencies have a non-monotonic behaviour in most central events, suggesting a change in the nature of the source of the correlations in those events.

For each of the three harmonics, the selected charged-particle $p_T$ range influences the value of the coefficients. Measurements with an upper limit of 5 GeV are more strongly correlated than those with the upper limit of 2 GeV. For the variation of the lower $p_T$ threshold consistent values of $\rho(v_3[2]^2, [p_T])$ and $\rho(v_4[2]^2, [p_T])$ coefficients are obtained for $N_{\text{part}} > 100$ and a difference of only 10-20% is seen for the $\rho(v_2[2]^2, [p_T])$ coefficient.

The novel measurement presented in this note provides insights into the interplay of the magnitude of the azimuthal anisotropies and the event mean $p_T$. As such, they can be used in further experimental studies to understand the underlying mechanism of QGP dynamics and constrain theoretical models attempting to describe them.
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