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The ATLAS Collaboration

Abstract

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1. Introduction

Recent observations of ridge-like structures in the two-particle correlation functions measured in proton-lead (p+Pb) collisions at 5.02 TeV [13] have led to differing theoretical explanations. These structures have been attributed either to mechanisms that emphasize initial-state effects, such as the saturation of parton distributions in the Pb-nucleus [14-17], or to final-state effects, such as jet-medium interactions [8], interactions induced by multiple partons [9-12], and collective anisotropic flow [13,18].

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

However, two-particle correlation studies performed recently on data from p+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ 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 Pb+Pb collisions.

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

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

(1)

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 $v_2$. 

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the impact parameter direction in nucleus-nucleus collisions. In contrast, $\Psi_2$ in proton-nucleus would be unrelated to the impact parameter and determined by the initial-state fluctuations. In nucleus-nucleus collisions, the $v_2$ coefficient in central collisions and the other $v_n$ coefficients in all collisions are related to various geometric configurations arising from fluctuations of the nucleon positions in the overlap region \cite{28}.

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

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

2. Event and track selections

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

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

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

Charged particle tracks are reconstructed in the ID using the standard algorithm optimized for $p+p$ minimum-bias measurements \cite{34}. Tracks are required to have at least six hits in the SCT detector and at least one hit in the pixel detector. A hit in the first pixel layer is also required when the track crosses an active pixel module in that layer. Additional requirements are imposed on the transverse ($d_0$) and longitudinal ($z_0\sin \theta$) impact parameters measured with respect to the primary vertex. These are: $|d_0|$ and $|z_0\sin \theta|$ must be smaller than 1.5 mm and must satisfy $|d_0|/\sigma_{d_0} < 3$ and $|z_0\sin \theta|/\sigma_z < 3$, where $\sigma_{d_0}$ and $\sigma_z$ are uncertainties on the transverse and longitudinal impact parameters, respectively, as obtained from the covariance matrix of...
the track fit. The analysis is restricted to charged particles with $0.3 < p_T < 5.0$ GeV and $|\eta| < 2.5$.

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

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

3. Data analysis

The cumulant method involves the calculation of $2k$-particle azimuthal correlations, $\text{corr}_n\{2k\}$, and cumulants, $c_n\{2k\}$, where $k = 1, 2$, for the analysis presented in this paper. The two- and four-particle correlations are defined as $\text{corr}_n\{2\} = \langle e^{i n (\phi_2 - \phi_1)} \rangle$ and $\text{corr}_n\{4\} = \langle e^{i n (\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle$, 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 $c_n\{2\} = \langle \text{corr}_n\{2\} \rangle$, and the four-particle cumulant $c_n\{4\} = \langle \text{corr}_n\{4\} \rangle - 2 \cdot \langle \text{corr}_n\{2\} \rangle^2$. The effect of two-particle correlation is explicitly removed in the expression for $c_n\{4\}$. Further details are given in Refs. [29, 30, 32].

Direct calculation of multi-particle correlations requires multiple passes over the particles in an event, and requires extensive computing time in high-multiplicity events. To mitigate this, it has been proposed in Ref. [32] to express multi-particle correlations in terms of the moments of the flow vector $Q_n$, defined as $Q_n = \sum_i e^{i n \phi_i}$, where the index $n$ denotes the flow harmonic and the sum runs

<table>
<thead>
<tr>
<th>$\Sigma E_T^{Pb}$ range</th>
<th>$\langle \Sigma E_T^{Pb} \rangle$ range in fraction of events</th>
<th>$\langle N_{\text{ch}} \rangle$ (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 80$</td>
<td>93.7</td>
<td>0.9</td>
</tr>
<tr>
<td>55–80</td>
<td>64.8</td>
<td>1.9–9.1</td>
</tr>
<tr>
<td>40–55</td>
<td>46.7</td>
<td>9.1–20.0</td>
</tr>
<tr>
<td>25–40</td>
<td>31.9</td>
<td>20.0–39.3</td>
</tr>
<tr>
<td>10–25</td>
<td>16.9</td>
<td>39.3–70.4</td>
</tr>
<tr>
<td>$&lt; 10$</td>
<td>4.9</td>
<td>70.4–100</td>
</tr>
</tbody>
</table>

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

\[
v_2^\text{ref}\{2\} = \sqrt{c_2\{2\}} , \quad (2) \\
v_2^\text{ref}\{4\} = \sqrt{-c_2\{4\}} , \quad (3)
\]

where \( v_2^\text{ref}\{2\} \) (\( v_2^\text{ref}\{4\} \)) 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 \( (\delta \eta = 0.1, \delta \phi = 2\pi/64) \) bin (labelled \( i \)), a weight is calculated as \( w_i(\eta, \phi) = \langle N(\delta \eta) \rangle / N_i(\delta \eta, \delta \phi) \), where \( \langle N(\delta \eta) \rangle \) is the event-averaged number of tracks in the \( \delta \eta \) slice to which this bin belongs, while \( N_i(\delta \eta, \delta \phi) \) is the number of tracks in an event within this bin. Using this weight forces the azimuthal angle distribution of reference particles to be uniform in \( \phi \), but it does not change the \( \eta \) distribution of reconstructed tracks. A weighted \( Q \)-vector is evaluated as \( Q_i = \sum w_i e^{i \phi} \) [32].

From Eqs. (2) and (3) it is clear that the cumulant method can be used to estimate \( v_2 \) only when \( c_2\{4\} \) is negative and \( c_2\{2\} \) positive.

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

\[
v_2\{2\}(p_T, \eta) = \frac{d_2\{2\}}{\sqrt{v_2\{2\}}} , \quad (4)
\]

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

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

![Fig. 2: The two-particle (upper plot) and four-particle (lower plot) cumulants calculated using the reference flow particles as a function of \( \Sigma E_T^\text{Pb} \) for data (circles), the fully simulated HIJING events (open squares) and the large generator-level HIJING sample (filled squares). For clarity, the points for the fully simulated (generated) HIJING events are slightly shifted to the left (right).](image)
was also checked that for these events $c_2\{4\}$ is un-
changed within errors for any high-multiplicity sele-
tion. For example, defining $N_{20}$ as the value of
$N_{\text{ch}}$ such that 20% of events have $N_{\text{ch}} < N_{20}$
(i.e. $N_{20}$ is the 20th percentile), then selecting
$N_{\text{ch}} > N_{20}$ leaves $c_2\{4\}$ unchanged within errors.
And for $\Sigma E_T > 25$ GeV this holds for any per-
centile selection.

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

The systematic uncertainties on $v_2\{2\}$ and $v_2\{4\}$
as a function of $p_T$ and $\Sigma E_T^{Pb}$ have been evaluated
by varying several aspects of the analysis pro-
dure. Azimuthal-angle sine terms in the Fourier
expansion should be zero, but a non-zero contribu-
tion can arise due to detector biases. It was found
that the magnitude of the sine terms relative to
the cosine terms is negligible (below 1%) for $v_2\{2\}$
measured as a function of $p_T$, as well as for the
$p_T$-integrated $v_2\{2\}$ and $v_2\{4\}$. In the case of the
measurement of the $p_T$-dependent $v_2\{4\}$, the sys-
tematic uncertainty attributed to the residual sine
terms varies between 6% and 14% in the different
$\Sigma E_T^{Pb}$ intervals. Uncertainties related to the track-
ing are obtained from the differences between the
main results and those using tracking requirements
modified to be either more or less restrictive. They
are found to be negligible (below 0.2%) for $v_2\{2\}$.
For the $p_T$-dependent $v_2\{4\}$ they give a contribu-
tion of less than 6% to the systematic uncertainty,
and less than 1% for the $p_T$-integrated $v_2\{4\}$. In ad-
dition 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 $v_2\{2\}$ and $v_2\{4\}$ measurements.

The correction of the azimuthal-angle uniformity is
checked by comparing the results to those obtained
with all weights, $w_i$, set equal to one. This change
leads to small relative differences, below 1%, for the
$v_2\{2\}$ measured as a function of $p_T$, as well as for
the $p_T$-integrated $v_2\{2\}$ and $v_2\{4\}$. Up to 4% dif-
ferences are observed in the $p_T$-dependent $v_2\{4\}$.
All individual contributions to the systematic un-
certainty are added in quadrature and quoted as the
total systematic uncertainty. The total systematic
uncertainties are below 1% for the $v_2\{2\}$ measure-
ment. The $v_2\{4\}$ measurement precision is limited
by large statistical errors, whereas the systematic
uncertainties stay below 15% for $v_2\{4\}(p_T)$ and be-
low 2% for the $p_T$-integrated $v_2\{4\}$.

4. Results

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

The shape and magnitude of the $p_T$-dependence
of $v_2\{4\}$ is found to be similar to that observed
in $p+Pb$ collisions using two-particle correla-
tions [2, 3]. The second-order harmonic, $v_2$, can be ex-
tracted from two-particle azimuthal correlations us-
ing charged particle pairs with a large pseudorapid-
ity gap to suppress the short-range correlations on
the near-side ($\Delta \phi \sim 0$) [3, 22]. However, the two-
particle correlation measured this way may still be
affected by the dijet correlations on the away-side
($\Delta \phi \sim \pi$), which can span a large range in $\Delta \eta$.
In Ref. [3], the away-side non-flow correlation is
estimated using the yield measured in the lowest
$\Sigma E_T^{Pb}$ collisions and is then subtracted from the
higher $\Sigma E_T^{Pb}$ collisions. The result of that study,
v$_2$\{2PC\}, is shown in Fig. 3 for the four activity
intervals with largest $\Sigma E_T^{Pb}$, and compared to
v$_2$\{4\}. Good agreement is observed between v$_2$\{4\}
and v$_2$\{2PC\} for collisions with $\Sigma E_T^{Pb} > 55$ GeV.
For $\Sigma E_T^{Pb} < 55$ GeV, the disagreement could be
due either to the subtraction procedure used to obtain
v$_2$\{2PC\} or to non-flow effects in v$_2$\{4\}, or to
a combination.

The dependence on the collision activity of the
second-order harmonic, integrated over $0.3 < p_T <
5$ GeV, is shown in Fig. 4. The large magnitude
of v$_2$\{2\} compared to v$_2$\{4\} suggests a sub-
stantial contamination from non-flow correlations.
The value of v$_2$\{4\} is approximately 0.06, with lit-
tle dependence on the overall event activity for
$\Sigma E_T^{Pb} > 25$ GeV. The extracted values of v$_2$\{4\}
are also compared to the v$_2$\{2PC\} values obtained
from two-particle correlations. Good agreement is
observed at large $\Sigma E_T^{Pb}$, while at lower $\Sigma E_T^{Pb}$ the
v$_2$\{2PC\} is smaller than v$_2$\{4\}, which may be due to
different sensitivity of the two methods to non-
flow contributions that become more important in
low $\Sigma E_T^{Pb}$ 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

\[
\Sigma E_T^{Pb} > 80 \text{ GeV} \quad \text{ATLAS} \quad 55 < \Sigma E_T^{Pb} < 80 \text{ GeV} \quad 40 < \Sigma E_T^{Pb} < 55 \text{ GeV} \quad 25 < \Sigma E_T^{Pb} < 40 \text{ GeV}
\]

Fig. 3: The second-order harmonic calculated with the two-particle (circles) and four-particle (stars) cumulants as a function of transverse momentum in four different activity intervals. Bars denote statistical errors; systematic uncertainties are shown as shaded bands. The v$_2$ derived from the Fourier decomposition of two-particle correlations [3] is shown by squares.
at $\sqrt{s_{NN}} = 2.76$ TeV [21] [22], although with a magnitude that is 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 [39] [41].

Harmonic flow coefficients in $p+$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 [13]. The predicted magnitude of the second-order harmonic 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.

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2We are grateful to the authors of Ref. [13] for providing us with the model predictions for charged particles with $\eta$ and $p_T$ ranging those used in the analysis. The model predictions are for two activity intervals corresponding to fractions of events of 0—3.4 % and 3.4—7.8 % which are then translated into the $\Sigma E_T^{Pb}$ intervals using Fig. 3.
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