MEASUREMENT OF LONG-RANGE AZIMUTHAL
CORRELATIONS IN PROTON–PROTON AND
PROTON–LEAD COLLISIONS WITH ATLAS*

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Measurement of correlations between two flow harmonics using three and four-particle cumulants with the ATLAS detector are presented in \( pp \), \( p+\text{Pb} \), and \( \text{Pb}+\text{Pb} \) collisions. The measurements probe the long-range collective nature of particle production in the small systems. Non-flow correlations in the standard cumulants are suppressed using the subevent technique. Anti-correlation between \( v_2 \) and \( v_3 \) and correlation between \( v_2 \) and \( v_4 \) over the full multiplicity range are observed with the three-subevent method, for all collision systems. The relative correlation strengths of the cumulants are obtained by dividing them with \( \langle v^2 \rangle \) from two-particle correlation. These normalised cumulants are found to be similar in the three-collision systems with weak dependence on the event multiplicity and transverse momentum. The results provide strong evidence for a similar long-range multi-particle collectivity in \( pp \), \( p+\text{Pb} \) and peripheral \( \text{Pb}+\text{Pb} \) collisions.

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1. Introduction

Azimuthal anisotropy of charged particles produced in heavy-ion collision is extensively studied to understand the properties and dynamics of the hot and dense medium created in the early stages [1]. The ridge-like correlations, enhanced particle pairs produced at small azimuthal angle (\( \Delta \phi \)) extended over a wide pseudorapidity range (\( \Delta \eta \)) are observed in small systems of \( pp \), \( p+A \) and \( d+A \) collisions [2, 3]. This raises a question of whether there is QGP formation in small systems as observed in the \( A+A \) system. Another

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question is whether these correlations reflect initial momentum correlations from gluon saturation effects [4], or a final-state hydrodynamic response to the initial transverse collision geometry [5].

The azimuthal anisotropic flow is studied using a multi-particle correlation technique known as cumulants [6]. 2k-particle cumulants $c_n\{2k\}$ probe the event-by-event fluctuations of flow harmonic $v_n$. Four-particle symmetric cumulants $sc_{n,m}\{4\}$ quantify the correlation between $v_n$ and $v_m$. Three-particle asymmetric cumulants such as $ac_n\{3\}$ [7] are sensitive to correlations involving both flow magnitude $v_n$ and phase $\Phi_n$.

One setback in the azimuthal correlation measurement in small system is the large contribution of non-flow correlations arising from various sources such as jets, dijets, resonances, etc. In two-particle correlation measurements, non-flow is suppressed by correlating particles separated by a pseudorapidity gap ($\Delta \eta$) and then applying the peripheral subtraction technique [8]. Non-flow in the multi-particle cumulants is suppressed by correlating particles from subevents divided with respect to $\eta$. This so-called "subevent method" has been demonstrated to measure reliably $c_n\{4\}$ and $sc_{n,m}\{4\}$ [7, 9].

Measurement of symmetric cumulants $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and asymmetric cumulant $ac_2\{3\}$ with the ATLAS detector [10] in $pp$ collisions at $\sqrt{s} = 13$ TeV, $p+Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV, and low-multiplicity Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are presented. Results are compared for these multi-particle cumulants obtained using the standard method and the subevent methods. The measurements probe event-by-event fluctuations in correlations between two flow harmonics.

## 2. Data analysis

This analysis is done using ATLAS data sets corresponding to integrated luminosities of 0.9 pb$^{-1}$ of $pp$ data recorded at $\sqrt{s} = 13$ TeV, 28 nb$^{-1}$ of $p+Pb$ data recorded at $\sqrt{s_{NN}} = 5.02$ TeV, and 7 $\mu$b$^{-1}$ of Pb+Pb data at $\sqrt{s_{NN}} = 2.76$ TeV. In the standard cumulant method, k-particle correlations are calculated in one event as

$$\langle\{2\}\rangle_n = \langle e^{in(\phi_1-\phi_2)}\rangle, \quad \langle\{3\}\rangle_n = \langle e^{in(\phi_1+\phi_2-2\phi_3)}\rangle \quad (1)$$

$$\langle\{4\}_{n,m}\rangle = \langle e^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)}\rangle. \quad (2)$$

The "\langle\rangle" represents average over all tracks in the event. The average is performed using per-particle normalised flow vector $q_{n,l} = \sum_j w_j^l e^{i n \phi_j} / \sum_j w_j^l$ in each event, where $w_j$ is the weight assigned to the $j^{th}$ track. The multi-particle correlations are averaged over events with similar $N_{ch}$. From these double weighted averaged "$\langle\langle\rangle\rangle$" correlations, symmetric and asymmetric cumulants are constructed.
\[ ac_n\{3\} = \langle\langle3\rangle\rangle_n, \quad sc_{n,m}\{4\} = \langle\langle4\rangle\rangle_{n,m} - \langle\langle2\rangle\rangle_n\langle\langle2\rangle\rangle_m. \] (3)

In the absence of non-flow correlations, \(sc_{n,m}\{4\}\) and \(ac_n\{3\}\) measure the correlation between flow harmonics

\[ ac_n\{3\} = \langle v_n^2 v_{2n} \cos 2n(\Phi_n - \Phi_{2n}) \rangle, \quad sc_{n,m}\{4\} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle. \] (4)

To suppress the non-flow in the standard method, the sample of charged tracks is divided into subevents, each covering a unique \(\eta\) interval. Multi-particle correlations are constructed using tracks from different subevents. Two-subevent cumulants can suppress single jets and three(or higher)-subevent cumulants can suppress both jets and dijets. Details on the subevent method can be found in Ref. [11]. Cumulants are normalised with corresponding \(\langle v_n^2 \rangle\) to remove the dependence on single flow harmonics and obtain the actual correlation strength

\[
\begin{align*}
nsc_{2,3}\{4\} &= \frac{sc_{2,3}\{4\}}{v_2^2 v_3^2} = \frac{\langle v_2^2 v_3^2 \rangle}{\langle v_2^2 \rangle \langle v_3^2 \rangle} - 1, \\
nsc_{2,4}\{4\} &= \frac{sc_{2,4}\{4\}}{v_2^2 v_4^2} = \frac{\langle v_2^2 v_4^2 \rangle}{\langle v_2^2 \rangle \langle v_4^2 \rangle} - 1, \\
nac_2\{3\} &= \frac{ac_2\{3\}}{v_2^2 v_4^2} = \frac{\langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle}{\langle v_2^2 \rangle \langle v_4^2 \rangle}. 
\end{align*}
\] (5-7)

The flow harmonics \(v_n(2)^2\) are obtained from two-particle correlation method with peripheral subtraction using a template-fit method [8].

### 3. Results

Figure 1 shows comparison between measurements of \(sc_{2,3}\{4\}\) using standard method and subevent methods for \(pp\), \(p+Pb\) and \(Pb+Pb\) systems (rows) with two different \(p_T\) intervals (columns). In \(Pb+Pb\), anti-correlation is observed and standard and subevent methods give consistent results. In \(p+Pb\), the standard method result is affected by non-flow for \(\langle N_{ch} \rangle < 140\) and is positive for \(\langle N_{ch} \rangle < 100\). The subevent methods show non-flow suppression at all \(\langle N_{ch} \rangle\). In \(pp\), the non-flow effect is largest, the standard method result is positive for all \(N_{ch}\), while subevent method results remain negative even at low \(N_{ch}\). Similar comparisons between the methods for \(sc_{2,4}\{4\}\) and \(ac_2\{3\}\) can be found in Ref. [11]. It is shown that non-flow has little effect in cumulant measurements in \(A+A\) collisions, while the effect is quite significant in small systems. This non-flow in standard method cumulants is suppressed by using the three-subevent method in small systems.
Fig. 1. Comparison of standard and subevent methods $s c_{2,3\{4\}}$ for $p p$, $p+Pb$ and $Pb+Pb$. Figure is taken from Ref. [11].

Figure 2 shows direct comparison of symmetric and asymmetric cumulants for the three systems using the three-subevent method. Anti-correlation between $v_2$ and $v_3$ and correlation between $v_2$ and $v_4$ are observed in all systems. In the $\langle N_{ch} \rangle$ range covered by the $p p$ collisions, the strengths of the correlation are approximately the same across all systems. For higher $\langle N_{ch} \rangle$, the magnitude of correlation is larger for $Pb+Pb$ than $p+Pb$. Figure 3 shows normalised version of the cumulants showing much
weaker dependence on \( \langle N_{\text{ch}} \rangle \). All three systems give similar results for large \( \langle N_{\text{ch}} \rangle \) and a relative 20–30\% difference for smaller \( \langle N_{\text{ch}} \rangle \). The only exception is \( nsc_{2,3}\{4\} \) in \( pp \), which is very different than \( p+Pb \) and \( Pb+Pb \). This is due to under-estimation of \( v_3\{2\} \) for \( pp \) collision from the template fit method \cite{11}.

Fig. 2. System comparison of \( sc_{2,3}\{4\} \), \( sc_{2,4}\{4\} \) and \( ac_{2}\{3\} \) using the three-subevent method. Figure is taken from Ref. \cite{11}.

Fig. 3. System comparison of \( nsc_{2,3}\{4\} \), \( nsc_{2,4}\{4\} \) and \( nac_{2}\{3\} \) using the three-subevent method. Figure is taken from Ref. \cite{11}.

4. Summary

In these proceedings, measurements of \( sc_{2,3}\{4\} \), \( sc_{2,4}\{4\} \) and \( ac_{2}\{3\} \) with the ATLAS detector in \( pp \), \( p+Pb \) and low-multiplicity \( Pb+Pb \) collisions are presented. Standard method is observed to be dominated by non-flow for \( pp \) and low multiplicity \( p+Pb \). Three-subevent cumulants are found to suppress non-flow significantly. Anti-correlation between \( v_2 \) and \( v_3 \) and correlation between \( v_2 \) and \( v_4 \) are observed for all collision systems over the full multiplicity range. The results provide strong evidence for similar behaviour of flow correlations and long-range multi-particle collectivity in \( pp \), \( p+Pb \) and peripheral \( Pb+Pb \) collisions.
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