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+Pb, and Pb+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 \( \langle v_2^n \rangle \) 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+Pb and peripheral Pb+Pb collisions.

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 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 like 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 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 standard cumulant method, k-particle correlations are calculated in one event as:

\[
\{\{2\}\}_n = \langle e^{in(\phi_1 - \phi_2)} \rangle, \{\{3\}\}_n = \langle e^{in(\phi_1 + \phi_2 - 2\phi_3)} \rangle
\]

\[
\{\{4\}\}_{n,m} = \langle e^{in(\phi_1 - \phi_2) + im(\phi_3 - \phi_4)} \rangle
\]

The “\(\langle \rangle\)” represents average over all tracks in the event. The average is performed using per-particle normalised flow vector \(q_{n,l} = \sum_j w_j e^{in\phi_j} / \sum_j w_j\) 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 \rangle” correlations, symmetric and asymmetric cumulants are constructed.

\[
ac_n\{3\} = \langle \{3\}_n \rangle, \quad sc_{n,m}\{4\} = \langle \{4\}_{n,m} \rangle - \langle \{2\}_n \rangle \langle \{2\}_m \rangle
\]  

(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 \(v_n^2\) to remove the dependence on single flow harmonics and obtain the actual correlation strength.

\[
nsc_{2,3}\{4\} = \frac{sc_{2,3}\{4\}}{v_2^2 v_3^2} = \frac{\langle v_3^2 v_3^2 \rangle}{\langle v_2^2 \rangle^2} - 1
\]  

(5)

\[
nsc_{2,4}\{4\} = \frac{sc_{2,4}\{4\}}{v_2^2 v_4^2} = \frac{\langle v_4^2 v_4^2 \rangle}{\langle v_2^2 \rangle^2} - 1
\]  

(6)

\[
nac_2\{3\} = \frac{ac_2\{3\}}{\sqrt{v_2^2 v_2^2}} = \frac{\langle v_2^2 \rangle \langle v_4^4 \rangle}{\langle v_2^2 \rangle^2} - 1
\]  

(7)

The flow harmonics \(v_n^2\) 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 \(pp\), 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 three-subevent method in small systems.

Figure 2 shows direct comparison of symmetric and asymmetric cumulants for the three systems using 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 $pp$ collisions, the strengths of the correlation are approximately 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. All three systems show much weaker dependence on $\langle N_{ch} \rangle$ and give consistent results. Only exception is
\textit{nsc}_{2,3\{4\}} in pp, which is much lower than \textit{p}+\textit{Pb} and \textit{Pb}+\textit{Pb}. This is due to under-estimation of $v_3\{2\}$ for \textit{pp} collision from the template fit method [11].

Fig. 2. System comparison of $sc_{2,3\{4\}}$, $sc_{2,4\{4\}}$ and $ac_{2\{3\}}$ using three subevent method. Figure is taken from Ref.[11]

Fig. 3. System comparison of $nsc_{2,3\{4\}}$, $nsc_{2,4\{4\}}$ and $nac_{2\{3\}}$ using three subevent method. Figure is taken from Ref.[11]

4. Summary

In this proceedings, measurements of $sc_{2,3\{4\}}$, $sc_{2,4\{4\}}$ and $ac_{n\{3\}}$ with ATLAS detector in \textit{pp}, \textit{p}+\textit{Pb} and low-multiplicity \textit{Pb}+\textit{Pb} collisions are presented. Standard method is observed to be dominated by non-flow for \textit{pp} and low multiplicity \textit{p}+\textit{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
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REFERENCES


