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 $\langle v_n^2 \rangle$ 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*+Pb and peripheral Pb+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 Φ_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 η. 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 μb^{-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

$$\langle\{2\}_n\rangle = \left\langle e^{in(\phi_1-\phi_2)}\right\rangle , \qquad \langle\{3\}_n\rangle = \left\langle e^{in(\phi_1+\phi_2-2\phi_3)}\right\rangle \tag{1}$$

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

The "$\langle\rangle$" represents average over all tracks in the event. The average is performed using per-particle normalised flow vector $q_{n;l} = \sum_j w_j^l e^{in\phi_j} / \sum_j w_j^l$ 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

$$ac_n\{3\} = \langle\langle\{3\}_n\rangle\rangle\,, \qquad sc_{n,m}\{4\} = \langle\langle\{4\}_{n,m}\rangle\rangle - \langle\langle\{2\}_n\rangle\rangle\langle\langle\{2\}_m\rangle\rangle\,. \tag{3}$$

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

$$ac_n\{3\} = \left\langle v_n^2 v_{2n} \cos 2n(\Phi_n - \Phi_{2n})\right\rangle\,, \qquad sc_{n,m}\{4\} = \left\langle v_n^2 v_m^2\right\rangle - \left\langle v_n^2\right\rangle\left\langle v_m^2\right\rangle\,. \tag{4}$$

To suppress the non-flow in the standard method, the sample of charged tracks is divided into subevents, each covering a unique η 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

$$nsc_{2,3}\{4\} = \frac{sc_{2,3}\{4\}}{v_2\{2\}^2 v_3\{2\}^2} = \frac{\left\langle v_2^2 v_3^2\right\rangle}{\left\langle v_2^2\right\rangle\left\langle v_3^2\right\rangle} - 1\,, \tag{5}$$

$$nsc_{2,4}\{4\} = \frac{sc_{2,4}\{4\}}{v_2\{2\}^2 v_4\{2\}^2} = \frac{\left\langle v_2^2 v_4^2\right\rangle}{\left\langle v_2^2\right\rangle\left\langle v_4^2\right\rangle} - 1\,, \tag{6}$$

$$nac_2\{3\} = \frac{ac_2\{3\}}{v_2\{2\}^2\sqrt{v_4\{2\}^2}} = \frac{\left\langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\right\rangle}{\left\langle v_2^2\right\rangle\sqrt{\left\langle v_4^2\right\rangle}}\,. \tag{7}$$

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 $\langle N_{\mathrm{ch}}\rangle < 140$ and is positive for $\langle N_{\mathrm{ch}}\rangle < 100$. The subevent methods show non-flow suppression at all $\langle N_{\mathrm{ch}}\rangle$. 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.

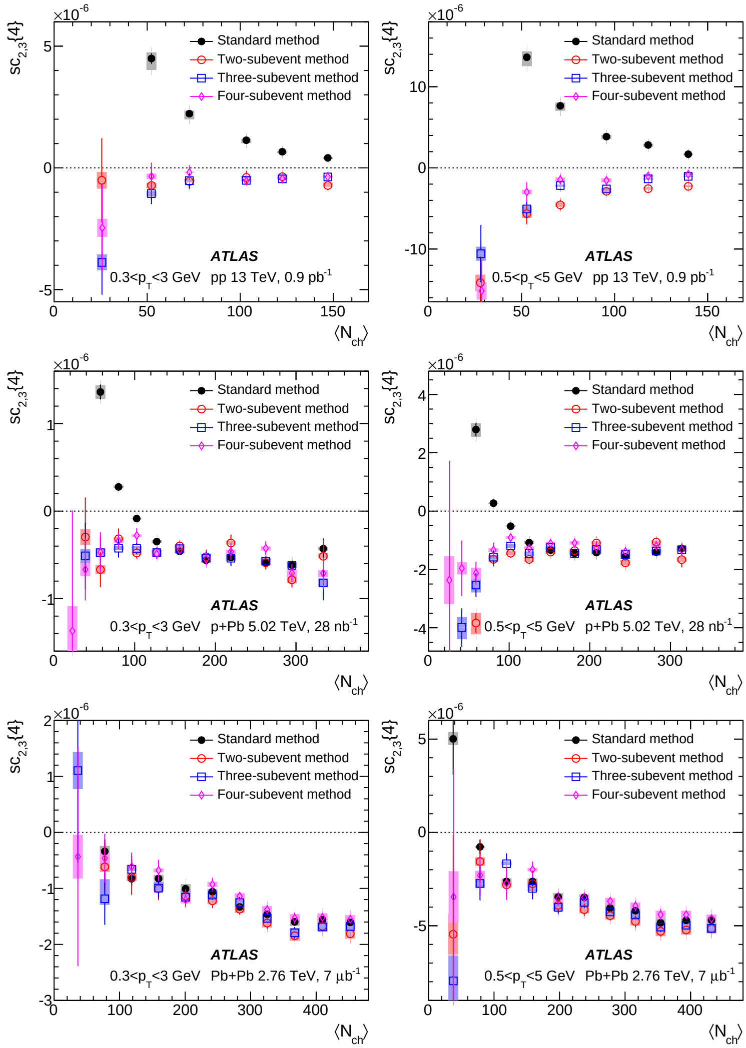

Fig. 1. Comparison of standard and subevent methods $sc_{2,3}\{4\}$ for *pp*, *p*+Pb and Pb+Pb. Figure is taken from Ref. [11].

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 $\langle N_{\rm ch}\rangle$ range covered by the *pp* collisions, the strengths of the correlation are approximately the same across all systems. For higher $\langle N_{\rm ch}\rangle$, 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 $\langle N_{\rm ch}\rangle$. All three systems give similar results for large $\langle N_{\rm ch}\rangle$ and a relative 20–30% difference for smaller $\langle N_{\rm ch}\rangle$. 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 [11].

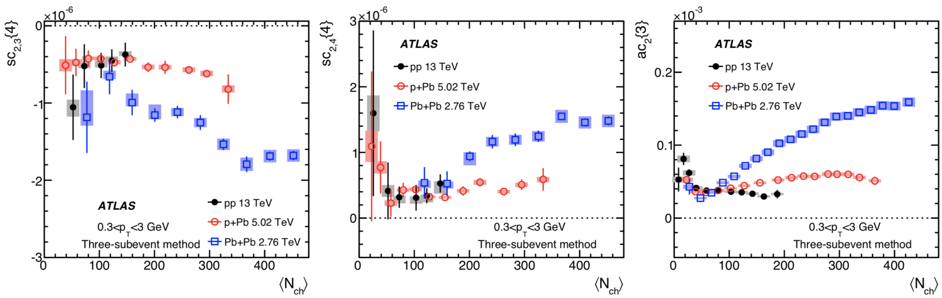

Fig. 2. System comparison of $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and $ac_2\{3\}$ using the three-subevent method. Figure is taken from Ref. [11].

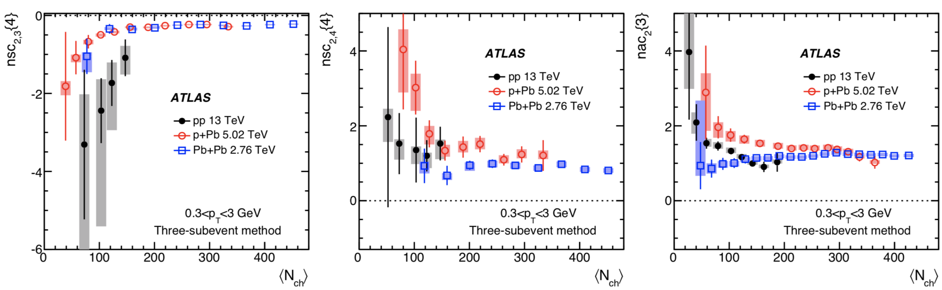

Fig. 3. System comparison of $nsc_{2,3}\{4\}$, $nsc_{2,4}\{4\}$ and $nac_2\{3\}$ using the three-subevent method. Figure is taken from Ref. [11].

4. Summary

In these proceedings, measurements of $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and $ac_n\{3\}$ 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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