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Measurement of the flow harmonic correlations in pp, p+Pb and low multiplicity Pb+Pb collisions with the ATLAS detector at the LHC

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Abstract

Recent measurements of the correlations between flow harmonics obtained using four-particle symmetric cumulants and three-particle asymmetric cumulants with the ATLAS detector at the LHC are described. The data sets of pp, p+Pb and peripheral Pb+Pb collisions at various energies are analyzed, aiming to probe the long-range collective nature of multi-particle production in small systems. The sensitivity of the standard cumulant method to non-flow correlations is investigated by introducing the subevents method. A systematic reduction of non-flow effects is observed when using the two-subevent method. Further reduction is observed with the three-subevent method that is consistent with the results obtained with the four-subevent one. A negative correlation between v_2 and v_3 and a positive correlation between v_2 and v_4, for all studied collision systems and over full multiplicity range, is observed. The correlation strength computed as symmetric cumulants normalized by the $\langle v_n^2 \rangle$ is similar for all collision systems and weakly depends on multiplicity. These measurements provide new evidence for long-range multi-particle collectivity in small collision systems and quantify the nature of its event-by-event fluctuations.

Keywords: QGP, heavy ion collisions, small systems, collectivity, symmetric cumulants, subevent cumulants

1. Introduction

Collective phenomena have been key observables in studies of the properties of the quark-gluon plasma (QGP). Typically the azimuthal distribution of charged particles is characterized by the Fourier decomposition of $\mathrm{d}N/\mathrm{d}\phi \propto 1 + 2\Sigma_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$, where v_n and Φ_n represent the magnitude and the event-plane angle of the n-th flow harmonic. It is understood that in high energy A+A collisions v_n coefficients carry information about the hydrodynamic medium response to the asymmetric initial conditions [1]. The presence of multi-particle correlations in small collision systems such as p+A and pp collisions [2, 3] open up the discussion on whether the physical processes responsible for the observed long range rapidity correlations

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and their azimuthal structure are of the same nature in small systems as in heavy ion collisions. The "symmetric cumulants", $\mathrm{sc}_{n,m}\{4\} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$, are novel observables that measure the correlation between two flow harmonics of different orders, v_n and v_m, using four-particle correlations, and were shown in A+A collisions to have better sensitivity to initial conditions and QGP transport properties than the magnitudes of the single harmonics v_n [4]. The measurement of symmetric cumulants in small systems could shed more light on the properties of the medium created in those collisions. However, experimentally the measurement of flow effects in small systems is sensitive to non-flow arising from correlations among limited number of particles due to, for example, resonance decays or jets production. It was clearly shown that the subevent cumulant method effectively suppresses non-flow in small systems [3] and thus would be essential in the unbiased measurement of the correlation between flow harmonics.

The goal of the analysis is to study the influence of non-flow on the $\mathrm{sc}_{n,m}\{4\}$ measurement and to compare the $v_n - v_m$ harmonics correlation across small and large collision systems. Additionally, the observable that involves correlations among three-particles, termed as "asymmetric cumulants", $\mathrm{ac_n}\{3\} = \langle v_n^2 v_{2n} \cos 2n(\Phi_n - \Phi_{2n}) \rangle$, is proposed to study the correlation of $v_n - v_{2n}$ harmonics. In contrast to $\mathrm{sc}_{n,m}\{4\}$, which measures only the correlation between the magnitude of v_n and v_m, $\mathrm{ac_n}\{3\}$ is sensitive to both the flow magnitude v_n and the flow phase Φ_n.

2. Data analysis

This analysis is based on ATLAS [5] data 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. The mathematical framework for cumulants is based on the Q-cumulant [6] and has been extended to the case of symmetric cumulants [7]. The formalism of the subevent method used for both standard cumulants and symmetric cumulants has been recently presented in [8]. Symmetric and asymmetric cumulants are constructed from the two-, three- and four-particle correlations in the following way:

$$\mathrm{ac}_n\{3\} = \langle\langle \{3\}_n \rangle\rangle\,, \quad \mathrm{sc}_{n,m}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle - \langle\langle \{2\}_n \rangle\rangle \langle\langle \{2\}_m \rangle\rangle\,. \tag{1}$$

The double angular brackets ($\langle\langle\rangle\rangle$) indicate that the averaging procedure has been performed in two steps. In the first step, the average is taken over all distinct particle multiplets in an event. In the second step, the average is calculated over an ensemble of events with similar $\langle \mathrm{N_{ch}} \rangle$, efficiency-corrected average number of charged particles. In the standard cumulant method all k-particle multiplets involved in $\langle\langle \{k\}_n \rangle\rangle$ and $\langle\langle \{k\}_{n,m} \rangle\rangle$ are selected using tracks from the entire detector pseudorapidity acceptance ($|\eta| < 2.5$). While four-particle correlations are sufficient to suppress non-flow effects in A+A collisions, this is not the case in small systems. To suppress further the non-flow correlations that typically involve a few particles within a localized region in η, the sample of charged particle tracks is divided into subevents, each covering a unique η interval. The multi-particle correlations are then constructed by only correlating tracks between different subevents. In the case of using two subevents, labeled a and b, the detector η acceptance is split in half and the per-event k-particle azimuthal correlations are constructed by correlating tracks from subevent a with tracks from subevent b. Here the $\mathrm{ac_n}\{3\}$ and $\mathrm{sc}_{n,m}\{4\}$ are defined as [8]:

$$\mathrm{ac}_n^{2a|b}\{3\} = \langle\langle \{3\}_n \rangle\rangle_{2a|b}\,, \quad \mathrm{sc}_{n,m}^{2a|2b}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle_{2a|2b} - \langle\langle \{2\}_n \rangle\rangle_{a|b} \langle\langle \{2\}_m \rangle\rangle_{a|b}\,. \tag{2}$$

Similarly, in the three-subevent method, the η acceptance is divided in three equal subevents a, b and c, which gives:

$$\mathrm{ac}_n^{a,b|c}\{3\} = \langle\langle \{3\}_n \rangle\rangle_{a,b|c}\,, \quad \mathrm{sc}_{n,m}^{a,b|2c}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle_{a,b|2c} - \langle\langle \{2\}_n \rangle\rangle_{a|c} \langle\langle \{2\}_m \rangle\rangle_{b|c}\,. \tag{3}$$

In the case of the four-subevent method, each of the subevents covers one fourth of the η acceptance, and the corresponding cumulant is defined as:

$$\mathrm{sc}_{n,m}^{a,b|c,d}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle_{a,b|c,d} - \langle\langle \{2\}_n \rangle\rangle_{a|c} \langle\langle \{2\}_m \rangle\rangle_{b|d}\,. \tag{4}$$

In order to improve statistical precision, results obtained from all combinations of subevents a, b, c (and d in the case of $\mathrm{sc}_{n,m}\{4\}$) are averaged to obtain the final values. The complete analysis description can be found in the ATLAS publication [9].

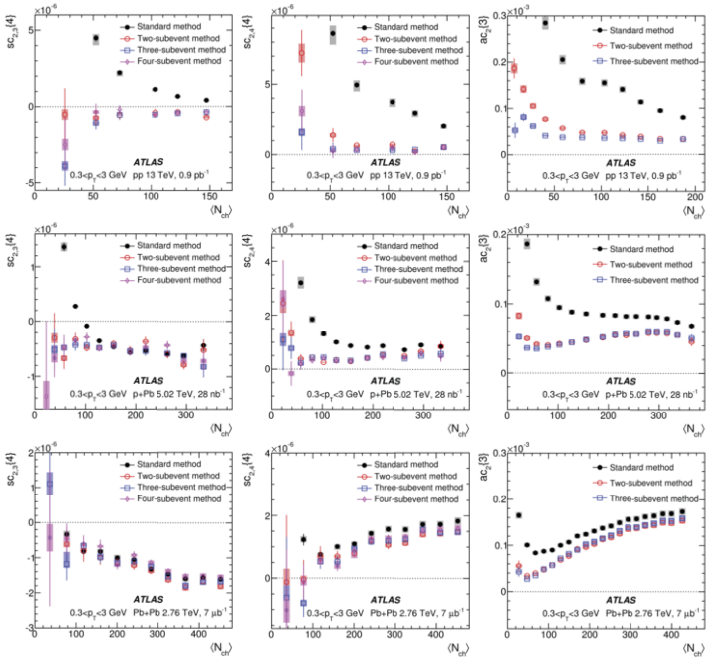

Fig. 1. The symmetric cumulants $sc_{2,3}\{4\}$ (left column), $sc_{2,4}\{4\}$ (middle column) and asymmetric cumulant $ac_2\{3\}$ (right column) as a function of $\langle N_{ch}\rangle$ obtained for *pp* collisions (top row), *p*+Pb collisions (middle row) and low-multiplicity Pb+Pb collisions (bottom row) [9]. In each panel, the results are obtained from the standard method (filled symbols), the two-subevent method (open circles), three-subevent method (open squares) and in the case of symmetric cumulants four-subevent method (open diamonds). The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively.

3. Results

Figure 1 compares the $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and $ac_2\{3\}$ (columns) obtained from the standard, two-, three- and four-subevent methods in *pp*, *p*+Pb and Pb+Pb collisions (rows). Values of the symmetric and asymmetric cumulants from the standard method in *pp* collisions (top row) are significantly larger than the values from the subevent methods that are in good agreement with each other. This is due to the strong influence of non-flow effects. In the most extreme case, the $sc_{2,3}\{4\}$ obtained with the standard method shows a positive correlation of v_2 and v_3 that is reduced to an anti-correlation after suppressing the non-flow with the subevent technique. In *p*+Pb collisions (middle row) the most pronounced difference between the standard and subevent cumulants is seen for the events with $\langle N_{ch}\rangle < 140$. Again, the $sc_{2,3}\{4\}$ at lower multiplicities shows a positive correlation between v_2 and v_3 that changes sign when the subevent method is applied. On the other hand, the $v_2 - v_4$ correlation is positive over the entire measured $\langle N_{ch}\rangle$ range, as measured by $sc_{2,4}\{4\}$ and $ac_2\{3\}$. Interestingly, for $\langle N_{ch}\rangle > 200$ values from the standard method are systematically larger than those obtained from the subevent method. Similar behaviour is observed in Pb+Pb collisions (bottom row) in the high $\langle N_{ch}\rangle$ region. This difference may be caused by non-flow contributions or could be attributed to flow decorrelation effects that are more significant in the case of the v_4 harmonic [10]. No differences are observed between the three- and four-subevent methods, indicating that with three subevents most of the non-flow effects are suppressed. As can be seen in Figure 1, $ac_2\{3\}$ reproduces all features observed in $sc_{2,4}\{4\}$, while it is measured with much better statistical precision thanks to the larger magnitude and larger number of three particle multiplets.

A direct comparison of the cumulants in the three collision systems using the three-subevent method is shown in Figure 2. The top row shows the results for $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and $ac_2\{3\}$. An anti-correlation

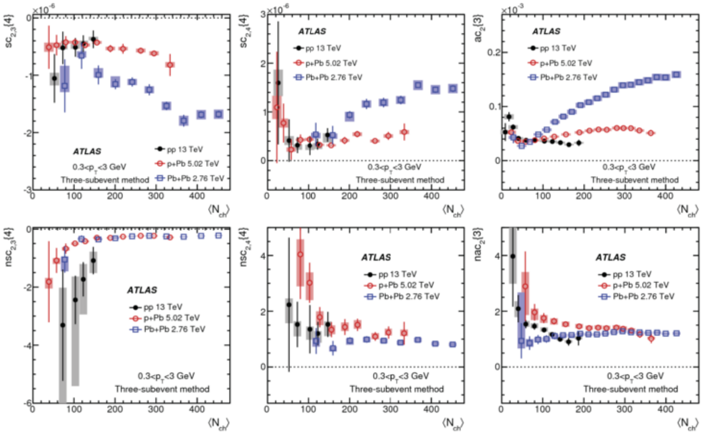

Fig. 2. The top row shows the $\langle N_{ch} \rangle$ dependence of $sc_{2,3}\{4\}$ (left column), $sc_{2,4}\{4\}$ (middle column) and $ac_2\{3\}$ (right column) obtained for *pp* collisions (solid circles), *p*+Pb collisions (open circles) and low-multiplicity Pb+Pb collisions (open squares) [9]. The bottom row shows the normalized versions of symmetric and asymmetric cumulants. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively.

between v_2 and v_3 and a correlation between v_2 and v_4 is observed in all systems. The strength of the correlation in the $\langle N_{ch} \rangle$ range covered by *pp* collisions is approximately the same across all systems and, for higher $\langle N_{ch} \rangle$, increases faster for Pb+Pb than for *p*+Pb collisions. To further investigate the strength of the correlation across different colliding systems and separate the contribution from the magnitudes of the flow harmonics, the $sc_{2,3}\{4\}$, $sc_{2,4}\{4\}$ and $ac_2\{3\}$ are normalized by the values of the corresponding v_n coefficients obtained from the two-particle correlation method [9] (Figure 2 bottom row). The normalized cumulants show much weaker multiplicity dependence than the unnormalized cumulants and are similar for different collision systems even at high $\langle N_{ch} \rangle$. The only exception is the normalized $sc_{2,3}\{4\}$ in *pp* interactions, which is significantly different from the $sc_{2,3}\{4\}$ measured in *p*+Pb and Pb+Pb collisions. As was already noticed in [11], the template fit with perhipheral subtraction tends to underestimate the odd harmonics, in this case v_3. The results presented here provide a further evidence that azimuthal correlations in small systems behave similarly to heavy ion collisions.

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