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Flow fluctuations in Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ATLAS detector

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Abstract

Measurements of four-particle cumulants $c_n\{4\}$ for $n = 1, 2, 3, 4$ are presented using 470 μb^{-1} of Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ATLAS detector at the LHC. These cumulants provide information on the event-by-event fluctuations of single harmonics $p(v_n)$. For the first time, a negative $c_1\{4\}$ is observed. The $c_4\{4\}$ is found to be negative in central collisions but changes sign around 20 – 25% centrality. This behavior is consistent with a nonlinear contribution to v_4 that is proportional to v_2^2. $c_2\{4\}$ and $c_3\{4\}$ are calculated using two reference event classes in order to investigate the influence of volume fluctuations. Over most of the centrality range, $c_2\{4\}$ and $c_3\{4\}$ are found to be negative, while in the ultra-central collisions, $c_2\{4\}$ changes sign and becomes positive, suggesting a deviation from Gaussian behavior in the event-by-event fluctuation of v_2. The magnitudes of the sign change are also found to be dependent of the event class definition.

Keywords: Multi-Particle Correlation, Cumulants, Heavy-ion, Flow Fluctuation

1. Introduction

Heavy-ion collisions at RHIC and the LHC create hot, dense matter whose space-time evolution is well described by relativistic viscous hydrodynamics [1]. Owing to strong event-by-event density fluctuations in the initial state, the distributions of the final-state particles also fluctuate event by event. These fluctuations lead to harmonic modulation of the particle densities in the azimuthal angle ϕ, characterized by a Fourier expansion $d\text{N}/d\phi \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)$, where v_n and Φ_n represent the magnitude and event-plane angle of the $n^{\rm th}$-order harmonic flow.

One important observable for studying the initial condition and final state dynamics of the medium is the probability density distribution $p(v_n)$ for events selected with similar centrality. They are directly related to event-by-event fluctuations of the eccentricities $p(\epsilon_n)$ [2], where ϵ_n describes the $n^{\rm th}$-order shape component in the initial state. In order to study the $p(v_n)$, multi-particle azimuthal correlations within the cumulant framework has been applied [3]. The $p(v_n)$ distribution can be inferred from $2k$-particle cumulants $c_n\{2k\}$,

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which are related to the moments of the $p(v_n)$. Most models of the initial state of A+A collisions predict a $p(v_n)$ whose shape is close to Gaussian, and that the four-particle cumulants $c_n\{4\}$ are zero or negative [4].

In heavy-ion collisions, v_n coefficients are often calculated for events with similar activity, defined as the particle multiplicity in a fixed pseudorapidity range. Due to fluctuations in the particle production process, the centrality for events selected to have the same particle multiplicity fluctuates from event to event. Since the v_n coefficients change with centrality, fluctuation of centrality may lead to additional fluctuations of v_n, which broaden the underlying $p(v_n)$ distribution. These centrality fluctuations, more commonly known as volume fluctuations, have been shown to contribute significantly to the event-by-event fluctuation of conserved quantities [5]. In this measurement, two reference event classes are used in the calculation of cumulants to study the influence of volume fluctuations on the flow cumulants.

2. Analysis details

This analysis uses 470 μb^{-1} of Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV collected by ATLAS [6]. The measurements are performed using the inner detector, the forward calorimeters (FCal), and the zero-degree calorimeters. To increase the number of recorded events from very central Pb+Pb collisions, a dedicated L1 trigger was used to select events requiring the total transverse energy (ΣE_T) in the FCal to be more than multiple threshold values.

The $c_n\{4\}$ for $n = 1, 2, 3, 4$ are calculated using the Q-cumulant method for charged particles in $|\eta| < 2.5$. The method calculates $2k$-particle azimuthal correlations $\langle\{2k\}_n\rangle$, and $2k$-particle cumulants, $c_n\{2k\}$, for the n^{th}-order flow harmonics. The two- and four-particle correlations in one event are obtained as:

$$\langle\{2\}_n\rangle = \langle e^{in(\phi_1-\phi_2)}\rangle, \langle\{4\}_n\rangle = \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle \quad (1)$$

where "$\langle\rangle$" denotes a single-event average over all pairs or quadruplets, respectively. The averages from Eq. 1 can be expressed in terms of per-particle normalized flow vectors $\boldsymbol{q}_{n;l}$ with $l = 1, 2...$ in each event: $\boldsymbol{q}_{n;l} \equiv \sum_j w_j^l e^{in\phi_j} / \sum_j w_j^l$, where the sum runs over all M particles in the event and w_j is a weight assigned to the j^{th} particle.

The two- and four-particle cumulants are obtained from the azimuthal correlations as:

$$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle, c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2 \quad (2)$$

where "$\langle\langle\rangle\rangle$" represents a weighted average of $\langle\{2k\}_n\rangle$ over an event ensemble, defined as events in either a narrow interval of ΣE_T or a narrow interval of $N_{\text{ch}}^{\text{rec}}$, the number of reconstructed charged particles in $0.5 < p_T < 5$ GeV. The $c_n\{4\}$ is then calculated separately for the two types of reference event classes, denoted as $c_n\{4, \Sigma E_T\}$ and $c_n\{4, N_{\text{ch}}^{\text{rec}}\}$, respectively. Furthermore, the recently proposed three-subevent cumulant method is also applied to quantify the residual non-flow contributions [7].

3. Results and discussions

Figure 1 shows the centrality dependence of $c_1\{4\}$ in several p_T ranges, obtained from the reference event class based on ΣE_T. In the hydrodynamic picture, $c_1\{4\}$ is sensitive to event-by-event fluctuations of the dipolar eccentricity ϵ_1 associated with initial-state geometry. Previously ATLAS measured v_1 using two-particle correlation method in Pb+Pb collisions at 2.76 TeV [8]: the $v_1\{2\}$ is observed to be negative at low p_T, change sign at $p_T \approx 1.2$ GeV, and increase quickly towards higher p_T. Therefore, it is naturally expected that a $c_1\{4\}$ signal is larger and therefore easier to measure at higher p_T. Furthermore, $c_1\{4\}$ are observed to be consistent in both the standard and three-subevent cumulant methods, suggesting that the influence of non-flow correlations is small.

Figure 2 shows the centrality dependence of $c_4\{4\}$ in several p_T ranges. The $c_4\{4\}$ values are negative in central collisions but change sign in the 25 − 30% centrality range. The centrality value at which the sign change occurs shifts towards more peripheral collisions as the p_T of the particles increases. It is well established that the v_4 in Pb+Pb collisions contains a linear contribution associated with initial geometry and

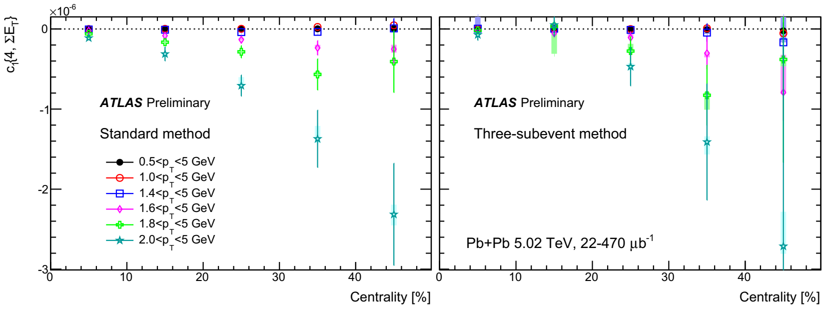

Fig. 1. The $c_1\{4\}$ calculated for charged particles in several p_T ranges with the standard cumulant method (left) and three-subevent method (right). The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively. Figure is taken from [9].

a mode-mixing contribution from lower-order harmonics due to nonlinear hydrodynamic response [10] $\boldsymbol{v}_4 = \boldsymbol{v}_{4L} + \beta \boldsymbol{v}_2^2$, where the linear component $\boldsymbol{v}_{4L}$ is driven by the corresponding eccentricity in the initial geometry, and β is a constant. Therefore this sign-change reflects the interplay between these two contributions: in central collisions, $c_4\{4\}$ is dominated by the negative contribution from $p(v_{4L})$, while in peripheral collisions $c_4\{4\}$ is dominated by the positive contribution from $p(v_2^2)$, even though the four-particle cumulant for $p(v_2)$ is negative. The change of the crossing point with p_T suggests that the relative contributions from these two sources are also a function of p_T.

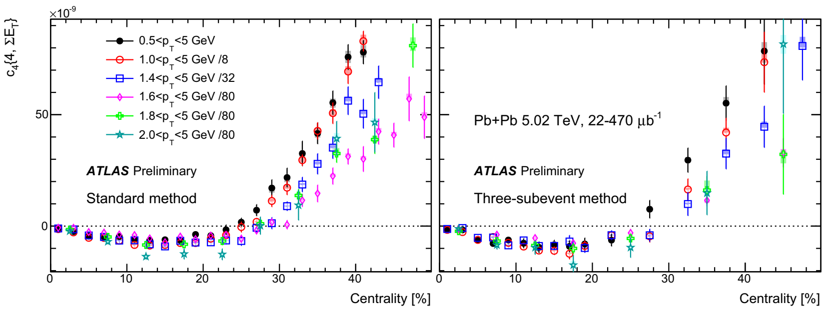

Fig. 2. The $c_4\{4\}$ calculated for charged particles in several p_T ranges with the standard cumulant method (left) and three-subevent method (right). The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively. The data for each p_T range are scaled by a constant factor indicated in the legend for the purpose of presentation. Figure is taken from [9].

Figure 3 compare the $c_2\{4\}$ and $c_3\{4\}$ obtained for the ΣE_T reference event class with those obtained for the N_{ch}^{rec} reference event class. They are obtained using the standard cumulant method. Events with the same N_{ch}^{rec} may have different ΣE_T, therefore the $c_n\{4\}$ values depend on the exact definition of reference event class used for averaging, due to a change in $p(v_n)$ associated with each reference event class. This comparison can shed light on the fine details of flow fluctuations and how they are correlated with centrality definition [5]. The figures show that the trends of the centrality dependence are very similar in both cases. However, the $c_3\{4, N_{ch}^{rec}\}$ values are significantly larger than the $c_3\{4, \Sigma E_T\}$ values.

The insert panels of Figure 3 show the trend of $c_2\{4\}$ and $c_3\{4\}$ in the ultra central collision range of $0 - 4.5\%$. The $c_2\{4, N_{ch}^{rec}\}$ values are significantly larger than $c_2\{4, \Sigma E_T\}$, and both quantities change sign and become positive toward more central collisions. In contrast, the $c_3\{4, N_{ch}^{rec}\}$ values suggest a change of sign in the same centrality range, although the $c_3\{4, \Sigma E_T\}$ always remains negative. All these observations indicate that volume fluctuation plays an important role in the flow cumulant measurement.

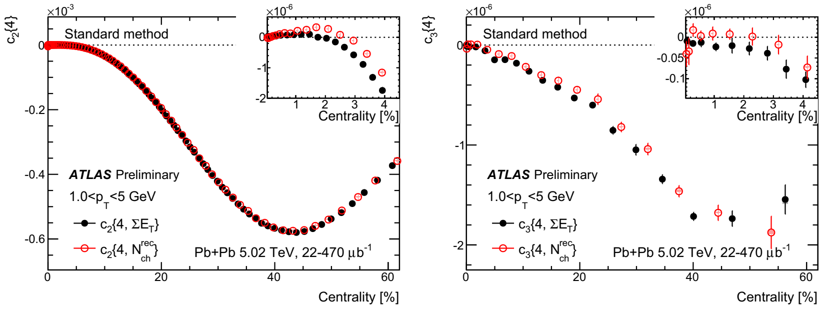

Fig. 3. The $c_2\{4\}$ (left) and $c_3\{4\}$ (right) calculated with ΣE_T and N_{ch}^{rec} event classes. The insert panels show the zoomed-in view of the trend of the data in the most central collisions. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively. Figure is taken from [9].

4. Summary

Measurements of four-particle cumulants $c_n\{4\}$ are presented using 470 μb^{-1} of Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with the ATLAS detector at the LHC. This proceedings provide the first measurement of a negative $c_1\{4\}$, which sheds light on the nature of the dipolar eccentricity fluctuation in the initial-state geometry. The values of $c_4\{4\}$ are found to be negative in central collisions but change sign around 20 − 25% centrality and increase quickly for more peripheral collisions. This behavior is consistent with a nonlinear contribution to v_4 that is proportional to v_2^2. In the ultra-central collisions, $c_2\{4\}$ changes sign and becomes positive. It also depends on the choice of the reference event class, suggesting the volume fluctuation should be considered in future flow cumulant measurement. These results provide new insights on the fluctuations of the initial-state geometry, especially in the ultra-central collisions, as well as the final-state dynamical evolution of the medium.

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