



# Investigations of anisotropic collectivity using multi-particle correlations in pp, p–Pb and Pb–Pb collisions

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## Abstract

Two- and multi-particle azimuthal correlations have proven to be an excellent tool to probe the properties of the strongly interacting matter created in heavy-ion collisions. Recently, the results obtained for multi-particle cumulants have been interpreted as evidence for collectivity in the small collision systems (pp and p–Pb) providing new insights into the systems' fluctuating initial conditions. In this article, first ALICE results on two- and multi-particle cumulants as a function of charged hadron multiplicity produced at midrapidity ( $|\eta| < 1.0$ ) in pp collisions at  $\sqrt{s} = 13$  TeV are reported. The results are compared with measurements in p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and in Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. A new method for the 4-particle cumulant with an  $\eta$  gap denoted as  $c_n\{4, |\Delta\eta|\}$  will be presented, which is capable of further suppressing non-flow effects in multi-particle cumulants. The results allow for further understanding of the origin of multi-particle correlations in pp collisions.

**Keywords:** LHC, ALICE, small systems, anisotropic flow, cumulants

## 1. Introduction

Measurements of anisotropic flow harmonic coefficients are sensitive to the properties of strongly interacting matter created in heavy-ion collisions, the so-called Quark–Gluon Plasma (QGP), and led to its description as a nearly perfect fluid [1]. Anisotropic flow harmonic coefficients  $v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$  are obtained from the Fourier expansion of azimuthal particle distributions in the final state relative to the symmetry plane [2]

$$\frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n e^{in(\varphi - \psi_n)}, \quad (1)$$

where  $v_n$  are the flow coefficients,  $\varphi$  is the azimuthal angle of particles and  $\psi_n$  is the symmetry plane of  $n$ -th harmonic.

Small collision systems, such as p–Pb or pp collisions, were considered as reference without signatures of QGP formation. However, a growing number of measurements in high multiplicity p–Pb collisions exhibit similar features as in Pb–Pb collisions. One of the promising probes of collectivity are multi-particle cumulants, which directly probe correlations among many particles (collective flow). A negative sign of the 4-particle cumulant, which is essential for the extraction of a non-imaginary anisotropic flow coefficient, was

observed in high multiplicity p–Pb collisions (see e.g. [3, 4, 5]). Recent observations of a long-range ridge-like structure in 2-particle correlations [6, 7, 8] and a negative 4-particle cumulant [8] in high multiplicity pp collisions suggest that particles show collective behavior also in smaller collision systems. Although multi-particle cumulants suppress non-flow effects (correlations of few particles, e.g. resonance decays) from lower order correlations, this might not be sufficient in pp collisions. Here, ALICE measurements of 2- and 4-particle cumulants in various collision systems with a focus on pp collisions and results using a new method for further reduction of non-flow effects are presented.

## 2. Analysis details

The data sample used for this analysis was recorded by ALICE during the Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV (2010), p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV (2013) and pp collisions at  $\sqrt{s} = 13$  TeV (2015) at the LHC. Collisions of Pb–Pb were collected with a minimum-bias trigger requiring coincidence of signals between two forward detectors (V0A and V0C). Apart from the minimum-bias trigger, events of p–Pb and pp collisions were also selected with a high multiplicity trigger requiring a large number of hits in the Silicon Pixel Detector (SPD). The results reported here were obtained from 9.2M Pb–Pb minimum-bias events, 58M minimum-bias and 1.3M high multiplicity p–Pb events, and finally 52M minimum-bias and 36M pp events from the high multiplicity trigger. For more information about the ALICE detector and its performance, please refer to [9].

Only charged particles with full azimuthal coverage in a pseudorapidity range  $|\eta| < 1.0$  were used for this analysis. Cumulants were extracted using the generic framework and corrected for non-uniform acceptance and tracking efficiency by weighting the Q-vectors as described in [10]. In particular, 2- and 4-particle cumulants are measured

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

where  $\langle\langle m \rangle\rangle$  represents the event average of  $m$ -particle azimuthal correlation. We note here that a negative sign of the 4-particle cumulant is crucial for the extraction of a real value of anisotropic flow harmonic ( $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$ ). A new method called the 4-particle cumulant with  $\eta$  gap,  $c_n\{4, |\Delta\eta|\}$  is introduced

$$c_n\{4, |\Delta\eta|\} = \langle\langle 4 \rangle\rangle_{|\Delta\eta|} - 2 \cdot \langle\langle 2 \rangle\rangle_{|\Delta\eta|}^2. \quad (3)$$

As opposed to the  $c_2\{4\}$  measurement where particles from the whole detector volume are included in the correlation, this observable correlates particles from two subevents separated by an  $\eta$  gap. This method should be able to further reduce non-flow effects which is especially important for non-flow dominated systems.

## 3. Results

Figure 1 presents the multiplicity dependence of 2- and 4-particle cumulants for different collision systems. The cumulant  $c_2\{2, |\Delta\eta| > 1.4\}$  increases with multiplicity in Pb–Pb and p–Pb collisions [5], while a very weak dependence is observed in pp collisions. In Fig. 1 (right) we find that while measurements from Pb–Pb and p–Pb collisions show a clearly negative sign of  $c_2\{4\}$  at high multiplicities, a negative sign of  $c_2\{4\}$  is not observed in pp collisions in a similar multiplicity range within uncertainties. No indication of collective behavior in pp collisions can be observed using standard cumulant measurements.

In a flow dominated system  $v_n\{4\}$  increases as a function of transverse momentum  $p_T$ , i.e.  $c_2\{4\}$  decreases to large negative values. On the other hand, non-flow effects should drive the  $c_2\{4\}$  to positive values.

Figure 2 (left) shows the 4-particle cumulant as a function of multiplicity in p–Pb collisions for three different  $p_T$  intervals [5]. Measurements of  $c_2\{4\}$  are positive at low multiplicities and increase with increasing minimum  $p_T$ . This indicates the presence of non-flow. In contrast, at high multiplicities  $c_2\{4\}$  decreases with increasing minimum  $p_T$ , suggesting that flow starts to override the non-flow effects and becomes dominant.

A similar study has been performed in pp collisions, as shown in Fig. 2 (right). While  $c_2\{4\}$  is observed to be negative at high multiplicities and decreasing with increasing minimum  $p_T$  in p–Pb (and Pb–Pb)

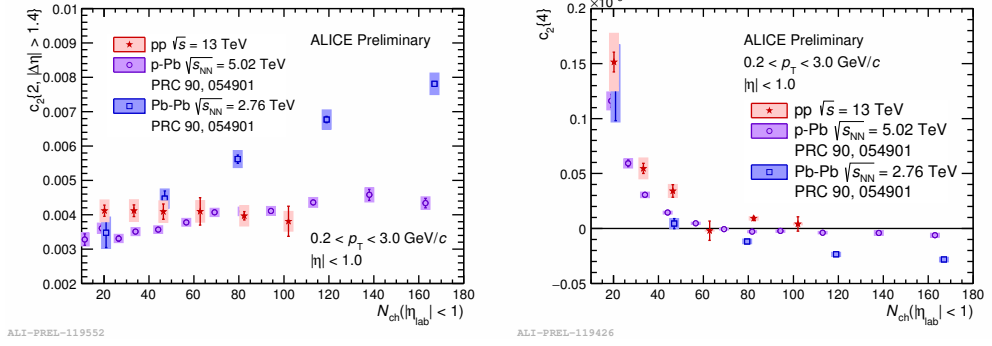


Fig. 1. Left: Multiplicity dependence of  $c_2\{2, |\Delta\eta| > 1.4\}$  from different collision systems. Right: Multiplicity dependence of 4-particle cumulant  $c_2\{4\}$  from different collision systems.

collisions,  $c_2\{4\}$  stays positive and increases with increasing minimum  $p_T$  in pp collisions at similar multiplicities. These observations again suggest that no collective expansion of the medium is established in high multiplicity pp collisions using standard cumulant measurements.

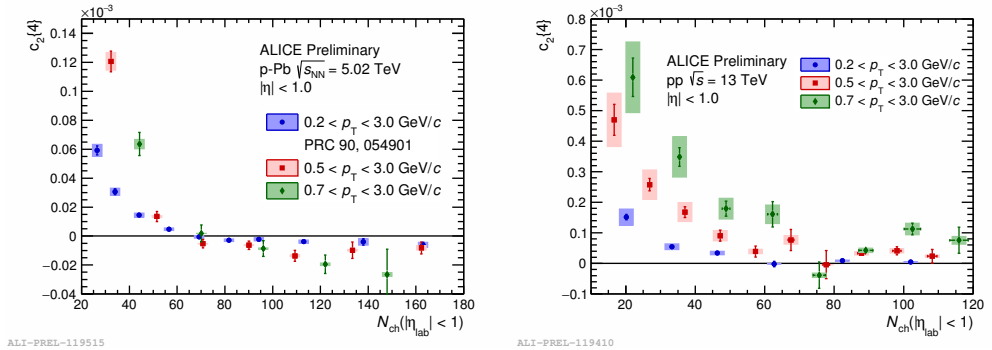


Fig. 2. Left: Multiplicity dependence of 4-particle cumulant  $c_2\{4\}$  in p-Pb collisions for different regions of transverse momentum. Right: Multiplicity dependence of 4-particle cumulant  $c_2\{4\}$  in pp collisions for different regions of transverse momentum.

Increasing the minimum  $p_T$  threshold did not reveal a negative sign of the 4-particle cumulant in high multiplicity pp collisions. This result alone is not conclusive as it is not clear whether the relative influences of flow and non-flow in small collision systems can be easily disentangled by looking at the sign of  $c_2\{4\}$  alone. A different approach is therefore described in this section, which aims for further suppression of non-flow in multi-particle cumulants. The new method, 4-particle cumulant with  $\eta$  gap, was introduced in section 2 and the first results are presented here.

The method was first tested with the PYTHIA8 event generator [11] and demonstrated the ability to further suppress the non-flow effects in multi-particle cumulants. Differences between the measurements with and without pseudorapidity gap are visible for the whole multiplicity region in p-Pb collisions (Fig. 3 (left)), and are more pronounced at smaller multiplicities. The values of  $c_2\{4, |\Delta\eta|\}$  for pp collisions are smaller than in the measurement without pseudorapidity gap. The effect is most visible at low multiplicities, as illustrated in Fig. 3 (right). These observations suggest that  $c_2\{4, |\Delta\eta|\}$  is less sensitive to non-flow effects from correlations among few particles.

Furthermore, no significant flow signal is observed in measurements of  $c_2\{4, |\Delta\eta|\}$  in high multiplicity pp collisions, even after reducing the contribution from non-flow.

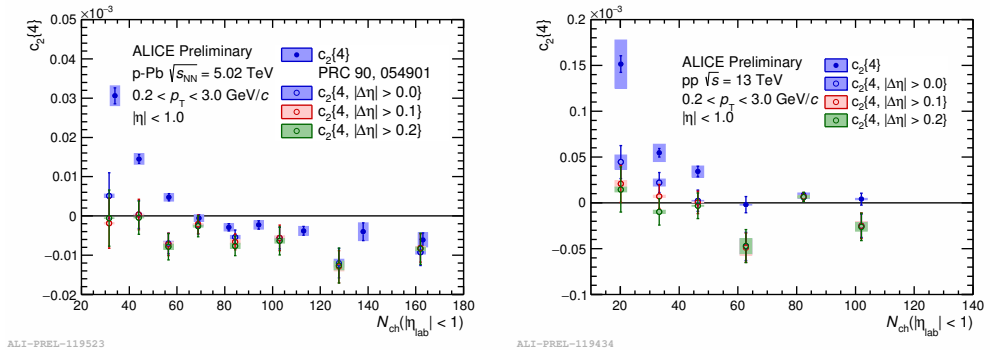


Fig. 3. Left: Multiplicity dependence of different 4-particle cumulant methods,  $c_2\{4\}$  and  $c_2\{4, |\Delta\eta|\}$  in p–Pb collisions. Right: Multiplicity dependence of different 4-particle cumulant methods,  $c_2\{4\}$  and  $c_2\{4, |\Delta\eta|\}$  in pp collisions.

#### 4. Summary

We have presented measurements of 2- and 4-particle cumulants in Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and in particular for pp collisions at  $\sqrt{s} = 13$  TeV. The measurement of  $c_2\{4\}$  in Pb–Pb and high multiplicity p–Pb collisions exhibits a negative sign suggesting collectivity of the created matter expansion in these collisions, which is not observed within uncertainties in high multiplicity pp collisions. No signs of collectivity are revealed in pp collisions even after increasing the minimum  $p_T$ , while it has the expected effect of a decrease of  $c_2\{4\}$  in Pb–Pb and p–Pb collisions. Eventually, a new method of the 4-particle cumulant with  $\eta$  gap was presented. The measured values of  $c_2\{4, |\Delta\eta|\}$  decrease w.r.t.  $c_2\{4\}$  in both p–Pb and pp collisions, validating the ability for a further reduction of non-flow effects in small systems. Because of the limited statistical precision in the analyzed data set a final conclusion about the presence of collectivity in high multiplicity pp collisions can not be drawn. More high quality data to be collected and reconstructed in future will allow us to investigate the anisotropic collectivity in small systems in more detail.

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