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New insights of multi-particle azimuthal correlations with symmetric cumulants in p-p, p-Pb, and Pb-Pb collisions

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Abstract

The first comparison of anisotropy harmonics (v_n, n = 2–4) and event-by-event correlations of different orders between p–p (13 TeV), p–Pb (5.02 and 8.16 TeV) and Pb–Pb (5.02 TeV) as a function of multiplicity is presented. The v_n coefficients are extracted via long-range ($|\Delta\eta| > 2$) two-particle correlations reaching a very-high-multiplicity region. Event-by-event correlations among v_2, v_3 and v_4 are measured using the four-particle symmetric cumulant (SC(n,m), n = 2, m = 3, 4). For high-multiplicity (more than 100 tracks) events, v_2 is found to have a negative correlation with the v_3, while the v_2 and v_4 are positively correlated. Normalized by the two-particle v_n, the SC(2,3) are quantitatively similar for p–Pb and Pb–Pb data, while a strong system size dependence is observed for SC(2,4). These new data provide important insights to the origin of collectivity observed in small collision systems.

Keywords: LHC, CMS, QGP, Heavy Ion, small systems, flow, correlations, symmetric cumulants, fluctuations

1. Introduction

Over the past decades, the properties of the hot, dense and strongly interacting matter known as Quark-Gluon Plasma (QGP) were extensively studied in ultrarelativistic nucleus-nucleus (A–A) collisions. In particular, the particles produced in such collisions exhibit a collective behavior which translate into an azimuthal anisotropy in the particle final-state distribution. This effect is called anisotropic flow and implies that all particles are correlated, event-by-event, to a common plane (event plane). This is well understood with hydrodynamics and infers that the QGP behaves like a nearly perfect fluid. In practice, the azimuthal correlations of emitted particle pairs are typically characterized by a Fourier serie decomposition and its coefficients (v_n). In particular, the second (v_2) and the third (v_3) coefficients are known as elliptic and triangular flow, respectively. These coefficients are carrying information about the medium response to the initial collision geometry and its fluctuations [1].

Surprisingly, CMS reported that v_n coefficients exhibit similar behavior when measured in high-multiplicity p–p or p–A collisions [2, 3, 4]. It has been recently established that the observed azimuthal anisotropy in the final-state results from a collective behavior of the particles produced in such collisions [5, 6]. Nevertheless, the collective mechanism behind this effect remains unclear and further detailed studies are needed.

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In particular, the ability of hydrodynamic calculations to describe the experimental results in small systems has to be tested [7].

One way to access a deeper level of details in our understanding of this final-state azimuthal anisotropy in all colliding systems is to measure the correlations between Fourier harmonic coefficients. In A–A, these correlations have been shown to be strongly sensitive to initial-state fluctuations and medium transport coefficients [8].

In the following, using data collected by the CMS experiment, the measurement of anisotropy harmonics (v_n, n=2-4) and event-by-event correlations of different v_n are presented in p–p, p–Pb and Pb–Pb collisions. The v_n results are extracted via long-range ($|\Delta\eta| > 2$) two-particle correlations as a function of event multiplicity. Event-by-event correlations of v_2 v.s. v_3 and v_2 v.s. v_4 are measured using four-particle Symmetric Cumulant (SC) method in all colliding systems available at the LHC.

2. Analysis technique

A detail description of the CMS detector can be found in Ref. [9] and more details about the analysis can be found in Ref. [10]. The v_n coefficients are extracted using a long-range ($|\Delta\eta| > 2$) two-particle correlations as already performed in previous CMS papers where the particle pair distribution can be expressed as:

$$\frac{dN_{pair}}{d\phi} \propto 1 + 2\sum_n V_{n\Delta}\cos[n\Delta\phi], \tag{1}$$

where, the Fourier coefficients, $V_{n\Delta}$, can be expressed in term of the product of single-particle anisotropy harmonic as:

$$V_{n\Delta} = v_n^2 \,. \tag{2}$$

The SC technique was first introduced by the ALICE collaboration [8] and is based on a 4-particle correlation calculations with cumulants. To study the correlation between an harmonic n and m, one can build 2-and 4-particle correlator with:

$$\langle\langle 4\rangle\rangle_{n,m} \equiv \left\langle\left\langle e^{i(n\phi_1+m\phi_2-n\phi_3-m\phi_4)}\right\rangle\right\rangle \sim \left\langle v_n^2 v_m^2\right\rangle,\ \langle\langle 2\rangle\rangle_n \equiv \left\langle\left\langle e^{i(n\phi_1-n\phi_2)}\right\rangle\right\rangle \sim \left\langle v_n^2\right\rangle \,. \tag{3}$$

The final observable, SC(n,m), is defined as follow:

$$\mathrm{SC}(n,m) = \langle\langle 4\rangle\rangle_{n,m} - \langle\langle 2\rangle\rangle_n \cdot \langle\langle 2\rangle\rangle_m \sim \left\langle v_n^2 v_m^2\right\rangle - \left\langle v_n^2\right\rangle \cdot \left\langle v_m^2\right\rangle, . \tag{4}$$

3. Results

Results of v_2, v_3 and v_4 harmonics for $0.3 < p_{\mathrm{T}} < 3$ GeV/c extracted from long-range two-particle correlations are shown in Fig. 1, as a function of multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}}$) in p–p at $\sqrt{s}$ = 13 TeV, p–Pb at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV, and Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV. The v_2 and v_3 harmonics for p–p and 5.02 TeV p–Pb data are already published results. Nevertheless, the v_n results before subtraction are also shown as lines in Fig. 1. The v_n multiplicity dependence exhibits similar pattern across different colliding systems. In addition, the comparison of p–Pb data between $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV shows a weak center-of-mass energy dependence of the results.

Results of symmetric cumulants SC(2,3) and SC(2,4) for $0.3 < p_T < 3$ GeV/c from four-particle correlations are shown in Fig. 2, as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in p–p at $\sqrt{s}$ = 13 TeV, p–Pb at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV, and Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV, to further explore the event-by-event correlations of different harmonics. A clear anti-correlation is observed for SC(2,3) in p–Pb and Pb–Pb at high multiplicities. In p–p, the statistical precision is not yet good enough to conclude despite the hint of a similar behavior. The SC(2,4) shows a correlation between v_2 and v_4 over the full multiplicity range and for all colliding systems. At low $N_{\mathrm{trk}}^{\mathrm{offline}}$ ranges, both SC(2,3) and SC(2,4) diverge toward positive values, likely due to dominating contribution of short-range correlations.