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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.

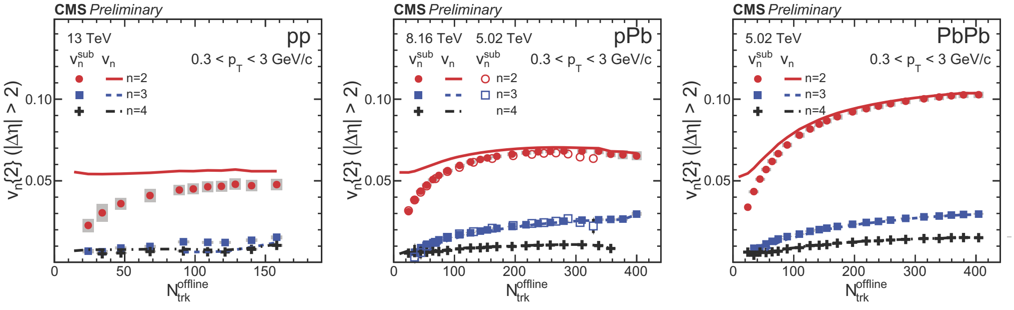

Fig. 1. The v_2, v_3 and v_4 harmonics from long-range two-particle correlations for $0.3 < p_T < 3$ GeV/c as a function of $N_{trk}^{offline}$ in p–p at $\sqrt{s} = 13$ TeV, p–Pb at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV, and Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV. The lines show the v_n results before subtraction of low-multiplicity correlations.

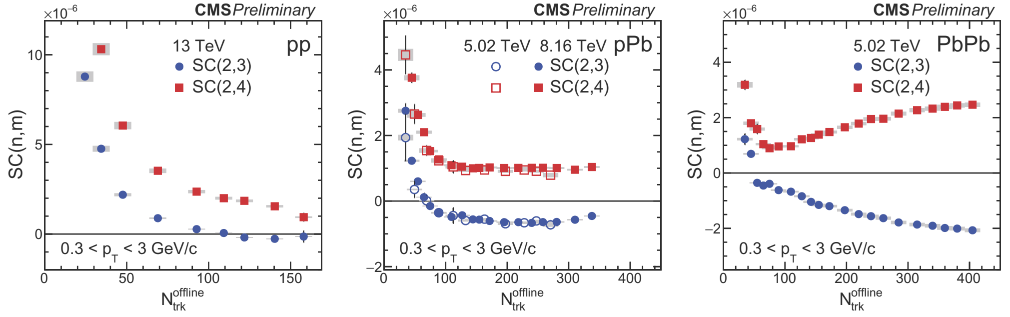

Fig. 2. The SC for the second and third harmonic (red points) and the second and forth harmonic (blue points) as a function of $N_{trk}^{offline}$ in p–p at $\sqrt{s} = 13$ TeV, p–Pb at $\sqrt{s_{NN}} = 8.16$ TeV, and Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV.

To further compare the results across different colliding systems and investigate the intrinsic correlation coefficient between harmonics the SC(n,m) are normalized by the value of corresponding v_n coefficient obtained in Fig. 1. The resulting normalized SC in all three systems are shown in Fig. 3. The normalized SC(2,3) are found to be very similar between p–Pb and Pb–Pb colliding systems at high $N_{trk}^{offline}$. On one hand, the SC(2,3) is believed to be exclusively sensitive to initial-state fluctuations and this result may suggest that the nature of initial-state fluctuations of the collective medium is the same between high-multiplicity large and small systems. Nevertheless, none of the initial-eccentricity calculations available currently [11, 12] is able to reproduce these results. Therefore, this measurement may also provide useful informations about how to model the initial-state fluctuation, the role of pre-flow in small and large systems or the contribution of the cubic response ($|\epsilon_2| \cdot \epsilon_2^2$) for such correlations. In addition, the striking similarity of the results across systems may further support the idea about a common description of hadronic colliding systems. On the other hand, the $SC(2,4)$ shows a clear dependence on the system size with a larger value for smaller system. Indeed, the correlation between the 2^{nd} and the 4^{th} harmonic coefficients is sensitive to both initial and final state. The observed difference between colliding systems suggest a different response of the medium when it comes to convert initial-state eccentricity into final-state v_n. For example, the SC(2,4) results may suggest different transport properties of the medium like the shear viscosity to entropy ratio (η/s) [8].

4. Summary

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, measured with data collected by the CMS experiment at

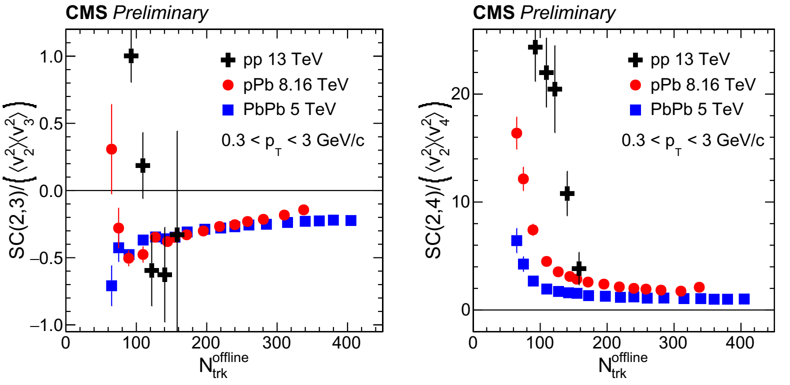

Fig. 3. The SC for the second and third harmonic (left) and the second and forth harmonic (right) normalized by $\langle v_2^2\rangle \cdot \langle v_3^2\rangle$ and $\langle v_2^2\rangle \cdot \langle v_4^2\rangle$ from dihardon correlations respectively. The results are shown as a function of $N_{trk}^{offline}$ 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 LHC. The v_2–v_4 Fourier coefficients are extracted via long-range 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. The v_n and SC(n,m) results exhibit similar behavior across systems and are weakly dependent on center-of-mass colliding energy. The SC(2,3) shows a clear anti-correlation between v_2 and v_3 in p–Pb and Pb–Pb systems while the positive value of SC(2,4) for all systems point to a correlation between v_2 and v_4. The normalized correlation coefficient of the 2^{nd} and 3^{rd} orders are found to be quantitatively similar between p–pPb and Pb–Pb over the probed multiplicity range. For the 2^{nd} and 4^{th} orders, a clear ordering between p–p, p–Pb and Pb–Pb is observed where SC(2,4) has larger values for smaller systems. These results may point to a different contribution from the initial-state correlations, different medium responses when converting initial-state eccentricity into final-state anisotropy. Finally, the results presented provide further strong evidence of a similar origin of collectivity observed in small and large hadronic collision systems, and also impose novel constraints on the theoretical calculations.

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