Observation of correlated azimuthal anisotropy Fourier harmonics in pp and pPb collisions at the LHC

The CMS Collaboration[*]

Abstract

The azimuthal anisotropy Fourier coefficients (v_n) in 8.16 TeV pPb data are extracted via long-range two-particle correlations as a function of event multiplicity and compared to corresponding results in pp and PbPb collisions. Using a four-particle cumulant technique, v_n correlations are measured for the first time in pp and pPb collisions. The v_2 and v_4 coefficients are found to be positively correlated in all collision systems. For high multiplicity pPb collisions an anticorrelation of v_2 and v_3 is observed, with a similar correlation strength as in PbPb data at the same multiplicity. The new correlation results strengthen the case for a common origin of the collectivity seen in pPb and PbPb collisions in the measured multiplicity range.

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Studies of multiparticle correlations provide important insights into the underlying mechanism of particle production in high-energy collisions of both protons and nuclei. A key feature of such correlations in ultrarelativistic nucleus-nucleus (AA) collisions is the observation of a pronounced structure on the near side (relative azimuthal angle $|\Delta\phi| \approx 0$) that extends over a large range in relative pseudorapidity ($|\Delta\eta|$ up to 4 units or more). This feature, known as the "ridge", has been found over a wide range of AA center-of-mass energies and system sizes at both the Relativistic Heavy Ion Collider at BNL [1–5] and the Large Hadron Collider (LHC) at CERN [6–10]. It is interpreted as arising primarily from the collective hydrodynamic flow of a strongly interacting, expanding medium [11, 12]. The azimuthal correlations of emitted particle pairs are typically assessed via their Fourier decomposition, $dN_{\text{pair}}/d\Delta\phi \propto 1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)$, where $V_{n\Delta}$ are the two-particle Fourier coefficients for particles separated by at least two units of η. The single-particle azimuthal anisotropy Fourier coefficients v_n can be extracted as $v_n = \sqrt{V_{n\Delta}}$ if factorization is assumed [13]. The second (v_2) and third (v_3) coefficients are known as elliptic and triangular flow, respectively [12]. In hydrodynamic models, v_2 and v_3 are directly related to the initial collision geometry and its fluctuations, which influence the medium evolution [14–16]. These Fourier components provide insights into the fundamental transport properties of the medium.

The correlations of different orders of v_n coefficients have been studied in PbPb collisions at the LHC using the event-shape engineering technique [17] and the symmetric cumulant (SC) method [18–20]. It is found that the v_2 coefficient exhibits a negative correlation with the v_3 coefficient, while the correlation is positive between the v_2 and v_4 coefficients, across the full PbPb centrality range. These correlations have been shown to be sensitive probes of initial-state fluctuations (v_2 vs. v_3) and medium transport coefficients (v_2 vs. v_4) [18, 20, 21].

Strong collective azimuthal final-state anisotropies have been observed in high-multiplicity pp and pPb collisions, similar to those in AA collisions [22–34]. The origin of collectivity in these small systems is still under debate, see for example Ref. [35]. Measurements of the correlations between v_n coefficients in small systems will provide new insights on the origin and properties of the observed long-range collectivity. Quantitative hydrodynamic predictions of azimuthal correlations in pp and pPb systems still have large uncertainties, mainly due to limited knowledge of initial-state fluctuations of energy density deposition at sub-nucleonic scales [35–37]. Detailed modeling of initial-state fluctuations in pp and pPb collisions [38] can be further constrained by the study of v_n coefficient correlations. For example, a positive correlation between v_2 and v_3 is predicted in pp collisions over the full multiplicity range [38], the opposite to what is observed in PbPb collisions [18]. Measuring v_n correlations in small colliding systems will help to understand if a common paradigm to describe collectivity in all hadronic systems can be found.

This Letter presents the measurement of anisotropy coefficients (v_n, $n = 2$–4) in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16\,\text{TeV}$, as well as correlations of different v_n in pp at $\sqrt{s} = 13\,\text{TeV}$ and pPb at $\sqrt{s_{\text{NN}}} = 5.02$ and $8.16\,\text{TeV}$ using data from the CMS experiment. In 8.16 TeV pPb collisions, the v_n coefficients are extracted via long-range ($|\Delta\eta| > 2$) two-particle correlations as a function of charged particle multiplicity, reaching higher multiplicities than previously experimentally accessible. The v_n results are compared to PbPb results at $\sqrt{s_{\text{NN}}} = 5.02\,\text{TeV}$, as well as previously published ones in pp at $\sqrt{s} = 13\,\text{TeV}$ [25] and pPb at $\sqrt{s_{\text{NN}}} = 5.02\,\text{TeV}$ [34] collisions. Correlations of v_2 vs. v_3 and v_2 vs. v_4 are measured using the four-particle SC method in pp, pPb, and PbPb.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are four primary

subdetectors including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For charged particles with transverse momentum $1 < p_T < 10\,\text{GeV}/c$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [39]. Iron and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the range $2.9 < |\eta| < 5.2$. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [40]. The detailed Monte Carlo (MC) simulation of the CMS detector response is based on GEANT4 [41].

The measurements presented in this Letter use data sets of pp collisions at $\sqrt{s} = 13\,\text{TeV}$, pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV, and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\text{TeV}$ with integrated luminosities of about $2\,\text{pb}^{-1}$, $35\,\text{nb}^{-1}$, $186\,\text{nb}^{-1}$, and $1.2\,\mu\text{b}^{-1}$, respectively. When measuring the v_n coefficients in pp and pPb collisions, the same event may contain multiple independent interactions (pileup), which constitutes a background for the analysis of high-multiplicity events. The average number of collisions per event in pp and pPb data varied between 0.1 to 1.3 and 0.1 to 0.25 interactions per bunch crossing respectively. A procedure similar to that described in Ref. [32] is used for identifying and rejecting events with pileup. It is based on the number of tracks associated with each reconstructed vertex and the distance between vertices. To further suppress this contamination in the 8.16 TeV pPb data, where the pileup was more common, data from the highest luminosity periods are excluded, resulting in an integrated luminosity of about $140\,\text{nb}^{-1}$ (out of a total of about $186\,\text{nb}^{-1}$ recorded). The SC analysis is found to be insensitive to pileup within the quoted experimental uncertainties and, therefore, the full recorded integrated luminosity is used. The PbPb data sample used for comparison is made of about 300 million peripheral (30–100% central) PbPb data at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\text{TeV}$ is also used for comparison. The collision centrality in PbPb events, i.e. the degree of overlap of the two colliding nuclei, is determined from the transverse energy (E_T) deposited in both HF calorimeters. Collision centrality bins are given in percentage ranges of the total inelastic hadronic cross section where 100% means no overlap between the two colliding nuclei [42]. The same reconstruction algorithm is applied to the pp, pPb, and PbPb events, in order to directly compare the three systems at similar track multiplicities.

Minimum bias (MB) pPb events at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\text{TeV}$ are triggered by energy deposits in at least one of the two HF calorimeters above a threshold of approximately 1 GeV and the presence of at least one track with $p_T > 0.4\,\text{GeV}/c$ in the pixel tracker. In order to collect a large sample of high-multiplicity pPb collisions, a dedicated trigger was implemented using the CMS level-1 (L1) and high-level trigger (HLT) systems. At L1, the total number of ECAL+HCAL energy towers above a threshold of 0.5 GeV in E_T is required to be greater than a given threshold (120 and 150). Track reconstruction is performed online as part of the HLT trigger with the identical reconstruction algorithm used offline [39]. For each event, the reconstructed vertex with the highest number of associated tracks is selected as the primary vertex. The number of tracks with $|\eta| < 2.4$, $p_T > 0.4\,\text{GeV}/c$, and a distance of closest approach less than 0.12 cm to the primary vertex is determined for each event and is required to exceed a certain threshold to enrich the sample with high-multiplicity events. In addition, events are also required to contain a primary vertex within 15 cm of the nominal interaction point along the beam axis and 0.2 cm in the transverse direction. The trigger, event reconstruction and selections used in pp at $\sqrt{s} = 13\,\text{TeV}$, pPb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV or PbPb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\text{TeV}$ collisions are similar to those in pPb at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\text{TeV}$ collisions, and are described in previous correlation

analyses [22, 25, 32, 43].

For all data sets analyzed, primary tracks, i.e. tracks that originate at the primary vertex and satisfy the high-purity criteria of Ref. [39], are used to perform the correlation measurements as well as to define event categories based on the charged-particle multiplicity ($N_{\text{trk}}^{\text{offline}}$). In addition, the impact parameter significance of the tracks with respect to the primary vertex in the beam direction is required to be less than 3 standard deviations, as is the corresponding impact parameter significance in the transverse plane. The relative p_{T} uncertainty must be less than 10%. Each track is also required to leave at least one hit in one of the three layers of the pixel tracker. To ensure high tracking efficiency, only tracks with $|\eta| < 2.4$ and $p_{\text{T}} > 0.3\,\text{GeV}/c$ are used in this analysis. For pPb collisions at 8.16 TeV, a MC sample was produced using the HIJING 1.0 generator [44], which was mainly employed for tracking efficiency corrections. The combined geometrical acceptance and efficiency for primary track reconstruction exceeds 60% for $|\eta| < 2.4$ and $p_{\text{T}} > 0.3\,\text{GeV}/c$. For the pp at $\sqrt{s} = 13$ TeV, as well as the pPb and PbPb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV analyses, the MC samples and corresponding event generators are described in Refs. [25, 34, 43].

The pp, pPb, and PbPb data are compared in classes of $N_{\text{trk}}^{\text{offline}}$, where $N_{\text{trk}}^{\text{offline}}$ is the number of primary tracks with $|\eta| < 2.4$ and $p_{\text{T}} > 0.4\,\text{GeV}/c$. The event classes are the same as in Refs. [24, 25].

The analysis techniques for two-particle correlations are identical to those used in Refs. [6, 7, 24, 26, 30, 32, 34]. The v_2, v_3, and v_4 Fourier coefficients are extracted by a minimum χ^2 fit of the long-range region ($|\Delta\eta| > 2$) of two-particle azimuthal correlations, averaged over $0.3 < p_{\text{T}} < 3.0\,\text{GeV}/c$, for pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV and peripheral PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are compared to published pPb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [24]. The v_4 coefficient in pp collisions at $\sqrt{s} = 13$ TeV is also measured, while the v_2 and v_3 coefficients have been obtained from Ref. [25].

The SC technique was first introduced by the ALICE Collaboration [18] and is based on four-particle correlations using cumulants. The main difference between the standard cumulant calculation and SC lies in the fact that the former is used to compute diagonal v_n terms and the latter is used for correlations between different coefficient orders. The framework for the calculation is the same as the one used in standard cumulant analysis and is based on the generic code distributed by Bilandzic et al. [45].

To study the correlation between the Fourier coefficients n and m, one can build 2- and 4-particle correlators with:

$$\langle\langle 2\rangle\rangle_n \equiv \left\langle\left\langle e^{i(n\phi_1 - n\phi_2)}\right\rangle\right\rangle \qquad \langle\langle 4\rangle\rangle_{n,m} \equiv \left\langle\left\langle e^{i(n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4)}\right\rangle\right\rangle, \tag{1}$$

where $\langle\langle\ldots\rangle\rangle$ denotes the average correlations over all events. The final observable, the *SC*, is defined as follows:

$$SC(n,m) = \langle\langle 4\rangle\rangle_{n,m} - \langle\langle 2\rangle\rangle_n \langle\langle 2\rangle\rangle_m. \tag{2}$$

Expressed as a function of v_n, the symmetric cumulant $SC(n,m)$ measures correlations of Fourier coefficients between the order of m and n:

$$SC(n,m) = \left\langle v_n^2 v_m^2\right\rangle - \left\langle v_n^2\right\rangle \left\langle v_m^2\right\rangle, \tag{3}$$

where $\langle\ldots\rangle$ denotes the average over all events. In this analysis, we compute a SC for events belonging to the same event multiplicity class ($N_{\text{trk}}^{\text{offline}}$) and with the same number of tracks entering in the calculation (i.e., $N_{\text{trk}}^{\text{ref}}$ with $0.3 < p_{\text{T}} < 3.0\,\text{GeV}/c$). Then, the different SCs are

combined into larger bins by using the total number of 4-particle combinations as a weight, i.e., in an event with track multiplicity M, this weight equals $M(M-1)(M-2)(M-3)$. This weighting procedure is necessary to reduce the impact of multiplicity fluctuations, which are particularly relevant at low multiplicity [24, 25].

The $SC(n, m)$ may also be normalized by $\langle v_n^2 \rangle \langle v_m^2 \rangle$ from long-range two-particle correlations in order to factorize the dependence on the magnitudes of $\langle v_n^2 \rangle$ and $\langle v_m^2 \rangle$.

The systematic uncertainties of the experimental procedure are evaluated as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ by varying the conditions in extracting v_n coefficients and SCs for both pPb at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ and PbPb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ samples. For pp at $\sqrt{s} = 13\,\mathrm{TeV}$ and pPb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, the systematic uncertainties are taken from Refs. [25, 34]. Systematic uncertainties due to tracking inefficiency and misreconstructed track rate are studied by varying the track quality requirements. The selection thresholds on the significance of the distance between the track and the primary vertex along the beam axis, d_z/σ_{d_z}, and the significance of track impact parameter in the transverse plane, $d_{xy}/\sigma_{d_{xy}}$, are varied from 2 to 5 standard deviations. In addition, the relative p_T uncertainty is varied from 5% to 10%. The resulting systematic uncertainty is found to be between 1% and 2% for v_n and SCs depending on multiplicity in both colliding systems. The sensitivity of the results to the primary vertex position along the beam axis (z_{vtx}) is quantified by comparing events with different z_{vtx} locations from -15 to $+15\,\mathrm{cm}$. The magnitude of this systematic effect is estimated to be between 1% and 2%, depending on multiplicity, and is independent of colliding system and method (v_n or SC). For the pPb at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ sample, two additional sources of systematic uncertainties are investigated. To study potential trigger biases, a comparison to high-multiplicity pPb data for a given multiplicity range that have been collected by a lower threshold trigger with 100% efficiency is performed. This uncertainty is found to be less than 1%. The possible contamination by residual pileup interactions is also studied by varying the pileup selection of events in the performed analysis, from no pileup rejection at all to selecting events with only one reconstructed vertex. For v_n results, this effect is more important at high multiplicities (3%) than at low ones (0.1%). For the SC method, the systematic effect on the results coming from pileup rejection is independent of multiplicity and estimated to be 1%.
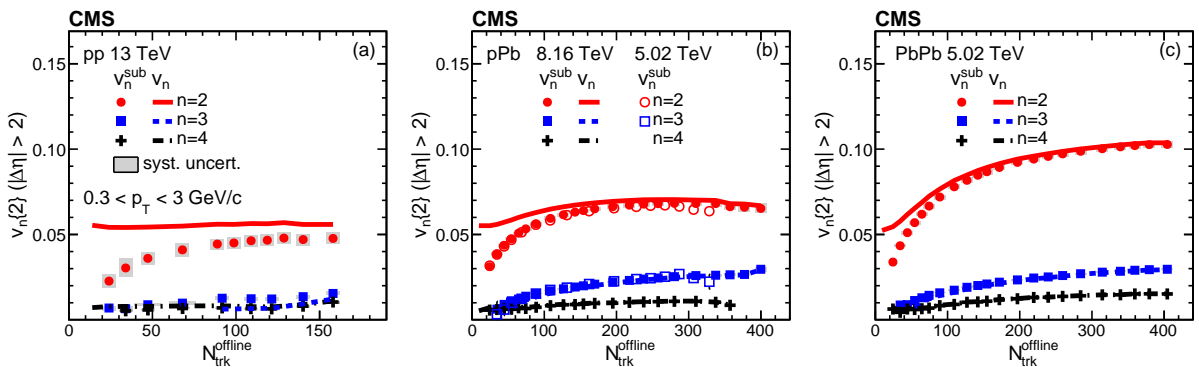

Figure 1: The v_2, v_3 [25], and v_4 coefficients from long-range two-particle correlations for $0.3 < p_T < 3\,\mathrm{GeV}/c$ as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in pp at $\sqrt{s} = 13\,\mathrm{TeV}$ (a), pPb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [32] and $8.16\,\mathrm{TeV}$ (b), and PbPb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ collisions (c). The results corrected by low-multiplicity subtraction are denoted as v_n^{sub}. The lines show the v_n results before subtraction of low-multiplicity correlations. The gray boxes represent systematic uncertainties.

Measurements of v_2, v_3, and v_4 coefficients for $0.3 < p_T < 3\,\mathrm{GeV}/c$ extracted from long-range two-particle correlations are shown in Fig. 1, as a function of multiplicity in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and $8.16\,\mathrm{TeV}$, and PbPb collisions at

$\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$. The v_2 and v_3 coefficients for pp at $\sqrt{s} = 13\,\mathrm{TeV}$ and pPb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ data are taken from Refs. [25, 32]. The contribution to v_n coefficients from back-to-back jet correlations are corrected by subtracting correlations from very low-multiplicity events (v_n^{sub}), as done in Refs. [25, 32]. The v_n results before subtraction are also shown as lines in Fig. 1. For $N_{\mathrm{trk}}^{\mathrm{offline}} > 200$, the low-multiplicity subtraction has very small effect in pPb and PbPb collisions. At low multiplicity, this correction plays a larger role, in particular for pp collisions where dijet correlations are expected to be the main source of correlations.

By comparison with pPb data at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, the new pPb results at 8.16 TeV extend the measurements of v_n coefficients to a higher-multiplicity region, due to the higher collision energy and integrated luminosity. The v_2 coefficient increases with $N_{\mathrm{trk}}^{\mathrm{offline}}$, saturating for $N_{\mathrm{trk}}^{\mathrm{offline}} > 200$. In the overlapping $N_{\mathrm{trk}}^{\mathrm{offline}}$ range, the v_2 and v_3 values for pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV agree well within uncertainties. Identical to the observation in Ref. [32] at lower energies, the v_3 coefficients for pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ are also found to be very similar over the full multiplicity range investigated. Finite v_4, which are about 50% smaller than the v_3 coefficients for $N_{\mathrm{trk}}^{\mathrm{offline}} > 100$, are also observed in all three systems.
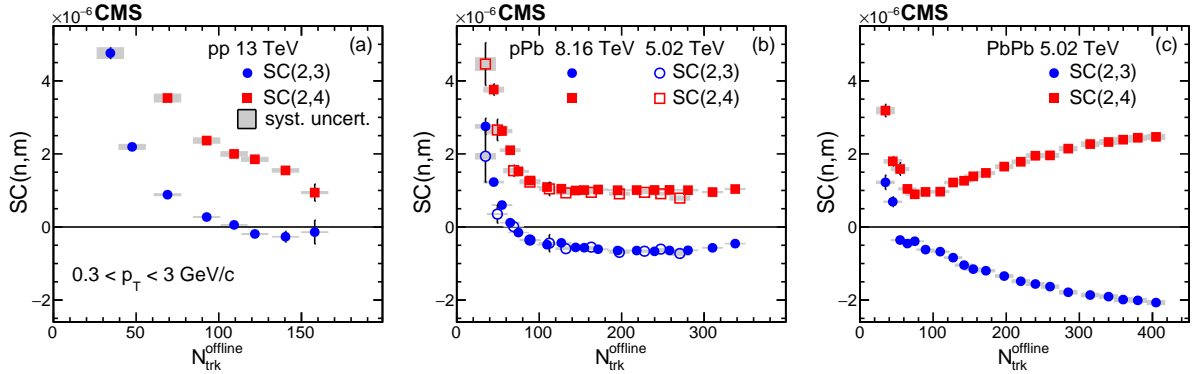

Figure 2: The SCs for the second and third coefficient (red points) and the second and fourth coefficient (blue points) as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ (a), pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV (b), and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ (c). The gray boxes represent systematic uncertainties.

Measurements of symmetric cumulants $SC(2,3)$ and $SC(2,4)$ for $0.3 < p_{\mathrm{T}} < 3\,\mathrm{GeV}/c$ from four-particle correlations are shown in Fig. 2, as a function of multiplicity in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 8.16 TeV, and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, to further study the correlations of different v_n coefficients. A negative value of SC indicates an anticorrelation between the two Fourier coefficients.

In pp collisions, both $SC(2,3)$ and $SC(2,4)$ decrease as $N_{\mathrm{trk}}^{\mathrm{offline}}$ increases. The $SC(2,4)$ values always remain positive, while there is an indication of a transition to negative values for $SC(2,3)$ at $N_{\mathrm{trk}}^{\mathrm{offline}} > 110$ but the measurement is not precise enough to draw a firm conclusion. For pPb and PbPb data at sufficiently high multiplicities (e.g., $N_{\mathrm{trk}}^{\mathrm{offline}} > 60$), clear negative values of $SC(2,3)$ are observed, while $SC(2,4)$ values are positive. The PbPb data are consistent with results reported at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ [18].

In hydrodynamic models, correlations of v_2 and v_3 can be directly related to the initial eccentricity correlations [18, 20, 21]. Theoretical studies of v_n correlations in small colliding systems were performed based on purely eccentricity correlations [38]. An anticorrelation of v_2 and v_3 in pPb collisions has been predicted at high multiplicities [38], which is consistent with the experimental observation. A positive correlation of v_2 and v_3 is predicted over the full mul-

tiplicity range in pp collisions [38], while a hint of anticorrelation is seen in the data at high multiplicity. However, larger pp data samples are needed to draw a definitive conclusion. At low $N_{\mathrm{trk}}^{\mathrm{offline}}$ ranges ($N_{\mathrm{trk}}^{\mathrm{offline}} < 100$) for all three systems, both $SC(2,3)$ and $SC(2,4)$ have positive values, which increase as $N_{\mathrm{trk}}^{\mathrm{offline}}$ decreases. It should be noted that, in the low multiplicity region, short-range few-body correlations such as jets are likely to have a dominant contribution, which need to be properly accounted for before comparing to models of long-range collective correlations. Indeed, the jet contribution at low $N_{\mathrm{trk}}^{\mathrm{offline}}$ might be different in pp, pPb and PbPb and lead to slightly different behaviors of the SCs in this multiplicity range as observed in the data. Recent calculations from initial state gluon correlations in the color-glass condensate framework have also been shown to capture the signs of the v_n correlation data [46, 47], although it remains to be seen if the magnitude of correlations in the measured multiplicity region can be quantitatively reproduced.

The absolute magnitudes of $SC(2,3)$ and $SC(2,4)$ are found to be larger in PbPb than in pPb system at high multiplicities. This may be related to the different magnitude of v_n coefficients as indicated in Fig. 1. To investigate the intrinsic correlation between v_n coefficients and compare across different collision systems in a more quantitative way, $SC(2,3)$ and $SC(2,4)$ are normalized by $\langle v_2^2 \rangle \langle v_3^2 \rangle$ and $\langle v_2^2 \rangle \langle v_4^2 \rangle$, respectively, based on the v_n values from two-particle correlations in Fig. 1. The resulting normalized SCs in all three colliding systems are shown in Fig. 3.
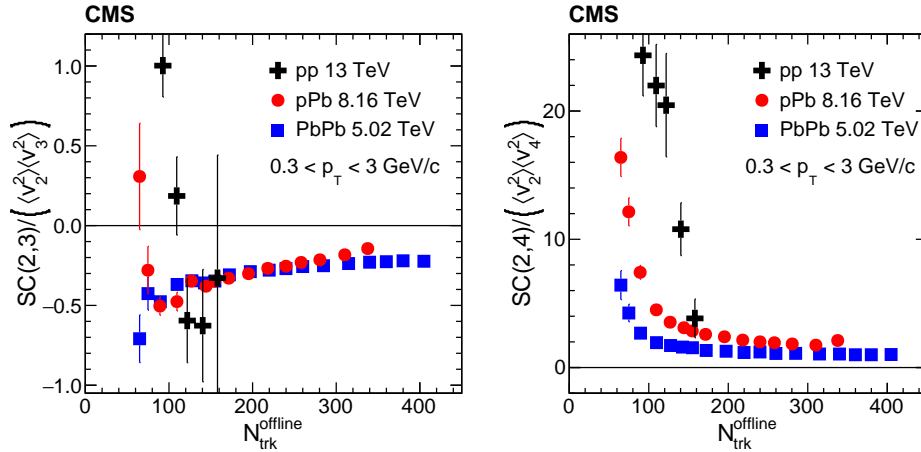

Figure 3: The SCs for the second and third coefficients (left) and the second and fourth coefficients (right) normalized by $\langle v_2^2 \rangle \langle v_3^2 \rangle$ and $\langle v_2^2 \rangle \langle v_4^2 \rangle$ from two-particle correlations. The track p_{T} range is $0.3 < p_{\mathrm{T}} < 3\,\mathrm{GeV}/c$ and the results are shown as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$, and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$.

The normalized $SC(2,3)$ values are found to be very similar between pPb and PbPb systems at high multiplicities. Together with the v_n results in Fig. 1, these measurements strongly suggest a unified paradigm to explain collective behavior observed in large and small hadronic collisions. In the context of hydrodynamic models, the $SC(2,3)$ data in pPb and PbPb collisions suggest similar fluctuations of initial-state energy density of the collective medium [18]. This common behavior may even apply to pp collisions for $N_{\mathrm{trk}}^{\mathrm{offline}} > 120$, where $SC(2,3)$ tends to converge to a unified value for all three systems, although statistical uncertainties are still too large to draw a firm conclusion. The $SC(2,4)$, on the other hand, shows a clear dependence on the system size with a larger value for smaller systems. The observed difference between $SC(2,4)$ values in pPb and PbPb collisions may point to a different contribution of initial-state fluctuations or transport properties of the medium such as the shear viscosity to entropy ratio [18]. Further calculations of $SC(2,3)$ and $SC(2,4)$ with full hydrodynamic evolution would

be needed for a quantitative comparison to the small system data.

In summary, the first measurements of azimuthal anisotropy Fourier coefficients and correlations of different coefficients in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV are presented based on data collected by the CMS experiment at the LHC. The v_2, v_3, and v_4 Fourier coefficients are extracted from long-range two-particle correlations in classes of event multiplicity, and are found to be consistent with pPb data at $\sqrt{s_{NN}} = 5.02$ TeV. The pPb results are compared to those in pp at $\sqrt{s} = 13$ TeV and PbPb at $\sqrt{s_{NN}} = 5.02$ TeV. Using a four-particle cumulant technique, correlations of different coefficient orders are obtained, where a negative (positive) correlation is observed between v_2 and v_3 (v_4) in pPb collisions. This behavior is similar to what is observed in the PbPb system, where the result is attributed to the hydrodynamic flow of a strongly interacting medium. Normalized correlation coefficients for v_2 and v_3 are found to be quantitatively similar between pPb and PbPb, while for v_2 and v_4 the results are larger in pPb than in PbPb. The corresponding result in pp collisions shows a similar trend at high multiplicity but the statistical uncertainties are too large to make a quantitative statement. The results presented in this Letter provide further evidence of a similar origin of collectivity observed in small and large hadronic systems and impose constraints on theoretical model calculations.

Acknowledgments

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