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Observation of Correlated Azimuthal Anisotropy Fourier Harmonics in pp and $p + \text{Pb}$ Collisions at the LHC

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The azimuthal anisotropy Fourier coefficients (v_n) in 8.16 TeV $p + \text{Pb}$ data are extracted via long-range two-particle correlations as a function of the 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 $p + \text{Pb}$ collisions. The v_2 and v_4 coefficients are found to be positively correlated in all collision systems. For high-multiplicity $p + \text{Pb}$ 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 $p + \text{Pb}$ 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 four 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 RHIC [1–5] and the LHC [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 frequently 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. 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 $p + \text{Pb}$ 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 $p + \text{Pb}$ systems still have large uncertainties, mainly due to a limited knowledge of initial-state fluctuations of energy deposition at subnucleonic scales [35–37]. Detailed modeling of initial-state fluctuations in pp and $p + \text{Pb}$ 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 high-precision measurements of anisotropy coefficients v_4 in pp at $\sqrt{s} = 13$ TeV, $p + \text{Pb}$ at $\sqrt{s_{NN}} = 8.16$ TeV, and PbPb at $\sqrt{s_{NN}} = 5.02$ TeV using data from the CMS experiment. The 8.16 TeV

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$p + \text{Pb}$ data provide access to higher multiplicities than previously experimentally accessible. The first measurement of correlations of different v_n in 13 TeV pp , 5.02 and 8.16 TeV $p + \text{Pb}$, and 5.02 TeV PbPb are also presented. The v_n coefficients are extracted via long-range ($|\Delta\eta| > 2$) two-particle correlations as a function of the charged-particle multiplicity. The v_n results are compared to 5.02 TeV PbPb, as well as previously published ones in 13 TeV pp [25] and 5.02 TeV $p + \text{Pb}$ [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 , $p + \text{Pb}$, 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 end cap sections. 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 can be found in Ref. [40]. The detailed Monte Carlo simulation of the CMS detector response is based on Geant 4 [41].

The measurements presented in this Letter use data sets of 13 TeV pp , 5.02 and 8.16 TeV $p + \text{Pb}$, and 5.02 TeV PbPb collisions with integrated luminosities of about 2 pb^{-1} , 35 nb^{-1} , 186 nb^{-1} , and $1.2 \mu\text{b}^{-1}$, respectively. When measuring the v_n coefficients in pp and $p + \text{Pb}$ 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 bunch crossing in pp and $p + \text{Pb}$ data varied between 0.1–1.3 and 0.1–0.25, respectively. A procedure similar to that described in Ref. [32] is used for identifying and rejecting events with pileup. To further suppress this contamination in the 8.16 TeV $p + \text{Pb}$ data, where the pileup was more common, data from the highest luminosity periods are excluded, resulting in an integrated luminosity of about 140 nb^{-1} . The SC analysis is found to be insensitive to pileup within the quoted experimental uncertainties, and, therefore, the $p + \text{Pb}$ data sample of full recorded integrated luminosity is used. The 5.02 TeV PbPb data sample used for comparison is made of about 300 million peripheral (30%–100% central) events, where 100% means no overlap between the two colliding nuclei [42]. The same reconstruction algorithm is applied to the pp , $p + \text{Pb}$, and PbPb events, in order to directly compare the three systems at similar track multiplicities.

Minimum bias 8.16 TeV $p + \text{Pb}$ events 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 $p + \text{Pb}$ 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 transverse energy (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 13 TeV pp and 5.02 TeV $p + \text{Pb}$ or PbPb collisions are similar to those in 8.16 TeV $p + \text{Pb}$ 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 longitudinal and the transverse direction are required to be less than 3 standard deviations. The relative p_T uncertainty must be less than 10%. To ensure high tracking efficiency, only tracks with $|\eta| < 2.4$ and $p_T > 0.3 \text{ GeV}/c$ are used in this analysis [39].

The pp , $p + \text{Pb}$, 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 $p_T > 0.4 \text{ GeV}/c$. The event classes are the same as in Refs. [24,25].

The analysis techniques for two-particle correlations, averaged over $0.3 < p_T < 3.0 \text{ GeV}/c$, are identical to those used in Refs. [6,7,24,26,30,32,34]. The results are compared to published 5.02 TeV $p + \text{Pb}$ [24] data. The v_4 coefficient in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ 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, Snellings, and Voloshin [44].

To study the correlation between the Fourier coefficients n and m , one can build two- and four-particle correlators with

$$\begin{aligned} \langle\langle 2 \rangle\rangle_n &\equiv \langle\langle e^{i(n\phi_1 - n\phi_2)} \rangle\rangle, \\ \langle\langle 4 \rangle\rangle_{n,m} &\equiv \langle\langle e^{i(n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4)} \rangle\rangle, \end{aligned} \quad (1)$$

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

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

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 :

$$SC(n, m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle, \quad (3)$$

where $\langle \dots \rangle$ 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 $0.3 < p_T < 3.0$ GeV/c). Then, the different SCs are combined into larger bins by using the total number of four-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 systematic uncertainties of the experimental procedure are evaluated as a function of $N_{\text{trk}}^{\text{offline}}$ by varying the conditions in extracting v_n coefficients and SCs for both 8.16 TeV $p + \text{Pb}$ and 5.02 TeV PbPb samples. For 13 TeV pp and 5.02 TeV $p + \text{Pb}$, the systematic uncertainties are taken from Refs. [25,34]. Systematic uncertainties due to

tracking inefficiency and a misreconstructed track rate are studied by varying the track quality requirements. The selection thresholds on the significance of the transverse and longitudinal track impact parameter divided by their uncertainties 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 1%–2% for v_n and SCs depending on the 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 $+15$ cm. The magnitude of this systematic effect is estimated to be 1%–2%, depending on the multiplicity, and is independent of the colliding system and method (v_n or SC). For the 8.16 TeV $p + \text{Pb}$ sample, two additional sources of systematic uncertainties are investigated. To study potential trigger biases, a comparison to high-multiplicity $p + \text{Pb}$ 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, it is independent of multiplicity and estimated to be 1%. The total systematic uncertainty is estimated to be 1.7%–4.1% for v_n depending on the multiplicity and 1.8% for SCs.

Measurements of v_2 , v_3 , and v_4 coefficients for $0.3 < p_T < 3$ GeV/c extracted from long-range two-particle correlations are shown in Fig. 1, as a function of multiplicity in 13 TeV pp , 5.02 and 8.16 TeV $p + \text{Pb}$, and 5.02 TeV PbPb collisions. 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

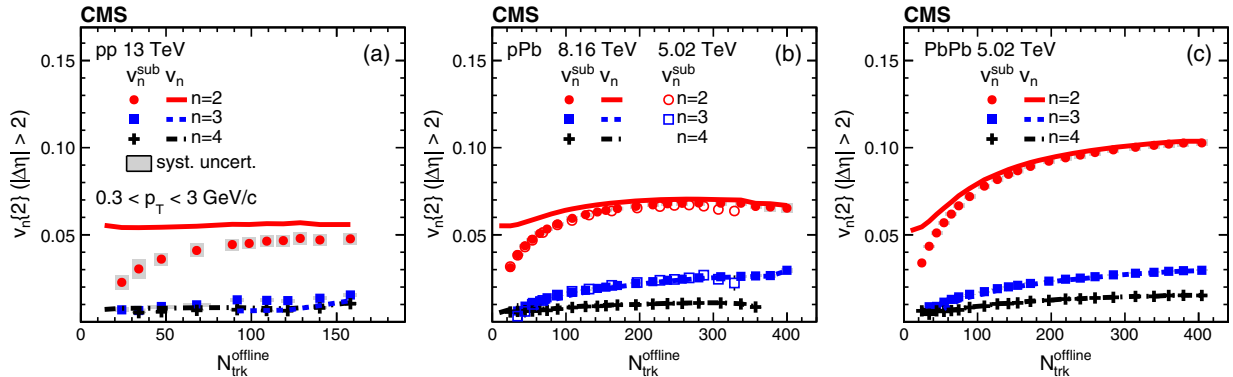


FIG. 1. The v_2 , v_3 [25], and v_4 coefficients from long-range two-particle correlations as a function of $N_{\text{trk}}^{\text{offline}}$ in 13 TeV pp (a), 5.02 [32] and 8.16 TeV $p + \text{Pb}$ (b), and 5.02 TeV PbPb collisions (c). The results corrected by low-multiplicity subtraction are denoted as v_n^{sub} . The lines show the v_n results before the subtraction of low-multiplicity correlations. The gray boxes represent systematic uncertainties.

subtraction are also shown as lines in Fig. 1. For $N_{\text{trk}}^{\text{offline}} > 200$, the low-multiplicity subtraction has a very small effect in $p + \text{Pb}$ and PbPb collisions. At a 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 5.02 TeV $p + \text{Pb}$ data, the new 8.16 TeV $p + \text{Pb}$ results 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 $N_{\text{trk}}^{\text{offline}}$, saturating for $N_{\text{trk}}^{\text{offline}} > 200$. Finite v_4 , which are about 50% smaller than the v_3 coefficients for $N_{\text{trk}}^{\text{offline}} > 100$, are also observed in all three systems.

Measurements of symmetric cumulants $\text{SC}(2,3)$ and $\text{SC}(2,4)$ for $0.3 < p_T < 3$ GeV/c from four-particle correlations are shown in Fig. 2, as a function of the multiplicity in 13 TeV pp , 5.02 and 8.16 TeV $p + \text{Pb}$, and 5.02 TeV PbPb , to further study the correlations of different v_n coefficients.

In pp collisions, both $\text{SC}(2,3)$ and $\text{SC}(2,4)$ decrease as $N_{\text{trk}}^{\text{offline}}$ increases. The $\text{SC}(2,4)$ values always remain positive, while there is an indication of a transition to negative values for $\text{SC}(2,3)$ at $N_{\text{trk}}^{\text{offline}} > 110$, but the measurement is not precise enough to draw a firm conclusion. For $p + \text{Pb}$ and PbPb data at sufficiently high multiplicities (e.g., $N_{\text{trk}}^{\text{offline}} > 60$), clear negative values of $\text{SC}(2,3)$ are observed, while $\text{SC}(2,4)$ values are positive. The PbPb data are consistent with results reported at $\sqrt{s_{NN}} = 2.76$ 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 $p + \text{Pb}$ 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 multiplicity range in pp collisions [38], while a hint of

anticorrelation is seen in the data at a high multiplicity. However, larger pp data samples are needed to draw a definitive conclusion. At low $N_{\text{trk}}^{\text{offline}}$ ranges ($N_{\text{trk}}^{\text{offline}} < 100$) for all three systems, both $\text{SC}(2,3)$ and $\text{SC}(2,4)$ have positive values, which increase as $N_{\text{trk}}^{\text{offline}}$ 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 needs to be properly accounted for before comparing to models of long-range collective correlations. Indeed, the jet contribution at low $N_{\text{trk}}^{\text{offline}}$ might be different in pp , $p + \text{Pb}$, and PbPb and lead to slightly different behaviors of the SCs in this multiplicity range as observed in the data. Finally, 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 [45,46], although it remains to be seen if the magnitude of correlations in the measured multiplicity region can be quantitatively reproduced. Recently, new methods have been proposed to suppress the contribution from jets down to low multiplicities by introducing sub-events in the cumulant calculation [47,48]. Future studies using these methods will be of high interest to better understand the short-range correlation contribution to correlation measurements at a low multiplicity.

The absolute magnitudes of $\text{SC}(2,3)$ and $\text{SC}(2,4)$ are found to be larger in PbPb than in the $p + \text{Pb}$ 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, $\text{SC}(2,3)$ and $\text{SC}(2,4)$ are normalized by $\langle (v_2^{\text{sub}})^2 \rangle \langle (v_3^{\text{sub}})^2 \rangle$ and $\langle (v_2^{\text{sub}})^2 \rangle \langle (v_4^{\text{sub}})^2 \rangle$, respectively, based on the v_n values from two-particle correlations in Fig. 1. As the two-particle correlation v_n^{sub} with a rapidity gap is used for the normalization, the results might be affected by the event-plane decorrelation measured in Ref. [49] at the level of a few percent. Nevertheless, all systems would be affected consistently such that the

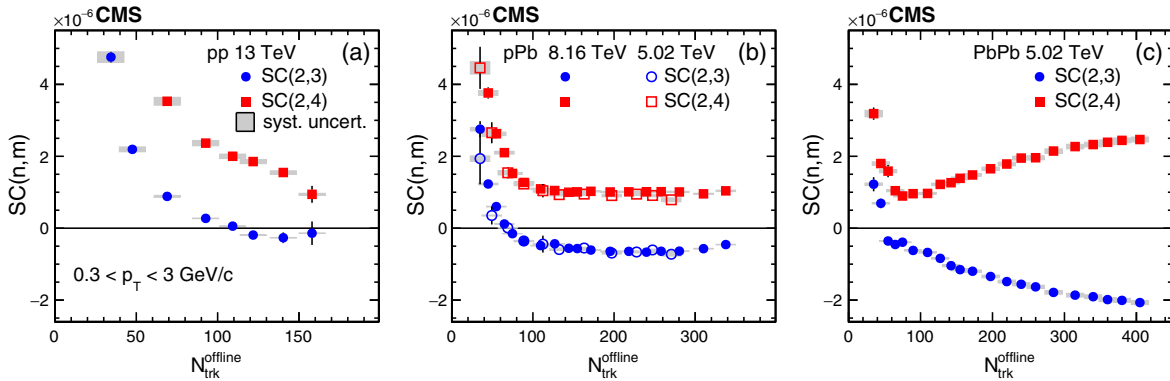


FIG. 2. The SCs for the second and third coefficients (red points) and the second and fourth coefficients (blue points) as a function of $N_{\text{trk}}^{\text{offline}}$ in 13 TeV pp (a), 5.02 and 8.16 TeV $p + \text{Pb}$ (b), and 5.02 TeV PbPb collisions (c). The gray boxes represent systematic uncertainties.

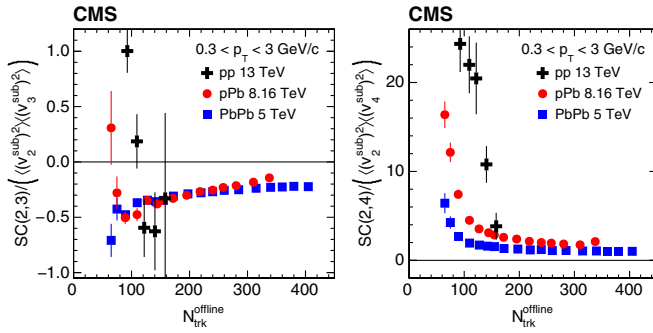


FIG. 3. The SCs for the second and third coefficients (left) and the second and fourth coefficients (right) normalized by $\langle (v_2^{\text{sub}})^2 \rangle \langle (v_3^{\text{sub}})^2 \rangle$ and $\langle (v_2^{\text{sub}})^2 \rangle \langle (v_4^{\text{sub}})^2 \rangle$ from two-particle correlations. The results are shown as a function of $N_{\text{trk}}^{\text{offline}}$ in 13 TeV pp , 8.16 TeV $p + \text{Pb}$, and 5.02 TeV PbPb collisions.

conclusions from the results would not be modified. In addition, the short-range correlation contribution is suppressed with different approaches in the numerator (SC) and the denominator ($\langle v_n^2 \rangle \langle v_m^2 \rangle$). The impact of the short-range correlation was investigated by using the unsubtracted v_n for the normalization. As expected, at a high multiplicity, the results remain unchanged. The resulting normalized SCs in all three colliding systems are shown in Fig. 3.

The normalized SC(2,3) values are found to be very similar between $p + \text{Pb}$ and PbPb systems at high multiplicities. Together with the v_n results in Fig. 1, these measurements strongly suggest a unified paradigm to explain the collective behavior observed in large and small hadronic collisions. In the context of hydrodynamic models, the SC(2,3) data in $p + \text{Pb}$ and PbPb collisions suggest similar fluctuations of the initial-state energy density of the collective medium [18]. This common behavior may even apply to pp collisions for $N_{\text{trk}}^{\text{offline}} > 120$, 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 $p + \text{Pb}$ 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 a 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 8.16 TeV $p + \text{Pb}$ collisions 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 5.02 TeV PbPb data. The $p + \text{Pb}$ results are compared to those in 13 TeV pp and 5.02 TeV PbPb. 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 $p + \text{Pb}$ 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 $p + \text{Pb}$ and PbPb, while for v_2 and v_4 the results are larger in $p + \text{Pb}$ than in PbPb. The corresponding result in pp collisions shows a similar trend at a 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 the collectivity observed in small and large hadronic systems and impose constraints on theoretical model calculations.

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