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Correlations of azimuthal anisotropy Fourier harmonics with subevent cumulants in $p\text{Pb}$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV

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Event-by-event long-range correlations of azimuthal anisotropy Fourier coefficients (v_n) in 8.16 TeV $p\text{Pb}$ data, collected by the CMS experiment at the CERN Large Hadron Collider, are extracted using a subevent four-particle cumulant technique applied to very low multiplicity events. Each combination of four charged particles is selected from either two, three, or four distinct subevent regions of a pseudorapidity range from -2.4 to 2.4 of the CMS tracker, and with transverse momentum between 0.3 and 3.0 GeV. Using the subevent cumulant technique, correlations between v_n of different orders are measured as functions of particle multiplicity and compared to the standard cumulant method without subevents over a wide event multiplicity range. At high multiplicities, the v_2 and v_3 coefficients exhibit an anticorrelation; this behavior is observed consistently using various methods. The v_2 and v_4 correlation strength is found to depend on the number of subevents used in the calculation. As the event multiplicity decreases, the results from different subevent methods diverge because of different contributions of noncollective or few-particle correlations. Correlations extracted with the four-subevent method exhibit a tendency to diminish monotonically toward the lowest multiplicity region (about 20 charged tracks) investigated. These findings extend previous studies to a significantly lower event multiplicity range and establish the evidence for the onset of long-range collective multiparticle correlations in small system collisions.

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I. INTRODUCTION

In high-energy ultrarelativistic nucleus-nucleus (AA) collisions, a dense and hot state of matter called the quark gluon plasma (QGP) is produced [1,2]. Studies of multiparticle correlations provide important insights into the underlying mechanism of particle production in this strongly coupled, nonperturbative regime. A key feature of such multiparticle correlations in AA collisions is 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 center-of-mass energies and system sizes in AA collisions at both the BNL Relativistic Heavy Ion Collider (RHIC) [3–6] and the CERN Large Hadron Collider (LHC) [7–11]. It is interpreted as arising primarily from the initial anisotropic geometry and its fluctuations coupled with the collective hydrodynamic flow of a strongly interacting, expanding medium [12,13]. The azimuthal correlations of emitted particle pairs are typically characterized by their

Fourier components as

$$\frac{dN^{\text{pair}}}{d\Delta\phi} \propto 1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi), \quad (1)$$

where $V_{n\Delta}$ are the two-particle Fourier coefficients. If factorization is assumed, $v_n = \sqrt{V_{n\Delta}}$ denote the single-particle anisotropy harmonics [14]. In particular, the second, third, and fourth Fourier components are known as elliptic (v_2), triangular (v_3), and quadrangular (v_4) flow, respectively [13].

In order to constrain the effects of the geometry and its fluctuations in the initial conditions, and the transport properties of the produced medium in AA collisions, new studies were carried out looking at correlations between different orders of v_n harmonics. In particular, event-by-event fluctuations of v_n harmonic amplitudes in PbPb collisions at the LHC were studied using the event shape engineering technique [15], and the four-particle symmetric cumulant (SC) method [16,17], where the SC method for two different harmonic orders n and m is defined as

$$\begin{aligned} \text{SC}(n, m) &= \langle \langle \cos(n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4) \rangle \rangle \\ &\quad - \langle \langle \cos(n\phi_1 - n\phi_2) \rangle \rangle \langle \langle \cos(m\phi_3 - m\phi_4) \rangle \rangle \\ &= \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle. \end{aligned} \quad (2)$$

Here, the double angular brackets indicate that the averaging procedure is done first on all distinct particle quadruplets in an event, and then over all the events, by weighting each single event average with its number of quadruplets. Over the full range of impact parameters in PbPb collisions, it was

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found that the v_2 harmonic exhibits a negative event-by-event correlation with the v_3 harmonic, while the correlation is positive between the v_2 and v_4 harmonics. These correlations are shown to be sensitive probes of initial-state fluctuations (v_2 vs. v_3) and medium transport coefficients (v_2 vs. v_4) [16,18–21].

In high-multiplicity pp and pA collisions, the “ridge” has been observed [22–28] and detailed studies have highlighted its collective nature [29–32]. Event-by-event correlations among the v_2 , v_3 , and v_4 Fourier harmonics have also been measured for both systems using the SC method [33]. The correlation data reveal features similar to those observed in PbPb collisions, where a negative correlation is found between the v_2 and v_3 harmonics, while the correlation is positive between the v_2 and v_4 harmonics. These observations may further support the hydrodynamic origin of collective correlations in high-multiplicity events for these small systems [16].

However, the nature of the long-range collectivity in small systems, especially for the low-multiplicity region (e. g., less than about 50–60 charged particles), still remains inconclusive and much debated (e. g., see reviews in Refs. [34,35]). It has been argued that the contribution of initial momentum space collectivity from the gluon saturation model may become dominant as the event multiplicity decreases [36]. Understanding the multiplicity dependence of the observed long-range collectivity is the key to disentangle contributions from various physical origins. Experimental investigation of collective multiparticle correlations for low-multiplicity events is largely hindered by the presence of significant noncollective correlations (nonflow), such as few-particle correlations from jets. The observed trend for the v_2 - v_3 correlation [SC(n, m)] to become positive is likely related to the nonflow effect [33]. In order to suppress these few-particle correlations and to explore possible collective correlation signals, subevent cumulant techniques have been proposed to require rapidity gaps among particles [37,38]. As detailed in Refs. [38–40], each combination of four particles is required to fall into two, three, or four distinct subevents within the full η range. There are already studies highlighting the importance of the nonflow contribution in cumulant calculations and the effectiveness of the subevent techniques to strongly suppress it [39,40].

Using a large data sample collected using the CMS detector, this paper presents the first measurement of event-by-event correlations of v_2 vs. v_3 and v_2 vs. v_4 using the SC method with subevents in pPb collisions at a nucleon-nucleon center-of mass energy $\sqrt{s_{NN}} = 8.16$ TeV covering a wide multiplicity range. The correlation measurements are performed using two, three, and four subevents, where the impact of few-particle correlations is systematically reduced in a data-driven way as the number of subevents increases. The results are also compared to previous measurements without the subevent technique.

II. THE CMS DETECTOR

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. The iron and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the range $3 < |\eta| < 5$. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For charged particles with transverse momentum $1 < p_T < 10$ 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 [41]. The Monte Carlo (MC) simulation of the full CMS detector response is based on Geant4 [42]. The detailed description of the CMS detector can be found in Ref. [43].

III. EVENT AND TRACK SELECTIONS

The measurements presented in this paper use the 8.16 TeV pPb data set with an integrated luminosity of 186 nb^{-1} , where the beam directions were reversed during the run after collecting the first 62.6 nb^{-1} . The beam energies were 6.5 TeV for protons and 2.56 TeV per nucleon for lead nuclei [44]. The results from both beam directions are combined using the convention that the proton-going direction defines positive pseudorapidity. As a result of the energy difference between the colliding beams, the nucleon-nucleon center-of-mass frame in the pPb collisions is not at rest with respect to the laboratory frame. Massless particles emitted at $\eta_{c.m.} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at $\eta_{lab} = 0.465$ in the laboratory frame. All pseudorapidities reported in this paper are given with respect to the laboratory frame. During the data taking, the average number of collisions per bunch crossing (pileup) varied from 0.10 to 0.25. A procedure similar to that described in Ref. [45] is used for identifying and rejecting events with pileup.

The minimum bias (MB) 8.16 TeV pPb events are triggered by requiring energy deposits in at least one of the two HF calorimeters above 1 GeV and the presence of at least one track with $p_T > 0.4$ GeV/c reconstructed using hits from the pixel tracker only. In order to collect a large sample of high-multiplicity pPb collisions, a dedicated trigger is implemented using the CMS level-1 (L1) and high-level trigger (HLT) systems [46]. At L1, the total number of ECAL+HCAL towers having deposited energy above an energy threshold of 0.5 GeV in transverse energy (E_T) is required to be greater than a given threshold (120 and 150 towers depending on the targeted multiplicity range). As part of the HLT trigger, the track reconstruction is performed online with the identical reconstruction algorithm used offline [41]. For each event selected at L1, the reconstructed vertex with the highest number of associated tracks is selected as the primary vertex at the HLT. The number of tracks with $|\eta| < 2.4$, $p_T > 0.4$ GeV/c, and a distance of closest approach less than 0.12 cm along the beam axis to the primary vertex is determined for each event and is required to exceed 120, 185, and 250 to enrich the sample with high-multiplicity (HM) events in the ranges 120–185, 185–250, and 250– ∞ , respectively. The events are 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. Finally, for high-multiplicity events, the trigger efficiency is required to be greater than 95%. In the multiplicity region where this requirement is not met ($N_{\text{trk}}^{\text{offline}} < 120$), MB triggered events are used.

In the offline analysis, the primary tracks, i. e., reconstructed tracks that originate from the primary vertex and satisfy the high-quality criteria of Ref. [41], are used to perform the correlation measurements, as well as to evaluate the charged-particle multiplicity ($N_{\text{trk}}^{\text{offline}}$) for each event. In addition, the significances of the track impact parameter with respect to the primary vertex in the transverse and longitudinal direction divided by their uncertainties are required to be less than 3. The relative p_T uncertainty must be less than 10%. To ensure high tracking efficiency, only tracks with $|\eta| < 2.4$ and $p_T > 0.3$ GeV/c are used in this analysis [41].

In this analysis, about 8×10^9 MB and 5×10^8 HM events are selected. Following the convention established in previous analyses [33,47,48], the pPb data are shown in classes of $N_{\text{trk}}^{\text{offline}}$, which is the number of primary tracks with $|\eta| < 2.4$ and $p_T > 0.4$ GeV/c, without corrections for acceptance and efficiency. The $N_{\text{trk}}^{\text{offline}}$ boundaries used for the results of this paper are: 10, 20, 40, 80, 120, 150, 185, 250, and 350. These boundaries are chosen to minimize the statistical uncertainty in each bin. The average $N_{\text{trk}}^{\text{offline}}$ for MB pPb events is about 40. The overall CMS acceptance and tracking efficiency is about 85%.

IV. ANALYSIS TECHNIQUE

The SC technique, first introduced in Ref. [16], is based on four-particle correlations using cumulants. The four-particle cumulant technique, by simultaneously correlating four particles, is known to have the advantage of suppressing nonflow quite efficiently compared to other methods [17,30]. To study the correlation between the Fourier coefficients n and m , one can build, for each event, a two-particle correlator $[\langle \cos(n\phi_1 - n\phi_2) \rangle]$ and a four-particle correlator $[\langle \cos(n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4) \rangle]$ with a complex notation average over all the events as

$$\begin{aligned} \langle\langle 2_{n,-n} \rangle\rangle &\equiv \langle\langle e^{i(n\phi_1 - n\phi_2)} \rangle\rangle, \\ \langle\langle 4_{n,m,-n,-m} \rangle\rangle &\equiv \langle\langle e^{i(n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4)} \rangle\rangle. \end{aligned} \quad (3)$$

In the above equations, the real part of the two- and four-particle correlators are the cosine terms presented in Eq. (2). The final observable, the SC, is defined as follows:

$$\text{SC}(n, m) = \langle\langle 4_{n,m,-n,-m} \rangle\rangle - \langle\langle 2_{n,-n} \rangle\rangle \langle\langle 2_{m,-m} \rangle\rangle. \quad (4)$$

Nevertheless, it was shown in previous studies [33] that the standard four-particle cumulant technique does not suppress all of the short-range correlation contribution. In particular, the increasing trend of SC toward low multiplicities, following a power law, is characteristic of remaining nonflow contaminations [49]. In that paper, to further suppress nonflow, the subevent technique is used based on the calculation published in Ref. [37]. In the two-subevent case, the first and second subevents are defined as $-2.4 < \eta < 0$ and $0 < \eta < 2.4$. The bounds for three subevents are $-2.4, -0.8, 0.8, 2.4$, and for

four subevents are $-2.4, -1.2, 0, 1.2, 2.4$. The formula of the SC calculation can be derived from Eq. (4):

$$\text{SC}_{2\text{sub}}(n, m) = \langle\langle 4_{n,m,-n,-m}^{aa|bb} \rangle\rangle - \langle\langle 2_{n,-n}^{a|b} \rangle\rangle \langle\langle 2_{m,-m}^{a|b} \rangle\rangle, \quad (5)$$

$$\text{SC}_{3\text{sub}}(n, m) = \langle\langle 4_{-n|m,n|-m}^{a|bb|c} \rangle\rangle - \langle\langle 2_{-n|n}^{a|b} \rangle\rangle \langle\langle 2_{m|-m}^{b|c} \rangle\rangle, \quad (6)$$

$$\text{SC}_{4\text{sub}}(n, m) = \langle\langle 4_{n|m|-n|-m}^{a|b|c|d} \rangle\rangle - \langle\langle 2_{n|-n}^{a|c} \rangle\rangle \langle\langle 2_{m|-m}^{b|d} \rangle\rangle. \quad (7)$$

where a, b, c , and d denote the particles chosen in each subevent for the calculation and n, m the corresponding harmonic attributed to this subevent. In Eq. (5), the notation $aa|bb$ in the four-particle correlator means that two particles are required to be in the first subevent (aa) while the other two are required to be in the second subevent (bb). Similarly, for the two-particle correlator, one particle in each subevent is required ($a|b$). A similar reasoning is applied in Eqs. (6) and (7).

The systematic uncertainties in the experimental procedure are evaluated by varying the conditions in extracting SC. The 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 transverse and longitudinal track impact parameter divided by their uncertainties are varied from 2 to 5. In addition, the relative p_T uncertainty is varied from 5 to 10%. The sensitivity of the results to the primary vertex position along the beam axis (z_{vtx}) is quantified by comparing results with different z_{vtx} selection: $|z_{\text{vtx}}| < 3$ cm and $3 < |z_{\text{vtx}}| < 15$ cm, and the possible contamination by residual pileup interactions is studied by varying the pileup rejection criteria from no pileup rejection at all to selecting events with only one reconstructed vertex. Finally, to study potential trigger biases, a comparison to high-multiplicity pPb data for a given multiplicity range that were collected by a lower-threshold trigger with 100% efficiency is performed. This uncertainty is found to be negligible, while the other systematic uncertainty sources have contributions of 1% each, independent of $N_{\text{trk}}^{\text{offline}}$. The total systematic uncertainties are estimated to be 1.8% for SC.

V. RESULTS

The results of symmetric cumulants $\text{SC}(2, 3)$ and $\text{SC}(2, 4)$ obtained with the two-, three-, and four-subevent methods for $0.3 < p_T < 3$ GeV/c are shown in Fig. 1, as functions of multiplicity in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. For comparison, the results with no subevents from Ref. [33] are also shown for the range $40 < N_{\text{trk}}^{\text{offline}} < 350$ (the SC with no subevents for lower multiplicities are out of range because of the choice of the y-axis scale). The systematic uncertainties are the same for no and n subevents ($n = 2, 3, 4$).

Both $\text{SC}(2, 3)$ and $\text{SC}(2, 4)$ diverge toward large positive values for low- $N_{\text{trk}}^{\text{offline}}$ ranges ($N_{\text{trk}}^{\text{offline}} < 80$) using the no-subevent method, likely because of a dominant contribution from few-particle short-range correlations, as discussed in Ref. [33]. Using the subevent method, the contributions from short-range correlations are significantly suppressed [39,40]. No significant positive $\text{SC}(2, 3)$ values with subevent methods are observed over the entire event multiplicity range. The

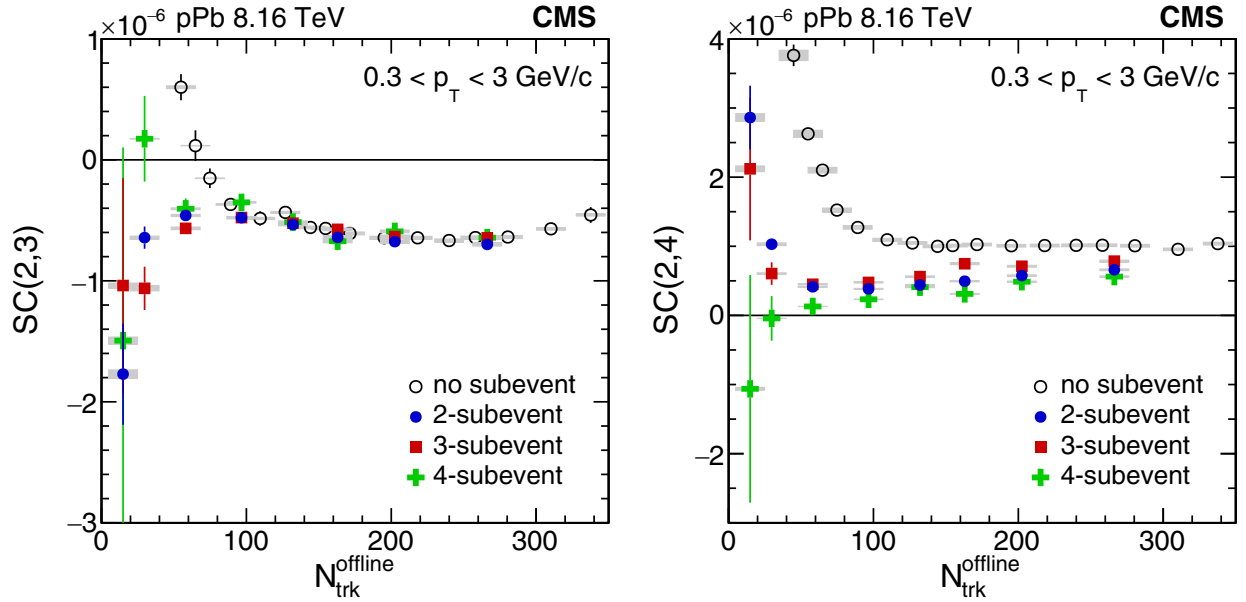


FIG. 1. The SC(2, 3) (left) and SC(2, 4) (right) distributions as functions of $N_{\text{trk}}^{\text{offline}}$ from two subevents (full blue circles), three subevents (red squares), and four subevents (green crosses). For comparison, published results from Ref. [33] with no subevents (open black circles), are also shown. Bars represent statistical uncertainties while grey areas represent the systematic uncertainties.

two- and three-subevent SC(2, 3) preserve significant negative signals down to $N_{\text{trk}}^{\text{offline}} \approx 20$, while the four-subevent SC(2, 3) tends to show a monotonic trend gradually converging to zero at $N_{\text{trk}}^{\text{offline}} \approx 20$. Similar behavior is also observed for SC(2, 4), where two- and three-subevent SC(2, 4) values remain positive but the four-subevent SC(2, 4) decreases to zero toward $N_{\text{trk}}^{\text{offline}} \approx 20$. As the four-subevent method is the most powerful in eliminating nonflow effects, the observed trends in four-subevent SC(2, 3) and SC(2, 4) provide

evidence for the onset of long-range collective particle correlations from low to high multiplicities in pPb collisions.

For $N_{\text{trk}}^{\text{offline}} > 80$, the no-subevent and n -subevent methods give consistent results for SC(2, 3), suggesting that the contribution from nonflow effects is negligible. For SC(2, 4), there is a difference clearly observed between no-subevent and n -subevent results even up to the highest multiplicities investigated. This observation is illustrated more clearly in Fig. 2, which shows the SC(2, 3) and SC(2, 4) relative

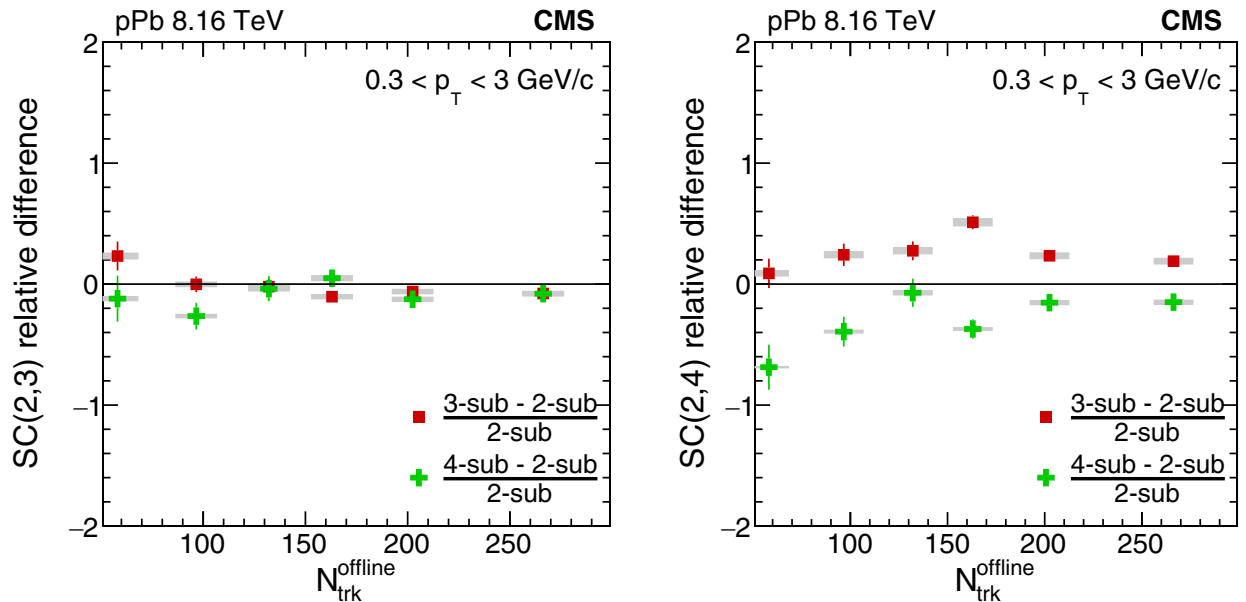


FIG. 2. The relative difference of SC(2, 3) (left) and SC(2, 4) (right) between two and three subevents (red squares) as well as between two and four subevents (green crosses) as a function of $N_{\text{trk}}^{\text{offline}}$. Bars represent statistical uncertainties while shaded areas represent the systematic uncertainties.

differences between two subevents and three or four subevents. The $SC(2, 3)$ results (Fig. 2, left) are consistent among the two-, three- and four-subevent methods, while there is an approximately 10–40% difference for $SC(2, 4)$ (Fig. 2, right) between the two-subevent and three- or four-subevent methods. The three-subevent $SC(2, 4)$ values are greater than the two-subevent values, contrary to what is typically expected from nonflow contributions. This behavior may suggest the sensitivity of $SC(2, 4)$ to other effects. In particular, the event-plane decorrelation [50] could be an important contribution to the observed behavior as also observed in Ref. [32]. The impact of event-plane decorrelation and how it may be different for $SC(2, 3)$ and $SC(2, 4)$ remains to be understood in future work.

VI. SUMMARY

The first measurement of event-by-event correlations of different Fourier harmonic orders in symmetric cumulants $SC(2, 3)$ and $SC(2, 4)$ with two, three, and four subevents in proton-lead (p Pb) collisions at $\sqrt{s_{NN}} = 8.16$ TeV is presented using a large data sample collected by the CMS experiment. The p Pb data analyzed with the subevent method are compared to previously published results using the technique without subevents. In all cases, an anticorrelation is observed between the single-particle anisotropy harmonics v_2 and v_3 , while v_2 and v_4 are positively correlated. For charged-particle multiplicity $N_{\text{trk}}^{\text{offline}} > 100$, both standard and n -subevent methods give similar results for $SC(2, 3)$, suggesting that nonflow effects have negligible contributions in this region. The $SC(2, 4)$ results show a somewhat different behavior, which depends on the number of subevents in the same multiplicity region. By significantly suppressing the nonflow contribution, the four-subevent results for both $SC(2, 3)$ and $SC(2, 4)$ show a monotonically decreasing magnitude toward zero at $N_{\text{trk}}^{\text{offline}} \approx 20$. These new results presented in this paper provide evidence for the onset of long-range collective particle correlations from low to high multiplicity events in p Pb collisions. The observed multiplicity dependence of multiparticle azimuthal correlations may further constrain the physical origin of the collectivity observed in small system collisions.

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