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

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

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Event-by-event long-range correlations of azimuthal anisotropy Fourier coefficients (v_n) in 8.16 TeV pPb 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

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

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

[*]Full author list given at the end of the article.

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 *p*Pb collisions at a nucleon-nucleon center-of mass energy $\sqrt{s_{NN}} = 8.16\,\text{TeV}$ 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 $1 < p_T < 10\,\text{GeV/c}$ 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 [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 *p*Pb 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 *p*Pb collisions is not at rest with respect to the laboratory frame. Massless particles emitted at $\eta_{\text{c. m.}} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at $\eta_{\text{lab}} = 0.465$ 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 *p*Pb 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 *p*Pb 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 $|\eta| < 2.4$, $p_T > 0.4\,\text{GeV/c}$, 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 ($N_{\mathrm{trk}}^{\mathrm{offline}} < 120$), 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 ($N_{\mathrm{trk}}^{\mathrm{offline}}$) 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 $p_T > 0.3\,\mathrm{GeV}/c$ 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 *p*Pb data are shown in classes of $N_{\mathrm{trk}}^{\mathrm{offline}}$, which is the number of primary tracks with $|\eta| < 2.4$ and $p_T > 0.4\,\mathrm{GeV}/c$, without corrections for acceptance and efficiency. The $N_{\mathrm{trk}}^{\mathrm{offline}}$ 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 $N_{\mathrm{trk}}^{\mathrm{offline}}$ 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

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

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:

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

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):

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

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

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

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: $|z_{\mathrm{vtx}}| < 3\,\mathrm{cm}$ and $3 < |z_{\mathrm{vtx}}| < 15\,\mathrm{cm}$, 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 *p*Pb 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 $N_{\mathrm{trk}}^{\mathrm{offline}}$. The total systematic uncertainties are estimated to be 1.8% for SC.

V. RESULTS

The results of symmetric cumulants SC(2, 3) and SC(2, 4) obtained with the two-, three-, and four-subevent methods for $0.3 < p_T < 3\,\mathrm{GeV}/c$ are shown in Fig. 1, as functions of multiplicity in *p*Pb collisions at $\sqrt{s_{NN}} = 8.16\,\mathrm{TeV}$. For comparison, the results with no subevents from Ref. [33] are also shown for the range $40 < N_{\mathrm{trk}}^{\mathrm{offline}} < 350$ (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 SC(2, 3) and SC(2, 4) diverge toward large positive values for low-$N_{\mathrm{trk}}^{\mathrm{offline}}$ ranges ($N_{\mathrm{trk}}^{\mathrm{offline}} < 80$) 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 SC(2, 3) values with subevent methods are observed over the entire event multiplicity range. The

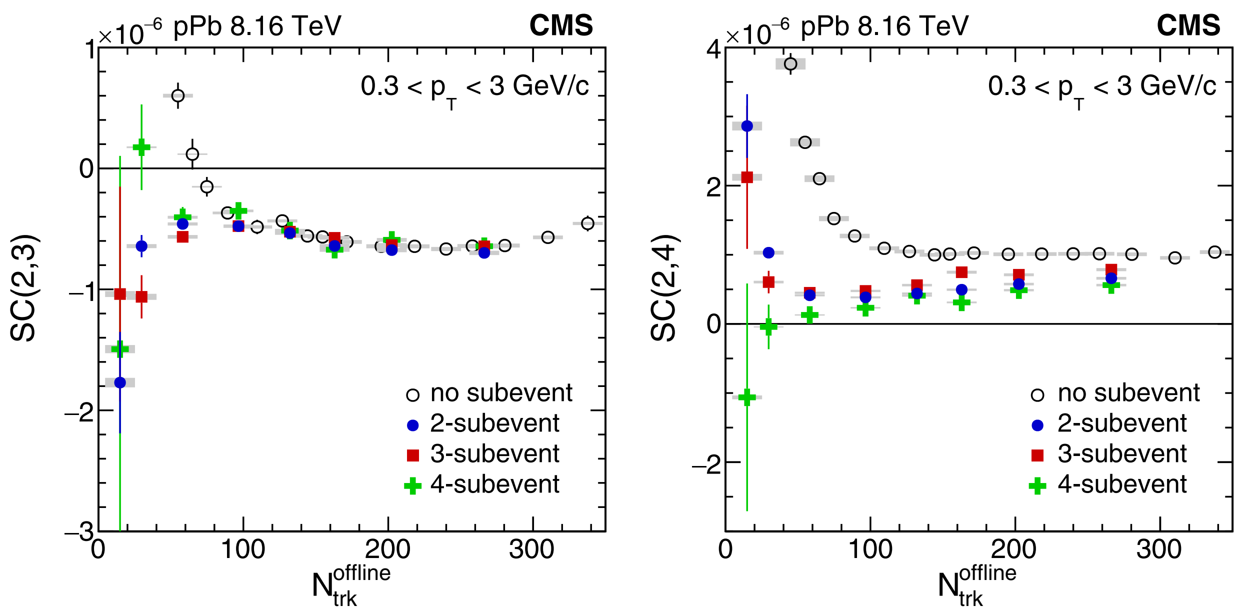

FIG. 1. The SC(2, 3) (left) and SC(2, 4) (right) distributions as functions of $N_{trk}^{offline}$ from two subevents (full blue circles), three subevents (red squares), and four subevents (green crosses). For comparison, published results from Ref. [33] with no subevents (open black circles), are also 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 $N_{trk}^{offline} \approx 20$, while the four-subevent SC(2, 3) tends to show a monotonic trend gradually converging to zero at $N_{trk}^{offline} \approx 20$. 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 $N_{trk}^{offline} \approx 20$. 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 *p*Pb collisions.

For $N_{trk}^{offline} > 80$, 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

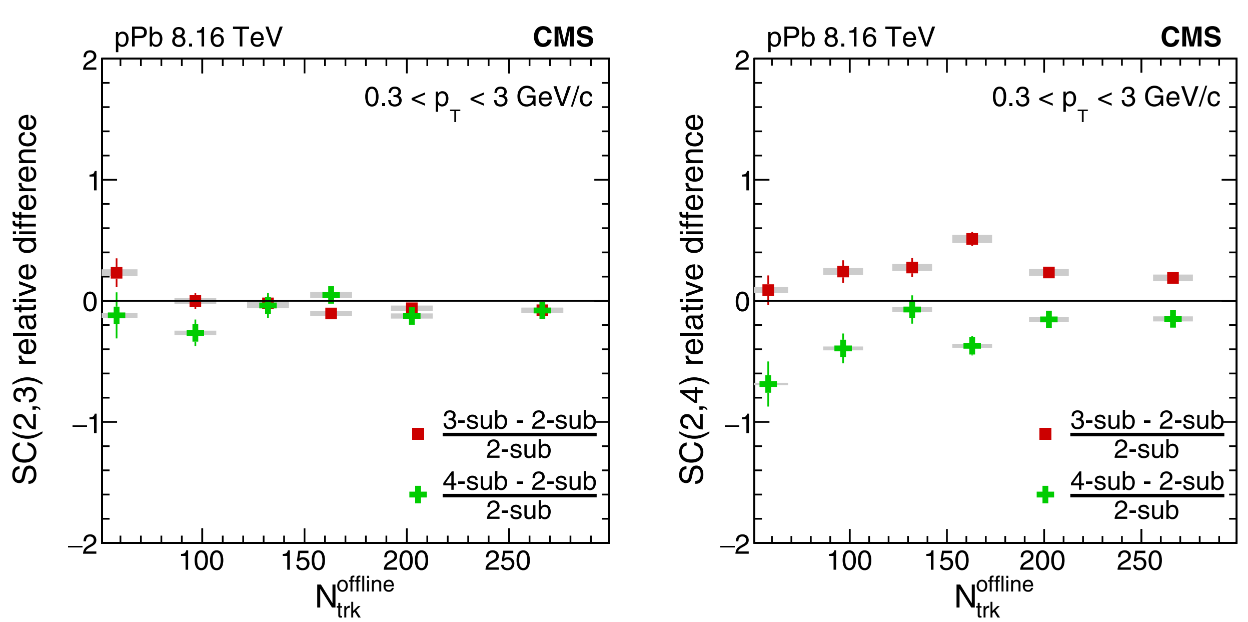

FIG. 2. The relative difference of SC(2, 3) (left) and SC(2, 4) (right) between two and three subevents (red squares) as well as between two and four subevents (green crosses) as a function of $N_{trk}^{offline}$. Bars represent statistical uncertainties while shaded areas represent the systematic uncertainties.

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 $\sqrt{s_{NN}} = 8.16\,\text{TeV}$ 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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L. Teodorescu,[154] S. Zahid,[154] K. Call,[155] J. Dittmann,[155] K. Hatakeyama,[155] H. Liu,[155] C. Madrid,[155] B. Mcmaster,[155] N. Pastika,[155] C. Smith,[155] R. Bartek,[156] A. Dominguez,[156] A. Buccilli,[157] S. I. Cooper,[157] C. Henderson,[157] P. Rumerio,[157] C. West,[157] D. Arcaro,[158] T. Bose,[158] D. Gastler,[158] D. Pinna,[158] D. Rankin,[158] C. Richardson,[158] J. Rohlf,[158] L. Sulak,[158] D. Zou,[158] G. Benelli,[159] X. Coubez,[159] D. Cutts,[159] M. Hadley,[159] J. Hakala,[159] U. Heintz,[159] J. M. Hogan,[159,bn] K. H. M. Kwok,[159] E. Laird,[159] G. Landsberg,[159] J. Lee,[159] Z. Mao,[159] M. Narain,[159] S. Sagir,[159,bo] R. Syarif,[159] E. Usai,[159] D. Yu,[159] R. Band,[160] C. Brainerd,[160] R. Breedon,[160] D. Burns,[160] M. Calderon De La Barca Sanchez,[160] M. Chertok,[160] J. Conway,[160] R. Conway,[160] P. T. Cox,[160] R. Erbacher,[160] C. Flores,[160] G. Funk,[160] W. Ko,[160] O. Kukral,[160] R. Lander,[160] M. Mulhearn,[160] D. Pellett,[160] J. Pilot,[160] S. Shalhout,[160] M. Shi,[160] D. Stolp,[160] D. Taylor,[160] K. Tos,[160] M. Tripathi,[160] Z. Wang,[160] F. Zhang,[160] M. Bachtis,[161] C. Bravo,[161] R. Cousins,[161] A. Dasgupta,[161] A. Florent,[161] J. Hauser,[161] M. Ignatenko,[161] N. Mccoll,[161] S. Regnard,[161] D. Saltzberg,[161] C. Schnaible,[161] V. Valuev,[161] E. Bouvier,[162] K. Burt,[162] R. Clare,[162] J. W. Gary,[162] S. M. A. Ghiasi Shirazi,[162] G. Hanson,[162] G. Karapostoli,[162] E. Kennedy,[162] F. Lacroix,[162] O. R. Long,[162] M. Olmedo Negrete,[162] M. I. Paneva,[162] W. Si,[162] L. Wang,[162] H. Wei,[162] S. Wimpenny,[162] B. R. Yates,[162] J. G. Branson,[163] P. Chang,[163] S. Cittolin,[163] M. Derdzinski,[163] R. Gerosa,[163] D. Gilbert,[163] B. Hashemi,[163] A. Holzner,[163] D. Klein,[163] G. Kole,[163] V. Krutelyov,[163] J. Letts,[163] M. Masciovecchio,[163] D. Olivito,[163] S. Padhi,[163] M. Pieri,[163] M. Sani,[163] V. Sharma,[163] S. Simon,[163] M. Tadel,[163] A. Vartak,[163] S. Wasserbaech,[163,bp] J. Wood,[163] F. Würthwein,[163] A. Yagil,[163] G. Zevi Della Porta,[163] N. Amin,[164] R. Bhandari,[164] J. Bradmiller-Feld,[164] C. Campagnari,[164] M. Citron,[164] A. Dishaw,[164] V. Dutta,[164] M. Franco Sevilla,[164] L. Gouskos,[164] R. Heller,[164] J. Incandela,[164] A. Ovcharova,[164] H. Qu,[164] J. Richman,[164] D. Stuart,[164] I. Suarez,[164] S. Wang,[164] J. Yoo,[164] D. Anderson,[165] A. Bornheim,[165] J. M. Lawhorn,[165] H. B. Newman,[165] T. Q. Nguyen,[165] M. Spiropulu,[165] J. R. Vlimant,[165] R. Wilkinson,[165] S. Xie,[165] Z. Zhang,[165] R. Y. Zhu,[165] M. B. Andrews,[166] T. Ferguson,[166] T. Mudholkar,[166] M. Paulini,[166] M. Sun,[166] I. Vorobiev,[166] M. Weinberg,[166] J. P. Cumalat,[167] W. T. Ford,[167] F. Jensen,[167] A. Johnson,[167] M. Krohn,[167] E. MacDonald,[167] T. Mulholland,[167] R. Patel,[167] A. Perloff,[167] K. Stenson,[167] K. A. Ulmer,[167] S. R. Wagner,[167] J. Alexander,[168] J. Chaves,[168] Y. Cheng,[168] J. Chu,[168] A. Datta,[168] K. Mcdermott,[168] N. Mirman,[168] J. R. Patterson,[168] D. Quach,[168] A. Rinkevicius,[168] A. Ryd,[168] L. Skinnari,[168] L. Soffi,[168] S. M. Tan,[168] Z. Tao,[168] J. Thom,[168] J. Tucker,[168] P. Wittich,[168] M. Zientek,[168] S. Abdullin,[169] M. Albrow,[169] M. Alyari,[169] G. Apollinari,[169] A. Apresyan,[169] A. Apyan,[169] S. Banerjee,[169] L. A. T. Bauerdick,[169] A. Beretvas,[169] J. Berryhill,[169] P. C. Bhat,[169] K. Burkett,[169] J. N. Butler,[169] A. Canepa,[169] G. B. Cerati,[169] H. W. K. Cheung,[169] F. Chlebana,[169] M. Cremonesi,[169] J. Duarte,[169] V. D. Elvira,[169] J. Freeman,[169] Z. Gecse,[169] E. Gottschalk,[169] L. Gray,[169] D. Green,[169] S. Grünendahl,[169] O. Gutsche,[169] J. Hanlon,[169] R. M. Harris,[169] S. Hasegawa,[169] J. Hirschauer,[169] Z. Hu,[169] B. Jayatilaka,[169] S. Jindariani,[169] M. Johnson,[169] U. Joshi,[169] B. Klima,[169] M. J. Kortelainen,[169] B. Kreis,[169] S. Lammel,[169] D. Lincoln,[169] R. Lipton,[169] M. Liu,[169] T. Liu,[169] J. Lykken,[169] K. Maeshima,[169] J. M. Marraffino,[169] D. Mason,[169] P. McBride,[169] P. Merkel,[169] S. Mrenna,[169] S. Nahn,[169] V. O'Dell,[169] K. Pedro,[169] C. Pena,[169] O. Prokofyev,[169] G. Rakness,[169] L. Ristori,[169] A. Savoy-Navarro,[169,bq] B. Schneider,[169] E. Sexton-Kennedy,[169] A. Soha,[169] W. J. Spalding,[169] L. Spiegel,[169] S. Stoynev,[169] J. Strait,[169] N. Strobbe,[169] L. Taylor,[169] S. Tkaczyk,[169] N. V. Tran,[169] L. Uplegger,[169] E. W. Vaandering,[169] C. Vernieri,[169] M. Verzocchi,[169] R. Vidal,[169] M. Wang,[169] H. A. Weber,[169] A. Whitbeck,[169] D. Acosta,[170] P. Avery,[170] P. Bortignon,[170] D. Bourilkov,[170] A. Brinkerhoff,[170] L. Cadamuro,[170] A. Carnes,[170] M. Carver,[170] D. Curry,[170] R. D. Field,[170] S. V. Gleyzer,[170] B. M. Joshi,[170] J. Konigsberg,[170] A. Korytov,[170] K. H. Lo,[170] P. Ma,[170] K. Matchev,[170] H. Mei,[170] G. Mitselmakher,[170] D. Rosenzweig,[170] K. Shi,[170] D. Sperka,[170] J. Wang,[170] S. Wang,[170] X. Zuo,[170] Y. R. Joshi,[171] S. Linn,[171] A. Ackert,[172] T. Adams,[172] A. Askew,[172] S. Hagopian,[172] V. Hagopian,[172] K. F. Johnson,[172] T. Kolberg,[172] G. Martinez,[172] T. Perry,[172] H. Prosper,[172] A. Saha,[172] C. Schiber,[172] R. Yohay,[172] M. M. Baarmand,[173] V. Bhopatkar,[173] S. Colafranceschi,[173] M. Hohlmann,[173] D. Noonan,[173] M. Rahmani,[173] T. Roy,[173] F. Yumiceva,[173] M. R. Adams,[174] L. Apanasevich,[174] D. Berry,[174] R. R. Betts,[174] R. Cavanaugh,[174] X. Chen,[174] S. Dittmer,[174] O. Evdokimov,[174] C. E. Gerber,[174] D. A. Hangal,[174] D. J. Hofman,[174] K. Jung,[174] J. Kamin,[174] C. Mills,[174] I. D. Sandoval Gonzalez,[174] M. B. Tonjes,[174] H. Trauger,[174] N. Varelas,[174] H. Wang,[174] X. Wang,[174] Z. Wu,[174] J. Zhang,[174] M. Alhusseini,[175] B. Bilki,[175,br] W. Clarida,[175] K. Dilsiz,[175,bs] S. Durgut,[175] R. P. Gandrajula,[175] M. Haytmyradov,[175] V. Khristenko,[175] J.-P. Merlo,[175] A. Mestvirishvili,[175] A. Moeller,[175] J. Nachtman,[175] H. Ogul,[175,bt] Y. Onel,[175] F. Ozok,[175,bu] A. Penzo,[175] C. Snyder,[175] E. Tiras,[175] J. Wetzel,[175] B. Blumenfeld,[176] A. Cocoros,[176] N. Eminizer,[176] D. Fehling,[176] L. Feng,[176] A. V. Gritsan,[176] W. T. Hung,[176] P. Maksimovic,[176] J. Roskes,[176] U. Sarica,[176] M. Swartz,[176] M. Xiao,[176] C. You,[176] A. Al-bataineh,[177] P. Baringer,[177] A. Bean,[177] S. Boren,[177] J. Bowen,[177] A. Bylinkin,[177] J. Castle,[177] S. Khalil,[177] A. Kropivnitskaya,[177] D. Majumder,[177] W. Mcbrayer,[177] M. Murray,[177] C. Rogan,[177] S. Sanders,[177] E. Schmitz,[177] J. D. Tapia Takaki,[177] Q. Wang,[177] S. Duric,[178] A. Ivanov,[178] K. Kaadze,[178] D. Kim,[178] Y. Maravin,[178] D. R. Mendis,[178] T. Mitchell,[178] A. Modak,[178] A. Mohammadi,[178] L. K. Saini,[178] N. Skhirtladze,[178] F. Rebassoo,[179] D. Wright,[179] A. Baden,[180] O. Baron,[180] A. Belloni,[180] S. C. Eno,[180] Y. Feng,[180] C. Ferraioli,[180] N. J. Hadley,[180] S. Jabeen,[180] G. Y. Jeng,[180] R. G. Kellogg,[180] J. Kunkle,[180] A. C. Mignerey,[180] S. Nabili,[180] F. Ricci-Tam,[180] Y. H. Shin,[180] A. Skuja,[180] S. C. Tonwar,[180] K. Wong,[180] D. Abercrombie,[181] B. Allen,[181] V. Azzolini,[181] A. Baty,[181] G. Bauer,[181] R. Bi,[181] S. Brandt,[181] W. Busza,[181] I. A. Cali,[181] M. D'Alfonso,[181] Z. Demiragli,[181] G. Gomez Ceballos,[181] M. Goncharov,[181] P. Harris,[181] D. Hsu,[181] M. Hu,[181] Y. Iiyama,[181] G. M. Innocenti,[181] M. Klute,[181] D. Kovalskyi,[181] Y.-J. Lee,[181] P. D. Luckey,[181] B. Maier,[181] A. C. Marini,[181] C. Mcginn,[181] C. Mironov,[181] S. Narayanan,[181] X. Niu,[181] C. Paus,[181] C. Roland,[181] G. Roland,[181] G. S. F. Stephans,[181] K. Sumorok,[181] K. Tatar,[181] D. Velicanu,[181] J. Wang,[181] T. W. Wang,[181] B. Wyslouch,[181] S. Zhaozhong,[181] A. C. Benvenuti,[182,bv] R. M. Chatterjee,[182] A. Evans,[182] P. Hansen,[182] Sh. Jain,[182] S. Kalafut,[182] Y. Kubota,[182] Z. Lesko,[182]

J. Mans,[182] N. Ruckstuhl,[182] R. Rusack,[182] J. Turkewitz,[182] M. A. Wadud,[182] J. G. Acosta,[183] S. Oliveros,[183] E. Avdeeva,[184] K. Bloom,[184] D. R. Claes,[184] C. Fangmeier,[184] F. Golf,[184] R. Gonzalez Suarez,[184] R. Kamalieddin,[184] I. Kravchenko,[184] J. Monroy,[184] J. E. Siado,[184] G. R. Snow,[184] B. Stieger,[184] A. Godshalk,[185] C. Harrington,[185] I. Iashvili,[185] A. Kharchilava,[185] C. Mclean,[185] D. Nguyen,[185] A. Parker,[185] S. Rappoccio,[185] B. Roozbahani,[185] G. Alverson,[186] E. Barberis,[186] C. Freer,[186] A. Hortiangtham,[186] D. M. Morse,[186] T. Orimoto,[186] R. Teixeira De Lima,[186] T. Wamorkar,[186] B. Wang,[186] A. Wisecarver,[186] D. Wood,[186] S. Bhattacharya,[187] O. Charaf,[187] K. A. Hahn,[187] N. Mucia,[187] N. Odell,[187] M. H. Schmitt,[187] K. Sung,[187] M. Trovato,[187] M. Velasco,[187] R. Bucci,[188] N. Dev,[188] M. Hildreth,[188] K. Hurtado Anampa,[188] C. Jessop,[188] D. J. Karmgard,[188] N. Kellams,[188] K. Lannon,[188] W. Li,[188] N. Loukas,[188] N. Marinelli,[188] F. Meng,[188] C. Mueller,[188] Y. Musienko,[188,bw] M. Planer,[188] A. Reinsvold,[188] R. Ruchti,[188] P. Siddireddy,[188] G. Smith,[188] S. Taroni,[188] M. Wayne,[188] A. Wightman,[188] M. Wolf,[188] A. Woodard,[188] J. Alimena,[189] L. Antonelli,[189] B. Bylsma,[189] L. S. Durkin,[189] S. Flowers,[189] B. Francis,[189] A. Hart,[189] C. Hill,[189] W. Ji,[189] T. Y. Ling,[189] W. Luo,[189] B. L. Winer,[189] S. Cooperstein,[190] P. Elmer,[190] J. Hardenbrook,[190] S. Higginbotham,[190] A. Kalogeropoulos,[190] D. Lange,[190] M. T. Lucchini,[190] J. Luo,[190] D. Marlow,[190] K. Mei,[190] I. Ojalvo,[190] J. Olsen,[190] C. Palmer,[190] P. Piroué,[190] J. Salfeld-Nebgen,[190] D. Stickland,[190] C. Tully,[190] S. Malik,[191] S. Norberg,[191] A. Barker,[192] V. E. Barnes,[192] S. Das,[192] L. Gutay,[192] M. Jones,[192] A. W. Jung,[192] A. Khatiwada,[192] B. Mahakud,[192] D. H. Miller,[192] N. Neumeister,[192] C. C. Peng,[192] S. Piperov,[192] H. Qiu,[192] J. F. Schulte,[192] J. Sun,[192] F. Wang,[192] R. Xiao,[192] W. Xie,[192] T. Cheng,[193] J. Dolen,[193] N. Parashar,[193] Z. Chen,[194] K. M. Ecklund,[194] S. Freed,[194] F. J. M. Geurts,[194] M. Kilpatrick,[194] W. Li,[194] B. P. Padley,[194] R. Redjimi,[194] J. Roberts,[194] J. Rorie,[194] W. Shi,[194] Z. Tu,[194] J. Zabel,[194] A. Zhang,[194] A. Bodek,[195] P. de Barbaro,[195] R. Demina,[195] Y. t. Duh,[195] J. L. Dulemba,[195] C. Fallon,[195] T. Ferbel,[195] M. Galanti,[195] A. Garcia-Bellido,[195] J. Han,[195] O. Hindrichs,[195] A. Khukhunaishvili,[195] P. Tan,[195] R. Taus,[195] A. Agapitos,[196] J. P. Chou,[196] Y. Gershtein,[196] E. Halkiadakis,[196] M. Heindl,[196] E. Hughes,[196] S. Kaplan,[196] R. Kunnawalkam Elayavalli,[196] S. Kyriacou,[196] A. Lath,[196] R. Montalvo,[196] K. Nash,[196] M. Osherson,[196] H. Saka,[196] S. Salur,[196] S. Schnetzer,[196] D. Sheffield,[196] S. Somalwar,[196] R. Stone,[196] S. Thomas,[196] P. Thomassen,[196] M. Walker,[196] A. G. Delannoy,[197] J. Heideman,[197] G. Riley,[197] S. Spanier,[197] O. Bouhali,[198,bx] A. Celik,[198] M. Dalchenko,[198] M. De Mattia,[198] A. Delgado,[198] S. Dildick,[198] R. Eusebi,[198] J. Gilmore,[198] T. Huang,[198] T. Kamon,[198,by] S. Luo,[198] R. Mueller,[198] D. Overton,[198] L. Perniè,[198] D. Rathjens,[198] A. Safonov,[198] N. Akchurin,[199] J. Damgov,[199] F. De Guio,[199] P. R. Dudero,[199] S. Kunori,[199] K. Lamichhane,[199] S. W. Lee,[199] T. Mengke,[199] S. Muthumuni,[199] T. Peltola,[199] S. Undleeb,[199] I. Volobouev,[199] Z. Wang,[199] S. Greene,[200] A. Gurrola,[200] R. Janjam,[200] W. Johns,[200] C. Maguire,[200] A. Melo,[200] H. Ni,[200] K. Padeken,[200] J. D. Ruiz Alvarez,[200] P. Sheldon,[200] S. Tuo,[200] J. Velkovska,[200] M. Verweij,[200] Q. Xu,[200] M. W. Arenton,[201] P. Barria,[201] B. Cox,[201] R. Hirosky,[201] M. Joyce,[201] A. Ledovskoy,[201] H. Li,[201] C. Neu,[201] T. Sinthuprasith,[201] Y. Wang,[201] E. Wolfe,[201] F. Xia,[201] R. Harr,[202] P. E. Karchin,[202] N. Poudyal,[202] J. Sturdy,[202] P. Thapa,[202] S. Zaleski,[202] M. Brodski,[203] J. Buchanan,[203] C. Caillol,[203] D. Carlsmith,[203] S. Dasu,[203] L. Dodd,[203] B. Gomber,[203] M. Grothe,[203] M. Herndon,[203] A. Hervé,[203] U. Hussain,[203] P. Klabbers,[203] A. Lanaro,[203] K. Long,[203] R. Loveless,[203] T. Ruggles,[203] A. Savin,[203] V. Sharma,[203] N. Smith,[203] W. H. Smith,[203] and N. Woods[203]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Wien, Austria*
[3]*Institute for Nuclear Problems, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussels, Brussels, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[10]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[11]*Universidade Estadual Paulista, São Paulo, Brazil*
[12]*Universidade Federal do ABC, São Paulo, Brazil*
[13]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[14]*University of Sofia, Sofia, Bulgaria*
[15]*Beihang University, Beijing, China*
[16]*Department of Physics, Tsinghua University, Beijing, China*
[17]*Institute of High Energy Physics, Beijing, China*
[18]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[19]*Universidad de Los Andes, Bogota, Colombia*
[20]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[21]*University of Split, Faculty of Science, Split, Croatia*
[22]*Institute Rudjer Boskovic, Zagreb, Croatia*
[23]*University of Cyprus, Nicosia, Cyprus*

[24]*Charles University, Prague, Czech Republic*
[25]*Escuela Politecnica Nacional, Quito, Ecuador*
[26]*Universidad San Francisco de Quito, Quito, Ecuador*
[27]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[28]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[29]*Department of Physics, University of Helsinki, Helsinki, Finland*
[30]*Helsinki Institute of Physics, Helsinki, Finland*
[31]*Lappeenranta University of Technology, Lappeenranta, Finland*
[32]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[33]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Paris, France*
[34]*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
[35]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
[36]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
[37]*Georgian Technical University, Tbilisi, Georgia*
[38]*Tbilisi State University, Tbilisi, Georgia*
[39]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[40]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[41]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[42]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[43]*University of Hamburg, Hamburg, Germany*
[44]*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
[45]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
[46]*National and Kapodistrian University of Athens, Athens, Greece*
[47]*National Technical University of Athens, Athens, Greece*
[48]*University of Ioánnina, Ioánnina, Greece*
[49]*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[50]*Wigner Research Centre for Physics, Budapest, Hungary*
[51]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[52]*Institute of Physics, University of Debrecen, Debrecen, Hungary*
[53]*Indian Institute of Science (IISc), Bangalore, India*
[54]*National Institute of Science Education and Research, HBNI, Bhubaneswar, India*
[55]*Panjab University, Chandigarh, India*
[56]*University of Delhi, Delhi, India*
[57]*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
[58]*Indian Institute of Technology Madras, Madras, India*
[59]*Bhabha Atomic Research Centre, Mumbai, India*
[60]*Tata Institute of Fundamental Research-A, Mumbai, India*
[61]*Tata Institute of Fundamental Research-B, Mumbai, India*
[62]*Indian Institute of Science Education and Research (IISER), Pune, India*
[63]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[64]*University College Dublin, Dublin, Ireland*
[65]*INFN Sezione di Bari, Bari, Italy*
[66]*Università di Bari, Bari, Italy*
[67]*Politecnico di Bari, Bari, Italy*
[68]*INFN Sezione di Bologna, Bologna, Italy*
[69]*Università di Bologna, Bologna, Italy*
[70]*INFN Sezione di Catania, Catania, Italy*
[71]*Università di Catania, Catania, Italy*
[72]*INFN Sezione di Firenze, Firenze, Italy*
[73]*Università di Firenze , Firenze, Italy*
[74]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[75]*INFN Sezione di Genova, Genova, Italy*
[76]*Università di Genova, Genova, Italy*
[77]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[78]*Università di Milano-Bicocca, Milano, Italy*
[79]*INFN Sezione di Napoli, Napoli, Italy*
[80]*Università di Napoli 'Federico II', Napoli, Italy*
[81]*Università della Basilicata, Potenza, Italy*
[82]*Università G. Marconi, Roma, Italy*

[83]*INFN Sezione di Padova, Padova, Italy*
[84]*Università di Padova, Padova, Italy*
[85]*Università di Trento, Trento, Italy*
[86]*INFN Sezione di Pavia, Pavia, Italy*
[87]*Università di Pavia, Pavia, Italy*
[88]*INFN Sezione di Perugia, Perugia, Italy*
[89]*Università di Perugia, Perugia, Italy*
[90]*INFN Sezione di Pisa, Pisa, Italy*
[91]*Università di Pisa, Pisa, Italy*
[92]*Scuola Normale Superiore di Pisa, Pisa, Italy*
[93]*INFN Sezione di Roma, Roma, Italy*
[94]*Sapienza Università di Roma, Rome, Italy*
[95]*INFN Sezione di Torino, Torino, Italy*
[96]*Università di Torino, Torino, Italy*
[97]*Università del Piemonte Orientale, Novara, Italy*
[98]*INFN Sezione di Trieste, Trieste, Italy*
[99]*Università di Trieste, Trieste, Italy*
[100]*Kyungpook National University, Daegu, Korea*
[101]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[102]*Hanyang University, Seoul, Korea*
[103]*Korea University, Seoul, Korea*
[104]*Sejong University, Seoul, Korea*
[105]*Seoul National University, Seoul, Korea*
[106]*University of Seoul, Seoul, Korea*
[107]*Sungkyunkwan University, Suwon, Korea*
[108]*Vilnius University, Vilnius, Lithuania*
[109]*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
[110]*Universidad de Sonora (UNISON), Hermosillo, Mexico*
[111]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[112]*Universidad Iberoamericana, Mexico City, Mexico*
[113]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[114]*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
[115]*University of Auckland, Auckland, New Zealand*
[116]*University of Canterbury, Christchurch, New Zealand*
[117]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[118]*National Centre for Nuclear Research, Swierk, Poland*
[119]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[120]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[121]*Joint Institute for Nuclear Research, Dubna, Russia*
[122]*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
[123]*Institute for Nuclear Research, Moscow, Russia*
[124]*Institute for Theoretical and Experimental Physics named by A. I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia*
[125]*Moscow Institute of Physics and Technology, Moscow, Russia*
[126]*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
[127]*P. N. Lebedev Physical Institute, Moscow, Russia*
[128]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[129]*Novosibirsk State University (NSU), Novosibirsk, Russia*
[130]*Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia*
[131]*National Research Tomsk Polytechnic University, Tomsk, Russia*
[132]*University of Belgrade, Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia*
[133]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[134]*Universidad Autónoma de Madrid, Madrid, Spain*
[135]*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
[136]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[137]*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
[138]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[139]*Paul Scherrer Institut, Villigen, Switzerland*
[140]*ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
[141]*Universität Zürich, Zurich, Switzerland*

[142]*National Central University, Chung-Li, Taiwan*
[143]*National Taiwan University (NTU), Taipei, Taiwan*
[144]*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
[145]*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
[146]*Middle East Technical University, Physics Department, Ankara, Turkey*
[147]*Bogazici University, Istanbul, Turkey*
[148]*Istanbul Technical University, Istanbul, Turkey*
[149]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
[150]*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[151]*University of Bristol, Bristol, United Kingdom*
[152]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[153]*Imperial College, London, United Kingdom*
[154]*Brunel University, Uxbridge, United Kingdom*
[155]*Baylor University, Waco, Texas, USA*
[156]*Catholic University of America, Washington, DC, USA*
[157]*The University of Alabama, Tuscaloosa, Alabama, USA*
[158]*Boston University, Boston, Massachusetts, USA*
[159]*Brown University, Providence, Rhode Island, USA*
[160]*University of California, Davis, Davis, California, USA*
[161]*University of California, Los Angeles, California, USA*
[162]*University of California, Riverside, Riverside, California, USA*
[163]*University of California, San Diego, La Jolla, California, USA*
[164]*Department of Physics, University of California, Santa BarbaraSanta Barbara, California, USA*
[165]*California Institute of Technology, Pasadena, California, USA*
[166]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[167]*University of Colorado Boulder, Boulder, Colorado, USA*
[168]*Cornell University, Ithaca, New York, USA*
[169]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[170]*University of Florida, Gainesville, Florida, USA*
[171]*Florida International University, Miami, Florida, USA*
[172]*Florida State University, Tallahassee, Florida, USA*
[173]*Florida Institute of Technology, Melbourne, Florida, USA*
[174]*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
[175]*The University of Iowa, Iowa City, Iowa, USA*
[176]*Johns Hopkins University, Baltimore, Maryland, USA*
[177]*The University of Kansas, Lawrence, Kansas, USA*
[178]*Kansas State University, Manhattan, Kansas, USA*
[179]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[180]*University of Maryland, College Park, Maryland, USA*
[181]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[182]*University of Minnesota, Minneapolis, Minnesota, USA*
[183]*University of Mississippi, Oxford, Mississippi, USA*
[184]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[185]*State University of New York at Buffalo, Buffalo, New York, USA*
[186]*Northeastern University, Boston, Massachusetts, USA*
[187]*Northwestern University, Evanston, Illinois, USA*
[188]*University of Notre Dame, Notre Dame, Indiana, USA*
[189]*The Ohio State University, Columbus, Ohio, USA*
[190]*Princeton University, Princeton, New Jersey, USA*
[191]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[192]*Purdue University, West Lafayette, Indiana, USA*
[193]*Purdue University Northwest, Hammond, Indiana, USA*
[194]*Rice University, Houston, Texas, USA*
[195]*University of Rochester, Rochester, New York, USA*
[196]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[197]*University of Tennessee, Knoxville, Tennessee, USA*
[198]*Texas A&M University, College Station, Texas, USA*
[199]*Texas Tech University, Lubbock, Texas, USA*
[200]*Vanderbilt University, Nashville, Tennessee, USA*

[201]*University of Virginia, Charlottesville, Virginia, USA*
[202]*Wayne State University, Detroit, Michigan, USA*
[203]*University of Wisconsin - Madison, Madison, Wisconsin, USA*

[a]Also at Vienna University of Technology, Vienna, Austria.
[b]Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[c]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[d]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[e]Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[f]Also at University of Chinese Academy of Sciences, Beijing, China.
[g]Also at Institute for Theoretical and Experimental Physics named by A. I. Alikhanov of NRC 'Kurchatov Institute' Moscow, Russia.
[h]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[i]Also at Cairo University, Cairo, Egypt.
[j]Also at Fayoum University, El-Fayoum, Egypt; British University in Egypt, Cairo, Egypt.
[k]Also at Fayoum University, El-Fayoum, Egypt.
[l]Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.
[m]Also at Université de Haute Alsace, Mulhouse, France.
[n]Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[o]Also at Tbilisi State University, Tbilisi, Georgia.
[p]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[q]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[r]Also at University of Hamburg, Hamburg, Germany.
[s]Also at Brandenburg University of Technology, Cottbus, Germany.
[t]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[u]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[v]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary; Deceased.
[w]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[x]Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
[y]Also at Institute of Physics, Bhubaneswar, India.
[z]Also at Shoolini University, Solan, India.
[aa]Also at University of Visva-Bharati, Santiniketan, India.
[ab]Also at Isfahan University of Technology, Isfahan, Iran.
[ac]Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[ad]Also at Università degli Studi di Siena, Siena, Italy.
[ae]Also at Kyung Hee University, Department of Physics, Seoul, Korea.
[af]Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[ag]Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[ah]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[ai]Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[aj]Also at Institute for Nuclear Research, Moscow, Russia; National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[ak]Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[al]Also at University of Florida, Gainesville, Florida, USA.
[am]Also at P. N. Lebedev Physical Institute, Moscow, Russia.
[an]Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[ao]Also at INFN Sezione di Padova, Italy; Universitá di Padova, Padova, Italy; Universitá di Trento (Trento), Padova, Italy.
[ap]Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[aq]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[ar]Also at INFN Sezione di Pavia, Pavia, Italy; Universitá di Pavia, Pavia, Italy.
[as]Also at University of Belgrade, Belgrade, Serbia.
[at]Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[au]Also at National and Kapodistrian University of Athens, Athens, Greece.
[av]Also at Riga Technical University, Riga, Latvia.
[aw]Also at Universität Zürich, Zurich, Switzerland.
[ax]Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
[ay]Also at Gaziosmanpasa University, Tokat, Turkey.
[az]Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey.
[ba]Also at Mersin University, Mersin, Turkey.
[bb]Also at Piri Reis University, Istanbul, Turkey.
[bc]Also at Adiyaman University, Adiyaman, Turkey.

[bd]Also at Ozyegin University, Istanbul, Turkey.
[be]Also at Izmir Institute of Technology, Izmir, Turkey.
[bf]Also at Marmara University, Istanbul, Turkey.
[bg]Also at Kafkas University, Kars, Turkey.
[bh]Also at Istanbul University, Istanbul, Turkey.
[bi]Also at Istanbul Bilgi University, Istanbul, Turkey.
[bj]Also at Hacettepe University, Ankara, Turkey.
[bk]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[bl]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[bm]Also at Monash University, Faculty of Science, Clayton, Australia.
[bn]Also at Bethel University, St. Paul, Minnesota, USA.
[bo]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[bp]Also at Utah Valley University, Orem, Utah, USA.
[bq]Also at Purdue University, West Lafayette, Indiana, USA.
[br]Also at Beykent University, Istanbul, Turkey.
[bs]Also at Bingol University, Bingol, Turkey.
[bt]Also at Sinop University, Sinop, Turkey.
[bu]Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[bv]Deceased.
[bw]Also at Institute for Nuclear Research, Moscow, Russia.
[bx]Also at Texas A&M University at Qatar, Doha, Qatar.
[by]Also at Kyungpook National University, Daegu, Korea.