



# Evidence for collective multi-particle correlations in pPb collisions

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## Abstract

The second-order azimuthal anisotropy Fourier harmonics,  $v_2$ , are obtained in pPb and PbPb collisions over a wide pseudorapidity ( $\eta$ ) range based on correlations among six or more charged particles. The pPb data, corresponding to an integrated luminosity of  $35 \text{ nb}^{-1}$ , were collected during the 2013 LHC pPb run at a nucleon-nucleon center-of-mass energy of 5.02 TeV by the CMS experiment. A sample of semi-peripheral PbPb collision data at  $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ , corresponding to an integrated luminosity of  $2.5 \mu\text{b}^{-1}$  and covering a similar range of particle multiplicities as the pPb data, is also analyzed for comparison. The six- and eight-particle cumulant and the Lee-Yang zeros methods are used to extract the  $v_2$  coefficients, extending previous studies of two- and four-particle correlations. For both the pPb and PbPb systems, the  $v_2$  values obtained with correlations among more than four particles are consistent with previously published four-particle results. These data support the interpretation of a collective origin for the previously observed long-range (large  $\Delta\eta$ ) correlations in both systems. The ratios of  $v_2$  values corresponding to correlations including different numbers of particles are compared to theoretical predictions that assume a hydrodynamic behavior of a pPb system dominated by fluctuations in the positions of participant nucleons. These results provide new insights into the multi-particle dynamics of collision systems with a very small overlapping region.

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Measurements at the CERN LHC have led to the discovery of two-particle azimuthal correlation structures at large relative pseudorapidity (long-range) in proton-proton (pp) [1] and proton-lead (pPb) [2–5] collisions. Similar long-range structure has also been observed for  $\sqrt{s_{\text{NN}}} = 200$  GeV deuteron-gold (dAu) collisions at RHIC [6, 7]. The results extend previous studies of relativistic heavy ion collisions, such as for the copper-copper [8], gold-gold [8–12], and lead-lead (PbPb) [13–18] systems, where similar long-range, two-particle correlations at small relative azimuthal angle  $|\Delta\phi| \approx 0$  were first observed. A fundamental question is whether the observed behavior results from correlations exclusively between particle pairs, or if it is a multi-particle, collective effect. It has been suggested that the hydrodynamic collective flow of a strongly interacting and expanding medium [19–21] is responsible for these long-range correlations in central and mid-central heavy ion collisions. The origin of the observed long-range correlations in collision systems with a small overlapping region, such as for pp and pPb collisions, is not clear since for these systems the formation of an extended hot medium is not necessarily expected. Various theoretical models have been proposed to interpret the pp [22, 23] and pPb results, including initial-state gluon saturation without any final state interactions [24, 25] and, similar to what is thought to occur in heavier systems, hydrodynamic behavior that develops in a conjectured high-density medium [26–28]. These models have been successful in describing different aspects of the previous experimental results.

To further investigate the multi-particle nature of the observed long-range correlation phenomena, in this Letter we present measurements of correlations among six or more charged particles for pPb collisions at a center-of-mass energy per nucleon pair of  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The azimuthal dependence of particle production is typically characterized by an expansion in Fourier harmonics ( $v_n$ ) [29]. In hydrodynamic models, the second ( $v_2$ ) and third ( $v_3$ ) harmonics, called “elliptic” and “triangular” flow [30], respectively, directly reflect the response to the initial collision geometry and fluctuations [31–33], providing insight into the fundamental transport properties of the medium. First attempts to establish the multi-particle nature of the correlations observed in pPb collisions were presented in Refs. [34, 35] by directly measuring four-particle azimuthal correlations, where the elliptic flow signal was obtained using the four-particle cumulant method [36]. However, four-particle correlations can still be affected by contributions from non-collective effects such as fragmentation of back-to-back jets. By extending the studies to six- and eight-particle cumulants [36] and by also obtaining results using the Lee-Yang zeros (LYZ) method, which involves correlations among all detected particles [37, 38], it is possible to further explore the collective nature of the correlations. High-statistics data obtained by the CMS experiment during the 2013 pPb run at the LHC are used. With a sample of very high final state multiplicity pPb collisions, the correlation data have been studied in a regime that is comparable to the charged particle multiplicity of the 50% most peripheral (semi-peripheral) PbPb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV.

The CMS detector comprises a number of subsystems [39]. The results in this Letter are mainly based on the silicon tracker information. The silicon tracker, located in the 3.8 T field of a superconducting solenoid, consists of 1 440 silicon pixel and 15 148 silicon strip detector modules. The silicon tracker measures charged particles within the pseudorapidity range  $|\eta| < 2.5$ , and provides an impact parameter resolution of  $\approx 15 \mu\text{m}$  and a transverse momentum ( $p_T$ ) resolution better than 1.5% at  $p_T \approx 100$  GeV/c. The electromagnetic (ECAL) and hadron (HCAL) calorimeters are also located inside the solenoid and cover the pseudorapidity range  $|\eta| < 3.0$ . The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates. The ECAL consists of lead tungstate crystals arranged in a quasiprojective geometry. Iron/quartz-fiber Čerenkov hadron forward (HF) calorimeters cover the range  $2.9 < |\eta| < 5.2$  on either side of the interaction region. These HF calorimeters are azimuthally subdivided into

20° modular wedges and further segmented to form  $0.175 \times 0.175$  rad ( $\Delta\eta \times \Delta\phi$ ) “towers”. The detailed Monte Carlo (MC) simulation of the CMS detector response is based on GEANT4 [40].

The analysis is performed using data recorded by CMS during the LHC pPb run in 2013. The data set corresponds to an integrated luminosity of  $35 \text{ nb}^{-1}$ . The beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The beam directions were reversed during the run allowing a check of one potential source of systematic uncertainties. As a result of the energy difference between the colliding beams, the nucleon-nucleon center-of-mass in the pPb collisions is not at rest with respect to the laboratory frame. Massless particles emitted at  $\eta_{\text{cm}} = 0$  in the nucleon-nucleon center-of-mass frame will be detected at  $\eta = -0.465$  (clockwise proton beam) or  $0.465$  (counterclockwise proton beam) in the laboratory frame. A sample of  $\sqrt{s_{\text{NN}}} = 2.76$  TeV PbPb data collected during the 2011 LHC heavy-ion run, corresponding to an integrated luminosity of  $2.3 \mu\text{b}^{-1}$ , is also analyzed for comparison purposes. The triggers and event selection, as well as track reconstruction and selection are summarized below and are identical to those used in Ref. [35].

Minimum bias (MB) pPb events were triggered by requiring at least one track with  $p_{\text{T}} > 0.4 \text{ GeV}/c$  to be found in the pixel tracker for a pPb bunch crossing. Only a small fraction ( $\sim 10^{-3}$ ) of all MB triggered events were recorded (i.e., the trigger was “prescaled”) because of hardware limits on the data acquisition rate. In order to select high-multiplicity pPb collisions, a dedicated high-multiplicity trigger was implemented using the CMS level-1 (L1) and high-level trigger (HLT) systems. At L1, three triggers requiring the total transverse energy summed over ECAL and HCAL to be greater than 20, 40, and 60 GeV were used since these cuts selected roughly the same events as the three HLT multiplicity selections discussed below. Online track reconstruction for the HLT was based on the three layers of pixel detectors, and required a track origin within a cylindrical region of length 30 cm along the beam and radius 0.2 cm perpendicular to the beam around the nominal interaction point. For each event, the vertex reconstructed with the highest number of pixel tracks was selected. The number of pixel tracks ( $N_{\text{trk}}^{\text{online}}$ ) with  $|\eta| < 2.4$ ,  $p_{\text{T}} > 0.4 \text{ GeV}/c$ , and a distance of closest approach to this vertex of 0.4 cm or less, was determined for each event. Several high-multiplicity ranges were defined with prescale factors that were progressively reduced until, for the highest multiplicity events, no prescaling was applied.

In the offline analysis, hadronic collisions are selected by requiring a coincidence of at least one HF calorimeter tower containing more than 3 GeV of total energy in each of the HF detectors. Only towers within  $3 < |\eta| < 5$  are used to avoid the edges of the HF acceptance. Events are also required to contain at least one reconstructed primary vertex within 15 cm of the nominal interaction point along the beam axis and within 0.15 cm transverse to the beam trajectory. At least two reconstructed tracks are required to be associated with the primary vertex. Beam related background is suppressed by rejecting events for which less than 25% of all reconstructed tracks pass the track selection criteria of this analysis. The pPb instantaneous luminosity provided by the LHC in the 2013 run resulted in an approximately 3% probability of at least one additional interaction occurring in the same bunch crossing. Following the procedure developed in Ref. [35] for rejecting such “pileup” events, a 99.8% purity of single-interaction events is achieved for the pPb collisions belonging to the highest multiplicity class studied in this Letter. In pPb interactions simulated with the EPOS [41] and HIJING [42] event generators, requiring at least one primary particle with total energy  $E > 3 \text{ GeV}$  in each of the  $\eta$  ranges  $-5 < \eta < -3$  and  $3 < \eta < 5$  is found to select 97–98% of the total inelastic hadronic cross section.

The CMS “high-quality” tracks, described in Ref. [43] are used in this analysis. Additionally, a reconstructed track is only considered as a candidate track from the primary vertex if the

significance of the separation along the beam axis ( $z$ ) between the track and the best vertex,  $d_z/\sigma(d_z)$ , and the significance of the track-vertex impact parameter measured transverse to the beam,  $d_T/\sigma(d_T)$ , are each less than 3. The relative uncertainty in the transverse-momentum measurement,  $\sigma(p_T)/p_T$ , is required to be less than 10%. To ensure high tracking efficiency and to reduce the rate of incorrectly reconstructed tracks, only tracks within  $|\eta| < 2.4$  and with  $0.3 < p_T < 3.0$  GeV/ $c$  are used in the analysis. A different  $p_T$  cutoff of 0.4 GeV/ $c$  is used in the multiplicity determination because of constraints on the online processing time for the HLT.

The entire pPb data set is divided into classes of reconstructed track multiplicity,  $N_{\text{trk}}^{\text{offline}}$ . The multiplicity classification in this analysis is identical to that used in Ref. [35], where more details are provided including a table relating  $N_{\text{trk}}^{\text{offline}}$  to the fraction of MB triggered events. A subset of semi-peripheral PbPb data collected during the 2011 LHC heavy-ion run with an MB trigger is also reanalyzed in order to directly compare the pPb and PbPb systems at the same track multiplicity. This PbPb sample is reprocessed using the same event selection and track reconstruction as for the present pPb analysis. A description of the 2011 PbPb data can be found in Ref. [44].

Extending the previous two- and four-particle azimuthal correlation measurements of Ref. [35], six- and eight-particle azimuthal correlations [36] are evaluated in this analysis as:

$$\begin{aligned}\langle\langle 6 \rangle\rangle &\equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)} \rangle\rangle, \\ \langle\langle 8 \rangle\rangle &\equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3+\phi_4-\phi_5-\phi_6-\phi_7-\phi_8)} \rangle\rangle.\end{aligned}\quad (1)$$

Here  $\phi_i$  ( $i = 1, \dots, 8$ ) are the azimuthal angles of one unique combination of multiple particles in an event,  $n$  is the harmonic number, and  $\langle\langle \dots \rangle\rangle$  represents the average over all combinations from all events within a given multiplicity range. The corresponding cumulants,  $c_n\{6\}$  and  $c_n\{8\}$ , are calculated as follows:

$$\begin{aligned}c_n\{6\} &= \langle\langle 6 \rangle\rangle - 9 \cdot \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle + 12 \cdot \langle\langle 2 \rangle\rangle^3, \\ c_n\{8\} &= \langle\langle 8 \rangle\rangle - 16 \cdot \langle\langle 6 \rangle\rangle \langle\langle 2 \rangle\rangle - 18 \cdot \langle\langle 4 \rangle\rangle^2 + 144 \cdot \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle^2 - 144 \langle\langle 2 \rangle\rangle^4,\end{aligned}\quad (2)$$

using the Q-cumulant method as formulated in Ref. [36], where  $\langle\langle 2 \rangle\rangle$  and  $\langle\langle 4 \rangle\rangle$  are defined similarly as in Eq. (1). The Fourier harmonics  $v_n$  that characterize the global azimuthal behavior are related to the multi-particle correlations [45] using

$$\begin{aligned}v_n\{6\} &= \sqrt[6]{\frac{1}{4}c_n\{6\}}, \\ v_n\{8\} &= \sqrt[8]{-\frac{1}{33}c_n\{8\}}.\end{aligned}\quad (3)$$

To account for detector effects, such as the tracking efficiency, the Q-cumulant method was extended in Ref. [45] to allow for particles having different weights. Each reconstructed track is weighted by a correction factor to account for the reconstruction efficiency, detector acceptance, and fraction of misreconstructed tracks. This factor is derived as a function of  $p_T$  and  $\eta$ , as described in Refs. [13, 14], based on MC simulations. The combined geometrical acceptance and efficiency for track reconstruction exceeds 60% for  $p_T \approx 0.3$  GeV/ $c$  and  $|\eta| < 2.4$ . The efficiency is greater than 90% in the  $|\eta| < 1$  region for  $p_T > 0.6$  GeV/ $c$ . For the entire multiplicity range (up to  $N_{\text{trk}}^{\text{offline}} \sim 350$ ) studied in this Letter, no dependence of the tracking efficiency on multiplicity is found and the rate of mis-reconstructed tracks remains at the 1–2% level. The software package provided by Ref. [45] is used to implement the weights of individual tracks in the cumulant calculations.

The LYZ method [37, 38] allows a direct study of the large-order behavior by using the asymptotic form of the cumulant expansion to relate locations of the zeros of a generating function to the azimuthal correlations. This method has been employed in previous CMS PbPb analyses [17, 46]. For each multiplicity bin, the  $v_2$  harmonic averaged over  $0.3 < p_T < 3.0 \text{ GeV}/c$  is found using an integral generating function [17]. Similar to the cumulant methods, a weight for each track is implemented to account for detector-related effects. In both methods, the statistical uncertainties are evaluated from data by dividing the data set into 20 subsets with roughly equal numbers of events and evaluating the standard deviation of the resulting distributions of the cumulant or  $v_2\{\text{LYZ}\}$  values. In the case of low multiplicity or small flow signal, the LYZ method may overestimate the true collective flow. This effect was studied using MC pseudo-experiments for the event multiplicities covered in this analysis and a small correction is applied to the data. The correction is less than 3% in the lowest multiplicity bin and becomes much smaller in higher-multiplicity bins. This correction is also included in the quoted LYZ systematic uncertainties.

Systematic uncertainties are estimated by varying the track quality requirements, by comparing the results using efficiency correction tables from different MC event generators, and by exploring the sensitivity of the results to the vertex position and to the  $N_{\text{trk}}^{\text{offline}}$  bin width. For the pPb data, potential HLT bias and pileup effects are also studied by requiring the presence of only a single reconstructed vertex. No evident  $N_{\text{trk}}^{\text{offline}}$  or beam direction dependent systematic effects are observed. For pPb collisions, a 5% systematic uncertainty is obtained for  $v_2\{6\}$  and a 6% uncertainty is found for both  $v_2\{8\}$  and  $v_2\{\text{LYZ}\}$ . The corresponding uncertainties for PbPb collisions are 2% for  $v_2\{6\}$  and  $v_2\{8\}$ , and 4% for  $v_2\{\text{LYZ}\}$ .

In Fig. 1, the six- and eight-particle cumulants,  $c_2\{6\}$  and  $c_2\{8\}$ , for particle  $p_T$  of 0.3–3.0 GeV/ $c$  in 2.76 TeV PbPb and 5.02 TeV pPb collisions are shown as a function of event multiplicity. The cumulants shown are required to be at least two standard deviations away from their physics boundaries ( $c_2\{6\}/\sigma_{c_2\{6\}} > 2$ ,  $c_2\{8\}/\sigma_{c_2\{8\}} < -2$ ), so that the statistical uncertainties can be propagated as Gaussian fluctuations [47]. Non-zero multi-particle correlation signals are observed in both PbPb and pPb collisions. The pPb data exhibit larger statistical uncertainties than the PbPb results, mainly because of the smaller magnitudes of the correlation signals. Because of the limited sample size, the  $c_2\{6\}$  and  $c_2\{8\}$  values in pPb collisions are derived for a smaller range in  $N_{\text{trk}}^{\text{offline}}$ .

The second-order anisotropy Fourier harmonics,  $v_2$ , averaged over the  $p_T$  range of 0.3–3.0 GeV/ $c$ , are shown in Fig. 2 based on six- and eight-particle cumulants (Eq. (3)) for 2.76 TeV PbPb (left) and 5.02 TeV pPb (right) collisions, as a function of event multiplicity. The open symbols are  $v_2$  results extracted by CMS using two- and four-particle correlations [35]. The  $v_2$  values derived using the LYZ method involving correlations among all particles are also shown. For each multiplicity bin, the values of  $v_2\{4\}$ ,  $v_2\{6\}$ ,  $v_2\{8\}$ , and  $v_2\{\text{LYZ}\}$  for pPb collisions are found to be in agreement within 10%. For part of the multiplicity range, the values for  $v_2\{4\}$  are larger than the others by a statistically significant amount, although still within 10%. The corresponding PbPb values are consistently higher than for pPb collisions, but within the PbPb system are found to be in agreement within 2% for most multiplicity ranges and within 10% for all multiplicities. This supports the collective nature of the observed correlations, i.e., involving all particles from each system, and is inconsistent with a jet-related origin involving correlations among only a few particles. The  $v_2$  data from two-particle correlations are consistently above the multi-particle correlation data. This behavior can be understood in hydrodynamic models, where event-by-event participant geometry fluctuations of the  $v_2$  coefficient are expected to affect the two- and multi-particle cumulants differently [48, 49]. Note that, to minimize jet-related non-flow effects, the  $v_2\{2\}$  values are obtained with an  $\eta$  gap of 2 units between the

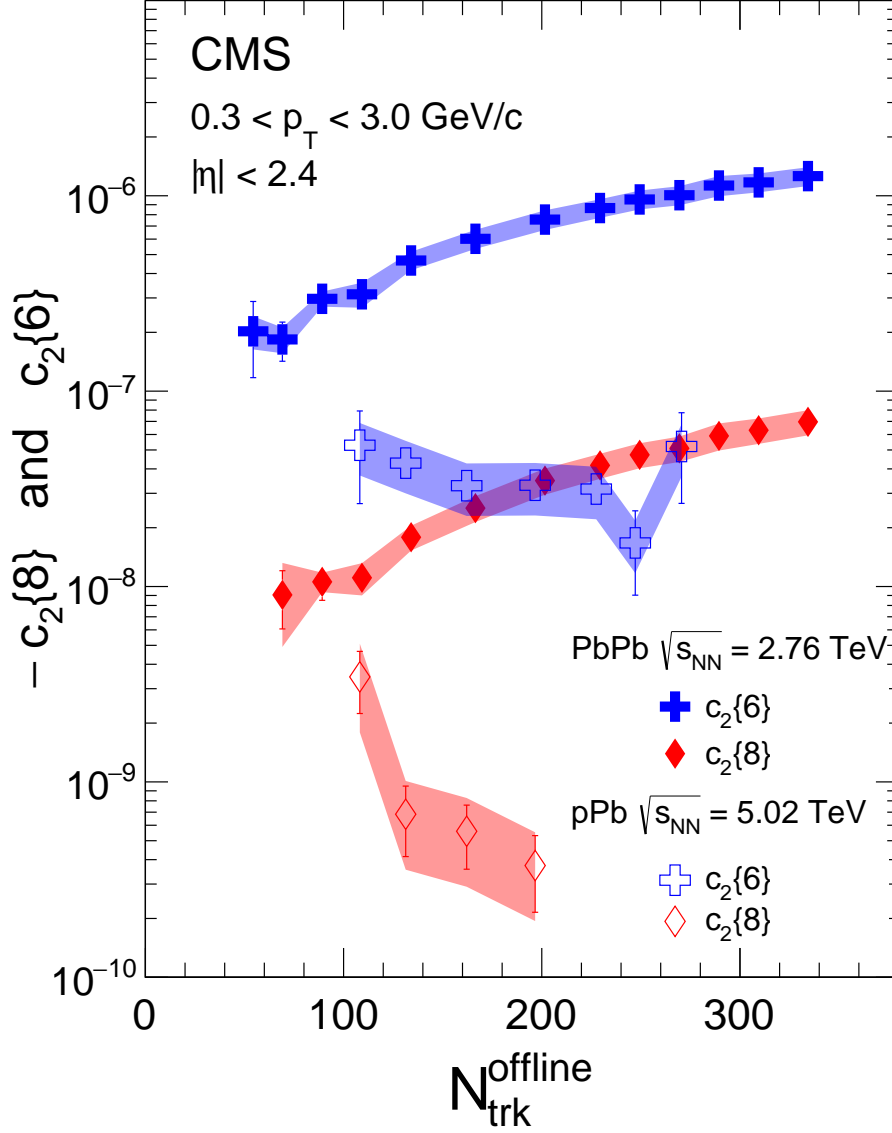


Figure 1: The cumulant  $c_2\{6\}$  and  $-c_2\{8\}$  results as a function of  $N_{\text{trk}}^{\text{offline}}$  for PbPb and pPb reactions. Error bars and shaded areas denote statistical and systematic uncertainties, respectively.

two particles. Possible residual non-flow effects resulting from back-to-back jet correlations are estimated using very low multiplicity events in Ref. [35]. Based on this analysis, such non-flow effects are expected to make a negligible contribution to  $v_2\{2\}$  in very high multiplicity events. In PbPb collisions, the  $v_2$  values from all methods show an increase with multiplicity, while little multiplicity dependence is seen for the pPb data. This difference might reflect the presence of a lenticular overlap geometry in PbPb collisions, which is not expected in pPb collisions, that gives rise to a large (and varying) initial elliptic asymmetry in the PbPb system.

The effect of fluctuation-driven initial-state eccentricities on multi-particle cumulants has recently been explored in the context of hydrodynamic behavior of the resulting medium [50, 51]. For fluctuation-driven initial-state conditions, ratios of  $v_2$  values derived from various orders of multi-particle cumulants are predicted to follow a universal behavior [50]. In Fig. 3, ratios of  $v_2\{6\}/v_2\{4\}$  (top) and  $v_2\{8\}/v_2\{6\}$  (bottom) are calculated and plotted against  $v_2\{4\}/v_2\{2\}$

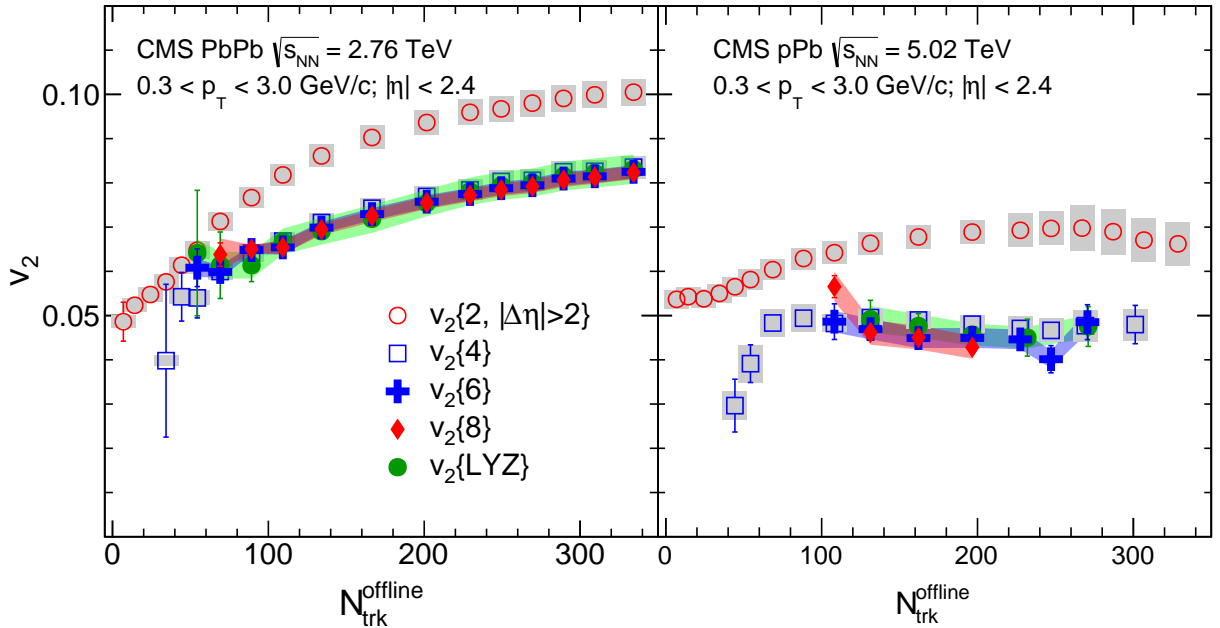


Figure 2: The  $v_2$  values as a function of  $N_{\text{trk}}^{\text{offline}}$ . Open data points are published two- and four-particle  $v_2$  results [35]. Solid data points are  $v_2$  results obtained from six- and eight-particle cumulants, and LYZ methods, averaged over the particle  $p_T$  range of 0.3–3.0 GeV/c, in PbPb at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV (left) and pPb at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV (right). Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

in pPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The  $v_2\{2\}$  and  $v_2\{4\}$  data are taken from previously published CMS results [35]. The solid curves correspond to theoretical predictions for both large and small systems based on hydrodynamics and the assumption that the initial-state geometry is purely driven by fluctuations [50]. The ratios from PbPb collisions are also shown for comparison. Note that the geometry of very central PbPb collisions might be dominated by fluctuations, but for these semi-peripheral PbPb collisions the lenticular shape of the overlap region should also strongly contribute to the  $v_2$  values. The CMS pPb data are consistent with the predictions within statistical and systematic uncertainties. The systematic uncertainties in the ratios presented in Fig. 3 are estimated to be 2.4% for  $v_2\{4\}/v_2\{2\}$  for both pPb and PbPb collisions, 1% for  $v_2\{6\}/v_2\{4\}$  in pPb and PbPb collisions, and 3.6% and 1% for  $v_2\{8\}/v_2\{6\}$  in pPb and PbPb collisions, respectively. Since they are all derived from the same data, the systematic uncertainties for the different cumulant orders are highly correlated and therefore partially cancel in the ratios.

Recently, other theoretical models based on quantum chromodynamics, and not involving hydrodynamics, have also been suggested to explain the observed multi-particle correlations in pPb collisions [52, 53]. Unlike the descriptions based on hydrodynamic behavior, these models do not require significant final-state interactions among quarks and gluons. They suggest similar values for  $v_2\{4\}$ ,  $v_2\{6\}$ ,  $v_2\{8\}$ , and  $v_2\{\text{LYZ}\}$ , without yet, however, providing quantitative predictions.

In summary, multi-particle azimuthal correlations among six, eight, and all particles have been measured in pPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV by the CMS experiment. The new measurements extend previous CMS two- and four-particle correlation analyses of pPb collisions and strongly constrain possible explanations for the observed correlations. A direct comparison of the correlation data for pPb and PbPb collisions is presented as a function of particle multi-



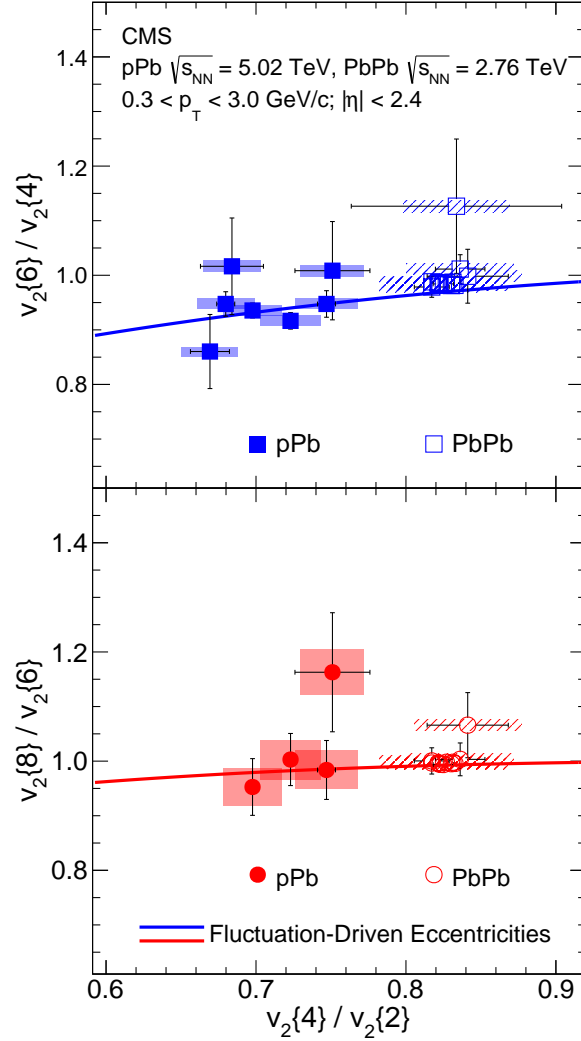


Figure 3: Cumulant ratios  $v_2\{6\}/v_2\{4\}$  (top) and  $v_2\{8\}/v_2\{6\}$  (bottom) as a function of  $v_2\{4\}/v_2\{2\}$  in pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. Error bars and shaded areas denote statistical and systematic uncertainties, respectively. The solid curves show the expected behavior based on a hydrodynamics motivated study of the role of initial-state fluctuations [50].

plicity. Averaging over the particle  $p_T$  range of 0.3–3.0 GeV/ $c$ , multi-particle correlation signals are observed in both pPb and PbPb collisions. The second-order azimuthal anisotropy Fourier harmonic,  $v_2$ , is extracted using six- and eight-particle cumulants and using the LYZ method which involves all particles. The  $v_2$  values obtained using correlation methods including four or more particles are consistent within  $\pm 2\%$  for the PbPb system, and within  $\pm 10\%$  for the pPb system. This measurement supports the collective nature of the observed correlations. The ratios of  $v_2$  values obtained using different numbers of particles are found to be consistent with hydrodynamic model calculations for pPb collisions.

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