Multiparticle correlation studies in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

The CMS Collaboration

Abstract

The second- and third-order azimuthal anisotropy Fourier harmonics of charged particles produced in pPb collisions, at $\sqrt{s_{NN}} = 8.16$ TeV, are studied over a wide range of event multiplicities. Multiparticle correlations are used to isolate global properties stemming from the collision overlap geometry. The second-order “elliptic” harmonic moment is obtained with high precision through four-, six-, and eight-particle correlations and, for the first time, the third-order “triangular” harmonic moment is studied using four-particle correlations. A sample of peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV that covers a similar range of event multiplicities as the pPb results is also analyzed. Model calculations of initial-state fluctuations in pPb and PbPb collisions can be directly compared to the high precision experimental results. This work provides new insight into the fluctuation-driven origin of the $v_3$ coefficients in pPb and PbPb collisions, and into the dominating overall collision geometry in PbPb collisions at the earliest stages of heavy ion interactions.

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In collisions of ultra relativistic heavy ions, two-particle azimuthal correlations between the large number of particles created over a broad range in pseudorapidity, were first observed in gold–gold and copper–copper collisions at the BNL RHIC [1–4], and have subsequently been studied in lead–lead (PbPb) collisions at the CERN LHC [5–9]. These correlations are thought to reflect the collective motion of a strongly interacting and expanding medium with quark and gluon degrees of freedom, namely, the quark-gluon plasma [10]. The observed azimuthal correlation structure can be characterized by Fourier harmonics, with the second ($v_2$) and third ($v_3$) harmonics referred to as “elliptic” and “triangular” flow, respectively. Within a hydrodynamic picture, the Fourier harmonics directly reflect the initial geometry of the colliding system and provide insight into the transport properties of the produced medium [11–13]. Fluctuations can also arise from the discrete substructure of the interaction region at the parton level [14, 15] and can have a significant effect on the observed higher-order harmonic coefficients.

Two-particle azimuthal correlations, which are long-range in pseudorapidity, are also found in small systems for collisions leading to high final-state particle densities. At the LHC, long-range correlations have been observed in proton–proton (pp) [16–18] and proton–lead (pPb) [19–22] collisions. Similar results have been obtained at RHIC in studies of deuteron–gold, proton–gold, and helium-3–gold collisions [23–26]. The origin of the long-range correlations in systems involving only a small number of participating nucleons is still under active discussion [27]. One possibility is that fluctuation-driven asymmetries in the initial-state nucleon locations within the overlap region are transferred to the final-state particle distributions through the hydrodynamic evolution of an expanding plasma [28–30]. Alternatively, it has been proposed that the observed behavior arises from the transfer of initial-state gluon correlations to the produced particles [31–33].

Studies of azimuthal correlations in small systems using two or more particles, as achieved through the use of a multiparticle cumulant expansion [34], show that the pp [35] and pPb [36] systems develop similar collective behavior to that found in heavier systems [37]. By requiring correlations among multiple particles, correlations that are not related to a bulk property of the medium, such as back-to-back jet correlations and resonance decays, are strongly suppressed [38]. The $v_n$ harmonics based on different orders of the multiparticle expansion provide information on the event-by-event fluctuation of the observed anisotropy [39]. Previous $v_2$ multiparticle cumulant results for pPb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV suggest a direct correlation of the final-state asymmetry with the initial-state eccentricity of the participating nucleons [35, 40]. In these earlier measurements, it was not possible to obtain a multiparticle expansion of the $v_3$ harmonic, which is expected to be dominated by initial-state fluctuations. With precise measurements of the $v_2$ and $v_3$ multiparticle cumulants, it becomes possible to make direct comparison of calculations based on eccentricity fluctuations in the initial-state geometry to the higher-order moments of the fluctuation distributions. The measurements provide key input for models that explore the hydrodynamic expansion of the medium [41, 42], as well as for models that propose that final-state asymmetries in light systems arise from partons scattering off localized domains of color charge in the initial state [43]. In the hydrodynamic picture, the $v_2$ and $v_3$ values are dominated by fluctuations in pPb collisions. In PbPb collisions, the $v_2$ value is dominated by the lenticular shape of the overlap geometry, while the $v_3$ value is dominated by initial-state fluctuations of the nucleon locations [14].

In this Letter, the results from pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV are studied with a significant improvement in the precision of the $v_2$ results compared to the earlier measurements at $\sqrt{s_{NN}} = 5.02$ TeV. For the first time, the $v_3$ harmonic is determined by multiparticle correlations. The pPb results are also compared to those found for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV where, for
noncentral collisions, the shape of the overlap region of the two nuclei during the collision is the
dominant cause of the large $v_2$ harmonic amplitude. The ratios between the four-particle and
two-particle $v_n$ values provide information on the relative importance of the global geometry
and the fluctuation-driven asymmetries [43]. These ratios are explored for both the $v_2$ and $v_3$
harmonics and are compared between the pPb and PbPb systems.

The CMS detector comprises a number of subsystems [44]. The results in this paper are mainly
based on the silicon tracker information. The silicon tracker, located in the 3.8 T field of a su-
perconducting solenoid, consists of 1 440 silicon pixel and 15 148 silicon strip detector mod-
ules. The silicon tracker measures charged particles within the laboratory 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% up to 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 quasi-
projective geometry. Iron and quartz-fiber Čerenkov hadron forward (HF) calorimeters cover
the range $3.0 < |\eta| < 5.2$ on either side of the interaction region. These HF calorimeters are
azimuthally subdivided into $20^{\circ}$ modular wedges and further segmented to form $0.175 \times 0.175$
rad ($\Delta \eta \times \Delta \phi$) cells. The ECAL and HCAL cells are grouped to form “towers.” The detailed
Monte Carlo (MC) simulation of the CMS detector response is based on GEANT4 [45].

The analysis is performed using data recorded by CMS during the LHC pPb run in 2016 and
corresponds to an integrated luminosity of 186 nb$^{-1}$ [46]. The beam energies were 6.5 TeV for
protons and 2.56 TeV per nucleon for lead nuclei, resulting in $\sqrt{s_{\text{NN}}} = 8.16$ TeV. The beam di-
rections were reversed during the run allowing a check of potential detector related systematic
uncertainties. No significant differences were detected and the merged results are reported.

The nucleon-nucleon center-of-mass in the pPb collisions is not at rest with respect to the labo-
ratory frame because of the energy difference between the colliding particles. 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 $\sqrt{s_{\text{NN}}} = 5.02$ TeV PbPb data collected during the 2015 LHC heavy ion run, corre-
spanding to an integrated luminosity of 1.2 $\mu$b$^{-1}$, is also analyzed for comparison purposes.

The triggers and event selection, as well as track reconstruction and selection, are identical to
those used in Ref. [47] and are summarized below.

Minimum bias (MB) pPb events were triggered by requiring that at least one track with $p_T >$
0.4 GeV/$c$ detected in the pixel tracker during a pPb bunch crossing, and at least one tower in
one of the two HF detecting an energy above a threshold of 1 GeV. 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 [48]. At L1, the total number of ECAL
and HCAL towers with the transverse energies above a threshold of 0.5 GeV is required to
exceed 120 and 150 in ECAL and HCAL, respectively. The L1 trigger seeds the subsequent
HLT. Track reconstruction is performed online as part of the HLT trigger with the identical
reconstruction algorithm used offline [49]. For each event, the vertex reconstructed with the
highest number of pixel detector tracks was selected. The number (multiplicity) of pixel tracks
($N_{\text{trk}}^{\text{online}}$) with $|\eta| < 2.4$, $p_T > 0.4$ GeV/$c$, and a distance of closest approach to this vertex of
0.4 cm or less, was determined for each event. Several multiplicity ranges were defined with
prescale factors that were reduced with increasing particle multiplicity until, for the highest-
multiplicity events, no prescale 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 within $3.0 < |\eta| < 5.2$. Events are also required to contain at least one reconstructed primary vertex within 15 cm from 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.

Tracks are used that pass the high-purity selection criteria described in Ref. [49]. In addition, a reconstructed track is only considered as a candidate track from the primary vertex if the separation along the beam axis ($z$) between the track and the best vertex, and the track-vertex impact parameter measured transverse to the beam are each less than three times their respective uncertainties. The relative uncertainty in the $p_T$ measurement is required to be less than 10%. To restrict the analysis to a kinematic region of high tracking efficiency and a low rate of incorrectly reconstructed tracks, only tracks with $|\eta| < 2.4$ and $0.3 < p_T < 3.0$ GeV/$c$ are used.

The entire pPb data set is divided into classes of reconstructed track multiplicity, $N_{\text{offline trk}}$, where primary tracks passing the high-purity criteria and with $|\eta| < 2.4$ and $p_T > 0.4$ GeV/$c$ are counted. The HLT $p_T$ cutoff is higher than that used for the analysis because of online processing time constraints. The multiplicity classification in this analysis is identical to that used in Ref. [38], where more details are provided, including a table relating $N_{\text{offline trk}}$ to the fraction of MB triggered events. The PbPb sample is reprocessed using the same event selection and track reconstruction as for the present pPb analysis. A description of the analysis of 2015 PbPb data can be found in Ref. [47].

The analysis is done using the $Q$-cumulant method [39]. Here it is possible to determine the $n^{\text{th}}$ harmonic moment based on correlations among all possible grouping of $m$ particles, where $m$ also corresponds to the cumulant order. The multiparticle correlations for cumulant orders 2 through 8 can be expressed as:

$$\langle \langle 2 \rangle \rangle \equiv \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle,$$

$$\langle \langle 4 \rangle \rangle \equiv \left\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle,$$

$$\langle \langle 6 \rangle \rangle \equiv \left\langle e^{in(\phi_1 + \phi_2 + \phi_3 - \phi_4 - \phi_5 - \phi_6)} \right\rangle,$$

$$\langle \langle 8 \rangle \rangle \equiv \left\langle e^{in(\phi_1 + \phi_2 + \phi_3 + \phi_4 - \phi_5 - \phi_6 - \phi_7 - \phi_8)} \right\rangle,$$

where $\phi_i$ ($i = 1, \ldots, m$) are the azimuthal angles of one unique combination of $m$ particles in an event, $n$ is the harmonic number (2 for elliptic and 3 for triangular flow, respectively), and $\langle \langle \cdots \rangle \rangle$ represents the average over all combinations from all events within a given $N_{\text{trk}}$ range. The higher-order cumulants, $c_n \{ m \}$, are calculated as [39]

$$c_n \{ 4 \} = \langle \langle 4 \rangle \rangle - 2\langle \langle 2 \rangle \rangle^2,$$

$$c_n \{ 6 \} = \langle \langle 6 \rangle \rangle - 9\langle \langle 4 \rangle \rangle\langle \langle 2 \rangle \rangle + 12\langle \langle 2 \rangle \rangle^3,$$

$$c_n \{ 8 \} = \langle \langle 8 \rangle \rangle - 16\langle \langle 6 \rangle \rangle\langle \langle 2 \rangle \rangle - 18\langle \langle 4 \rangle \rangle^2$$

$$+ 144\langle \langle 4 \rangle \rangle\langle \langle 2 \rangle \rangle^2 - 144\langle \langle 2 \rangle \rangle^4.$$

The Fourier harmonics $v_n \{ m \}$ that characterize the global azimuthal behavior can be related to
the $m$-particle correlations using a generic framework discussed in Ref. [50], with

\[ v_n\{4\} = \sqrt{2^4 c_n\{4\}}, \quad v_n\{6\} = \sqrt{1^6 c_n\{6\}}, \]

\[ v_n\{8\} = \sqrt{\frac{1}{33} c_n\{8\}}. \]

Each reconstructed track is weighted by a correction factor to account for the reconstruction efficiency, the detector acceptance, and the fraction of misreconstructed tracks. This factor is based on HIJING 1.383 MC simulations, and is determined as a function of $p_T$, $\eta$, and $\phi$, as described in Refs. [51]. The same method has been used in previous CMS analyses [36, 38, 52]. The two-particle correlation $v_n\{2\}$ can be measured as described in Ref. [47]. Increasing the numbers of particles used to determine the correlations for a given harmonic reduces the sensitivity of the results to few-particle correlations that are not related to a global behavior. The ratios between $v_n$ harmonics involving different number of particles can be used to test the system independence of fluctuation-driven initial-state anisotropies in the hydrodynamic picture. In particular, the triangular flow ratio $v_3\{4\}/v_3\{2\}$, which is dominated by fluctuations, can be used to confirm this expectation.

A number of potential sources of systematic uncertainties affecting the experimental $v_n\{m\}$ values are considered. The sensitivity of the results to the selection criteria for valid tracks was studied by varying the criteria. The sensitivity to the primary vertex position was explored by performing the analysis for different vertex ranges. The potential for an HLT trigger bias was investigated by changing the trigger thresholds. Pileup effects, where two or more interactions occur in the same bunch crossing, were studied by comparing results obtained during different beam differential luminosity periods. For the pPb results, the beam directions were reversed, allowing for potential detector acceptance effects to be explored. No evident $\Delta N_{\text{off}}$ dependent systematic effects are observed. The total systematic uncertainties, obtained by combining the individual uncertainties in quadrature, are found to be 1–2.4% for the $v_2$ coefficients for both pPb and PbPb collisions and 5 (2.6)% for the pPb (PbPb) $v_3$ results. The pPb (PbPb) $v_2\{8\}/v_2\{4\}$ and $v_2\{8\}/v_2\{6\}$ ratios systematic uncertainties are found to be 2.6 (1.4)% and 3.6 (1.4)% respectively.

The second- and third-order harmonic multiparticle cumulant results $v_2$ and $v_3$ for charged particles with $0.3 < p_T < 3.0 \text{GeV/c}$ and $|\eta| < 2.4$ are shown in Fig. 1 for pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{TeV}$ and for PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{TeV}$. The two-particle correlation results $v_2^{\text{sub}}\{2\}(|\Delta \eta| > 2)$ and $v_3^{\text{sub}}\{2\}(|\Delta \eta| > 2)$, with low-multiplicity subtraction to remove jet correlations, are described in details in Ref. [47]. The multiparticle elliptic flow harmonics $v_2\{4\}$, $v_2\{6\}$, and $v_2\{8\}$ are found to be real and of similar magnitude. The four-particle triangular flow harmonic, $v_3\{4\}$, is also found to be real. These results indicate collective behavior in high multiplicity pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{TeV}$ [41, 42]. Comparing the different systems, the $v_2$ values for PbPb collisions are higher than those for pPb collisions, which is consistent with the lenticular-shaped overlap geometry dominating this harmonic for PbPb collisions. The two-particle correlation $v_2$ and $v_3$ results are systematically higher than the multiparticle results for both pPb and PbPb collisions. This is expected if there is a significant fluctuation component, which is expected to increase the two-particle correlation results and decrease the multiparticle correlation results, as compared to case where fluctuations are absent [43]. With increasing $N_{\text{off}}$, the $v_2\{4\}$, $v_2\{6\}$, and $v_2\{8\}$ values all rise in PbPb collisions, while they fall slightly in pPb collisions. This might suggest that the fluctuation-driven component of the eccentricity is decreasing with increasing multiplicity, with an increasing influence of the lenticular overlap geometry in the PbPb system. The $v_3$ values are comparable for both
systems, as expected if this higher-order harmonic is dominated by fluctuation behavior. A (3+1)D event-by-event viscous hydrodynamic calculation of the four-particle cumulant $v_3\{4\}$ for pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [53] is also shown in Fig. 1 as a gray band. This calculation, with an entropy distribution taken as a two-dimensional Gaussian of width $\sigma = 0.4$ fm and having a shear viscosity-to-entropy ratio of $\eta/s = 0.08$, is found to be consistent with the data.

Figure 1: The multiparticle $v_2\{4, 6, 8\}$ and $v_3\{4\}$ harmonics are shown for pPb 8.16 TeV (left) and PbPb 5.02 TeV (right) as a function of $N_{\text{offline}}$. Two-particle results $v_2^{\text{sub}}\{2\}(\lvert \Delta \eta \rvert > 2)$ and $v_3^{\text{sub}}\{2\}(\lvert \Delta \eta \rvert > 2)$ are from Ref. [47]. Error bars and shaded boxes denote statistical and systematic uncertainties, respectively. The shaded area shows the hydrodynamic prediction of $v_3\{4\}$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [53].

Figure 2 shows the ratios $v_2\{4\}/v_2\{2\}$ and $v_3\{4\}/v_3\{2\}$ for both the pPb and PbPb systems. For pPb collisions, the ratios for $v_2$ and $v_3$ are similar within uncertainties, which is consistent with having both the second- and third-order harmonics arising from the same initial-state fluctuation mechanism. Comparing the pPb and PbPb systems, the $v_3$ ratios are comparable for both systems, while the $v_2$ ratios are higher in PbPb than in pPb for higher $N_{\text{trk}}$ values, again reflecting the larger geometric contribution for the heavier system collisions. The $v_2$ ratio for PbPb collisions saturates at large multiplicity while, for pPb collisions, the ratio continues to decrease as the multiplicity increases.

Initial-state eccentricities can also be characterized by the cumulants of the event-by-event distributions of their Fourier harmonics coefficients, $\varepsilon_n\{m\}$. In the hydrodynamic picture, the $v_n\{m\}$ values are proportional to $\varepsilon_n\{m\}$, with $v_n\{m\} = k_n \varepsilon_n\{m\}$, where $k_n$ reflects the medium properties and does not depend on the order of the cumulant. Therefore, ratios of different cumulant $v_n$ values can directly probe properties of initial-state eccentricity. This is shown in Fig. 2 based on Glauber model initial condition simulated using the TRENTo framework [54], and assuming a width $\sigma = 0.3$ fm of the source associated with each nucleon [42]. The calculations were done for pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by varying the geometric overlap of the colliding nuclei. It should be noted that the two-particle correlation results were obtained with a large pseudorapidity gap of $\lvert \Delta \eta \rvert > 2$. This gap can lead to a reduction in the observed correlations [55] and can cause the reported $v_2^{\text{sub}}\{2\}(\lvert \Delta \eta \rvert > 2)$ values being reduced by 10%; hence the ratio is increased by 10%.
In summary, the azimuthal anisotropy for pPb collisions at $\sqrt{s_{NN}} = 8.16 \text{ TeV}$ and PbPb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ are studied as functions of the final-state particle multiplicities with the CMS experiment. The $v_2$ Fourier coefficient is determined using cumulants obtained with four-, six-, and eight-particle correlations with greatly increased precision compared to previous measurements. The higher-order $v_3\{4\}$ coefficient is reported for the first time for a small system. For pPb collisions, the ratios $v_2\{4\}/v_2\{2\}$ and $v_3\{4\}/v_3\{2\}$ are comparable, consistent with a purely fluctuation-driven origin for the azimuthal asymmetry. Both the pPb and PbPb systems have very similar $v_3$ coefficients for the cumulant orders studied, indicating a similar, fluctuation-driven initial-state geometry. In contrast, both the magnitude of the $v_2$ coefficients and the $v_2\{4\}/v_2\{2\}$ ratio is larger for PbPb collisions, as expected if the overall collision geometry dominates. The $v_2$ cumulant ratios for pPb collisions are consistent with a collective flow behavior that originates from and is proportional to the initial-state anisotropy.

Figure 2: The ratios of four- and two-particle harmonics ($v_2\{4\}/v_2\{2\}$ and $v_3\{4\}/v_3\{2\}$) are shown for pPb at $\sqrt{s_{NN}} = 8.16 \text{ TeV}$ (left) and PbPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ (right) as a function of $N_{\text{off}}$. Error bars and shaded boxes denote statistical and systematic uncertainties, respectively. The dashed curves show a hydrodynamics-motivated initial-state fluctuation calculation of eccentricities $\varepsilon_{\eta}\{m\}$ for pPb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ [42].
Figure 3: Cumulant ratios $v_2\{6\} / v_2\{4\}$ (upper) and $v_2\{8\} / v_2\{6\}$ (lower) as a function of $v_2\{4\} / v_2^{\text{sub}}\{2\}$ in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 8.16 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 [40].

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