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Multiparticle correlations and higher order harmonics in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

Quan Wang on behalf of the CMS Collaboration[1]

The University of Kansas

Abstract

The elliptic and higher-order azimuthal anisotropy Fourier harmonics (v_n) are obtained for pPb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV over a wide range of event multiplicities based on multiparticle correlations. The data were collected by the CMS experiment during the 2016 LHC run. A sample of peripheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV covering a similar range of event multiplicities to the pPb results is also analyzed for comparison. The ratios of different harmonic moments are obtained for both v_2 and v_3 with high precision, which allows a direct comparison to theoretical predictions assuming a hydrodynamic evolution of the created medium with initial-state density fluctuations, particularly probing the non-Gaussian nature of initial-state fluctuations in small collision systems. The presented results provide crucial insights into the origin of collective long-range correlations observed in small collision systems.

Keywords: CMS, heavy ion, cumulant, flow, collectivity, small system, quark-gluon plasma

1. Introduction

Two-particle azimuthal correlations extending over large pseudorapidity ranges were first observed in AuAu and CuCu collisions at the BNL RHIC facility [1, 2], and have subsequently been studied with PbPb collisions at the CERN LHC [3]. 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 (QGP). The azimuthal anisotropy of the correlations can be characterized by Fourier harmonics, where the second (v_2) and third (v_3) harmonics, referred to as “elliptic” and “triangular” flow, respectively, directly reflect the initial geometry of the colliding system. Within a hydrodynamics picture, the harmonic coefficients provide insight into the medium transport properties [4].

The origin of the long-range correlations in systems involving only a small number of nucleon participants is still under active discussion. Studies of azimuthal correlations in small systems using multiple particles, as achieved by studying the correlations through a multiparticle cumulant expansion [5], show that the pp [6, 7] and pPb [8, 9] systems develop similar collective behavior to that found for heavier systems [10]. By requiring correlations among multiple particles, few-particle correlations that are not related to a bulk property of the medium, such as back-to-back jet correlations and resonance decays, are strongly

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suppressed. Differences in the v_n moments based on different orders of the cumulant multiparticle expansion also provide information on the higher moments of the fluctuation-driven initial-state anisotropy, as characterized by the initial-state eccentricity distribution [11]. Previous CMS v_2 multiparticle cumulant results for pPb collisions at 5.02 TeV have been well described by hydrodynamic model calculations that assume a direct correlation of the final state asymmetry with the fluctuation-dependent, initial-state eccentricity [8, 12].

In this work, pPb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV are studied with a significant improvement in the precision of the v_2 results compared to the earlier measurements at 5.02 TeV. For the first time, multiparticle cumulant correlations are determined for the v_3 harmonic. The pPb results are also compared to those found for PbPb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV where, for non-central collisions, the lenticular shape of the overlap region of the two nuclei during the collision is the dominant cause of the large v_2 harmonic amplitude.

2. Results

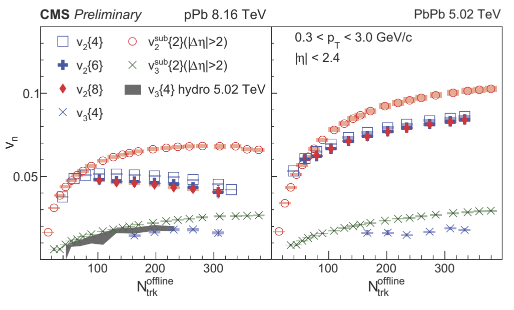

Fig. 1. The multiparticle $v_2\{4, 6, 8\}$ and $v_3\{4\}$ are shown for pPb 8.16 TeV (left) and PbPb 5.02 TeV (right) as a function of $N_{\rm trk}^{\rm offline}$ [13]. Two-particle results $v_2^{\rm sub}\{2\}(|\Delta\eta| > 2)$ and $v_3^{\rm sub}\{2\}(|\Delta\eta| > 2)$ are from Ref. [14]. Error bars and shaded boxes denote statistical and systematic uncertainties, respectively. The shaded area shows the hydrodynamic prediction of $v_3\{4\}$ in pPb collisions 5.02 TeV [15].

The second- and third-order harmonic multiparticle cumulant results v_2 and v_3 for charged particle with $0.3 < p_{\rm T} < 3.0$ GeV/c and $|\eta| < 2.4$ are shown in Fig. 1 [13] for pPb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV and for PbPb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. The two-particle correlation results $v_2^{\rm sub}\{2\}(|\Delta\eta| > 2)$ and $v_3^{\rm sub}\{2\}(|\Delta\eta| > 2)$ with low-multiplicity subtraction to remove jet correlations, are described in details in Ref. [14]. The multiparticle elliptic ($v_2\{4, 6, 8\}$) and triangular ($v_3\{4\}$) flow harmonics are found to be positive for both pPb and PbPb collisions, indicating collective behavior. Comparing the different systems, the v_2 values for PbPb collisions are higher than those for pPb collisions, which is expected as the lenticular-shaped overlap geometry dominates 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 collision, which is expected that the flow fluctuation contributes positively to the two-particle correlations while negatively to the multiparticle correlations. With increasing $N_{\rm trk}^{\rm offline}$, the $v_2\{4, 6, 8\}$ values rise in PbPb collisions, while they slightly decrease in pPb collisions, which might suggest that the fluctuation driven eccentricity is decreasing with increasing multiplicity. A similar trend is seen for the $v_2^{\rm sub}\{2\}(|\Delta\eta| > 2)$ values in the two systems. This might reflect the increasing importance of the collision overlap geometry in the PbPb system. The v_3 values are comparable for both systems, indicating that this higher order harmonic is dominated by the fluctuation behavior. A 3+1D event-by-event viscous hydrodynamic calculation of the four-particle cumulant $v_3\{4\}$ for pPb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV [15] is also presented. 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 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, the ratios for v_2 and v_3 are very similar, 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 that in pPb for

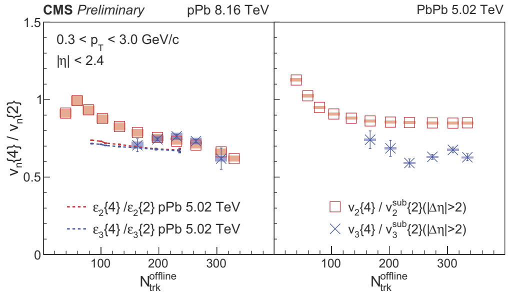

Fig. 2. The ratios of four- and two-particle harmonics ($v_2\{4\}/v_2\{2\}$ and $v_3\{4\}/v_3\{2\}$) are shown for pPb $\sqrt{s_{NN}}$ = 8.16 TeV (left) and PbPb at 5.02 TeV (right) as a function of $N_{trk}^{offline}$. Error bars and shaded boxes denote statistical and systematic uncertainties, respectively. The dashed curves show a hydrodynamics motivated initial-state fluctuation calculation for pPb collisions at 5.02 TeV [16].

higher $N_{trk}^{offline}$ values, again reflecting the larger geometric contribution for the heavier system collisions. The v_2 ratio for PbPb collisions saturates at large multiplicity while, in pPb, the ratio continues to decrease as the multiplicity increases.

Initial-state eccentricities can also be characterized by cumulant expansions. This is shown in Fig. 2 [13] based on Glauber model initial condion simulated using the TRENTo framework [17], with input parameter $p = 1$, and assuming a width $\sigma = 0.3$ fm of the source associated with each nucleon [16]. The calculation shows that the $v_n\{4\}/v_n\{2\}$ ratios for pPb collisions are expected to be very similar for the v_2 and v_3 harmonics, as found experimentally.

In Fig. 3 [13] the ratios $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{6\}$ are shown as functions of the ratio $v_2\{4\}/v_2\{2\}$ for pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV and compared to calculations based on fluctuation-driven eccentricities [12] with a universal power law distribution assumed for the eccentricities. These results are similar to those previously reported in Ref. [8] for pPb at $\sqrt{s_{NN}}$ = 5.02 TeV, as shown in the figure, but with greatly reduced statistical uncertainties. The model calculation slightly overestimates the $v_2\{6\}/v_2\{4\}$ ratios within uncertainties, while well reproducing the $v_2\{8\}/v_2\{6\}$ ratios. The good agreement of the calculations with the data shows that the differences found among the multiparticle cumulant results for the v_2 harmonic can be well-described by non-Gaussian initial-state fluctuations.

In summary, the azimuthal anisotropy for pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV are studied as a function of the final-state particle densities by 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 all cumulant orders, indicating a similar, fluctuation-driven origin. 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 would be expected if the global collision geometry dominates these results. The v_2 cumulant ratios for pPb collisions are consistent with collective flow behavior that originate from and are proportional to the initial-state anisotropy.

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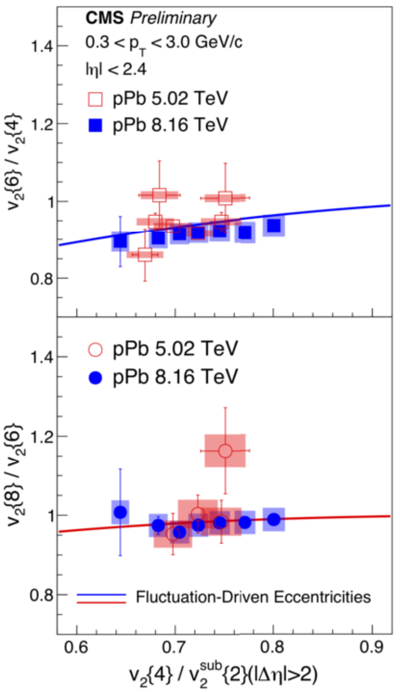

Fig. 3. Cumulant ratios $v_2\{6\}/v_2\{4\}$ (top) and $v_2\{8\}/v_2\{6\}$ (bottom) as a function of $v_2\{4\}/v_2\{2\}$ in pPb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV and 8.16 TeV. Error bars and shaded areas denote statistical and systematic uncertainties, respectively. The solid curves show the expected behavior based on a hydrodynamics motivated study of the role of initial-state fluctuations [12].

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