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Evidence for collective phenomena in pp collisions

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Abstract

Measurements of two- and multi-particle angular correlations in pp collisions at $\sqrt{s}$ = 5, 7, and 13 TeV are presented. The data, corresponding to integrated luminosities of 1.0 pb^{-1} (5 TeV), 6.2 pb^{-1} (7 TeV), and 0.7 pb^{-1} (13 TeV), were collected using the CMS detector at the LHC. The second-order (v_2) and third-order (v_3) azimuthal anisotropy harmonics of unidentified charged particles, as well as v_2 of K^0_S and $\Lambda/\overline{\Lambda}$ particles, are extracted from long-range two-particle correlations as functions of particle multiplicity and transverse momentum. For high-multiplicity pp events, a mass ordering is observed for the v_2 values of charged hadrons (mostly pions), K^0_S, and $\Lambda/\overline{\Lambda}$ at $p_T \lesssim 2$ GeV/c. The v_2 signals are also extracted from four- and six-particle correlations for 13 TeV pp collisions, with comparable magnitude to those from two-particle correlations. These observations strongly support the interpretation of a collective origin for the observed long-range correlations in high-multiplicity pp collisions.

Keywords: CMS, heavy ion, ridge, correlation, pp, collectivity

1. Introduction

Observation of long-range two-particle azimuthal correlations at large relative pseudorapidity in high-multiplicity proton-proton [1, 2] and proton-lead [3] collisions at CMS [4] has opened up new opportunities for studying novel dynamics of particle production in small, high-density quantum chromodynamic (QCD) systems. Such correlations have been extensively studied over the past decades in nucleus-nucleus collisions and have been suggested to result from the hydrodynamic collective flow of a strongly interacting and expanding medium.

In systems such as pp and pPb, where the transverse size of the overlap region is comparable to that of a single proton, the formation of a hot and dense fluid-like medium was not expected. Various theoretical models have been proposed to interpret the origin of the observed long-range correlations in small collision systems [5], including initial-state gluon correlations without final-state interactions and hydrodynamic flow that develops in a conjectured high-density medium. Owing to the magnitude of the correlation signal, significant progress has been made in unraveling the nature of the ridge correlations in high-multiplicity pPb collisions. CMS measured anisotropy Fourier harmonics (v_n) using identified particles [6] and multi-particle correlation techniques [7, 8], which reveal features that support a collective origin of the observed correlations.

In high-multiplicity pp collisions, the nature of the observed long-range correlation still remains poorly understood. To provide insights on such correlations, a detailed study of two- and multi-particle azimuthal

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correlations with unidentified charged particles, as well as correlations of reconstructed K^0_S and $\Lambda/\overline{\Lambda}$ particles at various LHC collision energies has been carried out. The results of v_2 and v_3 harmonics, extracted from two-particle correlations, are studied as functions of particle p_T and event multiplicity. The residual contribution to long-range correlations of back-to-back jet correlations is estimated and removed by subtracting correlations obtained from very low multiplicity pp events. The v_2 harmonics are also extracted using the multi-particle cumulant method to shed light on the possible collective nature of the correlations. The results are directly compared to those found for pPb and PbPb systems over a broad range of similar multiplicities.

2. Result

Results presented in this proceeding have been published in Ref. [9], where $v_n^{\rm sub}\{2\}$ denotes the v_n results, extracted from long-range ($|\Delta\eta| > 2$) two-particle correlations, after subtracting the jet contribution. By assuming the jet-induced correlations are invariant with event multiplicity, a procedure of removing jet-like correlations developed for pPb collisions [8] is employed. The method consists of subtracting the results for low-multiplicity events, where the ridge signal is not present, from those for high-multiplicity events.

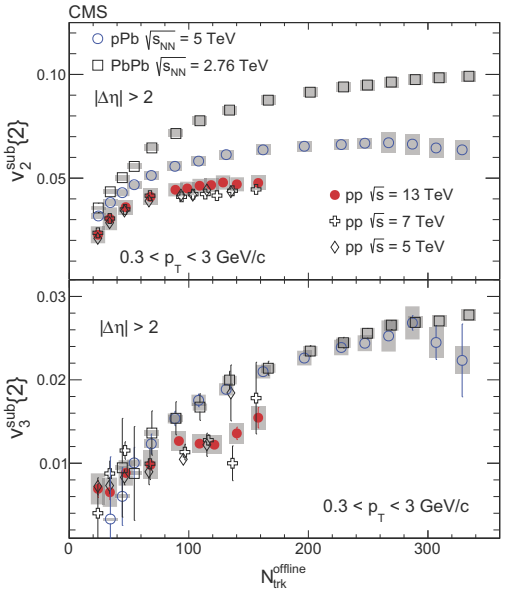

Fig. 1. The $v_2^{\rm sub}\{2\}$ (top) and $v_3^{\rm sub}\{2\}$ (bottom) results of charged particles as a function of $N_{\rm trk}^{\rm offline}$, averaged over $0.3 < p_T < 3.0$ GeV/c, in pp collisions at $\sqrt{s}$ = 5, 7, and 13 TeV, pPb collisions at $\sqrt{s_{NN}}$ = 5 TeV, and PbPb collisions $\sqrt{s_{NN}}$ = 2.76 TeV, after correcting for back-to-back jet correlations estimated from low-multiplicity data. The error bars correspond to the statistical uncertainties, while the shaded areas denote the systematic uncertainties. Systematic uncertainties are found to have no dependence on $\sqrt{s}$ for pp results and therefore are only shown for 13 TeV. Taken from Ref. [9].

The $v_2^{\rm sub}\{2\}$ and $v_3^{\rm sub}\{2\}$ flow harmonics for charged particles with $0.3 < p_T < 3.0$ GeV/c, after applying the jet correction procedure, are shown in Fig. 1 for pp collisions at $\sqrt{s}$ = 5, 7, and 13 TeV as function of $N_{\rm trk}^{\rm offline}$. Here, $N_{\rm trk}^{\rm offline}$ denotes the number of tracks with $|\eta| < 2.4$ and $p_T > 0.4$ GeV/c. The previously published pPb data at $\sqrt{s_{NN}}$ = 5 TeV and PbPb data at $\sqrt{s_{NN}}$ = 2.76 TeV are also shown for comparison among different collision systems.

Within experimental uncertainties, there is no or only a very weak energy dependence for the $v_2^{\rm sub}\{2\}$ values for pp collisions at all three energies,. The $v_2^{\rm sub}\{2\}$ results for pp collisions become relatively constant as $N_{\rm trk}^{\rm offline}$ increases, which is similar to pPb results, while the PbPb results show a moderate increase over

the entire $N_{\rm trk}^{\rm offline}$ range. A system size dependence has been observed in $v_2^{\rm sub}\{2\}$ signal. $v_2^{\rm sub}\{2\}$ results in pp collision are smaller than pPb data over a wide multiplicity range, while both systems show smaller $v_2^{\rm sub}\{2\}$ values than for PbPb. The $v_3^{\rm sub}\{2\}$ values of the three collision systems are found to be comparable at the very low multiplicity region $N_{\rm trk}^{\rm offline} < 60$, although systematic uncertainties are large. At higher $N_{\rm trk}^{\rm offline}$, $v_3^{\rm sub}\{2\}$ in pp collisions increases with multiplicity at a slower rate than observed in pPb and PbPb collisions. Within a hydrodynamic picture, the behavior of $v_2^{\rm sub}\{2\}$ might indicate very different initial-state collision geometry in the three collision systems, while the behavior of $v_3^{\rm sub}\{2\}$ can provide insights on the event-by-event initial-state fluctuations.

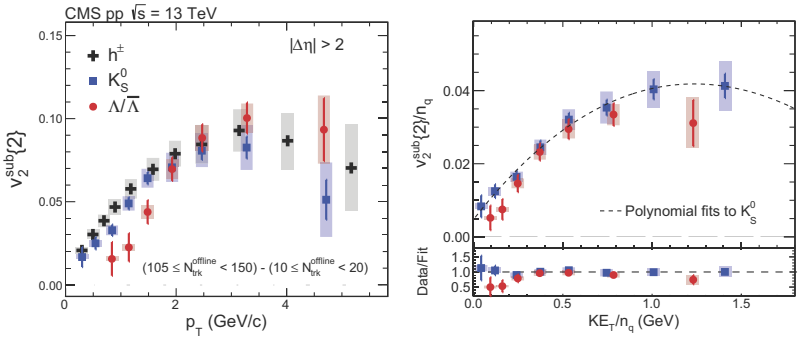

Fig. 2. Left: the $v_2^{\rm sub}\{2\}$ results of inclusive charged particles, K_S^0 and $\Lambda/\overline{\Lambda}$ particles as a function of pt for $105 \le N_{\rm trk}^{\rm offline} < 150$, after correcting for back-to-back jet correlations estimated from low-multiplicity data. Right: the n_q-scaled $v_2^{\rm sub}\{2\}$ results for K_S^0 and $\Lambda/\overline{\Lambda}$ particles as a function of KE_T/n_q. Ratios of $v_2^{\rm sub}\{2\}/n_q$ for K_S^0 and $\Lambda/\overline{\Lambda}$ particles to a smooth fit function of data for K_S^0 particles are also shown. The error bars correspond to the statistical uncertainties, while the shaded areas denote the systematic uncertainties. Taken from Ref. [9].

The dependence of the elliptic flow harmonic on particle species can shed further light on the nature of the correlations. The $v_2^{\rm sub}\{2\}$ data as a function of p_T for identified K_S^0 and $\Lambda/\overline{\Lambda}$ particles are extracted for pp collisions at $\sqrt{s} = 13$ TeV. In high-multiplicity pp events ($105 \le N_{\rm trk}^{\rm offline} < 150$, Fig. 2, left), a clear dependence of $v_2^{\rm sub}\{2\}$ on particle species is observed. In the lower p_T region of $\lesssim 2.5$ GeV/c, the $v_2^{\rm sub}\{2\}$ value of K_S^0 is greater than that of $\Lambda/\overline{\Lambda}$ at a given p_T value. Both are consistently below the inclusive charged particle $v_2^{\rm sub}\{2\}$ values. Since most charged particles are pions in this p_T range, this indicates that lighter particle species exhibit a stronger azimuthal anisotropy signal. This behavior is found to be qualitatively consistent with both hydrodynamic models [10, 11] and an alternative initial state interpretation [12]. The same feature is observed before jet contribution correction at high multiplicity but is absent at low multiplicity where the v_2 values are found to be similar for charged particles, K_S^0 and $\Lambda/\overline{\Lambda}$ hadrons across most of the p_T range.

The scaling behavior of $v_2^{\rm sub}\{2\}$ divided by the number of constituent quarks, n_q, as a function of transverse kinetic energy per quark, KE_T/n_q, is investigated for high-multiplicity pp events in Fig. 2 (right). The dashed curve corresponds to a polynomial fit to the K_S^0 data. The ratio of n_q-scaled $v_2^{\rm sub}\{2\}$ results for K_S^0 and $\Lambda/\overline{\Lambda}$ particles divided by this polynomial function fit is also shown. An approximate scaling is seen for $KE_T/n_q \gtrsim 0.2$ GeV within about ±10%.

To further explore the possible collective nature of the long-range correlations, a four- and six-particle cumulant analysis is used to extract the elliptic flow harmonics, $v_2\{4\}$ and $v_2\{6\}$. The results, averaged over $0.3 < p_T < 3.0$ GeV/c and $|\eta| < 2.4$, for pp collisions at $\sqrt{s} = 13$ TeV are shown in the left panel of Fig. 3, as a function of event multiplicity. The $v_2^{\rm sub}\{2\}$ data are also shown for comparison. Within experimental uncertainties, the multi-particle cumulant $v_2\{4\}$ and $v_2\{6\}$ values in high-multiplicity pp collisions are consistent with each other. This observation strongly supports the collective nature of the long-range correlations observed in pp collisions, i.e. involving all particles in the system, and is inconsistent with a jet-related origin among only a few particles. However, unlike for pPb and PbPb collisions where $v_2^{\rm sub}\{2\}$ values show a larger magnitude than multi-particle cumulant v_2 results, the v_2 values obtained from two-,

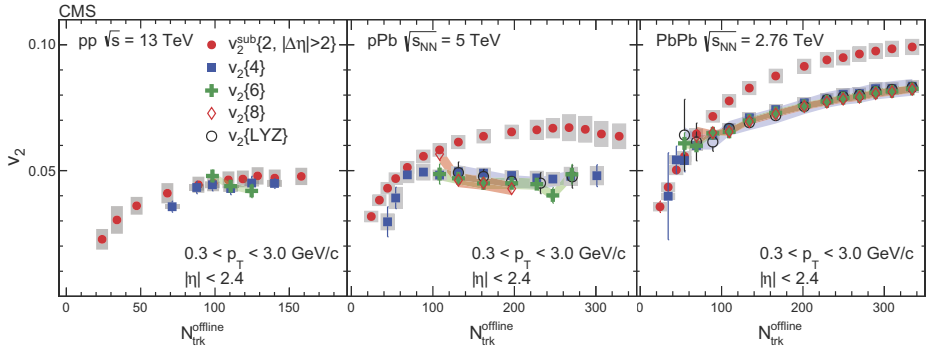

Fig. 3. Left: The $v_2^{\rm sub}\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ values as a function of $N_{\rm trk}^{\rm offline}$ for charged particles, averaged over $0.3 < p_{\rm T} < 3.0$ GeV/c and $|\eta| < 2.4$, in pp collisions at $\sqrt{s} = 13$ TeV. Middle: The $v_2^{\rm sub}\{2\} > 2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$, and $v_2\{\rm LYZ\}$ values in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV [8]. Right: The $v_2^{\rm sub}\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$, and $v_2\{\rm LYZ\}$ values in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [8]. The error bars correspond to the statistical uncertainties, while the shaded areas denote the systematic uncertainties. Taken from Ref. [9].

four-, and six-particle correlations are comparable in pp collisions at $\sqrt{s} = 13$ TeV within uncertainties. In the context of hydrodynamic models, the comparable magnitudes of $v_2^{\rm sub}\{2\}$ and $v_2\{4\}$ signals observed in pp collisions, compared to pPb collisions at similar multiplicities, may indicate a smaller number of initial fluctuating sources that drive the long-range correlations seen in the final state [13].

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