The Compact Muon Solenoid Experiment

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Azimuthal anisotropy harmonics from long-range correlations in high multiplicity pp collisions at CMS

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Measurements of two-particle angular correlations in pp collisions at $\sqrt{s} = 7$ TeV are presented as a function of charged-particle multiplicities. The data, corresponding to an integrated luminosity of about 6.2 pb^{-1} , were collected during the 2010 LHC pp run using the CMS detector. In high-multiplicity events, a long-range ($|\Delta\eta| > 2$), near-side ($\Delta\phi \approx 0$) structure is found in the two-particle $\Delta\eta$ - $\Delta\phi$ correlation functions. The second-order (v_2) and third-order (v_3) azimuthal anisotropy harmonics of charged particles, K_S^0 and $\Lambda/\bar{\Lambda}$ particles are extracted from long-range two-particle correlations as a function of particle multiplicity and transverse momentum, after correcting for the contribution of back-to-back jet correlations. A v_2 and v_3 value of about 4% and 1%, averaging over $0.3 < p_T < 3 \text{ GeV}/c$, are observed in the high-multiplicity region, and are found to be smaller than values obtained in pPb and PbPb collisions at similar multiplicities.

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Abstract

Measurements of two-particle angular correlations in pp collisions at $\sqrt{s} = 7$ TeV are presented as a function of charged-particle multiplicities. The data, corresponding to an integrated luminosity of about 6.2 pb^{-1} , were collected during the 2010 LHC pp run using the CMS detector. In high-multiplicity events, a long-range ($|\Delta\eta| > 2$), near-side ($\Delta\phi \approx 0$) structure is found in the two-particle $\Delta\eta$ - $\Delta\phi$ correlation functions. The second-order (v_2) and third-order (v_3) azimuthal anisotropy harmonics of charged particles, K_S^0 and $\Lambda/\bar{\Lambda}$ particles are extracted from long-range two-particle correlations as a function of particle multiplicity and transverse momentum, after correcting for the contribution of back-to-back jet correlations. A v_2 and v_3 value of about 4% and 1%, averaging over $0.3 < p_T < 3 \text{ GeV}/c$, are observed in the high-multiplicity region, and are found to be smaller than values obtained in pPb and PbPb collisions at similar multiplicities.

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

1. Introduction

Observation of long-range two-particle azimuthal correlations at large relative pseudorapidity in high-multiplicity proton-proton [1] and proton-lead [2] collisions at CMS has opened up new opportunities of studying novel dynamics of particle production in small but high-density Quantum Chromodynamic (QCD) systems. Similar long-range correlation structures at small relative azimuthal angle $\Delta\phi \approx 0$ were first observed in relativistic nucleus-nucleus (AA) collisions. Such correlations have been extensively studied and it has been suggested that the hydrodynamic collective flow of a strongly interacting and expanding medium is responsible for these long-range correlations in large heavy-ion collision systems.

In systems where the overlapping region is significantly smaller than found for AA collisions, such as for pp and pPb collisions, the formation of a hot and dense fluid-like medium was not necessarily expected. Various theoretical models including initial-state gluon correlations without any final-state interactions and hydrodynamic flow that develops in a conjectured high-density but spatially localized medium have been proposed to interpret the origin of the observed long-range correlations in pp and pPb [3, 4]. These models have been successful in describing different aspects of the previous experimental results.

To provide new insights on understanding the long-range correlation phenomenon in high-multiplicity pp collisions, this paper presents an analysis of two-particle azimuthal correlations with unidentified charged particles and identified particles of K_S^0 and $\Lambda/\bar{\Lambda}$. The anisotropy harmonics v_2 and v_3 are extracted from

long-range ($|\Delta\eta| > 2$) two-particle correlations by associating either an unidentified charged particle, or an identified V^0 particle (K_S^0 , $\Lambda/\bar{\Lambda}$) with another unidentified charged particle. The results are expressed as a function of particle p_T and event multiplicity. The contribution of back-to-back jet correlations is estimated and removed by subtracting correlations obtained from very low-multiplicity pp events. The resulting harmonic coefficients are directly compared to those found for the pPb and the PbPb systems over a broad range of similar multiplicities.

2. Corrections of back-to-back jet contributions in two particle correlations

Figure 1 shows the 2-D $\Delta\eta$ - $\Delta\phi$ correlation functions, for pairs of a charged (left), K_S^0 (middle) and $\Lambda/\bar{\Lambda}$ (right) trigger particles and a charged associated particle, in high-multiplicity ($110 \leq N_{\text{trk}}^{\text{offline}} < 150$) pp collisions at $\sqrt{s} = 7$ TeV. Here $N_{\text{trk}}^{\text{offline}}$ is defined in the same way as Refs.[1, 2, 6, 7]. For all three types of particles at high multiplicity, in addition to the correlation peak near $(\Delta\eta, \Delta\phi) = (0, 0)$ due to jet fragmentation, a long-range ridge structure is seen at $\Delta\phi \approx 0$ extending at least 4 units in $|\Delta\eta|$, while such structure is not observed at low multiplicity. On the away side ($\Delta\phi \approx \pi$) of the correlation functions, a long-range structure is also seen and found to exhibit a larger magnitude compared to that on the near side for this p_T range. This away-side correlation structure must contain contributions from back-to-back jets, which need to be accounted for before extracting any other source of correlations.

Fig. 1. The 2-D two-particle correlation functions for inclusive charged particles (left), K_S^0 particles (middle) and $\Lambda/\bar{\Lambda}$ particles (right), with $1 < p_T^{\text{trig}} < 3$ GeV/c and $1 < p_T^{\text{assoc}} < 3$ GeV/c, in high-multiplicity ($110 \leq N_{\text{trk}}^{\text{offline}} < 150$) pp collisions at $\sqrt{s} = 7$ TeV.

By assuming the jet-induced correlations are invariant with event multiplicity, a low multiplicity subtraction procedure is used in this analysis for pp collisions. The Fourier coefficients, $V_{n\Delta}$, for $10 \leq N_{\text{trk}}^{\text{offline}} < 20$ are subtracted from the data in the higher multiplicity region, with

$$V_{n\Delta}^{\text{sub}} = V_{n\Delta} - V_{n\Delta}(10 \leq N_{\text{trk}}^{\text{offline}} < 20) \times \frac{N_{\text{assoc}}(10 \leq N_{\text{trk}}^{\text{offline}} < 20)}{N_{\text{assoc}}} \times \frac{Y_{\text{jet}}}{Y_{\text{jet}}(10 \leq N_{\text{trk}}^{\text{offline}} < 20)}. \quad (1)$$

Here, Y_{jet} represents the near-side jet yield. The ratio, $Y_{\text{jet}}/Y_{\text{jet}}(10 \leq N_{\text{trk}}^{\text{offline}} < 20)$, is introduced to account for the enhanced jet correlations resulting from the selection of higher multiplicity events.

The low multiplicity subtraction procedure of removing back-to-back jet correlation effects in pp is verified using PYTHIA6 (Z2) and PYTHIA8 (4C) simulations, where no jet modification from initial-state or final-state effects is present. The residual $V_{n\Delta}$ after subtraction is found to be consistent with zero within 15% for both PYTHIA6 and PYTHIA8.

3. Results

To investigate the observed correlations in finer detail, the 2-D distributions shown in Fig. 1 are reduced to one-dimensional (1-D) distributions in $\Delta\phi$ by averaging over $|\Delta\eta| > 2$. Fourier coefficients, $V_{n\Delta}$, extracted from 1-D $\Delta\phi$ correlation functions are first studied for inclusive charged hadrons.

The elliptic (v_2) and triangular (v_3) flow harmonics for charged particles with $0.3 < p_T < 3$ GeV/c in pp collisions at $\sqrt{s} = 7$ TeV after applying the jet correction are shown in Fig. 2. The results of previous publication [5, 6] for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are also shown for comparison. In this paper, v_n^{sub} is determined as v_n value after correcting for back-to-back jet correlations estimated from low-multiplicity data with $10 \leq N_{trk}^{offline} < 20$ for pp collisions and $N_{trk}^{offline} < 20$ for pPb and PbPb collisions.

For pp collisions, v_2^{sub} shows a similar pattern as in pPb collisions but becomes relatively constant at a much smaller $N_{trk}^{offline}$ value. Overall, the pp collision results show a smaller v_2^{sub} signal than observed for pPb collisions over a wide multiplicity range, and both systems show smaller v_2^{sub} than observed for PbPb collisions. Within a hydrodynamic picture, this behavior is consistent with the elliptic flow v_2 component being sensitive to the initial-state collision geometry, which is very different for pp, pPb and PbPb systems. The v_3^{sub} values in pp collisions at $N_{trk}^{offline} < 90$ are comparable to those observed in pPb and PbPb collisions within the uncertainties. At higher $N_{trk}^{offline}$, v_3^{sub} in pp collisions starts to saturate while in pPb and PbPb collisions it continues to increase monotonically. This behavior might be due to different event-by-event geometry fluctuations of the three systems.

Fig. 2. The v_2^{sub} (top) and v_3^{sub} (bottom) results of charged particles as a function of $N_{trk}^{offline}$, averaged over $0.3 < p_T < 3$ GeV/c, in pp collisions at $\sqrt{s} = 7$ TeV, pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and PbPb collisions $\sqrt{s_{NN}} = 2.76$ TeV, after correcting for back-to-back jet correlations estimated from low-multiplicity data with $10 \leq N_{trk}^{offline} < 20$ for pp collisions and $N_{trk}^{offline} < 20$ for pPb and PbPb collisions. Results before correcting for jet correlations in pp collisions at $\sqrt{s} = 7$ TeV are also shown as curves. The systematic uncertainties are indicated by the shaded areas.

The v_2 results for pp collisions at $\sqrt{s} = 7$ TeV is also measured as a function of p_T for inclusive charged particles, K_S^0 and $\Lambda/\bar{\Lambda}$ particles, as shown in Fig. 3. For $10 \leq N_{trk}^{offline} < 20$, the v_2 values are largely identical within statistical uncertainties for all three types of particles. The extracted v_2 values mainly reflects back-

to-back jet correlations on the away side as there is no evidence of long-range near-side correlation being seen in these low-multiplicity events. However, for the high multiplicity events with $110 \leq N_{\text{trk}}^{\text{offline}} < 150$, a deviation of v_2 between particle species is observed. In the lower p_T region of $\lesssim 2.5$ GeV/c, the v_2 of K_S^0 is bigger than that of $\Lambda/\bar{\Lambda}$ at a given p_T value. Both are consistently below the inclusive charged particle v_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. A similar trend is observed in AA collisions and pPb collisions [7]. This behavior is found to be qualitatively consistent with hydrodynamic models. The v_2^{sub} results as a function of p_T for $110 \leq N_{\text{trk}}^{\text{offline}} < 150$ is shown in the bottom panel. The amount of v_2 being subtracted increases as a function of p_T for all particle species, which is consistent with the observation of stronger jet-like correlation at higher p_T observed from v_2 results for $10 \leq N_{\text{trk}}^{\text{offline}} < 20$. The v_2^{sub} values for all three types of particle are found to increase with p_T , reaching 8% at $2 < p_T < 3$ GeV/c, and then converges to zero at higher p_T values. The particle mass dependence of v_2 at lower p_T region is also observed after applying jet correction, while at higher p_T v_2^{sub} become identical within uncertainties for all three types of particles.

Fig. 3. The v_2 results of inclusive charged particles, K_S^0 and $\Lambda/\bar{\Lambda}$ as a function of p_T in pp collisions at $\sqrt{s} = 7$ TeV, for $10 \leq N_{\text{trk}}^{\text{offline}} < 20$ (left), and $110 \leq N_{\text{trk}}^{\text{offline}} < 150$ (right). The v_2^{sub} results as a function of p_T for $110 \leq N_{\text{trk}}^{\text{offline}} < 150$ is shown in the bottom panel. The systematic uncertainties are indicated by the shaded areas.

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