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Azimuthal anisotropy of charged particles with transverse momentum up to 100 GeV/*c* in PbPb collisions at √sNN = 5.02TeV

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Azimuthal anisotropy of charged particles with transverse momentum up to 100 GeV/c in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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ABSTRACT

The Fourier coefficients v_2 and v_3 characterizing the anisotropy of the azimuthal distribution of charged particles produced in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are measured with data collected by the CMS experiment. The measurements cover a broad transverse momentum range, $1 < p_T < 100$ GeV/c. The analysis focuses on the $p_T > 10$ GeV/c range, where anisotropic azimuthal distributions should reflect the path-length dependence of parton energy loss in the created medium. Results are presented in several bins of PbPb collision centrality, spanning the 60% most central events. The v_2 coefficient is measured with the scalar product and the multiparticle cumulant methods, which have different sensitivities to initial-state fluctuations. The values from both methods remain positive up to $p_T \sim 60$–80 GeV/c, in all examined centrality classes. The v_3 coefficient, only measured with the scalar product method, tends to zero for $p_T \gtrsim 20$ GeV/c. Comparisons between theoretical calculations and data provide new constraints on the path-length dependence of parton energy loss in heavy ion collisions and highlight the importance of the initial-state fluctuations.

1. Introduction

Several observations made at RHIC in AuAu collisions at center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 200$ GeV [1–4] and at the LHC in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [5–10] establish that high-energy partons lose a significant fraction of their energy while traversing the hot and dense medium created in these collisions. Measurements of the nuclear modification factor (R_{AA}), a ratio that quantifies the modification of particle spectra between pp and heavy ion collisions, show a large suppression of high transverse-momentum (p_T) charged hadrons at RHIC [11–16] and at LHC [7–10]. Also, a strong asymmetry is observed in the energies of the two jets in dijet events in PbPb collisions [5,6]. These observations have triggered much progress in the understanding of jet quenching phenomena, but do not provide sufficient information for a detailed understanding of how the parton energy loss depends on the distance traversed by the partons in the medium. The study of anisotropies in the azimuthal angle distributions of high-p_T hadrons can provide revealing information that is complementary to previous measurements. These anisotropies are characterized by the v_n coefficients of a Fourier expansion in the distributions of azimuthal angle measured with respect to the event plane, defined by the direction of maximum particle density in the transverse plane [17]. Such studies have been performed at RHIC [18] and at the LHC [19–21] up to $p_T \approx 10$ and 60 GeV/c, respectively. Most jet quenching models are unable to simultaneously reproduce the R_{AA} and v_2 measurements [22–24]. Nevertheless, recent attempts to solve this puzzle have shown promise by considering initial-state collision geometry asymmetries and fluctuations [25,26], which are predicted to strongly affect the high-p_T v_n coefficients, but not the R_{AA} values. In particular, the fluctuations generate odd harmonics [27] and the measurement of the v_3 coefficient up to very high p_T is expected to clarify the importance of considering initial-state fluctuations in the modeling of parton energy loss [25,26].

In this Letter, the azimuthal anisotropy of charged particles produced in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is measured up to $p_T \approx 100$ GeV/c. The scalar product (SP) method [28,29] is used to determine the v_2 and v_3 coefficients as a function of p_T and collision centrality in the pseudorapidity range $|\eta| < 1$. The unprecedented statistical reach of the $\sqrt{s_{NN}} = 5.02$ TeV PbPb sample for high-p_T particles allows for the first precise measurement of the v_2 and v_3 coefficients at high p_T. Furthermore, v_2 is also measured with the multiparticle cumulant analysis method [30], using 4-, 6- and 8-particle correlations.

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2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing a 3.8 T field. Within the solenoid volume there are a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within $|\eta| < 2.5$ and provides a p_T resolution of about 1.5% for 100 GeV charged particles. Furthermore, the track impact parameter resolution is about 25–90 (45–150) μm in the transverse (longitudinal) dimension, depending on η and p_T [31]. Iron and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the range $2.9 < |\eta| < 5.2$ on either side of the interaction region. The granularity of the HF towers is $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$ radians, allowing an accurate reconstruction of the heavy ion event plane. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [32]. The detailed Monte Carlo simulation of the CMS detector response is based on Geant4 [33].

3. Event and track selections

The analysis of PbPb collisions is based on a data set corresponding to an integrated luminosity of 404 μb^{-1}, collected in 2015. Events were collected with several trigger algorithms, composed of a hardware-based level 1 (L1) trigger, followed by a software-based high-level trigger (HLT). The p_T region up to 14 GeV/c is covered by a minimum-bias trigger, which requires energy deposits in both HF calorimeters above a predefined threshold of approximately 1 GeV. This minimum-bias trigger was prescaled during data taking. To extend the measurement to higher order coefficients and higher p_T (e.g., up to 100 GeV/c), a dedicated trigger that selects events containing a high-p_T particle was used. The L1 trigger requirement was based on the transverse energy (E_T) of the highest E_T calorimeter region ($\Delta\eta \times \Delta\phi = 0.348 \times 0.348$) in the barrel region ($|\eta| < 1.044$). In the HLT farm, a fast version of the offline tracking algorithms was employed and the highest p_T track was required to pass the strict selection criteria described hereafter, resulting in a trigger efficiency of nearly 100%. Different E_T and p_T thresholds [10] were used at L1 and HLT, respectively, to enrich the data sample with events that contain high-p_T tracks.

In the offline analysis, an additional selection of hadronic collisions is applied by requiring at least three towers with an energy deposit of more than 3 GeV per tower in each of the HF detectors. The events are required to have a reconstructed primary vertex, formed by two or more tracks and required to have a distance from the nominal interaction point of less than 15 cm along the beam axis and less than 0.15 cm in the transverse plane. The collision centrality in PbPb events, i.e. the degree of overlap of the two colliding nuclei, is determined from the E_T deposited in both HF calorimeters. Collision centrality bins are given in percentage ranges of the total hadronic cross section, 0–5% corresponding to the 5% of collisions with the largest overlap of the two nuclei [34].

A standard CMS high-purity track selection [31,35] is used to select primary tracks (tracks associated with the primary vertex). Additional requirements are applied to enhance the purity of these primary tracks. The track must be consistent with originating from the primary vertex by less than 3 standard deviations when estimating both the longitudinal and transverse distances of closest approach. The relative uncertainty of the p_T measurement, $\sigma(p_T)/p_T$, must be less than 10%. To ensure high tracking efficiency and reduce the rate of misreconstructed tracks, primary tracks are restricted to the $|\eta| < 1$ and $p_T > 1$ GeV/c region. Furthermore, tracks with $p_T > 20$ GeV/c are required to match a compatible energy deposit in the calorimeters (ECAL + HCAL). The tracking efficiency and detector acceptance in PbPb collisions are evaluated using simulated hydjet 1.9 [36] minimum bias and hydjet-embedded pythia [37] dijet events. The combined geometrical acceptance and efficiency for primary track reconstruction, for $p_T > 1$ GeV/c and $|\eta| < 1$, is 60–75%, depending on centrality. Finally, the rate of misreconstructed tracks reaches its maximum in the most central events, where it approaches 10%.

4. Analysis technique

The anisotropies of the particle azimuthal angle distributions are characterized by the v_n Fourier coefficients, determined by the expansion $\mathrm{d}N/\mathrm{d}\phi \sim 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]$, where N is the number of particles and Ψ_n is the nth harmonic symmetry plane angle. Event-by-event variations in the initial energy density of the collision lead to the measured event plane fluctuations about the (experimentally inaccessible) symmetry plane [38]. The SP method is used to measure azimuthal correlations and extract Fourier coefficients. In this method, the v_n coefficients can be expressed in terms of Q_n-vectors,

$$v_n\{\mathrm{SP}\} \equiv \frac{\langle Q_n Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}},$$

$$\text{with } Q_n,\ Q_{nA},\ Q_{nB},\ Q_{nC} \equiv \sum_{k=1}^{M} \omega_k \, e^{in\phi_k}, \tag{1}$$

where M represents the number of tracks or HF towers with energy above a certain threshold in each event, ϕ_k is the azimuthal angle of the kth track or HF tower, and ω_k is a weighting factor equal to unity for Q_n, p_T for the tracks (Q_{nC}), and E_T for the HF towers (Q_{nA} and Q_{nB}). The angular brackets $\langle\rangle$ denote averages over all events. The Q_n vector is based on the particles of interest, i.e., tracks with $|\eta| < 1$. The Q_{nA} and Q_{nB} vectors are determined from the two HF calorimeters, covering the range $3 < |\eta| < 5$, while the Q_{nC} vector is obtained using tracks with $|\eta| < 0.75$. If the particle of interest comes from the positive-η side of the tracker, then Q_{nA} is calculated using the negative-η side of HF, and vice versa. The large η gap imposed between Q_{nA} and Q_n suppresses few-particle correlations, such as those induced by high-p_T jets and particle decays, which do not depend on the event plane direction Ψ_n^{EP}. The real part is taken for all averages of Q-vector products over the events. Azimuthal asymmetries that arise from the acceptance and other detector-related effects are taken into account using a two-step process, where the Q-vector is first recentered and subsequently flattened [39]. These corrections and their effects on the results are negligible for the CMS detector. Since the measurements include correlations between low- and high-p_T particles, the recently established event-plane decorrelation effect [40] cannot be neglected. It is expected to reduce the v_n values in comparison to those determined if the event planes would be established exclusively using high-p_T particles. The model calculations that include fluctuations in the initial state take into account this effect [26].

The multiparticle cumulant method [30,41] is also used to measure v_2 from genuine 4-, 6-, and 8-particle correlations, with the advantage of being less sensitive to few-particle correlations, e.g., jet fragmentation. The cumulants are expressed in terms of the corresponding Q_n vectors. We first define the 2-, 4-, 6-, and 8-particle correlators as

$$\begin{aligned}\langle\langle 2\rangle\rangle &= \left\langle\!\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\!\right\rangle,\\ \langle\langle 4\rangle\rangle &= \left\langle\!\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\!\right\rangle,\\ \langle\langle 6\rangle\rangle &= \left\langle\!\left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\right\rangle\!\right\rangle,\\ \langle\langle 8\rangle\rangle &= \left\langle\!\left\langle e^{in(\phi_1+\phi_2+\phi_3+\phi_4-\phi_5-\phi_6-\phi_7-\phi_8)}\right\rangle\!\right\rangle,\end{aligned} \tag{2}$$

where the double average symbol $\langle\langle\ \rangle\rangle$ indicates that the average is taken over all particle combinations and for all events. The unbiased estimators of the reference multiparticle cumulants, $c_n\{\}$, are defined as [41–43]

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

In order to perform a measurement differential in p_T in the multiparticle cumulant framework, one of the particles in Eq. (3) is restricted to belong to a certain p_T bin. Denoting by $\langle\langle 2'\rangle\rangle$, etc., the modified particle correlators, the differential multiparticle cumulants are defined in Ref. [43] and can be derived as described in Ref. [41],

$$\begin{aligned}d_n\{4\} &= \langle\langle 4'\rangle\rangle - 2\,\langle\langle 2'\rangle\rangle\langle\langle 2\rangle\rangle,\\ d_n\{6\} &= \langle\langle 6'\rangle\rangle - 6\,\langle\langle 4'\rangle\rangle\langle\langle 2\rangle\rangle - 3\,\langle\langle 2'\rangle\rangle\langle\langle 4\rangle\rangle + 12\,\langle\langle 2'\rangle\rangle\langle\langle 2\rangle\rangle^2,\\ d_n\{8\} &= \langle\langle 8'\rangle\rangle - 12\,\langle\langle 6'\rangle\rangle\langle\langle 2\rangle\rangle - 4\,\langle\langle 2'\rangle\rangle\langle\langle 6\rangle\rangle - 18\,\langle\langle 4'\rangle\rangle\langle\langle 4\rangle\rangle\\ &\quad + 72\,\langle\langle 4'\rangle\rangle\langle\langle 2\rangle\rangle^2 + 72\,\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle\langle\langle 2'\rangle\rangle - 144\,\langle\langle 2'\rangle\rangle\langle\langle 2\rangle\rangle^3.\end{aligned} \tag{4}$$

Finally, with respect to the reference multiparticle cumulants, the differential 4-, 6-, and 8-particle $v_n(p_T,\eta)$ coefficients are derived as

$$\begin{aligned}v_n\{4\}(p_T,\eta) &= -\,d_n\{4\}\,(-c_n\{4\})^{-3/4},\\ v_n\{6\}(p_T,\eta) &= \,d_n\{6\}\,(c_n\{6\})^{-5/6}\,4^{-1/6},\\ v_n\{8\}(p_T,\eta) &= -\,d_n\{8\}\,(-c_n\{8\})^{-7/8}\,33^{-1/8}.\end{aligned} \tag{5}$$

The statistical uncertainties are evaluated with a data-driven method, as previously employed in Ref. [42]. The data set is divided into 10 subsets with roughly equal numbers of events and the standard deviation of the resulting distribution of the cumulant is used to estimate the uncertainties.

5. Systematic uncertainties

At low p_T, the relative systematic uncertainties for $v_2\{SP\}$ and $v_3\{SP\}$ are found to be similar. At high p_T, the $v_3\{SP\}$ statistical uncertainties are too large to properly disentangle statistical fluctuations from systematic effects. Therefore, the v_2 systematic uncertainties, expressed in terms of relative values in %, are applied to v_3, with the exception of the uncertainties due to the few-particle correlations, discussed below. The systematic uncertainties due to the vertex position selection and to the p_T dependence of the tracking efficiency corrections are common to the SP and cumulant analyses. They are found to be less than 1% and independent of p_T and centrality. The systematic uncertainties due to misreconstructed tracks are derived by changing the track selection criteria. The results are found to depend on p_T but not centrality, and are also different for the cumulant and SP methods. The track selection uncertainties have been found to gradually increase from $\sim 2\%$ at low p_T to $\sim 50\%$ for $p_T > 60$ GeV/c for the SP method, and from $\sim 2\%$ to $\sim 2\%$ for the cumulant analysis. The SP results have an additional uncertainty arising from few-particle correlations. This uncertainty is determined by varying the η gap and contributes differently to the v_2 and v_3 measurements. It is found to depend on both p_T and centrality, and ranges in absolute value from 0 to 0.022 for v_2 and from 0 to 0.030 for v_3.

6. Results

Fig. 1 shows the v_2 and v_3 results obtained from the SP method as a function of p_T, up to about 100 GeV/c, in seven collision centrality ranges. From low- to high-p_T, the v_2 and v_3 values first increase with increasing p_T, up to a maximum near $p_T \approx 3$ GeV/c, before decreasing again. In most centrality ranges, v_2 remains positive up to $p_T \sim 60$–80 GeV/c, becoming consistent with zero at higher p_T. Positive v_3 values are found up to $p_T \approx 20$ GeV/c over the 0–40% centrality range. At higher p_T, the measured v_3 value is consistent with zero within the experimental uncertainties. Given the systematic uncertainties, the measured values are compatible with zero. Some negative v_3 values are seen at high p_T in the 40–50% centrality range, but such peripheral events are the most contaminated by back-to-back jet correlations. This is confirmed by studying the η gap dependence of the results in both measured and simulated events, where the latter include dijets embedded into HYDJET events with zero input anisotropy. In the centrality range 50–60%, v_3 is only measured up to 20 GeV/c because of lack of events containing higher p_T particles.

The v_2 and v_3 results are compared to the CUJET3.0 [44] and SHEE [25] models for several centrality bins. A key difference between these two models is that the SHEE framework includes initial-state geometry fluctuations, while CUJET3.0 uses a smooth hydrodynamic background. The CUJET3.0 model uses perturbative quantum chromodynamics (pQCD) calculations to describe the hard parton interactions in the quark–gluon plasma (QGP), complemented by a perfect-fluid hydrodynamic expansion of the medium. The SHEE calculations use viscous hydrodynamics including event-by-event fluctuations in the soft sector [26,45,46], in addition to an energy loss model [26,47,48]. They are performed with a low shear viscosity to entropy density ratio (η/s), less than or equal to 0.12 (although higher values do not affect the high-p_T predictions), a chemical freezout temperature of 160 MeV, and a linear path-length dependence of the energy loss inspired by pQCD, similar to that in CUJET3.0. In addition, both model calculations are only valid for $p_T > 10$ GeV/c.

Over the full centrality range, the CUJET3.0 calculations describe qualitatively the trend observed in the v_2 data for $p_T > 10$ GeV/c, but fail to quantitatively reproduce the results. For instance, in the centrality range 0–30% and for $10 < p_T < 40$ GeV/c, v_2 is overestimated by 10–50%, while the model largely underestimates it in the peripheral bins. The SHEE calculations of both v_2 and v_3 are in good agreement with the data for $p_T > 10$ GeV/c over the full centrality range. The success of the SHEE framework suggests that modeling the initial-state fluctuations may be a crucial ingredient to describe the experimental data related to parton energy loss. Although not shown in the figure, a scenario in the SHEE framework with a quadratic path-length dependence of the energy loss, inspired by gauge-gravity duality [49,50], was also tested and seen to disagree with the data. As just one example, this alternative path-length dependence is found to overestimate the data by 30–40% for $p_T > 20$ GeV/c in the 20–30% centrality range.

The v_2 values are also obtained from 4-, 6-, and 8-particle cumulant analyses, as shown in Fig. 2, where the SP v_2 results are also included for comparison. For $p_T < 3$ GeV/c, the results follow the expectation from Bessel-Gaussian or elliptic power v_2 distribu-

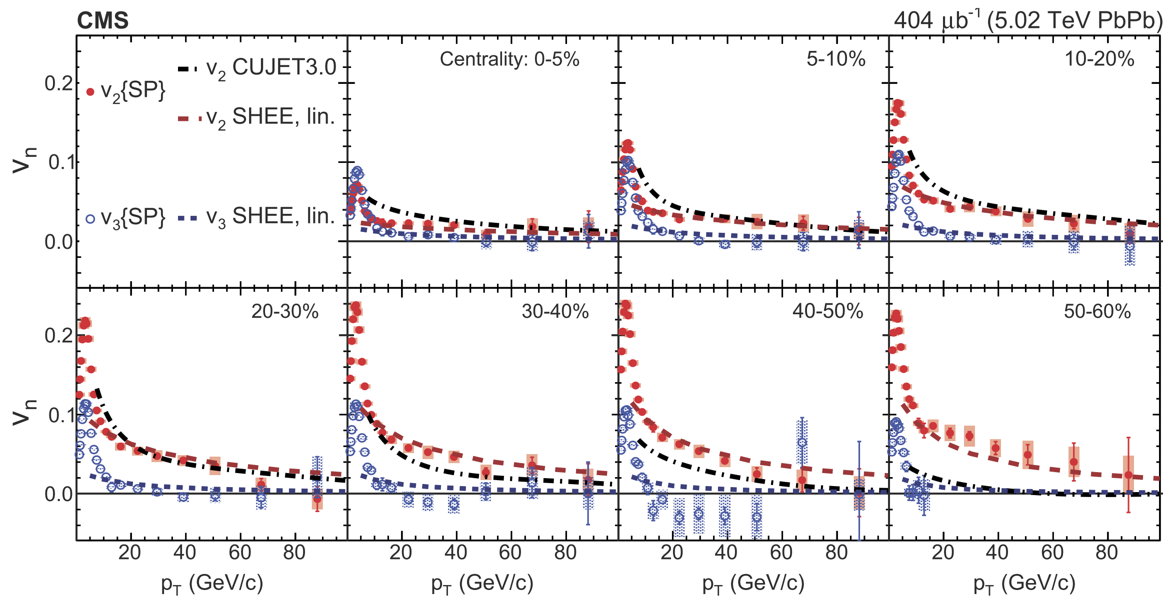

Fig. 1. The v_2 and v_3 results from the SP method as a function of p_T, in seven collision centrality ranges from 0–5% to 50–60%. The vertical bars (shaded boxes) represent the statistical (systematic) uncertainties. The curves represent calculations made with the CUJET3.0 [44] and the SHEE models [26] (see text).

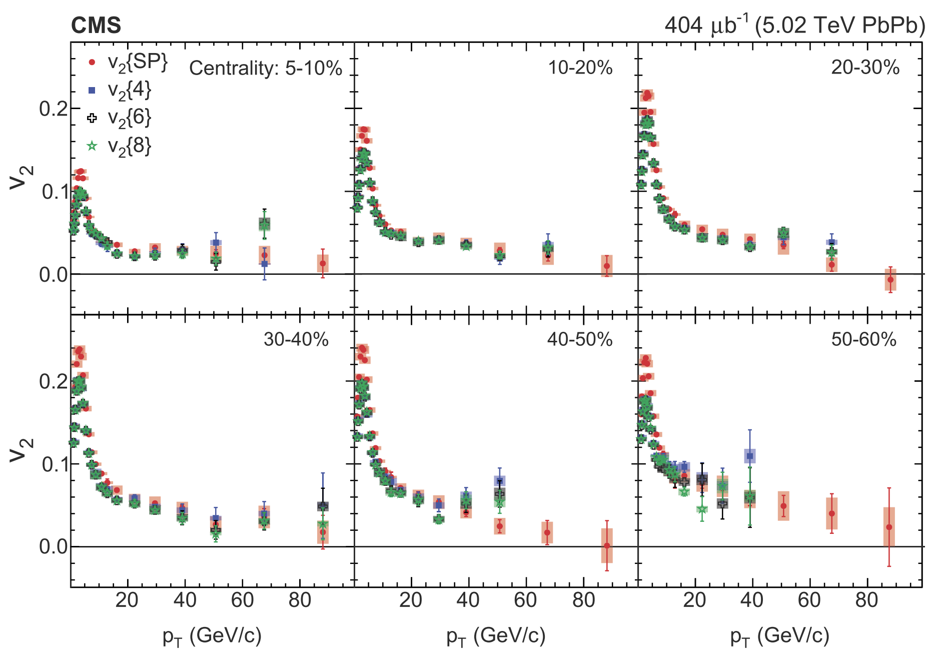

Fig. 2. Comparison between the v_2 results from the SP and the 4-, 6-, and 8-particle cumulant methods, as a function of p_T, in six centrality ranges from 0–5% to 50–60%. The vertical bars (shaded boxes) represent the statistical (systematic) uncertainties.

tions, which predict $v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ [51–53]. The observation that the multiparticle cumulant values remain similar up to $p_T = 100$ GeV/c ($v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$), further suggests that the azimuthal anisotropy is strongly affected by the initial-state geometry and its event-by-event fluctuations [25,26]. At higher p_T, the difference between SP and multiparticle cumulant results shows a tendency to decrease. Nevertheless, the uncertainties are too large to draw a firm conclusion. This tendency might be due to p_T dependence of flow vector fluctuations, which depends on the shear viscosity over entropy density ratio of the medium [26,54]. Therefore, the results presented in Fig. 2 provide important information to constrain the QGP shear viscosity in PbPb collisions.

Fig. 3 shows the correlation between high-p_T and low-p_T v_2 values, for investigating the connection between the azimuthal anisotropies induced by hydrodynamic flow and the path-length dependence of parton energy loss [25,26]. The most peripheral $v_2\{SP\}$ and $v_2\{4\}$ data points are the ones with the largest error bars. Linear fits to the centrality dependent v_2 correlation between the low- and high-p_T regions are shown in the figure. Here a zero intercept is assumed. The corresponding χ^2 over the number of degree of freedom values are found to be near 1–1.5, except for the $26 < p_T < 35$ GeV/c range, where a positive intercept is indicated for the $v_2\{SP\}$ results. The non-zero intercept might reflect a centrality dependent event-plane decorrelation that increases going to higher p_T. The slope values for $v_2\{SP\}$ and $v_2\{4\}$ are found

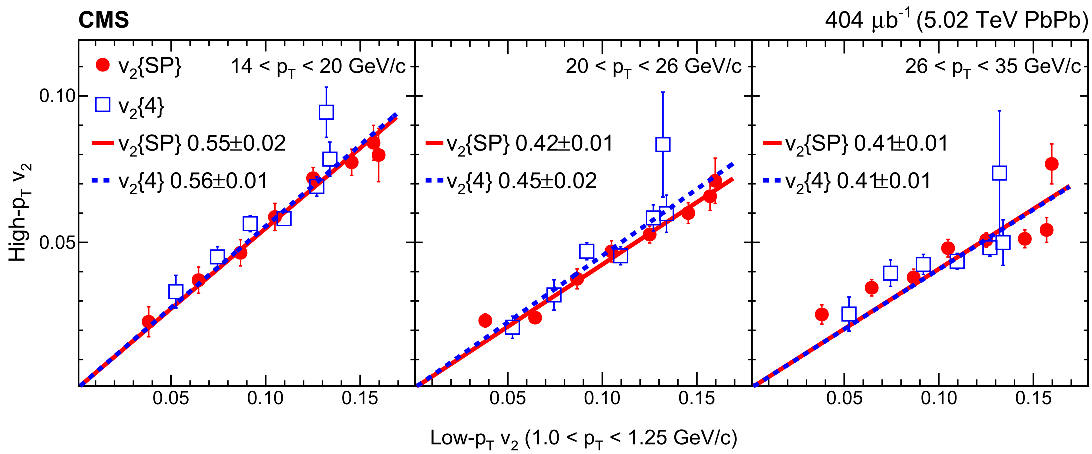

Fig. 3. Correlation between the high-p_T v_2 measured in the 14–20 (left), 20–26 (middle), and 26–35 GeV/c (right) p_T ranges and the low-p_T v_2 measured in the $1 < p_T < 1.25$ GeV/c range, with the SP (closed circles) and cumulant (open squares) methods. The points represent the centrality bins 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–50, and 50–60% for the SP results. For the cumulant method, the bin 0–5% is not shown. Lines represent a linear fit to the SP results (red) and cumulant results (dashed blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to be compatible within statistical uncertainties and to decrease when selecting higher p_T particles. This suggests that the initial-state geometry and its fluctuations are likely to be the common causes of the observed particle azimuthal anisotropies at both low and high p_T.

7. Summary

The azimuthal anisotropy of charged particles produced in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been studied using data collected by the CMS experiment. The v_2 and v_3 coefficients are determined, as a function of collision centrality, over the widest transverse momentum range studied to date (from 1 up to 100 GeV/c). For the first time, the multiparticle cumulant method is used for $p_T > 20$ GeV/c. Over the measured centrality range, positive v_2 values are found up to $p_T \sim 60$–80 GeV/c, while the v_3 values are consistent with zero for $p_T > 20$ GeV/c. For $p_T < 3$ GeV/c, $v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$, consistent with a collective behavior arising from the hydrodynamic expansion of a quark–gluon plasma. The similarity of $v_2\{SP\}$, $v_2\{4\}$, $v_2\{6\}$, and $v_2\{8\}$ at high p_T suggests that v_2 originates from the path-length dependence of parton energy loss associated with an asymmetric initial collision geometry. In addition, a common trend in the centrality dependence of v_2 is observed over the full p_T range, further supporting a common connection to the initial-state geometry and its fluctuations. A model calculation (SHEE) incorporating initial-state fluctuations with a linear path-length dependence of parton energy loss is found to be in good agreement with the data, over the wide p_T and centrality ranges probed in this analysis.

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