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Mixed higher-order anisotropic flow and nonlinear response coefficients of charged particles in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV

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Abstract Anisotropies in the initial energy density distribution of the quark-gluon plasma created in high energy heavy ion collisions lead to anisotropies in the azimuthal distributions of the final-state particles known as collective anisotropic flow. Fourier harmonic decomposition is used to quantify these anisotropies. The higher-order harmonics can be induced by the same order anisotropies (linear response) or by the combined influence of several lower order anisotropies (nonlinear response) in the initial state. The mixed higher-order anisotropic flow and nonlinear response coefficients of charged particles are measured as functions of transverse momentum and centrality in PbPb collisions at nucleon-nucleon center-of-mass energies $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV with the CMS detector. The results are compared with viscous hydrodynamic calculations using several different initial conditions, as well as microscopic transport model calculations. None of the models provides a simultaneous description of the mixed higher-order flow harmonics and nonlinear response coefficients.

1 Introduction

The azimuthal anisotropy of particle production in a heavy ion collision can be characterized by the Fourier expansion of the particle azimuthal angle distribution [1],

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\phi}, \quad (1)$$

where $V_n = v_n \exp(in\Psi_n)$ is the n th complex anisotropic flow coefficient [2]. The v_n and Ψ_n are the magnitude and phase (also known as the n th order symmetry plane angle) of V_n , respectively. Anisotropic flow plays a major role in probing the properties of the produced medium in heavy ion collisions at the BNL RHIC [3–6] and CERN LHC [7–9]. Studies of flow harmonics higher than the second order [10–12], flow

fluctuations [13–16], the correlation between the magnitude and phase of different harmonics [17–24], and the transverse momentum (p_T) and pseudorapidity (η) dependence of symmetry plane angles [25,26], have led to a broader and deeper understanding of the initial conditions [3,27] and the properties of the produced hot and dense matter. There are significant correlations between the symmetry plane angles of different orders [20], which indicate that higher-order mixed harmonics can be studied with respect to multiple lower-order symmetry plane angles.

In hydrodynamical models describing the quark-gluon plasma (QGP) created in relativistic heavy ion collisions, anisotropic flow arises from the evolution of the medium in the presence of an anisotropy in the initial-state energy density, as characterized by the eccentricities ϵ_n [10]. The magnitudes of the second- and third-order harmonic final state coefficients, v_2 and v_3 , are to a good approximation linearly proportional to the initial-state anisotropies, ϵ_2 and ϵ_3 , respectively [10,17]. In contrast, V_4 and higher harmonics can arise from initial-state anisotropies in the same-order harmonic (linear response) or can be induced by lower-order harmonics (nonlinear response) [1,28,29]. More specifically, these harmonics can be decomposed into linear and nonlinear response contributions as follows [1,28]:

$$\begin{aligned} V_4 &= V_{4L} + \chi_{422} V_2^2, \\ V_5 &= V_{5L} + \chi_{523} V_2 V_3, \\ V_6 &= V_{6L} + \chi_{624} V_2 V_4L + \chi_{633} V_3^2 + \chi_{6222} V_2^3, \\ V_7 &= V_{7L} + \chi_{725} V_2 V_5L + \chi_{734} V_3 V_4L + \chi_{7223} V_2^2 V_3, \end{aligned} \quad (2)$$

where V_{nL} denotes the part of V_n that is not induced by lower-order harmonics [29–31], and the χ are the nonlinear response coefficients. Each nonlinear response coefficient has its associated mixed harmonic, which is V_n measured with respect to the lower-order symmetry plane angle or angles. The strength of each nonlinear response coefficient determines the magnitude of its associated mixed harmonic. The V_1 terms are neglected in the decomposition in Eq. (2)

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because the correlation between V_n and $V_1 V_{n-1}$ was shown to be negligible after correcting V_1 for global momentum conservation [28]. This analysis focuses on the terms that only involve the two largest anisotropic flow coefficients V_2 and V_3 on the right-hand side of Eq. (2). The procedures used to extract both mixed-harmonic and nonlinear response coefficients are given in Sect. 4.

It is difficult to use measured v_2 and v_3 coefficients to evaluate hydrodynamic theories because these flow observables have a strong dependence on the initial anisotropies, which cannot be experimentally determined or tightly constrained. In contrast, most of the nonlinear response coefficients are not strongly sensitive to the initial anisotropies, which largely cancel in the dimensionless ratios used to determine these coefficients [1, 28, 31, 32]. As a result, their experimental values can serve as unique and robust probes of hydrodynamic behavior of the QGP [31].

Most previous flow measurements focused on V_n (overall flow), i.e., v_n with respect to Ψ_n , which does not separate the linear and nonlinear parts of Eq. (2). Direct measurements of the mixed higher-order flow harmonics, v_4 and v_6 with respect to Ψ_2 , already exist at both RHIC [33] and LHC [11] energies, but were performed using the event plane method [34]. This method has been criticized for yielding an ambiguous measure lying somewhere between the event-averaged mean value $\langle v_n \rangle$ and the root-mean-square value $\sqrt{\langle v_n^2 \rangle}$ of the v_n distribution, depending on the resolution of the method [13, 16, 35]. This ambiguity can be removed by using the scalar-product method [35, 36], which always measures the root-mean-square values of v_n . The difference between the two methods is typically a few percent for v_2 , $\sim 10\%$ for v_3 , and much larger for mixed harmonics [35].

This paper presents the mixed higher-order flow harmonics and nonlinear response coefficients for $n = 4, 5, 6$, and 7 using the scalar-product method. These variables are measured in PbPb collisions at nucleon-nucleon center-of-mass energies $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV, as functions of collision centrality and charged particle p_T in the region $|\eta| < 0.8$. To compare the mixed flow harmonics with the overall flow coefficients, the higher-order flow harmonics with respect to the same-order symmetry plane, measured using the scalar-product method, are also presented.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a nearly constant magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and

two endcap sections. In this analysis, the tracker and the forward hadron (HF) calorimeter subsystems are of particular importance. The HF uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the center of the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. These calorimeters are azimuthally subdivided into 20° modular wedges and further segmented to form 0.175×0.175 ($\Delta\eta \times \Delta\phi$) “towers”, where the angle ϕ is in radians. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15,148 silicon strip detector modules. For nonisolated particles of $1 < p_T < 10$ GeV/c and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [37]. The Beam Pick-up Timing for the eXperiments (BPTX) devices are located around the beam pipe at a distance of 175 m from the interaction region on both sides, and are designed to provide precise information on the LHC bunch structure and timing of the incoming beams. 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. [38]. The Monte Carlo simulation of the particle propagation and detector response is based on the GEANT4 [39] program.

3 Event and track selections

This analysis is performed using minimum bias PbPb data collected with the CMS detector at $\sqrt{s_{\text{NN}}} = 5.02$ and 2.76 TeV in 2015 and 2011, corresponding to integrated luminosities of $13 \mu\text{b}^{-1}$ and $3.9 \mu\text{b}^{-1}$, respectively. The minimum bias trigger [40] used in this analysis requires coincident signals in the HF calorimeters at both ends of the CMS detector with total energy deposits above a predefined energy threshold of approximately 1 GeV and the presence of both colliding bunches in the interaction region as determined using the BPTX. By requiring colliding bunches, events due to noise (e.g., cosmic rays and beam backgrounds) are largely suppressed. In the offline analysis, events are required to have at least one reconstructed primary vertex, which is chosen as the reconstructed vertex with the largest number of associated tracks. The primary vertex is formed by two or more associated tracks and is required to have a distance of less than 15 cm along the beam axis from the center of the nominal interaction region and less than 0.15 cm from the beam position in the transverse plane. An additional selection of hadronic collisions is applied by requiring at least three towers, each with total energy above 3 GeV in each of the two HF calorimeters. The average number of collisions per bunch crossing is less than 0.001 for the events used in this analysis, with a pileup fraction less than 0.05%, which has a negligible

effect on the results. Events are classified using a centrality variable that is related to the degree of geometric overlap between the two colliding nuclei. Events with complete (no) overlap are denoted as centrality 0 (100)%, where the number is the fraction of events in a given class with respect to the total number of inelastic hadronic collisions. The centrality is determined offline via the sum of the HF energies in each event. Very central events (centrality approaching 0%) are characterized by a large energy deposit in the HF calorimeters. The results reported in this paper are presented up to 60% in centrality. The minimum bias trigger and event selections are fully efficient in this centrality range.

Track reconstruction [37,41] is performed in two iterations to ease the computational load for high-multiplicity central PbPb collisions. The first iteration reconstructs tracks from signals (“hits”) in the silicon pixel and strip detectors compatible with a trajectory of $p_T > 0.9 \text{ GeV}/c$. The significance of the separation along the beam axis (z) between the track and the primary vertex, $d_z/\sigma(d_z)$, and the significance of the impact parameter relative to the primary vertex transverse to the beam, $d_0/\sigma(d_0)$, must be less than 2. In addition, the relative uncertainty of the p_T measurement, $\sigma(p_T)/p_T$, must be less than 5%, and tracks are required to have at least 11 out of the possible 14 hits along their trajectories in the pixel and strip trackers. To reduce the number of misidentified tracks, the chi-squared per degree of freedom, χ^2/dof , associated with fitting the track trajectory through the different pixel and strip layers, must be less than 0.15 times the total number of layers having hits along the trajectory of the track. The second iteration reconstructs tracks compatible with a trajectory of $p_T > 0.2 \text{ GeV}/c$ using solely the pixel detector. These tracks are required to have $d_z/\sigma(d_z) < 6$ and a fit χ^2/dof value less than 9 times the number of layers with hits along the trajectory of the track. In the final analysis, first iteration tracks with $p_T > 1.0 \text{ GeV}/c$ are combined with pixel-detector-only tracks that have $0.2 < p_T < 2.4 \text{ GeV}/c$. After removing duplicates [7], the merged track collection has a combined geometric acceptance and efficiency exceeding 60% for $p_T \approx 1.0 \text{ GeV}/c$ and $|\eta| < 0.8$, as determined using the HYDJET event generator [42]. When the track p_T is below 1 GeV/c, the acceptance and efficiency steadily drops, reaching approximately 40% at $p_T \approx 0.3 \text{ GeV}/c$, which is the lower limit for p_T in this analysis.

4 Analysis technique

The analysis technique follows the method described in Refs. [1,28] using detector information from both HF and the tracker. The notation $V_n = v_n \exp(in\psi_n) = \langle e^{in\phi} \rangle$ in Eq. (1) will be replaced by the measured complex flow vector Q_n

with real and imaginary parts defined as

$$\text{Re}(Q_n) = \frac{1}{\sum w_j} \sum_j^M w_j \cos(n\phi_j) - \left\langle \frac{1}{\sum w_j} \sum_j^M w_j \cos(n\phi_j) \right\rangle, \tag{3}$$

$$\text{Im}(Q_n) = \frac{1}{\sum w_j} \sum_j^M w_j \sin(n\phi_j) - \left\langle \frac{1}{\sum w_j} \sum_j^M w_j \sin(n\phi_j) \right\rangle, \tag{4}$$

where M represents the number of tracks or HF towers used for calculating the Q vector, ϕ_j is the azimuthal angle of the j th track or HF tower, and w_j is a weighting factor equal to transverse energy for HF Q vectors. To correct for the tracking inefficiency, $w_j = 1/\epsilon_j$ is the inverse of the tracking efficiency $\epsilon_j(p_T, \eta)$ of the j th track. Unlike the averages over particles in a single event in the definitions of Q_n , the angle brackets in Eqs. (3) and (4) denote an average over all the events within a given centrality range. Subtraction of the event-averaged quantity removes biases due to the detector acceptance.

The mixed higher-order harmonics in each p_T range are extracted using the scalar-product method as shown in Eqs. (5)–(9) [1], which describe the various harmonics measured with respect to symmetry plane angles of different orders. Equations (5)–(9) show v_4 with respect to the second-order, v_5 with respect to the second- and third-order, v_6 with respect to the second-order, v_6 with respect to the third-order, and v_7 with respect to the second- and third-order symmetry plane angles, respectively.

$$v_4\{\psi_{22}\} \equiv \frac{\text{Re}\langle Q_4 Q_{2A}^* Q_{2B}^* \rangle}{\sqrt{\text{Re}\langle Q_{2A} Q_{2A} Q_{2B}^* Q_{2B}^* \rangle}} \tag{5}$$

$$v_5\{\psi_{23}\} \equiv \frac{\text{Re}\langle Q_5 Q_{2A}^* Q_{3B}^* \rangle}{\sqrt{\text{Re}\langle Q_{2A} Q_{3A} Q_{2B}^* Q_{3B}^* \rangle}} \tag{6}$$

$$v_6\{\psi_{222}\} \equiv \frac{\text{Re}\langle Q_6 Q_{2A}^* Q_{2B}^* Q_{2B}^* \rangle}{\sqrt{\text{Re}\langle Q_{2A} Q_{2A} Q_{2A} Q_{2B}^* Q_{2B}^* Q_{2B}^* \rangle}} \tag{7}$$

$$v_6\{\psi_{33}\} \equiv \frac{\text{Re}\langle Q_6 Q_{3A}^* Q_{3B}^* \rangle}{\sqrt{\text{Re}\langle Q_{3A} Q_{3A} Q_{3B}^* Q_{3B}^* \rangle}} \tag{8}$$

$$v_7\{\psi_{223}\} \equiv \frac{\text{Re}\langle Q_7 Q_{2A}^* Q_{2B}^* Q_{3B}^* \rangle}{\sqrt{\text{Re}\langle Q_{2A} Q_{2A} Q_{3A} Q_{2B}^* Q_{2B}^* Q_{3B}^* \rangle}} \tag{9}$$

Here, Q_{nA} and Q_{nB} are vectors from two different parts of the detector, specifically the positive and negative sides of HF, Q_n is the vector from charged particles in each p_T range within $|\eta| < 0.8$, and angle brackets denote the average (weighted by the number of particles) over all events within a given centrality range. The minimum η gap between tracks

used to find the charged-particle Q vector and towers used for the HF Q vectors is 2.2 units of η .

With the assumption that the linear and nonlinear terms in Eq. (2) are uncorrelated, the nonlinear response coefficients in each p_T range can be expressed as [1, 28],

$$\chi_{422} = \frac{\text{Re}\langle Q_4 Q_{2A}^* Q_{2B}^* \rangle}{\text{Re}\langle Q_2 Q_2 Q_{2A}^* Q_{2B}^* \rangle}, \quad (10)$$

$$\chi_{523} = \frac{\text{Re}\langle Q_5 Q_{2A}^* Q_{3B}^* \rangle}{\text{Re}\langle Q_2 Q_3 Q_{2A}^* Q_{3B}^* \rangle}, \quad (11)$$

$$\chi_{622} = \frac{\text{Re}\langle Q_6 Q_{2A}^* Q_{2B}^* Q_{2B}^* \rangle}{\text{Re}\langle Q_2 Q_2 Q_2 Q_{2A}^* Q_{2B}^* Q_{2B}^* \rangle}, \quad (12)$$

$$\chi_{633} = \frac{\text{Re}\langle Q_6 Q_{3A}^* Q_{3B}^* \rangle}{\text{Re}\langle Q_3 Q_3 Q_{3A}^* Q_{3B}^* \rangle}, \quad (13)$$

$$\chi_{723} = \frac{\text{Re}\langle Q_7 Q_{2A}^* Q_{2B}^* Q_{3B}^* \rangle}{\text{Re}\langle Q_2 Q_2 Q_3 Q_{2A}^* Q_{2B}^* Q_{3B}^* \rangle}, \quad (14)$$

where the charged-particle Q_n vector enters both the numerator and the denominator.

5 Systematic uncertainties

Six sources of systematic uncertainties are considered in this analysis. The systematic uncertainty due to vertex position selection is estimated by comparing the results with events from vertex position ranges $|v_z| < 3$ cm to $3 < |v_z| < 15$ cm. For both mixed harmonic and nonlinear response coefficients, this uncertainty is estimated to be 1–3%, with no dependence on p_T or centrality. Systematic uncertainty due to track quality requirements are examined by varying the track selections for $d_z/\sigma(d_z)$ and $d_0/\sigma(d_0)$ from 1.5 to 5, the pixel track $d_z/\sigma(d_z)$ from 5 to 10, and the fit χ^2/dof value from 7 to 18 times the number of layers with hits. The uncertainty is estimated to be 1–4% depending on p_T and centrality for both mixed harmonic and nonlinear response coefficients.

The charged-particle tracking efficiency depends on the efficiency of detecting different types of charged particles and the species composition of the set of particles. Two event generators (HYDJET [42] and EPOS LHC [43]) with different particle composition are used to study the tracking efficiency, and the systematic uncertainty is obtained by comparing the results using efficiencies from the two generators mentioned above. The systematic uncertainty from this source is 3% for the mixed harmonics and less than 1% for the nonlinear response coefficients, with no dependence on p_T or centrality.

The sensitivity of the results to the centrality calibration is evaluated by varying the trigger and event selection efficiency by $\pm 2\%$. The resulting uncertainty is estimated to be less than 1%. The minimum η gap between the correlated charged particles and the Q vectors in the HF region is changed from

2.2 to 3.2 units of η (achieved by changing the η ranges of the HF Q vectors) to estimate the uncertainty due to short-range correlations from resonance decays and jets. This study results in a systematic uncertainty of 1–8%, depending on both p_T and centrality. This η gap uncertainty also includes a possible physics effect from the η -dependent fluctuations of symmetry plane angles [26, 44], although a recent study from the ALICE experiment indicates that this effect is small for correlations between symmetry plane angles of different order [45].

When the same set of HF towers are used for different Q vectors in the equations of mixed harmonic and nonlinear response coefficients, the product of these Q vectors contains self-correlations. An algorithm for removing the duplicated terms when multiplying two or more Q vectors, the same as the approach of Ref. [46], is used. The algorithm only works perfectly when the detector has fine granularity and there is no merging of HF towers. Therefore, the difference before and after correcting for this effect is taken as the systematic uncertainty, yielding values which depend on centrality but are always less than 3%.

The different systematic sources described above are added in quadrature to obtain the overall systematic uncertainty, which is about 10% at low p_T and decreases to around 5% for p_T larger than 1 GeV/c. As a function of centrality, the overall systematic uncertainty ranges from 3 to 9% for different coefficients, with larger uncertainties for central events.

6 Results

The measurements in this paper are presented using tracks in the range of $|\eta| < 0.8$. Figure 1 shows the mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$, and $v_7\{\Psi_{223}\}$ from the scalar-product method at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV as a function of p_T in the 0–20% (upper row) and 20–60% (lower row) centrality ranges.

It is observed that the shapes of the mixed higher-order flow harmonics as a function of p_T are qualitatively similar to the published overall flow harmonics with respect to Ψ_n [7, 11], first increasing at low p_T , reaching a maximum at about 3–4 GeV/c, then decreasing at higher p_T . This may indicate that, for each p_T region, the underlying physics processes that generate the flow harmonics are the same for the nonlinear and the linear parts. Similar to previous observation that the overall flow shows a weak energy dependence from RHIC to LHC energies [7, 8], the mixed harmonics are also found to be consistent between the two collision energies within the uncertainties, except for $v_4\{\Psi_{22}\}$ and $v_5\{\Psi_{23}\}$ at p_T larger than 3 GeV/c in the mid-central collisions, with 5.02 TeV results slightly above 2.76 TeV results.

A direct comparison of the mixed higher-order flow harmonics and overall flow at 5.02 TeV is presented in Fig. 2 as

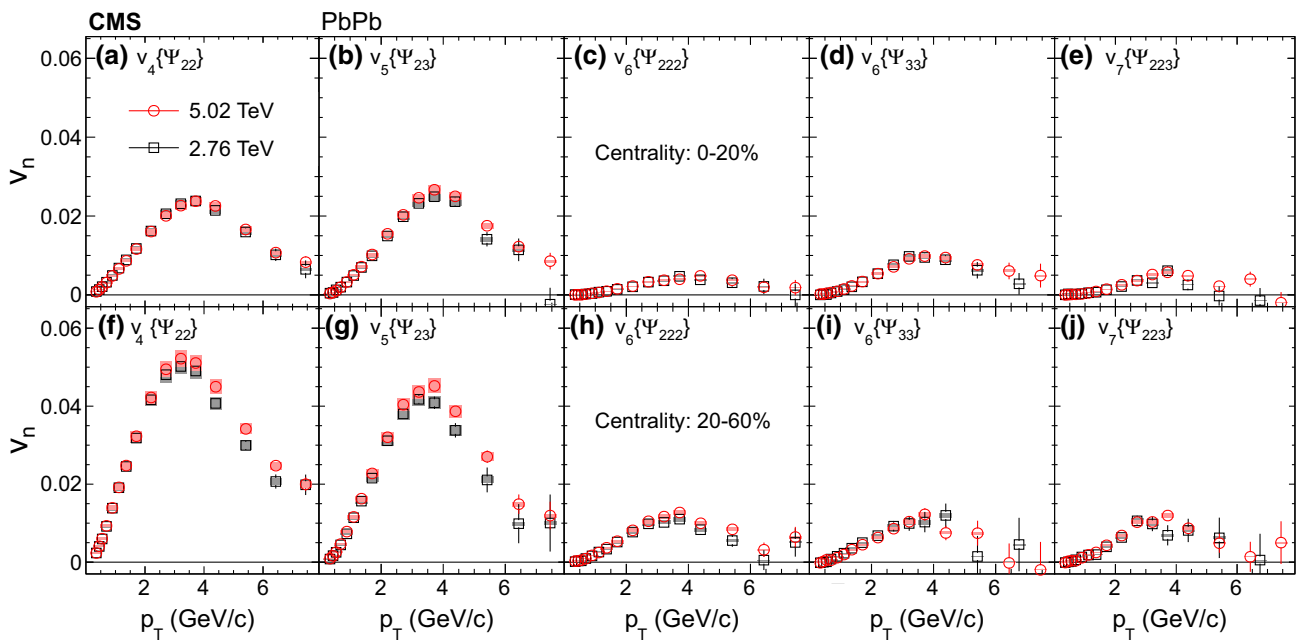


Fig. 1 Mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$, and $v_7\{\Psi_{223}\}$ from the scalar-product method at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV as a function of p_T in the 0–20% (upper row) and 20–60% (lower row) centrality ranges. Statistical (bars) and systematic (shaded boxes) uncertainties are shown

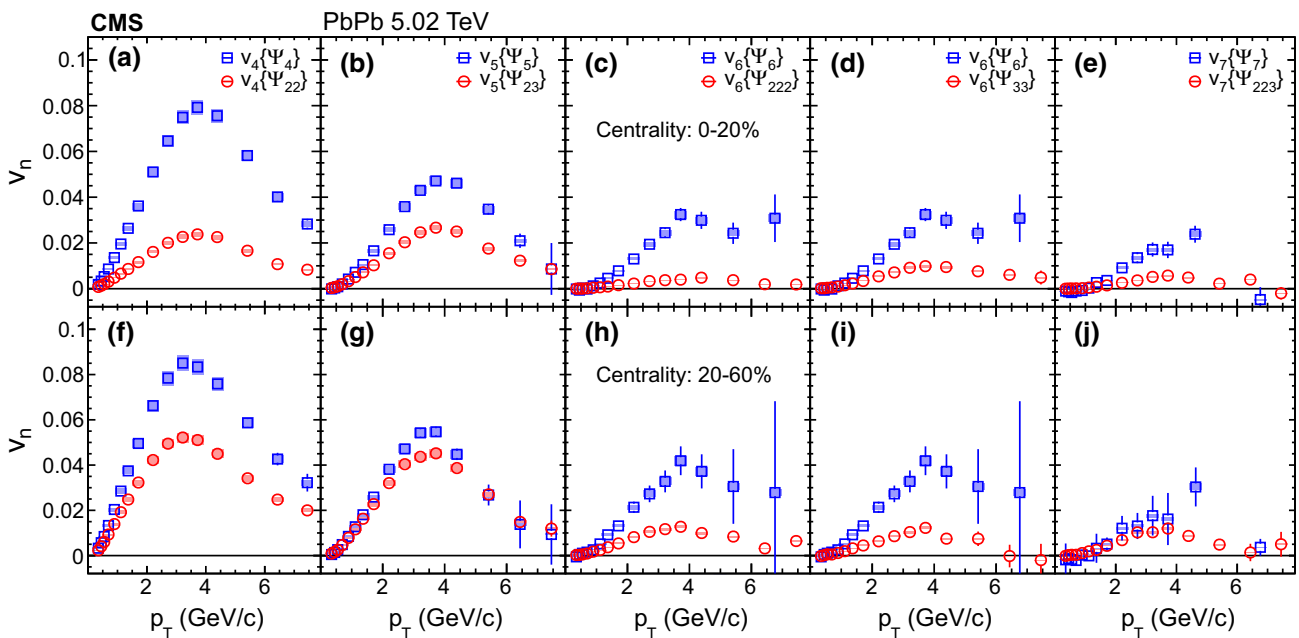


Fig. 2 Comparison of mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$ and $v_7\{\Psi_{223}\}$ with the corresponding overall flow, $v_4\{\Psi_4\}$, $v_5\{\Psi_5\}$, $v_6\{\Psi_6\}$, $v_6\{\Psi_6\}$ and $v_7\{\Psi_7\}$, respectively, at $\sqrt{s_{NN}} = 5.02$ TeV as a function p_T in the 0–20% (upper row) and 20–60% (lower row) centrality ranges. Statistical (bars) and systematic (shaded boxes) uncertainties are shown

a function of p_T in the two centrality ranges. Hydrodynamic models predict that the contribution of the nonlinear response to the overall flow increases towards peripheral collisions for v_4 and v_5 [17, 29, 47]. From a comparison of the relative con-

tribution in the two centrality ranges, the present results are consistent with these predictions, as well as an estimate by the ATLAS Collaboration using a two-component fit of the correlation between flow harmonics [21], and a recent study

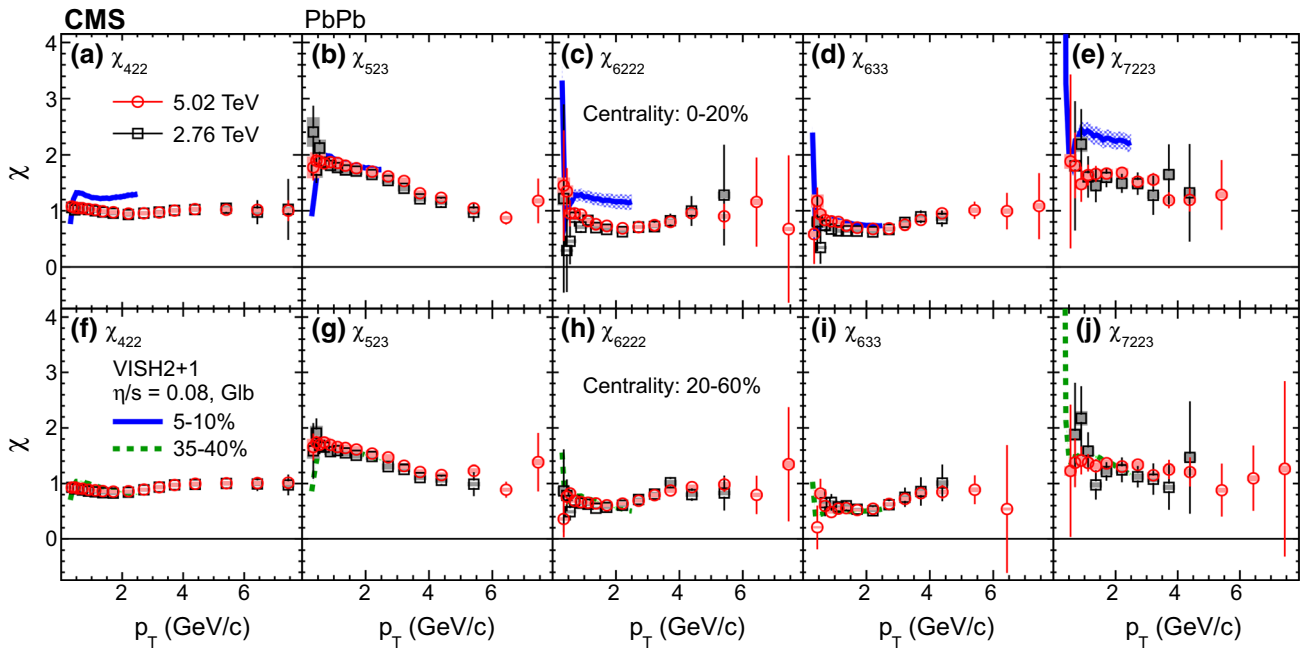


Fig. 3 Nonlinear response coefficients, χ_{422} , χ_{523} , χ_{6222} , χ_{633} , and χ_{7223} from the scalar-product method at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV as a function of p_T in the 0–20% (upper row) and 20–60% (lower row) centrality ranges. Statistical (bars) and systematic (shaded boxes)

uncertainties are shown. The results are compared with hydrodynamic predictions [30] at $\sqrt{s_{NN}} = 2.76$ TeV with $\eta/s = 0.08$ and Glauber initial conditions in the 5–10% (blue lines) and 35–40% (dashed green lines) centrality ranges

of the nonlinear mode by the ALICE Collaboration [45]. By comparing different harmonics, the contribution of the nonlinear response for v_5 is larger than those for the other harmonics in the centrality range 20–60%.

The nonlinear response coefficients, χ_{422} , χ_{523} , χ_{6222} , χ_{633} , and χ_{7223} are presented in Fig. 3 as a function of p_T in the two centrality ranges. It is observed that the odd harmonic coefficients χ_{523} and χ_{7223} are larger than those for the even harmonics for p_T less than 3 GeV/c in the two explored centrality ranges. The values for the even harmonics first decrease slightly as p_T increases, reach a minimum at p_T about 2 GeV/c, and then slowly increase until appearing to plateau for p_T above 4 GeV/c. The results are compared with viscous hydrodynamic predictions [30] at $\sqrt{s_{NN}} = 2.76$ TeV with $\eta/s = 0.08$ (where η/s is the shear viscosity to entropy density ratio of the hydrodynamic medium, and here η denotes shear viscosity rather than pseudorapidity) and Glauber initial conditions in two centrality ranges (5–10% and 35–40%) which roughly match those of the data (0–20% and 20–60%). In the model, as p_T increases from 0.3 to 1 GeV/c, the predicted coefficients increase for $n = 4$ and 5, but decrease and then increase for $n = 6$ and 7, with a much stronger p_T dependence than the data. The strong p_T dependence, attributed to the large variance of the flow angles Ψ_n at small p_T [30], is not observed in data for $n = 4$ and 5.

Figure 4 shows the mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$, and $v_7\{\Psi_{223}\}$ from the scalar-product method, as a function of centrality in the p_T range from 0.3 to 3.0 GeV/c. Hydrodynamic predictions with a deformed symmetric Gaussian density profile as the initial conditions for $v_5\{\Psi_{23}\}$ and $v_7\{\Psi_{223}\}$ [1] at $\sqrt{s_{NN}} = 2.76$ TeV are compared with the data. The model qualitatively describes $v_5\{\Psi_{23}\}$ in the 0–40% centrality range but underestimates the result for more peripheral collisions. For $v_7\{\Psi_{223}\}$, the predicted values are much smaller than the data, especially for centrality from 35 to 50%.

The nonlinear response coefficients, χ_{422} , χ_{523} , χ_{6222} , χ_{633} , and χ_{7223} are presented in Figs. 5 and 6, as a function of centrality in the p_T range from 0.3 to 3.0 GeV/c. The results are compared with predictions at $\sqrt{s_{NN}} = 2.76$ TeV from the microscopic transport model AMPT [48,49], a macroscopic hydrodynamic model using a deformed symmetric Gaussian density profile as the initial conditions with $\eta/s = 0.08$ [1], and from another hydrodynamic calculation (iEBE-VISHNU) with both Glauber and Kharzeev–Levin–Nardi (KLN) gluon saturation initial conditions using the same η/s [28]. The model with Gaussian profile initial conditions gives a better description of the nonlinear response coefficients compared to other calculations, but it underestimates the values of $v_7\{\Psi_{223}\}$ for centrality above 30%, as shown in Fig. 4. In Fig. 6, the same results are compared with the predictions from hydrodynamics + hadronic cas-

Fig. 4 Mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$, and $v_7\{\Psi_{223}\}$ from the scalar-product method at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, as a function of centrality. Statistical (bars) and systematic (shaded boxes) uncertainties are shown. Hydrodynamic predictions [1] with $\eta/s = 0.08$ (blue lines) at 2.76 TeV are shown in (b) and (e)

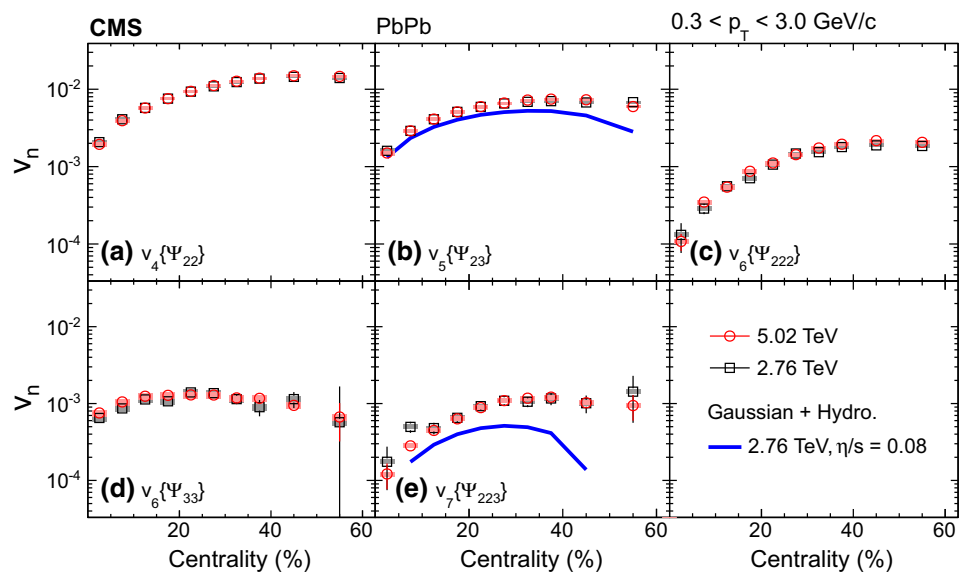
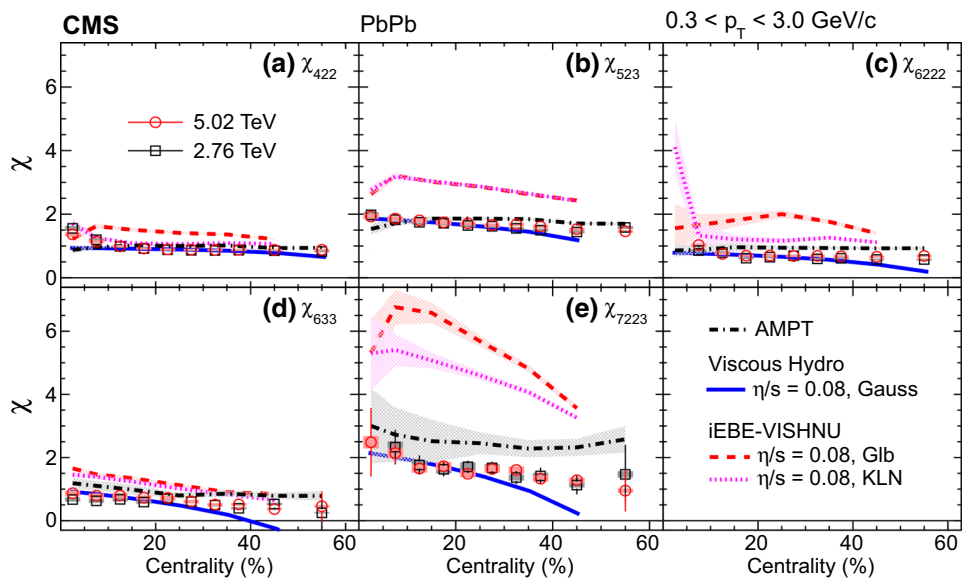


Fig. 5 Nonlinear response coefficients, χ_{422} , χ_{523} , χ_{6222} , χ_{633} , and χ_{7223} from the scalar-product method at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, as a function of centrality. Statistical (bars) and systematic (shaded boxes) uncertainties are shown. The results are compared with predictions at $\sqrt{s_{NN}} = 2.76$ TeV from AMPT [48] as well as hydrodynamics with a deformed symmetric Gaussian density profile as the initial conditions using $\eta/s = 0.08$ from Ref. [1], and from iEBE-VISHNU hydrodynamics with both Glauber and the KLN initial conditions using the same η/s [28]



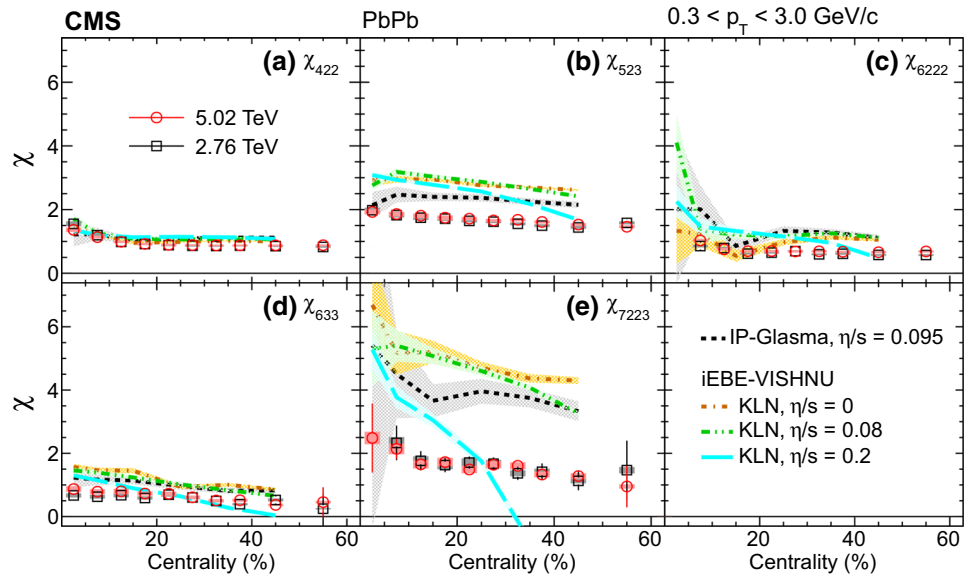
cade hybrid approach with the IP-Glasma initial conditions using $\eta/s = 0.095$ [50] at $\sqrt{s_{NN}} = 5.02$ TeV and from iEBE-VISHNU hydrodynamics with the KLN initial conditions using $\eta/s = 0, 0.08$ and 0.2 [28] at $\sqrt{s_{NN}} = 2.76$ TeV. All the calculations describe the χ_{422} well, but none of them are successful for χ_{523} and χ_{7223} . The model calculations of χ_{7223} are quite different for various initial conditions and η/s , which suggests that the first-time measurement of χ_{7223} presented in this paper could provide strong constraints on models.

7 Summary

The mixed higher-order flow harmonics and nonlinear response coefficients of charged particles have been stud-

ied as functions of transverse momentum p_T and centrality in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV using the CMS detector. The measurements use the scalar-product method, covering a p_T range from 0.3 to 8.0 GeV/c, pseudorapidity $|\eta| < 0.8$, and a centrality range of 0–60%. The mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$, and $v_7\{\Psi_{223}\}$ all have a qualitatively similar p_T dependence, first increasing at low p_T , reaching a maximum at about 3–4 GeV/c, and then decreasing at higher p_T . As a comparison, the overall v_n harmonics ($n = 4-7$) with respect to their own symmetry planes are measured in the same p_T , η , and centrality ranges. The relative contribution of the nonlinear part for v_5 is larger than for other harmonics in the centrality range 20–60%. In addition, the nonlinear response coefficients of the odd harmonics are observed to be

Fig. 6 The same results as in Fig. 5 but compared with predictions from a hydrodynamics + hadronic cascade hybrid approach with the IP-Glasma initial conditions using $\eta/s = 0.095$ [50] at $\sqrt{s_{NN}} = 5.02$ TeV and from iEBE-VISHNU hydrodynamics with the KLN initial conditions using $\eta/s = 0, 0.08$ (the same curve as in Fig. 5) and 0.2 [28] at $\sqrt{s_{NN}} = 2.76$ TeV



larger than those of even harmonics for p_T less than 3 GeV/c. At p_T less than 1 GeV/c, a viscous hydrodynamic calculation with Glauber initial conditions and shear viscosity to entropy density ratio $\eta/s = 0.08$ predicts a much stronger p_T dependence for the nonlinear response coefficients. The coefficients, including the first-time measurement of χ_{7223} , as a function of centrality, are compared with AMPT and hydrodynamic predictions using different η/s and initial conditions. Compared to the data, none of the models provides a simultaneous description of the mixed higher-order flow harmonics and nonlinear response coefficients. Therefore, these results can constrain both initial conditions and transport properties of the produced medium.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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



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



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










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


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















































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











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





















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






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



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












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





















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





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







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






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



















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
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


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











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










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



































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

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


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



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






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



































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


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- 4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- 5: Also at UFMS, Nova Andradina, Brazil
- 6: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 7: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 8: Also at University of Chinese Academy of Sciences, Beijing, China
- 9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
- 10: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 11: Also at Suez University, Suez, Egypt
- 12: Now at Zewail British University in Egypt, Cairo, Egypt
- 13: Also at Purdue University, West Lafayette, USA
- 14: Also at Université de Haute Alsace, Mulhouse, France
- 15: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 18: Also at University of Hamburg, Hamburg, Germany
- 19: Also at Brandenburg University of Technology, Cottbus, Germany
- 20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
- 21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

- 22: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
- 23: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
- 24: Also at Institute of Physics, Bhubaneswar, India
- 25: Also at Shoolini University, Solan, India
- 26: Also at University of Visva-Bharati, Santiniketan, India
- 27: Also at Isfahan University of Technology, Isfahan, Iran
- 28: Now at INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy
- 29: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 30: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 31: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 32: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
- 33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 36: Also at Institute for Nuclear Research, Moscow, Russia
- 37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 39: Also at University of Florida, Gainesville, USA
- 40: Also at Imperial College, London, UK
- 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 42: Also at INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy, Università di Trento^c, Trento, Italy, Padua, Italy
- 43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 45: Also at Università degli Studi di Siena, Siena, Italy
- 46: Also at INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy, Pavia, Italy
- 47: Also at National and Kapodistrian University of Athens, Athens, Greece
- 48: Also at Universität Zürich, Zurich, Switzerland
- 49: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
- 50: Also at Burdur Mehmet Akif Ersoy University, Burdur, Turkey
- 51: Also at Adiyaman University, Adiyaman, Turkey
- 52: Also at Şırnak University, Sırnak, Turkey
- 53: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
- 54: Also at Istanbul Aydin University, Istanbul, Turkey
- 55: Also at Mersin University, Mersin, Turkey
- 56: Also at Piri Reis University, Istanbul, Turkey
- 57: Also at Gaziosmanpasa University, Tokat, Turkey
- 58: Also at Ozyegin University, Istanbul, Turkey
- 59: Also at Izmir Institute of Technology, Izmir, Turkey
- 60: Also at Marmara University, Istanbul, Turkey
- 61: Also at Kafkas University, Kars, Turkey
- 62: Also at Istanbul Bilgi University, Istanbul, Turkey
- 63: Also at Hacettepe University, Ankara, Turkey
- 64: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 65: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
- 66: Also at IPPP Durham University, Durham, UK
- 67: Also at Monash University, Faculty of Science, Clayton, Australia
- 68: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
- 69: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 70: Also at Vilnius University, Vilnius, Lithuania
- 71: Also at Bingol University, Bingol, Turkey
- 72: Also at Georgian Technical University, Tbilisi, Georgia
- 73: Also at Sinop University, Sinop, Turkey

74: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

75: Also at Texas A&M University at Qatar, Doha, Qatar

76: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea

77: Also at University of Hyderabad, Hyderabad, India