EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-211
2020/07/03

CMS-HIN-17-005

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

The CMS Collaboration*

arXiv:1910.08789v2 [hep-ex] 2 Jul 2020

## 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 $\sqrt{s_{\mathrm{NN}}} = 2.76$ 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.

*"Published in the European Physical Journal C as doi:10.1140/epjc/s10052-020-7834-9."*

© 2020 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license

*See Appendix A for the list of collaboration members

# 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],

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

where $V_n = v_n \exp(in\Psi_n)$ is the $n$-th complex anisotropic flow coefficient [2]. The $v_n$ and $\Psi_n$ 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 ($p_{\mathrm{T}}$) and pseudorapidity ($\eta$) 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 $\epsilon_n$ [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, $\epsilon_2$ and $\epsilon_3$, 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]:

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

where $V_{nL}$ denotes the part of $V_n$ that is not induced by lower-order harmonics [29–31], and the $\chi$ 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) 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 Section 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 $\Psi_n$, 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 $\Psi_2$, 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 $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV, as functions of collision centrality and charged particle $p_{\mathrm{T}}$ 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 $0.175 \times 0.175$ ($\Delta\eta \times \Delta\phi$) "towers", where the angle $\phi$ 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 $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}/c$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in $p_{\mathrm{T}}$ and 25–90 (45–150) $\mu$m 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 2.76 TeV in 2015 and 2011, corresponding to integrated luminosities of 13 $\mu\mathrm{b}^{-1}$

and 3.9 $\mu b^{-1}$, 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, $\chi^2/\text{dof}$, 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 $\chi^2/\text{dof}$ 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

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

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

where $M$ represents the number of tracks or HF towers used for calculating the $Q$ vector, $\phi_j$ 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, $w_j = 1/\varepsilon_j$ is the inverse of the tracking efficiency $\varepsilon_j(p_\mathrm{T}, \eta)$ 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 $p_\mathrm{T}$ 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.

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

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

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

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

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

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 $p_\mathrm{T}$ 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 $\eta$ gap between tracks used to find the charged-particle $Q$ vector and towers used for the HF $Q$ vectors is 2.2 units of $\eta$.

With the assumption that the linear and nonlinear terms in Eq. (2) are uncorrelated, the nonlinear response coefficients in each $p_\mathrm{T}$ range can be expressed as [1, 28],

$$\chi_{422} = \frac{\mathrm{Re}\langle Q_4 Q_{2A}^* Q_{2B}^*\rangle}{\mathrm{Re}\langle Q_2 Q_2 Q_{2A}^* Q_{2B}^*\rangle}, \tag{10}$$

$$\chi_{523} = \frac{\mathrm{Re}\langle Q_5 Q_{2A}^* Q_{3B}^*\rangle}{\mathrm{Re}\langle Q_2 Q_3 Q_{2A}^* Q_{3B}^*\rangle}, \tag{11}$$

$$\chi_{6222} = \frac{\mathrm{Re}\langle Q_6 Q_{2A}^* Q_{2B}^* Q_{2B}^* \rangle}{\mathrm{Re}\langle Q_2 Q_2 Q_2 Q_{2A}^* Q_{2B}^* Q_{2B}^* \rangle}, \tag{12}$$

$$\chi_{633} = \frac{\mathrm{Re}\langle Q_6 Q_{3A}^* Q_{3B}^* \rangle}{\mathrm{Re}\langle Q_3 Q_3 Q_{3A}^* Q_{3B}^* \rangle}, \tag{13}$$

$$\chi_{7223} = \frac{\mathrm{Re}\langle Q_7 Q_{2A}^* Q_{2B}^* Q_{3B}^* \rangle}{\mathrm{Re}\langle Q_2 Q_2 Q_3 Q_{2A}^* Q_{2B}^* Q_{3B}^* \rangle}, \tag{14}$$

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 $|v_z| < 3\,\mathrm{cm}$ to $3 < |v_z| < 15\,\mathrm{cm}$. For both mixed harmonic and nonlinear response coefficients, this uncertainty is estimated to be 1–3%, with no dependence on $p_\mathrm{T}$ 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 $\chi^2/\mathrm{dof}$ value from 7 to 18 times the number of layers with hits. The uncertainty is estimated to be 1–4% depending on $p_\mathrm{T}$ 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 $p_\mathrm{T}$ 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 $\eta$ gap between the correlated charged particles and the $Q$ vectors in the HF region is changed from 2.2 to 3.2 units of $\eta$ (achieved by changing the $\eta$ 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 $p_\mathrm{T}$ and centrality. This $\eta$ gap uncertainty also includes a possible physics effect from the $\eta$-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 $p_\mathrm{T}$ and decreases to around 5% for $p_\mathrm{T}$ larger than $1\,\mathrm{GeV}/c$. 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

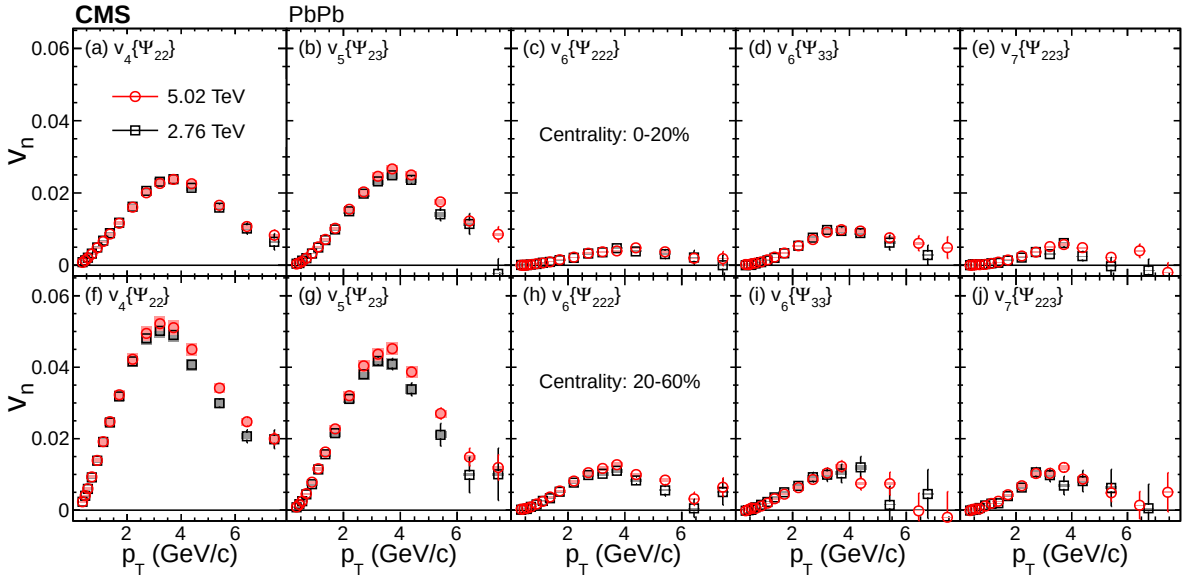


Figure 1: Mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$, and $v_7\{\Psi_{223}\}$ from the scalar-product method at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV as a function of $p_{\mathrm{T}}$ in the 0–20% (upper row) and 20–60% (lower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

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 $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV as a function of $p_{\mathrm{T}}$ in the 0–20% (upper row) and 20–60% (lower row) centrality ranges.

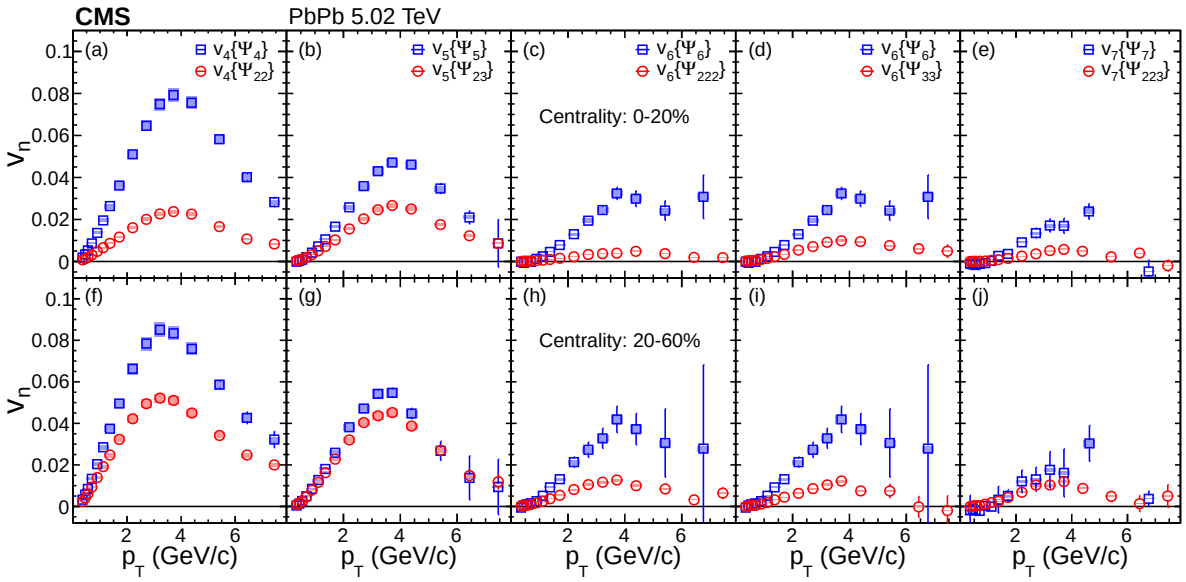


Figure 2: Comparison of mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$ and $v_7\{\Psi_{223}\}$ with the corresponding overall flow, $v_4\{\Psi_4\}$, $v_5\{\Psi_5\}$, $v_6\{\Psi_6\}$, $v_6\{\Psi_6\}$ and $v_7\{\Psi_7\}$, respectively,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

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 $\Psi_n$ [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.

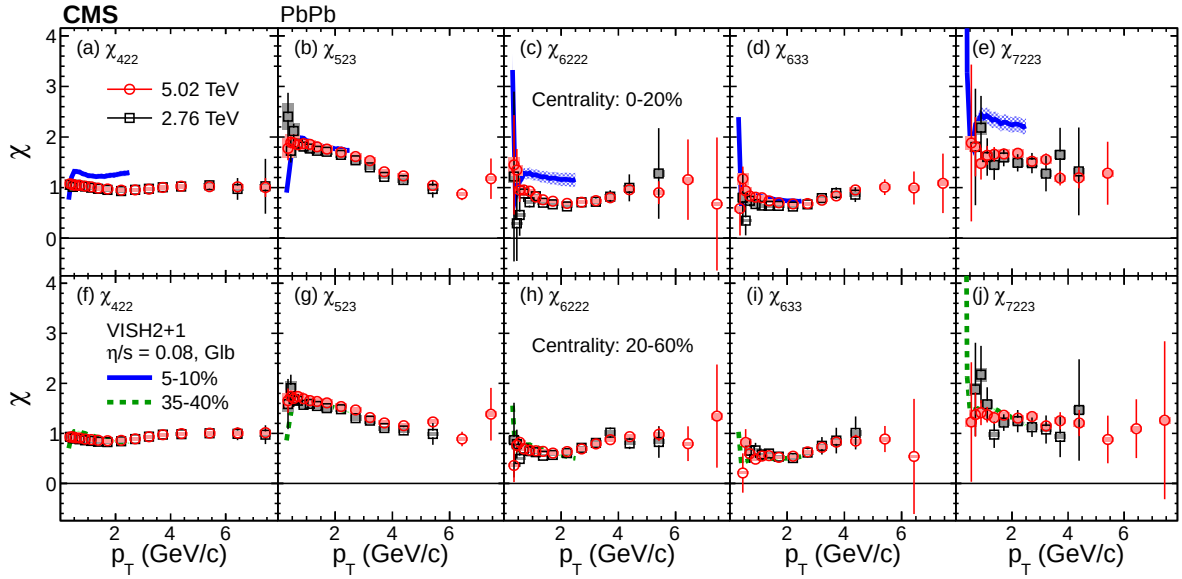


Figure 3: Nonlinear response coefficients, $\chi_{422}$, $\chi_{523}$, $\chi_{6222}$, $\chi_{633}$, and $\chi_{7223}$ from the scalar-product method at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV as a function of $p_T$ in the 0–20% (upper row) and 20–60% (lower row) centrality ranges. Statistical (bars) and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

A direct comparison of the mixed higher-order flow harmonics and overall flow at 5.02 TeV is presented in Fig. 2 as 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 contribution 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 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, $\chi_{422}$, $\chi_{523}$, $\chi_{6222}$, $\chi_{633}$, and $\chi_{7223}$ are presented in Fig. 3 as a function of $p_T$ in the two centrality ranges. It is observed that the odd harmonic coefficients $\chi_{523}$ and $\chi_{7223}$ 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 $\eta/s$ is the shear viscosity to entropy

density ratio of the hydrodynamic medium, and here $\eta$ 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 $p_{\mathrm{T}}$ 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 $p_{\mathrm{T}}$ dependence than the data. The strong $p_{\mathrm{T}}$ dependence, attributed to the large variance of the flow angles $\Psi_n$ at small $p_{\mathrm{T}}$ [30], is not observed in data for $n = 4$ and 5.

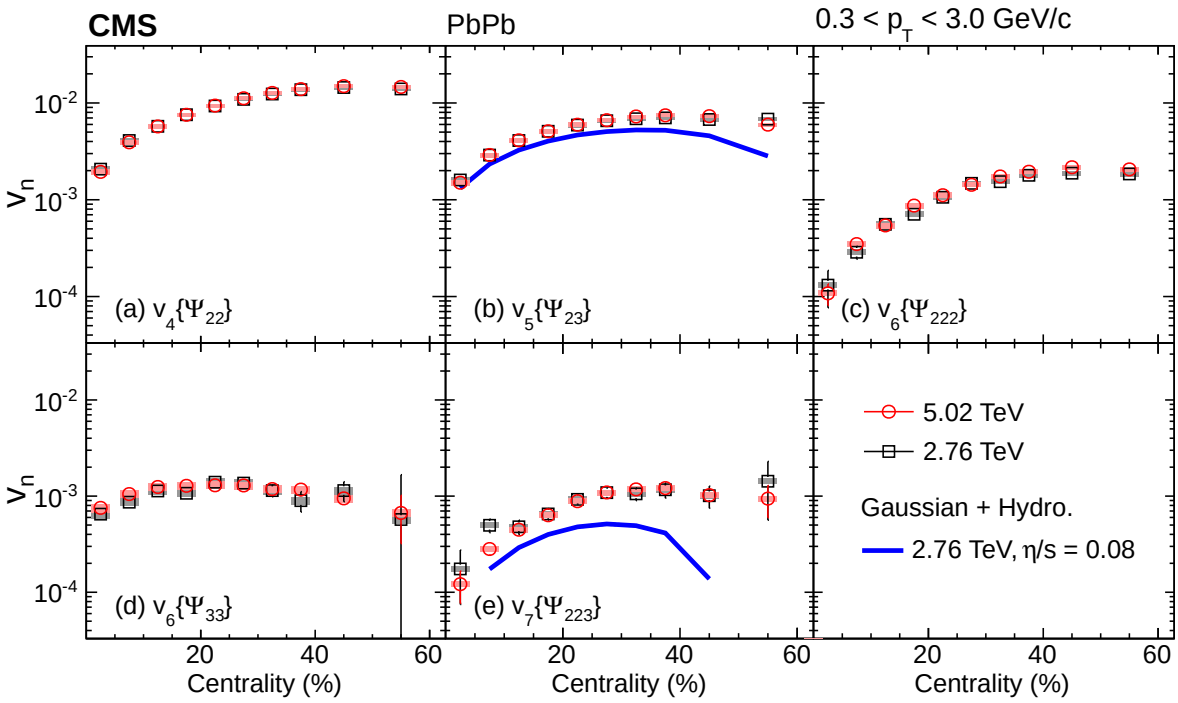


Figure 4: Mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$, and $v_7\{\Psi_{223}\}$ from the scalar-product method at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV, as a function of centrality. Statistical (bars) and systematic (shaded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

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 $p_{\mathrm{T}}$ 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 $\sqrt{s_{\mathrm{NN}}} = 2.76$ 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, $\chi_{422}$, $\chi_{523}$, $\chi_{6222}$, $\chi_{633}$, and $\chi_{7223}$ are presented in Figs. 5 and 6, as a function of centrality in the $p_{\mathrm{T}}$ range from 0.3 to 3.0 GeV/$c$. The results are compared with predictions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ 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 $\eta/s$ [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 cascade hy-

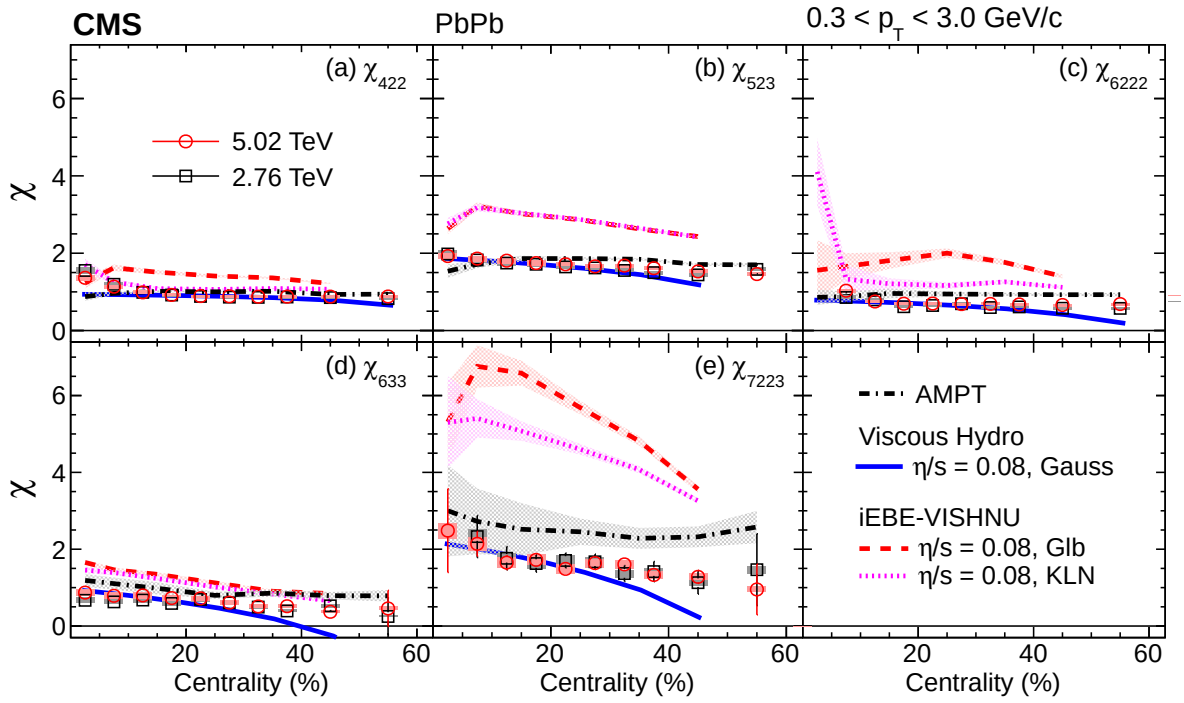


Figure 5: Nonlinear response coefficients, $\chi_{422}$, $\chi_{523}$, $\chi_{6222}$, $\chi_{633}$, and $\chi_{7223}$ from the scalar-product method at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV, as a function of centrality. Statistical (bars) and systematic (shaded boxes) uncertainties are shown. The results are compared with predictions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ 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 $\eta/s$ [28].

brid approach with the IP-Glasma initial conditions using $\eta/s = 0.095$ [50] at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and from iEBE-VISHNU hydrodynamics with the KLN initial conditions using $\eta/s = 0$, 0.08 and 0.2 [28] at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. All the calculations describe the $\chi_{422}$ well, but none of them are successful for $\chi_{523}$ and $\chi_{7223}$. The model calculations of $\chi_{7223}$ are quite different for various initial conditions and $\eta/s$, which suggests that the first-time measurement of $\chi_{7223}$ 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 studied as functions of transverse momentum $p_{\mathrm{T}}$ and centrality in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV using the CMS detector. The measurements use the scalar-product method, covering a $p_{\mathrm{T}}$ 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 $p_{\mathrm{T}}$ dependence, first increasing at low $p_{\mathrm{T}}$, reaching a maximum at about 3–4 GeV/$c$, and then decreasing at higher $p_{\mathrm{T}}$. As a comparison, the overall $v_n$ harmonics ($n$ = 4–7) with respect to their own symmetry planes are measured in the same $p_{\mathrm{T}}$, $\eta$, 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 larger than those of even harmonics for $p_{\mathrm{T}}$ less than 3 GeV/$c$. At $p_{\mathrm{T}}$ less than 1 GeV/$c$, a viscous hydrodynamic calculation

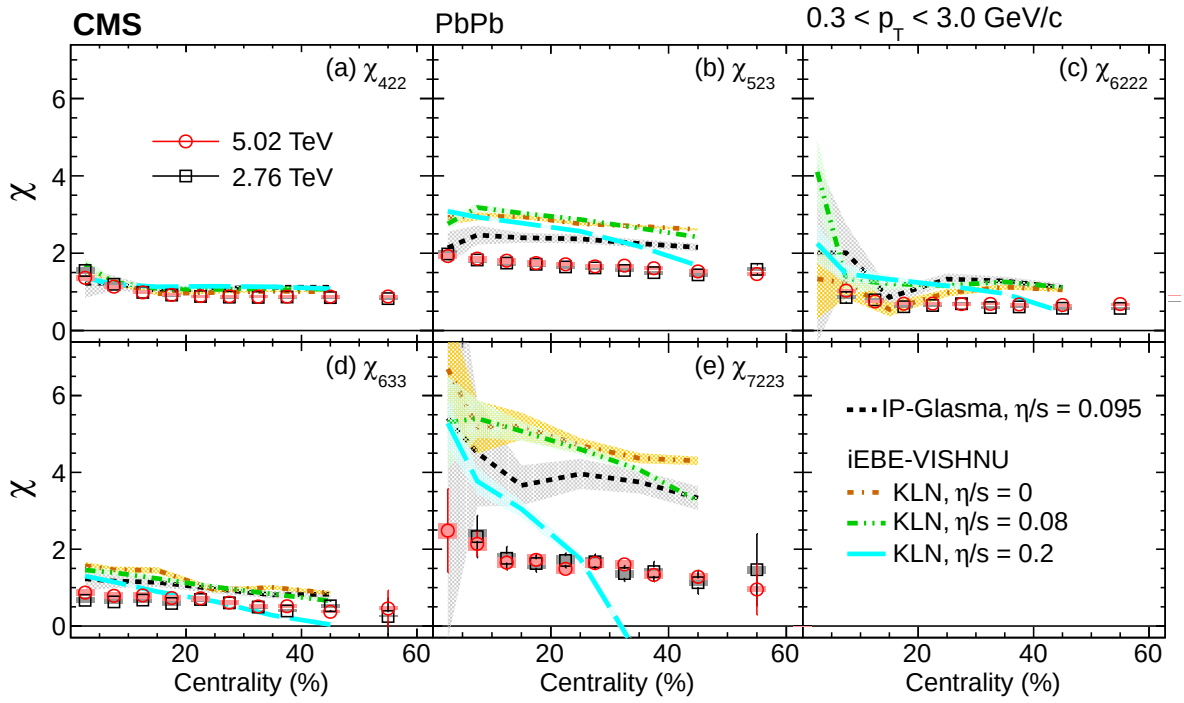


Figure 6: The same results as in Fig. 5 but compared with predictions from a hydrodynamics + hadronic cascade hybrid approach with the IP-Glasma initial conditions using $\eta/s = 0.095$ [50] at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ and from iEBE-VISHNU hydrodynamics with the KLN initial conditions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

with Glauber initial conditions and shear viscosity to entropy density ratio $\eta/s = 0.08$ predicts a much stronger $p_{\mathrm{T}}$ dependence for the nonlinear response coefficients. The coefficients, including the first-time measurement of $\chi_{7223}$, as a function of centrality, are compared with AMPT and hydrodynamic predictions using different $\eta/s$ 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.

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Mon-

tenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z181100004218003; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, grant no. 3.2989.2017 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Nvidia Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

## References

[1] L. Yan and J.-Y. Ollitrault, "$\nu_4, \nu_5, \nu_6, \nu_7$: nonlinear hydrodynamic response versus LHC data", *Phys. Lett. B* **744** (2015) 82, doi:10.1016/j.physletb.2015.03.040, arXiv:1502.02502.

[2] S. Voloshin and Y. Zhang, "Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions", *Z. Phys. C* **70** (1996) 665, doi:10.1007/s002880050141, arXiv:hep-ph/9407282.

[3] PHENIX Collaboration, "Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration", *Nucl. Phys. A* **757** (2005) 184, doi:10.1016/j.nuclphysa.2005.03.086, arXiv:nucl-ex/0410003.

[4] STAR Collaboration, "Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR collaboration's critical assessment of the evidence from RHIC collisions", *Nucl. Phys. A* **757** (2005) 102, doi:10.1016/j.nuclphysa.2005.03.085, arXiv:nucl-ex/0501009.

[5] PHOBOS Collaboration, "The PHOBOS perspective on discoveries at RHIC", *Nucl. Phys. A* **757** (2005) 28, doi:10.1016/j.nuclphysa.2005.03.084, arXiv:nucl-ex/0410022.

[6] BRAHMS Collaboration, "Quark gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment", *Nucl. Phys. A* **757** (2005) 1, doi:10.1016/j.nuclphysa.2005.02.130, arXiv:nucl-ex/0410020.

[7] CMS Collaboration, "Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$", *Phys. Rev. C* **87** (2013) 014902, doi:10.1103/PhysRevC.87.014902, arXiv:1204.1409.

[8] ALICE Collaboration, "Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV", *Phys. Rev. Lett.* **105** (2010) 252302, doi:10.1103/PhysRevLett.105.252302, arXiv:1011.3914.

[9] ATLAS Collaboration, "Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ with the ATLAS detector", *Phys. Lett. B* **707** (2012) 330, doi:10.1016/j.physletb.2011.12.056, arXiv:1108.6018.

[10] B. Alver and G. Roland, "Collision geometry fluctuations and triangular flow in heavy-ion collisions", *Phys. Rev. C* **81** (2010) 054905, doi:10.1103/PhysRevC.81.054905, arXiv:1003.0194. [Erratum: doi:10.1103/PhysRevC.82.039903].

[11] CMS Collaboration, "Measurement of higher-order harmonic azimuthal anisotropy in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$", *Phys. Rev. C* **89** (2014) 044906, doi:10.1103/PhysRevC.89.044906, arXiv:1310.8651.

[12] ALICE Collaboration, "Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$", *Phys. Rev. Lett.* **107** (2011) 032301, doi:10.1103/PhysRevLett.107.032301, arXiv:1105.3865.

[13] B. Alver et al., "Importance of correlations and fluctuations on the initial source eccentricity in high-energy nucleus-nucleus collisions", *Phys. Rev. C* **77** (2008) 014906, doi:10.1103/PhysRevC.77.014906, arXiv:0711.3724.

[14] STAR Collaboration, "Elliptic flow fluctuations in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *J. Phys. G* **35** (2008) 104102, doi:10.1088/0954-3899/35/10/104102, arXiv:0808.0356.

[15] PHOBOS Collaboration, "Non-flow correlations and elliptic flow fluctuations in gold-gold collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *Phys. Rev. C* **81** (2010) 034915, doi:10.1103/PhysRevC.81.034915, arXiv:1002.0534.

[16] J.-Y. Ollitrault, A. M. Poskanzer, and S. A. Voloshin, "Effect of flow fluctuations and nonflow on elliptic flow methods", *Phys. Rev. C* **80** (2009) 014904, doi:10.1103/PhysRevC.80.014904, arXiv:0904.2315.

[17] Z. Qiu and U. W. Heinz, "Event-by-event shape and flow fluctuations of relativistic heavy-ion collision fireballs", *Phys. Rev. C* **84** (2011) 024911, doi:10.1103/PhysRevC.84.024911, arXiv:1104.0650.

[18] PHENIX Collaboration, "Measurements of higher-order flow harmonics in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200\,\text{GeV}$", *Phys. Rev. Lett.* **107** (2011) 252301, doi:10.1103/PhysRevLett.107.252301, arXiv:1105.3928.

[19] H. Niemi, G. S. Denicol, H. Holopainen, and P. Huovinen, "Event-by-event distributions of azimuthal asymmetries in ultrarelativistic heavy-ion collisions", *Phys. Rev. C* **87** (2013) 054901, doi:10.1103/PhysRevC.87.054901, arXiv:1212.1008.

[20] ATLAS Collaboration, "Measurement of event-plane correlations in $\sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$ lead-lead collisions with the ATLAS detector", *Phys. Rev. C* **90** (2014) 024905, doi:10.1103/PhysRevC.90.024905, arXiv:1403.0489.

[21] ATLAS Collaboration, "Measurement of the correlation between flow harmonics of different order in lead-lead collisions at $\sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$ with the ATLAS detector", *Phys. Rev. C* **92** (2015) 034903, doi:10.1103/PhysRevC.92.034903, arXiv:1504.01289.

[22] ALICE Collaboration, "Correlated event-by-event fluctuations of flow harmonics in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$", *Phys. Rev. Lett.* **117** (2016) 182301, doi:10.1103/PhysRevLett.117.182301, arXiv:1604.07663.

[23] CMS Collaboration, "Observation of correlated azimuthal anisotropy Fourier harmonics in pp and p+Pb collisions at the LHC", *Phys. Rev. Lett.* **120** (2018) 092301, doi:10.1103/PhysRevLett.120.092301, arXiv:1709.09189.

[24] STAR Collaboration, "Correlation measurements between flow harmonics in Au+Au collisions at RHIC", *Phys. Lett. B* **783** (2018) 459, doi:10.1016/j.physletb.2018.05.076, arXiv:1803.03876.

[25] U. Heinz, Z. Qiu, and C. Shen, "Fluctuating flow angles and anisotropic flow measurements", *Phys. Rev. C* **87** (2013) 034913, doi:10.1103/PhysRevC.87.034913, arXiv:1302.3535.

[26] CMS Collaboration, "Evidence for transverse momentum and pseudorapidity dependent event plane fluctuations in PbPb and pPb collisions", *Phys. Rev. C* **92** (2015) 034911, doi:10.1103/PhysRevC.92.034911, arXiv:1503.01692.

[27] W. Busza, K. Rajagopal, and W. van der Schee, "Heavy ion collisions: The big picture, and the big questions", *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 339, doi:10.1146/annurev-nucl-101917-020852, arXiv:1802.04801.

[28] J. Qian, U. W. Heinz, and J. Liu, "Mode-coupling effects in anisotropic flow in heavy-ion collisions", *Phys. Rev. C* **93** (2016) 064901, doi:10.1103/PhysRevC.93.064901, arXiv:1602.02813.

[29] D. Teaney and L. Yan, "Non linearities in the harmonic spectrum of heavy ion collisions with ideal and viscous hydrodynamics", *Phys. Rev. C* **86** (2012) 044908, doi:10.1103/PhysRevC.86.044908, arXiv:1206.1905.

[30] J. Qian, U. Heinz, R. He, and L. Huo, "Differential flow correlations in relativistic heavy-ion collisions", *Phys. Rev. C* **95** (2017) 054908, doi:10.1103/PhysRevC.95.054908, arXiv:1703.04077.

[31] G. Giacalone, L. Yan, and J.-Y. Ollitrault, "Nonlinear coupling of flow harmonics: Hexagonal flow and beyond", *Phys. Rev. C* **97** (2018) 054905, doi:10.1103/PhysRevC.97.054905, arXiv:1803.00253.

[32] W. Zhao, H.-j. Xu, and H. Song, "Collective flow in 2.76 A TeV and 5.02 A TeV Pb+Pb collisions", *Eur. Phys. J. C* **77** (2017) 645, doi:10.1140/epjc/s10052-017-5186-x, arXiv:1703.10792.

[33] STAR Collaboration, "Azimuthal anisotropy at RHIC: The first and fourth harmonics", *Phys. Rev. Lett.* **92** (2004) 062301, doi:10.1103/PhysRevLett.92.062301, arXiv:nucl-ex/0310029.

[34] A. M. Poskanzer and S. A. Voloshin, "Methods for analyzing anisotropic flow in relativistic nuclear collisions", *Phys. Rev. C* **58** (1998) 1671, doi:10.1103/PhysRevC.58.1671, arXiv:nucl-ex/9805001.

[35] M. Luzum and J.-Y. Ollitrault, "Eliminating experimental bias in anisotropic-flow measurements of high-energy nuclear collisions", *Phys. Rev. C* **87** (2013) 044907, doi:10.1103/PhysRevC.87.044907, arXiv:1209.2323.

[36] STAR Collaboration, "Elliptic flow from two and four particle correlations in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 130\,\mathrm{GeV}$", *Phys. Rev. C* **66** (2002) 034904, doi:10.1103/PhysRevC.66.034904, arXiv:nucl-ex/0206001.

[37] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[38] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[39] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[40] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[41] CMS Collaboration, "Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *JHEP* **04** (2017) 039, doi:10.1007/JHEP04(2017)039, arXiv:1611.01664.

[42] I. P. Lokhtin and A. M. Snigirev, "A model of jet quenching in ultrarelativistic heavy ion collisions and high-$p_{\mathrm{T}}$ hadron spectra at RHIC", *Eur. Phys. J. C* **45** (2006) 211, doi:10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.

[43] T. Pierog et al., "EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider", *Phys. Rev. C* **92** (2015) 034906, doi:10.1103/PhysRevC.92.034906, arXiv:1306.0121.

[44] L.-G. Pang et al., "Longitudinal decorrelation of anisotropic flows in heavy-ion collisions at the CERN Large Hadron Collider", *Phys. Rev. C* **91** (2015) 044904, doi:10.1103/PhysRevC.91.044904, arXiv:1410.8690.

[45] ALICE Collaboration, "Linear and non-linear flow modes in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV", *Phys. Lett. B* **773** (2017) 68, doi:10.1016/j.physletb.2017.07.060, arXiv:1705.04377.

[46] A. Bilandzic et al., "Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations", *Phys. Rev. C* **89** (2014) 064904, doi:10.1103/PhysRevC.89.064904, arXiv:1312.3572.

[47] F. G. Gardim, F. Grassi, M. Luzum, and J.-Y. Ollitrault, "Mapping the hydrodynamic response to the initial geometry in heavy-ion collisions", *Phys. Rev. C* **85** (2012) 024908, doi:10.1103/PhysRevC.85.024908, arXiv:1111.6538.

[48] L. Yan, S. Pal, and J.-Y. Ollitrault, "Nonlinear hydrodynamic response confronts LHC data", *Nucl. Phys. A* **956** (2016) 340, doi:10.1016/j.nuclphysa.2016.01.010, arXiv:1601.00040.

[49] Z.-W. Lin et al., "A multi-phase transport model for relativistic heavy ion collisions", *Phys. Rev. C* **72** (2005) 064901, doi:10.1103/PhysRevC.72.064901, arXiv:nucl-th/0411110.

[50] S. McDonald et al., "Hydrodynamic predictions for Pb+Pb collisions at 5.02 TeV", *Phys. Rev. C* **95** (2017) 064913, doi:10.1103/PhysRevC.95.064913, arXiv:1609.02958.

# A The CMS Collaboration

**Yerevan Physics Institute, Yerevan, Armenia**
A.M. Sirunyan[†], A. Tumasyan

**Institut für Hochenergiephysik, Wien, Austria**
W. Adam, F. Ambrogi, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, C.-E. Wulz[1], M. Zarucki

**Institute for Nuclear Problems, Minsk, Belarus**
V. Drugakov, V. Mossolov, J. Suarez Gonzalez

**Universiteit Antwerpen, Antwerpen, Belgium**
M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

**Vrije Universiteit Brussel, Brussel, Belgium**
F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

**Université Libre de Bruxelles, Bruxelles, Belgium**
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

**Ghent University, Ghent, Belgium**
T. Cornelis, D. Dobur, I. Khvastunov[2], M. Niedziela, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

**Université Catholique de Louvain, Louvain-la-Neuve, Belgium**
O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, A. Magitteri, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

**Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil**
F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

**Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil**
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, J. Martins[5], D. Matos Figueiredo, M. Medina Jaime[6], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

**Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil**
C.A. Bernardes[a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], D.S. Lemos, P.G. Mercadante[b], S.F. Novaes[a], SandraS. Padula[a]

**Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria**
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

**University of Sofia, Sofia, Bulgaria**
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

**Beihang University, Beijing, China**
W. Fang[7], X. Gao[7], L. Yuan

**Institute of High Energy Physics, Beijing, China**
M. Ahmad, G.M. Chen, H.S. Chen, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen[8], A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[8], J. Zhao

**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**
A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

**Tsinghua University, Beijing, China**
Z. Hu, Y. Wang

**Universidad de Los Andes, Bogota, Colombia**
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

**Universidad de Antioquia, Medellin, Colombia**
J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

**University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**
D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

**University of Split, Faculty of Science, Split, Croatia**
Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**
V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov[9], T. Susa

**University of Cyprus, Nicosia, Cyprus**
M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

**Charles University, Prague, Czech Republic**
M. Finger[10], M. Finger Jr.[10], A. Kveton, J. Tomsa

**Escuela Politecnica Nacional, Quito, Ecuador**
E. Ayala

**Universidad San Francisco de Quito, Quito, Ecuador**
E. Carrera Jarrin

**Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**
Y. Assran[11,12], S. Elgammal[12]

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**
F. Garcia, J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

**Lappeenranta University of Technology, Lappeenranta, Finland**
T. Tuuva

**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[13], M. Titov

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris**
S. Ahuja, C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**
J.-L. Agram[14], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte[14], J.-C. Fontaine[14], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**
S. Gadrat

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France**
S. Beauceron, C. Bernet, G. Boudoul, C. Camen, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, F. Lagarde, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

**Georgian Technical University, Tbilisi, Georgia**
A. Khvedelidze[10]

**Tbilisi State University, Tbilisi, Georgia**
Z. Tsamalaidze[10]

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**
A. Albert, M. Erdmann, S. Erdweg, T. Esch, B. Fischer, R. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, M. Rieger, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Thüer, S. Wiedenbeck, S. Zaleski

**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**
G. Flügge, W. Haj Ahmad[15], O. Hlushchenko, T. Kress, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[16]

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**
M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras[17], V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[18], A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem[17], M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, J. Lidrych, K. Lipka, W. Lohmann[19], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

**University of Hamburg, Hamburg, Germany**
R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaup, C.E.N. Niemeyer, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**
M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, A. Gottmann, M.A. Harrendorf, F. Hartmann[16], U. Husemann, S. Kudella, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf

**Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece**
G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

**National and Kapodistrian University of Athens, Athens, Greece**
M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis, E. Vourliotis

**National Technical University of Athens, Athens, Greece**
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

**University of Ioánnina, Ioánnina, Greece**
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**
M. Bartók[20], R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

**Wigner Research Centre for Physics, Budapest, Hungary**
G. Bencze, C. Hajdu, D. Horvath[21], F. Sikler, T.. Vámi, V. Veszpremi, G. Vesztergombi†

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**
N. Beni, S. Czellar, J. Karancsi[20], A. Makovec, J. Molnar, Z. Szillasi

**Institute of Physics, University of Debrecen, Debrecen, Hungary**
P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

**Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary**
T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

**Indian Institute of Science (IISc), Bangalore, India**
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

**National Institute of Science Education and Research, HBNI, Bhubaneswar, India**
S. Bahinipati[23], C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak[24], D.K. Sahoo[23], S.K. Swain

**Panjab University, Chandigarh, India**
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

**University of Delhi, Delhi, India**
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**
R. Bhardwaj[25], M. Bharti[25], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[25], D. Bhowmik, S. Dey, S. Dutta, S. Ghosh, M. Maity[26], K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, T. Sarkar[26], M. Sharan, B. Singh[25], S. Thakur[25]

**Indian Institute of Technology Madras, Madras, India**
P.K. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

**Bhabha Atomic Research Centre, Mumbai, India**
D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

**Tata Institute of Fundamental Research-A, Mumbai, India**
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

**Tata Institute of Fundamental Research-B, Mumbai, India**
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

**Indian Institute of Science Education and Research (IISER), Pune, India**
S. Chauhan, S. Dube, V. Hegde, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**
S. Chenarani[27], E. Eskandari Tadavani, S.M. Etesami[27], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

**University College Dublin, Dublin, Ireland**
M. Felcini, M. Grunewald

**INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy**
M. Abbrescia[a,b], R. Aly[a,b,28], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c],

M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], R. Venditti[a], P. Verwilligen[a]

**INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy**
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,29], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

**INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy**
S. Albergo[a,b,30], S. Costa[a,b], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,30], C. Tuve[a,b]

**INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy**
G. Barbagli[a], R. Ceccarelli, K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], D. Strom[a], L. Viliani[a]

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**
L. Benussi, S. Bianco, D. Piccolo

**INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy**
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

**INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy**
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], V. Ciriolo[a,b,16], S. Di Guida[a,b,16], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], G. Ortona[a,b], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

**INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy**
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A.O.M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,16], P. Paolucci[a,16], B. Rossi[a], C. Sciacca[a,b], E. Voevodina[a,b]

**INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy**
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S.Y. Hoh[a,b], P. Lujan[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko[a], M. Tosi[a,b], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

**INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy**
A. Braghieri[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

**INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy**
M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

**INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy**
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a],

R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[31], S. Roy Chowdhury, A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini, A. Venturi[a], P.G. Verdini[a]

**INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy**
F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], E. Longo[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a,b]

**INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy**
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], R. Salvatico[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a]

**INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy**
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], F. Vazzoler[a,b], A. Zanetti[a]

**Kyungpook National University, Daegu, Korea**
B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea**
H. Kim, D.H. Moon, G. Oh

**Hanyang University, Seoul, Korea**
B. Francois, T.J. Kim, J. Park

**Korea University, Seoul, Korea**
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh, J. Yoo

**Kyung Hee University, Department of Physics**
J. Goh

**Sejong University, Seoul, Korea**
H.S. Kim

**Seoul National University, Seoul, Korea**
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon, G.B. Yu

**University of Seoul, Seoul, Korea**
D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, I. Watson

**Sungkyunkwan University, Suwon, Korea**
Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

**Riga Technical University, Riga, Latvia**
V. Veckalns[32]

**Vilnius University, Vilnius, Lithuania**
V. Dudenas, A. Juodagalvis, G. Tamulaitis, J. Vaitkus

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**
Z.A. Ibrahim, F. Mohamad Idris[33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

**Universidad de Sonora (UNISON), Hermosillo, Mexico**
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[34], R. Lopez-Fernandez, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

**Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico**
A. Morelos Pineda

**University of Montenegro, Podgorica, Montenegro**
N. Raicevic

**University of Auckland, Auckland, New Zealand**
D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**
S. Bheesette, P.H. Butler

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

**AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**
V. Avati, L. Grzanka, M. Malawski

**National Centre for Nuclear Research, Swierk, Poland**
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**
K. Bunkowski, A. Byszuk[35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**
M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev[36,37], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**
L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim[38], E. Kuznetsova[39], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

**Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia**
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[40], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

**Moscow Institute of Physics and Technology, Moscow, Russia**
T. Aushev

**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**
O. Bychkova, R. Chistov[41], M. Danilov[41], S. Polikarpov[41], E. Tarkovskii

**P.N. Lebedev Physical Institute, Moscow, Russia**
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**
A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy[42], O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

**Novosibirsk State University (NSU), Novosibirsk, Russia**
A. Barnyakov[43], V. Blinov[43], T. Dimova[43], L. Kardapoltsev[43], Y. Skovpen[43]

**Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia**
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**National Research Tomsk Polytechnic University, Tomsk, Russia**
A. Babaev, A. Iuzhakov, V. Okhotnikov

**Tomsk State University, Tomsk, Russia**
V. Borchsh, V. Ivanchenko, E. Tcherniaev

**University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences**
P. Adzic[44], P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**
M. Aguilar-Benitez, J. Alcaraz Maestre, A. lvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, . Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

**Universidad Autónoma de Madrid, Madrid, Spain**
C. Albajar, J.F. de Trocóniz

**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Russo[45], L. Scodellaro, N. Trevisani, I. Vila, J.M. Vizan Garcia

**University of Colombo, Colombo, Sri Lanka**
K. Malagalage

**University of Ruhuna, Department of Physics, Matara, Sri Lanka**
W.G.D. Dharmaratna, N. Wickramage

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**
D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, C. Botta, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, N. Deelen, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[46], D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, P. Janot, O. Karacheban[19], J. Kaspar, J. Kieseler, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[16], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[47], J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, A. Vartak, M. Verzetti, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**
L. Caminada[48], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

**ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**
M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

**Universität Zürich, Zurich, Switzerland**
T.K. Aarrestad, C. Amsler[49], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

**National Central University, Chung-Li, Taiwan**
T.H. Doan, C.M. Kuo, W. Lin, A. Roy, S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

**Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand**
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

**ukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**
A. Bat, F. Boran, A. Celik[50], S. Cerci[51], S. Damarseckin[52], Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, EmineGurpinar Guler[53], Y. Guler, I. Hos[54], C. Isik, E.E. Kangal[55], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[56], S. Ozturk[57], A.E. Simsek, D. Sunar Cerci[51], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**
B. Isildak[58], G. Karapinar[59], M. Yalvac

**Bogazici University, Istanbul, Turkey**
I.O. Atakisi, E. Gülmez, M. Kaya[60], O. Kaya[61], B. Kaynak, Ö. Özçelik, S. Tekten, E.A. Yetkin[62]

**Istanbul Technical University, Istanbul, Turkey**
A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[63]

**Istanbul University, Istanbul, Turkey**
S. Ozkorucuklu

**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine**
B. Grynyov

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**
L. Levchuk

**University of Bristol, Bristol, United Kingdom**
F. Ball, E. Bhal, S. Bologna, J.J. Brooke, D. Burns[64], E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, S. Paramesvaran, B. Penning, T. Sakuma, S. Seif El Nasr-Storey, D. Smith[64], V.J. Smith, J. Taylor, A. Titterton

**Rutherford Appleton Laboratory, Didcot, United Kingdom**
K.W. Bell, A. Belyaev[65], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

**Imperial College, London, United Kingdom**
R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, GurpreetSingh CHAHAL[66], D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash[67], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee[16], N. Wardle, D. Winterbottom, J. Wright, A.G. Zecchinelli, S.C. Zenz

**Brunel University, Uxbridge, United Kingdom**
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

**Baylor University, Waco, USA**
K. Call, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

**Catholic University of America, Washington, DC, USA**
R. Bartek, A. Dominguez, R. Uniyal

**The University of Alabama, Tuscaloosa, USA**
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

**Boston University, Boston, USA**
D. Arcaro, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

**Brown University, Providence, USA**
G. Benelli, B. Burkle, X. Coubez[17], D. Cutts, Y.t. Duh, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan[68], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir[69], R. Syarif, E. Usai, D. Yu, W. Zhang

**University of California, Davis, Davis, USA**
R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

**University of California, Los Angeles, USA**
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

**University of California, Riverside, Riverside, USA**
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates, Y. Zhang

**University of California, San Diego, La Jolla, USA**
J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

**University of California, Santa Barbara - Department of Physics, Santa Barbara, USA**
N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

**California Institute of Technology, Pasadena, USA**
D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

**University of Colorado Boulder, Boulder, USA**
J.P. Cumalat, W.T. Ford, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

**Cornell University, Ithaca, USA**
J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, J.R. Patterson, D. Quach, A. Rinkevicius[70], A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

**Fermi National Accelerator Laboratory, Batavia, USA**
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa,

G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, AllisonReinsvold Hall, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena, G. Rakness, F. Ravera, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber

**University of Florida, Gainesville, USA**
D. Acosta, P. Avery, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, V. Cherepanov, D. Curry, F. Errico, R.D. Field, S.V. Gleyzer, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

**Florida International University, Miami, USA**
Y.R. Joshi

**Florida State University, Tallahassee, USA**
T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

**Florida Institute of Technology, Melbourne, USA**
M.M. Baarmand, V. Bhopatkar, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

**University of Illinois at Chicago (UIC), Chicago, USA**
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, C. Mills, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

**The University of Iowa, Iowa City, USA**
M. Alhusseini, B. Bilki[53], W. Clarida, K. Dilsiz[71], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[72], A. Moeller, J. Nachtman, H. Ogul[73], Y. Onel, F. Ozok[74], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

**Johns Hopkins University, Baltimore, USA**
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, M. Swartz, M. Xiao

**The University of Kansas, Lawrence, USA**
C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

**Kansas State University, Manhattan, USA**
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

**Lawrence Livermore National Laboratory, Livermore, USA**
F. Rebassoo, D. Wright

**University of Maryland, College Park, USA**
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

**Massachusetts Institute of Technology, Cambridge, USA**
D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

**University of Minnesota, Minneapolis, USA**
A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, S. Guts, P. Hansen, J. Hiltbrand, Sh. Jain, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

**University of Mississippi, Oxford, USA**
J.G. Acosta, S. Oliveros

**University of Nebraska-Lincoln, Lincoln, USA**
K. Bloom, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow, B. Stieger, W. Tabb

**State University of New York at Buffalo, Buffalo, USA**
G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

**Northeastern University, Boston, USA**
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

**Northwestern University, Evanston, USA**
S. Bhattacharya, J. Bueghly, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

**University of Notre Dame, Notre Dame, USA**
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, C. Mueller, Y. Musienko[36], M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

**The Ohio State University, Columbus, USA**
J. Alimena, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

**Princeton University, Princeton, USA**
S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

**University of Puerto Rico, Mayaguez, USA**
S. Malik, S. Norberg

**Purdue University, West Lafayette, USA**
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud,

D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

**Purdue University Northwest, Hammond, USA**
T. Cheng, J. Dolen, N. Parashar

**Rice University, Houston, USA**
K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

**University of Rochester, Rochester, USA**
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

**Rutgers, The State University of New Jersey, Piscataway, USA**
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

**University of Tennessee, Knoxville, USA**
H. Acharya, A.G. Delannoy, G. Riley, S. Spanier

**Texas A&M University, College Station, USA**
O. Bouhali[75], M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[76], S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

**Texas Tech University, Lubbock, USA**
N. Akchurin, J. Damgov, F. De Guio, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

**Vanderbilt University, Nashville, USA**
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

**University of Virginia, Charlottesville, USA**
M.W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

**Wayne State University, Detroit, USA**
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

**University of Wisconsin - Madison, Madison, WI, USA**
T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, F. Fiori, C. Galloni, B. Gomber[77], H. He, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Loeliger, K. Long, R. Loveless, J. Madhusudanan Sreekala, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
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 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, United Kingdom
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, Padova, 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, Sirnak, 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, United Kingdom
66: Also at IPPP Durham University, Durham, United Kingdom
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