

# Higher-order moments of the elliptic flow distribution in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

The CMS Collaboration\*

## Abstract

The hydrodynamic flow-like behavior of charged hadrons in high-energy lead-lead collisions is studied through multiparticle correlations. The elliptic anisotropy values based on different orders of multiparticle cumulants,  $v_2\{2k\}$ , are measured up to the tenth order ( $k = 5$ ) as functions of the collision centrality at a nucleon-nucleon center-of-mass energy of  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The data were recorded by the CMS experiment at the LHC and correspond to an integrated luminosity of  $0.607 \text{ nb}^{-1}$ . A hierarchy is observed between the coefficients, with  $v_2\{2\} > v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\} \gtrsim v_2\{10\}$ . Based on these results, centrality-dependent moments for the fluctuation-driven event-by-event  $v_2$  distribution are determined, including the skewness, kurtosis and, for the first time, superskewness. Assuming a hydrodynamic expansion of the produced medium, these moments directly probe the initial-state geometry in high-energy nucleus-nucleus collisions.

*Submitted to the Journal of High Energy Physics*



## 1 Introduction

In high-energy nucleus-nucleus collisions, a hot and dense state of strongly interacting quarks and gluons is created, the so-called quark-gluon plasma (QGP). Clear evidence for this state was obtained at the BNL RHIC [1–4]. Experiments at the CERN LHC, performed with nucleus-nucleus collisions at nucleon-nucleon center-of-mass energies up to more than twenty times greater than available for the RHIC studies, confirmed the main RHIC results with much larger event samples and kinematic ranges. Unexpectedly, a similar behavior has been observed in smaller systems formed in high-multiplicity proton-proton and proton-nucleus collisions [5, 6]. One important feature of the QGP is its apparent collective hydrodynamic expansion. The initial spatial geometry of the overlap region of the colliding nuclei results in anisotropic pressure gradients that, in turn, are reflected in the azimuthal angle distribution of outgoing particles. This anisotropy has been used to perform detailed studies of the QGP formed at the LHC [7–19]. Fluctuations in nuclear densities that appear due to the fluctuations in the position of nucleons within the incident nuclei also have a significant influence on the QGP expansion [8, 12, 20–22]. The effect of these geometry fluctuations on the observed particle anisotropy can give insight into the early-stage dynamics of the collisions [23–25].

Figure 1 schematically depicts a collision of two nuclei in the transverse  $X' - Y'$  plane that is perpendicular to the beam axis  $Z$ , in the laboratory frame. The impact parameter vector  $\mathbf{b}$ , which is not experimentally accessible, connects the centers of the colliding nuclei in the transverse plane. The symmetry plane of the collision, denoted  $X - Y$ , defined in terms of the beam direction and  $\mathbf{b}$ , is randomly oriented with respect to the  $X' - Y'$  plane. In this schematic figure,  $\phi$  denotes the azimuthal angle of one of the outgoing particles. The anisotropic flow is quantified in terms of coefficients in the Fourier expansion of the  $\phi$  dependence of the invariant yield of particles relative to the event-plane angle  $\Psi_{EP}$ ,

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_{EP})] \right], \quad (1)$$

where  $E$  is the energy of the particle,  $p_T$  its transverse momentum, and  $y$  its rapidity. The event-plane angle  $\Psi_{EP}$  is defined to be in the direction of maximum outgoing particle density [26] and is, on average, the same as the rotation angle of the symmetry plane with respect to the laboratory frame. The direction of  $\Psi_{EP}$  fluctuates about the symmetry plane rotation angle because of fluctuations in the initial state geometry and resolution effects arising from finite particle multiplicities. The elliptic flow harmonic  $v_2$  is the leading term of the Fourier series expansion of the azimuthal angle distribution in the event plane frame.

Many methods have been developed to study the anisotropic expansion of the system formed in nuclear collisions [26–28]. The cumulant method was introduced in Refs. [29, 30] based on multiparticle correlations which do not require an explicit measure of the event-plane angle. In this method,  $v_n$  values can be extracted from  $c_n\{2k\}$  cumulant coefficients, where  $n$  is the order of the Fourier expansion term and  $2k$  is the number of particles used to determine the correlation. For example,  $v_2\{2\}$ ,  $v_2\{4\}$ , and  $v_2\{6\}$  are referred to as the 2-, 4-, and 6-particle cumulant based values for the elliptic flow harmonic, respectively. Nonflow, short-range correlations arising from jets and resonance decays, can be suppressed by correlating four or more particles. It is then possible to determine the central moments of the event-by-event, fluctuation-driven,  $v_2$  distribution based on the  $v_2\{2k\}$  values. The 3rd, 4th, and 5th central moments are called the skewness ( $s$ ), kurtosis ( $\kappa$ ), and superskewness ( $p$ ) respectively. The skewness describes the overall asymmetry of the  $v_2$  distribution, while the superskewness gives a measure of the asymmetry of the tails. The kurtosis describes the peakedness of the center, or equivalently, the relative contribution (heaviness) of the distribution tails. In a hydrodynamic expansion

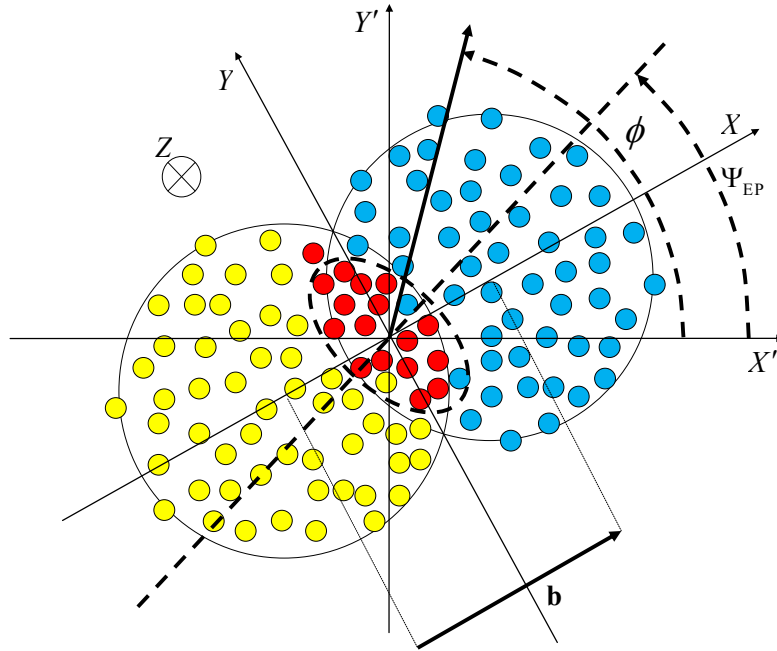


Figure 1: A schematic view of a non-central nucleus-nucleus collision in the transverse plane.

the  $v_2$  is proportional to the initial-state eccentricity  $\epsilon_2$ , and therefore  $\epsilon_2$  fluctuations produce non-Gaussian  $v_2$  distributions [31]. Thus, the central moments can be related to the initial state geometry and reveal its detailed structure.

In this paper, the cumulant based values are determined using the Q-cumulant method in which one calculates multiparticle cumulants in terms of moments of Q-vectors [32]. Determining the cumulant based  $v_2\{2k\}$  ( $k = 1, 2, 3, \dots$ ) values of the  $v_2$  distribution is a way to study the fluctuation behavior related to the initial-state geometry [30]. For Gaussian fluctuations, the higher central moments vanish and the  $v_2\{2k\}$  values with  $k > 1$  are all expected to have the same value [33]. The measured higher-order  $v_2\{2k\}$  ( $k = 2, 3, 4$ ) values, however, show a fine splitting [34, 35],  $v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\}$ , that can be attributed to a non-Gaussian behavior [31]. In Ref. [36], it is noted that the main signature of non-Gaussian fluctuations is a nonzero skewness of the  $v_2$  distribution. This is used to suggest, as described in Ref. [36], a hydrodynamic probe based on the ratio  $(v_2\{6\} - v_2\{8\}) / (v_2\{4\} - v_2\{6\})$ . The basic premise of a hydrodynamic probe is that the observed azimuthal angle correlations that appear in the bulk medium can be related to the initial-state geometry.

We present for the first time a measurement of  $v_2\{10\}$ , derived from ten-particle cumulants, for lead-lead (PbPb) collisions at a center-of-mass energy per nucleon pair of  $\sqrt{s_{NN}} = 5.02$  TeV. The data used in this analysis correspond to an integrated luminosity of  $0.607 \text{ nb}^{-1}$  and were recorded with the CMS detector at the LHC. This enables the development of a new hydrodynamic probe using the  $v_2\{10\}$  value and the corresponding lower-order  $v_2\{2k\}$  values. Both the original and the new hydrodynamic probes should be independent of collision centrality if moments of the  $v_2$  distribution with order higher than the skewness are negligible [36]. Centrality refers to the percentage of the total inelastic hadronic nucleus-nucleus cross section [37], with 0% corresponding to the maximum overlap of the colliding nuclei. This connection between the centrality dependence of the hydrodynamic probes and higher order moments of the  $v_2$  distribution is investigated by measuring both the centrality dependence itself and also by using the cumulants to extract the higher order moments directly.

This paper is organized as follows. In Section 2 and in Appendix A, we derive formulas for the  $v_2\{10\}$  harmonic and its statistical uncertainty. Section 3 and Appendices B, and C present derivations of the formulas used in this analysis to calculate the hydrodynamic probe ratios. In Section 4, we introduce and derive formulas for the standardized moments (denoted as  $\gamma_i^{\text{exp}}$ ,  $i = 1, 2, 3$ ) and the corrected moments (denoted as  $\gamma_{i, \text{corr}}^{\text{exp}}$ ,  $i = 1, 2, 3$ ) of the fluctuation-driven, event-by-event  $v_2$  distribution. Section 5, 6, and 7 present the experimental details, results, and summary, respectively. The numerical values of the results for this analysis are tabulated in the HEPDATA record [38].

## 2 Analysis procedure

A version of the cumulant method, the Q-cumulant method, was introduced in Ref. [32] and is based on the flow vector  $Q_n$ , with  $Q_n = \sum_{j=1}^M e^{in\phi_j}$ . Here,  $n$  is the flow harmonic order,  $M$  denotes the event multiplicity, i.e., the number of analyzed tracks in the given event, and  $\phi_j$  is the azimuthal angle of the  $j$ th track measured in the laboratory frame.

The  $2m$ -particle azimuthal angle correlators  $\langle 2m \rangle$  [32] are expressed through the flow vector  $Q_n$  with

$$\langle 2m \rangle = \langle e^{in(\phi_1 + \dots + \phi_m - \phi_{m+1} - \dots - \phi_{2m})} \rangle = \frac{(M-2m)!}{M!} \sum_{j_1 \neq \dots \neq j_{2m}=1}^M e^{in(\phi_{j_1} + \dots + \phi_{j_m} - \phi_{j_{m+1}} - \dots - \phi_{j_{2m}})}. \quad (2)$$

Here the summation is over all unique track indices. The weighted mean of the  $2m$ -particle azimuthal angle correlator  $\langle\langle 2m \rangle\rangle$  is defined as

$$\langle\langle 2m \rangle\rangle = \frac{\sum_j^{\text{events}} (W_{\langle 2m \rangle})_j \langle 2m \rangle_j}{\sum_j^{\text{events}} (W_{\langle 2m \rangle})_j}, \quad m = 1, \dots, k, \quad (3)$$

where the double brackets  $\langle\langle \dots \rangle\rangle$  denote a weighted average over all events within a given class [39]. The weight is taken as the number of distinct  $2m$ -particle combinations that can be formed for an event [39]:

$$W_{\langle 2m \rangle} = \prod_{j=0}^{2m-1} (M-j) = \frac{M!}{(M-2m)!}. \quad (4)$$

The Q-cumulant  $c_n\{2k\}$  values are multivariate polynomial functions of the  $\langle\langle 2m \rangle\rangle$  values. The relationship between the  $c_n\{2k\}$  values (up to the 8th order) and corresponding  $\langle\langle 2m \rangle\rangle$  correlations are known [32, 39]. A recursion relationship for the  $c_n\{2k\}$  values [40] is given with

$$c_n\{2k\} = \langle\langle 2k \rangle\rangle - \sum_{m=1}^{k-1} \binom{k}{m} \binom{k-1}{m} \langle\langle 2m \rangle\rangle c_n\{2k-2m\}. \quad (5)$$

In Refs. [39, 41] it is shown that

$$\langle\langle 2k \rangle\rangle = \langle v_n^{2k} \rangle. \quad (6)$$

Based on Eqs. (5) and (6), one finds

$$v_n = \sqrt[2k]{a_{2k}^{-1} c_n\{2k\}}, \quad (7)$$

where the  $a_{2k}$  coefficients can be determined using the recursion relationship

$$a_{2k} = 1 - \sum_{m=1}^{k-1} \binom{k}{m} \binom{k-1}{m} a_{2k-2m}, \quad \text{with } a_2 = 1. \quad (8)$$

In the ideal case, all  $2k$ -particle cumulants  $c_n\{2k\}$  with  $k > 1$  result in the same flow harmonic value  $v_n$ . But, non-Gaussian flow fluctuations and non-flow correlations result in a splitting of the  $c_n\{2k\}$  values with  $k > 1$ . In this case, the  $v_n\{2k\}$  values will depend on the cumulant orders as

$$v_n\{2k\} \equiv \sqrt[2k]{a_{2k}^{-1}c_n\{2k\}}, \quad (9)$$

Details concerning the Q-cumulant method up to the  $k = 4$  order can be found in Refs. [32, 39]. In the case where  $k = 5$ , the above equations give the relationship between the  $v_n\{10\}$  magnitude and the corresponding  $c_n\{10\}$  value, with

$$c_n\{10\} = \langle\langle 10 \rangle\rangle - 25\langle\langle 2 \rangle\rangle\langle\langle 8 \rangle\rangle - 100\langle\langle 4 \rangle\rangle\langle\langle 6 \rangle\rangle + 400\langle\langle 6 \rangle\rangle\langle\langle 2 \rangle\rangle^2 + 900\langle\langle 2 \rangle\rangle\langle\langle 4 \rangle\rangle^2 - 3600\langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle^3 + 2880\langle\langle 2 \rangle\rangle^5. \quad (10)$$

and

$$v_n\{10\} = \sqrt[10]{\frac{1}{456}c_n\{10\}}. \quad (11)$$

Formulas for the analytic calculations of the statistical uncertainties in the  $v_n\{2k\}$  ( $k = 1, \dots, 4$ ) magnitudes are given in Ref. [40]. Appendix A discusses the analytical calculation of the statistical uncertainty for the  $v_2\{10\}$  value.

### 3 Hydrodynamic probes

A compact formulation for the cumulant expansion is given through the formalism of generating functions. The Fourier–Laplace transform of the symmetry plane elliptic harmonic vector  $\mathbf{v}_2 = v_x \mathbf{e}_x + v_y \mathbf{e}_y$  is  $\langle e^{\mathbf{l} \cdot \mathbf{v}_2} \rangle$ , with a vector variable  $\mathbf{l} = l_x \mathbf{e}_x + l_y \mathbf{e}_y$ . Here,  $\mathbf{e}_x$  is the unit vector in the direction of the impact parameter, while  $\mathbf{e}_y$  is the unit vector perpendicular to  $\mathbf{b}$ . The angle brackets  $\langle \rangle$  indicate an event average that, for this analysis, involves an average over events within a centrality class. As the distribution of  $(v_x, v_y)$  is symmetric under  $v_y \rightarrow -v_y$ , the mean value of the  $x$ - and  $y$ -component of  $\mathbf{v}_2$  are  $\langle v_x \rangle \equiv \bar{v}_2$ , and  $\langle v_y \rangle = 0$ . The variances are  $\sigma_x^2 = \langle (v_x - \langle v_x \rangle)^2 \rangle$  and  $\sigma_y^2 = \langle v_y^2 \rangle$ . Higher-order central moments up to the kurtosis are defined in Ref. [42] in terms of the components of the elliptic harmonic vector. The expressions found in Ref. [42] are reproduced here, expanded to include terms related to the superskewness:

$$\begin{aligned} s_{30} &= \langle (v_x - \langle v_x \rangle)^3 \rangle, \\ s_{12} &= \langle (v_x - \langle v_x \rangle)v_y^2 \rangle, \\ \kappa_{40} &= \langle (v_x - \langle v_x \rangle)^4 \rangle - 3\sigma_x^4, \\ \kappa_{22} &= \langle (v_x - \langle v_x \rangle)^2 v_y^2 \rangle - \sigma_x^2 \sigma_y^2, \\ \kappa_{04} &= \langle v_y^4 \rangle - 3\sigma_y^4, \\ p_{50} &= \langle (v_x - \langle v_x \rangle)^5 \rangle - 10\sigma_x^2 s_{30}, \\ p_{32} &= \langle (v_x - \langle v_x \rangle)^3 v_y^2 \rangle - \sigma_y^2 s_{30} - 3\sigma_x^2 s_{12}, \quad \text{and} \\ p_{14} &= \langle (v_x - \langle v_x \rangle)v_y^4 \rangle - 6\sigma_y^2 s_{12}. \end{aligned} \quad (12)$$

In Ref. [36], the generating function of the cumulant is defined as  $\ln \langle e^{\mathbf{l} \cdot \mathbf{v}_2} \rangle$ . If one expands this generating function up to the 4th power in  $(l_x, l_y)$  one gets the expression in terms of central moments of the  $(v_x, v_y)$  distribution, that includes the  $\sigma$ ,  $s$ , and  $\kappa$  terms [42]. By extending this expansion up to the 5th power in  $(l_x, l_y)$ , we obtain

$$\ln\langle e^{l \cdot v_2} \rangle \approx l_x \bar{v}_2 + \frac{1}{2!}(l_x^2 \sigma_x^2 + l_y^2 \sigma_y^2) + \frac{1}{3!}(l_x^3 s_{30} + 3l_x l_y^2 s_{12}) \\ + \frac{1}{4!}(l_x^4 \kappa_{40} + 6l_x^2 l_y^2 \kappa_{22} + l_y^4 \kappa_{04}) + \frac{1}{5!}(l_x^5 p_{50} + 10l_x^3 l_y^2 p_{32} + 5l_x l_y^4 p_{14}). \quad (13)$$

One can follow the procedure for expanding the generating function of the  $v_2\{2k\}$  cumulants [36] to derive expressions for the hydrodynamic probes that include higher-order moments of the  $v_2$  distribution. Instead of using Eq. (7) from Ref. [36], in this analysis Eq. (13) is used. The difference is that in the earlier work the expansion is performed up to the skewness, while the current analysis additionally covers the 4th and 5th moments. Then, for the higher-order  $v_2\{2k\}$  ( $k = 2, \dots, 5$ ) values, we find

$$v_2\{4\} \approx \bar{v}_2 + \frac{\sigma_y^2 - \sigma_x^2}{2\bar{v}_2} - \frac{s_{30} + s_{12}}{\bar{v}_2^2} \\ - \frac{\kappa_{40} + 2\kappa_{22} + \kappa_{04}}{4\bar{v}_2^3} - \frac{5(\sigma_y^2 - \sigma_x^2)^2}{8\bar{v}_2^3} + \frac{(\sigma_y^2 - \sigma_x^2)(3s_{30} + 3s_{12})}{2\bar{v}_2^4}, \quad (14)$$

$$v_2\{6\} \approx \bar{v}_2 + \frac{\sigma_y^2 - \sigma_x^2}{2\bar{v}_2} - \frac{\frac{2}{3}s_{30} + s_{12}}{\bar{v}_2^2} \\ + \frac{\kappa_{40} - \kappa_{04}}{4\bar{v}_2^3} - \frac{5(\sigma_y^2 - \sigma_x^2)^2}{8\bar{v}_2^3} + \frac{p_{50} + 2p_{32} + p_{14}}{4\bar{v}_2^4} + \frac{(\sigma_y^2 - \sigma_x^2)(4s_{30} + 15s_{12})}{6\bar{v}_2^4}, \quad (15)$$

$$v_2\{8\} \approx \bar{v}_2 + \frac{\sigma_y^2 - \sigma_x^2}{2\bar{v}_2} - \frac{\frac{7}{11}s_{30} + s_{12}}{\bar{v}_2^2} + \frac{\frac{31}{33}\kappa_{40} + \frac{2}{11}\kappa_{22} - \kappa_{04}}{4\bar{v}_2^3} - \frac{5(\sigma_y^2 - \sigma_x^2)^2}{8\bar{v}_2^3} \\ + \frac{\frac{5}{3}p_{50} + \frac{14}{3}p_{32} + 3p_{14}}{11\bar{v}_2^4} + \frac{(\sigma_y^2 - \sigma_x^2)(13s_{30} + 57s_{12})}{22\bar{v}_2^4}, \quad \text{and} \quad (16)$$

$$v_2\{10\} \approx \bar{v}_2 + \frac{\sigma_y^2 - \sigma_x^2}{2\bar{v}_2} - \frac{\frac{12}{19}s_{30} + s_{12}}{\bar{v}_2^2} + \frac{\frac{53}{57}\kappa_{40} + \frac{4}{19}\kappa_{22} - \kappa_{04}}{4\bar{v}_2^3} - \frac{5(\sigma_y^2 - \sigma_x^2)^2}{8\bar{v}_2^3} \\ + \frac{\frac{163}{60}p_{50} + \frac{47}{6}p_{32} + \frac{21}{4}p_{14}}{19\bar{v}_2^4} + \frac{(\sigma_y^2 - \sigma_x^2)(11s_{30} + \frac{99}{2}s_{12})}{19\bar{v}_2^4}. \quad (17)$$

If one neglects the 5th-order moments  $p$ , as well as the terms with the multiplier  $(\sigma_y^2 - \sigma_x^2)$ , then the hydrodynamic probe proposed with Eq. (14) in Ref. [36] is given as

$$\frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} \approx \frac{1}{11} - \frac{4\kappa_{40}}{11[2\bar{v}_2 s_{30} + 3(\kappa_{40} + \kappa_{22})]}. \quad (18)$$

Here, one can see that neglecting the kurtosis  $\kappa$  moment, with respect to the skewness, would reduce the right-hand side of Eq. (18) to a constant value of  $1/11$ . Appendix C shows the relation that corresponds to Eq. (18) if none of the terms in Eqs. (14)–(16) are neglected.

The approximation given by Eq. (18) can be tested by expressing the right-hand side in terms of the measurable quantities  $v_2\{2k\}$ , with  $k = 2, 3$ , and 4. Based on Taylor expansion of the  $v_2\{2k\}^2$  values, as shown in Appendix B, one finds

$$h_1 = \frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} \approx h_1^{\text{Taylor}} = \frac{1}{11} - \frac{1}{11} \frac{v_2\{4\}^2 - 12v_2\{6\}^2 + 11v_2\{8\}^2}{v_2\{4\}^2 - v_2\{6\}^2} \quad (19)$$

if terms with  $(\sigma_y^2 - \sigma_x^2)$  are neglected.

In the above relation,  $h_1$  denotes the hydrodynamic probe and  $h_1^{\text{Taylor}}$  denotes the corresponding Taylor expansion of this probe as expressed in terms of the measured  $v_2\{2k\}$  values.

By employing the  $v_2\{10\}$  harmonic, we define a new hydrodynamic probe  $h_2$  as

$$\frac{v_2\{8\} - v_2\{10\}}{v_2\{6\} - v_2\{8\}} \approx \frac{3}{19} + \frac{88p_{50}}{95[4s_{30}\bar{v}_2^2 - 2\bar{v}_2(\kappa_{40} - 3\kappa_{22}) - (13p_{50} + 10p_{32} - 3p_{14}) - 2(\sigma_y^2 - \sigma_x^2)(5s_{30} - 6s_{12})]}. \quad (20)$$

In the derivation of Eq. (20), none of the terms in Eqs. (15)–(17) have been neglected. If one neglects the 5th  $p$  moment, then the right-hand side of the Eq. (20) will reduce to the constant value of  $3/19$ . A deviation from this constant value indicates that the  $p$  moment cannot be neglected.

Again, as in the case with the derivation of the Eq. (19), one can express the right-hand side of Eq. (20) through the second power of the higher-order  $v_2\{2k\}$  terms, with  $k = 3, 4, 5$  (as shown in Appendix B):

$$\frac{v_2\{8\} - v_2\{10\}}{v_2\{6\} - v_2\{8\}} \approx \frac{3}{19} - \frac{1}{19} \frac{3v_2\{6\}^2 - 22v_2\{8\}^2 + 19v_2\{10\}^2}{v_2\{6\}^2 - v_2\{8\}^2 + \frac{(\sigma_y^2 - \sigma_x^2)s_{30}}{33\bar{v}_2^3}}. \quad (21)$$

If one neglects the term with the multiplier  $(\sigma_y^2 - \sigma_x^2)$ , Eq. (21) reduces to

$$h_2 = \frac{v_2\{8\} - v_2\{10\}}{v_2\{6\} - v_2\{8\}} \approx h_2^{\text{Taylor}} = \frac{3}{19} - \frac{1}{19} \frac{3v_2\{6\}^2 - 22v_2\{8\}^2 + 19v_2\{10\}^2}{v_2\{6\}^2 - v_2\{8\}^2}, \quad (22)$$

where  $h_2$  denotes the new hydrodynamic probe and  $h_2^{\text{Taylor}}$  denotes the Taylor expansion of this probe, as expressed in terms of the measured  $v_2\{2k\}$  values.

In Section 6, it will be shown that the term proportional to the asymmetry of the fluctuations  $(\sigma_y^2 - \sigma_x^2)$  is negligible. The same conclusion is found in Ref. [36].

## 4 The standardized and corrected moments

The standardized skewness,  $\gamma_1$ , and standardized kurtosis,  $\gamma_2$ , are defined as

$$\gamma_1 \equiv \frac{s_{30}}{\sigma_x^3}, \quad \text{and} \quad \gamma_2 \equiv \frac{\kappa_{40}}{\sigma_x^4}. \quad (23)$$

The corresponding expressions given in terms of the measured  $v_2\{2k\}$  values, are derived in Ref. [42] as

$$\gamma_1^{\text{exp}} = -2^{3/2} \frac{v_2\{4\}^3 - v_2\{6\}^3}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}, \quad \text{and} \quad (24)$$

$$\gamma_2^{\text{exp}} = -\frac{3v_2\{4\}^4 - 12v_2\{6\}^4 + 11v_2\{8\}^4}{2(v_2\{2\}^2 - v_2\{4\}^2)^2}.$$

The standardized superskewness,  $\gamma_3$ , is defined as

$$\gamma_3 \equiv \frac{p_{50}}{\sigma_x^5}. \quad (25)$$



In order to express the standardized superskewness through the measured  $v_2\{2k\}$  values with  $k = 1, \dots, 5$ , one can use the expansion of the fifth power of the  $v_2\{2k\}$  value (as discussed in Appendix B). The resulting expression for the standardized superskewness, expressed in terms of measurable quantities, is

$$\gamma_3^{\text{exp}} = 6\sqrt{2} \frac{3v_2\{6\}^5 - 22v_2\{8\}^5 + 19v_2\{10\}^5}{(v_2\{2\}^2 - v_2\{4\}^2)^{5/2}}. \quad (26)$$

The standardized moments,  $\gamma_i^{\text{exp}}$  ( $i = 1, 2, 3$ ), have contributions from higher-order moments of the  $v_2$  distribution that are not negligible (as shown by Eq. (13) in Ref. [42]). For example, if higher-order moments are considered, then for the standardized skewness we obtain additional terms  $O_N$  and  $O_D$ , with

$$\gamma_1^{\text{exp}} = -2^{3/2} \frac{v_2\{4\}^3 - v_2\{6\}^3}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}} \approx -2^{3/2} \frac{-s_{30} - O_N}{(2\sigma_x^2 + O_D)^{3/2}}, \quad (27)$$

where

$$\begin{aligned} O_N &= \frac{3(\kappa_{40} + \kappa_{22})}{2\bar{v}_2} - \frac{3(p_{50} + 2p_{32} + p_{14})}{4\bar{v}_2^2} + \frac{3(\sigma_y^2 - \sigma_x^2)(s_{30} - 2s_{12})}{2\bar{v}_2^2} + \dots, \quad \text{and} \\ O_D &= \frac{2}{\bar{v}_2}(s_{30} + s_{12}) + \frac{\kappa_{40} + 2\kappa_{22} + \kappa_{04}}{2\bar{v}_2^2} + \frac{(\sigma_y^2 - \sigma_x^2)^2}{\bar{v}_2^2} - \frac{2(\sigma_y^2 - \sigma_x^2)(s_{30} - s_{12})}{\bar{v}_2^3} + \dots \end{aligned} \quad (28)$$

Corrected moments, which are free of contributions from higher-order moments, can be defined if

$$s_{12} \approx \frac{s_{30}}{3}, \quad \kappa_{22} \approx \frac{\kappa_{40}}{3}, \quad \text{and} \quad p_{32} \approx p_{14} \approx \frac{p_{50}}{5}. \quad (29)$$

These conditions are satisfied with the elliptic power distribution [43] if the eccentricity parameter  $\epsilon_0$  in this model satisfies the condition  $\epsilon_0 \leq 0.15$  and a linear flow response is assumed. Mathematical details that support the validity of the conditions given by Eq. (29) are presented in Appendix D. With these conditions, the corrected moments can be expressed in terms of the measured  $v_n\{2k\}$  ( $k = 1, \dots, 5$ ) values. As an example, the corrected skewness can be expressed as

$$\gamma_{1,\text{corr}}^{\text{exp}} = -2^{3/2} \frac{187v_2\{8\}^3 - 16v_2\{6\}^3 - 171v_2\{10\}^3}{(v_2\{2\}^2 - 40v_2\{6\}^2 + 495v_2\{8\}^2 - 456v_2\{10\}^2)^{3/2}}. \quad (30)$$

If one replaces the powers that appear in Eq. (30) with the expansions given in Appendix B, one finds

$$\gamma_{1,\text{corr}}^{\text{exp}} \approx -2^{3/2} \frac{-s_{30} - \bar{O}_N}{(2\sigma_x^2 + \bar{O}_D)^{3/2}} \approx \frac{s_{30}}{\sigma_x^3} \equiv \gamma_1, \quad (31)$$

where  $\bar{O}_N$  and  $\bar{O}_D$  are given by

$$\begin{aligned} \bar{O}_N &= \frac{3(\sigma_y^2 - \sigma_x^2)(s_{30} - 2s_{12})}{2\bar{v}_2^2} + \dots, \quad \text{and} \\ \bar{O}_D &= -\frac{2(\sigma_y^2 - \sigma_x^2)(s_{30} - s_{12})}{\bar{v}_2^3} + \dots \end{aligned} \quad (32)$$

We note that the contribution from the term proportional to  $(\sigma_y^2 - \sigma_x^2)$  as well as the contributions from moments of order higher than 5 are negligible.

The same correction procedure can also be applied to the standardized kurtosis and the standardized superskewness. The corrected form of these moments are given by

$$\begin{aligned}\gamma_{2,\text{corr}}^{\text{exp}} &= -\frac{3}{2} \frac{v_2\{4\}^4 + 24v_2\{6\}^4 - 253v_2\{8\}^4 + 228v_2\{10\}^4}{(v_2\{2\}^2 - 40v_2\{6\}^2 + 495v_2\{8\}^2 - 456v_2\{10\}^2)^2}, \quad \text{and} \\ \gamma_{3,\text{corr}}^{\text{exp}} &= 6\sqrt{2} \frac{3v_2\{6\}^5 - 22v_2\{8\}^5 + 19v_2\{10\}^5}{(v_2\{2\}^2 - 40v_2\{6\}^2 + 495v_2\{8\}^2 - 456v_2\{10\}^2)^{5/2}}.\end{aligned}\quad (33)$$

## 5 CMS detector, event selection, and systematic uncertainties

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters (HF), made of steel and quartz-fibres, extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. 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. [44].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz [45]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to about 5 to 8 kHz before data storage [46].

The data analyzed in this paper, before applying the selection described below, consist of  $4.27 \times 10^9$  minimum bias lead-lead (PbPb) collision events at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV, collected in 2018 with an integrated luminosity of  $0.607 \text{ nb}^{-1}$  [47, 48]. The minimum bias events are triggered by requiring signals above readout thresholds of 3 GeV in each of the two HF calorimeters [46]. Further selections are applied to reject events from beam-gas interactions and nonhadronic collisions [49]. The events are also required to have at least one reconstructed primary vertex (based on two or more tracks) within a distance ( $|z_{\text{vtx}}|$ ) of 15 cm from the nominal interaction point along the beam axis. If multiple vertices are found in an event then the primary vertex is selected as the one with the highest track multiplicity in the event. The total energy deposited in both HF calorimeters is used for determination of the event centrality [50].

Only tracks that satisfy the high-purity selection criteria described in Ref. [49] are used in the analysis. In addition, a reconstructed track is only considered as a candidate track from the primary vertex if the separation along the beam axis between the track and the vertex ( $d_z$ ), and the track-vertex impact parameter measured transverse to the beam ( $d_{xy}$ ), are both less than three times their respective uncertainties  $\sigma_z$  and  $\sigma_{xy}$ . The relative uncertainty in the transverse momentum ( $\sigma_{p_T}/p_T$ ) measurement is required to be less than 10%. In addition, tracks must have 11 or more hits ( $n_{\text{hits}}$ ) along their trajectory in the pixel and strip tracking detectors combined. The relative  $\chi^2$  of the track fit ( $\chi^2/N_{\text{dof}}/N_{\text{layers}}$ ) is required to be less than 0.18, where  $N_{\text{dof}}$  is the number of degrees of freedom during the track fitting and  $N_{\text{layers}}$  is the number of tracking layers used.

Each reconstructed track is weighted by the inverse of the efficiency factor  $w(\eta, p_T, \text{centrality})$  calculated based on Monte Carlo HYDJET 1.9 [51]. The efficiency factor accounts for the recon-

struction efficiency  $\epsilon$  and the fraction of misreconstructed tracks  $f_{\text{misrec}}(\eta, p_T, \text{centrality})$ , with  $w = \epsilon / (1 - f_{\text{misrec}})$  [52]. The response of the CMS detector to the generated events is simulated with GEANT4 [53].

The systematic uncertainties are determined by varying the vertex selection, the track selection, the centrality determination, and the efficiency correction. For each of the indicated sources of systematic uncertainty, an absolute difference between results from the varied and nominal values are used to obtain the uncertainty. The vertex selection uncertainty is found by performing the analysis with  $|z_{\text{vtx}}| < 3$  cm and with  $3 < |z_{\text{vtx}}| < 15$  cm. The uncertainty related to the track selection is determined by comparing tight ( $d_z/\sigma_z < 2$ ,  $d_{xy}/\sigma_{xy} < 2$ ,  $\sigma_{p_T}/p_T < 0.05$  and  $\chi^2/N_{\text{dof}}/N_{\text{layers}} < 0.15$ ) criterion and loose ( $d_z/\sigma_z < 5$ ,  $d_{xy}/\sigma_{xy} < 5$ ,  $\sigma_{p_T}/p_T < 0.15$  and  $\chi^2/N_{\text{dof}}/N_{\text{layers}} < 0.18$ ) criterion for tracks with the results obtained with the nominal values. The finite HF energy resolution results in small migration of events across the centrality bin boundaries. The centrality calibration is varied to calculate the effect of the minimum bias event selection efficiency of the HF calorimeters [54]. Differences in the  $p_T$  spectra between the data and the Monte Carlo simulation can affect the efficiency factor. To estimate the systematic uncertainty arising from these differences, the efficiency factor  $w$  is varied by  $\pm 5\%$ . The final systematic uncertainty is taken as a quadratic sum of the four indicated sources, with the track selection found to have the dominant contribution.

## 6 Results

It was previously shown in Ref. [36] that the presence of non-Gaussian fluctuations in the initial-state energy density leads to a fine splitting between the higher-order  $v_n\{2k\}$  cumulants. The  $v_2\{2k\}$  ( $k = 1, \dots, 5$ ) values are presented in Fig. 2 as functions of centrality in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. These results are obtained from charged particles with  $|\eta| < 2.4$  and  $0.5 < p_T < 3.0$  GeV/c. The statistical uncertainties are about two orders of magnitude smaller than the systematic ones. A clear splitting between the  $v_2\{2\}$  and higher-orders cumulant based  $v_2\{2k\}$  ( $k = 2, \dots, 5$ ) values is visible. The difference is attributed to flow fluctuations, with  $v_2\{2\}^2 \approx v_2\{2k\}^2 + 2\sigma_v^2$  for  $k > 1$  [36, 55], where  $\sigma_v^2$  is the  $v_2$  variance. From Fig. 2, it is clear that the flow fluctuations become larger going to more peripheral collisions (higher centrality percentages).

In Fig. 2, the ordering and a fine splitting between the  $v_2\{2k\}$  ( $k = 2, \dots, 5$ ) values are not clearly visible. The  $v_2\{2k\}$  ( $k = 1, \dots, 5$ ) values need to satisfy the ordering relationship  $v_2\{2k\} > v_2\{2(k+1)\}$  in order to define the hydrodynamic probes given by Eqs. (19) and (22). The splitting between the higher-order cumulant based  $v_2\{2k\}$  values  $v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\} \gtrsim v_2\{10\}$  becomes much finer than the splitting with respect to the lowest-order cumulant based  $v_2\{2\}$  value. Figure 3 shows the corresponding relative differences  $(v_2\{2k\} - v_2\{10\})/v_2\{10\}$  ( $k = 1, \dots, 4$ ) as functions of centrality. The magnitudes of these differences are plotted using a logarithmic scale. The fine splitting between cumulants of different orders as well as the expected hydrodynamic ordering of the splittings is clearly seen. The relative difference between adjacent  $v_2\{2k\} - v_2\{10\}$  values decreases by about an order of magnitude for each increment in  $k$ .

The measured cumulants of different orders are used to calculate the hydrodynamic probes given by the left-hand sides of Eqs. (19) and (22). Figure 4 displays these distributions with closed symbols. Open symbols in the same figure show the right-hand sides of Eqs. (19) and (22). These are also constructed using the measured  $v_2\{2k\}$  ( $k = 1, \dots, 5$ ) cumulants.

As a consequence of the low multiplicities involved in the calculation of the cumulant based

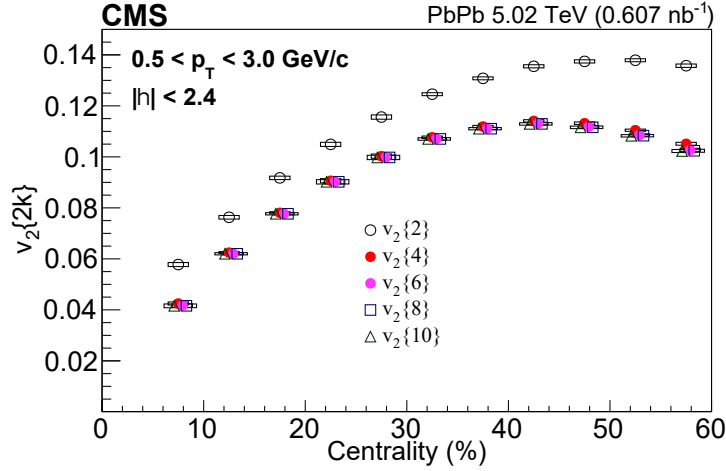


Figure 2: The  $v_2\{2k\}$  ( $k = 1, \dots, 5$ ) values as functions of centrality in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The vertical sizes of the open boxes denote the systematic uncertainties. Statistical uncertainties are negligible compared to the marker size. Points are plotted at the center of the respective centrality ranges. The markers are displaced horizontally for better visibility.

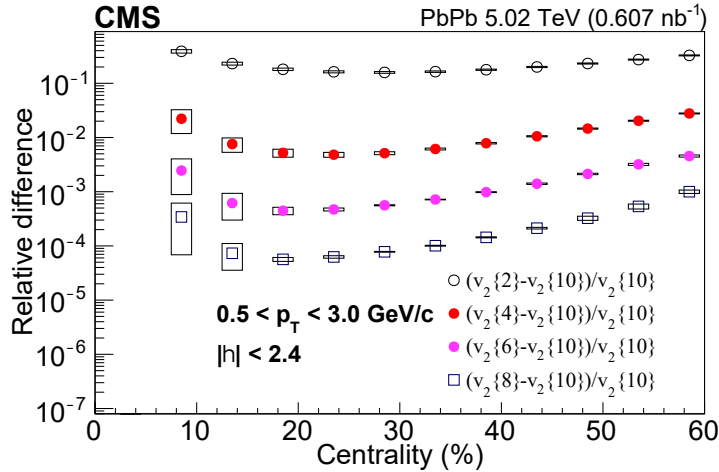


Figure 3: The relative differences  $(v_2\{2k\} - v_2\{10\})/v_2\{10\}$  ( $k = 1, \dots, 4$ ) as functions of centrality in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The vertical sizes of the open boxes denote the systematic uncertainties. Statistical uncertainties are negligible compared to the marker size. Points are plotted at the center of the respective centrality ranges.

$v_2\{2k\}$  values, statistical and systematic uncertainties quickly increase as peripheral collisions are approached. Also, in the region of very central collisions, because of the small magnitudes of the cumulant based  $v_2\{2k\}$  values, the statistical and systematic uncertainties are larger and, therefore, statistical and systematic uncertainties of the hydrodynamic probes are increased. The magnitudes of the statistical uncertainties of the  $h_2$  distribution are larger with respect to those corresponding to the  $h_1$  distribution because higher-order cumulants are involved. After the 0–5% centrality bin, where the measurement uncertainties are large, the  $h_1$  and  $h_2$  values show an increasing trend going to more peripheral events. Based on an event-by-event measurement of the  $v_2$  distribution, it was reported in Ref. [34] that the  $h_1$  has a value of  $0.143 \pm 0.008$  (stat)  $\pm 0.014$  (syst) for 20–25% central events, and increases to  $0.185 \pm 0.005$  (stat)  $\pm 0.012$  (syst) as the centrality increases to 55–60%. Using the Q-cumulant method, Ref. [35] compares the measured  $v_2\{6\} - v_2\{8\}$  and  $\frac{1}{11}(v_2\{4\} - v_2\{6\})$  distributions.

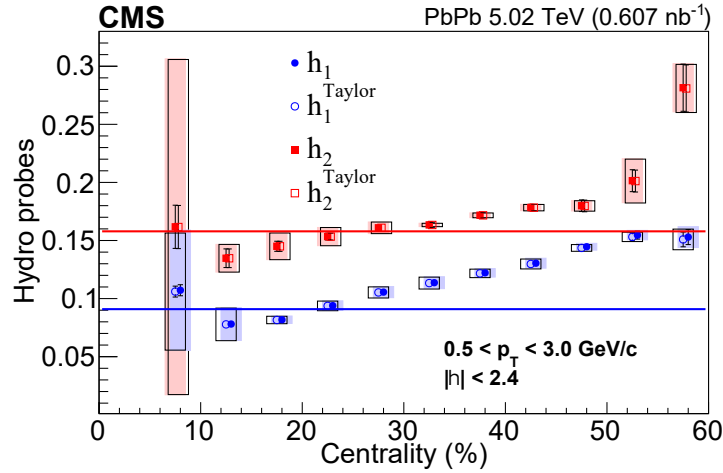


Figure 4: The  $h_1 = (v_2\{6\} - v_2\{8\}) / (v_2\{4\} - v_2\{6\})$  (closed blue circles) and the  $h_2 = (v_2\{8\} - v_2\{10\}) / (v_2\{6\} - v_2\{8\})$  (closed red squares) hydrodynamic probes as functions of centrality in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The distributions depicted with the open circles and squares represent the corresponding Taylor expansions given by  $h_1^{\text{Taylor}}$  and  $h_2^{\text{Taylor}}$ , respectively. The horizontal blue (red) line represents a constant value of  $1/11$  ( $3/19$ ). The bars (the vertical sizes of the open boxes) denote the statistical (systematic) uncertainties. Points are plotted at the center of the respective centrality ranges.

Taking into consideration differences in acceptance, the current analysis is consistent with the results of previous analyses [34, 35], although with smaller uncertainties. There is a very good agreement between the distributions obtained by the expressions given on left-hand and right-hand sides of Eq. (19) and Eq. (22) in Fig. 4. This indicates the importance of including higher-order terms in the Taylor expansion of the  $v_2$  generating function.

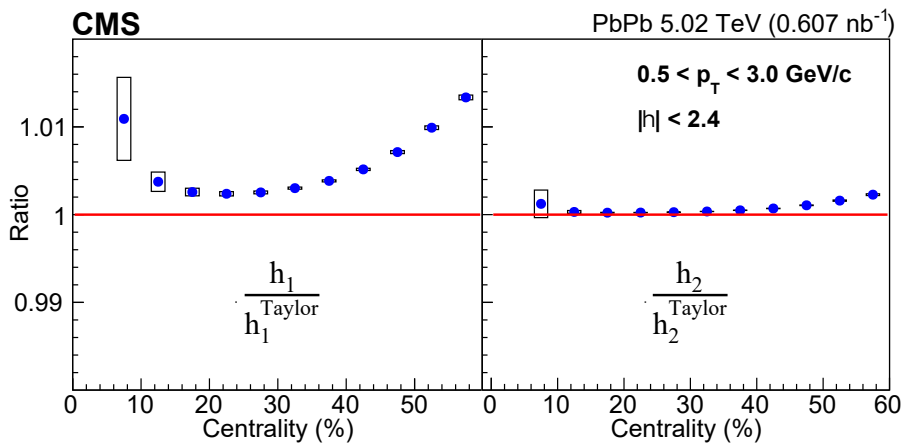


Figure 5: The ratios between the hydrodynamic probes and their Taylor expansions. The ratios are plotted as functions of centrality in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The vertical sizes of the open boxes denote systematic uncertainties. Statistical uncertainties are negligible compared to the marker size. Points are plotted at the center of the respective centrality ranges.

Figure 5 shows ratios between the left- and right-hand sides of the hydrodynamic probes given by Eq. (19) (left plot) and Eq. (22) (right plot) as functions of centrality. The two sides differ by less than 1.3% and 0.3% in the cases of Eqs. (19) and (22), respectively. Thus, based on

Eqs. (C.2) and (21), which differ from the Eqs. (19) and (22) only by the term that is proportional to  $(\sigma_y^2 - \sigma_x^2)$ , one can conclude that the contribution of this term is quite small and can be neglected.

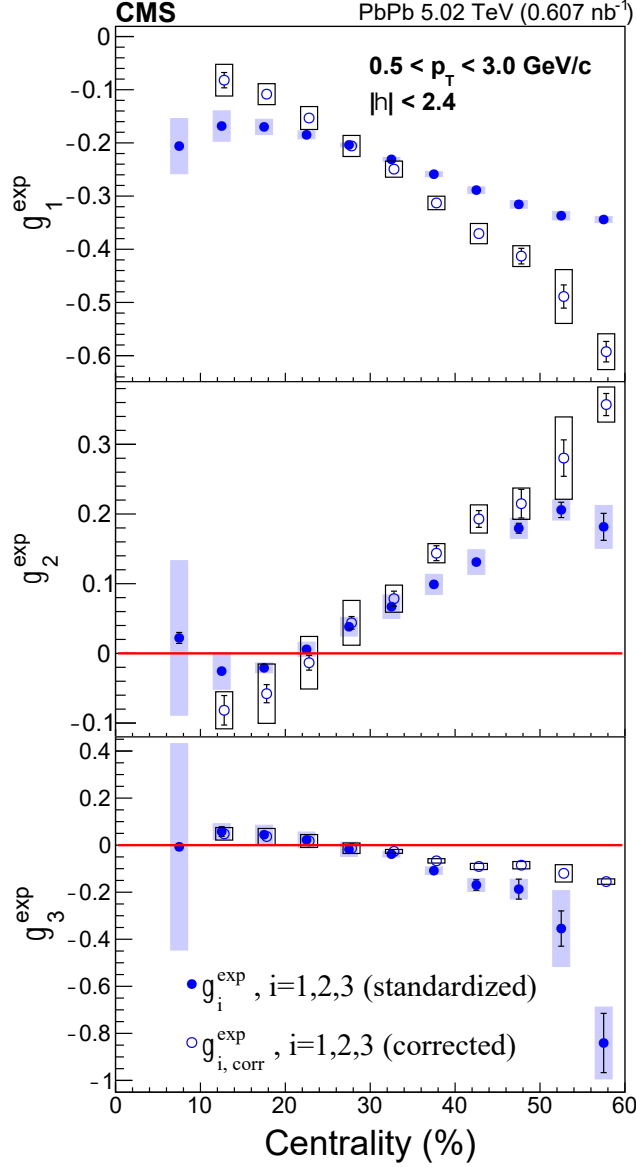


Figure 6: The magnitudes of the measured (closed circles) standardized skewness  $\gamma_1^{\text{exp}}$  (upper), standardized kurtosis  $\gamma_2^{\text{exp}}$  (middle), and standardized superskewness  $\gamma_3^{\text{exp}}$  (lower) as functions of centrality in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV. The magnitudes of the corrected skewness  $\gamma_{1,\text{corr}}^{\text{exp}}$  (upper), corrected kurtosis  $\gamma_{2,\text{corr}}^{\text{exp}}$  (middle), and corrected superskewness  $\gamma_{3,\text{corr}}^{\text{exp}}$  (lower) are presented with the open circles. The bars (the vertical sizes of the open boxes) denote statistical (systematic) uncertainties. Points are plotted at the center of the respective centrality ranges.

Figure 6 displays the distributions of the measured standardized skewness  $\gamma_1^{\text{exp}}$ , standardized kurtosis  $\gamma_2^{\text{exp}}$ , and standardized superskewness  $\gamma_3^{\text{exp}}$  as functions of centrality. The distributions of the corrected skewness  $\gamma_{1,\text{corr}}^{\text{exp}}$  (upper), corrected kurtosis  $\gamma_{2,\text{corr}}^{\text{exp}}$  (middle), and corrected superskewness  $\gamma_{3,\text{corr}}^{\text{exp}}$  (lower) are presented with the open blue circles. The systematic uncertainties are generally larger than the statistical ones. The values of the corrected moments

in the first analyzed centrality bin (5–10%) are not shown because of the very large systematic uncertainties for this centrality range.

Although with different acceptance and differences in the applied methodology, the obtained results for the experimentally measured standardized skewness are in a fair agreement with the results obtained in Ref. [34]. The  $\gamma_1^{\text{exp}}$  is negative over the entire analyzed centrality range. This is a consequence of the  $v_{2,x}$  distribution having a long tail on the low  $v_{2,x}$  side (as shown in Fig. 1 of Ref. [36]). The  $v_{2,y}$  distribution is symmetric and thus its skewness is equal to zero. The  $\gamma_1^{\text{exp}}$  had been predicted to become more negative as the centrality percentile increases [36]. This measurement confirms the prediction.

Similarly to the case of the skewness, although with different acceptance and a difference in the applied methodology to obtain the  $v_2\{2k\}$  values, the  $\gamma_2^{\text{exp}}$  values are in reasonable agreement with the results presented in Ref. [42]. The  $\gamma_2^{\text{exp}}$  values are positive over nearly the entire analyzed centrality range. The exception is the centrality range of 10–20%. The sign of  $\gamma_2^{\text{exp}}$  is driven by the mean eccentricity  $\epsilon_0$ , and is predicted to be negative for  $\epsilon_0 < 0.28$  and positive for  $\epsilon_0 > 0.29$  [42]. Our results are qualitatively in an agreement with this prediction. If the  $v_2$  values were to reflect a purely linear response to the initial-state eccentricity  $\epsilon_2$ , the corresponding kurtosis would equal the kurtosis of the initial  $\epsilon_2$  fluctuations. Although a fully linear response is not expected, calculations predict that deviations from a Gaussian behavior for the skewness and kurtosis, although significantly reduced by the hydrodynamic evolution, are still influenced by the early stage hydrodynamics [36, 56].

Except for collisions with centrality less than 25%, where it is either positive or vanishes, the  $\gamma_3^{\text{exp}}$  moment is negative, with its absolute magnitude increasing towards more peripheral collisions. This is the first measurement of this moment of the  $v_2$  distribution. Without the superskewness, it would be impossible to describe the centrality dependence observed for the new hydrodynamic probe  $h_2$ .

In addition to the experimental results for the standardized skewness, kurtosis, and superskewness, the corresponding corrected moments are also presented. Except for the superskewness, the corrected skewness and kurtosis have larger slopes with respect to the standardized ones. The corrected moments give additional constraints on models of the initial-state geometry.

## 7 Summary

The elliptic anisotropy values based on different orders of multiparticle cumulants,  $v_2\{2k\}$  ( $1 \leq k \leq 5$ ), are determined as functions of centrality in lead-lead collisions at a center-of-mass energy per nucleon pair of  $\sqrt{s_{\text{NN}}} = 5.02$  TeV, with an integrated luminosity of  $0.607 \text{ nb}^{-1}$ . The  $v_2\{10\}$  value is determined for the first time. A fine splitting is observed between the harmonic values based on different cumulant orders, with  $v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\} \gtrsim v_2\{10\}$ . The ordering of the  $v_2\{2k\}$  values is consistent with a hydrodynamic evolution of the quark-gluon plasma (QGP). This splitting is attributed to a non-Gaussian behavior in the event-by-event fluctuations of the  $v_2$  distribution, leading to nonzero values of the skewness, kurtosis, and superskewness. The splitting becomes finer as the  $k$  value increases, with the difference between the adjacent  $v_2\{2k\}$  values decreasing by about an order of magnitude for each increment. The standardized magnitude of the  $v_2$  moments are presented, together with their corrected values, where contributions from higher-order moments (up to the 5th moment) are removed. The large data set of lead-lead collisions collected by the CMS experiment enables a precise measurement of the hydrodynamic probe  $h_1$  as a function of centrality, where  $h_1 = (v_2\{6\} - v_2\{8\}) / (v_2\{4\} - v_2\{6\})$ . A strong centrality dependence is observed, with

values slowly increasing going to more peripheral collisions. This contrasts with an earlier hydrodynamic expectation that had taken the skewness of the initial-state geometry as the main source of non-Gaussian fluctuations. In that case, the ratio was not expected to depend on centrality. Based on the first  $v_2\{10\}$  measurements, a new hydrodynamic probe is introduced that gives an even more precise measure of the initial-state geometry assuming a hydrodynamic evolution of the QGP. The new probe,  $h_2$ , defined as  $h_2 = (v_2\{8\} - v_2\{10\}) / (v_2\{6\} - v_2\{8\})$ , is also found to have a centrality dependence, with a shape similar to the  $h_1$  results. The centrality dependence of both ratios can be understood in terms of the evolving shape of the interaction region with centrality. Based on these results, centrality-dependent moments for the fluctuation-driven event-by-event  $v_2$  distribution are determined, including the skewness, kurtosis and, for the first time, superskewness. The results provide basic input for a precision test of models that assume a hydrodynamic expansion of the QGP.

## 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 and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (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 (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (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, 724704, 752730, 758316, 765710, 824093, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); 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. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP,



the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing, funded by the EU NexGeneration program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF “a way of making Europe”, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

## References

- [1] 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.
- [2] 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.
- [3] 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.
- [4] 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.
- [5] CMS Collaboration, “Evidence for collectivity in pp collisions at the LHC”, *Phys. Lett. B* **765** (2017) 193, doi:10.1016/j.physletb.2016.12.009, arXiv:1606.06198.
- [6] CMS Collaboration, “Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions”, *Phys. Lett. B* **724** (2013) 213, doi:10.1016/j.physletb.2013.06.028, arXiv:1305.0609.
- [7] 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.
- [8] ALICE Collaboration, “Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV”, *Phys. Rev. Lett.* **107** (2011) 032301, doi:10.1103/PhysRevLett.107.032301, arXiv:1105.3865.

- 
- [9] ALICE Collaboration, "Elliptic flow of identified hadrons in Pb-Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV", *JHEP* **06** (2015) 190, doi:10.1007/JHEP06(2015)190, arXiv:1405.4632.
- [10] ALICE Collaboration, "Anisotropic flow of charged particles in Pb-Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV", *Phys. Rev. Lett.* **116** (2016) 132302, doi:10.1103/PhysRevLett.116.132302, arXiv:1602.01119.
- [11] ATLAS Collaboration, "Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead-lead collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV with the ATLAS detector", *Phys. Lett. B* **707** (2012) 330, doi:10.1016/j.physletb.2011.12.056, arXiv:1108.6018.
- [12] ATLAS Collaboration, "Measurement of the azimuthal anisotropy for charged particle production in  $\sqrt{s_{\text{NN}}} = 2.76$  TeV lead-lead collisions with the ATLAS detector", *Phys. Rev. C* **86** (2012) 014907, doi:10.1103/PhysRevC.86.014907, arXiv:1203.3087.
- [13] ATLAS Collaboration, "Measurement of the distributions of event-by-event flow harmonics in lead-lead collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV with the ATLAS detector at the LHC", *JHEP* **11** (2013) 183, doi:10.1007/JHEP11(2013)183, arXiv:1305.2942.
- [14] CMS Collaboration, "Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV", *Eur. Phys. J. C* **72** (2012) 2012, doi:10.1140/epjc/s10052-012-2012-3, arXiv:1201.3158.
- [15] CMS Collaboration, "Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV", *Phys. Rev. C* **87** (2013) 014902, doi:10.1103/PhysRevC.87.014902, arXiv:1204.1409.
- [16] CMS Collaboration, "Measurement of higher-order harmonic azimuthal anisotropy in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV", *Phys. Rev. C* **89** (2014) 044906, doi:10.1103/PhysRevC.89.044906, arXiv:1310.8651.
- [17] CMS Collaboration, "Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV", *JHEP* **02** (2014) 088, doi:10.1007/JHEP02(2014)088, arXiv:1312.1845.
- [18] 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.
- [19] CMS Collaboration, "Principal-component analysis of two-particle azimuthal correlations in PbPb and pPb collisions at CMS", *Phys. Rev. C* **96** (2017) 064902, doi:10.1103/PhysRevC.96.064902, arXiv:1708.07113.
- [20] PHOBOS Collaboration, "System size, energy, pseudorapidity, and centrality dependence of elliptic flow", *Phys. Rev. Lett.* **98** (2007) 242302, doi:10.1103/PhysRevLett.98.242302, arXiv:nucl-ex/0610037.
- [21] PHOBOS Collaboration, "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.

- [22] 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.82.039903, arXiv:1003.0194.
- [23] R. S. Bhalerao, M. Luzum, and J.-Y. Ollitrault, "Determining initial-state fluctuations from flow measurements in heavy-ion collisions", *Phys. Rev. C* **84** (2011) 034910, doi:10.1103/PhysRevC.84.034910, arXiv:1104.4740.
- [24] E. Retinskaya, M. Luzum, and J.-Y. Ollitrault, "Constraining models of initial conditions with elliptic and triangular flow data", *Phys. Rev. C* **89** (2014) 014902, doi:10.1103/PhysRevC.89.014902, arXiv:1311.5339.
- [25] G. Giacalone, J. Noronha-Hostler, and J.-Y. Ollitrault, "Relative flow fluctuations as a probe of initial state fluctuations", *Phys. Rev. C* **95** (2017) 054910, doi:10.1103/PhysRevC.95.054910, arXiv:1702.01730.
- [26] 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.
- [27] J.-Y. Ollitrault, "Determination of the reaction plane in ultrarelativistic nuclear collisions", *Phys. Rev. D* **48** (1993) 1132, doi:10.1103/PhysRevD.48.1132, arXiv:hep-ph/9303247.
- [28] 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.
- [29] N. Borghini, P. M. Dinh, and J.-Y. Ollitrault, "A new method for measuring azimuthal distributions in nucleus-nucleus collisions", *Phys. Rev. C* **63** (2001) 054906, doi:10.1103/PhysRevC.63.054906, arXiv:nucl-th/0007063.
- [30] N. Borghini, P. M. Dinh, and J.-Y. Ollitrault, "Flow analysis from multiparticle azimuthal correlations", *Phys. Rev. C* **64** (2001) 054901, doi:10.1103/PhysRevC.64.054901, arXiv:nucl-th/0105040.
- [31] L. Yan, J.-Y. Ollitrault, and A. M. Poskanzer, "Azimuthal anisotropy distributions in high-energy collisions", *Phys. Lett. B* **742** (2015) 290, doi:10.1016/j.physletb.2015.01.039, arXiv:1408.0921.
- [32] A. Bilandzic, R. Snellings, and S. Voloshin, "Flow analysis with cumulants: Direct calculations", *Phys. Rev. C* **83** (2011) 044913, doi:10.1103/PhysRevC.83.044913, arXiv:1010.0233.
- [33] S. A. Voloshin, A. M. Poskanzer, A. Tang, and G. Wang, "Elliptic flow in the Gaussian model of eccentricity fluctuations", *Phys. Lett. B* **659** (2008) 537, doi:10.1016/j.physletb.2007.11.043, arXiv:0708.0800.
- [34] CMS Collaboration, "Non-Gaussian elliptic-flow fluctuations in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV", *Phys. Lett. B* **789** (2019) 643, doi:10.1016/j.physletb.2018.11.063, arXiv:1711.05594.
- [35] ALICE Collaboration, "Energy dependence and fluctuations of anisotropic flow in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  and 2.76 TeV", *JHEP* **07** (2018) 103, doi:10.1007/JHEP07(2018)103, arXiv:1804.02944.

- 
- [36] G. Giacalone, L. Yan, J. Noronha-Hostler, and J.-Y. Ollitrault, “Skewness of elliptic flow fluctuations”, *Phys. Rev. C* **95** (2017) 014913, doi:10.1103/PhysRevC.95.014913, arXiv:1608.01823.
- [37] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, “Glauber modeling in high energy nuclear collisions”, *Ann. Rev. Nucl. Part. Sci.* **57** (2007) 205, doi:10.1146/annurev.nucl.57.090506.123020, arXiv:nucl-ex/0701025.
- [38] HEPData record for this analysis, 2023. doi:10.17182/hepdata.132638.
- [39] A. Bilandzic, “Anisotropic flow measurements in ALICE at the Large Hadron Collider”. PhD thesis, Utrecht University, 2012. CERN-THESIS-2012-018, <https://cds.cern.ch/record/1432210>.
- [40] L. Nadderd, J. Milosevic, and F. Wang, “Statistical uncertainties of the  $v_n\{2k\}$  harmonics from Q cumulants”, *Phys. Rev. C* **104** (2021) 034906, doi:10.1103/PhysRevC.104.034906, arXiv:2104.00588.
- [41] S. Wang et al., “Measurement of collective flow in heavy ion collisions using particle pair correlations”, *Phys. Rev. C* **44** (1991) 1091, doi:10.1103/PhysRevC.44.1091.
- [42] R. S. Bhalerao, G. Giacalone, and J.-Y. Ollitrault, “Kurtosis of elliptic flow fluctuations”, *Phys. Rev. C* **99** (2019) 014907, doi:10.1103/PhysRevC.99.014907, arXiv:1811.00837.
- [43] L. Yan, J.-Y. Ollitrault, and A. M. Poskanzer, “Eccentricity distributions in nucleus-nucleus collisions”, *Phys. Rev. C* **90** (2014) 024903, doi:10.1103/PhysRevC.90.024903, arXiv:1405.6595.
- [44] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [45] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at  $\sqrt{s}=13$  TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [46] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [47] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at  $\sqrt{s}=13$  TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [48] CMS Collaboration, “CMS luminosity measurement using nucleus-nucleus collisions at  $\sqrt{s_{NN}}=5.02$  TeV in 2018”, CMS Physics Analysis Summary CMS-PAS-LUM-18-001, 2022.
- [49] CMS Collaboration, “Charged-particle nuclear modification factors in PbPb and pPb collisions at  $\sqrt{s_{NN}}=5.02$  TeV”, *JHEP* **04** (2017) 039, doi:10.1007/JHEP04(2017)039, arXiv:1611.01664.
- [50] CMS Collaboration, “Observation and studies of jet quenching in PbPb collisions at nucleon-nucleon center-of-mass energy  $\sqrt{s_{NN}}=2.76$  TeV”, *Phys. Rev. C* **84** (2011) 024906, doi:10.1103/PhysRevC.84.024906, arXiv:1102.1957.

- [51] I. P. Lokhtin and A. M. Snigirev, “A model of jet quenching in ultrarelativistic heavy ion collisions and high- $p_T$  hadron spectra at RHIC”, *Eur. Phys. J. C* **45** (2006) 211, doi:10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.
- [52] 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.
- [53] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [54] CMS Collaboration, “Constraints on the initial state of Pb-Pb collisions via measurements of Z-boson yields and azimuthal anisotropy at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Rev. Lett.* **127** (2021) 102002, doi:10.1103/PhysRevLett.127.102002, arXiv:2103.14089.
- [55] CMS Collaboration, “Strange hadron collectivity in pPb and PbPb collisions”, *JHEP* **05** (2023) 007, doi:10.1007/JHEP05(2023)007, arXiv:2205.00080.
- [56] N. Abbasi, D. Allahbakhshi, A. Davody, and S. F. Taghavi, “Standardized cumulants of flow harmonic fluctuations”, *Phys. Rev. C* **98** (2018) 024906, doi:10.1103/PhysRevC.98.024906, arXiv:1704.06295.

## A Analytic calculation of $v_n\{10\}$ statistical uncertainty

The statistical uncertainty in  $v_n\{10\}$  (given by Eq. (11)) can be expressed analytically using the procedure described in Ref. [40]. Based on the experimental  $\langle\langle 2m \rangle\rangle$  azimuthal correlations, the  $v_n\{10\}$  statistical uncertainty is given by

$$\begin{aligned}
s^2[v_n\{10\}]4560^2(v_n\{10\})^{18} = & A^2\sigma_{\langle\langle 2 \rangle\rangle}^2 + B^2\sigma_{\langle\langle 4 \rangle\rangle}^2 + C^2\sigma_{\langle\langle 6 \rangle\rangle}^2 + D^2\sigma_{\langle\langle 8 \rangle\rangle}^2 + \sigma_{\langle\langle 10 \rangle\rangle}^2 \\
& + 2AB\sigma_{\langle\langle 2 \rangle\rangle, \langle\langle 4 \rangle\rangle} + 2AC\sigma_{\langle\langle 2 \rangle\rangle, \langle\langle 6 \rangle\rangle} + 2AD\sigma_{\langle\langle 2 \rangle\rangle, \langle\langle 8 \rangle\rangle} \\
& + 2A\sigma_{\langle\langle 2 \rangle\rangle, \langle\langle 10 \rangle\rangle} + 2BC\sigma_{\langle\langle 4 \rangle\rangle, \langle\langle 6 \rangle\rangle} + 2BD\sigma_{\langle\langle 4 \rangle\rangle, \langle\langle 8 \rangle\rangle} \\
& + 2B\sigma_{\langle\langle 4 \rangle\rangle, \langle\langle 10 \rangle\rangle} + 2CD\sigma_{\langle\langle 6 \rangle\rangle, \langle\langle 8 \rangle\rangle} + 2C\sigma_{\langle\langle 6 \rangle\rangle, \langle\langle 10 \rangle\rangle} \\
& + 2D\sigma_{\langle\langle 8 \rangle\rangle, \langle\langle 10 \rangle\rangle},
\end{aligned} \tag{A.1}$$

where  $\sigma_{\langle\langle 2k \rangle\rangle}^2$ ,  $k = 1, \dots, 5$  and  $\sigma_{\langle\langle 2k \rangle\rangle, \langle\langle 2l \rangle\rangle}$ , with  $k = 1, \dots, 4$  and  $l = 2, \dots, 5$  are corresponding variances and covariances, respectively. The coefficients  $A$ ,  $B$ ,  $C$ , and  $D$  are given by

$$\begin{aligned}
A &= 14400\langle\langle 2 \rangle\rangle^4 - 10800\langle\langle 2 \rangle\rangle^2\langle\langle 4 \rangle\rangle + 800\langle\langle 6 \rangle\rangle\langle\langle 2 \rangle\rangle + 900\langle\langle 4 \rangle\rangle^2 - 25\langle\langle 8 \rangle\rangle, \\
B &= 1800\langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle - 3600\langle\langle 2 \rangle\rangle^3 - 100\langle\langle 6 \rangle\rangle, \\
C &= 400\langle\langle 2 \rangle\rangle^2 - 100\langle\langle 4 \rangle\rangle, \quad \text{and} \\
D &= -25\langle\langle 2 \rangle\rangle.
\end{aligned} \tag{A.2}$$

## B Central moment expansions of $v_2\{2k\}^2$ , $v_2\{2k\}^3$ , $v_2\{2k\}^4$ , and $v_2\{2k\}^5$

To obtain expressions for the hydrodynamic probes and the standardized and corrected moments in terms of the measured  $v_2\{2k\}$  values, it is necessary to express different powers of the cumulant  $v_2\{2k\}$  values in terms of the central moments. This appendix shows the needed expressions for  $v_2\{2k\}^2$ ,  $v_2\{2k\}^3$ ,  $v_2\{2k\}^4$ , and  $v_2\{2k\}^5$ . The expressions only extend to the fifth central moments.

For  $v_2\{2k\}^2$ :

$$\begin{aligned}
v_2\{4\}^2 &\approx \bar{v}_2^2 + (\sigma_y^2 - \sigma_x^2) - \frac{2s_{30} + 2s_{12}}{\bar{v}_2} - \frac{\kappa_{40} + 2\kappa_{22} + \kappa_{04}}{2\bar{v}_2^2} \\
&\quad - \frac{(\sigma_y^2 - \sigma_x^2)^2}{\bar{v}_2^2} + \frac{2(\sigma_y^2 - \sigma_x^2)(s_{30} + s_{12})}{\bar{v}_2^3}, \\
v_2\{6\}^2 &\approx \bar{v}_2^2 + (\sigma_y^2 - \sigma_x^2) - \frac{4s_{30} + 6s_{12}}{3\bar{v}_2} + \frac{\kappa_{40} - \kappa_{04}}{2\bar{v}_2^2} \\
&\quad - \frac{(\sigma_y^2 - \sigma_x^2)^2}{\bar{v}_2^2} + \frac{p_{50} + 2p_{32} + p_{14}}{2\bar{v}_2^3} + \frac{(\sigma_y^2 - \sigma_x^2)(\frac{2}{3}s_{30} + 4s_{12})}{\bar{v}_2^3}, \\
v_2\{8\}^2 &\approx \bar{v}_2^2 + (\sigma_y^2 - \sigma_x^2) - \frac{14s_{30} + 22s_{12}}{11\bar{v}_2} + \frac{\frac{31}{33}\kappa_{40} + \frac{2}{11}\kappa_{22} - \kappa_{04}}{2\bar{v}_2^2} \\
&\quad - \frac{(\sigma_y^2 - \sigma_x^2)^2}{\bar{v}_2^2} + \frac{10p_{50} + 28p_{32} + 18p_{14}}{33\bar{v}_2^3} + \frac{(\sigma_y^2 - \sigma_x^2)(6s_{30} + 46s_{12})}{11\bar{v}_2^3}, \quad \text{and} \\
v_2\{10\}^2 &\approx \bar{v}_2^2 + (\sigma_y^2 - \sigma_x^2) - \frac{24s_{30} + 38s_{12}}{19\bar{v}_2} + \frac{\frac{53}{19}\kappa_{40} + \frac{12}{19}\kappa_{22} - 3\kappa_{04}}{6\bar{v}_2^2} \\
&\quad - \frac{(\sigma_y^2 - \sigma_x^2)^2}{\bar{v}_2^2} + \frac{\frac{163}{30}p_{50} + \frac{47}{3}p_{32} + \frac{21}{2}p_{14}}{19\bar{v}_2^3} + \frac{(\sigma_y^2 - \sigma_x^2)(10s_{30} + 80s_{12})}{19\bar{v}_2^3}.
\end{aligned} \tag{B.1}$$

For  $v_2\{2k\}^3$ :

$$\begin{aligned}
v_2\{4\}^3 &\approx \bar{v}_2^3 + \frac{3\bar{v}_2(\sigma_y^2 - \sigma_x^2)}{2} - (3s_{30} + 3s_{12}) - \frac{3\kappa_{40} + 6\kappa_{22} + 3\kappa_{04}}{4\bar{v}_2} \\
&\quad - \frac{9(\sigma_y^2 - \sigma_x^2)^2}{8\bar{v}_2} + \frac{3(\sigma_y^2 - \sigma_x^2)(s_{30} + s_{12})}{2\bar{v}_2^2}, \\
v_2\{6\}^3 &\approx \bar{v}_2^3 + \frac{3\bar{v}_2(\sigma_y^2 - \sigma_x^2)}{2} - (2s_{30} + 3s_{12}) - \frac{-3\kappa_{40} + 3\kappa_{04}}{4\bar{v}_2} \\
&\quad - \frac{9(\sigma_y^2 - \sigma_x^2)^2}{8\bar{v}_2} + \frac{3p_{50} + 6p_{32} + 3p_{14}}{4\bar{v}_2^2} + \frac{9(\sigma_y^2 - \sigma_x^2)s_{12}}{2\bar{v}_2^2}, \\
v_2\{8\}^3 &\approx \bar{v}_2^3 + \frac{3\bar{v}_2(\sigma_y^2 - \sigma_x^2)}{2} - \left(\frac{21}{11}s_{30} + 3s_{12}\right) - \frac{-\frac{31}{11}\kappa_{40} - \frac{6}{11}\kappa_{22} + 3\kappa_{04}}{4\bar{v}_2} \\
&\quad - \frac{9(\sigma_y^2 - \sigma_x^2)^2}{8\bar{v}_2} + \frac{\frac{20}{11}p_{50} + \frac{56}{11}p_{32} + \frac{36}{11}p_{14}}{4\bar{v}_2^2} + \frac{(\sigma_y^2 - \sigma_x^2)(\frac{-3}{11}s_{30} + \frac{105}{11}s_{12})}{2\bar{v}_2^2}, \quad \text{and} \\
v_2\{10\}^3 &\approx \bar{v}_2^3 + \frac{3\bar{v}_2(\sigma_y^2 - \sigma_x^2)}{2} - \left(\frac{36}{19}s_{30} + 3s_{12}\right) - \frac{-\frac{53}{19}\kappa_{40} - \frac{12}{19}\kappa_{22} + 3\kappa_{04}}{4\bar{v}_2} \\
&\quad - \frac{9(\sigma_y^2 - \sigma_x^2)^2}{8\bar{v}_2} + \frac{\frac{163}{95}p_{50} + \frac{94}{19}p_{32} + \frac{63}{19}p_{14}}{4\bar{v}_2^2} + \frac{(\sigma_y^2 - \sigma_x^2)(\frac{-6}{19}s_{30} + \frac{183}{19}s_{12})}{2\bar{v}_2^2}.
\end{aligned} \tag{B.2}$$

For  $v_2\{2k\}^4$ :

$$\begin{aligned}
v_2\{4\}^4 &\approx \bar{v}_2^4 + 2\bar{v}_2^2(\sigma_y^2 - \sigma_x^2) - 4\bar{v}_2(s_{30} + s_{12}) - (\kappa_{40} + 2\kappa_{22} + \kappa_{04}) \\
&\quad - (\sigma_y^2 - \sigma_x^2)^2, \\
v_2\{6\}^4 &\approx \bar{v}_2^4 + 2\bar{v}_2^2(\sigma_y^2 - \sigma_x^2) - 4\bar{v}_2\left(\frac{2}{3}s_{30} + s_{12}\right) + (\kappa_{40} - \kappa_{04}) \\
&\quad - (\sigma_y^2 - \sigma_x^2)^2 + \frac{p_{50} + 2p_{32} + p_{14}}{\bar{v}_2} - \frac{(\sigma_y^2 - \sigma_x^2)\left(\frac{4}{3}s_{30} - 4s_{12}\right)}{\bar{v}_2}, \\
v_2\{8\}^4 &\approx \bar{v}_2^4 + 2\bar{v}_2^2(\sigma_y^2 - \sigma_x^2) - \bar{v}_2\left(\frac{28}{11}s_{30} + 4s_{12}\right) + \left(\frac{31}{30}\kappa_{40} + \frac{2}{11}\kappa_{22} - \kappa_{04}\right) \\
&\quad - (\sigma_y^2 - \sigma_x^2)^2 + \frac{\frac{20}{33}p_{50} + \frac{56}{33}p_{32} + \frac{12}{11}p_{14}}{\bar{v}_2} - \frac{(\sigma_y^2 - \sigma_x^2)\left(\frac{16}{11}s_{30} - \frac{48}{11}s_{12}\right)}{\bar{v}_2}, \quad \text{and} \\
v_2\{10\}^4 &\approx \bar{v}_2^4 + 2\bar{v}_2^2(\sigma_y^2 - \sigma_x^2) - \bar{v}_2\left(\frac{48}{19}s_{30} + 4s_{12}\right) + \left(\frac{53}{57}\kappa_{40} + \frac{4}{19}\kappa_{22} - \kappa_{04}\right) \\
&\quad - (\sigma_y^2 - \sigma_x^2)^2 + \frac{\frac{163}{285}p_{50} + \frac{94}{57}p_{32} + \frac{21}{19}p_{14}}{\bar{v}_2} - \frac{(\sigma_y^2 - \sigma_x^2)\left(\frac{28}{19}s_{30} - \frac{84}{19}s_{12}\right)}{\bar{v}_2}.
\end{aligned} \tag{B.3}$$

Finally, for  $v_2\{2k\}^5$ :

$$\begin{aligned}
v_2\{4\}^5 &\approx \bar{v}_2^5 + \frac{5}{2}\bar{v}_2^3(\sigma_y^2 - \sigma_x^2) - \bar{v}_2^2(5s_{30} + 5s_{12}) - \frac{5}{4}\bar{v}_2(\kappa_{40} + 2\kappa_{22} + \kappa_{04}) \\
&\quad - \frac{5}{8}\bar{v}_2(\sigma_y^2 - \sigma_x^2)^2 - (\sigma_y^2 - \sigma_x^2)\left(\frac{5}{2}s_{30} + \frac{5}{2}s_{12}\right), \\
v_2\{6\}^5 &\approx \bar{v}_2^5 + \frac{5}{2}\bar{v}_2^3(\sigma_y^2 - \sigma_x^2) - \bar{v}_2^2\left(\frac{10}{3}s_{30} + 5s_{12}\right) + \frac{5}{4}\bar{v}_2(\kappa_{40} - \kappa_{04}) \\
&\quad - \frac{5}{8}\bar{v}_2(\sigma_y^2 - \sigma_x^2)^2 + \frac{5}{4}(p_{50} + 2p_{32} + p_{14}) - (\sigma_y^2 - \sigma_x^2)\left(\frac{10}{3}s_{30} - \frac{5}{2}s_{12}\right), \\
v_2\{8\}^5 &\approx \bar{v}_2^5 + \frac{5}{2}\bar{v}_2^3(\sigma_y^2 - \sigma_x^2) - \bar{v}_2^2\left(\frac{35}{11}s_{30} + 5s_{12}\right) + \bar{v}_2\left(\frac{155}{132}\kappa_{40} + \frac{5}{22}\kappa_{22} - \frac{5}{4}\kappa_{04}\right) \\
&\quad - \frac{5}{8}\bar{v}_2(\sigma_y^2 - \sigma_x^2)^2 + \left(\frac{25}{33}p_{50} + \frac{70}{33}p_{32} + \frac{15}{11}p_{14}\right) - (\sigma_y^2 - \sigma_x^2)\left(\frac{75}{22}s_{30} - \frac{65}{22}s_{12}\right), \quad \text{and} \\
v_2\{10\}^5 &\approx \bar{v}_2^5 + \frac{5}{2}\bar{v}_2^3(\sigma_y^2 - \sigma_x^2) - \bar{v}_2^2\left(\frac{60}{19}s_{30} + 5s_{12}\right) + \bar{v}_2\left(\frac{265}{228}\kappa_{40} + \frac{5}{19}\kappa_{22} - \frac{5}{4}\kappa_{04}\right) \\
&\quad - \frac{5}{8}\bar{v}_2(\sigma_y^2 - \sigma_x^2)^2 + \left(\frac{163}{228}p_{50} + \frac{235}{114}p_{32} + \frac{105}{76}p_{14}\right) - (\sigma_y^2 - \sigma_x^2)\left(\frac{65}{19}s_{30} - \frac{115}{38}s_{12}\right).
\end{aligned} \tag{B.4}$$

## C Expanding the $h_1$ hydrodynamic probe to include terms up to the fifth central moment

The hydrodynamic probe,  $h_1$ , was introduced in Ref. [36], but in this earlier reference its Taylor expansion was only shown to the 3rd moment of the  $(v_x, v_y)$  distribution. If none of the terms from Eqs. (14)–(16) are neglected, the right-hand side of Eq. (18) becomes

$$\frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} \approx \frac{1}{11} \left( 1 - \frac{4\kappa_{40} + \frac{8(p_{50} + p_{32})}{\bar{v}_2}}{2\bar{v}_2 s_{30} + 3(\kappa_{40} + \kappa_{22}) + \frac{3(p_{50} + 2p_{32} + p_{14}) - 2(\sigma_y^2 - \sigma_x^2)(5s_{30} - 6s_{12})}{2\bar{v}_2}} \right). \tag{C.1}$$



Without neglecting any terms in Eq. (B.1), the full relationship corresponding to Eq. (19) is

$$\frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} \approx \frac{1}{11} - \frac{1}{11} \frac{v_2\{4\}^2 - 12v_2\{6\}^2 + 11v_2\{8\}^2}{v_2\{4\}^2 - v_2\{6\}^2 + \frac{(\sigma_y^2 - \sigma_x^2)s_{30}}{3\bar{v}_2^2}}. \quad (\text{C.2})$$

## D Validity of the conditions given by Eq. (29)

Moments of the elliptic-power distribution are obtained in Ref. [43]:

$$\begin{aligned} \langle \epsilon_{n,x}^{2k} \epsilon_{n,y}^{2l} \rangle &= X_{2k} {}_3\tilde{F}_2\left(k + \frac{1}{2}, \alpha + 1, \alpha + \frac{1}{2}; \frac{1}{2}, 1 + l + k + \alpha; \epsilon_0^2\right), \quad \text{and} \\ \langle \epsilon_{n,x}^{2k+1} \epsilon_{n,y}^{2l} \rangle &= \epsilon_0 X_{2k+1} {}_3\tilde{F}_2\left(k + \frac{3}{2}, \alpha + 1, \alpha + \frac{3}{2}; \frac{3}{2}, 2 + l + k + \alpha; \epsilon_0^2\right), \end{aligned} \quad (\text{D.1})$$

where

$$\begin{aligned} X_{2k} &= \frac{\alpha}{\sqrt{\pi}} (1 - \epsilon_0^2)^{\alpha+1/2} \Gamma(\alpha) \Gamma\left(k + \frac{1}{2}\right) \Gamma\left(l + \frac{1}{2}\right), \quad \text{and} \\ X_{2k+1} &= \frac{\alpha(1 + 2\alpha)}{2\sqrt{\pi}} (1 - \epsilon_0^2)^{\alpha+1/2} \Gamma(\alpha) \Gamma\left(k + \frac{3}{2}\right) \Gamma\left(l + \frac{1}{2}\right), \end{aligned} \quad (\text{D.2})$$

and  ${}_3\tilde{F}_2$  is the regularized hypergeometric function. For the case when the ellipticity parameter tends to zero,  $\epsilon_0 \rightarrow 0$ , the upper formulas give the following ratios between moments of the initial anisotropy distribution:


$$\begin{aligned} \frac{\langle \epsilon_{n,x}^1 \epsilon_{n,y}^2 \rangle}{\langle \epsilon_{n,x}^3 \epsilon_{n,y}^0 \rangle} &= \frac{\Gamma\left(\frac{3}{2}\right) \Gamma\left(\frac{3}{2}\right)}{\Gamma\left(\frac{5}{2}\right) \Gamma\left(\frac{1}{2}\right)} = \frac{1}{3}, \\ \frac{\langle \epsilon_{n,x}^2 \epsilon_{n,y}^2 \rangle}{\langle \epsilon_{n,x}^4 \epsilon_{n,y}^0 \rangle} &= \frac{\Gamma\left(\frac{3}{2}\right) \Gamma\left(\frac{3}{2}\right)}{\Gamma\left(\frac{5}{2}\right) \Gamma\left(\frac{1}{2}\right)} = \frac{1}{3}, \quad \text{and} \\ \frac{\langle \epsilon_{n,x}^1 \epsilon_{n,y}^4 \rangle}{\langle \epsilon_{n,x}^5 \epsilon_{n,y}^0 \rangle} &= \frac{\langle \epsilon_{n,x}^3 \epsilon_{n,y}^2 \rangle}{\langle \epsilon_{n,x}^5 \epsilon_{n,y}^0 \rangle} = \frac{\Gamma\left(\frac{5}{2}\right) \Gamma\left(\frac{3}{2}\right)}{\Gamma\left(\frac{7}{2}\right) \Gamma\left(\frac{1}{2}\right)} = \frac{1}{5}. \end{aligned} \quad (\text{D.3})$$

By assuming linear response between the flow and the initial anisotropy, the relations given by Eq. (D.3) are also well satisfied for the corresponding moments of the  $v_n$  distribution. Furthermore, these relations are considerably transferred to relations between the corresponding central moments of the  $v_n$  distribution given by Eq. (29). We tested these conditions numerically and found that they are satisfied to a reasonable degree in the range of the eccentricity parameter  $\epsilon_0 \leq 0.15$ .

























## E The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan 














### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic , T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , P.S. Hussain , M. Jeitler<sup>1</sup> , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch , F.M. Pitters , J. Schieck<sup>1</sup> , R. Schöfbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz<sup>1</sup> 

### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>2</sup> , T. Janssen , T. Kello<sup>3</sup> , H. Rejeb Sfar , P. Van Mechelen 

### Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck , D. Vannerom 

### Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux , G. De Lentdecker , L. Favart , D. Hohov , J. Jaramillo , K. Lee , M. Mahdavihorrani , I. Makarenko , A. Malara , S. Paredes , L. Pétré , N. Postiau , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 






### Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach , C. Rendón , A. Samalan , K. Skovpen , M. Tytgat , N. Van Den Bossche , B. Vermassen , L. Wezenbeek 






















### Université Catholique de Louvain, Louvain-la-Neuve, Belgium

A. Benecke , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaitre , K. Mondal , A. Taliercio , T.T. Tran , P. Vischia , S. Wertz 








### Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , A. Moraes , P. Rebello Teles 

### Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato<sup>4</sup> , E.M. Da Costa , G.G. Da Silveira<sup>5</sup> , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins<sup>6</sup> , C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima , A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel , A. Vilela Pereira 

### Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes<sup>5</sup> , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 


### Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov , G. Antchev , R. Hadjiiska , P. Iaydjiev , M. Misheva , M. Rodozov , M. Shopova , G. Sultanov 

### University of Sofia, Sofia, Bulgaria

A. Dimitrov , T. Ivanov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka 





### Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

S. Thakur 

**Beihang University, Beijing, China**

T. Cheng , T. Javaid<sup>7</sup> , M. Mittal , L. Yuan 

**Department of Physics, Tsinghua University, Beijing, China**

M. Ahmad , G. Bauer<sup>8</sup>, Z. Hu , S. Lezki , K. Yi<sup>8,9</sup> 

**Institute of High Energy Physics, Beijing, China**

G.M. Chen<sup>7</sup> , H.S. Chen<sup>7</sup> , M. Chen<sup>7</sup> , F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao , Z.-A. Liu<sup>10</sup> , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao 


**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**

A. Agapitos , Y. An , Y. Ban , A. Levin , C. Li , Q. Li , X. Lyu, Y. Mao, S.J. Qian , X. Sun , D. Wang , J. Xiao , H. Yang

**Sun Yat-Sen University, Guangzhou, China**

M. Lu , Z. You 

**University of Science and Technology of China, Hefei, China**

N. Lu 

**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**

X. Gao<sup>3</sup> , D. Leggat, H. Okawa , Y. Zhang 

**Zhejiang University, Hangzhou, Zhejiang, China**

Z. Lin , C. Lu , M. Xiao 

**Universidad de Los Andes, Bogota, Colombia**

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga 

**Universidad de Antioquia, Medellin, Colombia**

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 








**University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**

D. Giljanovic , N. Godinovic , D. Lelas , I. Puljak 

**University of Split, Faculty of Science, Split, Croatia**

Z. Antunovic, M. Kovac , T. Sculac 




**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra , M. Roguljic , A. Starodumov<sup>11</sup> , T. Susa 

**University of Cyprus, Nicosia, Cyprus**

A. Attikis , K. Christoforou , M. Kolosova , S. Konstantinou , J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

**Charles University, Prague, Czech Republic**

M. Finger , M. Finger Jr. , A. Kveton 

**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**

S. Elgammal<sup>12</sup>, A. Ellithi Kamel<sup>13</sup>

**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**

M.A. Mahmoud , Y. Mohammed 

















**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola , H. Kirschenmann , K. Osterberg , M. Voutilainen 
















**Helsinki Institute of Physics, Helsinki, Finland**

S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen, T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti, L. Martikainen , M. Myllymäki , J. Ott , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi 





























**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

P. Luukka , H. Petrow , T. Tuuva












**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**

C. Amendola , M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro<sup>14</sup> , P. Simkina , M. Titov 


















**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

C. Baldenegro Barrera , F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati , C. Charlot , F. Damas , O. Davignon , B. Diab , G. Falmagne , B.A. Fontana Santos Alves , S. Ghosh , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , R. Salerno , U. Sarkar , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche 




**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**

J.-L. Agram<sup>15</sup> , J. Andrea , D. Apparu , D. Bloch , G. Bourgatte , J.-M. Brom , E.C. Chabert , C. Collard , D. Darej, U. Goerlach , C. Grimault, A.-C. Le Bihan , P. Van Hove 



**Institut de Physique des 2 Infinis de Lyon (IP2I ), Villeurbanne, France**

S. Beauceron , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen<sup>16</sup> , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, L. Torterotot , M. Vander Donckt , P. Verdier , S. Viret


























**Georgian Technical University, Tbilisi, Georgia**

D. Chokheli , I. Lomidze , Z. Tsamalaidze<sup>11</sup> 









**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert , M. Teroerde 

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , M. Erdmann , P. Fackeldey , D. Fasanella , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee , L. Mastrolorenzo, M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll , A. Novak , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , H. Reithler , A. Schmidt , S.C. Schuler, A. Sharma , A. Stein , F. Torres Da Silva De Araujo<sup>17</sup> , L. Vigilante, S. Wiedenbeck , S. Zaleski



















### **RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

C. Dziwok , G. Flügge , W. Haj Ahmad<sup>18</sup> , O. Hlushchenko, T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 



















### **Deutsches Elektronen-Synchrotron, Hamburg, Germany**

H. Aarup Petersen , M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou , O. Behnke , A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , F. Blekman<sup>19</sup> , K. Borrás<sup>20</sup> , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina , S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , L. Didukh , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo<sup>19</sup> , A. Geiser , A. Giraldi , G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari<sup>21</sup> , N.Z. Jomhari , B. Kaech , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka<sup>22</sup> , W. Lohmann<sup>23</sup> , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham<sup>24,20</sup> , V. Scheurer, S. Schnake<sup>20</sup> , P. Schütze , C. Schwanenberger<sup>19</sup> , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon<sup>†</sup> , M. Van De Klundert , F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann, L. Wiens<sup>20</sup> , C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos 

### **University of Hamburg, Hamburg, Germany**

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , M. Bonanomi , P. Connor , K. De Leo , M. Eich, K. El Morabit , F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , M. Hajheidari, J. Haller , A. Hinzmann , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , A. Mehta , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , M. Rieger , O. Rieger, D. Savoiu , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf 









### **Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann<sup>25</sup> , M. Horzela , U. Husemann , M. Klute , R. Koppenhöfer , M. Link, A. Lintuluoto , S. Maier , S. Mitra , Th. Müller , M. Neukum, M. Oh , G. Quast , K. Rabbertz , J. Rauser, M. Schnepf, I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube , M. Wassmer , S. Wieland , R. Wolf , S. Wozniowski , S. Wunsch, X. Zuo 




### **Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece**

G. Anagnostou, P. Assiouras , G. Daskalakis , A. Kyriakis, A. Stakia 


### **National and Kapodistrian University of Athens, Athens, Greece**

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , A. Manousakis-Katsikakis , A. Panagiotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 






#### National Technical University of Athens, Athens, Greece

G. Bakas , T. Chatzistavrou, K. Kousouris , I. Papakrivopoulos , G. Tsipolitis, A. Zacharopoulou

#### University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Gianneios , C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

#### HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók<sup>26</sup> , G. Bencze, C. Hajdu , D. Horvath<sup>27,28</sup> , F. Sikler , V. Veszpremi 


#### MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Csanád , K. Farkas , M.M.A. Gadallah<sup>29</sup> , S. Lökös<sup>30</sup> , P. Major , K. Mandal , G. Pásztor , A.J. Rádl<sup>31</sup> , O. Surányi , G.I. Veres 




#### Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni , S. Czellar, J. Karancsi<sup>26</sup> , J. Molnar, Z. Szillasi, D. Teyssier 


















#### Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari<sup>32</sup> 

#### Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo<sup>31</sup> , F. Nemes<sup>31</sup> , T. Novak 










#### Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra<sup>33</sup> , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh<sup>34</sup> , A. Singla , A. K. Viridi 















#### University of Delhi, Delhi, India

A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , M. Naimuddin , K. Ranjan , S. Saumya 


#### Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman<sup>35</sup> , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber<sup>36</sup> , M. Maity<sup>35</sup> , P. Palit , G. Saha , B. Sahu , S. Sarkar




#### Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , S. Chatterjee , P. Kalbhor , J.R. Komaragiri<sup>37</sup> , D. Kumar<sup>37</sup> , A. Muhammad , L. Panwar<sup>37</sup> , R. Pradhan , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , S. Verma 



#### Bhabha Atomic Research Centre, Mumbai, India

K. Naskar<sup>38</sup> 

#### Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, I. Das , S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara

#### Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee , R. Chudasama , M. Guchait , S. Karmakar , S. Kumar , G. Majumder ,  
K. Mazumdar , S. Mukherjee , A. Thachayath 

**National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**

S. Bahinipati<sup>39</sup> , A.K. Das , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu<sup>40</sup> , A. Nayak<sup>40</sup> , P. Saha , S.K. Swain , D. Vats<sup>40</sup> 

**Indian Institute of Science Education and Research (IISER), Pune, India**

A. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma 

**Isfahan University of Technology, Isfahan, Iran**

H. Bakhshiansohi<sup>41,42</sup> , E. Khazaie<sup>42</sup> , M. Zeinali<sup>43</sup> 
































**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**

S. Chenarani<sup>44</sup> , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























**University College Dublin, Dublin, Ireland**

M. Grunewald 

**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup> , R. Aly<sup>a,b,45</sup> , C. Aruta<sup>a,b</sup> , A. Colaleo<sup>a</sup> , D. Creanza<sup>a,c</sup> ,  
N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , A. Di Florio<sup>a,b</sup> , W. Elmetenawee<sup>a,b</sup> ,  
F. Errico<sup>a,b</sup> , L. Fiore<sup>a</sup> , G. Iaselli<sup>a,c</sup> , G. Maggi<sup>a,c</sup> , M. Maggi<sup>a</sup> , I. Margjeka<sup>a,b</sup> ,  
V. Mastrapasqua<sup>a,b</sup> , S. My<sup>a,b</sup> , S. Nuzzo<sup>a,b</sup> , A. Pellecchia<sup>a,b</sup> , A. Pompili<sup>a,b</sup> ,  
G. Pugliese<sup>a,c</sup> , R. Radogna<sup>a</sup> , D. Ramos<sup>a</sup> , A. Ranieri<sup>a</sup> , G. Selvaggi<sup>a,b</sup> ,  
L. Silvestris<sup>a</sup> , F.M. Simone<sup>a,b</sup> , Ü. Sözbilir<sup>a</sup> , A. Stamerra<sup>a</sup> , R. Venditti<sup>a</sup> ,  
P. Verwilligen<sup>a</sup> 


















**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup> , C. Battilana<sup>a,b</sup> , D. Bonacorsi<sup>a,b</sup> , L. Borgonovi<sup>a</sup> , L. Brigliadori<sup>a</sup>,  
R. Campanini<sup>a,b</sup> , P. Capiluppi<sup>a,b</sup> , A. Castro<sup>a,b</sup> , F.R. Cavallo<sup>a</sup> , M. Cuffiani<sup>a,b</sup> ,  
G.M. Dallavalle<sup>a</sup> , T. Diotallevi<sup>a,b</sup> , F. Fabbri<sup>a</sup> , A. Fanfani<sup>a,b</sup> , P. Giacomelli<sup>a</sup> ,  
L. Giommi<sup>a,b</sup> , C. Grandi<sup>a</sup> , L. Guiducci<sup>a,b</sup> , S. Lo Meo<sup>a,46</sup> , L. Lunerti<sup>a,b</sup> ,  
S. Marcellini<sup>a</sup> , G. Masetti<sup>a</sup> , F.L. Navarria<sup>a,b</sup> , A. Perrotta<sup>a</sup> , F. Primavera<sup>a,b</sup> ,  
A.M. Rossi<sup>a,b</sup> , T. Rovelli<sup>a,b</sup> , G.P. Siroli<sup>a,b</sup> 

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

S. Costa<sup>a,b,47</sup> , A. Di Mattia<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,47</sup> , C. Tuve<sup>a,b</sup> 






**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup> , G. Bardelli<sup>a,b</sup> , B. Camaiani<sup>a,b</sup> , A. Cassese<sup>a</sup> , R. Ceccarelli<sup>a,b</sup> ,  
V. Ciulli<sup>a,b</sup> , C. Civinini<sup>a</sup> , R. D'Alessandro<sup>a,b</sup> , E. Focardi<sup>a,b</sup> , G. Latino<sup>a,b</sup> ,  
P. Lenzi<sup>a,b</sup> , M. Lizzo<sup>a,b</sup> , M. Meschini<sup>a</sup> , S. Paoletti<sup>a</sup> , R. Seidita<sup>a,b</sup> , G. Sguazzoni<sup>a</sup> ,  
L. Viliani<sup>a</sup> 












**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi , S. Bianco , S. Meola<sup>48</sup> , D. Piccolo 












**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**

M. Bozzo<sup>a,b</sup> , P. Chatagnon<sup>a</sup> , F. Ferro<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> 




**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a</sup> , G. Boldrini<sup>a</sup> , F. Brivio<sup>a,b</sup> , F. Cetorelli<sup>a,b</sup> , F. De Guio<sup>a,b</sup> ,  
M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a,b</sup> 


























M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup> , S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , D. Pedrini<sup>a</sup> , B.S. Pinolini<sup>a</sup>, S. Ragazzi<sup>a,b</sup> , N. Redaelli<sup>a</sup> , T. Tabarelli de Fatis<sup>a,b</sup> , D. Zuolo<sup>a,b</sup> 












**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Scuola Superiore Meridionale (SSM)<sup>d</sup>, Napoli, Italy**

S. Buontempo<sup>a</sup> , F. Carnevali<sup>a,b</sup>, N. Cavallo<sup>a,c</sup> , A. De Iorio<sup>a,b</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,49</sup> , P. Paolucci<sup>a,25</sup> , B. Rossi<sup>a</sup> , C. Sciacca<sup>a,b</sup> 















**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**

P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,50</sup> , P. Bortignon<sup>a</sup> , A. Bragagnolo<sup>a,b</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a</sup> , F. Gasparini<sup>a,b</sup> , U. Gasparini<sup>a,b</sup> , G. Grosso<sup>a</sup>, L. Layer<sup>a,51</sup>, E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , A.T. Meneguzzo<sup>a,b</sup> , M. Michelotto<sup>a</sup> , F. Montecassiano<sup>a</sup> , J. Pazzini<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup> , F. Simonetto<sup>a,b</sup> , G. Strong<sup>a</sup> , M. Tosi<sup>a,b</sup> , H. Yarar<sup>a,b</sup>, M. Zanetti<sup>a,b</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> 



































**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**

S. Abu Zeid<sup>a,52</sup> , C. Aimè<sup>a,b</sup> , A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a,b</sup> , D. Fiorina<sup>a,b</sup> , P. Montagna<sup>a,b</sup> , V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a</sup> , P. Vitulo<sup>a,b</sup> 






**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**

P. Asenov<sup>a,53</sup> , G.M. Bilei<sup>a</sup> , D. Ciangottini<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , M. Magherini<sup>a,b</sup> , G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,53</sup> , A. Piccinelli<sup>a,b</sup> , M. Presilla<sup>a,b</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> 







































**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy**

P. Azzurri<sup>a</sup> , G. Bagliesi<sup>a</sup> , V. Bertacchi<sup>a,c</sup> , R. Bhattacharya<sup>a</sup> , L. Bianchini<sup>a,b</sup> , T. Boccali<sup>a</sup> , E. Bossini<sup>a,b</sup> , D. Bruschini<sup>a,c</sup> , R. Castaldi<sup>a</sup> , M.A. Ciocci<sup>a,b</sup> , V. D'Amante<sup>a,d</sup> , R. Dell'Orso<sup>a</sup> , M.R. Di Domenico<sup>a,d</sup> , S. Donato<sup>a</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , G. Mandorli<sup>a,c</sup> , D. Matos Figueiredo<sup>a</sup>, A. Messineo<sup>a,b</sup> , M. Musich<sup>a,b</sup> , F. Palla<sup>a</sup> , S. Parolia<sup>a</sup> , G. Ramirez-Sanchez<sup>a,c</sup> , A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a</sup> , T. Sarkar<sup>a</sup> , A. Scribano<sup>a</sup> , N. Shafiei<sup>a,b</sup> , P. Spagnolo<sup>a</sup> , R. Tenchini<sup>a</sup> , G. Tonelli<sup>a,b</sup> , N. Turini<sup>a,d</sup> , A. Venturi<sup>a</sup> , P.G. Verdini<sup>a</sup> 




**INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy**

P. Barria<sup>a</sup> , M. Campana<sup>a,b</sup> , F. Cavallari<sup>a</sup> , D. Del Re<sup>a,b</sup> , E. Di Marco<sup>a</sup> , M. Diemoz<sup>a</sup> , E. Longo<sup>a,b</sup> , P. Meridiani<sup>a</sup> , G. Organtini<sup>a,b</sup> , F. Pandolfi<sup>a</sup> , R. Paramatti<sup>a,b</sup> , C. Quaranta<sup>a,b</sup> , S. Rahatlou<sup>a,b</sup> , C. Rovelli<sup>a</sup> , F. Santanastasio<sup>a,b</sup> , L. Soffi<sup>a</sup> , R. Tramontano<sup>a,b</sup> 















**INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup> , R. Arcidiacono<sup>a,c</sup> , S. Argiro<sup>a,b</sup> , M. Arneodo<sup>a,c</sup> , N. Bartosik<sup>a</sup> , R. Bellan<sup>a,b</sup> , A. Bellora<sup>a,b</sup> , C. Biino<sup>a</sup> , N. Cartiglia<sup>a</sup> , M. Costa<sup>a,b</sup> , R. Covarelli<sup>a,b</sup> , N. Demaria<sup>a</sup> , M. Grippo<sup>a,b</sup> , B. Kiani<sup>a,b</sup> , F. Legger<sup>a</sup> , C. Mariotti<sup>a</sup> , S. Maselli<sup>a</sup> , A. Mecca<sup>a,b</sup> , E. Migliore<sup>a,b</sup> , E. Monteil<sup>a,b</sup> , M. Monteno<sup>a</sup> , R. Mulargia<sup>a</sup> , M.M. Obertino<sup>a,b</sup> , G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<sup>a</sup> , M. Pelliccioni<sup>a</sup> , M. Ruspa<sup>a,c</sup> , K. Shchelina<sup>a</sup> , F. Siviero<sup>a,b</sup> , V. Sola<sup>a,b</sup> , A. Solano<sup>a,b</sup> , D. Soldi<sup>a,b</sup> , A. Staiano<sup>a</sup> , M. Tornago<sup>a,b</sup> , D. Trocino<sup>a</sup> , G. Umoret<sup>a,b</sup> , A. Vagnerini<sup>a,b</sup> 

**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup> , V. Candelise<sup>a,b</sup> , M. Casarsa<sup>a</sup> , F. Cossutti<sup>a</sup> , A. Da Rold<sup>a,b</sup> ,  
G. Della Ricca<sup>a,b</sup> , G. Sorrentino<sup>a,b</sup> 




**Kyungpook National University, Daegu, Korea**

S. Dogra , C. Huh , B. Kim , D.H. Kim , G.N. Kim , J. Kim , J. Lee , S.W. Lee ,  
C.S. Moon , Y.D. Oh , S.I. Pak , M.S. Ryu , S. Sekmen , Y.C. Yang 










**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea**

H. Kim , D.H. Moon 

**Hanyang University, Seoul, Korea**

E. Asilar , T.J. Kim , J. Park 

**Korea University, Seoul, Korea**

S. Choi , S. Han , B. Hong , K. Lee , K.S. Lee , J. Lim , J. Park , S.K. Park , J. Yoo 

**Kyung Hee University, Department of Physics, Seoul, Korea**

J. Goh 

**Sejong University, Seoul, Korea**

H. S. Kim , Y. Kim , S. Lee 



**Seoul National University, Seoul, Korea**

J. Almond , J.H. Bhyun , J. Choi , S. Jeon , J. Kim , J.S. Kim , S. Ko , H. Kwon , H. Lee ,  
S. Lee , B.H. Oh , S.B. Oh , H. Seo , U.K. Yang , I. Yoon 







**University of Seoul, Seoul, Korea**

W. Jang , D.Y. Kang , Y. Kang , D. Kim , S. Kim , B. Ko , J.S.H. Lee , Y. Lee , J.A. Merlin ,  
I.C. Park , Y. Roh , D. Song , I.J. Watson , S. Yang 



**Yonsei University, Department of Physics, Seoul, Korea**

S. Ha , H.D. Yoo 

**Sungkyunkwan University, Suwon, Korea**

M. Choi , M.R. Kim , H. Lee , Y. Lee , Y. Lee , I. Yu 

**College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait**

T. Beyrouthy , Y. Maghrbi 





**Riga Technical University, Riga, Latvia**

K. Dreimanis , G. Pikurs , A. Potrebko , M. Seidel , V. Veckalns<sup>54</sup> 









**Vilnius University, Vilnius, Lithuania**

M. Ambrozas , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius ,  
G. Tamulaitis 

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**

N. Bin Norjoharuddeen , S.Y. Hoh<sup>55</sup> , I. Yusuff<sup>55</sup> , Z. Zolkapli 

**Universidad de Sonora (UNISON), Hermosillo, Mexico**

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta , L.G. Gallegos Maríñez ,  
M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo 

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**

G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz<sup>56</sup> , R. Lopez-Fernandez 

C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 

**Universidad Iberoamericana, Mexico City, Mexico**

C. Oropeza Barrera , F. Vazquez Valencia 








**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

**University of Montenegro, Podgorica, Montenegro**

I. Bubanja, J. Mijuskovic<sup>57</sup> , N. Raicevic 








**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, M. Gul , H.R. Hoorani ,  
W.A. Khan , M. Shoaib , M. Waqas 






**AGH University of Krakow, 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. Szeleper ,  
P. Zalewski 






**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski 





























**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

M. Araujo , P. Bargassa , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar ,  
N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , J. Varela 

**VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**

P. Adzic<sup>58</sup> , M. Dordevic , P. Milenovic , J. Milosevic , L. Nadder 













**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

M. Aguilar-Benitez, J. Alcaraz Maestre , A. Álvarez Fernández , M. Barrio Luna,  
Cristina F. Bedoya , C.A. Carrillo Montoya , M. Cepeda , M. Cerrada , N. Colino ,  
B. De La Cruz , A. Delgado Peris , D. Fernández Del Val , J.P. Fernández Ramos ,  
J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez ,  
M.I. Josa , J. León Holgado , D. Moran , C. Perez Dengra , A. Pérez-Calero Yzquierdo ,  
J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas ,  
J. Sastre , L. Urda Gómez , J. Vazquez Escobar , C. Willmott













**Universidad Autónoma de Madrid, Madrid, Spain**

J.F. de Trocóniz 

**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero ,  
J.R. González Fernández , E. Palencia Cortezon , C. Ramón Álvarez ,  
V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba 

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez ,  
C. Fernandez Madrazo , A. García Alonso, G. Gomez , C. Lasiosa García ,  
C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas 

J. Piedra Gomez , C. Prieels, L. Scodellaro , I. Vila , J.M. Vizan Garcia 

**University of Colombo, Colombo, Sri Lanka**

M.K. Jayananda , B. Kailasapathy<sup>59</sup> , D.U.J. Sonnadara , D.D.C. Wickramarathna 





**University of Ruhuna, Department of Physics, Matara, Sri Lanka**

W.G.D. Dharmaratna , K. Liyanage , N. Perera , N. Wickramage 




































**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo , J. Alimena , E. Auffray , G. Auzinger , J. Baechler, P. Baillon<sup>†</sup>, D. Barney , J. Bendavid , M. Bianco , B. Bilin , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury, M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont, F. Fallavollita<sup>60</sup>, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabady , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas<sup>61</sup> , A.G. Stahl Leitner , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsirou, J. Wanczyk<sup>62</sup> , K.A. Wozniak , W.D. Zeuner
























**Paul Scherrer Institut, Villigen, Switzerland**

L. Caminada<sup>63</sup> , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli<sup>63</sup> , L. Noehte<sup>63</sup> , T. Rohe 




**ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**

T.K. Aarrestad , K. Androsov<sup>62</sup> , M. Backhaus , P. Berger, A. Calandri , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani<sup>62</sup> , F. Nessi-Tedaldi , J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini, D.A. Sanz Becerra , J. Steggemann<sup>62</sup> , D. Valsecchi<sup>25</sup> , R. Wallny 











**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>64</sup> , P. Bäertschi , C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechi , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi 

**National Central University, Chung-Li, Taiwan**


C. Adloff<sup>65</sup>, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari<sup>37</sup> , S.S. Yu 

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





















L. Ceard, Y. Chao , K.F. Chen , P.s. Chen, H. Cheng , W.-S. Hou , R. Khurana, G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , A. Psallidas, A. Steen , H.y. Wu, E. Yazgan , P.r. Yu

**High Energy Physics Research Unit, Department of Physics, Faculty of Science,**



**Chulalongkorn University, Bangkok, Thailand**

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

**Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu<sup>66</sup> , E. Eskut ,  
Y. Guler<sup>67</sup> , E. Gurpinar Guler<sup>67</sup> , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu ,  
G. Onengut , K. Ozdemir<sup>68</sup> , A. Polatoz , A.E. Simsek , B. Tali<sup>69</sup> , U.G. Tok ,  
S. Turkcapar , E. Uslan , I.S. Zorbakir 

**Middle East Technical University, Physics Department, Ankara, Turkey**

G. Karapinar<sup>70</sup>, K. Ocalan<sup>71</sup> , M. Yalvac<sup>72</sup> 

**Bogazici University, Istanbul, Turkey**

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya<sup>73</sup> , O. Kaya<sup>74</sup> , S. Tekten<sup>75</sup> 


**Istanbul Technical University, Istanbul, Turkey**

A. Cakir , K. Cankocak<sup>66</sup> , Y. Komurcu , S. Sen<sup>66</sup> 

**Istanbul University, Istanbul, Turkey**

O. Aydilek , S. Cerci<sup>69</sup> , B. Hacisahinoglu , I. Hos<sup>76</sup> , B. Isildak<sup>77</sup> , B. Kaynak ,  
S. Ozkorucuklu , C. Simsek , D. Sunar Cerci<sup>69</sup> 
















**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine**

B. Grynyov 



















**National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine**

L. Levchuk 



































**University of Bristol, Bristol, United Kingdom**

D. Anthony , E. Bhal , J.J. Brooke , A. Bundock , E. Clement , D. Cussans ,  
H. Flacher , M. Glowacki, J. Goldstein , H.F. Heath , L. Kreczko , B. Krikler ,  
S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou<sup>78</sup> , K. Walkingshaw Pass,  
R. White 




**Rutherford Appleton Laboratory, Didcot, United Kingdom**

A.H. Ball, K.W. Bell , A. Belyaev<sup>79</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill ,  
C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg<sup>80</sup> , Sh. Jain , J. Linacre ,  
K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh,  
C.H. Shepherd-Themistocleous , I.R. Tomalin , T. Williams 

**Imperial College, London, United Kingdom**








R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , C.E. Brown , O. Buchmuller, V. Cacchio,  
V. Cepaitis , G.S. Chahal<sup>81</sup> , D. Colling , J.S. Dancu, P. Dauncey , G. Davies , J. Davies,  
M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles ,  
J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen ,  
D.G. Monk , J. Nash<sup>82</sup> , M. Pesaresi, B.C. Radburn-Smith , D.M. Raymond, A. Richards,  
A. Rose , E. Scott , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley ,  
L.H. Vage, T. Virdee<sup>25</sup> , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom 

**Brunel University, Uxbridge, United Kingdom**



K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 

**Baylor University, Waco, Texas, USA**

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanu-

ganti , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , M. Toms ,  
J. Wilson 

















**Catholic University of America, Washington, DC, USA**

R. Bartek , A. Dominguez , R. Uniyal , A.M. Vargas Hernandez 



















**The University of Alabama, Tuscaloosa, Alabama, USA**

S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio<sup>83</sup> ,  
C. West 


















**Boston University, Boston, Massachusetts, USA**

A. Akpınar , A. Albert , D. Arcaro , C. Cosby , Z. Demiragli , C. Erice ,  
E. Fontanesi , D. Gastler , S. May , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart ,  
I. Suarez , A. Tsatsos , S. Yuan 















**Brown University, Providence, Rhode Island, USA**

G. Benelli , B. Burkle , X. Coubez<sup>20</sup>, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan<sup>84</sup> ,  
T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan ,  
S. Sagir<sup>85</sup> , F. Simpson , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang









**University of California, Davis, Davis, California, USA**

J. Bonilla , C. Brainerd , R. Breedon , M. Calderon De La Barca Sanchez , M. Chertok ,  
J. Conway , P.T. Cox , R. Erbacher , G. Haza , F. Jensen , O. Kukral , G. Mocellin ,  
M. Mulhearn , D. Pellett , B. Regnery , Y. Yao , F. Zhang 
























**University of California, Los Angeles, California, USA**

M. Bachtis , R. Cousins , A. Datta , D. Hamilton , J. Hauser , M. Ignatenko ,  
M.A. Iqbal , T. Lam , E. Manca , W.A. Nash , S. Regnard , D. Saltzberg , B. Stone ,  
V. Valuev 





















**University of California, Riverside, Riverside, California, USA**

R. Clare , J.W. Gary , M. Gordon, G. Hanson , G. Karapostoli , O.R. Long ,  
N. Manganelli , W. Si , S. Wimpenny 












**University of California, San Diego, La Jolla, California, USA**

J.G. Branson , P. Chang , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte ,  
R. Gerosa , L. Giannini , J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts ,  
M. Masciovecchio , F. Mokhtar , M. Pieri , B.V. Sathia Narayanan , V. Sharma ,  
M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 














**University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA**

N. Amin, C. Campagnari , M. Citron , G. Collura , A. Dorsett , V. Dutta ,  
J. Incandela , M. Kilpatrick , J. Kim , A.J. Li , P. Masterson , H. Mei , M. Oshiro ,  
M. Quinnan , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , P. Siddireddy,  
D. Stuart , S. Wang 













**California Institute of Technology, Pasadena, California, USA**

A. Bornheim , O. Cerri, I. Dutta , A. Latorre, J.M. Lawhorn , J. Mao , H.B. Newman ,  
T. Q. Nguyen , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 


















**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**

J. Alison , S. An , M.B. Andrews , P. Bryant , T. Ferguson , A. Harilal , C. Liu ,  
T. Mudholkar , S. Murthy , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 
































































**University of Colorado Boulder, Boulder, Colorado, USA**

J.P. Cumalat , W.T. Ford , A. Hassani , G. Karathanasis , E. MacDonald, F. Marini , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper 



















**Cornell University, Ithaca, New York, USA**

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , D. Gadkari , S. Hogan , J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 











**Fermi National Accelerator Laboratory, Batavia, Illinois, USA**

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , K.F. Di Petrillo , J. Dickinson , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gece , L. Gray , D. Green, S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>86</sup> , F. Ravera , A. Reinsvold Hall<sup>87</sup> , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 







**University of Florida, Gainesville, Florida, USA**

P. Avery , D. Bourilkov , L. Cadamuro , V. Cherepanov , R.D. Field, M. Kim, E. Koenig , J. Konigsberg , A. Korytov , E. Kuznetsova<sup>88</sup> , K.H. Lo, K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig , K. Shi , J. Wang , Z. Wu 



















**Florida State University, Tallahassee, Florida, USA**

T. Adams , A. Askew , N. Bower , R. Habibullah , V. Hagopian , T. Kolberg , G. Martinez, H. Prosper , O. Viazlo , M. Wulansatiti , R. Yohay , J. Zhang












**Florida Institute of Technology, Melbourne, Florida, USA**

M.M. Baarmand , S. Butalla , T. Elkafrawy<sup>52</sup> , M. Hohmann , R. Kumar Verma , M. Rahmani, F. Yumiceva 












**University of Illinois Chicago, Chicago, USA, Chicago, USA**

M.R. Adams , H. Becerril Gonzalez , R. Cavanaugh , S. Dittmer , O. Evdokimov , C.E. Gerber , D.J. Hofman , D. S. Lemos , A.H. Merrit , C. Mills , G. Oh , T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , X. Wang , Z. Ye , J. Yoo 







**The University of Iowa, Iowa City, Iowa, USA**

















M. Alhousseini , K. Dilsiz<sup>89</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>90</sup> , J. Nachtman , O. Neogi, H. Ogul<sup>91</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>92</sup> 

**Johns Hopkins University, Baltimore, Maryland, USA**







O. Amram , B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , S. Kyriacou , P. Maksimovic , J. Roskes , S. Sekhar , M. Swartz , T.Á. Vámi 

**The University of Kansas, Lawrence, Kansas, USA**

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers 

T. Isidori , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey, J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 


















#### **Kansas State University, Manhattan, Kansas, USA**

B. Allmond , S. Duric, A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim, Y. Maravin , T. Mitchell, A. Modak, K. Nam, D. Roy 























#### **Lawrence Livermore National Laboratory, Livermore, California, USA**

F. Rebassoo , D. Wright 















#### **University of Maryland, College Park, Maryland, USA**

E. Adams , A. Baden , O. Baron, A. Belloni , A. Bethani , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , L. Wang , K. Wong 

#### **Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**

D. Abercrombie, W. Busza , I.A. Cali , Y. Chen , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, P. Harris, M. Hu , D. Kovalskyi , J. Krupa , Y.-J. Lee , K. Long , C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland , Z. Shi , G.S.F. Stephans , J. Wang, Z. Wang , B. Wyslouch , T. J. Yang 

#### **University of Minnesota, Minneapolis, Minnesota, USA**

R.M. Chatterjee, B. Crossman , A. Evans , J. Hiltbrand , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 

#### **University of Mississippi, Oxford, Mississippi, USA**

L.M. Cremaldi 




















#### **University of Nebraska-Lincoln, Lincoln, Nebraska, USA**

K. Bloom , M. Bryson, D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , R. Kamalieddin, I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow<sup>†</sup>, W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 








#### **State University of New York at Buffalo, Buffalo, New York, USA**

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , A. Williams 





















#### **Northeastern University, Boston, Massachusetts, USA**

G. Alverson , E. Barberis , Y. Haddad , Y. Han , A. Krishna , J. Li , J. Lidrych , G. Madigan , B. Marzocchi , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , A. Tishelman-Charny , T. Wamorkar , B. Wang , A. Wisecarver , D. Wood 

#### **Northwestern University, Evanston, Illinois, USA**










S. Bhattacharya , J. Bueghly, Z. Chen , A. Gilbert , K.A. Hahn , Y. Liu , N. Odell , M.H. Schmitt , M. Velasco

#### **University of Notre Dame, Notre Dame, Indiana, USA**

















R. Band , R. Bucci, M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko<sup>11</sup> , R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 



**The Ohio State University, Columbus, Ohio, USA**

B. Bylsma, M. Carrigan , L.S. Durkin , B. Francis , C. Hill , M. Joyce , A. Lesauvage , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 




















**Princeton University, Princeton, New Jersey, USA**

F.M. Addesa , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich , S. Higginbotham , G. Kopp , S. Kwan , D. Lange , D. Marlow , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 



**University of Puerto Rico, Mayaguez, Puerto Rico, USA**

S. Malik , S. Norberg















**Purdue University, West Lafayette, Indiana, USA**

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung , D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic<sup>14</sup> , J. Thieman , F. Wang , R. Xiao , W. Xie 













**Purdue University Northwest, Hammond, Indiana, USA**

J. Dolen , N. Parashar 


**Rice University, Houston, Texas, USA**

D. Acosta , A. Baty , T. Carnahan , S. Dildick , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li , B.P. Padley , R. Redjimi, J. Rotter , S. Yang , E. Yigitbasi , L. Zhang<sup>93</sup>, Y. Zhang 

















**University of Rochester, Rochester, New York, USA**

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , C. Fallon, M. Galanti, A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , P. Parygin , E. Popova , E. Ranken , R. Taus , G.P. Van Onsem 

**The Rockefeller University, New York, New York, USA**

K. Goulianos 














**Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA**

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl , D. Jaroslawski , O. Karacheban<sup>23</sup> , I. Laflotte , A. Lath , R. Montalvo, K. Nash, M. Osherson , H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, H. Wang 

**University of Tennessee, Knoxville, Tennessee, USA**

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier 










**Texas A&M University, College Station, Texas, USA**

O. Bouhali<sup>94</sup> , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang , T. Kamon<sup>95</sup> , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens , A. Safonov 

**Texas Tech University, Lubbock, Texas, USA**

N. Akchurin , J. Damgov , V. Hegde , K. Lamichhane , S.W. Lee , T. Mengke, S. Muthumuni , T. Peltola , I. Volobouev , A. Whitbeck 

**Vanderbilt University, Nashville, Tennessee, USA**

E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 






















**University of Virginia, Charlottesville, Virginia, USA**

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , A. Ledovskoy ,  
A. Li , C. Neu , C.E. Perez Lara , B. Tannenwald 



















































**Wayne State University, Detroit, Michigan, USA**

P.E. Karchin , N. Poudyal 

**University of Wisconsin - Madison, Madison, Wisconsin, USA**

S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni,  
H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, A. Loeliger , R. Loveless ,  
J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida ,  
D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi ,  
W. Vetens 

**Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN**

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev ,  
A. Belyaev , V. Blinov<sup>96</sup>, E. Boos , V. Borshch , D. Budkouski , V. Chekhovsky,  
R. Chistov<sup>96</sup> , M. Danilov<sup>96</sup> , A. Demiyarov , A. Dermenev , T. Dimova<sup>96</sup> ,  
I. Dreminev , V. Epshteyn , A. Ershov , G. Gavrillov , V. Gavrillov , S. Gninenko ,  
V. Golovtsov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin , Y. Ivanov ,  
V. Kachanov , L. Kardapoltsev<sup>96</sup> , V. Karjavine , A. Karneyev , L. Khein, V. Kim<sup>96</sup> ,  
M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , O. Kodolova<sup>97</sup> , D. Konstantinov ,  
V. Korenkov , V. Korotkikh, A. Kozyrev<sup>96</sup> , N. Krasnikov , A. Lanev , P. Levchenko ,  
A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev<sup>96</sup> ,  
V. Murzin , A. Nikitenko<sup>98</sup> , S. Obraztsov , I. Ovtin<sup>96</sup> , V. Palichik , V. Perelygin ,  
S. Petrushanko , S. Polikarpov<sup>96</sup> , V. Popov, O. Radchenko<sup>96</sup> , M. Savina , V. Savrin ,  
D. Selivanova , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen<sup>96</sup> , S. Slabospitskii ,  
V. Smirnov , A. Snigirev , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov ,  
O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , I. Vardanyan ,  
E. Vlasov , A. Vorobyev, N. Voytishin , B.S. Yuldashev<sup>99</sup>, A. Zarubin , I. Zhizhin ,  
A. Zhokin 

†: Deceased

<sup>1</sup>Also at TU Wien, Vienna, Austria

<sup>2</sup>Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

<sup>3</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium

<sup>4</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil

<sup>5</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

<sup>6</sup>Also at UFMS, Nova Andradina, Brazil

<sup>7</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>8</sup>Also at Nanjing Normal University, Nanjing, China

<sup>9</sup>Now at The University of Iowa, Iowa City, Iowa, USA

<sup>10</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>11</sup>Also at an institute or an international laboratory covered by a cooperation agreement with CERN

<sup>12</sup>Now at British University in Egypt, Cairo, Egypt

<sup>13</sup>Now at Cairo University, Cairo, Egypt

<sup>14</sup>Also at Purdue University, West Lafayette, Indiana, USA

<sup>15</sup>Also at Université de Haute Alsace, Mulhouse, France

- 
- <sup>16</sup>Also at Department of Physics, Tsinghua University, Beijing, China
- <sup>17</sup>Also at The University of the State of Amazonas, Manaus, Brazil
- <sup>18</sup>Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- <sup>19</sup>Also at University of Hamburg, Hamburg, Germany
- <sup>20</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- <sup>21</sup>Also at Isfahan University of Technology, Isfahan, Iran
- <sup>22</sup>Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- <sup>23</sup>Also at Brandenburg University of Technology, Cottbus, Germany
- <sup>24</sup>Also at Forschungszentrum Jülich, Juelich, Germany
- <sup>25</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- <sup>26</sup>Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- <sup>27</sup>Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- <sup>28</sup>Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- <sup>29</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- <sup>30</sup>Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- <sup>31</sup>Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- <sup>32</sup>Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- <sup>33</sup>Also at Punjab Agricultural University, Ludhiana, India
- <sup>34</sup>Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- <sup>35</sup>Also at University of Visva-Bharati, Santiniketan, India
- <sup>36</sup>Also at University of Hyderabad, Hyderabad, India
- <sup>37</sup>Also at Indian Institute of Science (IISc), Bangalore, India
- <sup>38</sup>Also at Indian Institute of Technology (IIT), Mumbai, India
- <sup>39</sup>Also at IIT Bhubaneswar, Bhubaneswar, India
- <sup>40</sup>Also at Institute of Physics, Bhubaneswar, India
- <sup>41</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- <sup>42</sup>Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- <sup>43</sup>Also at Sharif University of Technology, Tehran, Iran
- <sup>44</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>45</sup>Also at Helwan University, Cairo, Egypt
- <sup>46</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>47</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>48</sup>Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>49</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>50</sup>Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- <sup>51</sup>Also at Università di Napoli 'Federico II', Napoli, Italy
- <sup>52</sup>Also at Ain Shams University, Cairo, Egypt
- <sup>53</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>54</sup>Also at Riga Technical University, Riga, Latvia
- <sup>55</sup>Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- <sup>56</sup>Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- <sup>57</sup>Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- <sup>58</sup>Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- <sup>59</sup>Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- <sup>60</sup>Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- <sup>61</sup>Also at National and Kapodistrian University of Athens, Athens, Greece

<sup>62</sup>Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland

<sup>63</sup>Also at Universität Zürich, Zurich, Switzerland

<sup>64</sup>Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria

<sup>65</sup>Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

<sup>66</sup>Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey

<sup>67</sup>Also at Konya Technical University, Konya, Turkey

<sup>68</sup>Also at Izmir Bakircay University, Izmir, Turkey

<sup>69</sup>Also at Adiyaman University, Adiyaman, Turkey

<sup>70</sup>Also at Istanbul Gedik University, Istanbul, Turkey

<sup>71</sup>Also at Necmettin Erbakan University, Konya, Turkey

<sup>72</sup>Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey

<sup>73</sup>Also at Marmara University, Istanbul, Turkey

<sup>74</sup>Also at Milli Savunma University, Istanbul, Turkey

<sup>75</sup>Also at Kafkas University, Kars, Turkey

<sup>76</sup>Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

<sup>77</sup>Also at Ozyegin University, Istanbul, Turkey

<sup>78</sup>Also at Vrije Universiteit Brussel, Brussel, Belgium

<sup>79</sup>Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

<sup>80</sup>Also at University of Bristol, Bristol, United Kingdom

<sup>81</sup>Also at IPPP Durham University, Durham, United Kingdom

<sup>82</sup>Also at Monash University, Faculty of Science, Clayton, Australia

<sup>83</sup>Also at Università di Torino, Torino, Italy

<sup>84</sup>Also at Bethel University, St. Paul, Minnesota, USA

<sup>85</sup>Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

<sup>86</sup>Also at California Institute of Technology, Pasadena, California, USA

<sup>87</sup>Also at United States Naval Academy, Annapolis, Maryland, USA

<sup>88</sup>Also at University of Florida, Gainesville, Florida, USA

<sup>89</sup>Also at Bingol University, Bingol, Turkey

<sup>90</sup>Also at Georgian Technical University, Tbilisi, Georgia

<sup>91</sup>Also at Sinop University, Sinop, Turkey

<sup>92</sup>Also at Erciyes University, Kayseri, Turkey

<sup>93</sup>Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

<sup>94</sup>Also at Texas A&M University at Qatar, Doha, Qatar

<sup>95</sup>Also at Kyungpook National University, Daegu, Korea

<sup>96</sup>Also at another institute or international laboratory covered by a cooperation agreement with CERN

<sup>97</sup>Also at Yerevan Physics Institute, Yerevan, Armenia

<sup>98</sup>Also at Imperial College, London, United Kingdom

<sup>99</sup>Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan