



Non-Gaussian elliptic-flow fluctuations in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration^{*}

CERN, Switzerland

ARTICLE INFO

Article history:

Received 15 November 2017
Received in revised form 18 November 2018
Accepted 23 November 2018
Available online 2 January 2019
Editor: M. Doser

Keywords:

Event-by-event elliptic flow
Non-Gaussian flow fluctuations
Unfolding

ABSTRACT

Event-by-event fluctuations in the elliptic-flow coefficient v_2 are studied in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the CMS detector at the CERN LHC. Elliptic-flow probability distributions $p(v_2)$ for charged particles with transverse momentum $0.3 < p_T < 3.0$ GeV/c and pseudorapidity $|\eta| < 1.0$ are determined for different collision centrality classes. The moments of the $p(v_2)$ distributions are used to calculate the v_2 coefficients based on cumulant orders 2, 4, 6, and 8. A rank ordering of the higher-order cumulant results and nonzero standardized skewness values obtained for the $p(v_2)$ distributions indicate non-Gaussian initial-state fluctuations. Bessel–Gaussian and elliptic power fits to the flow distributions are studied to characterize the initial-state spatial anisotropy.

© 2018 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

Ultrarelativistic heavy ion collisions at both the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC) create a hot and dense state of matter that consists of strongly interacting quarks and gluons, the “quark–gluon plasma” (QGP) [1–7]. Measurements of azimuthal particle correlations resulting from these collisions reveal properties of the QGP, but also of the initial state of a heavy-ion collision. In particular, the overall shape and fluctuations in the initial-state transverse energy density transformed by the hydrodynamic evolution of the medium into anisotropies in the final-state momentum space for the emitted particles [8–10], as reflected in the azimuthal charged-particle density. The early RHIC measurements of the azimuthal correlations showed that the QGP could be described well by hydrodynamic models [11], with a shear viscosity to entropy density ratio (η/s) that is of the order of the lowest possible value for a quantum fluid [12,13].

The azimuthal charged-particle density can be characterized by a Fourier expansion, with

$$\frac{dN_{ch}}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]. \quad (1)$$

Here, the n th-order flow vector for a given event is $\vec{v}_n \equiv (v_n \cos \Phi_n, v_n \sin \Phi_n)$, where Φ_n is the angle of the intrinsic n th-order flow

symmetry plane, as determined by the geometry of the participant nucleons. The experimentally accessible “event plane” angle, Ψ_n^{obs} , is based on the direction of maximum outgoing particle density and is, on average, in the same direction as Φ_n , but fluctuates about Φ_n because of resolution effects due to finite particle multiplicities.

By calculating the flow coefficients over a large number of events, the underlying probability distribution functions of individual Fourier coefficients can be determined. While the mean values of the v_n distributions can be related to the overall shape of the interaction region, the higher order moments can be used to constrain the origin and the nature of the initial-state fluctuations and help disentangle the initial-state effects from the subsequent evolution of the medium [14,15]. Here, an event-by-event analysis is performed where it is possible to reduce the sensitivity of the results to nonflow correlations [16] and to clearly establish higher-order moments of the $n = 2$ (elliptic) distribution function. The mean of this distribution, $\langle v_2 \rangle$, is largely determined by the lenticular shape of the collision overlap region.

While the final-state particle distribution is characterized by the $\vec{v}_n$ coefficients, the initial-state spatial anisotropy can be characterized by a harmonic expansion in terms of eccentricity vectors $\vec{\epsilon}_n$ [17–20]. For a given impact parameter, fluctuations in the initial-state transverse energy density lead to event-by-event differences in the orientation and magnitude of the $\vec{\epsilon}_n$ vectors with respect to the experimentally inaccessible “reaction plane,” defined by the collision impact parameter and beam directions. The presence of a nonzero viscosity will degrade the correspondence between initial-

^{*} E-mail address: cms-publication-committee-chair@cern.ch.

and final-state anisotropies [11,21]. Still, an almost linear dependence is expected for the lowest order $n = 2$ [22–26] and $n = 3$ [9,18] harmonics, with $v_n = k_n \varepsilon_n$ [19]. Here, $v_n \equiv |\vec{v}_n|$, $\varepsilon_n \equiv |\vec{\varepsilon}_n|$, and k_n is the flow response coefficient. The probability distribution functions of the magnitudes of the $\vec{\varepsilon}_n$ vectors, $p(\varepsilon_n)$, can be related to the corresponding $p(v_n)$ distribution assuming a linear response, according to:

$$p(v_n) = \frac{d\varepsilon_n}{dv_n} p(\varepsilon_n) = \frac{1}{k_n} p\left(\frac{v_n}{k_n}\right), \quad (2)$$

where the k_n term is expected to depend on the hydrodynamic evolution of the medium [27,28].

The elliptic-flow $p(v_2)$ distribution can be characterized using the experimentally determined multiparticle cumulant flow harmonics $v_2\{m\}$ [29,30], where m is the cumulant order. Alternatively, the distribution can be determined directly, as shown by the ATLAS Collaboration [16] and as done here, by removing finite-multiplicity resolution effects in the measured $p(v_2^{\text{obs}})$ distribution through an unfolding technique. The cumulant harmonics are expressed in terms of the moments of the $p(v_2)$ distribution [31,32]:

$$\begin{aligned} v_2\{2\}^2 &\equiv E(v_2^2), \\ v_2\{4\}^4 &\equiv -E(v_2^4) + 2E(v_2^2)^2, \\ v_2\{6\}^6 &\equiv (E(v_2^6) - 9E(v_2^4)E(v_2^2) + 12E(v_2^2)^3)/4, \\ v_2\{8\}^8 &\equiv -(E(v_2^8) - 16E(v_2^6)E(v_2^2) - 18E(v_2^4)^2 \\ &\quad + 144E(v_2^4)E(v_2^2)^2 - 144E(v_2^2)^4)/33, \end{aligned} \quad (3)$$

where $E(v_2^k) \equiv \int v_2^k p(v_2) dv_2$. The unitless standardized skewness of a probability distribution is a measure of the asymmetry about its mean. For the case of elliptic flow, the standardized skewness with respect to the reaction plane can be estimated using the cumulant flow harmonics as in Ref. [33]:

$$\gamma_1^{\text{exp}} \equiv -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}. \quad (4)$$

Hydrodynamic calculations find this estimate to be in good agreement with the actual skewness except for the most peripheral events [33].

The standardized skewness estimate vanishes for fluctuations that arise from an isotropic Gaussian transverse initial-state energy density profile. In this case, the $p(v_2)$ distribution is found by taking an integral over the azimuthal dependence of the two-dimensional Gaussian function [31,34]. The resultant, one-dimensional distribution has a Bessel–Gaussian shape, where the even cumulant coefficients $v_2\{m\}$ with $m \geq 4$ are degenerate [31]. The observation for PbPb collisions that $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ [35–37], where the approximate equalities are within a few percent, suggests that the $\vec{v}_2$ fluctuations can be well described by a two-dimensional Gaussian function [31].

Still, non-Gaussian fluctuations are expected in the initial-state energy density [33], which should lead to differences in the higher order cumulant coefficients. Such differences have been reported by the ATLAS Collaboration [16] in a similar measurement of peripheral PbPb collisions to that reported here. The precision of the LHC measurements allows for these differences to be explored in detail, giving a new method to investigate the initial-state behavior. The elliptic power function has been suggested to describe the asymmetric behavior of the $p(\varepsilon_n)$ distributions [14,15,38], noting that the Bessel–Gaussian distribution reproduces neither Glauber

Monte Carlo nor IP-Glasma results other than for very central events [14]. This function is based on the assumption that the initial energy density profile of the collision is a superposition of N point-like, independent sources. In terms of the harmonic-flow coefficients and assuming a linear response,

$$p(v_n) = \frac{2\alpha v_n}{\pi k_n^2} (1 - \varepsilon_0^2)^{\alpha+1/2} \int_0^\pi \frac{(1 - v_n^2/k_n^2)^{\alpha-1} d\phi}{(1 - \varepsilon_0 v_n \cos \phi/k_n)^{2\alpha+1}}, \quad (5)$$

where ε_0 is approximately equal to the mean eccentricity in the reaction plane and α , which is approximately proportional to N , describes the size of the eccentricity fluctuations. The elliptic power distribution reduces to a Gaussian, Bessel–Gaussian, or power distribution form with the appropriate choice of parameters [39] and has the advantage of naturally incorporating the unit constraint on eccentricity, where $|\varepsilon_n| < 1$.

In this Letter, the $p(v_2)$ distributions for charged particles in the pseudorapidity range $|\eta| < 1.0$ and with transverse momenta $0.3 < p_T < 3.0$ GeV/c are presented for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV collected with the CMS detector at the LHC. The results are shown in bins of centrality, defined as fractions of the total inelastic hadronic cross section, where 0% corresponds to the events with the greatest hadronic activity in the forward direction ($|\eta| > 3.0$). The elliptic-flow harmonic values for different cumulant orders are determined based on the moments of the $p(v_2)$ distributions, with these results used to estimate the standardized skewness of the flow distribution. Elliptic power and Bessel–Gaussian fits to the flow distributions are presented to gain further insight into the initial-state and its fluctuations.

2. The CMS detector

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, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

The barrel and endcap detectors provide coverage in the range $|\eta| < 3.0$, with Hadron Forward calorimeters (HF) extending the pseudorapidity coverage to $3.0 < |\eta| < 5.2$. The HF detectors are used both to select events for the analysis and to determine the collision centrality. The HF calorimeters are azimuthally subdivided into 20° modular wedges and further segmented to form $0.175 \times 10^\circ$ ($\Delta\eta \times \Delta\phi$) towers. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15148 silicon strip detector modules. At midrapidity, there are 3 pixel detector layers and 10 strip detector layers. At the outer edge of the tracker acceptance, there are 2 pixel detector layers and 12 strip detector layers. For nonisolated particles of $1 < p_T < 10$ GeV/c and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) distance of closest approach [40]. 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. [41].

3. Event and track selection

This analysis is based on a PbPb minimum bias data set with $\sqrt{s_{NN}} = 5.02$ TeV and corresponding to an integrated luminosity of $26 \mu\text{b}^{-1}$, collected in 2015. The minimum-bias trigger used requires coincident signals in the HF calorimeters at both ends of

the CMS detector with energy deposits above a predefined energy threshold of approximately 1 GeV and the presence of both colliding bunches at the interaction point as determined using beam pickup timing monitors. By requiring colliding bunches, events due to noise (e.g., cosmic rays and beam backgrounds) are largely suppressed. Events are further selected offline by requiring at least three towers with an energy above 3 GeV in each of the two HF calorimeters. The primary vertex for each event is chosen as the reconstructed vertex with the largest number of associated tracks. Primary vertices are required to have at least two associated tracks and to be located within 15 (0.2) cm of the nominal collision point along the longitudinal (transverse) direction. To suppress contamination from events with multiple collisions in the same bunch crossing (pileup), the procedure outlined in Ref. [6] is followed. Here, compatibility scores based on the number of pixel clusters with widths compatible with particles originating from each primary vertex are determined and events with primary vertices with compatibility scores below a predefined threshold are rejected as pileup. After applying the selection criteria, the average number of collisions per bunch crossing is less than ≈ 0.001 for the events used in this analysis, with a pileup fraction $< 0.05\%$.

Track reconstruction [40,42] is performed in two iterations to ease the computational load for high-multiplicity central PbPb collisions. The first iteration reconstructs tracks from signals (“hits”) in the silicon pixel and strip detectors compatible with a trajectory of $p_T > 0.9$ GeV/c. These tracks are required to have consistency with originating from the primary vertex, having a longitudinal association significance (d_z/σ_{d_z}) and a distance of closest approach significance (d_0/σ_{d_0}) each less than 3. In addition, the p_T resolution [40,42] for each track, σ_{p_T}/p_T , is required to be less than 10% and tracks are required to have at least 11 out of the 14 possible hits along their trajectory in the pixel and strip trackers. To reduce the number of misidentified tracks, which can occur when the hit pattern is consistent with more than one possible track solution, the chi-squared per degree of freedom, χ^2/dof , associated with fitting the track trajectory through the different pixel and strip layers must be less than 0.15 times the total number of layers with hits along the trajectory of the track. The second iteration reconstructs tracks compatible with a trajectory of $p_T > 0.2$ GeV/c using solely the pixel detector. These tracks are required to have longitudinal association significance $d_z/\sigma_{d_z} < 8$ and a fit χ^2/dof value less than 12 times the number of layers with hits along the trajectory of the track. In the final analysis, first iteration tracks with $p_T > 1.0$ GeV/c are used together with pixel-detector-only tracks with $p_T < 2.4$ GeV/c after removing duplicates. Track reconstruction for the merged iterations has a combined geometric acceptance and efficiency exceeding 60% for $p_T \approx 1.0$ GeV/c and $|\eta| < 1.0$. When the track p_T is below 1 GeV/c, the acceptance and efficiency steadily drops, reaching approximately 40% at $p_T \approx 0.3$ GeV/c.

4. Analysis technique

Analyses of flow harmonics using multiparticle cumulants were initially introduced as a way to minimize nonflow effects [30]. These analyses have been based on either the generating function formalism [30] or, more recently, through direct calculation [43]. The unfolding procedure employed here, as introduced by the ATLAS collaboration [16], is expected to give similar results to a multiparticle cumulant analysis, but with reduced sensitivity to multiplicity fluctuations and nonflow effects [44].

The event-by-event v_2 coefficients and phases in Eq. (1) can be estimated with

$$\begin{aligned} v_{2,x}^{\text{obs}} &= |\vec{v}_2^{\text{obs}}| \cos(2\Psi_2^{\text{obs}}) = \langle \cos(2\phi) \rangle = \frac{\sum_i w_i \cos(2\phi_i)}{\sum_i w_i}, \\ v_{2,y}^{\text{obs}} &= |\vec{v}_2^{\text{obs}}| \sin(2\Psi_2^{\text{obs}}) = \langle \sin(2\phi) \rangle = \frac{\sum_i w_i \sin(2\phi_i)}{\sum_i w_i}, \quad (6) \\ |\vec{v}_2^{\text{obs}}| &= \sqrt{(v_{2,x}^{\text{obs}})^2 + (v_{2,y}^{\text{obs}})^2}, \end{aligned}$$

where ϕ_i is the azimuthal angle of the track, Ψ_2^{obs} is the event plane angle for the 2nd harmonic, the angular brackets denote an efficiency weighted average over all particles in a given range of phase space for an event, and $w_i = 1/\varepsilon_i$ is the inverse of the tracking efficiency $\varepsilon_i(p_T, \eta)$ of the i th track. The analysis does not require the explicit calculation of the event plane angle for each event. In the absence of particle correlations unrelated to the hydrodynamic flow behavior (“nonflow”), the observed event-by-event flow vectors of Eq. (6) will approach the true underlying flow vectors as the particle multiplicity becomes large. In addition to the efficiency weighting, a standard recentering procedure [45], where the event average x - and y -components of the flow vector are required to equal zero, is applied to further suppress acceptance biases.

Events are sorted into different centrality classes, as determined by the transverse energy deposited in the HF calorimeters [6], and the magnitudes of the estimated flow vectors are used to construct the “observed” $p(v_2^{\text{obs}})$ distributions for each class. Finite particle multiplicities result in a statistical fluctuation of the v_2^{obs} estimate for a given event about the true underlying v_2 value by a response function $p(v_2^{\text{obs}}|v_2)$. This, in turn, results in a $p(v_2^{\text{obs}})$ distribution that is broader than the underlying $p(v_2)$ behavior. The observed distribution can be expressed as a convolution of the underlying flow behavior and the response function

$$p(v_2^{\text{obs}}) = p(v_2^{\text{obs}}|v_2) * p(v_2). \quad (7)$$

A data-based technique, first introduced by the ATLAS Collaboration [16], was used to build the response function in Eq. (7). This technique divides the full event sample into two symmetric subevents (a and b) based on pseudorapidity. Given that $v_2(\eta)$ is symmetric about $\eta = 0$ on average for the symmetric PbPb system, the physical flow signal cancels in the distribution of flow vector differences from each subevent $p(\vec{v}_a - \vec{v}_b)$. The resulting distribution contains residual effects from multiplicity-related fluctuations and nonflow effects [44] and provides a basis for building the response function. The ability of the analysis procedure to suppress nonflow effects was studied by introducing a v_2 signal on top of HIJING 1.383 [46] simulated events, which contain nonflow. The EbyE analysis is found to recover the “truth” to within 0.1%.

To unfold the effects of multiplicity-related fluctuations, the D’Agostini iterative method with early stopping (regularization) [47–49] was used to obtain a maximum likelihood estimate of the underlying $p(v_2)$ behavior. The analysis was done using the RooUNFOLD [50] package of the ROOT data analysis framework [51]. The unfolding procedure becomes increasingly sensitive to statistical fluctuations when the number of iterations is allowed to run to large values, resulting in unphysical oscillations in the low event count tails of the unfolded distribution. The regularization criterion used to suppress these oscillations is to apply the response function to each unfolding iteration (“refolding”) and compare the resulting distribution to the observed one. Iterations are stopped when the χ^2/dof between the refolded and observed distribution is approximately equal to one. After this final unfolding iteration is reached, the resulting distribution is truncated above $\langle v_2 \rangle + 4\sigma_{v_2}$ to further suppress any residual artifacts in the tails that result from the unfolding procedure. Representative final unfolded distributions are shown in Fig. 1. In addition, $p(v_2^{\text{obs}})$ distributions

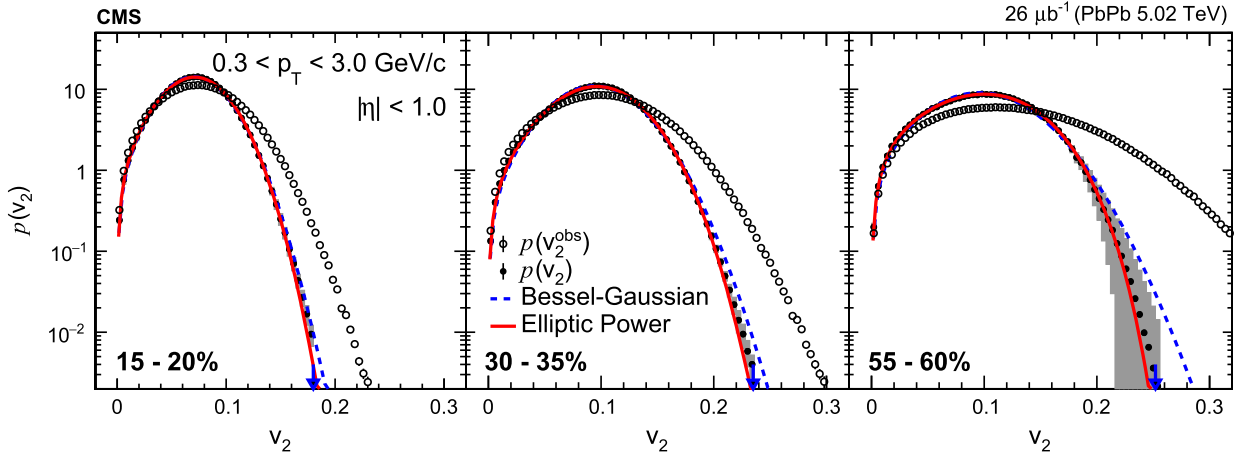


Fig. 1. Representative final unfolded $p(v_2)$ distributions (closed black circles) in three centrality bins (15–20%, 30–35%, and 55–60%) obtained using D’Agostini iteration unfolding. Respective observed $p(v_2^{\text{obs}})$ distributions (open black squares) are shown to illustrate the statistical resolution present in each centrality bin prior to unfolding. Systematic uncertainties from the unfolding procedure are presented as shaded bands. Distributions are fitted with Bessel–Gaussian (dashed blue lines) and elliptic power (solid red lines) functions to infer information on the underlying $p(\varepsilon_2)$ distributions. The vertical blue arrows indicate the $\langle v_2 \rangle + 4\sigma_{v_2}$ cutoff discussed in the text.

are plotted for each centrality to illustrate the statistical resolution effects present prior to unfolding. The fits shown in Fig. 1 are discussed in Section 6.

5. Systematic uncertainties

A number of potential sources of systematic uncertainties for the $v_2\{m\}$ values extracted from the unfolded $p(v_2)$ distributions were considered. The systematic uncertainties that arise from the vertex z position were investigated by splitting the default vertex range into two windows of $|z_{\text{vtx}}| < 3.0$ cm and $3.0 < |z_{\text{vtx}}| < 15.0$ cm and comparing the results from the two ranges. The resulting uncertainties range from 5% for central events, decreasing to 0.5% for mid-central events. To estimate the bias from misidentified tracks, the track quality criteria described in Section 3 were varied. Two scenarios were considered, with one increasing and the other decreasing the probability of misidentifying a track. The results of these two scenarios were compared to the values obtained in the default analysis. The resulting uncertainties range from 2% for central events to 1% for mid-central events. To estimate the systematic uncertainty in the choice of response function, the unfolding procedure was repeated using an analytic response function obtained from a Gaussian fit to the data-driven statistical resolution distribution [16]. The resulting uncertainties are 3% for central events and decrease to 1% for mid-central events. Other sources of potential systematic bias were explored and found to be negligible. To assess the potential bias from residual pileup events, the threshold for determining pileup events was raised to decrease the probability of including events with multiple collisions in the analysis. The bias from unfolding regularization was studied by modifying the χ^2/dof goodness-of-fit regularization criteria and comparing the cases when the refolding χ^2/dof cutoff is 2.0 relative to when it is 1.0. To test the potential bias that might result from the 4σ truncation of the final unfolded distributions, the truncation point was varied between 3.5σ and 4.5σ . To assess the uncertainty on the choice of the prior, the unfolding was repeated using priors that were systematically transformed to have 10% larger and smaller means than the default prior. No significant bias was found with these variations of the prior. The total systematic uncertainties were obtained by adding the contribution from each source in quadrature. The v_2 values calculated for the different cumulant orders have a total systematic uncertainty of the order of 5% for central collisions, which decreases to 1% in mid-central collisions.

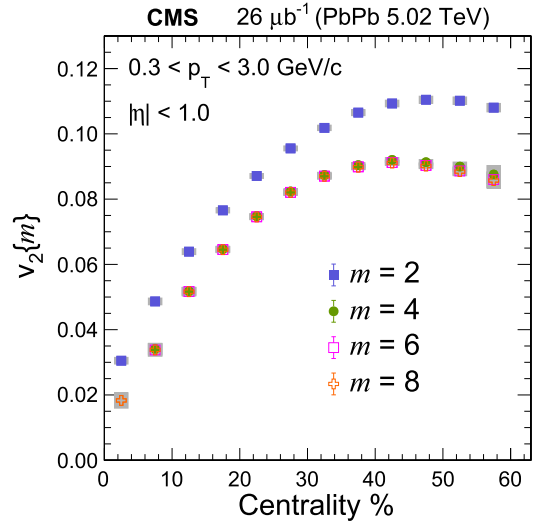


Fig. 2. Elliptic-flow cumulant harmonics with values obtained from the moments of the unfolded $p(v_2)$ distributions. Systematic uncertainties are shown as gray bands. For most centralities, the uncertainties are smaller than the symbol size.

As all of the systematic uncertainties are expected to be correlated between the different cumulant orders, with the same data used in the calculation of each order, all of the above studies were also performed for the ratios of different orders and for the skewness estimate given by Eq. (4). For the ratios, the total systematic uncertainty is found as 1% for central collisions, decreasing to 0.1% for mid-central collisions. The standardized skewness is very sensitive to small fluctuations in the cumulant flow harmonics, resulting in a systematic uncertainty of 100% for central collisions that reduces to 20% for mid-central collisions.

6. Results

The cumulant elliptic-flow harmonics obtained from the moments of the unfolded $p(v_2)$ distributions using Eq. (3) are shown in Fig. 2 for cumulant orders 2, 4, 6, and 8. It was not possible to obtain 0–5% central results for $v_2\{4\}$ and $v_2\{6\}$ because the right-hand side of Eq. (3) was found to be negative for these values. This behavior might be a consequence of volume fluctuations dominating the cumulant behavior for these central events, as discussed

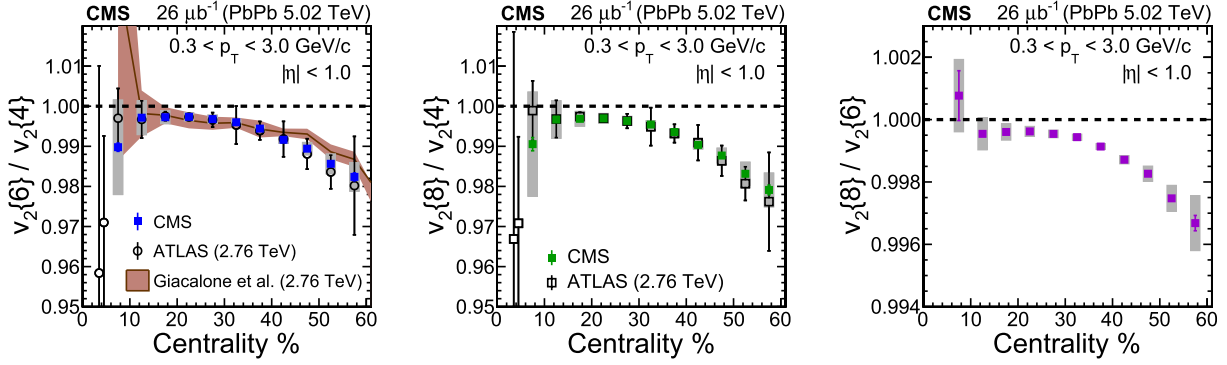


Fig. 3. Ratios of higher order cumulant elliptic-flow harmonics with values obtained from the moments of the unfolded $p(v_2)$ distributions. Both statistical (lines) and systematic (gray bands) uncertainties are shown. Hydrodynamic predictions for 2.76 TeV collisions from Ref. [33] are presented as a dark color band and are compared to the measured $v_2\{6\}/v_2\{4\}$ ratio. In addition, higher order cumulant ratios reported by the ATLAS Collaboration for 2.76 TeV collisions [37] with $0.5 < p_T < 20.0$ GeV/c and $|\eta| < 2.5$ are compared to the 5.02 TeV measurement. The error bars on the ATLAS measurement represent the quadratic sum of statistical and systematic uncertainties and points are offset horizontally for clarity.

in Ref. [52]. The cumulant results exhibit the previously observed $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ behavior. The centrality-dependent ratios for the elliptic-flow coefficients obtained for different cumulant orders are shown in Fig. 3. For most centrality ranges, the ratios indicate a rank ordering of the cumulants, with differences on the order of a few percent and with $v_2\{4\} > v_2\{6\} > v_2\{8\}$, that is qualitatively inconsistent with a pure Gaussian fluctuation model of flow harmonics. The differences increase as the collisions become more peripheral. The calculated $v_2\{6\}/v_2\{4\}$ ratio based on an event-by-event hydrodynamic calculation using Monte Carlo Glauber initial conditions [53] and an η/s value of 0.08 is shown by the shaded band. This simulation is for pions with $0.2 < p_T < 3.0$ GeV/c in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [33]. Also shown are results from the ATLAS Collaboration [37] for PbPb collisions at 2.76 TeV and for charged particles with $0.5 < p_T < 20.0$ GeV/c and $|\eta| < 2.5$. The calculation is consistent with the experimental results found at both beam energies. The similarity between experimental results with 2.76 and 5.02 TeV is consistent with the small changes in the initial-state eccentricities expected between these energies [54] and the expectation that the cumulant flow harmonic ratios follow those of the corresponding eccentricity ratios [33].

Fig. 4 shows the centrality dependence of the standardized skewness γ_1^{exp} . Finite values are found for the standardized skewness for collisions with centralities greater than $\approx 15\%$. The hydrodynamic predictions for the γ_1^{exp} values for PbPb collisions at 2.76 TeV from Ref. [33] are also shown and found to be consistent with the current measurements. Within the hydrodynamic model and allowing for a finite skewness of the event-by-event v_2 distribution, the small splitting between the cumulant orders is expected to follow the relationship $(v_2\{6\} - v_2\{8\})/(v_2\{4\} - v_2\{6\}) = 0.091$ [33]. Experimentally, we find a value for this splitting ratio of $0.143 \pm 0.008(\text{stat}) \pm 0.014(\text{syst})$ for 20–25% central events, with the ratio increasing to $0.185 \pm 0.005(\text{stat}) \pm 0.012(\text{syst})$ as the centrality increases to 55–60%. The observed values might suggest higher order terms in a cumulant expansion of the v_2 distribution are required to account for the skewness. This relationship was recently examined by the ALICE collaboration in Ref. [55] using a q-cumulant analysis, with results comparable to the findings in this paper when considering systematic uncertainties and a different kinematic range for the ALICE measurement.

Both elliptic power and Bessel–Gaussian parametrizations used for fits such as shown in Fig. 1 assume a linear response between eccentricity and flow, but only the elliptic power law allows for a finite skewness. For a Bessel–Gaussian distribution, the skewness is equal to zero. This feature results in the elliptic power function being in better agreement with the observed fluctuation behavior

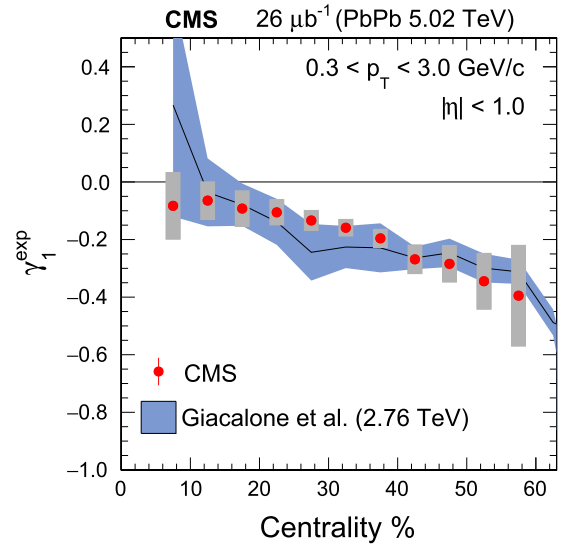


Fig. 4. The skewness estimate with respect to the reaction plane determined using the elliptic-flow harmonic based on different cumulant orders. Both statistical and systematic uncertainties are shown, where statistical uncertainties are smaller than the data points. Hydrodynamic model predictions for 2.76 TeV PbPb collisions from Ref. [33] are shown as a colored band.

than the Bessel–Gaussian parametrization, yielding χ^2/dof values on the order of unity. To avoid bin-to-bin correlations introduced by the unfolding procedure, goodness of fit values are obtained by refolding the fitted distributions with the response matrix and comparing to the measured distribution. The elliptic power χ^2/dof values vary between 0.8 and 1.5 from central to peripheral collisions, while the Bessel–Gaussian χ^2/dof values vary between 3 and 9. Point-by-point systematic uncertainties on the unfolded distributions are correlated and are thus not considered in the fits.

The fit parameters for the elliptic power function are shown in Fig. 5 for the different centrality bins. As also found in Ref. [15], the fits do not converge for central collisions where the distributions become very close to a Bessel–Gaussian form. Consequently, the parameters are shown for centralities $> 15\%$. The experimental k_2 values show only a weak centrality dependence. Viscous hydrodynamic calculations indicate that deviations from thermal equilibrium should lead to a reduced correspondence between the initial-state geometry and the flow signal in peripheral collisions [27,28]. This effect is suggested in Fig. 5 by the decrease in the k_2 value with increasing centrality, although the systematic uncer-

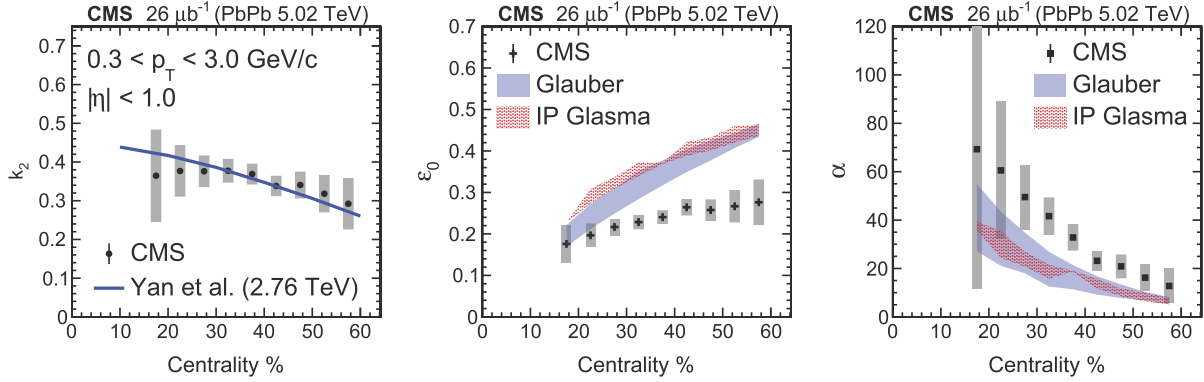


Fig. 5. Centrality dependence of the parameters extracted from elliptic power function fits to the unfolded $p(v_2)$ distributions. Both statistical (error bars) and systematic (shaded boxes) uncertainties are shown. The solid line represents a theoretical calculation [15] using viscous hydrodynamics with Glauber initial conditions and an η/s value of 0.19 to determine the response coefficient k_2 . Glauber (blue shaded band) and IP-Glasma (red shaded band) model calculations from Ref. [15] are shown for the α and ε_0 parameters. The systematic uncertainties account for the highly correlated parameters of the elliptic power function fit and for the bin-to-bin correlations in the unfolded distributions introduced by the unfolding procedure.

tainties are too large for this to be a definitive observation. The calculated decrease is greater than observed, although within the systematic uncertainties of the measurement. The eccentricity parameter of the power law fit, ε_0 , is found to first increase, and then level off with increasing centrality. The leveling occurs for centralities $> 40\%$, which is also where the v_2 values start to level off and then decrease. The α parameter, which reflects the number of sources in the power-law fit, is found to steadily decrease with increasing centrality, as expected.

Theoretical predictions at 2.76 TeV from Ref. [15] are compared to the current analysis in Fig. 5. A viscous hydrodynamic calculation with Glauber initial conditions and an η/s value of 0.19 is in agreement with the experimental k_2 values. This coefficient is expected to have only a weak dependence on the initial state, with its centrality dependence largely determined by the viscosity of the medium [15]. Predictions obtained using Glauber and IP-Glasma [56,57] initial conditions, where the IP-Glasma model includes gluon saturation effects, are shown for the ε_0 and α parameters. These latter two calculations qualitatively capture the observed behavior for the α -parameter, but a significant difference is found in comparing the theoretical ε_0 values with experiment. This difference might reflect a nonlinear response term, which will alter the magnitude of the flow response coefficient and consequently the ε_0 and α parameters, as suggested in Ref. [15].

7. Summary

In summary, a non-Gaussian behavior is observed in the event-by-event fluctuations of the elliptic flow v_2 coefficients in PbPb collisions recorded by the CMS detector at $\sqrt{s_{NN}} = 5.02$ TeV. The probability distributions $p(v_2)$ for 5%-centrality bins between 5% and 60% centrality are found by unfolding statistical resolution effects from measured flow distributions. The v_2 coefficients corresponding to different cumulant orders are calculated from the moments of the unfolded $p(v_2)$ distributions. A rank ordering of $v_2\{4\} > v_2\{6\} > v_2\{8\}$, with differences on the order of a few percent, is observed for noncentral events with centralities greater than $\approx 15\%$. The standardized skewness of each $p(v_2)$ distribution is calculated using the cumulant results. In cases where there is a difference in the cumulant values, the standardized skewness is found to be negative with an increasing magnitude as collisions become less central. Bessel-Gaussian and elliptic power functions are fitted to the unfolded $p(v_2)$ distributions. The two distributions are similar for central collisions, though the elliptic power function provides a better description for noncentral collisions.

Based on the elliptic power function fits, the centrality dependence of the flow response coefficient, which relates the final state geometry to the initial state energy density distribution, is found to be consistent with model calculations. However, the observed eccentricities are smaller than predictions based on either the Glauber model or the IP-Glasma model initial conditions with an assumed linear flow response. This difference might indicate the need for a nonlinear response term. The current results illustrate that LHC experiments now have the precision to explore the details of the initial-state fluctuations.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEP-Center, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (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 No. 675440 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture

(FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] I. Arsene, et al., BRAHMS, Quark–gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment, Nucl. Phys. A 757 (2005) 1, <https://doi.org/10.1016/j.nuclphysa.2005.02.130>, arXiv:nucl-ex/0410020.
- [2] K. Adcox, et al., PHENIX, Formation of dense partonic matter in relativistic nucleus–nucleus collisions at RHIC: experimental evaluation by the PHENIX Collaboration, Nucl. Phys. A 757 (2005) 184, <https://doi.org/10.1016/j.nuclphysa.2005.03.086>, arXiv:nucl-ex/0410003.
- [3] B.B. Back, et al., PHOBOS, The PHOBOS perspective on discoveries at RHIC, Nucl. Phys. A 757 (2005) 28, <https://doi.org/10.1016/j.nuclphysa.2005.03.084>, arXiv:nucl-ex/0410022.
- [4] J. Adams, et al., STAR, 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, <https://doi.org/10.1016/j.nuclphysa.2005.03.085>, arXiv:nucl-ex/0501009.
- [5] ATLAS Collaboration, Observation of a centrality-dependent dijet asymmetry in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC, Phys. Rev. Lett. 105 (2010) 252303, <https://doi.org/10.1103/PhysRevLett.105.252303>, arXiv:1011.6182.
- [6] CMS Collaboration, Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. C 84 (2011) 024906, <https://doi.org/10.1103/PhysRevC.84.024906>, arXiv:1102.1957.
- [7] ALICE Collaboration, Suppression of charged particle production at large transverse momentum in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Lett. B 696 (2011) 30, <https://doi.org/10.1016/j.physletb.2010.12.020>, arXiv:1012.1004.
- [8] J.-Y. Ollitrault, Anisotropy as a signature of transverse collective flow, Phys. Rev. D 46 (1992) 229, <https://doi.org/10.1103/PhysRevD.46.229>.
- [9] B. Alver, G. Roland, Collision-geometry fluctuations and triangular flow in heavy-ion collisions, Phys. Rev. C 81 (2010) 054905, <https://doi.org/10.1103/PhysRevC.81.054905>, arXiv:1003.0194, Erratum: <https://doi.org/10.1103/PhysRevC.82.039903>.
- [10] H. Grönqvist, J.-P. Blaizot, J.-Y. Ollitrault, Non-Gaussian eccentricity fluctuations, Phys. Rev. C 94 (2016) 034905, <https://doi.org/10.1103/PhysRevC.94.034905>, arXiv:1604.07230.
- [11] U. Heinz, C. Shen, H. Song, The viscosity of quark–gluon plasma at RHIC and the LHC, AIP Conf. Proc. 1441 (2012) 766, <https://doi.org/10.1063/1.3700674>, arXiv:1108.5323.
- [12] G. Policastro, D.T. Son, A.O. Starinets, Shear viscosity of strongly coupled $N = 4$ supersymmetric Yang–Mills plasma, Phys. Rev. Lett. 87 (2001) 081601, <https://doi.org/10.1103/PhysRevLett.87.081601>, arXiv:hep-th/0104066.
- [13] P. Kovtun, D.T. Son, A.O. Starinets, Viscosity in strongly interacting quantum field theories from black hole physics, Phys. Rev. Lett. 94 (2005) 111601, <https://doi.org/10.1103/PhysRevLett.94.111601>, arXiv:hep-th/0405231.
- [14] L. Yan, J.-Y. Ollitrault, A.M. Poskanzer, Eccentricity distributions in nucleus–nucleus collisions, Phys. Rev. C 90 (2014) 024903, <https://doi.org/10.1103/PhysRevC.90.024903>, arXiv:1405.6595.
- [15] L. Yan, J.-Y. Ollitrault, A.M. Poskanzer, Azimuthal anisotropy distributions in high-energy collisions, Phys. Lett. B 742 (2015) 290, <https://doi.org/10.1016/j.physletb.2015.01.039>, arXiv:1408.0921.
- [16] ATLAS Collaboration, Measurement of the distributions of event-by-event flow harmonics in lead–lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC, J. High Energy Phys. 11 (2013) 183, [https://doi.org/10.1007/JHEP11\(2013\)183](https://doi.org/10.1007/JHEP11(2013)183), arXiv:1305.2942.
- [17] S.A. Voloshin, A.M. Poskanzer, R. Snellings, Collective phenomena in non-central nuclear collisions, in: R. Stock (Ed.), Springer Materials – the Landolt–Börnstein Database, in: Relativistic Heavy Ion Physics, vol. 23, Springer-Verlag, 2010, p. 293, https://doi.org/10.1007/978-3-642-01539-7_10, arXiv:0809.2949.
- [18] D. Teaney, L. Yan, Triangularity and dipole asymmetry in relativistic heavy ion collisions, Phys. Rev. C 83 (2011) 064904, <https://doi.org/10.1103/PhysRevC.83.064904>, arXiv:1010.1876.
- [19] Z. Qiu, U.W. Heinz, Event-by-event shape and flow fluctuations of relativistic heavy-ion collision fireballs, Phys. Rev. C 84 (2011) 024911, <https://doi.org/10.1103/PhysRevC.84.024911>, arXiv:1104.0650.
- [20] F.G. Gardim, F. Grassi, M. Luzum, J.-Y. Ollitrault, Mapping the hydrodynamic response to the initial geometry in heavy-ion collisions, Phys. Rev. C 85 (2012) 024908, <https://doi.org/10.1103/PhysRevC.85.024908>, arXiv:1111.6538.
- [21] H. Song, QGP viscosity at RHIC and the LHC—a 2012 status report, Nucl. Phys. A 904–905 (2013) 114c, <https://doi.org/10.1016/j.nuclphysa.2013.01.052>, arXiv:1210.5778.
- [22] P.F. Kolb, J. Sollfrank, U.W. Heinz, Anisotropic transverse flow and the quark hadron phase transition, Phys. Rev. C 62 (2000) 054909, <https://doi.org/10.1103/PhysRevC.62.054909>, arXiv:hep-ph/0006129.
- [23] R.S. Bhalerao, J.-P. Blaizot, N. Borghini, J.-Y. Ollitrault, Elliptic flow and incomplete equilibration at RHIC, Phys. Lett. B 627 (2005) 49, <https://doi.org/10.1016/j.physletb.2005.08.131>, arXiv:nucl-th/0508009.
- [24] R.S. Bhalerao, J.-Y. Ollitrault, Eccentricity fluctuations and elliptic flow at RHIC, Phys. Lett. B 641 (2006) 260, <https://doi.org/10.1016/j.physletb.2006.08.055>, arXiv:nucl-th/0607009.
- [25] B. Alver, et al., PHOBOS, Importance of correlations and fluctuations on the initial source eccentricity in high-energy nucleus–nucleus collisions, Phys. Rev. C 77 (2008) 014906, <https://doi.org/10.1103/PhysRevC.77.014906>, arXiv:0711.3724.
- [26] C. Gombeaud, J.-Y. Ollitrault, Effects of flow fluctuations and partial thermalization on $v(4)$, Phys. Rev. C 81 (2010) 014901, <https://doi.org/10.1103/PhysRevC.81.014901>, arXiv:0907.4664.
- [27] S.A. Voloshin, A.M. Poskanzer, The physics of the centrality dependence of elliptic flow, Phys. Lett. B 474 (2000) 27, [https://doi.org/10.1016/S0370-2693\(00\)00017-4](https://doi.org/10.1016/S0370-2693(00)00017-4), arXiv:nucl-th/9906075.
- [28] H.-J. Drescher, A. Dumitru, C. Gombeaud, J.-Y. Ollitrault, Centrality dependence of elliptic flow, the hydrodynamic limit, and the viscosity of hot QCD, Phys. Rev. C 76 (2007) 024905, <https://doi.org/10.1103/PhysRevC.76.024905>, arXiv:0704.3553.
- [29] N. Borghini, P.M. Dinh, J.-Y. Ollitrault, New method for measuring azimuthal distributions in nucleus–nucleus collisions, Phys. Rev. C 63 (2001) 054906, <https://doi.org/10.1103/PhysRevC.63.054906>, arXiv:nucl-th/0007063.
- [30] N. Borghini, P.M. Dinh, J.-Y. Ollitrault, Flow analysis from multiparticle azimuthal correlations, Phys. Rev. C 64 (2001) 054901, <https://doi.org/10.1103/PhysRevC.64.054901>, arXiv:nucl-th/0105040.
- [31] S.A. Voloshin, A.M. Poskanzer, A. Tang, G. Wang, Elliptic flow in the Gaussian model of eccentricity fluctuations, Phys. Lett. B 659 (2008) 537, <https://doi.org/10.1016/j.physletb.2007.11.043>, arXiv:0708.0800.
- [32] J. Jia, Event-shape fluctuations and flow correlations in ultra-relativistic heavy-ion collisions, J. Phys. G 41 (2014) 124003, <https://doi.org/10.1088/0954-3889/41/12/124003>, arXiv:1407.6057.
- [33] G. Giacalone, L. Yan, J. Noronha-Hostler, J.-Y. Ollitrault, Skewness of elliptic flow fluctuations, Phys. Rev. C 95 (2017) 014913, <https://doi.org/10.1103/PhysRevC.95.014913>, arXiv:1608.01823.
- [34] S. Voloshin, Y. Zhang, Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions, Z. Phys. C 70 (1996) 665, <https://doi.org/10.1007/s002880050141>, arXiv:hep-ph/9407282.
- [35] CMS Collaboration, Evidence for collective multiparticle correlations in p–Pb collisions, Phys. Rev. Lett. 115 (2015) 012301, <https://doi.org/10.1103/PhysRevLett.115.012301>, arXiv:1502.05382.
- [36] ALICE Collaboration, Multiparticle azimuthal correlations in p–Pb and Pb–Pb collisions at the CERN large hadron collider, Phys. Rev. C 90 (2014) 054901, <https://doi.org/10.1103/PhysRevC.90.054901>, arXiv:1406.2474.
- [37] ATLAS Collaboration, Measurement of flow harmonics with multi-particle cumulants in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector, Eur. Phys. J. C 74 (2014) 3157, <https://doi.org/10.1140/epjc/s10052-014-3157-z>, arXiv:1408.4342.
- [38] L. Yan, J.-Y. Ollitrault, A.M. Poskanzer, Universal parameterization of initial-state fluctuations and its applications to event-by-event anisotropy, Nucl. Phys. A 931 (2014) 1007, <https://doi.org/10.1016/j.nuclphysa.2014.09.021>, arXiv:1408.0709.
- [39] L. Yan, J.-Y. Ollitrault, Universal fluctuation-driven eccentricities in proton–proton, proton–nucleus and nucleus–nucleus collisions, Phys. Rev. Lett. 112 (2014) 082301, <https://doi.org/10.1103/PhysRevLett.112.082301>, arXiv:1312.6555.
- [40] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. 9 (2014) P10009, <https://doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [41] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [42] CMS Collaboration, Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, J. High Energy Phys. 04 (2017) 039, [https://doi.org/10.1007/JHEP04\(2017\)039](https://doi.org/10.1007/JHEP04(2017)039), arXiv:1611.01664.

- [43] A. Bilandzic, C.H. Christensen, K. Gulbrandsen, A. Hansen, Y. Zhou, Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations, *Phys. Rev.* 89 (2014) 064904, <https://doi.org/10.1103/PhysRevC.89.064904>, arXiv:1312.3572.
- [44] J. Jia, S. Mohapatra, Disentangling flow and nonflow correlations via Bayesian unfolding of the event-by-event distributions of harmonic coefficients in ultrarelativistic heavy-ion collisions, *Phys. Rev. C* 88 (2013) 014907, <https://doi.org/10.1103/PhysRevC.88.014907>, arXiv:1304.1471.
- [45] A.M. Poskanzer, S.A. Voloshin, Methods for analyzing anisotropic flow in relativistic nuclear collisions, *Phys. Rev. C* 58 (1998) 1671, <https://doi.org/10.1103/PhysRevC.58.1671>, arXiv:nucl-ex/9805001.
- [46] M. Gyulassy, X.-N. Wang, HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions, *Comput. Phys. Commun.* 83 (1994) 307, [https://doi.org/10.1016/0010-4655\(94\)90057-4](https://doi.org/10.1016/0010-4655(94)90057-4), arXiv:nucl-th/9502021.
- [47] G. D'Agostini, A multidimensional unfolding method based on Bayes' theorem, *Nucl. Instrum. Meth. A* 362 (1995) 487, [https://doi.org/10.1016/0168-9002\(95\)00274-X](https://doi.org/10.1016/0168-9002(95)00274-X).
- [48] W.H. Richardson, Bayesian-based iterative method of image restoration, *J. Opt. Soc. Am.* 62 (1972) 55, <https://doi.org/10.1364/JOSA.62.000055>.
- [49] L.B. Lucy, An iterative technique for the rectification of observed distributions, *Astron. J.* 79 (1974) 745, <https://doi.org/10.1086/111605>.
- [50] T. Adye, Unfolding algorithms and tests using RooUnfold, in: H. Prosper, L. Lyons (Eds.), *PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding*, CERN, CERN, Geneva, Switzerland, 2011, p. 313, <https://doi.org/10.5170/CERN-2011-006.313>, arXiv:1105.1160.
- [51] R. Brun, F. Rademakers, ROOT—An object oriented data analysis framework, *Nucl. Instrum. Methods A* 389 (1997) 81, [https://doi.org/10.1016/S0168-9002\(97\)00048-X](https://doi.org/10.1016/S0168-9002(97)00048-X).
- [52] M. Zhou, J. Jia, Centrality fluctuations in heavy-ion collisions, *Phys. Rev. C* 98 (2018) 044903, <https://doi.org/10.1103/PhysRevC.98.044903>, arXiv:1803.01812.
- [53] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Glauber modeling in high energy nuclear collisions, *Annu. Rev. Nucl. Part. Sci.* 57 (2007) 205, <https://doi.org/10.1146/annurev.nucl.57.090506.123020>, arXiv:nucl-ex/0701025.
- [54] J. Noronha-Hostler, M. Luzum, J.-Y. Ollitrault, Hydrodynamic predictions for 5.02 TeV Pb–Pb collisions, *Phys. Rev. C* 93 (2016) 034912, <https://doi.org/10.1103/PhysRevC.93.034912>, arXiv:1511.06289.
- [55] ALICE Collaboration, Energy dependence and fluctuations of anisotropic flow in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV, *J. High Energy Phys.* 07 (2018) 103, [https://doi.org/10.1007/JHEP07\(2018\)103](https://doi.org/10.1007/JHEP07(2018)103).
- [56] B. Schenke, P. Tribedy, R. Venugopalan, Event-by-event gluon multiplicity, energy density, and eccentricities in ultrarelativistic heavy-ion collisions, *Phys. Rev. C* 86 (2012) 034908, <https://doi.org/10.1103/PhysRevC.86.034908>, arXiv:1206.6805.
- [57] B. Schenke, P. Tribedy, R. Venugopalan, Gluon field fluctuations in nuclear collisions: multiplicity and eccentricity distributions, *Nucl. Phys. A* 926 (2014) 102, <https://doi.org/10.1016/j.nuclphysa.2014.03.001>, arXiv:1312.5588.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler¹, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck¹, R. Schöffbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov³, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, P. David, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri,

A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

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

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote⁴, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

S. Ahuja^a, C.A. Bernardes^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas^a

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

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

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

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁶, X. Gao⁶, L. Yuan

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, S. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, J. Li, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁷, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger⁸, M. Finger Jr.⁸

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim^{9,10}, Y. Mohammed¹¹, E. Salama^{12,13}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, C. Leloup, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

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

A. Abdulsalam, C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

J.-L. Agram¹⁴, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁴, X. Coubez, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹⁵, V. Sordini, M. Vander Donckt, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili¹⁶

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze⁸

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, V. Zhukov¹⁵

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

A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁷

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁸, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁹, J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel²⁰, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann²⁰, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁷, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁷, S.M. Heindl, U. Husemann, F. Kassel¹⁷, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, I. Topsis-Giotis

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

G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsionis

University of Ioánnina, Ioánnina, Greece

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres²¹

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

G. Bencze, C. Hajdu, D. Horvath²², Á. Hunyadi, F. Sikler, V. Veszpremi

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²³, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók²¹, P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²⁴, S. Bhowmik, P. Mal, K. Mandal, A. Nayak²⁵, D.K. Sahoo²⁴, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, Ashok Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, Aashaq Shah, R. Sharma

University of Delhi, Delhi, India

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁷, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁶, G. Majumder, K. Mazumdar, T. Sarkar²⁶, N. Wickramage²⁷

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani²⁸, E. Eskandari Tadavani, S.M. Etesami²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁹, F. Rezaei Hosseinabadi, B. Safarzadeh³⁰, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c},
M. De Palma^{a,b}, F. Errico^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b},
S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a,
L. Silvestris^{a,17}, R. Venditti^a, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borghonovi^{a,b}, S. Braibant-Giacomelli^{a,b},
R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b},
G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b},
S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b},
G.P. Siroli^{a,b}, N. Tosi^a

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b},
M. Meschini^a, S. Paoletti^a, L. Russo^{a,31}, G. Sguazzoni^a, D. Strom^a, L. Viliani^{a,b,17}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁷

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli^{a,b}, F. Ferro^a, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,17}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b},
S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, D. Menasce^a,
L. Moroni^a, M. Paganoni^{a,b}, K. Pauwels^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b,32}, S. Ragazzi^{a,b},
T. Tabarelli de Fatis^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,17}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A.O.M. Iorio^{a,b}, W.A. Khan^a,
L. Lista^a, S. Meola^{a,d,17}, P. Paolucci^{a,17}, C. Sciacca^{a,b}, F. Thyssen^a

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^a, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b},
A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a,
F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, M. Gulmini^{a,33}, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b},
A.T. Meneguzzo^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, E. Torassa^a, S. Ventura^a, M. Zanetti^{a,b},
G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b *Università di Padova, Padova, Italy*^c *Università di Trento, Trento, Italy*

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b},
P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

^a *INFN Sezione di Pavia, Pavia, Italy*^b *Università di Pavia, Pavia, Italy*

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, R. Leonardi^{a,b},
E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

^a *INFN Sezione di Perugia, Perugia, Italy*^b *Università di Perugia, Perugia, Italy*

K. Androsova^a, P. Azzurri^{a,17}, G. Bagliesi^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b},
R. Dell'Orso^a, G. Fedi^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^{a,31}, F. Ligabue^{a,c}, T. Lomtadze^a,
E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,34}, P. Spagnolo^a,
R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

^a *INFN Sezione di Pisa, Pisa, Italy*^b *Università di Pisa, Pisa, Italy*^c *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b,17}, E. Di Marco^{a,b}, M. Diemoz^a,
S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^{a,b},
F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

^a *INFN Sezione di Roma, Rome, Italy*^b *Sapienza Università di Roma, Rome, Italy*

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a,
N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, B. Kiani^{a,b},
C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b},
L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c},
R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

^a *INFN Sezione di Torino, Torino, Italy*^b *Università di Torino, Torino, Italy*^c *Università del Piemonte Orientale, Novara, Italy*

S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^a

^a *INFN Sezione di Trieste, Trieste, Italy*^b *Università di Trieste, Trieste, Italy*

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali³⁵, F. Mohamad Idris³⁶, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

M.C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, G. Ramirez-Sanchez, I. Heredia-De La Cruz³⁷, R.I. Rabadan-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁸, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucio, J. Varela

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

A. Baginyan, A. Golunov, I. Golutvin, V. Karjavin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev^{39,40}, V.V. Mitsyn, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, B.S. Yuldashev⁴¹, A. Zarubin, V. Zhiltsov

Joint Institute for Nuclear Research, Dubna, Russia

Y. Ivanov, V. Kim⁴², E. Kuznetsova⁴³, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tilsov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepanov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev, A. Bylinkin⁴⁰

Moscow Institute of Physics and Technology, Moscow, Russia

R. Chistov⁴⁴, M. Danilov⁴⁴, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii, E. Zhemchugov

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin⁴⁰, I. Dremin⁴⁰, M. Kirakosyan⁴⁰, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy⁴⁵, O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, E. Nazarova, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov⁴⁶, D. Shtol⁴⁶, Y. Skovpen⁴⁶

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic⁴⁷, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

C. Albajar, J.F. de Trocóniz, M. Missiroli

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban²⁰, J. Kieseler, V. Knünz, A. Kornmayer, M.J. Kortelainen, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁸, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabaday, A. Racz, T. Reis, G. Rolandi⁴⁹, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁵⁰, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns⁵¹, M. Verweij, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl[†], L. Caminada⁵², K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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

T.K. Aarrestad, C. Amsler⁵³, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

Universität Zürich, Zurich, Switzerland

V. Candelise, Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Arun Kumar, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

M.N. Bakirci⁵⁴, A. Bat, F. Boran, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵⁵, E.E. Kangal⁵⁶, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut⁵⁷, K. Ozdemir⁵⁸, A. Polatoz, U.G. Tok, H. Topakli⁵⁴, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Bilin, G. Karapinar⁵⁹, K. Ocalan⁶⁰, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya⁶¹, O. Kaya⁶², S. Tekten, E.A. Yetkin⁶³

Bogazici University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, I. Köseoglu

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶⁴, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

A. Belyaev⁶⁵, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

G. Auzinger, R. Bainbridge, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko⁷, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁶, T. Virdee¹⁷, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington DC, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, D. Cutts, A. Garabedian, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Los Angeles, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁷, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, F. Golf, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

University of California, Santa Barbara – Department of Physics, Santa Barbara, USA

D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger,

E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

University of Illinois at Chicago (UIC), Chicago, USA

B. Bilki⁶⁸, W. Clarida, K. Dilsiz⁶⁹, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁷⁰, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷¹, Y. Onel, F. Ozok⁷², A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans,

K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, D. Trocino, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁹, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, N. Parashar, J. Stupak

Purdue University Northwest, Hammond, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

R. Ciesielski, K. Goulios, C. Mesropian

The Rockefeller University, New York, USA

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali⁷³, A. Castaneda Hernandez⁷³, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁴, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duerdo, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

Wayne State University, Detroit, USA

M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at State Key Laboratory of Nuclear Physics and Technology; Peking University, Beijing, China.

³ Also at IRFU; CEA; Université Paris-Saclay, Gif-sur-Yvette, France.

⁴ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁵ Also at Universidade Federal de Pelotas, Pelotas, Brazil.

⁶ Also at Université Libre de Bruxelles, Bruxelles, Belgium.

⁷ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

⁸ Also at Joint Institute for Nuclear Research, Dubna, Russia.

⁹ Also at Helwan University, Cairo, Egypt.

¹⁰ Now at Zewail City of Science and Technology, Zewail, Egypt.

¹¹ Now at Fayoum University, El-Fayoum, Egypt.

¹² Also at British University in Egypt, Cairo, Egypt.

¹³ Now at Ain Shams University, Cairo, Egypt.

¹⁴ Also at Université de Haute Alsace, Mulhouse, France.

- ¹⁵ Also at Skobeltsyn Institute of Nuclear Physics; Lomonosov Moscow State University, Moscow, Russia.
- ¹⁶ Also at Tbilisi State University, Tbilisi, Georgia.
- ¹⁷ Also at CERN; European Organization for Nuclear Research, Geneva, Switzerland.
- ¹⁸ Also at RWTH Aachen University; III. Physikalisches Institut A, Aachen, Germany.
- ¹⁹ Also at University of Hamburg, Hamburg, Germany.
- ²⁰ Also at Brandenburg University of Technology, Cottbus, Germany.
- ²¹ Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group; Eötvös Loránd University, Budapest, Hungary.
- ²² Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ²³ Also at Institute of Physics; University of Debrecen, Debrecen, Hungary.
- ²⁴ Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
- ²⁵ Also at Institute of Physics, Bhubaneswar, India.
- ²⁶ Also at University of Visva-Bharati, Santiniketan, India.
- ²⁷ Also at University of Ruhuna, Matara, Sri Lanka.
- ²⁸ Also at Isfahan University of Technology, Isfahan, Iran.
- ²⁹ Also at Yazd University, Yazd, Iran.
- ³⁰ Also at Plasma Physics Research Center; Science and Research Branch; Islamic Azad University, Tehran, Iran.
- ³¹ Also at Università degli Studi di Siena, Siena, Italy.
- ³² Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy.
- ³³ Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
- ³⁴ Also at Purdue University, West Lafayette, USA.
- ³⁵ Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ³⁶ Also at Malaysian Nuclear Agency; MOSTI, Kajang, Malaysia.
- ³⁷ Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- ³⁸ Also at Warsaw University of Technology; Institute of Electronic Systems, Warsaw, Poland.
- ³⁹ Also at Institute for Nuclear Research, Moscow, Russia.
- ⁴⁰ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ⁴¹ Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
- ⁴² Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ⁴³ Also at University of Florida, Gainesville, USA.
- ⁴⁴ Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ⁴⁵ Also at INFN Sezione di Padova; Università di Padova; Università di Trento (Trento), Padova, Italy.
- ⁴⁶ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ⁴⁷ Also at Faculty of Physics; University of Belgrade, Belgrade, Serbia.
- ⁴⁸ Also at University of Belgrade; Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁴⁹ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ⁵⁰ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁵¹ Also at Riga Technical University, Riga, Latvia.
- ⁵² Also at Universität Zürich, Zurich, Switzerland.
- ⁵³ Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
- ⁵⁴ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁵⁵ Also at Istanbul Aydin University, Istanbul, Turkey.
- ⁵⁶ Also at Mersin University, Mersin, Turkey.
- ⁵⁷ Also at Cag University, Mersin, Turkey.
- ⁵⁸ Also at Piri Reis University, Istanbul, Turkey.
- ⁵⁹ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁶⁰ Also at Necmettin Erbakan University, Konya, Turkey.
- ⁶¹ Also at Marmara University, Istanbul, Turkey.
- ⁶² Also at Kafkas University, Kars, Turkey.
- ⁶³ Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁶⁴ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ⁶⁵ Also at School of Physics and Astronomy; University of Southampton, Southampton, United Kingdom.
- ⁶⁶ Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- ⁶⁷ Also at Utah Valley University, Orem, USA.
- ⁶⁸ Also at Beykent University, Istanbul, Turkey.
- ⁶⁹ Also at Bingol University, Bingol, Turkey.
- ⁷⁰ Also at Erzincan University, Erzincan, Turkey.
- ⁷¹ Also at Sinop University, Sinop, Turkey.
- ⁷² Also at Mimar Sinan University; Istanbul, Istanbul, Turkey.
- ⁷³ Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁷⁴ Also at Kyungpook National University, Daegu, Korea.