Physics Letters B 751 (2015) 143–163

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Pseudorapidity distribution of charged hadrons in proton–proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 21 July 2015
Received in revised form 20 September 2015
Accepted 1 October 2015
Available online 8 October 2015
Editor: M. Doser

Keywords:
CMS
Physics
Proton–proton
13 TeV
Hadrons
Spectra

ABSTRACT

The pseudorapidity distribution of charged hadrons in pp collisions at $\sqrt{s} = 13$ TeV is measured using a data sample obtained with the CMS detector, operated at zero magnetic field, at the CERN LHC. The yield of primary charged long-lived hadrons produced in inelastic pp collisions is determined in the central region of the CMS pixel detector ($|\eta| < 2$) using both hit pairs and reconstructed tracks. For central pseudorapidities ($|\eta| < 0.5$), the charged-hadron multiplicity density is $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|<0.5} = 5.49 \pm 0.01\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst})$, a value obtained by combining the two methods. The result is compared to predictions from Monte Carlo event generators and to similar measurements made at lower collision energies.

© 2015 CERN for the benefit of the CMS Collaboration. 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 SCOAP[3].

1. Introduction

The yields of charged hadrons are among the most basic physical observables in high-energy particle collisions and provide an essential first step in exploring the physics of a new energy regime. Studies of such yields have a long history in high-energy particle and nuclear physics, as well as in cosmic ray physics. At collider energies, the inclusive production of charged hadrons is driven by a combination of perturbative and nonperturbative quantum chromodynamics (QCD) phenomena, such as saturation of parton densities, multiparton interactions, parton hadronization, and soft diffractive scattering.

The yields of primary charged hadrons are commonly studied using their multiplicity as a function of pseudorapidity, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$. Of particular interest for understanding the physics of hadron production is the dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ on the collision energy, which reflects the relative roles of soft- and hard-scattering contributions. Soft interactions, which are modeled phenomenologically, give rise to a significant fraction of the produced particles. Contributions from hard-scattering processes increase with increasing collision energies. Measurements are necessary to tune the modeling of these contributions in Monte Carlo (MC) event generators, and as reference data to study nuclear effects in proton–nucleus and nucleus–nucleus collisions. A good understanding of inclusive hadron production is also important to control the pileup backgrounds, from overlapping proton–proton collisions in a given bunch crossing, that affect all physics analyses at the LHC.

In this Letter, measurements of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ in the range $|\eta| < 2$ are reported for inelastic proton–proton (pp) collisions delivered by the CERN LHC at a center-of-mass energy of 13 TeV in June 2015. The analysis is based on 11.5 million events recorded at zero magnetic field during a special low-intensity beam configuration with 0.2–5% proton–proton interaction probability per bunch crossing. This special run was prepared by steering the beams such that their transverse separation was $\pm 3\sigma$ at the nominal CMS interaction point, where σ denotes the standard deviation of the Gaussian beam profile. Following earlier analyses at $\sqrt{s} = 0.9$ TeV, 2.36 TeV [1], 7 TeV [2], and 8 TeV [3], N_{ch} is defined to include decay products of particles with decay length $c\tau < 1$ cm, where τ is the lifetime of the particle and c is the velocity of light. Products of secondary interactions are excluded, and contributions from prompt leptons are removed.

The data are compared to PYTHIA8 v208 [4,5] (with the CMS underlying event tunes [6]: CUETP8S1 and CUETP8M1, using different parton densities), and to EPOS LHC [7] (LHC tune [8]). Both MC event generators reproduce well the main characteristics of the experimental data measured in hadronic collisions at lower energies, and provide predictions for the $\sqrt{s}$-dependence of hadron production observables using different implementations of the dominant

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

http://dx.doi.org/10.1016/j.physletb.2015.10.004
0370-2693/© 2015 CERN for the benefit of the CMS Collaboration. 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 SCOAP[3].

underlying phenomena (multiparton interactions, parton saturation, diffractive scattering) [9,10].

2. CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the magnet volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter. The tracker measures charged particles within $|\eta| < 2.4$. It has 1440 silicon pixel and 15 148 silicon strip detector modules, arranged in 14 tracking layers. The barrel region of the CMS pixel detector consists of three layers very close to the beam line. They are located at average radii of 4.3 cm (layer 1), 7.2 cm (layer 2), and 11.0 cm (layer 3), and provide excellent position resolution with their 150 μm × 100 μm pixels. The data sample used for this analysis was obtained while the magnet was off. Under these conditions, charged particles follow approximately straight trajectories, perturbed mostly by multiple Coulomb scattering. The pixel hits alone are sufficient to reconstruct vertices and tracks with high precision and purity. The beam pickup for timing (BPTX) devices were used to trigger the detector readout. They are located around the beam pipe at a distance of 175 m from the interaction point (IP) on either side, and are designed to provide precise information on the LHC bunch structure and the timing of the incoming beams. A detailed description of the CMS detector can be found in Ref. [11].

3. Event selection

Inelastic collision events are selected as follows: (i) online, a coincidence of signals from both BPTX devices is required, indicating the presence of both proton bunches crossing the IP; (ii) offline, at least one reconstructed interaction vertex is required, according to the tracklet or track vertex reconstruction methods described in Sections 4.1 and 4.2, respectively. While only the reconstructed collision vertex with the highest multiplicity (primary vertex) is used in the tracklet analysis, all reconstructed vertices in a given bunch crossing are processed for the track analysis.

A study of noncolliding bunches shows that the above requirements are sufficient to reject all backgrounds not originating from pp collisions. The probability to select events in the presence of a single (noncolliding) beam is about 5×10^{-5} per bunch crossing, while the same probability is smaller than 3×10^{-6} per bunch crossing in the absence of any beam. Consequently, the contribution of background events from beam, beam halo, and cosmic ray sources to the observed yields is negligible.

The results are corrected to correspond to a sample of inelastic collisions. The corrections from the detector-level offline event selection to the hadron-level event definitions are derived from MC simulations with PYTHIA8 v208 (tune CUETP8M1) and EPOS LHC (tune LHC), which cover a wide range of possible model ingredients. The detector response is simulated with GEANT4 [12] and processed through the same event reconstruction chain as collision data. The MC simulations are produced with the location and shape of the interaction region as extracted from data.

4. Data analysis

The analysis of the recorded data is performed with two reconstruction techniques based on hits of charged particles detected by the CMS pixel detector. While both start by searching for hit pairs in different layers at similar azimuthal angles ϕ, the tracklet method (using hit pairs) performs background subtraction based on control samples in data, while the track method (using hit triplets) minimizes background contributions by requiring an additional hit in the detector. This results in a slightly narrower accessible η range for the track method as compared to the tracklet method. Since various factors, such as detector alignment, material, detector response, and dependence on MC event generators, influence the two techniques somewhat differently, their final combination into a single measurement provides a more robust result.

4.1. Tracklets

Tracklets are pairs of hits in two layers of the silicon pixel detector. For a tracklet that is consistent with a charged hadron that originates at the primary vertex, the difference in pseudorapidity ($\Delta\eta$) and the azimuthal angle ($\Delta\phi$) between the two hits that make up the tracklet is small. The correlation between the hits in two silicon layers is analyzed to determine the charged hadron $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$. This method is capable of measuring and correcting for the combinatorial background and it is sensitive to hadrons with transverse momentum p_{T} as low as 0.04 GeV/c.

A tracklet-based vertex finder, as described in Ref. [13], is used for primary vertex reconstruction. In the first step, a hit from layer 1 is selected and a matching hit from layer 2 is sought. If the $|\Delta\phi|$ of the hits is smaller than 0.05, the z position with respect to the counterclockwise-beam direction of the hits is extrapolated linearly and projected onto the beam axis. This procedure is repeated for every hit in layer 1, and the calculated z positions are saved as vertex candidates. The primary vertex is determined in a second step. If the magnitude of the difference between the z positions of any two vertex candidates is smaller than 0.12 cm, they are combined into a vertex cluster. The vertex cluster with the highest number of associated vertex candidates is selected as the primary vertex, and the final vertex z position z_v is given by the average z position of the associated vertex candidates. The typical resolution of the primary vertex z position is 0.02–0.1 cm, depending on the number of pixel hits. The vertex reconstruction efficiency is high even for low-multiplicity events with few pixel hits, with around 80% efficiency for events with 3 to 4 hits in layer 1, and 100% efficiency for events with more than 8 hits in layer 1.

The tracklet reconstruction is a separate procedure from the vertex reconstruction. There is no requirement on the $\Delta\phi$ of the hits. Instead, hits with the smallest $|\Delta\eta|$ are paired first to form tracklets (Fig. 1, top), and no hit may be used more than once. In contrast to the track analysis, all hits are accepted for the tracklet reconstruction, such that the analysis is relatively insensitive to the cluster charge simulation. Tracklets corresponding to charged hadrons that originate at the primary vertex display a sharp peak at $\Delta\phi = 0$, while the background tracklets from uncorrelated pixel hits have a wide $\Delta\phi$ spectrum. Fig. 1 (bottom) shows the combined data of primary charged hadrons (sharp peak) and tracklets from uncorrelated pixel hits (wide tails). To suppress the combinatorial background, only tracklets with $|\Delta\eta| < 0.1$ and $|\Delta\phi| < 1$ are selected. Since the combinatorial background is flat in $\Delta\phi$, a sideband region $1 < |\Delta\phi| < 2$ can be defined and used to estimate its magnitude, which is then subtracted from the signal region $|\Delta\phi| < 1$ to obtain the uncorrected $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$. Typical values of the estimated background fraction in the signal region increase with $|\eta|$ from 6% to 25%. The η range for the tracklet method is limited to $|\eta| < 2$ to avoid a large acceptance correction.

Contributions from secondary particles, as well as the tracklet acceptance and reconstruction efficiency, have to be accounted for in order to determine the charged hadron $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distribution. These correction factors are calculated as a function of the primary vertex z position, pseudorapidity, and tracklet multiplicity, using the PYTHIA8 CUETP8M1 tune as a reference.

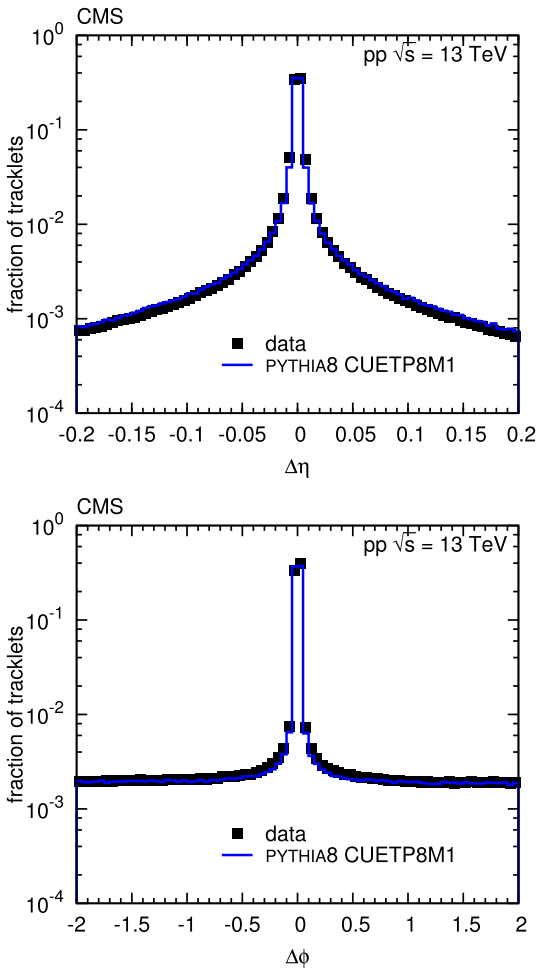

Fig. 1. The $\Delta\eta$ (top) and $\Delta\phi$ (bottom) distributions of hit pairs on tracklets in the data (squares) and from MC simulation (histogram).

To account for the difference between the actual pixel detector geometry and that used in the simulation, an additional correction is applied as a function of η and the primary vertex position. This correction is obtained by taking the ratio between data and simulation of the geometrical distribution of tracklets in (η, z_v) bins. The size of this correction ranges from 0 to 5%. The largest correction factors are associated with the presence of inactive tracker modules in the data.

4.2. Tracks

The analysis only uses clusters whose width in the z direction is compatible with that of a charged particle originating from the nominal collision point. The difference between the measured and the geometrically predicted widths is required to be smaller than 5 pixels.

Track finding involves identifying pixel hit triplets that fall on a straight line. All possible hit pairs are taken, the first hit from layer 1, and the second one from layer 2. If the difference between their azimuthal angles ϕ_1 and ϕ_2 is smaller than a certain value, $\Delta\phi_{1,2} < \alpha$, they are kept for the next step. For each hit pair, hits from layer 3 that have a small azimuthal difference with respect to the hit in layer 2 ($|\Delta\phi_{2,3}| < \alpha$) are collected. In addition, the vector joining the hits in the first and second layers and the vector joining the hits in the second and third layers are required to have polar angles that differ by, at most, α ($|\Delta\theta_{12,23}| < \alpha$). If multiple hits in the third layer satisfy the conditions above, the one with the smallest $\Delta\phi^2_{2,3} + \Delta\theta^2_{12,23}$ value is selected. The comparison of the $\Delta\phi$ distributions from signal and background shows that a value of $\alpha = 0.02$ gives the best signal significance.

The coordinates of the hits of the resulting triplets are used to perform a straight-line fit with parameters (z_0, η, ϕ) using Newton's method for minimization, where z_0 is the z coordinate of the point of closest approach to the beam axis. The transverse impact parameter d_0 with respect to the beam axis is fixed to 0 for this fit. The average distance $\bar{d}$ from the fitted line to the hits is used in the determination of the vertex position to estimate the uncertainty in z, as $\sigma_z = \bar{d}/\sin\theta$. A track is accepted if the straight-line fit to the hits gives a vertex position $|z_0| < 20$ cm.

The acceptance of the track method is $|\eta| < 1.8$, slightly reduced compared to the tracklet method, since all three pixel barrel layers are used. According to the samples of pp events generated with PYTHIA8 CUETP8M1 and EPOS LHC, the tracking efficiency is flat at 80% in the region $|\eta| < 1.6$ owing to losses at low p_T, and increases to 85% for $p_T > 0.2$ GeV/c. For $|\eta| > 1.6$, the efficiency falls and is on average around 50%. The wide p_T coverage down to 0.05 GeV/c ensures a robust performance and fairly insensitive behavior to variations in the p_T spectrum. The rate of duplicate tracks is below the percent level, while the fraction of misidentified tracks is in the range of 2–6%, rising with higher $|\eta|$ values. The fraction of reconstructed nonprimary particles is 2–3%.

An agglomerative vertex reconstruction [14] is performed using the fitted (z_0, σ_z) values from the reconstructed tracks. The clustering of tracks into vertices ends when the smallest σ_z-normalized distance between vertex candidates is larger than 50. Duplicate tracks are removed based on the angle enclosed by their direction vectors. If this angle is smaller than 0.01, the one with a larger average distance $\bar{d}$ is removed. Vertices with at least three tracks are kept, unless there is only one vertex found in the event. In that case, there is no minimum for the number of tracks. Only tracks associated with a primary vertex are used in the physics analysis.

The hits of the final tracks are refitted by allowing the impact parameter d_0 to vary. The resulting set of parameters is used in a three-dimensional vertex fit, which is also used to determine the location and shape of the interaction region. As Fig. 2 (top) shows, the distribution of the number of reconstructed tracks in data is in fair agreement with the MC event generator predictions in particular at the higher multiplicities. The correction from track to charged particle multiplicity depends on the fraction of detected events as well as on the distribution of high multiplicity events (not shown in the figure).

Owing to the excellent vertex resolution (≈250 μm), the η resolution is also very good. Thus, potential migrations between neighboring bins are very small, and the final generator-dependent corrections are applied bin-by-bin. The measured yields in each η bin are multiplied by the ratio of the number of simulated primary charged hadrons to the number of the reconstructed tracks.

The performance of vertexing in simulation and in data was compared by determining the probability of reconstructing k vertices in case of $n = 1, 2,$ and 3 simultaneous pp collisions. The extracted $p(k|n)$ conditional probabilities are used to estimate the average inelastic interaction probability μ per bunch crossing by assuming a Poissonian distribution for n. While PYTHIA8 CUETP8M1 gives $\mu = 0.0525 \pm 0.0003\,(\text{stat})$, EPOS LHC leads to $0.0545 \pm 0.0002\,(\text{stat})$. Taking their average as the central value and the difference as the systematic uncertainty, we estimate $\mu = 0.0535 \pm 0.0013\,(\text{syst})$. The product of the number of analyzed bunch crossings and μ gives the number of inelastic collision events, to be used for the calculation of the final $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ values.

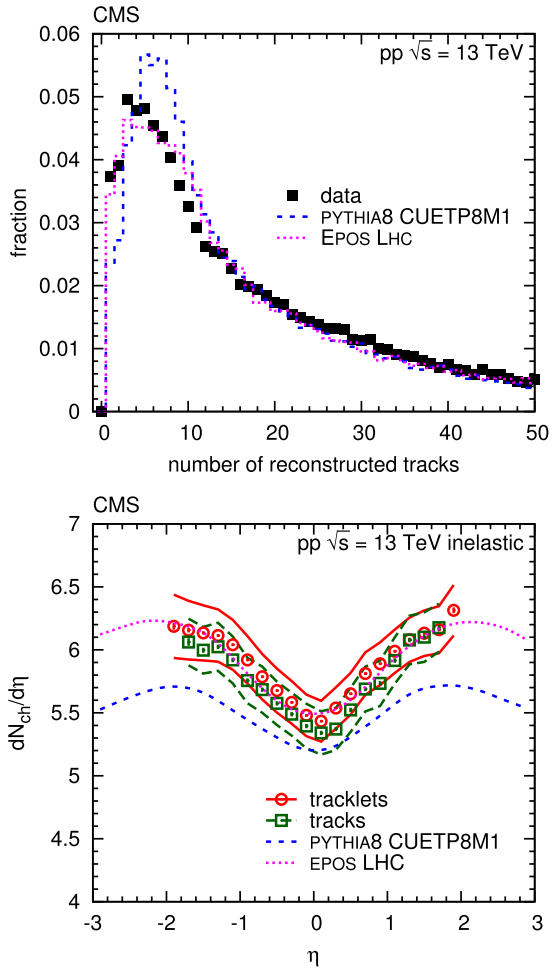

Fig. 2. (Top) Distributions of the number of reconstructed tracks per event from data and from simulations, for inelastic pp collisions. (Bottom) Distributions of the pseudorapidity density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$) of charged hadrons in the region $|\eta| < 2$ for inelastic collision events, reconstructed using tracklets (open circles), and tracks (open squares), compared to PYTHIA8 CUETP8M1 and EPOS LHC predictions, shown as dashed and dotted curves, respectively. The solid and long-dashed lines encompassing the data points indicate the systematic uncertainties of the two reconstruction methods.

4.3. Systematic uncertainties

The systematic uncertainties in the final physics result come from several sources. According to the two MC event generators used, the two reconstruction techniques detect about 86–89% (for the tracklet method) and 86–90% (for the track method) of the inelastic pp events. The uncertainty in the number of unseen, mostly single-diffractive, collisions contributes about 3% to the total systematic uncertainty.

The systematic uncertainties in the tracklet method take into account the effects of the amount of noise in the pixel hits (1–3%), detector misalignment, pixel hit reconstruction efficiency, and cluster splitting (all below 1%). The tracklet-to-hadron correction shows a 2–3% dependence on the choice of the MC event generator. The total systematic uncertainty of the tracklet method is in the range 3–4%.

For the track method, requiring three hits on a straight line greatly reduces the effects of pixel noise and cluster splitting. In addition, hits with cluster shapes that are not compatible with their positions are excluded from the analysis, and tracks close in (η, ϕ) are cleaned as described in Section 4.2. The loss of any of the three hits because of pixel reconstruction inefficiency would lead to the loss of the triplet, resulting in a systematic uncertainty of 1.8% from the tracking efficiency, independent of the choice of the MC event generator. The effect of detector misalignment on the angular distributions is several orders of magnitude smaller than the values of the selection criteria, and is therefore neglected. The sensitivity to the vertexing efficiency is included in the 2–3% systematic uncertainty associated with the estimate of μ, as discussed in Section 4.2. Uncertainties on track-level corrections are estimated from the differences obtained using the two MC generators, and are at the level of 2–3%. The total systematic uncertainty of the track method is in the range of 3–4%.

The track analysis was also performed using only matched hits of double-sided modules in the strip tracker. The result is compatible with that from the pixel-only analysis within the systematic uncertainties. Because of the larger corrections and the more restricted $|\eta|$ range, the result with the strip tracker is not included in the final combination.

Finally, we also used the method of counting reconstructed pixel hits, as described in Ref. [2], which is subject to different background and systematic effects, and the measurements are within the systematic uncertainties of the results reported in this Letter.

5. Results

For the tracklet analysis, all recorded bunch crossings are used (about 170 000 collision events), while for the track analysis only 1 million of them are used (about 55 000 collision events). After corrections, the agreement between the tracklet and track $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ results is better than 2% at central pseudorapidity and better than 3% at forward pseudorapidities, as shown in Fig. 2 (bottom). Hence, averaging their $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ values is justified. Since the systematic uncertainties dominate and are mostly correlated between the two analyses, the simple mean of the central values and of systematic uncertainties are taken. The fraction of primary charged leptons is ≈1% of the total long-lived charged particles produced, and the correction from detector-level tracklets and tracks is done for charged hadrons only.

Pseudorapidity density distributions of charged hadrons in the region $|\eta| < 2$ for inelastic pp events are shown in Fig. 3 (top). The data points and uncertainties are symmetrized in $\pm\eta$. In the range $|\eta| < 0.5$ the average pseudorapidity density is $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|<0.5} = 5.49 \pm 0.01\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst})$. While the predictions of both PYTHIA8 (with CUETP8S1 and CUETP8M1) and EPOS LHC agree with the measured central value, the measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distribution in the full η range is better described by the latter. The uncertainty band of PYTHIA8 corresponds to the envelope of the uncertainties of the tune parameters of CUETP8S1; the EPOS LHC predictions have no uncertainty associated with its parameter settings.

The center-of-mass energy dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ is shown in Fig. 3 (bottom). For comparison with the $\sqrt{s} = 13$ TeV results presented in this Letter, inelastic pp measurements at lower energies (ISR [15,16], UA5 [17,18], PHOBOS [19], and ALICE [20]) are also plotted. The measured values are empirically fitted using a second-order polynomial in $\ln(s)$ as $1.55 - 0.113\ln(s) + 0.0168\ln(s)^2$, where s has the units GeV^2, which provides a good description of the available data over the full energy range. The PYTHIA8 and EPOS LHC event generators globally reproduce the collision-energy dependence of hadron production in inelastic pp collisions.

6. Summary

The pseudorapidity distribution of charged hadrons has been measured by the CMS experiment, operated at zero magnetic field, at the LHC in proton–proton collisions at $\sqrt{s} = 13$ TeV. Using two

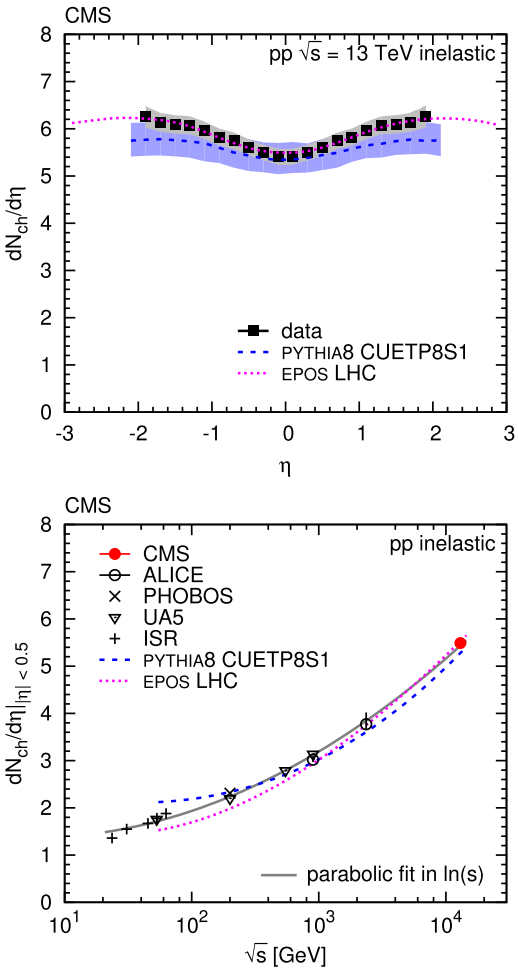

Fig. 3. (Top) Distributions of the pseudorapidity density of charged hadrons in the region $|\eta| < 2$ in inelastic pp collisions at 13 TeV measured in data (solid markers, combined track and tracklet results, symmetrized in η), and predicted by the PYTHIA8 CUETP8S1 and the EPOS LHC event generators (curves). The grey shaded area encompassing the data points indicates their correlated systematic uncertainties. The blue band corresponds to the envelope of the CUETP8S1 tune parametric uncertainties. (Bottom) Center-of-mass energy dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|<0.5}$ including ISR [15,16], UA5 [17,18], PHOBOS [19], and ALICE [20] data. The solid curve shows a second-order polynomial in $\ln(s)$ fit to the data points, including the new result at $\sqrt{s} = 13$ TeV. The dashed and dotted curves show the PYTHIA8 CUETP8S1 and EPOS LHC predictions, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

methods, based on hit pairs and straight-line tracks in the barrel region of the CMS pixel detector, a charged hadron multiplicity at midrapidity, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta|_{|\eta|<0.5} = 5.49 \pm 0.01\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst})$, has been obtained for inelastic pp events. In the central region, the measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distribution is consistent with predictions of the PYTHIA8 (with the CMS underlying event tunes CUETP8S1 and CUETP8M1) and EPOS LHC (LHC tune) event generators, while those in a wider η range are better described by the latter. These results constitute the first CMS measurement of hadron production at the new center-of-mass energy frontier, and provide new constraints for the improvement of perturbative and nonperturbative QCD aspects implemented in hadronic event generators.

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 centres 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); 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); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, 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 programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the Alfred 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 programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); and the Welch Foundation.

References

[1] CMS Collaboration, Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV, J. High Energy Phys. 02 (2010) 041, http://dx.doi.org/10.1007/JHEP02(2010)041, arXiv:1002.0621.

[2] CMS Collaboration, Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. Lett. 105 (2010) 022002, http://dx.doi.org/10.1103/PhysRevLett.105.022002, arXiv:1005.3299.

[3] CMS and TOTEM Collaborations, Measurement of pseudorapidity distributions of charged particles in proton–proton collisions at $\sqrt{s} = 8$ TeV by the CMS and TOTEM experiments, Eur. Phys. J. C 74 (2014) 3053, http://dx.doi.org/10.1140/epjc/s10052-014-3053-6, arXiv:1405.0722.

[4] T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, http://dx.doi.org/10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[5] T. Sjöstrand, S. Mrenna, P.Z. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852, http://dx.doi.org/10.1016/j.cpc.2008.01.036, arXiv:0710.3820.

[6] CMS Collaboration, Underlying event tunes and double parton scattering, CMS Physics Analysis Summary CMS-PAS-GEN-14-001, http://cdsweb.cern.ch/record/1697700, 2014.

[7] K. Werner, F.-M. Liu, T. Pierog, Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron–gold collisions at the BNL Relativistic Heavy Ion Collider, Phys. Rev. C 74 (2006) 044902, http://dx.doi.org/10.1103/PhysRevC.74.044902, arXiv:hep-ph/0506232.

[8] T. Pierog, I. Karpenko, J.M. Katzy, E. Yatsenko, K. Werner, EPOS LHC: test of collective hadronization with LHC data, arXiv:1306.0121, 2013, dESY-13-125.

[9] D. d'Enterria, R. Engel, T. Pierog, S. Ostapchenko, K. Werner, Constraints from the first LHC data on hadronic event generators for ultra-high energy cosmic-ray physics, Astropart. Phys. 35 (2011) 98, http://dx.doi.org/10.1016/j.astropartphys.2011.05.002, arXiv:1101.5596.

[10] CMS Collaboration, Production of leading charged particles and leading charged-particle jets at small transverse momenta in pp collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. D (2015), submitted for publication, arXiv:1507.00233.

[11] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, http://dx.doi.org/10.1088/1748-0221/3/08/S08004.

[12] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A 506 (2003) 250, http://dx.doi.org/10.1016/S0168-9002(03)01368-8.

[13] CMS Collaboration, Dependence on pseudorapidity and centrality of charged hadron production in PbPb collisions at a nucleon–nucleon centre-of-mass energy of 2.76 TeV, J. High Energy Phys. 08 (2011) 141, http://dx.doi.org/10.1007/JHEP08(2011)141, arXiv:1107.4800.

[14] F. Siklér, Study of clustering methods to improve primary vertex finding for collider detectors, Nucl. Instrum. Methods Phys. Res., Sect. A 621 (2010) 526, http://dx.doi.org/10.1016/j.nima.2010.04.058, arXiv:0911.2767.

[15] A.M. Rossi, G. Vannini, A. Bussière, E. Albini, D. D'Alessandro, G. Giacomelli, Experimental study of the energy dependence in proton–proton inclusive reactions, Nucl. Phys. B 84 (1975) 269, http://dx.doi.org/10.1016/0550-3213(75)90307-7.

[16] W. Thome, et al., Aachen-CERN-Heidelberg-Munich Collaboration, Charged particle multiplicity distributions in pp collisions at ISR energies, Nucl. Phys. B 129 (1977) 365, http://dx.doi.org/10.1016/0550-3213(77)90122-5.

[17] G.J. Alner, et al., UA5 Collaboration, Scaling of pseudorapidity distributions at c.m. energies up to 0.9 TeV, Z. Phys. C 33 (1986) 1, http://dx.doi.org/10.1007/BF01410446.

[18] G.J. Alner, et al., UA5 Collaboration, UA5: A general study of proton–antiproton physics at $\sqrt{s} = 546$ GeV, Phys. Rep. 154 (1987) 247, http://dx.doi.org/10.1016/0370-1573(87)90130-X.

[19] B.B. Back, et al., PHOBOS Collaboration, Pseudorapidity distribution of charged particles in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. Lett. 93 (2004) 082301, http://dx.doi.org/10.1103/PhysRevLett.93.082301, arXiv:nucl-ex/0311009.

[20] ALICE Collaboration, Charged-particle multiplicity measurement in proton–proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV with ALICE at LHC, Eur. Phys. J. C 68 (2010) 89, http://dx.doi.org/10.1140/epjc/s10052-010-1339-x, arXiv:1004.3034.

CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth [1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler [1], V. Knünz, A. König, M. Krammer [1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady [2], B. Rahbaran, H. Rohringer, J. Schieck [1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, G. Fasanella, L. Favart, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang [3]

Université Libre de Bruxelles, Bruxelles, Belgium

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi [4], O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco [5], J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov [6], L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Beliy, G.H. Hammad

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [7], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote [7], A. Vilela Pereira

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

S. Ahuja [a], C.A. Bernardes [b], A. De Souza Santos [b], S. Dogra [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], P.G. Mercadante [b], C.S. Moon [a,8], S.F. Novaes [a], Sandra S. Padula [a], D. Romero Abad, J.C. Ruiz Vargas

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina [9], F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, 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, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

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, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Bodlak, M. Finger [10], M. Finger Jr. [10]

Charles University, Prague, Czech Republic

Y. Assran [11], M. El Sawy [12,13], S. Elgammal [13], A. Ellithi Kamel [14], M. Kamel [15], M.A. Mahmoud [15], Y. Mohammed [15]

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

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France

J.-L. Agram [16], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte [16], X. Coubez, J.-C. Fontaine [16], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin [2], K. Skovpen, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, 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, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

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

T. Toriashvili [17]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [10]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov [6]

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann [2], A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

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

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras [18], A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, P. Connor, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo [19], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, J. Hauk, M. Hempel [20], H. Jung, A. Kalogeropoulos, O. Karacheban [20], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann [20], R. Mankel, I. Marfin [20], I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo [2], T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann [2], S.M. Heindl, U. Husemann, I. Katkov [6], A. Kornmayer [2], P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath [21], F. Sikler, V. Veszpremi, G. Vesztergombi [22], A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [23], J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók [24], A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

P. Mal, K. Mandal, D.K. Sahoo, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

R. Bhardwaj, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty [2], L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik [25], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu [26], G. Kole, S. Kumar, B. Mahakud, M. Maity [25], G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar [25], N. Sur, B. Sutar, N. Wickramage [27]

Tata Institute of Fundamental Research, Mumbai, India

S. Chauhan, S. Dube, S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami [28], A. Fahim [29], R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh [30], 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], C. Caputo [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], G. Maggi [a,c], M. Maggi [a], G. Miniello [a,b], S. My [a,c], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a,2], R. Venditti [a,b], 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 [2], A.C. Benvenuti [a], D. Bonacorsi [a,b], S. Braibant-Giacomelli [a,b], L. Brigliadori [a,b], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], S.S. Chhibra [a,b], 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,b], R. Travaglini [a,b]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

G. Cappello [a], M. Chiorboli [a,b], S. Costa [a,b], 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
[c] CSFNSM, Catania, Italy

G. Barbagli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], S. Gonzi [a,b], V. Gori [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], A. Tropiano [a,b], L. Viliani [a,b]

[a] INFN Sezione di Firenze, Firenze, Italy
[b] Università di Firenze, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli [a,b], F. Ferro [a], M. Lo Vetere [a,b], M.R. Monge [a,b], E. Robutti [a], S. Tosi [a,b]

[a] INFN Sezione di Genova, Genova, Italy
[b] Università di Genova, Genova, Italy

L. Brianza, M.E. Dinardo [a,b], S. Fiorendi [a,b], S. Gennai [a], R. Gerosa [a,b], A. Ghezzi [a,b], P. Govoni [a,b], S. Malvezzi [a], R.A. Manzoni [a,b], B. Marzocchi [a,b,2], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], N. Redaelli [a], 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,2], M. Esposito [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], G. Lanza [a], L. Lista [a], S. Meola [a,d,2], M. Merola [a], P. Paolucci [a,2], C. Sciacca [a,b], F. Thyssen

[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,2], N. Bacchetta [a], L. Benato [a,b], D. Bisello [a,b], A. Boletti [a,b], A. Branca [a,b], R. Carlin [a,b], P. Checchia [a], M. Dall'Osso [a,b,2], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], F. Gonella [a], A. Gozzelino [a], K. Kanishchev [a,c], S. Lacaprara [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Tosi [a,b], M. Zanetti, P. Zotto [a,b], A. Zucchetta [a,b,2], 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], C. Riccardi [a,b], P. Salvini [a], I. Vai [a], 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], D. Ciangottini [a,b,2], L. Fanò [a,b], P. Lariccia [a,b], G. Mantovani [a,b], M. Menichelli [a], A. Saha [a], A. Santocchia [a,b], A. Spiezia [a,b]

[a] INFN Sezione di Perugia, Perugia, Italy
[b] Università di Perugia, Perugia, Italy

K. Androsov [a,31], P. Azzurri [a], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], G. Broccolo [a,c], R. Castaldi [a], M.A. Ciocci [a,31], R. Dell'Orso [a], S. Donato [a,c,2], G. Fedi, L. Foà [a,c,†], A. Giassi [a], M.T. Grippo [a,31], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,b], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A. Savoy-Navarro [a,32], A.T. Serban [a], P. Spagnolo [a], P. Squillacioti [a,31], 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], G. D'imperio [a,b,2], D. Del Re [a,b], M. Diemoz [a], S. Gelli [a,b], C. Jorda [a], E. Longo [a,b], F. Margaroli [a,b], P. Meridiani [a], G. Organtini [a,b], R. Paramatti [a], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], P. Traczyk [a,b,2]

[a] *INFN Sezione di Roma, Roma, Italy*
[b] *Università di Roma, Roma, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c,2], S. Argiro [a,b], M. Arneodo [a,c], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], A. Degano [a,b], N. Demaria [a], L. Finco [a,b,2], B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M. Musich [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], A. Solano [a,b], A. Staiano [a], U. Tamponi [a]

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

S. Belforte [a], V. Candelise [a,b,2], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], B. Gobbo [a], C. La Licata [a,b], M. Marone [a,b], A. Schizzi [a,b], A. Zanetti [a]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

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

Chonbuk National University, Jeonju, Republic of Korea

S. Song

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

S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali [33], F. Mohamad Idris [34], W.A.T. Wan Abdullah, M.N. Yusli

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [35], A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen

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, W.A. Khan, T. Khurshid, M. Shoaib

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

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

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, A. Byszuk [36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, 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, P.G. Ferreira Parracho, M. Gallinaro, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev [37], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim [38], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, 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. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Bylinkin

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

V. Andreev, M. Azarkin [39], I. Dremin [39], M. Kirakosyan, A. Leonidov [39], G. Mesyats, S.V. Rusakov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, L. Khein, V. Klyukhin, O. Kodolova, I. Lokhtin, O. Lukina, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic [40], J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares

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

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

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli [41], L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi [42], M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas [43], D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres [22], N. Wardle, H.K. Wöhri, A. Zagozdzinska [36], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Quittnat, M. Rossini, A. Starodumov [44], M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler [45], L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, Y. Yang

Universität Zürich, Zurich, Switzerland

M. Cardaci, K.H. Chen, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng

National Taiwan University (NTU), Taipei, Taiwan

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

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

A. Adiguzel, S. Cerci [46], Z.S. Demiroglu, C. Dozen, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal [47], A. Kayis Topaksu, G. Onengut [48], K. Ozdemir [49], S. Ozturk [50], B. Tali [46], H. Topakli [50], M. Vergili, C. Zorbilmez

Cukurova University, Adana, Turkey

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak [51], G. Karapinar [52], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E.A. Albayrak [53], E. Gülmez, M. Kaya [54], O. Kaya [55], T. Yetkin [56]

Bogazici University, Istanbul, Turkey

K. Cankocak, S. Sen [57], F.I. Vardarlı

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold [58], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

D. Barducci, K.W. Bell, A. Belyaev [59], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Kenzie, R. Lane, R. Lucas [58], L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko [44], J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta [60], T. Virdee, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

Boston University, Boston, USA

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, N. Dhingra, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, T. Sinthuprasith, R. Syarif

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [61], C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, W. To, C. West, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan [†], S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, H.A. Weber, A. Whitbeck, F. Yang

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic [62], G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi [63], M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

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

B. Bilki [64], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya [65], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok [53], A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B.A. Barnett, B. Blumenfeld, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, A. Sady, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, C. Bruner, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, S. Sanders, R. Stringer, Q. Wang

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. Mcginn, C. Mironov, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northeastern University, Boston, USA

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko [37], T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

University of Rochester, Rochester, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, S. Panwalkar, M. Park, 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

M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

University of Tennessee, Knoxville, USA

O. Bouhali [66], A. Castaneda Hernandez [66], M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon [67], V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer [2]

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin, Madison, USA

† Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[3] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[4] Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
[5] Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
[6] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[7] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[8] Also at Centre National de la Recherche Scientifique (CNRS) – IN2P3, Paris, France.
[9] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
[10] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[11] Now at Suez University, Suez, Egypt.
[12] Also at Beni-Suef University, Bani Sweif, Egypt.
[13] Now at British University in Egypt, Cairo, Egypt.
[14] Also at Cairo University, Cairo, Egypt.
[15] Now at Fayoum University, El-Fayoum, Egypt.
[16] Also at Université de Haute Alsace, Mulhouse, France.
[17] Also at Tbilisi State University, Tbilisi, Georgia.
[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 Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[22] Also at Eötvös Loránd University, Budapest, Hungary.
[23] Also at University of Debrecen, Debrecen, Hungary.
[24] Also at Wigner Research Centre for Physics, Budapest, Hungary.
[25] Also at University of Visva-Bharati, Santiniketan, India.
[26] Now at King Abdulaziz University, Jeddah, Saudi Arabia.
[27] Also at University of Ruhuna, Matara, Sri Lanka.
[28] Also at Isfahan University of Technology, Isfahan, Iran.
[29] Also at University of Tehran, Department of Engineering Science, Tehran, 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 Purdue University, West Lafayette, USA.
[33] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[34] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[35] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[36] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[37] Also at Institute for Nuclear Research, Moscow, Russia.
[38] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[39] Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[40] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[41] Also at National Technical University of Athens, Athens, Greece.
[42] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[43] Also at University of Athens, Athens, Greece.
[44] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[45] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

[46] Also at Adiyaman University, Adiyaman, Turkey.
[47] Also at Mersin University, Mersin, Turkey.
[48] Also at Cag University, Mersin, Turkey.
[49] Also at Piri Reis University, Istanbul, Turkey.
[50] Also at Gaziosmanpasa University, Tokat, Turkey.
[51] Also at Ozyegin University, Istanbul, Turkey.
[52] Also at Izmir Institute of Technology, Izmir, Turkey.
[53] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[54] Also at Marmara University, Istanbul, Turkey.
[55] Also at Kafkas University, Kars, Turkey.
[56] Also at Yildiz Technical University, Istanbul, Turkey.
[57] Also at Hacettepe University, Ankara, Turkey.
[58] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[59] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[60] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[61] Also at Utah Valley University, Orem, USA.
[62] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[63] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[64] Also at Argonne National Laboratory, Argonne, USA.
[65] Also at Erzincan University, Erzincan, Turkey.
[66] Also at Texas A&M University at Qatar, Doha, Qatar.
[67] Also at Kyungpook National University, Daegu, Republic of Korea.