Phys. Lett. B 861 (2025) 139279

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Pseudorapidity distributions of charged hadrons in lead-lead collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.36$ TeV

The CMS Collaboration *

CERN, Geneva, Switzerland

ARTICLE INFO

Editor: M. Doser

Keywords:
CMS
Hadrons
Multiplicity
Spectra

ABSTRACT

The pseudorapidity (η) distributions of charged hadrons are measured using data collected at the highest ever nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{\mathrm{NN}}}} = 5.36$ TeV for collisions of lead-lead ions. The data were recorded by the CMS experiment at the LHC in 2022 and correspond to an integrated luminosity of $0.30 \pm 0.03\ \mu\mathrm{b}^{-1}$. Using the CMS silicon pixel detector, the yields of primary charged hadrons produced in the range $|\eta| < 2.6$ are reported. The evolution of the midrapidity particle density as a function of collision centrality is also reported. In the 5% most central collisions, the charged-hadron η density in the range $|\eta| < 0.5$ is found to be 2032 ± 91 (syst), with negligible statistical uncertainty. This result is consistent with an extrapolation from nucleus-nucleus collision data at lower center-of-mass energies. Comparisons are made to various Monte Carlo event generators and to previous measurements of lead-lead and xenon-xenon collisions at similar collision energies. These new data detail the dependence of particle production on the collision energy, initial collision geometry, and the size of the colliding nuclei.

1. Introduction

A hot medium of deconfined quarks and gluons, known as the quark-gluon plasma (QGP), is created in high-energy heavy ion collisions [1]. These collisions provide a unique avenue for the experimental study of matter whose properties are dictated by quantum chromodynamics (QCD).

One of most interesting aspects of the QGP is its behavior as an "almost perfect" liquid, i.e., having a very low shear viscosity to entropy density ratio, and the ability of hydrodynamic models to describe the evolution of the system [2]. Charged-hadron pseudorapidity (η) distributions and overall multiplicities (N_{ch}) can be used to constrain the initial conditions and subsequent evolution of the medium in these models [3]. Furthermore, information regarding nuclear shadowing and gluon saturation effects [4] can be extracted by studying the dependence of the N_{ch} on the initial geometry and center-of-mass energy of the collision system. Other interesting questions regarding the relative contributions to particle production of hard and soft scattering processes [5] and the modeling of these various processes [6] can be studied using these observables. Therefore, the measurements of the N_{ch} and its η dependence are important observables for understanding the formation and properties of the QGP in heavy ion collisions.

In 2022, the CMS experiment collected a sample of lead-lead (PbPb) collision events at the highest ever nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{\mathrm{NN}}}} = 5.36$ TeV, corresponding to an integrated luminosity of $0.30 \pm 0.03\ \mu\mathrm{b}^{-1}$. The collection of these data marked the beginning of the Run 3 era (2022–2025) at the CERN LHC for heavy ion collisions and provides an opportunity to examine the center-of-mass energy dependence of charged-particle production. Previous measurements of copper-copper (CuCu) [7] and gold-gold (AuAu) [8,9] collisions at lower energies at RHIC, as well as xenon-xenon (XeXe) collisions at 5.44 TeV [10,11] and PbPb collisions at 2.76 TeV [12,13] and 5.02 TeV [14] at the LHC, have indicated an approximate power-law scaling of charged-particle production as a function of the center-of-mass energy. This scaling law, as well as models that have been tuned at lower energies [15–17], can be tested using the new higher-energy data to determine how far the extrapolations from these empirical formulae and models can extend to higher center-of-mass energy systems.

In this Letter, measurements of the pseudorapidity density, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, of primary charged hadrons having $|\eta| < 2.6$ are reported for PbPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.36$ TeV. Primary charged hadrons are defined as prompt charged hadrons and decay products of all particles with proper decay length $c\tau < 1$ cm, where c is the speed of light in vacuum and τ is the proper lifetime of the particle. The same definitions were used in previous analyses of proton-proton (pp) collisions at 0.9–13 TeV [18–22],

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

https://doi.org/10.1016/j.physletb.2025.139279
Received 1 September 2024; Received in revised form 22 December 2024; Accepted 19 January 2025

Available online 20 January 2025

pPb collisions at 5.02 and 8.16 TeV [23], and PbPb and XeXe collisions at 2.76 and 5.44 TeV [10,13], respectively. Contributions from prompt leptons, decay products of longer-lived particles, and secondary interactions are excluded. The measurements are reported as functions of charged hadron η and the impact parameter between the two incoming ions in the collision. The data are also compared to theoretical predictions from modern event generators. Tabulated results are provided in the HEPData record for this analysis [24].

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 covering the range $|\eta| < 2.5$, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters (HF), made of steel and quartz-fibers and located on either side of the interaction point, extend the pseudorapidity coverage provided by the barrel and endcap detectors to $|\eta| < 5.2$. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The beam pickup timing for experiments (BPTX) devices are located around the beam pipe at a distance of 175 m from the interaction point on either side and provide precise information on the timing of the incoming beams. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [25].

Charged hadrons are reconstructed using the silicon pixel detector installed during the Phase-1 upgrade [26], which consists of four concentric cylindrical shells (layers) in the barrel region (BPIX) and three disks on each side of the interaction point in the forward region (FPIX). The BPIX and FPIX consist of a total of 1184 and 672 modules, respectively, and provide excellent position resolution with their 100×150 μm pixels. In this Letter, the layers of the BPIX are denoted in increasing order of their radial distance from the beam axis, i.e., the layer closest to the beam axis is referred to as layer 1, the next closest layer is referred to as layer 2, and so on, while the disks of the FPIX are referred to in increasing order of their longitudinal distance from the nominal interaction point.

3. Event selection

Online, minimum-bias events were selected using a trigger that required a coincidence of signals from both BPTX detectors and at least one energy deposit above 3 GeV in each HF calorimeter. Offline, events were required to have at least two energy deposits above 4 GeV in each of the HF calorimeters and at least one reconstructed primary vertex using the tracklet-based vertexing algorithm described in Ref. [13]. The tracklet reconstruction procedure is described in Section 4. A total of 50,000 events that pass these selections were used for the analysis. By analyzing data collected during the crossing of noncolliding ion bunches, the event selection requirements were found to successfully reject all backgrounds not arising from lead ion interactions. Thus, beam backgrounds, beam-halo effects, and cosmic ray sources have a negligible impact on this analysis.

Although this analysis is predominantly focused on hadronic collisions, electromagnetic (EM) interactions between the lead ions must be accounted for. The EM contribution is studied with simulated events generated by STARLIGHT 2.2 [27] interfaced with DPMJET-III 3.0-5 [28]. These simulations estimate the contamination rate, which is included in the event selection efficiency uncertainty. Residual EM contributions are estimated from STARLIGHT and cross-checked with data-driven methods that involve comparison between data and simulation with events that have small activities in the HF calorimeters. Single-diffractive events may also pass the event selections. Their contribution is subtracted using simulated events generated by EPOS LHC v3400 [16,29], in bins of tracklet multiplicity. The total hadronic event selection efficiency is calculated by comparing the total transverse energy distribution in the HF calorimeter with a template extracted from simulated EPOS LHC events [13]. The EM contamination rate is also factored into the total event selection efficiency uncertainty.

Because heavy ions are extended objects, their collisions can be characterized using the concept of "centrality," which is related to the collision impact parameter. This analysis estimates collision centrality by summing the transverse energy in the HF calorimeters, a procedure typically used in CMS analyses [13,30]. After correcting for the total event selection efficiency, the transverse energy distribution is partitioned into equal sections, which are labeled with a centrality percentage. This percentage corresponds to a fraction of the total hadronic nuclear interaction cross section [13]. By convention, the most central collisions, i.e., the ones having the smallest impact parameter, are labeled with small percentiles. This analysis is restricted to collisions in the 0–80% range, where the event selection efficiency is 100% and EM contamination effects are small (<1% contribution). The collision centrality is correlated with the number of participating nucleons N_{part} in the event. A Glauber model calculation [31,32] is used to determine the average N_{part} that a given centrality range corresponds to. These values are available in tabulated form in the supplemental material. For the purpose of this calculation, the nucleon-nucleon inelastic cross section is taken to be 68.0 ± 1.2 mb [32]. The nuclear radius and skin depth [33] of the lead nucleus are set to 6.69 ± 0.03 and 0.56 ± 0.03 fm [34], respectively.

4. Analysis

The $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ measurement uses pairs of pixel clusters from two different layers (disks) of the silicon pixel detector. These clusters are formed from adjacent pixels with a charge above the readout threshold. These pairs, known as tracklets, have clusters with relatively small differences in η and azimuthal angle ϕ (in radians) with respect to the primary vertex when they originate from a single charged particle. The correlations in η and ϕ can be used to select tracklets that correspond to primary charged hadrons. Reference [13] contains more information on the tracklet and vertex reconstruction algorithms.

This analysis uses nine different types of tracklets, which are distinguished by the layers in the pixel detector that are used to form the cluster pair. Six types result from using clusters in all possible combinations of the four barrel detector layers, and the remaining three come from combining pairs of the three forward disks. The combinations between barrel layers and forward disks are not used as they are sensitive to looper background from low transverse momentum (p_{T}) charged particles, which can have looping trajectories in the strong magnetic field and therefore leave multiple clusters in any given pixel layer. The $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ distributions from all nine tracklet types, after applying the corrections discussed below, are averaged and symmetrized around $\eta = 0$ to yield the final $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ result. $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta$ distributions coming from each individual tracklet type have different sensitivities to the charged-hadron p_{T} spectrum and can therefore be used as a systematic check.

A small fraction of detector modules were found to exhibit a significantly different response in the data when compared to Monte-Carlo (MC) simulations. These detector modules are identified and excluded from subsequent analysis procedures.

From the two clusters in a tracklet pair, a measure of angular distance

$$\Delta r = \sqrt{\left(\eta_{\mathrm{i}} - \eta_{\mathrm{j}}\right)^2 + \left(\phi_{\mathrm{i}} - \phi_{\mathrm{j}}\right)^2} \tag{1}$$

is defined. Here, $\eta_{\mathrm{i(j)}}$ is the pseudorapidity of the cluster in the i(j)th layer or disk with respect to the primary vertex position, and $\phi_{\mathrm{i(j)}}$ is defined similarly for the azimuthal angle. The fraction of tracklets resulting from combinatorial background, formed by clusters originating from different charged particles, is estimated in the MC and found to dominate at $\Delta r > 0.5$ in the simulation. To increase the purity of the tracklet sample and to reduce the sensitivity to the modeling of combinatorial background effects, only tracklets having $\Delta r < 0.5$ are used in the analysis.

This selection also suppresses the looper background related to low-p_T charged particles. After the tracklet selection, the background rate (including misreconstructed tracklets and the particles that are not primary charged hadrons), geometric acceptance, reconstruction efficiency, and event selection efficiency of the detector are taken into account. These corrections include an extrapolation to a tracklet p_T of zero to remove the effect of the minimum reconstructed charged-hadron p_T. The minimum charged-hadron p_T that can be reconstructed with this method is 40 MeV, corresponding to the tracklets formed using the inner two barrel pixel layers. The correction factors are calculated using samples of the previously discussed MC generators that have been interfaced with GEANT4 [35] to emulate the detector response. The typical magnitude of the corrections ranges from 30% to 130%. The tracklet efficiency shows minimal centrality dependence, but contamination rises in more central collisions due to acceptance effects and extrapolation to $p_T = 0$.

The Δr spectrum calculated with the EPOS LHC sample is found to most closely match the data in the region where the combinatorial background is significant (i.e., $0.4 < \Delta r < 0.5$), so this sample is used for calculating the corrections for the nominal result in this analysis. The simulated samples from other event generators are used to study systematic uncertainties. The correction factors are calculated as functions of η, primary vertex position along the beam axis v_z, and tracklet multiplicity.

5. Systematic uncertainties

The uncertainties resulting from various systematic effects affecting the measurement are evaluated:

- *Different probability of pixel cluster splitting in data and simulation.* Pixel cluster splitting refers to the condition where the charge deposit from a single charged particle is reconstructed as two pixel clusters in close proximity. The difference in the relative fraction of split clusters between data and simulation can be estimated by artificially splitting the pixel clusters in simulation and comparing the resulting modified Δr distribution of cluster pairs in simulation to that in data. This difference in this relative fraction is found to be at most 2.0%, which results in a variation of up to 2.0% in the $dN_{ch}/d\eta$ results.
- *v_z consistency.* The potential mismodeling of the alignment of the pixel detector in the simulations affects the correction factors. This effect is studied by comparing data with different v_z values which correspond to variations in η acceptance. The variation, which depends on centrality and η, ranges from 0.5 to 4.5%.
- *Tracklet selection.* The tracklet selection criteria affect the minimum p_T and signal-to-background ratio of reconstructed tracklets. The sensitivity of correction factors to selection criteria is examined by adjusting the nominal Δr criterion by ± 0.1. This adjustment effectively acts as a filter for the minimum p_T, as particles with lower p_T exhibit larger Δr values. Specifically, changing the Δr cut modifies the minimum p_T by approximately 50 MeV for particles detected by combining the 1st and 4th layers in the barrel pixel detector. This uncertainty is less than 0.5%.
- *Deviation from averaged and symmetrized results.* In any given η range, measurements can be made using multiple tracklet combinations. The maximum deviation in the measurements, obtained using each tracklet combination from the final averaged and symmetrized result, varies as a function of centrality and η, ranging from 1.0 to 4.0%, and these values are used for the uncertainty.
- *Model dependence of the corrections.* The model dependence of the correction factors is studied by using alternative sets of correction factors derived from HYDJET 1.9 [17] and AMPT 1.26t5 [36], which have different descriptions of the particle production mechanisms. The predicted particle p_T distributions and the lepton fraction can differ significantly among the event generators, which affect the correction for leptons and the extrapolation of the measured tracklet spectra to $p_T = 0$. The maximum deviation from the nominal results varies as a function of centrality and η, ranging from 0.5 to 2.0%.
- *Centrality calibration.* The determination of event centrality depends on the hadronic event selection efficiency, as well as the amount of contamination from EM processes. Since the inefficiency is limited to the most peripheral collisions (events with the largest centrality), the effect of the uncertainty in the event selection efficiency is to shift the events into other centrality intervals. Hence, to evaluate the uncertainty in the final results, different sets of centrality calibrations, derived after varying the event selection efficiency by its uncertainty, are used to categorize the data. This uncertainty increases from 0.1% in central collisions to 2.5% in peripheral events.

Table 1
Sources of systematic uncertainty affecting the measurement of charged-hadron multiplicities as a function of $\langle N_{part}\rangle$ in PbPb collisions at $\sqrt{s_{NN}} = 5.36$ TeV.

Source	[%]
Pixel cluster splitting	1.4–2.0
Consistency between primary vertex position	0.5–4.5
Tracklet selection	<0.5
Consistency between tracklet combinations	1.0–4.0
Model dependence	0.5–2.0
Centrality calibration	0.1–2.5
Total systematic uncertainty	2.5–6.4

A summary of the systematic uncertainties affecting the measurement of charged hadron multiplicities in events with different mean number of participating nucleons ($\langle N_{part}\rangle$) is given in Table 1. The individual contributions are then summed in quadrature to give the total systematic uncertainty, assuming them to be uncorrelated. At forward η, the uncertainty related to the primary vertex position is the leading uncertainty. At midrapidity, the dominant uncertainty comes from the consistency between tracklet combinations, except for peripheral events where the centrality calibration uncertainty is larger.

6. Results

Fig. 1 (top) shows the charged-hadron η distribution for the 0–80% centrality class, while Fig. 1 (bottom) presents this distribution for both the 0–5% centrality class, indicating head-on collisions, and the 50–55% class, which represents collisions with a larger impact parameter.

The results are compared to predictions from the EPOS LHC v3400, HYDJET 1.9, and AMPT 1.26t5 event generators. The EPOS generator is based on Gribov–Regge theory [37,38] and includes the effect of collective hadronization in hadron-hadron scatterings. The HYDJET generator treats a heavy ion collision as a superposition of a hydrodynamically parametrized soft component and a hard component resulting from multi-parton fragmentation. The AMPT generator combines the HIJING event generator [39] with Zhang's parton cascade procedure [40] and the ART model [41] for the last stage of parton hadronization. For the 0–80% event class and midrapidity region, the data match predictions from both AMPT with string melting and HYDJET. The string melting mechanism in AMPT transforms all excited strings from heavy-ion collisions into partons and employs a spatial quark coalescence model for hadronization.

Similar conclusions hold for 0–5% events when comparing to HYDJET, but the agreement with AMPT with string melting seems to be better in the forward region than in the midrapidity region in this centrality interval. The prediction of AMPT without string melting systematically overpredicts the data for all the centrality classes in the midrapidity region, while the predictions of EPOS LHC significantly undershoot the data for all η values and all of the centrality selections studied. The lower panels of Fig. 1 show the ratios of the MC models to data with the normalization set such that the ratio is unity at $\eta = 0$. It can be seen that,

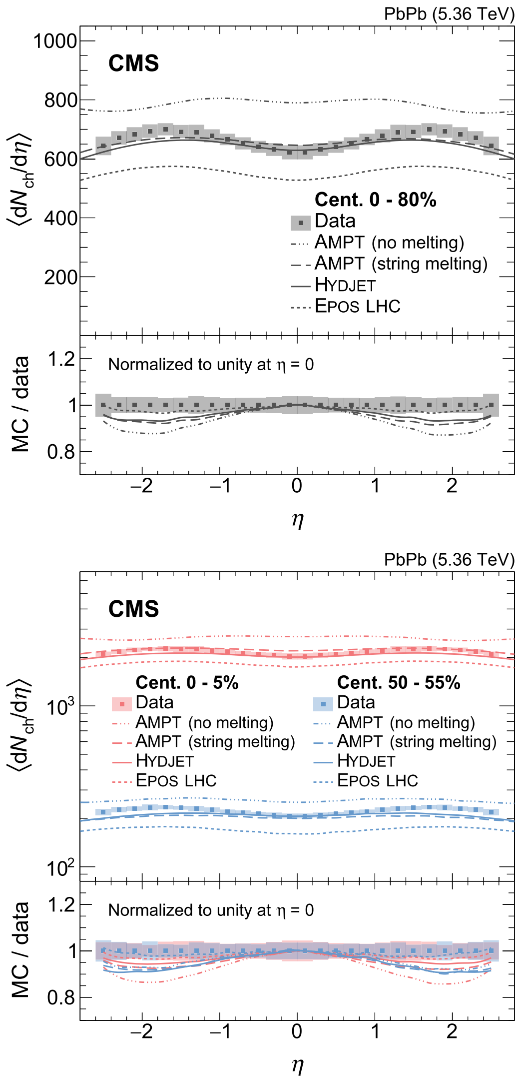

Fig. 1. The $dN_{ch}/d\eta$ distributions in PbPb collisions at $\sqrt{s_{NN}} = 5.36$ TeV for events in the 0–80% centrality class (top) and in the 0–5 and 50–55% centrality classes (bottom). The results have been averaged and symmetrized around $\eta = 0$. Predictions from the HYDJET 1.9 [17], AMPT 1.26t5 [36], and EPOS LHC v3400 event generators are also displayed. The ratios of the $dN_{ch}/d\eta$ distributions of simulation and data, normalized to unity at midrapidity, are shown in the bottom panels. The bands denote the total systematic uncertainties and the statistical uncertainties are negligible. In the ratio panels, the uncertainty band displayed represents the relative uncertainty of the data.

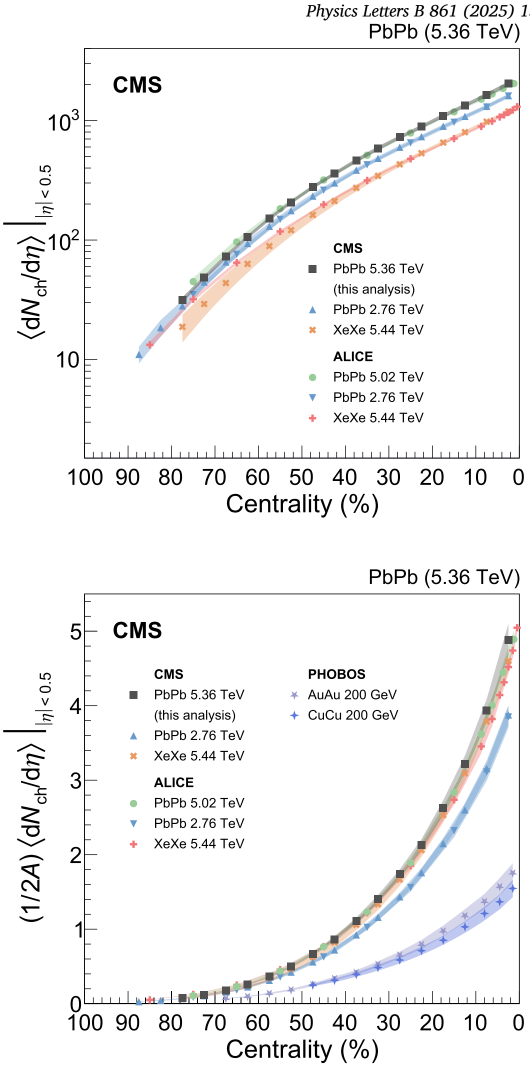

Fig. 2. Charged-hadron $dN_{ch}/d\eta$ in PbPb collisions at $\sqrt{s_{NN}} = 5.36$ TeV at midrapidity as a function of event centrality, shown as is (top) and normalized by $2A$ (bottom), where A is the atomic number of the nuclei. The results are compared to measurements in PbPb and XeXe collisions by the CMS [10,13] and ALICE [11,14,42] Collaborations, and to measurements in CuCu and AuAu collisions by the PHOBOS Collaboration [43]. The bands around the data points denote the total systematic uncertainties, while the statistical uncertainties are negligible.

after normalization, differences are accounted for, EPOS LHC does the best job of all the models examined of predicting the shape of the η distribution. Similar conclusions were found in studies of XeXe collisions at $\sqrt{s_{NN}} = 5.44$ TeV by the CMS [10] and ALICE [11] Collaborations. Nonetheless, none of the MC generators examined here are able to describe both the shape and magnitude of the charged-hadron distribution across the full range of η probed.

The charged-hadron $dN_{ch}/d\eta$ at midrapidity as a function of centrality is shown in Fig. 2 (top). The value of $dN_{ch}/d\eta$ is found to be 2032 ± 91 (syst) $(207 \pm 7$ (syst)) at $|\eta| < 0.5$ for events in the 0–5 (50–55%) centrality class. Previous measurements of PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV by the CMS [13] and ALICE [14,42] Collaborations, as well as previously discussed measurements of XeXe collisions at 5.44 TeV [10,11], are also shown. In general, at the same centrality $dN_{ch}/d\eta$ is larger for the collision systems with heavier ions. The PbPb data show a higher charged hadron $dN_{ch}/d\eta$ at higher collision energy for central events, as expected. The new 5.36 TeV CMS data are consistent with the ALICE data from 5.02 TeV collisions within uncertainties.

Previous analyses have noted that $dN_{ch}/d\eta$ approximately scales with $2A$ for collisions of different ion species at the same collision energy [10], where A represents the atomic number of the colliding nuclei. Fig. 2 (bottom) displays the normalized particle density $(dN_{ch}/d\eta)/2A$ as a function of collision centrality for the same data sets shown in Fig. 2 (top). Although the 5.36 TeV data are closer in collision energy to the 5.44 TeV XeXe data than the previous 5.02 TeV PbPb data, they tend to have slightly higher normalized $dN_{ch}/d\eta$ than 5.02 TeV PbPb, indicating that this scaling law is only approximate.

The value of $(dN_{ch}/d\eta)/\langle N_{part} \rangle$ is shown as a function of $\langle N_{part} \rangle$ in Fig. 3 (top) to study the role of the number of participating nucleons in particle production. The results are also compared to lower-energy measurements of CuCu and AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV, in addition to those from LHC experiments. It is important to note that the same number of participants can correspond to different centrality classes across various collision systems. The measured multiplicity per participant increases with higher collision energy for events with a sim-

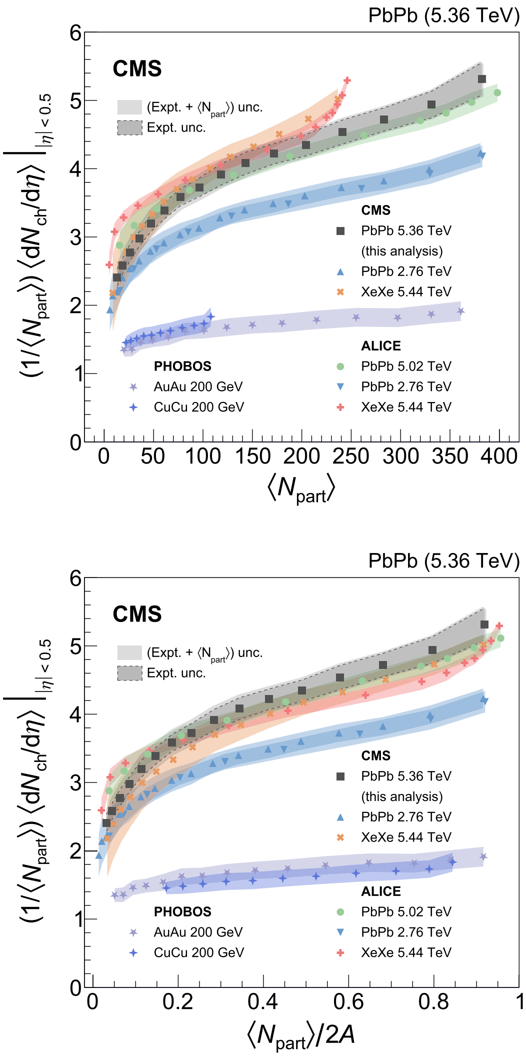

Fig. 3. Average $dN_{ch}/d\eta$ at midrapidity normalized by $\langle N_{part}\rangle$, shown as a function of $\langle N_{part}\rangle$ (top) and $\langle N_{part}\rangle/2A$ (bottom), where A is the atomic number of the nuclei. The results are compared to measurements in PbPb and XeXe collisions by the CMS [10,13], ALICE [11,14,42] Collaborations, and to measurements in CuCu and AuAu collisions by the PHOBOS Collaboration [43]. The bands around the data points denote the systematic uncertainties, while the statistical uncertainties are negligible.

ilar $\langle N_{part}\rangle$. At similar collision energy, the shapes of the distributions are inconsistent between PbPb and XeXe collisions. This is particularly apparent when examining the behavior around $\langle N_{part}\rangle = 200$, corresponding to the most central XeXe collisions. However, as shown in Fig. 3 (bottom), the per-participant N_{ch} for different colliding nuclei is consistent within uncertainties when the fraction of nucleons participating ($\langle N_{part}\rangle/2A$) and energy of the compared systems are the same. These data clearly suggest that the initial collision geometry is a crucial factor when predicting particle production at LHC energies [7].

Fig. 4 shows the dependence of $dN_{ch}/d\eta$ normalized by $\langle N_{part}\rangle$ on the collision energy for various collision systems and event selections. Power law fits to the previous measurements reproduced from Ref. [23] are displayed using dashed lines to guide the eye. The new CMS data, shown by the red point at $\sqrt{s_{NN}} = 5.36$ TeV, are consistent with this extrapolation from lower ion-ion collision energies; the central PbPb results at 5.36 TeV are about two times larger than non-single-diffractive (NSD) pp collisions. It has been previously noted in Ref. [23] that NSD pPb collisions (shown by yellow markers) have a lower normalized charged-particle density compared to NSD pp collisions (black markers) at the same energy, potentially because of the presence of non-QGP

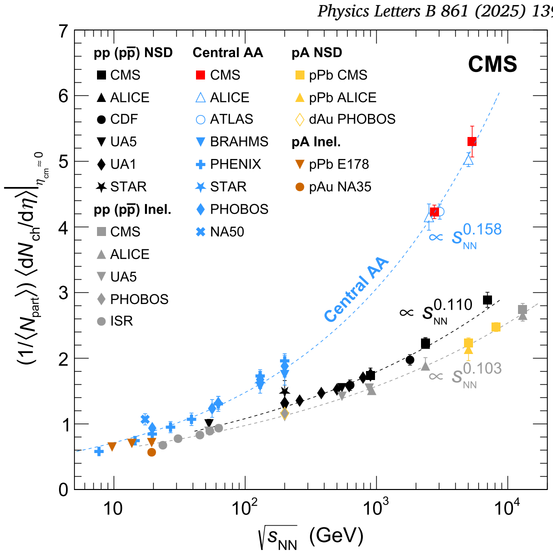

Fig. 4. Comparison of average $dN_{ch}/d\eta$ at midrapidity, scaled by $\langle N_{part}\rangle$ in pPb [23,44], pAu [45], dAu [46–48] (pA) and central heavy ion collisions [9, 13,42,43,47,49–57], as well as non-single-diffractive (NSD) [18,19,57–60] and inelastic [22,43,61,62] pp collisions. The data points for nucleus-nucleus (AA) collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been shifted horizontally for visibility. The dashed curves, reproduced from Ref. [23], are included to guide the eye, and correspond to a power law functional form.

related effects. Although such effects may also be present in ion-ion collisions to some extent, the different trends of ion-ion and proton-ion (pA) data with respect to NSD pp collisions highlight the complexity of the interplay between non-QGP and QGP-related effects when considering soft-particle production. These data clearly indicate that ion-ion collisions are more efficient than smaller collision systems at converting the initial collision energy into final-state particle multiplicity, and they are not merely superpositions of pp or pA collisions.

7. Summary

The pseudorapidity (η) distributions of charged hadrons are measured in the range $|\eta| < 2.6$ for multiple centrality intervals using data collected in lead-lead (PbPb) collisions at the highest center-of-mass energy of $\sqrt{s_{NN}} = 5.36$ TeV. The dependence on η and centrality are compared to the event generators EPOS LHC v3400, HYDJET 1.9, and AMPT 1.26t5; none of these event generators are able to fully describe the measurements in terms of the magnitude, η dependence, and centrality dependence of the $dN_{ch}/d\eta$ distributions. The charged hadron density at midrapidity rises with collision energy and centrality, aligning with extrapolations from lower energies. Additionally, the scaling of this observable with the size of the colliding nuclei is found to be only approximate.

In the 5% most central collisions, the charged-hadron density $dN_{ch}/d\eta$ for the range $|\eta| < 0.5$ is found to be 2032 ± 91 (syst), with negligible statistical uncertainty. The results at midrapidity are also compared to previous measurements in various collision systems, including PbPb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, xenon-xenon collisions at 5.44 TeV, as well as copper-copper and gold-gold collisions at $\sqrt{s_{NN}} = 200$ GeV. Normalizing $dN_{ch}/d\eta$ by the number of participating nucleons shows that larger systems convert collision energy to particles more efficiently than smaller ones. These comparisons are new constraints on models and generators which describe multiparticle production in relativistic heavy ion collisions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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 and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); Minciencias (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science – EOS” – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 “Quantum Universe” – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF “a way of making Europe”, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2025.139279.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

References

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

[2] U. Heinz, R. Snellings, Collective flow and viscosity in relativistic heavy-ion collisions, Annu. Rev. Nucl. Part. Sci. 63 (2013) 123, https://doi.org/10.1146/annurev-nucl-102212-170540, arXiv:1301.2826.

[3] P. Romatschke, U. Romatschke, Relativistic Fluid Dynamics in and Out of Equilibrium, Cambridge Monographs on Mathematical Physics, Cambridge University Press, 2019, arXiv:1712.05815.

[4] J.L. Albacete, C. Marquet, Gluon saturation and initial conditions for relativistic heavy ion collisions, Prog. Part. Nucl. Phys. 76 (2014) 1, https://doi.org/10.1016/j.ppnp.2014.01.004, arXiv:1401.4866.

[5] D. Kharzeev, M. Nardi, Hadron production in nuclear collisions at RHIC and high density QCD, Phys. Lett. B 507 (2001) 121, https://doi.org/10.1016/S0370-2693(01)00457-9, arXiv:nucl-th/0012025.

[6] 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, https://doi.org/10.1016/j.astropartphys.2011.05.002, arXiv:1101.5596.

[7] B. Alver, et al., PHOBOS, System size, energy and centrality dependence of pseudorapidity distributions of charged particles in relativistic heavy ion collisions, Phys. Rev. Lett. 102 (2009) 142301, https://doi.org/10.1103/PhysRevLett.102.142301, arXiv:0709.4008.

[8] B.B. Back, et al., PHOBOS, Charged-particle pseudorapidity distributions in Au+Au collisions at $\sqrt{s_{_{NN}}} = 62.4$ GeV, Phys. Rev. C 74 (2006) 021901, https://doi.org/10.1103/PhysRevC.74.021901, arXiv:nucl-ex/0509034.

[9] I.G. Bearden, et al., BRAHMS, Pseudorapidity distributions of charged particles from Au+Au collisions at the maximum RHIC energy, Phys. Rev. Lett. 88 (2002) 202301, https://doi.org/10.1103/PhysRevLett.88.202301, arXiv:nucl-ex/0112001.

[10] CMS Collaboration, Pseudorapidity distributions of charged hadrons in xenon-xenon collisions at $\sqrt{s_{_{NN}}} = 5.44$ TeV, Phys. Lett. B 799 (2019) 135049, https://doi.org/10.1016/j.physletb.2019.135049, arXiv:1902.03603.

[11] ALICE Collaboration, Centrality and pseudorapidity dependence of the charged-particle multiplicity density in Xe-Xe collisions at $\sqrt{s_{_{NN}}} = 5.44$ TeV, Phys. Lett. B 790 (2019) 35, https://doi.org/10.1016/j.physletb.2018.12.048, arXiv:1805.04432.

[12] ALICE Collaboration, Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Phys. Rev. Lett. 106 (2011) 032301, https://doi.org/10.1103/PhysRevLett.106.032301, arXiv:1012.1657.

[13] CMS Collaboration, Dependence on pseudorapidity and on centrality of charged hadron production in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, J. High Energy Phys. 08 (2011) 141, https://doi.org/10.1007/JHEP08(2011)141, arXiv:1107.4800.

[14] ALICE Collaboration, Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Rev. Lett. 116 (2016) 222302, https://doi.org/10.1103/PhysRevLett.116.222302, arXiv:1512.06104.

[15] W.-T. Deng, X.-N. Wang, R. Xu, Gluon shadowing and hadron production in heavy-ion collisions at LHC, Phys. Lett. B 701 (2011) 133, https://doi.org/10.1016/j.physletb.2011.05.040, arXiv:1011.5907.

[16] T. Pierog, I. Karpenko, J.M. Katzy, E. Yatsenko, K. Werner, EPOS LHC: test of collective hadronization with data measured at the CERN Large Hadron Collider, Phys.

Rev. C 92 (2015) 034906, https://doi.org/10.1103/PhysRevC.92.034906, arXiv:1306.0121.
[17] I.P. Lokhtin, A.M. Snigirev, A model of jet quenching in ultrarelativistic heavy ion collisions and high-p_T hadron spectra at RHIC, Eur. Phys. J. C 45 (2006) 211, https://doi.org/10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.
[18] 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, https://doi.org/10.1007/JHEP02(2010)041, arXiv:1002.0621.
[19] CMS Collaboration, Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. Lett. 105 (2010) 022002, https://doi.org/10.1103/PhysRevLett.105.022002, arXiv:1005.3299.
[20] CMS Collaboration, Charged particle multiplicities in pp interactions at $\sqrt{s} = 0.9$, 2.36, and 7 TeV, J. High Energy Phys. 01 (2011) 079, https://doi.org/10.1007/JHEP01(2011)079, arXiv:1011.5531.
[21] CMS 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, https://doi.org/10.1140/epjc/s10052-014-3053-6, arXiv:1405.0722.
[22] CMS Collaboration, Pseudorapidity distribution of charged hadrons in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B 751 (2015) 143, https://doi.org/10.1016/j.physletb.2015.10.004, arXiv:1507.05915.
[23] CMS Collaboration, Pseudorapidity distributions of charged hadrons in proton-lead collisions at $\sqrt{s_{_{NN}}} = 5.02$ and 8.16 TeV, J. High Energy Phys. 01 (2018) 045, https://doi.org/10.1007/JHEP01(2018)045, arXiv:1710.09355.
[24] CMS Collaboration, HEPData record for this analysis, https://doi.org/10.17182/hepdata.153190, 2024.
[25] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.
[26] CMS Collaboration, CMS Technical Design Report for the Pixel Detector Upgrade, Technical Report, 2012, https://doi.org/10.2172/1151650.
[27] S.R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, J. Butterworth, STARlight: a Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions, Comput. Phys. Commun. 212 (2017) 258, https://doi.org/10.1016/j.cpc.2016.10.016, arXiv:1607.03838.
[28] S. Roesler, R. Engel, J. Ranft, The Monte Carlo event generator DPMJET-III, in: Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, Proceedings, Conference, MC2000, Lisbon, Portugal, October 23-26, 2000, 1033, 2000, arXiv:hep-ph/0012252.
[29] 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, https://doi.org/10.1103/PhysRevC.74.044902, arXiv:hep-ph/0506232.
[30] 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.
[31] 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.
[32] C. Loizides, J. Kamin, D. d'Enterria, Improved Monte Carlo Glauber predictions at present and future nuclear colliders, Phys. Rev. C 97 (2018) 054910, https://doi.org/10.1103/PhysRevC.97.054910, arXiv:1710.07098.
[33] C.M. Tarbert, et al., Neutron skin of ^{208}Pb from coherent pion photoproduction, Phys. Rev. Lett. 112 (2014) 242502, https://doi.org/10.1103/PhysRevLett.112.242502, arXiv:1311.0168.
[34] C. Loizides, J. Nagle, P. Steinberg, Improved version of the PHOBOS Glauber Monte Carlo, SoftwareX 1–2 (2014) 13, https://doi.org/10.1016/j.softx.2015.05.001, arXiv:1408.2549.
[35] S. Agostinelli, et al., GEANT4, Geant4—a simulation toolkit, Nucl. Instrum. Meth. A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.
[36] Z.-W. Lin, C.M. Ko, B.-A. Li, B. Zhang, S. Pal, A multi-phase transport model for relativistic heavy ion collisions, Phys. Rev. C 72 (2005) 064901, https://doi.org/10.1103/PhysRevC.72.064901, arXiv:nucl-th/0411110.
[37] V.N. Gribov, A Reggeon diagram technique, Sov. Phys. JETP 26 (1968) 414, Zh. Eksp. Teor. Fiz. 53 (1967) 654.
[38] H.J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, K. Werner, Parton based Gribov-Regge theory, Phys. Rep. 350 (2001) 93, https://doi.org/10.1016/S0370-1573(00)00122-8, arXiv:hep-ph/0007198.
[39] X.-N. Wang, M. Gyulassy, HIJING: a Monte Carlo model for multiple jet production in pp, pA and AA collisions, Phys. Rev. D 44 (1991) 3501, https://doi.org/10.1103/PhysRevD.44.3501.
[40] B. Zhang, ZPC 1.0.1: a parton cascade for ultrarelativistic heavy ion collisions, Comput. Phys. Commun. 109 (1998) 193, https://doi.org/10.1016/S0010-4655(98)00010-1, arXiv:nucl-th/9709009.
[41] B.-A. Li, C.M. Ko, Formation of superdense hadronic matter in high energy heavy-ion collisions, Phys. Rev. C 52 (1995) 2037, https://doi.org/10.1103/PhysRevC.52.2037, arXiv:nucl-th/9505016.
[42] ALICE Collaboration, Charged-particle multiplicity density at midrapidity in central Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Phys. Rev. Lett. 105 (2010) 252301, https://doi.org/10.1103/PhysRevLett.105.252301, arXiv:1011.3916.
[43] B. Alver, et al., PHOBOS, Phobos results on charged particle multiplicity and pseudorapidity distributions in Au+Au, Cu+Cu, d+Au, and p+p collisions at ultra-relativistic energies, Phys. Rev. C 83 (2011) 024913, https://doi.org/10.1103/PhysRevC.83.024913, arXiv:1011.1940.
[44] ALICE Collaboration, Pseudorapidity density of charged particles in pp+Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Rev. Lett. 110 (2013) 032301, https://doi.org/10.1103/PhysRevLett.110.032301, arXiv:1210.3615.
[45] T. Alber, et al., NA35, Charged particle production in proton-, deuteron-, oxygen- and sulphur-nucleus collisions at 200 GeV per nucleon, Eur. Phys. J. C 2 (1998) 643, https://doi.org/10.1007/s100520050167, arXiv:hep-ex/9711001.
[46] B.B. Back, et al., PHOBOS, Pseudorapidity distribution of charged particles in d+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. Lett. 93 (2004) 082301, https://doi.org/10.1103/PhysRevLett.93.082301, arXiv:nucl-ex/0311009.
[47] A. Adare, et al., PHENIX, Transverse energy production and charged-particle multiplicity at midrapidity in various systems from $\sqrt{s_{_{NN}}} = 7.7$ to 200 GeV, Phys. Rev. C 93 (2016) 024901, https://doi.org/10.1103/PhysRevC.93.024901, arXiv:1509.06727.
[48] C. Aidala, et al., PHENIX, Measurements of azimuthal anisotropy and charged-particle multiplicity in d+Au collisions at $\sqrt{s_{_{NN}}} = 200$, 62.4, 39, and 19.6 GeV, Phys. Rev. C 96 (2017) 064905, https://doi.org/10.1103/PhysRevC.96.064905, arXiv:1708.06983.
[49] M.C. Abreu, et al., NA50, Scaling of charged particle multiplicity in PbPb collisions at SPS energies, Phys. Lett. B 530 (2002) 43, https://doi.org/10.1016/S0370-2693(02)01353-9.
[50] C. Adler, et al., STAR, Multiplicity distribution and spectra of negatively charged hadrons in Au+Au collisions at $\sqrt{s_{_{NN}}} = 130$ GeV, Phys. Rev. Lett. 87 (2001) 112303, https://doi.org/10.1103/PhysRevLett.87.112303, arXiv:nucl-ex/0106004.
[51] I.G. Bearden, et al., BRAHMS, Charged particle densities from Au+Au collisions at $\sqrt{s_{_{NN}}} = 130$ GeV, Phys. Lett. B 523 (2001) 227, https://doi.org/10.1016/S0370-2693(01)01333-8, arXiv:nucl-ex/0108016.
[52] K. Adcox, et al., PHENIX, Centrality dependence of charged particle multiplicity in Au-Au collisions at $\sqrt{s_{_{NN}}} = 130$ GeV, Phys. Rev. Lett. 86 (2001) 3500, https://doi.org/10.1103/PhysRevLett.86.3500, arXiv:nucl-ex/0012008.
[53] B.B. Back, et al., PHOBOS, Charged-particle multiplicity near midrapidity in central Au+Au collisions at $\sqrt{s_{_{NN}}} = 56$ and 130 GeV, Phys. Rev. Lett. 85 (2000) 3100, https://doi.org/10.1103/PhysRevLett.85.3100, arXiv:hep-ex/0007036.
[54] B.B. Back, et al., PHOBOS, Charged-particle pseudorapidity density distributions from Au+Au collisions at $\sqrt{s_{_{NN}}} = 130$ GeV, Phys. Rev. Lett. 87 (2001) 102303, https://doi.org/10.1103/PhysRevLett.87.102303, arXiv:nucl-ex/0106006.
[55] ATLAS Collaboration, Measurement of the centrality dependence of the charged particle pseudorapidity distribution in lead-lead collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV with the ATLAS detector, Phys. Lett. B 710 (2012) 363, https://doi.org/10.1016/j.physletb.2012.02.045, arXiv:1108.6027.
[56] B.I. Abelev, et al., STAR, Identified particle production, azimuthal anisotropy, and interferometry measurements in Au+Au collisions at $\sqrt{s_{_{NN}}} = 9.2$ GeV, Phys. Rev. C 81 (2010) 024911, https://doi.org/10.1103/PhysRevC.81.024911, arXiv:0909.4131.
[57] B.I. Abelev, et al., STAR, Systematic measurements of identified particle spectra in pp, d+Au and Au+Au collisions from STAR, Phys. Rev. C 79 (2009) 034909, https://doi.org/10.1103/PhysRevC.79.034909, arXiv:0808.2041.
[58] C. Albajar, et al., (UA1), A study of the general characteristics of $p\bar{p}$ collisions at $\sqrt{s} = 0.2$ TeV to 0.9 TeV, Nucl. Phys. B 335 (1990) 261, https://doi.org/10.1016/0550-3213(90)90493-W.
[59] K. Alpgard, et al., UA5, Particle multiplicities in $p\bar{p}$ interactions at $\sqrt{s} = 540$ GeV, Phys. Lett. B 121 (1983) 209, https://doi.org/10.1016/0370-2693(83)90916-4.
[60] F. Abe, et al., CDF, Pseudorapidity distributions of charged particles produced in $\bar{p}p$ interactions at $\sqrt{s} = 630$ GeV and 1800 GeV, Phys. Rev. D 41 (1990) 2330, https://doi.org/10.1103/PhysRevD.41.2330.
[61] W. Thome, et al., Aachen-CERN-Heidelberg-Munich, Charged particle multiplicity distributions in pp collisions at ISR energies, Nucl. Phys. B 129 (1977) 365, https://doi.org/10.1016/0550-3213(77)90122-5.
[62] 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, https://doi.org/10.1140/epjc/s10052-010-1339-x, arXiv:1004.3034.

The CMS collaboration

A. Hayrapetyan, A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish[3], T. Janssen, P. Van Mechelen

Universiteit Antwerpen, Antwerpen, Belgium

N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[4], G.P. Van Onsem, S. Van Putte, D. Vannerom

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, D. Hohov, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, V. Makarenko, A. Malara, S. Paredes, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Université Libre de Bruxelles, Bruxelles, Belgium

M. De Coen, D. Dobur, G. Gokbulut, Y. Hong, J. Knolle, L. Lambrecht, D. Marckx, G. Mestdach, K. Mota Amarilo, C. Rendón, A. Samalan, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

Ghent University, Ghent, Belgium

A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

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

G.A. Alves, E. Coelho, C. Hensel, T. Menezes De Oliveira, A. Moraes, P. Rebello Teles, M. Soeiro, A. Vilela Pereira[5]

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins[8], C. Mora Herrera, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

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

C.A. Bernardes[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

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

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, 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, A. Petrov, E. Shumka

University of Sofia, Sofia, Bulgaria

S. Keshri, S. Thakur

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

T. Cheng, T. Javaid, L. Yuan

Beihang University, Beijing, China

Z. Hu, Z. Liang, J. Liu, K. Yi[9,10]

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen[11], H.S. Chen[11], M. Chen[11], F. Iemmi, C.H. Jiang, A. Kapoor[12], H. Liao, Z.-A. Liu[13], M.A. Shahzad[11], R. Sharma[14], J.N. Song[13], J. Tao, C. Wang[11], J. Wang, Z. Wang[11], H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, L. Zhang, Y. Zhao, C. Zhou

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

S. Yang

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China

Z. You

Sun Yat-Sen University, Guangzhou, China

K. Jaffel, N. Lu

University of Science and Technology of China, Hefei, China

G. Bauer[15], B. Li, J. Zhang

Nanjing Normal University, Nanjing, China

X. Gao[16]

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

Z. Lin, C. Lu, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

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

Universidad de Los Andes, Bogota, Colombia

F. Ramirez, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

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

M. Kovac, A. Petkovic, T. Sculac

University of Split, Faculty of Science, Split, Croatia

P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, S. Mishra, A. Starodumov[17], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

H. Abdalla[18], S. Abu Zeid[19], Y. Assran[20,21]

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

M.A. Mahmoud, Y. Mohammed

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

S. Bharthuar, N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[22], P. Simkina, M. Titov, M. Tornago

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

F. Beaudette, P. Busson, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

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

J.-L. Agram[23], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

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

A. Di Florio

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

D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[24], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

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

A. Khvedelidze[17], I. Lomidze, Z. Tsamalaidze[17]

Georgian Technical University, Tbilisi, Georgia

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

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

S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[25], S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

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

H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, S. Bhattacharya, F. Blekman[26], K. Borras[27], A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[26], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[28], W. Lohmann[29], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, Y. Otarid, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, A. Saggio, M. Scham[30,27], S. Schnake[27], P. Schütze, C. Schwanenberger[26], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[27], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

University of Hamburg, Hamburg, Germany

S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[31], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, B. Maier, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[31], A. Stakia

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

P. Kontaxakis, G. Melachroinos, Z. Painesis, A. Panagiotou, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

C. Hajdu, D. Horvath[32,33], K. Márton, A.J. Rádl[34], F. Sikler, V. Veszpremi

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

M. Csanád, K. Farkas, A. Fehérkuti[35], M.M.A. Gadallah[36], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

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

P. Raics, B. Ujvari, G. Zilizi

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

T. Csorgo[35], F. Nemes[35], T. Novak

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

J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[37], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Baradia, S. Barman[38], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[39], D. Kumar[39], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Indian Institute of Technology Madras, Madras, India

S. Dugad, M. Kumar, G.B. Mohanty, B. Parida, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-A, Mumbai, India

A. Bala, S. Banerjee, R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati[40], C. Kar, D. Maity[41], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[41], K. Naskar[41], A. Nayak[41], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[41], D. Vats[41]

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

S. Acharya [42], A. Alpana, S. Dube, B. Gomber [42], P. Hazarika, B. Kansal, A. Laha, B. Sahu [42], S. Sharma, K.Y. Vaish

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

H. Bakhshiansohi [43], A. Jafari [44], M. Zeinali [45]

Isfahan University of Technology, Isfahan, Iran

S. Bashiri, S. Chenarani [46], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie [47], M. Mohammadi Najafabadi, S. Tizchang [48]

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], A. Colaleo [a,b], D. Creanza [a,c], B. D'Anzi [a,b], N. De Filippis [a,c], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], M. Louka [a,b], G. Maggi [a,c], M. Maggi [a], I. Margjeka [a], V. Mastrapasqua [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pellecchia [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], D. Ramos [a], A. Ranieri [a], L. Silvestris [a], F.M. Simone [a,c], Ü. Sözbilir [a], A. Stamerra [a,b], D. Troiano [a,b], R. Venditti [a,b], P. Verwilligen [a], A. Zaza [a,b]

[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. Borgonovi [a], P. Capiluppi [a,b], A. Castro [a,b,†], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], T. Diotalevi [a,b], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a], P. Giacomelli [a], L. Giommi [a,b], C. Grandi [a], L. Guiducci [a,b], S. Lo Meo [a,49], M. Lorusso [a,b], L. Lunerti [a], S. Marcellini [a], G. Masetti [a], F.L. Navarria [a,b], G. Paggi [a,b], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], S. Rossi Tisbeni [a,b], T. Rovelli [a,b], G.P. Siroli [a,b]

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

S. Costa [a,b,50], A. Di Mattia [a], A. Lapertosa [a], R. Potenza [a,b], A. Tricomi [a,b,50], C. Tuve [a,b]

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

P. Assiouras [a], G. Barbagli [a], G. Bardelli [a,b], B. Camaiani [a,b], A. Cassese [a], R. Ceccarelli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], T. Kello [a], G. Latino [a,b], P. Lenzi [a,b], M. Lizzo [a], M. Meschini [a], S. Paoletti [a], A. Papanastassiou [a,b], G. Sguazzoni [a], L. Viliani [a]

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

L. Benussi, S. Bianco, S. Meola [51], D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Chatagnon [a], 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], G. Boldrini [a,b], F. Brivio [a], F. Cetorelli [a,b], F. De Guio [a,b], M.E. Dinardo [a,b], P. Dini [a], S. Gennai [a], R. Gerosa [a,b], A. Ghezzi [a,b], P. Govoni [a,b], L. Guzzi [a], M.T. Lucchini [a,b], M. Malberti [a], S. Malvezzi [a], A. Massironi [a], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], S. Palluotto [a,b], D. Pedrini [a], A. Perego [a,b], B.S. Pinolini [a], G. Pizzati [a,b], 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], A. Cagnotta [a,b], F. Carnevali [a,b], N. Cavallo [a,c], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a,b,52], P. Paolucci [a,31], B. Rossi [a], C. Sciacca [a,b]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli 'Federico II', Napoli, Italy
[c] Università della Basilicata, Potenza, Italy
[d] Scuola Superiore Meridionale (SSM), Napoli, Italy

R. Ardino [a], P. Azzi [a], N. Bacchetta [a,53], D. Bisello [a,b], P. Bortignon [a], G. Bortolato [a,b], A. Bragagnolo [a,b], A.C.M. Bulla [a], R. Carlin [a,b], T. Dorigo [a], S. Fantinel [a], F. Gasparini [a,b], U. Gasparini [a,b], E. Lusiani [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], M. Migliorini [a,b], J. Pazzini [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], G. Strong [a], M. Tosi [a,b], A. Triossi [a,b], S. Ventura [a], M. Zanetti [a,b], P. Zotto [a,b], A. Zucchetta [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

C. Aimè [a], A. Braghieri [a], S. Calzaferri [a], D. Fiorina [a], P. Montagna [a,b], V. Re [a], 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

S. Ajmal [a,b], M.E. Ascioti [a,b], G.M. Bilei [a], C. Carrivale [a,b], D. Ciangottini [a,b], L. Fanò [a,b], M. Magherini [a,b], V. Mariani [a,b], M. Menichelli [a], F. Moscatelli [a,54], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a], T. Tedeschi [a,b]

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

C.A. Alexe [a,c], P. Asenov [a,b], P. Azzurri [a], G. Bagliesi [a], R. Bhattacharya [a], L. Bianchini [a,b], T. Boccali [a], E. Bossini [a], D. Bruschini [a,c], R. Castaldi [a], M.A. Ciocci [a,b], M. Cipriani [a,b], V. D'Amante [a,d], R. Dell'Orso [a], S. Donato [a], A. Giassi [a], F. Ligabue [a,c], D. Matos Figueiredo [a], A. Messineo [a,b], M. Musich [a,b], F. Palla [a], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a], T. Sarkar [a], A. Scribano [a], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini [a,d], F. Vaselli [a,c], 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
[d] Università di Siena, Siena, Italy

C. Baldenegro Barrera [a,b], P. Barria [a], C. Basile [a,b], M. Campana [a,b], F. Cavallari [a], L. Cunqueiro Mendez [a,b], D. Del Re [a,b], E. Di Marco [a], M. Diemoz [a], F. Errico [a,b], E. Longo [a,b], J. Mijuskovic [a,b], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], C. Quaranta [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], L. Soffi [a]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], A. Bellora [a,b], C. Biino [a], C. Borca [a,b], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], L. Finco [a], M. Grippo [a,b], B. Kiani [a,b], F. Legger [a], F. Luongo [a,b], C. Mariotti [a], L. Markovic [a,b], S. Maselli [a], A. Mecca [a,b], L. Menzio [a,b], P. Meridiani [a], E. Migliore [a,b], M. Monteno [a], R. Mulargia [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], M. Ruspa [a,c],

F. Siviero [a,b], V. Sola [a,b], A. Solano [a,b], A. Staiano [a], C. Tarricone [a,b], D. Trocino [a], G. Umoret [a,b], E. Vlasov [a,b], R. White [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], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], K. De Leo [a], G. Della Ricca [a,b]

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

S. Dogra, J. Hong, C. Huh, B. Kim, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Kyungpook National University, Daegu, Korea

M.S. Kim

Department of Mathematics and Physics - GWNU, Gangneung, Korea

G. Bak, P. Gwak, H. Kim, D.H. Moon

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

E. Asilar, J. Choi, D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

J. Goh, S. Yang

Kyung Hee University, Department of Physics, Seoul, Korea

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

Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Gharbia

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

F. Alazemi

Kuwait University - College of Science - Department of Physics, Safat, Kuwait

K. Dreimanis, A. Gaile, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

Riga Technical University, Riga, Latvia

N.R. Strautnieks

University of Latvia (LU), Riga, Latvia

M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

Vilnius University, Vilnius, Lithuania

I. Yusuff [55], Z. Zolkapli

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

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

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz [56], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, A. Sánchez Hernández

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

C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, N. Raicevic

University of Montenegro, Podgorica, Montenegro

P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

V. Avati, L. Grzanka, M. Malawski

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Pozniak, W. Zabolotny

Warsaw University of Technology, Warsaw, Poland

M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

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

P. Adzic, P. Milenovic

Faculty of Physics, University of Belgrade, Belgrade, Serbia

M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic

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

J. Alcaraz Maestre, Cristina F. Bedoya, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Martin Viscasillas, D. Moran, C.M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, J. Vazquez Escobar

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

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

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

S. Bhowmik, S. Blanco Fernández, J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

B. Kailasapathy[57], D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna[58], K. Liyanage, N. Perera

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

D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, B. Bilin, A.A. Bin Anuar, A. Bocci, C. Botta, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, L. Malgeri, M. Mannelli, A.C. Marini, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, H. Qu, D. Rabady, B. Ribeiro Lopes, M. Rovere, H. Sakulin, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[59], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[60], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T. Bevilacqua[61], L. Caminada[61], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[61], L. Noehte[61], T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

T.K. Aarrestad, K. Androsov[60], M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[60], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[60], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, R. Seidita, J. Steggemann[60], A. Tarabini, D. Valsecchi, R. Wallny

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

C. Amsler [62], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, U. Molinatti, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

Universität Zürich, Zurich, Switzerland

C. Adloff [63], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari [39], S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, K.F. Chen, P.s. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, H.y. Wu, E. Yazgan

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

D. Agyel, F. Boran, F. Dolek, I. Dumanoglu [64], E. Eskut, Y. Guler [65], E. Gurpinar Guler [65], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [66], A. Polatoz, B. Tali [67], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

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

G. Sokmen, M. Yalvac [68]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya [69], O. Kaya [70], S. Tekten [71]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak [64,72], G.G. Dincer [64], Y. Komurcu, S. Sen [73]

Istanbul Technical University, Istanbul, Turkey

O. Aydilek [74], V. Epshteyn, B. Hacisahinoglu, I. Hos [75], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Istanbul University, Istanbul, Turkey

S. Cerci [67], B. Isildak [76], D. Sunar Cerci, T. Yetkin

Yildiz Technical University, Istanbul, Turkey

A. Boyaryntsev, B. Grynyov

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

L. Levchuk

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

D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou [77], K. Walkingshaw Pass

University of Bristol, Bristol, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev [78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

I. Andreou, R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal [79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, M. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, S. Mallios, M. Mieskolainen, J. Nash [80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee [31], M. Vojinovic, N. Wardle, D. Winterbottom

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

S. Abdullin, A. Brinkerhoff, B. Caraway, E. Collins, J. Dittmann, K. Hatakeyama, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Baylor University, Waco, TX, USA

R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio [81], E. Usai, R. Yi

The University of Alabama, Tuscaloosa, AL, USA

A. Akpinar, C. Cosby, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, J. O'cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, A.G. Zecchinelli

Boston University, Boston, MA, USA

G. Benelli, X. Coubez [27], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan [82], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, M. Narain [†], N. Pervan, S. Sagir [83], F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan, W. Zhang

Brown University, Providence, RI, USA

S. Abbott, J. Bonilla, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, Y. Yao, S. Yoo, F. Zhang

University of California, Davis, Davis, CA, USA

M. Bachtis, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Los Angeles, CA, USA

R. Clare, J.W. Gary, M. Gordon, G. Hanson, W. Si, S. Wimpenny [†]

University of California, Riverside, Riverside, CA, USA

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

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

A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, S. Wang, D. Zhang

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

A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, CA, USA

J. Alison, S. An, M.B. Andrews, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, C. Liu, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

Carnegie Mellon University, Pittsburgh, PA, USA

J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, G. Karathanasis, N. Manganelli, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

University of Colorado Boulder, Boulder, CO, USA

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

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[84], F. Ravera, A. Reinsvold Hall[85], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, USA

C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

University of Florida, Gainesville, FL, USA

T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Habibullah, V. Hagopian, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida State University, Tallahassee, FL, USA

B. Alsufyani, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[19], M. Hohlmann, M. Rahmani, E. Yanes

Florida Institute of Technology, Melbourne, FL, USA

M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D.S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

University of Illinois Chicago, Chicago, USA

M. Alhusseini, D. Blend, K. Dilsiz[86], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[87], O. Neogi, H. Ogul[88], Y. Onel, A. Penzo, C. Snyder, E. Tiras[89]

The University of Iowa, Iowa City, IA, USA

B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

Johns Hopkins University, Baltimore, MD, USA

A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, N. Minafra, M. Murray, M. Nickel, M. Pitt, S. Popescu[90], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, G. Wilson

The University of Kansas, Lawrence, KS, USA

B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

Kansas State University, Manhattan, KS, USA

A. Baden, A. Belloni, J. Bistany-riebman, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, L. Wang

University of Maryland, College Park, MD, USA

J. Bendavid, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M.I. Park, C. Paus, D. Rankin, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, Z. Wang, B. Wyslouch, T.J. Yang

Massachusetts Institute of Technology, Cambridge, MA, USA

B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, R. Saradhy, N. Strobbe

University of Minnesota, Minneapolis, MN, USA

L.M. Cremaldi

University of Mississippi, Oxford, MS, USA

K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

University of Nebraska-Lincoln, Lincoln, NE, USA

H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

State University of New York at Buffalo, Buffalo, NY, USA

G. Alverson, E. Barberis, J. Dervan, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, D. Wood

Northeastern University, Boston, MA, USA

J. Bueghly, S. Dittmer, K.A. Hahn, Y. Liu, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

Northwestern University, Evanston, IL, USA

G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[17], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

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

The Ohio State University, Columbus, OH, USA

H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, A. Shevelev, D. Stickland, C. Tully

Princeton University, Princeton, NJ, USA

S. Malik

University of Puerto Rico, Mayaguez, PR, USA

A.S. Bakshi, V.E. Barnes, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A.K. Virdi, F. Wang, W. Xie

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar, A. Pathak

Purdue University Northwest, Hammond, IN, USA

D. Acosta, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

Rice University, Houston, TX, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[91], E. Popova[91], R. Taus

University of Rochester, Rochester, NY, USA

K. Goulianos

The Rockefeller University, New York, NY, USA

B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, O. Karacheban[29], S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

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

H. Acharya, D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

University of Tennessee, Knoxville, TN, USA

D. Aebi, M. Ahmad, T. Akhter, O. Bouhali [92], R. Eusebi, J. Gilmore, T. Huang, T. Kamon [93], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

N. Akchurin, J. Damgov, N. Gogate, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Peltola, I. Volobouev

Texas Tech University, Lubbock, TX, USA

E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

Vanderbilt University, Nashville, TN, USA

B. Cardwell, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu

University of Virginia, Charlottesville, VA, USA

S. Bhattacharya, P.E. Karchin

Wayne State University, Detroit, MI, USA

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

University of Wisconsin - Madison, Madison, WI, USA

S. Afanasiev, V. Alexakhin, D. Budkouski, V. Chekhovsky, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev [94], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev [95], A. Zarubin, I. Zhizhin, G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim [94], P. Levchenko [96], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev [†], Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, V. Gavrilov, N. Lychkovskaya, A. Nikitenko [97,98], V. Popov, A. Zhokin, M. Chadeeva [94], R. Chistov [94], S. Polikarpov [94], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, L. Khein, O. Kodolova [98], V. Korotkikh, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan, V. Blinov [94], T. Dimova [94], A. Kozyrev [94], O. Radchenko [94], Y. Skovpen [94], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin [99], E. Tcherniaev

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

[†] Deceased.
[1] Also at Yerevan State University, Yerevan, Armenia.
[2] Also at TU Wien, Vienna, Austria.
[3] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[4] Also at Ghent University, Ghent, Belgium.
[5] Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil.
[6] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[7] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

[8] Also at UFMS, Nova Andradina, Brazil.
[9] Also at Nanjing Normal University, Nanjing, China.
[10] Now at The University of Iowa, Iowa City, Iowa, USA.
[11] Also at University of Chinese Academy of Sciences, Beijing, China.
[12] Also at China Center of Advanced Science and Technology, Beijing, China.
[13] Also at University of Chinese Academy of Sciences, Beijing, China.
[14] Also at China Spallation Neutron Source, Guangdong, China.
[15] Now at Henan Normal University, Xinxiang, China.
[16] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[17] Also at an institute or an international laboratory covered by a cooperation agreement with CERN.
[18] Also at Cairo University, Cairo, Egypt.
[19] Also at Ain Shams University, Cairo, Egypt.
[20] Also at Suez University, Suez, Egypt.
[21] Now at British University in Egypt, Cairo, Egypt.
[22] Also at Purdue University, West Lafayette, Indiana, USA.
[23] Also at Université de Haute Alsace, Mulhouse, France.
[24] Also at Istinye University, Istanbul, Turkey.
[25] Also at The University of the State of Amazonas, Manaus, Brazil.
[26] Also at University of Hamburg, Hamburg, Germany.
[27] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[28] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[29] Also at Brandenburg University of Technology, Cottbus, Germany.
[30] Also at Forschungszentrum Jülich, Juelich, Germany.
[31] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[32] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[33] Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania.
[34] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[35] Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[36] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[37] Also at Punjab Agricultural University, Ludhiana, India.
[38] Also at University of Visva-Bharati, Santiniketan, India.
[39] Also at Indian Institute of Science (IISc), Bangalore, India.
[40] Also at IIT Bhubaneswar, Bhubaneswar, India.
[41] Also at Institute of Physics, Bhubaneswar, India.
[42] Also at University of Hyderabad, Hyderabad, India.
[43] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[44] Also at Isfahan University of Technology, Isfahan, Iran.
[45] Also at Sharif University of Technology, Tehran, Iran.
[46] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[47] Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
[48] Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran.
[49] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[50] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[51] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[52] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[53] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[54] Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy.
[55] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[56] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[57] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[58] Also at Saegis Campus, Nugegoda, Sri Lanka.
[59] Also at National and Kapodistrian University of Athens, Athens, Greece.
[60] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[61] Also at Universität Zürich, Zurich, Switzerland.
[62] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[63] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[64] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[65] Also at Konya Technical University, Konya, Turkey.
[66] Also at Izmir Bakircay University, Izmir, Turkey.
[67] Also at Adiyaman University, Adiyaman, Turkey.
[68] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[69] Also at Marmara University, Istanbul, Turkey.
[70] Also at Milli Savunma University, Istanbul, Turkey.
[71] Also at Kafkas University, Kars, Turkey.
[72] Now at Istanbul Okan University, Istanbul, Turkey.
[73] Also at Hacettepe University, Ankara, Turkey.
[74] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[75] Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[76] Also at Yildiz Technical University, Istanbul, Turkey.
[77] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[78] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[79] Also at IPPP Durham University, Durham, United Kingdom.
[80] Also at Monash University, Faculty of Science, Clayton, Australia.
[81] Also at Università di Torino, Torino, Italy.
[82] Also at Bethel University, St. Paul, Minnesota, USA.
[83] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[84] Also at California Institute of Technology, Pasadena, California, USA.
[85] Also at United States Naval Academy, Annapolis, Maryland, USA.
[86] Also at Bingol University, Bingol, Turkey.
[87] Also at Georgian Technical University, Tbilisi, Georgia.

[88] Also at Sinop University, Sinop, Turkey.
[89] Also at Erciyes University, Kayseri, Turkey.
[90] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[91] Now at another institute or international laboratory covered by a cooperation agreement with CERN.
[92] Also at Texas A&M University at Qatar, Doha, Qatar.
[93] Also at Kyungpook National University, Daegu, Korea.
[94] Also at another institute or international laboratory covered by a cooperation agreement with CERN.
[95] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
[96] Also at Northeastern University, Boston, Massachusetts, USA.
[97] Also at Imperial College, London, United Kingdom.
[98] Now at Yerevan Physics Institute, Yerevan, Armenia.
[99] Also at Universiteit Antwerpen, Antwerpen, Belgium.