

Precision measurement of the mass difference between light nuclei and anti-nuclei

Alexandre, D.; Barnby, Lee Stuart; Bhasin, A.; Bombara, M.; Evans, D.; Hanratty, Luke; Jones, Peter; Jusko, A.; Krivda, M.; Lee, Graham; Lietava, R.; Villalobos Baillie, O.; ALICE Collaboration

DOI:
[10.1038/nphys3432](https://doi.org/10.1038/nphys3432)

License:
Creative Commons: Attribution (CC BY)

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Alexandre, D, Barnby, LS, Bhasin, A, Bombara, M, Evans, D, Hanratty, L, Jones, P, Jusko, A, Krivda, M, Lee, G, Lietava, R, Villalobos Baillie, O & ALICE Collaboration 2015, 'Precision measurement of the mass difference between light nuclei and anti-nuclei', *Nature Physics*, vol. 11, no. 10, pp. 811-814.
<https://doi.org/10.1038/nphys3432>

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:
Published as above, final version of record available at DOI
<http://dx.doi.org/10.1038/nphys3432>.

Checked 16/5/18.

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Precision measurement of the mass difference between light nuclei and anti-nuclei

ALICE Collaboration[†]

The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons^{1,2}. The extension of such measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories³, but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons (d) and anti-deuterons (\bar{d}), and ^3He and $^3\bar{\text{He}}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment)⁴ detector in Pb-Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirms CPT invariance to an unprecedented precision in the sector of light nuclei^{5,6}. This fundamental symmetry of nature, which exchanges particles with anti-particles, implies that all physics laws are the same under the simultaneous reversal of charge(s) (charge conjugation C), reflection of spatial coordinates (parity transformation P) and time inversion (T).

Heavy ions are collided at very high energies at the CERN Large Hadron Collider (LHC) to study matter at extremely high temperatures and densities. Under these conditions heavy-ion collisions are a copious source of matter and anti-matter particles and thus are suitable for an experimental investigation of their properties such as mass and electric charge. In relativistic heavy-ion collisions, nuclei and corresponding anti-nuclei are produced with nearly equal rates⁷. Their yields have been measured at the Relativistic Heavy Ion Collider (RHIC) by the STAR (ref. 8) and PHENIX (ref. 9) experiments and at the LHC by the ALICE (ref. 4) experiment. So far, the heaviest anti-nucleus which has been observed⁷ is $^4\bar{\text{He}}$ (anti- α); meanwhile, for lighter nuclei and anti-nuclei, which are more copiously produced, a detailed comparison of their properties is possible. This comparison represents an interesting test of CPT symmetry in an analogous way as done for elementary fermions^{10,11} and bosons¹², and for QED (refs 13, 14) and QCD systems^{1,2,15–17} (a particular example for the latter being the measurements carried out on neutral kaon decays¹⁸), with different levels of precision which span over several orders of magnitude. All these measurements can be used to constrain, for different interactions, the parameters of effective field theories that add explicit CPT violating terms to the standard model Lagrangian, such as the standard model extension¹⁹ (SME).

The measurements reported in this paper are based on the high-precision tracking and identification capabilities of the ALICE experiment²⁰. The main detectors employed in this analysis are the ITS (inner tracking system)²¹ for the determination of the interaction vertex, the TPC (time projection chamber)²² for tracking

and specific energy loss (dE/dx) measurements, and the TOF (time of flight)²³ detector to measure the time t_{TOF} needed by each track to traverse the detector. The combined ITS and TPC information is used to determine the track length (L) and the rigidity (p/z , where p is the momentum and z the electric charge in units of the elementary charge e) of the charged particles in the solenoidal 0.5 T magnetic field of the ALICE central barrel (pseudorapidity $|\eta| < 0.8$). On the basis of these measurements, we can extract the squared mass-over-charge ratio $\mu_{\text{TOF}}^2 \equiv (m/z)_{\text{TOF}}^2 = (p/z)^2 [(t_{\text{TOF}}/L)^2 - 1/c^2]$. The choice of this variable is motivated by the fact that μ^2 is directly proportional to the square of the time of flight, allowing to better preserve its Gaussian behaviour.

The high precision of the TOF detector, which determines the arrival time of the particle with a resolution of 80 ps (ref. 20), allows us to measure a clear signal for (anti-)protons, (anti-)deuterons and (anti-) ^3He nuclei over a wide rigidity range ($1 < p/|z| < 4 \text{ GeV}/c$). The main source of background, which is potentially of the same order of the signal, arises from tracks erroneously associated to a TOF hit. To reduce this contamination, a 2σ cut (where σ is the standard deviation) around the expected TPC dE/dx signal is applied. Such a requirement strongly suppresses (to below 4%) this background for rigidities below $p/|z| < 2.0 \text{ GeV}/c$ for (anti-)deuterons and for all rigidities for (anti-) ^3He (to below 1%). For each of the species under study, the mass is extracted by fitting the mass-squared distributions in narrow $p/|z|$ and η intervals, using a Gaussian with a small exponential tail that reflects the time signal distribution of the TOF detector. Examples of the mass-squared distributions for (anti-)deuterons and (anti-) ^3He candidates are reported in Fig. 1 in selected rigidity intervals.

Using mass differences, rather than absolute masses, allows us to reduce the systematic uncertainties related to tracking, spatial alignment (affecting the measurement of the track momentum and length) and time calibration. Despite that, residual effects are still present, due to imperfections in the detector alignment and the description of the magnetic field, which can lead to position-dependent systematic uncertainties. In terms of relative uncertainties, the ones affecting the measurement of the momentum are the largest and independent of the mass, and are the same for all positive (negative) particles in a given momentum interval. It is therefore possible to correct the (anti-)deuteron and the (anti-) ^3He masses by scaling them with the ratio between the (anti-)proton masses recommended by the PDG (particle data group)²⁴ ($\mu_{p(\bar{p})}^{\text{PDG}}$) and the ones measured in the analysis presented here ($\mu_{p(\bar{p})}^{\text{TOF}}$), namely, $\mu_{A(\bar{A})} = \mu_{A(\bar{A})}^{\text{TOF}} \times (\mu_{p(\bar{p})}^{\text{PDG}} / \mu_{p(\bar{p})}^{\text{TOF}})$. These correction factors, which depend on the rigidity, deviate from unity by at most 1%. Conversely, systematic effects connected to the track-length measurement are mass dependent and cannot be completely accounted for using the above correction. However, they are expected to be symmetric for positive and negative particles when

[†]A full list of authors and affiliations appears at the end of the paper.

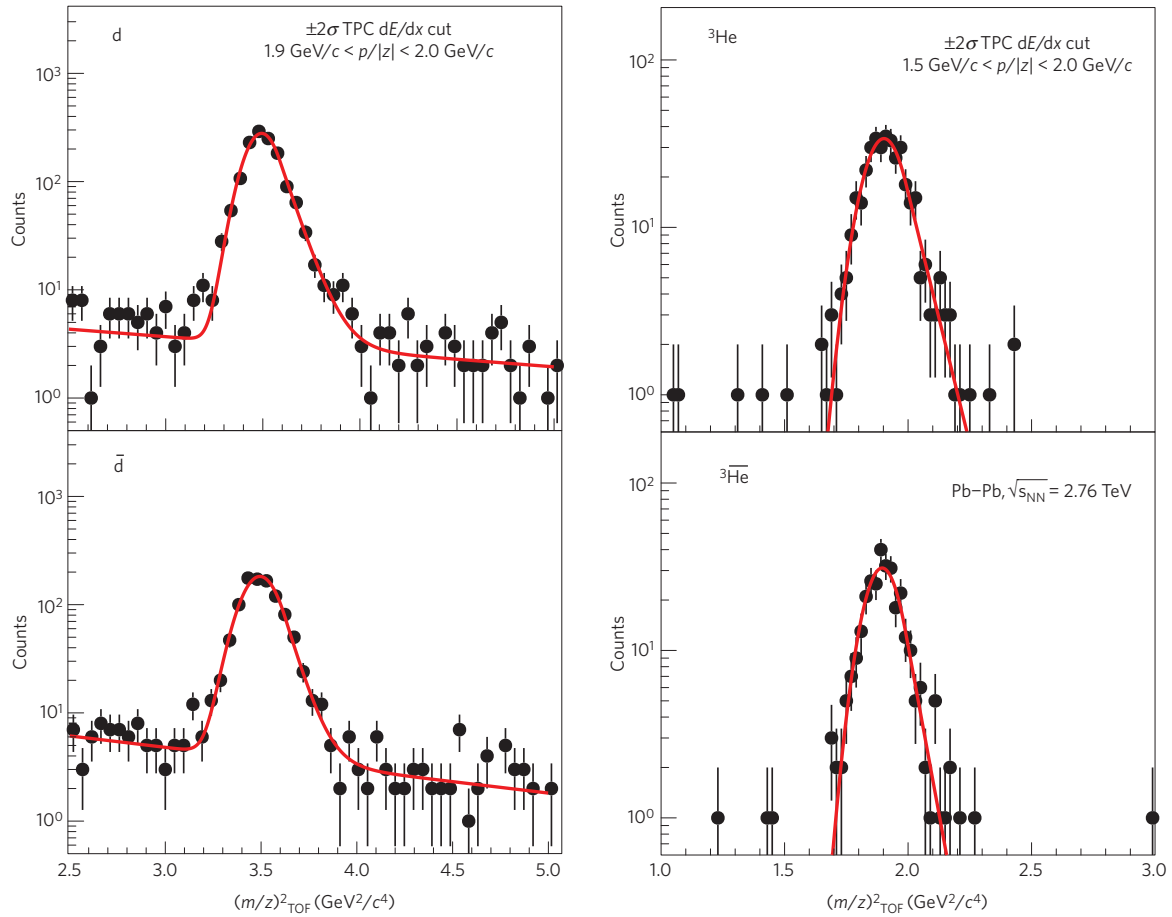


Figure 1 | Examples of squared mass-over-charge ratio distributions in selected rigidity intervals. Particle and anti-particle spectra for deuterons (left) and ${}^3\text{He}$ (right) are in the top and bottom plots, respectively. The fit function (red curve) also includes, for the (anti-)deuteron case, an exponential term to describe the background. In the rigidity intervals shown here the background is about 4% for (anti-)deuterons, whereas it is 0.7% for ${}^3\text{He}$ and ${}^3\overline{\text{He}}$. The error bars display the statistical uncertainty.

inverting the magnetic field. Any residual asymmetry is therefore indicative of remaining systematic uncertainties related to the detector conditions. To estimate them, and keep these effects under control, both nuclei and anti-nuclei measurements are performed for two opposite magnetic field configurations and then averaged. Their half-difference is taken as the estimate of this systematic uncertainty. Other sources of systematic uncertainties are evaluated by varying energy loss corrections applied to the reconstructed momentum, the range and the shape of the background function assumed in the fit of the mass-squared distributions and the track selection criteria. In particular, TPC dE/dx cuts are varied between one and four standard deviations to probe the sensitivity of the fit results on the residual background, and a tracking quality cut on the distance of closest approach of the track to the vertex is varied to evaluate the influence of secondary particles on the measurement. The sources of systematic uncertainties are found to be fully correlated among all the rigidity intervals, except for those due to the fit procedure and the TPC selection criteria, where the uncertainties are uncorrelated. For deuterons and anti-deuterons, the largest relative systematic uncertainties on $\Delta\mu/\mu$ come from the detector alignment ($\sim 0.7 \times 10^{-4}$), the TPC selection criteria ($\sim 0.7 \times 10^{-4}$) and the secondaries ($\sim 1.0 \times 10^{-4}$). For ${}^3\text{He}$ and ${}^3\overline{\text{He}}$, they come from the energy loss corrections ($\sim 0.7 \times 10^{-3}$), the fit procedure ($\sim 0.5 \times 10^{-3}$) and the TPC selection criteria ($\sim 0.4 \times 10^{-3}$).

The (anti-)deuteron and (anti-) ${}^3\text{He}$ masses are measured as the peak position of the fitting curves of the mass-squared distribution. The mass-over-charge ratio differences between the deuteron

and ${}^3\text{He}$ and their respective anti-particle are then evaluated as a function of the rigidity of the track, as shown in Fig. 2. The measurements in the individual rigidity intervals are combined, taking into account statistical and systematic uncertainties (correlated and uncorrelated), and the final result is shown in the same figure with one and two standard deviation uncertainty bands. The measured mass-over-charge ratio differences are

$$\Delta\mu_{d\bar{d}} = (1.7 \pm 0.9(\text{stat.}) \pm 2.6(\text{syst.})) \times 10^{-4} \text{ GeV}/c^2 \quad (1)$$

$$\Delta\mu_{{}^3\text{He}{}^3\overline{\text{He}}} = (-1.7 \pm 1.2(\text{stat.}) \pm 1.4(\text{syst.})) \times 10^{-3} \text{ GeV}/c^2 \quad (2)$$

corresponding to

$$\frac{\Delta\mu_{d\bar{d}}}{\mu_d} = (0.9 \pm 0.5(\text{stat.}) \pm 1.4(\text{syst.})) \times 10^{-4}$$

$$\frac{\Delta\mu_{{}^3\text{He}{}^3\overline{\text{He}}}}{\mu_{{}^3\text{He}}} = (-1.2 \pm 0.9(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^{-3}$$

where μ_d and $\mu_{{}^3\text{He}}$ are the values recommended by CODATA (ref. 25). The mass-over-charge differences are compatible with zero within the estimated uncertainties, in agreement with CPT invariance expectations.

Given that $z_{\bar{d}} = -z_d$ and $z_{{}^3\overline{\text{He}}} = -z_{{}^3\text{He}}$ as for the proton and anti-proton^{1,2}, the mass-over-charge differences in equations (1) and (2) and the measurement of the mass differences between proton and

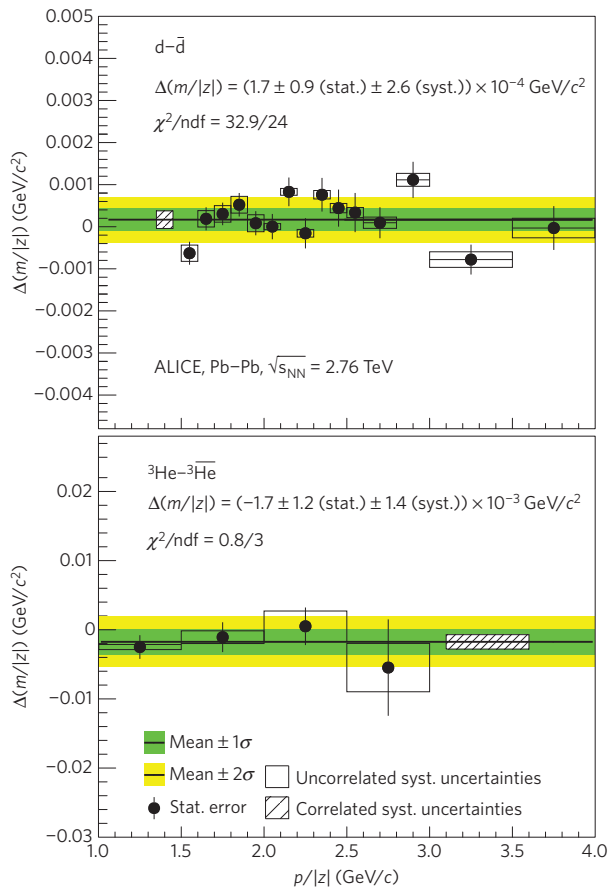


Figure 2 | $d-\bar{d}$ (top) and ${}^3\text{He}-\bar{{}^3\text{He}}$ (bottom) mass-over-charge ratio difference measurements as a function of the particle rigidity. Vertical bars and open boxes show the statistical and the uncorrelated systematic uncertainties (standard deviations), respectively. Both are taken into account to extract the combined result in the full rigidity range, together with the correlated systematic uncertainty, which is shown as a box with tilted lines. Also shown are the 1σ and 2σ bands around the central value, where σ is the sum in quadrature of the statistical and systematic uncertainties.

anti-proton^{1,2} and between neutron and anti-neutron^{15,16} can be used to derive the relative binding energy differences between the two studied particle species. We obtain

$$\frac{\Delta \varepsilon_{d\bar{d}}}{\varepsilon_d} = -0.04 \pm 0.05 \text{ (stat.)} \pm 0.12 \text{ (syst.)}$$

$$\frac{\Delta \varepsilon_{{}^3\text{He}\bar{{}^3\text{He}}}}{\varepsilon_{{}^3\text{He}}} = 0.24 \pm 0.16 \text{ (stat.)} \pm 0.18 \text{ (syst.)}$$

where $\varepsilon_A = Zm_p + (A - Z)m_n - m_A$, with m_p and m_n being the proton and neutron mass values recommended by the PDG (ref. 24) and m_A the mass value of the nucleus with atomic number Z and mass number A , recommended by CODATA (ref. 25). This quantity allows one to explicitly isolate possible violations of the CPT symmetry in the (anti-)nucleon interaction from that connected to the (anti-)nucleon masses, the latter being constrained with a precision of 7×10^{-10} for the proton/anti-proton system^{1,2}. Our results and the comparisons with previous mass difference measurements for ($d-\bar{d}$) (refs 26,27) and (${}^3\text{He}-\bar{{}^3\text{He}}$) (ref. 28), as well as binding energy measurements for ($d-\bar{d}$) (refs 29,30), are reported in Fig. 3.

We have shown that the copious production of (anti-)nuclei in relativistic heavy-ion collisions at the LHC represents a unique opportunity to test the CPT invariance of nucleon-nucleon

interactions using light nuclei. In particular, we have measured the mass-over-charge ratio differences for deuterons and ${}^3\text{He}$. The values are compatible, within uncertainties, with zero and represent a CPT invariance test in systems bound by nuclear forces. The results reported here (Fig. 3, left) represent the highest precision direct measurements of mass differences in the sector of nuclei and they improve by one to two orders of magnitude analogous results originally obtained more than 40 years ago^{26–28}, and precisely 50 years ago for the anti-deuteron^{26,27}. Remarkably, such an improvement is reached in an experiment which is not specifically dedicated to test the CPT invariance in nuclear systems. In the forthcoming years the increase in luminosity and centre-of-mass energy at the LHC will allow the sensitivity of these measurements to be pushed forwards, and possibly extend the study to (anti-) ${}^4\text{He}$. Given the equivalence between mass and binding energy differences, our results also improve (Fig. 3, right) by a factor two the constraints on CPT invariance inferred by existing measurements^{29,30} in the (anti-)deuteron system. The binding energy difference has been determined for the first time in the case of (anti-) ${}^3\text{He}$, with a relative precision comparable to that obtained in the (anti-)deuteron system.

Received 2 March 2015; accepted 9 June 2015;
published online 17 August 2015

References

- Hori, M. *et al.* Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio. *Nature* **475**, 484–488 (2011).
- Gabrielse, G. *et al.* Precision mass spectroscopy of the antiproton and proton using simultaneously trapped particles. *Phys. Rev. Lett.* **82**, 3198–3201 (1999).
- van Kolck, U. Effective field theory of nuclear forces. *Prog. Part. Nucl. Phys.* **43**, 337–418 (1999).
- Aamodt, K. *et al.* (ALICE collaboration). The ALICE experiment at the CERN LHC. *J. Instrum.* **3**, S08002 (2008).
- Lüders, G. On the equivalence of invariance under time reversal and under particle-antiparticle conjugation for relativistic field theories. *K. Dan. Vidensk. Selsk. Mat. Fys. Medd.* **28N5**, 1–17 (1954).
- Pauli, W. in *Niels Bohr and the Development of Physics* (ed. Pauli, W.) 30–51 (Pergamon, 1955).
- Agakishiev, H. *et al.* (STAR collaboration). Observation of the antimatter helium-4 nucleus. *Nature* **473**, 353–356 (2011).
- Harris, J. W. *et al.* (Star Collaboration). The STAR experiment at the relativistic heavy ion collider. *Nucl. Phys. A* **566**, 277C–285C (1994).
- Nagamiya, S. *et al.* (PHENIX collaboration). PHENIX experiment at RHIC. *Nucl. Phys. A* **566**, 287–298 (1994).
- Fee, M. S. *et al.* Measurement of the positronium $1\ ^3S_1-2\ ^3S_1$ interval by continuous-wave two-photon excitation. *Phys. Rev. A* **48**, 192–219 (1993).
- Van Dyck, R. S. Jr, Schwinger, P. B. & Dehmelt, H. G. New high-precision comparison of electron and positron g factors. *Phys. Rev. Lett.* **59**, 26–29 (1987).
- Abe, F. *et al.* (CDF collaboration). A measurement of the W -boson mass. *Phys. Rev. Lett.* **65**, 2243–2246 (1990).
- Amole, C. *et al.* Resonant quantum transitions in trapped antihydrogen atoms. *Nature* **483**, 439–443 (2012).
- Amole, C. *et al.* An experimental limit on the charge of antihydrogen. *Nature Commun.* **5**, 3955 (2014).
- Cresti, M., Pasquali, G., Peruzzo, L., Pinori, C. & Sartori, G. Measurement of the anti-neutron mass. *Phys. Lett. B* **177**, 206–210 (1986).
- Cresti, M., Pasquali, G., Peruzzo, L., Pinori, C. & Sartori, G. *Phys. Lett. B* **200**, 587–588 (1988); erratum.
- Di Sciacca, J. *et al.* (ATRAP collaboration). One-particle measurement of the antiproton magnetic moment. *Phys. Rev. Lett.* **110**, 130801 (2013).
- Ambrosino, F. *et al.* (KLOE collaboration). Determination of CP and CPT violation parameters in the neutral kaon system using the Bell-Steinberger relation and data from the KLOE experiment. *J. High Energy Phys.* **0612**, 011 (2006).
- Kostelecký, V. A. & Russel, N. Data tables for Lorentz and CPT violation. *Rev. Mod. Phys.* **83**, 11–31 (2011).
- Abelev, B. I. *et al.* (ALICE collaboration). Performance of the ALICE experiment at the CERN LHC. *Int. J. Mod. Phys. A* **29**, 1430044 (2014).
- Aamodt, K. *et al.* (ALICE collaboration). Alignment of the ALICE inner tracking system with cosmic-ray tracks. *J. Instrum.* **5**, P03003 (2010).
- Alme, J. *et al.* The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events. *Nucl. Instrum. Methods A* **622**, 316–367 (2010).

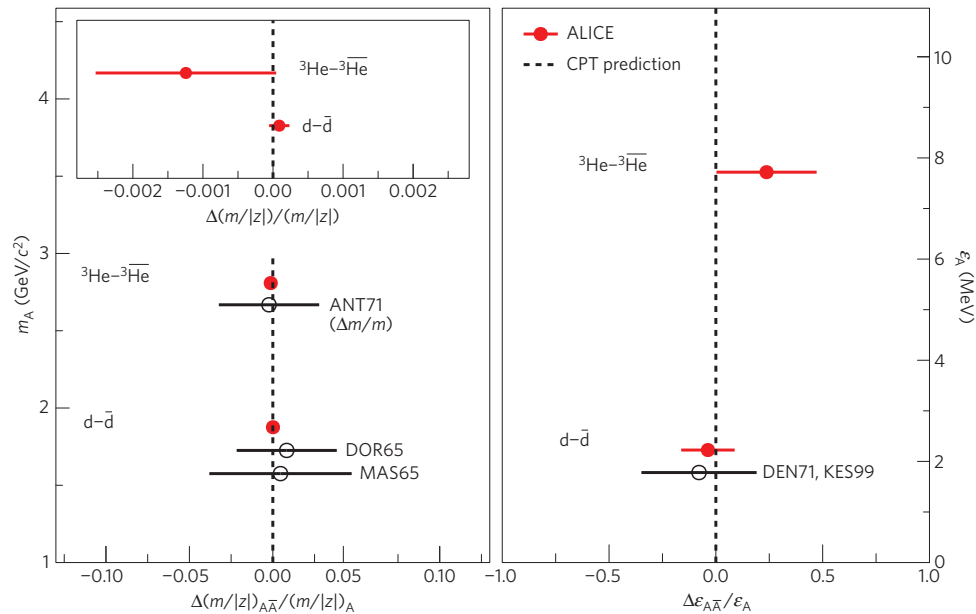


Figure 3 | Measurements of the mass-over-charge ratio and binding energies differences for $d-\bar{d}$ and ${}^3\text{He}-\bar{{}^3\text{He}}$. The left panel shows ALICE measurements of the mass-over-charge ratio differences compared with CPT invariance expectation (dotted lines) and existing mass measurements MAS65 (ref. 26), DOR65 (ref. 27) and ANT71 (ref. 28). The inset shows the ALICE results on a finer $\Delta(m/|z|)/(m/|z|)$ scale. The right panel shows our determination of the binding energy differences compared with direct measurements from DEN71 (ref. 29) and KES99 (ref. 30). Error bars represent the sum in quadrature of the statistical and systematic uncertainties (standard deviations).

23. Akhondov, A. *et al.* Performance of the ALICE time-of-flight detector at the LHC. *Eur. Phys. J. Plus* **128**, 44 (2013).
24. Olive, K. A. *et al.* (Particle data group collaboration). Review of particle physics. *Chin. Phys. C* **38**, 090001 (2014).
25. Mohr, P. J., Taylor, B. N. & Newell, D. B. CODATA recommended values of the fundamental physical constants: 2010. *Rev. Mod. Phys.* **84**, 1527–1605 (2012).
26. Massam, T., Muller, Th., Righini, B., Schneegans, M. & Zichichi, A. Experimental observation of antideuteron production. *Nuovo Cimento* **39**, 10–14 (1965).
27. Dorfan, D. E., Eades, J., Lederman, L. M., Lee, W. & Ting, C. C. Observation of antideuterons. *Phys. Rev. Lett.* **14**, 1003–1006 (1965).
28. Antipov, Yu. M. *et al.* Observation of antihelium-3. *Nucl. Phys. B* **31**, 235–252 (1971).
29. Denisov, S. P. *et al.* Measurements of anti-deuteron absorption and stripping cross sections at the momentum 13.3 GeV/c. *Nucl. Phys. B* **31**, 253–260 (1971).
30. Kessler, E. G. Jr *et al.* The deuteron binding energy and the neutron mass. *Phys. Lett. A* **255**, 221–229 (1999).

Acknowledgements

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: State Committee of Science, World Federation of Scientists (WFS) and Swiss Fonds Kidagan, Armenia; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP); National Natural Science Foundation of China (NSFC), the Chinese Ministry of Education (CMOE) and the Ministry of Science and Technology of China (MSTC); Ministry of Education and Youth of the Czech Republic; Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation; The European Research Council under the European Community's Seventh Framework Programme; Helsinki Institute of Physics and the Academy of Finland; French CNRS-IN2P3, the 'Region Pays de Loire', 'Region Alsace', 'Region Auvergne' and CEA, France; German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) and the Helmholtz Association; General Secretariat for Research and Technology, Ministry of Development, Greece; Hungarian Országos Tudományos Kutatási Alapprogramok (OTKA) and National Office for Research and Technology (NKTH); Department of Atomic Energy and Department of Science and Technology of the Government of India; Istituto Nazionale di Fisica Nucleare (INFN) and Centro Fermi-Museo Storico della Fisica e Centro Studi e Ricerche 'Enrico Fermi', Italy; MEXT Grant-in-Aid for Specially Promoted Research, Japan; Joint Institute for Nuclear Research, Dubna; National Research Foundation of Korea (NRF); Consejo Nacional de Ciencia y Tecnología (CONACYT), Dirección General de Asuntos del Personal Académico (DGAPA), México; Amérique Latine Formation académique

European Commission (ALFA-EC) and the EPLANET Program (European Particle Physics Latin American Network) Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; Research Council of Norway (NFR); National Science Centre, Poland; Ministry of National Education/Institute for Atomic Physics and Consiliul Național al Cercetării Științifice-Executive Agency for Higher Education Research Development and Innovation Funding (CNCS-UEFISCDI)-Romania; Ministry of Education and Science of Russian Federation, Russian Academy of Sciences, Russian Federal Agency of Atomic Energy, Russian Federal Agency for Science and Innovations and The Russian Foundation for Basic Research; Ministry of Education of Slovakia; Department of Science and Technology, South Africa; Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), E-Infrastructure shared between Europe and Latin America (EELA), Ministerio de Economía y Competitividad (MINECO) of Spain, Xunta de Galicia (Consellería de Educación), Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency); Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW); Ukraine Ministry of Education and Science; United Kingdom Science and Technology Facilities Council (STFC); The United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio; Ministry of Science, Education and Sports of Croatia and Unity through Knowledge Fund, Croatia; Council of Scientific and Industrial Research (CSIR), New Delhi, India.

Author contributions

All authors have contributed to the publication, being variously involved in the design and the construction of the detectors, in writing software, calibrating subsystems, operating the detectors and acquiring data, and finally analysing the processed data. The ALICE Collaboration members discussed and approved the scientific results. The manuscript was prepared by a subgroup of authors appointed by the collaboration and subject to an internal collaboration-wide review process. All authors reviewed and approved the final version of the manuscript.

Additional information

Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to the Alice Collaboration (alice-publications@cern.ch).

Competing financial interests

The authors declare no competing financial interests.



This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0>

ALICE Collaboration

J. Adam⁴⁰, D. Adamová⁸³, M. M. Aggarwal⁸⁷, G. Aglieri Rinella³⁶, M. Agnello¹¹¹, N. Agrawal⁴⁸, Z. Ahammed¹³¹, I. Ahmed¹⁶, S. U. Ahn⁶⁸, I. Aimo^{94,111}, S. Aiola¹³⁵, M. Ajaz¹⁶, A. Akhmedov⁵⁸, S. N. Alam¹³¹, D. Aleksandrov¹⁰⁰, B. Alessandro¹¹¹, D. Alexandre¹⁰², R. Alfaro Molina⁶⁴, A. Alici^{105,12}, A. Alkin³, J. Alme³⁸, T. Alt⁴³, S. Altinpinar¹⁸, I. Altsybeev¹³⁰, C. Alves Garcia Prado¹¹⁹, C. Andrei⁷⁸, A. Andronic⁹⁷, V. Anguelov⁹³, J. Anielski⁵⁴, T. Antičić⁹⁸, F. Antinori¹⁰⁸, P. Antonioli¹⁰⁵, L. Aphecetche¹¹³, H. Appelshäuser⁵³, S. Arcelli²⁸, N. Armesto¹⁷, R. Arnaldi¹¹¹, T. Aronsson¹³⁵, I. C. Arsene²², M. Arslanok⁵³, A. Augustinus³⁶, R. Averbach⁹⁷, M. D. Azmi¹⁹, M. Bach⁴³, A. Badala¹⁰⁷, Y. W. Baek⁴⁴, S. Bagnasco¹¹¹, R. Bailhache⁵³, R. Bala⁹⁰, A. Baldisseri¹⁵, M. Ball⁹², F. Baltasar Dos Santos Pedrosa³⁶, R. C. Baral⁶¹, A. M. Barbano¹¹¹, R. Barbera²⁹, F. Barile³³, G. G. Barnaföldi¹³⁴, L. S. Barnby¹⁰², V. Barret⁷⁰, P. Bartalini⁷, J. Bartke¹¹⁶, E. Bartsch⁵³, M. Basile²⁸, N. Bastid⁷⁰, S. Basu¹³¹, B. Bathen⁵⁴, G. Batigne¹¹³, A. Batista Camejo⁷⁰, B. Batyunya⁶⁶, P. C. Batzing²², I. G. Bearden⁸⁰, H. Beck⁵³, C. Bedda¹¹¹, N. K. Behera^{49,48}, I. Belikov⁵⁵, F. Bellini²⁸, H. Bello Martinez², R. Bellwied¹²¹, R. Belmont¹³³, E. Belmont-Moreno⁶⁴, V. Belyaev⁷⁶, G. Bencedi¹³⁴, S. Beole²⁷, I. Berceanu⁷⁸, A. Bercuci⁷⁸, Y. Berdnikov⁸⁵, D. Berenyi¹³⁴, R. A. Bertens⁵⁷, D. Berzano^{36,27}, L. Betev³⁶, A. Bhasin⁹⁰, I. R. Bhat⁹⁰, A. K. Bhati⁸⁷, B. Bhattacharjee⁴⁵, J. Bhowmik¹²⁷, L. Bianchi^{27,121}, N. Bianchi⁷², C. Bianchin^{133,57}, J. Bielčič⁴⁰, J. Bielčíková⁸³, A. Bilandžić⁸⁰, S. Biswas⁷⁹, S. Bjelogrić⁵⁷, F. Blanco¹⁰, D. Blau¹⁰⁰, C. Blume⁵³, F. Bock^{74,93}, A. Bogdanov⁷⁶, H. Bøggild⁸⁰, L. Boldizsár¹³⁴, M. Bombara⁴¹, J. Book⁵³, H. Borel¹⁵, A. Borissov⁹⁶, M. Borri⁸², F. Bossú⁶⁵, M. Botje⁸¹, E. Botta²⁷, S. Böttger⁵², P. Braun-Munzinger⁹⁷, M. Bregant¹¹⁹, T. Breitner⁵², T. A. Brooker⁵³, T. A. Browning⁹⁵, M. Broz⁴⁰, E. J. Brucken⁴⁶, E. Bruna¹¹¹, G. E. Bruno³³, D. Budnikov⁹⁹, H. Buesching⁵³, S. Bufalino^{36,111}, P. Buncic³⁶, O. Busch⁹³, Z. Buthelezi⁶⁵, J. T. Buxton²⁰, D. Caffarri^{36,30}, X. Cai⁷, H. Caines¹³⁵, L. Calero Diaz⁷², A. Caliva⁵⁷, E. Calvo Villar¹⁰³, P. Camerini²⁶, F. Carena³⁶, W. Carena³⁶, J. Castillo Castellanos¹⁵, A. J. Castro¹²⁴, E. A. R. Casula²⁵, C. Cavicchioli³⁶, C. Ceballos Sanchez⁹, J. Cepila⁴⁰, P. Cerello¹¹¹, B. Chang¹²², S. Chapeland³⁶, M. Chartier¹²³, J. L. Charvet¹⁵, Subhasis Chattopadhyay¹³¹, Sukalyan Chattopadhyay¹⁰¹, V. Chelnokov³, M. Cherney⁸⁶, C. Cheshkov¹²⁹, B. Cheynis¹²⁹, V. Chibante Barroso³⁶, D. D. Chinellato¹²⁰, P. Chochula³⁶, K. Choi⁹⁶, M. Chojnacki⁸⁰, S. Choudhury¹³¹, P. Christakoglou⁸¹, C. H. Christensen⁸⁰, P. Christiansen³⁴, T. Chujo¹²⁷, S. U. Chung⁹⁶, C. Cicalo¹⁰⁶, L. Cifarelli^{12,28}, F. Cindolo¹⁰⁵, J. Cleymans⁸⁹, F. Colamaria³³, D. Colella³³, A. Collu²⁵, M. Colocci²⁸, G. Conesa Balbastre⁷¹, Z. Conesa del Valle⁵¹, M. E. Connors¹³⁵, J. G. Contreras^{11,40}, T. M. Cormier⁸⁴, Y. Corrales Morales²⁷, I. Cortés Maldonado², P. Cortese³², M. R. Cosentino¹¹⁹, F. Costa³⁶, P. Crochet⁷⁰, R. Cruz Albino¹¹, E. Cuautle⁶³, L. Cunqueiro³⁶, T. Dahms^{92,37}, A. Dainese¹⁰⁸, A. Danu⁶², D. Das¹⁰¹, I. Das^{51,101}, S. Das⁴, A. Dash¹²⁰, S. Dash⁴⁸, S. De^{131,119}, A. De Caro^{31,12}, G. de Cataldo¹⁰⁴, J. de Cuijland⁴³, A. De Falco²⁵, D. De Gruttola^{12,31}, N. De Marco¹¹¹, S. De Pasquale¹¹¹, A. Deisting^{97,93}, A. Deloff⁷⁷, E. Dénes¹³⁴, G. D'Erasmus³³, D. Di Bari³³, A. Di Mauro³⁶, P. Di Nezza⁷², M. A. Diaz Corchero¹⁰, T. Dietel⁸⁹, P. Dillenseger⁵³, R. Divià³⁶, Ø. Djuvsland¹⁸, A. Dobrin^{57,81}, T. Dobrowolski⁷⁷, D. Domenicis Gimenez¹¹⁹, B. Dönigus⁵³, O. Dordic²², A. K. Dubey¹³¹, A. Dubla⁵⁷, L. Ducroux¹²⁹, P. Dupieux⁷⁰, R. J. Ehlers¹³⁵, D. Elia¹⁰⁴, H. Engel⁵², B. Erasmus^{113,36}, F. Erhardt¹²⁸, D. Eschweiler⁴³, B. Espagnon⁵¹, M. Estienne¹¹³, S. Esumi¹²⁷, D. Evans¹⁰², S. Evdokimov¹¹², G. Eyyubova⁴⁰, L. Fabbietti^{37,92}, D. Fabris¹⁰⁸, J. Faivre⁷¹, A. Fantoni⁷², M. Fasel⁷⁴, L. Feldkamp⁵⁴, D. Felea⁶², A. Feliciello¹¹¹, G. Feofilov¹³⁰, J. Ferencei⁸³, A. Fernández Téllez², E. G. Ferreira¹⁷, A. Ferretti²⁷, A. Festanti³⁰, J. Figiel¹¹⁶, M. A. S. Figueredo¹²³, S. Filchagin⁹⁹, D. Finogeev⁵⁶, F. M. Fionda¹⁰⁴, E. M. Fiore³³, M. G. Fleck⁹³, M. Floris³⁶, S. Foertsch⁶⁵, P. Foka⁹⁷, S. Fokin¹⁰⁰, E. Fragiaco¹¹⁰, A. Francescon^{36,30}, U. Frankenfeld⁹⁷, U. Fuchs³⁶, C. Furget⁷¹, A. Furs⁵⁶, M. Fusco Girard³¹, J. J. Gaardhøje⁸⁰, M. Gagliardi²⁷, A. M. Gago¹⁰³, M. Gallio²⁷, D. R. Gangadharan⁷⁴, P. Ganoti⁸⁸, C. Gao⁷, C. Garabatos⁹⁷, E. Garcia-Solis¹³, C. Gargiulo³⁶, P. Gasik^{37,92}, M. Germain¹¹³, A. Gheata³⁶, M. Gheata^{36,62}, P. Ghosh¹³¹, S. K. Ghosh⁴, P. Gianotti⁷², P. Giubellino³⁶, P. Giubilato³⁰, E. Gladysz-Dziadus¹¹⁶, P. Gläsel⁹³, D. M. Gómez Coral⁶⁴, A. Gomez Ramirez⁵², P. González-Zamora¹⁰, S. Gorbunov⁴³, L. Görlich¹¹⁶, S. Gotovac¹¹⁵, V. Grabski⁶⁴, L. K. Graczykowski¹³², A. Grelli⁵⁷, A. Grigoras³⁶, C. Grigoras³⁶, V. Grigoriev⁷⁶, A. Grigoryan¹, S. Grigoryan⁶⁶, B. Grinyov³, N. Grion¹¹⁰, J. F. Grosse-Oetringhaus³⁶, J.-Y. Grossiord¹²⁹, R. Grosso³⁶, F. Guber⁵⁶, R. Guernane⁷¹, B. Guerzoni²⁸, K. Gulbrandsen⁸⁰, H. Gulkanyan¹, T. Gunji¹²⁶, A. Gupta⁹⁰, R. Gupta⁹⁰, R. Haake⁵⁴, Ø. Haaland¹⁸, C. Hadjidakis⁵¹, M. Haiduc⁶², H. Hamagaki¹²⁶, G. Hamar¹³⁴, L. D. Hanratty¹⁰², A. Hansen⁸⁰, J. W. Harris¹³⁵, H. Hartmann⁴³, A. Harton¹³, D. Hatzifotiadiou¹⁰⁵, S. Hayashi¹²⁶, S. T. Heckel⁵³, M. Heide⁵⁴, H. Helstrup³⁸, A. Herghelegiu⁷⁸, G. Herrera Corral¹¹, B. A. Hess³⁵, K. F. Hetland³⁸, T. E. Hilden⁴⁶, H. Hillemanns³⁶, B. Hippolyte⁵⁵, P. Hristov³⁶, M. Huang¹⁸, T. J. Humanic²⁰, N. Hussain⁴⁵, T. Hussain¹⁹, D. Hutter⁴³, D. S. Hwang²¹, R. Ilkaev⁹⁹, I. Ilkiv⁷⁷, M. Inaba¹²⁷, C. Ionita³⁶, M. Ippolitov^{76,100}, M. Irfan¹⁹, M. Ivanov⁹⁷, V. Ivanov⁸⁵, V. Izucheev¹¹², P. M. Jacobs⁷⁴, C. Jahnke¹¹⁹, H. J. Jang⁶⁸, M. A. Janik¹³², P. H. S. Y. Jayarathna¹²¹, C. Jena³⁰, S. Jena¹²¹, R. T. Jimenez Bustamante⁶³, P. G. Jones¹⁰², H. Jung⁴⁴, A. Jusko¹⁰², P. Kalinac⁵⁹, A. Kalweit³⁶, J. Kamin⁵³, J. H. Kang¹³⁶, V. Kaplin⁷⁶, S. Kar¹³¹, A. Karasu Uysal⁶⁹, O. Karavichev⁵⁶, T. Karavicheva⁵⁶, E. Karpechev⁵⁶, U. Keschull⁵², R. Keidel¹³⁷, D. L. D. Keijdener⁵⁷, M. Keil³⁶, K. H. Khan¹⁶, M. Mohisin Khan¹⁹, P. Khan¹⁰¹, S. A. Khan¹³¹, A. Khanzadeev⁸⁵, Y. Kharlov¹¹², B. Kileng³⁸, B. Kim¹³⁶, D. W. Kim^{44,68}, D. J. Kim¹²², H. Kim¹³⁶, J. S. Kim⁴⁴, M. Kim⁴⁴, Minwoo Kim¹³⁶, S. Kim²¹, T. Kim¹³⁶, S. Kirsch⁴³, I. Kisel⁴³, S. Kiselev⁵⁸, A. Kisiel¹³², G. Kiss¹³⁴, J. L. Klay⁶, C. Klein⁵³, J. Klein⁹³, C. Klein-Bösing⁵⁴, A. Kluge³⁶, M. L. Knichel⁹³, A. G. Knospe¹¹⁷, T. Kobayashi¹²⁷, C. Kobdaj¹¹⁴, M. Kofarago³⁶, M. K. Köhler⁹⁷, T. Kollegger^{97,43}, A. Kolojvari¹³⁰, V. Kondratiev¹³⁰, N. Kondratyeva⁷⁶, E. Kondratyuk¹¹², A. Konevskikh⁵⁶, M. Kour⁹⁰, C. Kouzinopoulos³⁶, V. Kovalenko¹³⁰, M. Kowalski^{116,36}, S. Kox⁷¹, G. Koyithatta Meethalevedu⁴⁸, J. Kral¹²², I. Králik⁵⁹, A. Kravčáková⁴¹, M. Krelina⁴⁰, M. Kretz⁴³, M. Krivda^{102,59}, F. Krizek⁸³, E. Kryshen³⁶, M. Krzewicki^{97,43}, A. M. Kubera²⁰, V. Kučera⁸³, Y. Kucheriaev¹⁰⁰, T. Kugathasan³⁶, C. Kuhn⁵⁵, P. G. Kuijer⁸¹, I. Kulakov⁴³, A. Kumar⁹⁰, J. Kumar⁴⁸, L. Kumar^{79,87}, P. Kurashvili⁷⁷, A. Kurepin⁵⁶, A. B. Kurepin⁵⁶, A. Kuryakin⁹⁹, S. Kushpil⁸³, M. J. Kwon⁵⁰, Y. Kwon¹³⁶, S. L. La Pointe¹¹¹, P. La Rocca²⁹, C. Lagana Fernandes¹¹⁹, I. Lakomov^{36,51}, R. Langoy⁴², C. Lara⁵², A. Lardeux¹⁵, A. Lattuca²⁷, E. Laudi³⁶, R. Lea²⁶, L. Leardini⁹³, G. R. Lee¹⁰², S. Lee¹³⁶, I. Legrand³⁶

J. Lehnert⁵³, R. C. Lemmon⁸², V. Lenti¹⁰⁴, E. Leogrande⁵⁷, I. León Monzón¹¹⁸, M. Leoncino²⁷, P. Lévai¹³⁴, S. Li^{7,70}, X. Li¹⁴, J. Lien⁴², R. Lietava¹⁰², S. Lindal²², V. Lindenstruth⁴³, C. Lippmann⁹⁷, M. A. Lisa²⁰, H. M. Ljunggren³⁴, D. F. Lodato⁵⁷, P. I. Loenne¹⁸, V. R. Loggins¹³³, V. Loginov⁷⁶, C. Loizides⁷⁴, X. Lopez⁷⁰, E. López Torres⁹, A. Lowe¹³⁴, X.-G. Lu⁹³, P. Luetig⁵³, M. Lunardon³⁰, G. Luparello^{57,26}, A. Maevskaya⁵⁶, M. Mager³⁶, S. Mahajan⁹⁰, S. M. Mahmood²², A. Maire⁵⁵, R. D. Majka¹³⁵, M. Malaev⁸⁵, I. Maldonado Cervantes⁶³, L. Malinina⁶⁶, D. Mal'kevich⁵⁸, P. Malzacher⁹⁷, A. Mamonov⁹⁹, L. Manceau¹¹¹, V. Manko¹⁰⁰, F. Manso⁷⁰, V. Manzari^{104,36}, M. Marchisone²⁷, J. Mareš⁶⁰, G. V. Margagliotti²⁶, A. Margotti¹⁰⁵, J. Margutti⁵⁷, A. Marín⁹⁷, C. Markert¹¹⁷, M. Marquard⁵³, I. Martashvili¹²⁴, N. A. Martin⁹⁷, J. Martin Blanco¹¹³, P. Martinengo³⁶, M. I. Martínez², G. Martínez García¹¹³, M. Martinez Pedreira³⁶, Y. Martynov³, A. Mas¹¹⁹, S. Masciocchi⁹⁷, M. Maser²⁷, A. Masoni¹⁰⁶, L. Massacrier¹¹³, A. Mastroserio³³, A. Matyja¹¹⁶, C. Mayer¹¹⁶, J. Mazer¹²⁴, M. A. Mazzoni¹⁰⁹, D. McDonald¹²¹, F. Meddi²⁴, A. Menchaca-Rocha⁶⁴, E. Meninno³¹, J. Mercado Pérez⁹³, M. Meres³⁹, Y. Miake¹²⁷, M. M. Mieskolainen⁴⁶, K. Mikhaylov^{58,66}, L. Milano³⁶, J. Milosevic²², L. M. Minervini^{104,23}, A. Mischke⁵⁷, A. N. Mishra⁴⁹, D. Miśkowiec⁹⁷, J. Mitra¹³¹, C. M. Mitu⁶², N. Mohammadi⁵⁷, B. Mohanty^{79,131}, L. Molnar⁵⁵, L. Montaña Zetina¹¹, E. Montes¹⁰, M. Morando³⁰, D. A. Moreira De Godoy¹¹³, L. A. P. Moreno², S. Moretto³⁰, A. Morreale¹¹³, A. Morsch³⁶, V. Muccifora⁷², E. Mudnic¹¹⁵, D. Mühlheim⁵⁴, S. Muhuri¹³¹, M. Mukherjee¹³¹, H. Müller³⁶, J. D. Mulligan¹³⁵, M. G. Munhoz¹¹⁹, S. Murray⁶⁵, L. Musa³⁶, J. Musinsky⁵⁹, B. K. Nandi⁴⁸, R. Nania¹⁰⁵, E. Nappi¹⁰⁴, M. U. Naru¹⁶, C. Nattrass¹²⁴, K. Nayak⁷⁹, T. K. Nayak¹³¹, S. Nazarenko⁹⁹, A. Nedosekin⁵⁸, L. Nellen⁶³, F. Ng¹²¹, M. Nicassio⁹⁷, M. Niculescu^{62,36}, J. Niedziela³⁶, B. S. Nielsen⁸⁰, S. Nikolaev¹⁰⁰, S. Nikulin¹⁰⁰, V. Nikulin⁸⁵, F. Noferini^{105,12}, P. Nomokonov⁶⁶, G. Nooren⁵⁷, J. Norman¹²³, A. Nyanin¹⁰⁰, J. Nystrand¹⁸, H. Oeschler⁹³, S. Oh¹³⁵, S. K. Oh⁶⁷, A. Ohlson³⁶, A. Okatan⁶⁹, T. Okubo⁴⁷, L. Olah¹³⁴, J. Oleniacz¹³², A. C. Oliveira Da Silva¹¹⁹, M. H. Oliver¹³⁵, J. Onderwaater⁹⁷, C. Oppedisano¹¹¹, A. Ortiz Velasquez⁶³, A. Oskarsson³⁴, J. Otwinowski^{97,116}, K. Oyama⁹³, M. Ozdemir⁵³, Y. Pachmayer⁹³, P. Pagano³¹, G. Paic⁶³, C. Pajares¹⁷, S. K. Pal¹³¹, J. Pan¹³³, A. K. Pandey⁴⁸, D. Pant⁴⁸, V. Papikyan¹, G. S. Pappalardo¹⁰⁷, P. Pareek⁴⁹, W. J. Park⁹⁷, S. Parmar⁸⁷, A. Passfeld⁵⁴, V. Paticchio¹⁰⁴, B. Paul¹⁰¹, T. Pawlak¹³², T. Peitzmann⁵⁷, H. Pereira Da Costa¹⁵, E. Pereira De Oliveira Filho¹¹⁹, D. Peresunko^{76,100}, C. E. Pérez Lara⁸¹, V. Peskov⁵³, Y. Pestov⁵, V. Petráček⁴⁰, V. Petrov¹¹², M. Petrovici⁷⁸, C. Petta²⁹, S. Piano¹¹⁰, M. Pikna³⁹, P. Pillot¹¹³, O. Pinazza^{105,36}, L. Pinsky¹²¹, D. B. Piyarathna¹²¹, M. Płoskon⁷⁴, M. Planinic¹²⁸, J. Pluta¹³², S. Pochybova¹³⁴, P. L. M. Podesta-Lerma¹¹⁸, M. G. Poghosyan⁸⁶, B. Polichtchouk¹¹², N. Poljak¹²⁸, W. Poonsawat¹¹⁴, A. Pop⁷⁸, S. Porteboeuf-Houssais⁷⁰, J. Porter⁷⁴, J. Pospisil⁸³, S. K. Prasad⁴, R. Preghenella^{105,36}, F. Prino¹¹¹, C. A. Pruneau¹³³, I. Pshenichnov⁵⁶, M. Puccio¹¹¹, G. Puddu²⁵, P. Pujahari¹³³, V. Punin⁹⁹, J. Putschke¹³³, H. Qvigstad²², A. Rachevski¹¹⁰, S. Raha⁴, S. Rajput⁹⁰, J. Rak¹²², A. Rakotzafindrabe¹⁵, L. Ramello³², R. Raniwala⁹¹, S. Raniwala⁹¹, S. S. Räsänen⁴⁶, B. T. Rascanu⁵³, D. Rathee⁸⁷, V. Razazi²⁵, K. F. Read¹²⁴, J. S. Real⁷¹, K. Redlich⁷⁷, R. J. Reed¹³³, A. Rehman¹⁸, P. Reichelt⁵³, M. Reicher⁵⁷, F. Reidt^{93,36}, X. Ren⁷, R. Renfordt⁵³, A. R. Reolon⁷², A. Reshetin⁵⁶, F. Rettig⁴³, J.-P. Revol¹², K. Reygers⁹³, V. Riabov⁸⁵, R. A. Ricci⁷³, T. Richert³⁴, M. Richter²², P. Riedler³⁶, W. Riegler³⁶, F. Riggi²⁹, C. Ristea⁶², A. Rivetti¹¹¹, E. Rocco⁵⁷, M. Rodríguez Cahuantzi^{11,2}, A. Rodríguez Manso⁸¹, K. Røed²², E. Rogochaya⁶⁶, D. Rohr⁴³, D. Röhrich¹⁸, R. Romita¹²³, F. Ronchetti⁷², L. Ronflette¹¹³, P. Rosnet⁷⁰, A. Rossi³⁶, F. Roukoutakis⁸⁸, A. Roy⁴⁹, C. Roy⁵⁵, P. Roy¹⁰¹, A. J. Rubio Montero¹⁰, R. Rui²⁶, R. Russo²⁷, E. Ryabinkin¹⁰⁰, Y. Ryabov⁸⁵, A. Rybicki¹¹⁶, S. Sadovsky¹¹², K. Šafařík³⁶, B. Sahlmuller⁵³, P. Sahoo⁴⁹, R. Sahoo⁴⁹, S. Sahoo⁶¹, P. K. Sahu⁶¹, J. Saini¹³¹, S. Sakai⁷², M. A. Saleh¹³³, C. A. Salgado¹⁷, J. Salzwedel²⁰, S. Sambyal⁹⁰, V. Samsonov⁸⁵, X. Sanchez Castro⁵⁵, L. Sándor⁵⁹, A. Sandoval⁶⁴, M. Sano¹²⁷, G. Santagati²⁹, D. Sarkar¹³¹, E. Scapparone¹⁰⁵, F. Scarlassara³⁰, R. P. Scharenberg⁹⁵, C. Schiaua⁷⁸, R. Schicker⁹³, C. Schmidt⁹⁷, H. R. Schmidt³⁵, S. Schuchmann⁵³, J. Schukraft³⁶, M. Schulc⁴⁰, T. Schuster¹³⁵, Y. Schutz^{113,36}, K. Schwarz⁹⁷, K. Schweda⁹⁷, G. Scioli²⁸, E. Scomparin¹¹¹, R. Scott¹²⁴, K. S. Seeder¹¹⁹, J. E. Seger⁸⁶, Y. Sekiguchi¹²⁶, I. Selyuzhenkov⁹⁷, K. Senosi⁶⁵, J. Seo^{67,96}, E. Serradilla^{10,64}, A. Sevcenco⁶², A. Shabanov⁵⁶, A. Shabetai¹¹³, O. Shadura³, R. Shahoyan³⁶, A. Shangaraev¹¹², A. Sharma⁹⁰, M. Sharma⁹⁰, N. Sharma^{124,61}, K. Shigaki⁴⁷, K. Shtejer^{9,27}, Y. Sibiraki¹⁰⁰, S. Siddhanta¹⁰⁶, K. M. Sielewicz³⁶, T. Siemiarczuk⁷⁷, D. Silvermyr^{84,34}, C. Silvestre⁷¹, G. Simatovic¹²⁸, G. Simonetti³⁶, R. Singaraju¹³¹, R. Singh^{90,79}, S. Singha^{79,131}, V. Singhal¹³¹, B. C. Sinha¹³¹, T. Sinha¹⁰¹, B. Sitar³⁹, M. Sitta³², T. B. Skaali²², M. Słupecki¹²², N. Smirnov¹³⁵, R. J. M. Snellings⁵⁷, T. W. Snellman¹²², C. Søgaard³⁴, R. Soltz⁷⁵, J. Song⁹⁶, M. Song¹³⁶, Z. Song⁷, F. Soramel³⁰, S. Sorensen¹²⁴, M. Spacek⁴⁰, E. Spiriti⁷², I. Sputowska¹¹⁶, M. Spyropoulou-Stassinaki⁸⁸, B. K. Srivastava⁹⁵, J. Stachel⁹³, I. Stan⁶², G. Stefanek⁷⁷, M. Steinpreis²⁰, E. Stenlund³⁴, G. Steyn⁶⁵, J. H. Stiller⁹³, D. Stocco¹¹³, P. Strmen³⁹, A. A. P. Suaide¹¹⁹, T. Sugitate⁴⁷, C. Suire⁵¹, M. Suleymanov¹⁶, R. Sultanov⁵⁸, M. Šumbera⁸³, T. J. M. Symons⁷⁴, A. Szabo³⁹, A. Szanto de Toledo¹¹⁹, I. Szarka³⁹, A. Szczepankiewicz³⁶, M. Szymanski¹³², J. Takahashi¹²⁰, N. Tanaka¹²⁷, M. A. Tangaro³³, J. D. Tapia Takaki⁵¹, A. Tarantola Peloni⁵³, M. Tariq¹⁹, M. G. Tazila⁷⁸, A. Tauro³⁶, G. Tejada Muñoz², A. Telesca³⁶, K. Terasaki¹²⁶, C. Terrevoli^{30,25}, B. Teyssier¹²⁹, J. Thäder^{97,74}, D. Thomas^{57,117}, R. Tieulent¹²⁹, A. R. Timmins¹²¹, A. Toia⁵³, S. Trogolo¹¹¹, V. Trubnikov³, W. H. Trzaska¹²², T. Tsuji¹²⁶, A. Tumkin⁹⁹, R. Turrisi¹⁰⁸, T. S. Tveter²², K. Ullaland¹⁸, A. Uras¹²⁹, G. L. Usai²⁵, A. Utrobicic¹²⁸, M. Vajzer⁸³, M. Vala⁵⁹, L. Valencia Palomo⁷⁰, S. Vallerio²⁷, J. Van Der Maarel⁵⁷, J. W. Van Hoorne³⁶, M. van Leeuwen⁵⁷, T. Vanat⁸³, P. Vande Vyvre³⁶, D. Varga¹³⁴, A. Vargas², M. Vargyas¹²², R. Varma⁴⁸, M. Vasileiou⁸⁸, A. Vasiliev¹⁰⁰, A. Vauthier⁷¹, V. Vechernin¹³⁰, A. M. Veen⁵⁷, M. Veldhoen⁵⁷, A. Velure¹⁸, M. Venaruzzo⁷³, E. Vercellin²⁷, S. Vergara Limón², R. Vernet⁸, M. Verweij¹³³, L. Vickovic¹¹⁵, G. Viesti³⁰, J. Viinikainen¹²², Z. Vilakazi¹²⁵, O. Villalobos Baillie¹⁰², A. Villatoro Tello², A. Vinogradov¹⁰⁰, L. Vinogradov¹³⁰, Y. Vinogradov⁹⁹, T. Virgili³¹, V. Vislavicius³⁴, Y. P. Viyogi¹³¹, A. Vodopyanov⁶⁶, M. A. Völkl⁹³, K. Voloshin⁵⁸, S. A. Voloshin¹³³, G. Volpe^{134,36}, B. von Haller³⁶, I. Vorobyev^{37,92}, D. Vranic^{36,97}, J. Vrláková⁴¹, B. Vulpescu⁷⁰, A. Vyushin⁹⁹, B. Wagner¹⁸, J. Wagner⁹⁷, H. Wang⁵⁷, M. Wang^{7,113}, Y. Wang⁹³, D. Watanabe¹²⁷, M. Weber^{36,121}, S. G. Weber⁹⁷, J. P. Wessels⁵⁴, U. Westerhoff⁵⁴, J. Wiechula³⁵, J. Wikne²², M. Wilde⁵⁴, G. Wilk⁷⁷, J. Wilkinson⁹³, M. C. S. Williams¹⁰⁵, B. Windelband⁹³, M. Winn⁹³, C. G. Yaldo¹³³, Y. Yamaguchi¹²⁶, H. Yang⁵⁷, P. Yang⁷, S. Yano⁴⁷, S. Yasnopolskiy¹⁰⁰, Z. Yin⁷,

H. Yokoyama¹²⁷, I.-K. Yoo⁹⁶, V. Yurchenko³, I. Yushmanov¹⁰⁰, A. Zaborowska¹³², V. Zaccolo⁸⁰, A. Zaman¹⁶, C. Zampolli¹⁰⁵, H. J. C. Zanoli¹¹⁹, S. Zaporozhets⁶⁶, A. Zarochentsev¹³⁰, P. Závada⁶⁰, N. Zaviyalov⁹⁹, H. Zbroszczyk¹³², I. S. Zgura⁶², M. Zhalov⁸⁵, H. Zhang^{18,7}, X. Zhang⁷⁴, Y. Zhang⁷, C. Zhao²², N. Zhigareva⁵⁸, D. Zhou⁷, Y. Zhou^{80,57}, Z. Zhou¹⁸, H. Zhu^{18,7}, J. Zhu^{113,7}, X. Zhu⁷, A. Zichichi^{12,28}, A. Zimmermann⁹³, M. B. Zimmermann^{54,36}, G. Zinovjev³, M. Zyzak⁴³

Affiliations

¹A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia. ²Benemérita Universidad Autónoma de Puebla, Puebla, Mexico. ³Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine. ⁴Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India. ⁵Budker Institute for Nuclear Physics, Novosibirsk, Russia. ⁶California Polytechnic State University, San Luis Obispo, California, USA. ⁷Central China Normal University, Wuhan, China. ⁸Centre de Calcul de l'IN2P3, Villeurbanne, France. ⁹Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba. ¹⁰Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain. ¹¹Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico. ¹²Centro Fermi-Museo Storico della Fisica e Centro Studi e Ricerche 'Enrico Fermi', Rome, Italy. ¹³Chicago State University, Chicago, Illinois, USA. ¹⁴China Institute of Atomic Energy, Beijing, China. ¹⁵Commissariat à l'Energie Atomique, IRFU, Saclay, France. ¹⁶COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan. ¹⁷Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain. ¹⁸Department of Physics and Technology, University of Bergen, Bergen, Norway. ¹⁹Department of Physics, Aligarh Muslim University, Aligarh, India. ²⁰Department of Physics, Ohio State University, Columbus, Ohio, USA. ²¹Department of Physics, Sejong University, Seoul, South Korea. ²²Department of Physics, University of Oslo, Oslo, Norway. ²³Dipartimento di Elettrotecnica ed Elettronica del Politecnico, Bari, Italy. ²⁴Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN Rome, Italy. ²⁵Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy. ²⁶Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy. ²⁷Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy. ²⁸Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy. ²⁹Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy. ³⁰Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy. ³¹Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy. ³²Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy. ³³Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy. ³⁴Division of Experimental High Energy Physics, University of Lund, Lund, Sweden. ³⁵Eberhard Karls Universität Tübingen, Tübingen, Germany. ³⁶European Organization for Nuclear Research (CERN), Geneva, Switzerland. ³⁷Excellence Cluster Universe, Technische Universität München, Munich, Germany. ³⁸Faculty of Engineering, Bergen University College, Bergen, Norway. ³⁹Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia. ⁴⁰Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic. ⁴¹Faculty of Science, P.J. Šafárik University, Košice, Slovakia. ⁴²Faculty of Technology, Buskerud and Vestfold University College, Vestfold, Norway. ⁴³Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany. ⁴⁴Gangneung-Wonju National University, Gangneung, South Korea. ⁴⁵Gauhati University, Department of Physics, Guwahati, India. ⁴⁶Helsinki Institute of Physics (HIP), Helsinki, Finland. ⁴⁷Hiroshima University, Hiroshima, Japan. ⁴⁸Indian Institute of Technology Bombay (IIT), Mumbai, India. ⁴⁹Indian Institute of Technology Indore, Indore (IITI), India. ⁵⁰Inha University, Incheon, South Korea. ⁵¹Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France. ⁵²Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany. ⁵³Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany. ⁵⁴Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany. ⁵⁵Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France. ⁵⁶Institute for Nuclear Research, Academy of Sciences, Moscow, Russia. ⁵⁷Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands. ⁵⁸Institute for Theoretical and Experimental Physics, Moscow, Russia. ⁵⁹Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia. ⁶⁰Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic. ⁶¹Institute of Physics, Bhubaneswar, India. ⁶²Institute of Space Science (ISS), Bucharest, Romania. ⁶³Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico. ⁶⁴Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico. ⁶⁵IThemba LABS, National Research Foundation, Somerset West, South Africa. ⁶⁶Joint Institute for Nuclear Research (JINR), Dubna, Russia. ⁶⁷Konkuk University, Seoul, South Korea. ⁶⁸Korea Institute of Science and Technology Information, Daejeon, South Korea. ⁶⁹KTO Karatay University, Konya, Turkey. ⁷⁰Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France. ⁷¹Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France. ⁷²Laboratori Nazionali di Frascati, INFN, Frascati, Italy. ⁷³Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy. ⁷⁴Lawrence Berkeley National Laboratory, Berkeley, California, USA. ⁷⁵Lawrence Livermore National Laboratory, Livermore, California, USA. ⁷⁶Moscow Engineering Physics Institute, Moscow, Russia. ⁷⁷National Centre for Nuclear Studies, Warsaw, Poland. ⁷⁸National Institute for Physics and Nuclear Engineering, Bucharest, Romania. ⁷⁹National Institute of Science Education and Research, Bhubaneswar, India. ⁸⁰Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark. ⁸¹Nikhef, Nationaal instituut voor subatomaire fysica, Amsterdam, Netherlands. ⁸²Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, UK. ⁸³Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic. ⁸⁴Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. ⁸⁵Petersburg Nuclear Physics Institute, Gatchina, Russia. ⁸⁶Physics Department, Creighton University, Omaha, Nebraska, USA. ⁸⁷Physics Department, Panjab University, Chandigarh, India. ⁸⁸Physics Department, University of Athens, Athens, Greece. ⁸⁹Physics Department, University of Cape Town, Cape Town, South Africa. ⁹⁰Physics Department, University of Jammu, Jammu, India. ⁹¹Physics Department, University of Rajasthan, Jaipur, India. ⁹²Physik Department, Technische Universität München, Munich, Germany. ⁹³Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany. ⁹⁴Politecnico di Torino, Turin, Italy. ⁹⁵Purdue University, West Lafayette, Indiana, USA. ⁹⁶Pusan National University, Pusan, South Korea. ⁹⁷Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany. ⁹⁸Rudjer Bošković Institute, Zagreb, Croatia. ⁹⁹Russian Federal Nuclear Center (VNIIEF), Sarov, Russia. ¹⁰⁰Russian Research Centre Kurchatov Institute, Moscow, Russia. ¹⁰¹Saha Institute of Nuclear Physics, Kolkata, India. ¹⁰²School of Physics and Astronomy, University of Birmingham, Birmingham, UK. ¹⁰³Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru. ¹⁰⁴Sezione INFN, Bari, Italy. ¹⁰⁵Sezione INFN, Bologna, Italy. ¹⁰⁶Sezione INFN, Cagliari, Italy. ¹⁰⁷Sezione INFN, Catania, Italy. ¹⁰⁸Sezione INFN, Padova, Italy. ¹⁰⁹Sezione INFN, Rome, Italy. ¹¹⁰Sezione INFN, Trieste, Italy. ¹¹¹Sezione INFN, Turin, Italy. ¹¹²SSC IHEP of NRC Kurchatov institute, Protvino, Russia. ¹¹³SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France. ¹¹⁴Suranaree University of Technology, Nakhon Ratchasima, Thailand. ¹¹⁵Technical University of Split FESB, Split, Croatia. ¹¹⁶The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland. ¹¹⁷The University of Texas at Austin, Physics Department, Austin, Texas, USA. ¹¹⁸Universidad Autónoma de Sinaloa, Culiacán, Mexico. ¹¹⁹Universidade de São Paulo (USP), São Paulo, Brazil. ¹²⁰Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil. ¹²¹University of Houston, Houston, Texas, USA. ¹²²University of Jyväskylä, Jyväskylä, Finland. ¹²³University of Liverpool, Liverpool, UK. ¹²⁴University of Tennessee, Knoxville, Tennessee, USA. ¹²⁵University of the Witwatersrand, Johannesburg, South Africa. ¹²⁶University of Tokyo, Tokyo, Japan. ¹²⁷University of Tsukuba, Tsukuba, Japan. ¹²⁸University of Zagreb, Zagreb, Croatia. ¹²⁹Université de Lyon, Université Lyon 1, CNRS-IN2P3, IPN-Lyon, Villeurbanne, France. ¹³⁰V. Fock Institute for Physics, St Petersburg State University, St Petersburg, Russia. ¹³¹Variable Energy Cyclotron Centre, Kolkata, India. ¹³²Warsaw University of Technology, Warsaw, Poland. ¹³³Wayne State University, Detroit, Michigan, USA. ¹³⁴Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary. ¹³⁵Yale University, New Haven, Connecticut, USA. ¹³⁶Yonsei University, Seoul, South Korea. ¹³⁷Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany.