EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2023-268
20 November 2023

Measurements of chemical potentials in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Supplemental material

ALICE Collaboration*

Abstract

This document presents additional material about the most precise measurement to date of the matter/antimatter imbalance at midrapidity in Pb–Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV. Using the Statistical Hadronization framework, it is possible to obtain the value of the electric charge and baryon chemical potentials, $\mu_Q = -0.18 \pm 0.90$ MeV and $\mu_B = 0.71 \pm 0.45$ MeV, with unprecedented precision. A centrality-differential study of the antiparticle-to-particle yield ratios of charged pions, protons, Ω-baryons, and light (hyper)nuclei is performed. These results indicate that the system created in Pb–Pb collisions at the LHC is on average baryon–free and electrically neutral at midrapidity.

*See Appendix A for the list of collaboration members

1 Antiparticle-to-particle ratios

1.1 Particle identification of tracked species

The particle identification (PID) of charged pions, protons, ^{3}He, and tritons is performed by measuring the specific energy loss (dE/dx) in both the TPC and the ITS, and particle velocity depending on the transverse momentum of the measured particles with the Time-Of-Flight detector (TOF). Due to its electric charge $Z = 2$, ^{3}He is identified using the TPC dE/dx within $|n\sigma^{\rm TPC}| < 3$, where $n\sigma$ is the deviation of the measured dE/dx from the expected one, normalized to the experimental resolution. A similar approach is applied to protons for $p_{\rm T} < 1$ GeV/c after a preliminary $|n\sigma^{\rm ITS}| < 3$ selection, which is required to reduce the electron contamination. Higher-$p_{\rm T}$ protons, pions, and tritons are identified using TOF after preliminary TPC PID selections. These PID pre-selections lead to a signal loss smaller than 0.5% taken into account by the efficiency corrections computed via Monte Carlo simulations. The main contamination to the charged pion and proton PID is due to charged kaons and electrons. In the light-nuclei sector, the triton PID is mainly contaminated by deuterons, while tritons slightly affect the ^{3}He PID for $p_{\rm T} < 3$ GeV/c. The contribution of such misidentified tracks is estimated by fitting the corresponding $n\sigma^{\rm TPC}$ and $n\sigma^{\rm TOF}$ distributions. The $n\sigma^{\rm TPC}$ or $n\sigma^{\rm TOF}$ background distributions are fitted outside of the signal window. Their extrapolation within the signal region is integrated to statistically subtract the contamination due to either misidentified particles or the mismatch of TPC tracks and TOF space points.

1.2 Machine Learning analysis of Ω and $^3_\Lambda$H

The Machine Learning (ML) selection of Ω and $^3_\Lambda$H candidates is based on Boosted Decision Trees (BDT). The optimization of the BDT internal parameters is performed using samples of correctly classified signal and background candidates. The signal sample is built from simulated candidates injected on top of a HIJING Pb–Pb event with a Blast-wave $p_{\rm T}$ distribution [1] derived from the measured production of light flavor hadrons for Ω [2] and of ^{3}He for $^3_\Lambda$H [3]. The background $^3_\Lambda$H candidates are obtained in the data from same-sign combinations of ^{3}He and π tracks. For Ω^-, all the candidates with an invariant-mass deviating more than 7σ from the nominal Ω^- mass are considered as background candidates, with $\sigma \approx 1.7$ MeV/c^2 being the invariant-mass resolution in the data. The same training variables used in previous analyses are employed for $^3_\Lambda$H [4, 5]: the cosine of the pointing angle $\cos(\theta_p)$ (i.e., the angle between the reconstructed candidate momentum and the straight line connecting the production and decay vertices), the DCA between the decay tracks and the primary vertex (PV), and between the two tracks themselves, the number of TPC space points for the ^{3}He track, and the $n\sigma^{\rm TPC}$ of the decay tracks. For the Ω^-, the BDT input variables include the DCA of the K$^-$, π^- and p to the PV, the DCA of the reconstructed Λ to the PV, the minimum distance between the π^- and p, and between the K$^-$ and Λ. The $\cos(\theta_p)$ for both the Ω^- and Λ, and the $n\sigma^{\rm TPC}$ for p, are also used as BDT input variables. Signal candidates are selected requiring a BDT output score larger than a preset threshold. For $^3_\Lambda$H, the threshold is optimized by maximizing the expected signal significance; for the Ω^-, a BDT signal selection efficiency of 50% is required, as it ensures a consistent BDT response in data and MC.

1.3 Efficiency and absorption corrections

The efficiency corrections applied in this Letter take into account the tracking and candidate-selection efficiencies, including PID. Charged pions, protons, and tritons are selected with an efficiency of about 40% when requiring TOF PID, while protons having $p_{\rm T} < 1$ GeV/c and ^{3}He candidates are selected with an efficiency of approximately 70%. For antiproton, antitriton, and $^3\overline{\rm He}$ candidates, the obtained efficiencies are lower than those of their respective charge-conjugates by about 5% to 10% due to their larger absorption cross sections inside the ALICE apparatus. For Ω^- baryons, the efficiency of the preliminary selections is about 5%, while the BDT signal-selection efficiency is about 50%. For $^3_\Lambda$H, these two efficiencies are about 30% and 70%, respectively.

The modeling of the absorption cross sections in GEANT 4 is improved by using the available measurements of absorption cross sections in different materials [6–20]. Dedicated correction factors are computed as the ratios between the efficiencies computed using either the default parameterizations or those re-tuned on the experimental data. For charged pions and protons, the measurements obtained in lower energy experiments are used, while for tritons and ^{3}He the available ALICE measurements are employed. For the light (anti)nuclei, the observed effect is between 1% and 3% across the analysed p_{T} range. The uncertainties on the measured cross sections are propagated to the antiparticle-to-particle ratios as centrality-correlated sources of systematic uncertainties. The resulting uncertainties are reported in Table 1. For the $^{3}_{\Lambda}$H, an absorption factor is computed to correct for undetected hypernuclei that are absorbed in the apparatus before decaying. A sample of simulated ^{3}He candidates is used to approximate the absorption of $^{3}_{\Lambda}$H inside the ALICE apparatus. The absorbed fraction is about 6% and 4% for $^{3}_{\overline{\Lambda}}\overline{\mathrm{H}}$ and $^{3}_{\Lambda}$H, respectively.

1.4 Systematic uncertainties

The centrality-uncorrelated systematic uncertainty on the yield ratio is obtained as the variance of multiple reanalyses done by varying the tracking and PID selections for π, p, ^{3}He, and ^{3}H, and of the BDT output selections for $^{3}_{\Lambda}$H and Ω^{-} around their nominal values used in the analysis. The background fit function is also changed from exponential to polynomial in the invariant mass fit of $^{3}_{\Lambda}$H and Ω^{-}, while the yields of ^{3}He and ^{3}H are alternatively extracted as the integral of a Gaussian fit to the $n\sigma^{\mathrm{TPC}}$ and $n\sigma^{\mathrm{TOF}}$ distributions, respectively. The variations are applied coherently to antiparticles and particles to allow for the cancelation of correlated contributions in the antiparticle-to-particle yield ratios. The MC statistical precision is also considered as a centrality-uncorrelated source of systematic uncertainty. The uncertainty on the material-budget description in MC simulations is correlated with centrality. It is evaluated by varying the amount of material crossed by simulated particles by its uncertainty, estimated to be $\pm 4.5\%$ [21]. The uncertainties on the measured absorption cross sections used to correct the GEANT4 ones are also propagated to the ratios. The consistency of the results obtained with opposite magnetic field polarities is assessed by repeating the measurement separately with the two configurations: a statistically significant discrepancy of about 0.4% and 0.6% due to imperfections in the MC description is observed in semicentral and central collisions, respectively. The maximum half dispersion between the opposite field polarity results is then assigned as a further centrality-correlated uncertainty. The values of the various contributions are summarised in Table 1.

Table 1: Relative systematic uncertainty on the average antiparticle-to-particle ratios due to the different sources considered in the analysis. Only the statistically significant contributions to systematic uncertainties are reported in the table.

Source	$\overline{\Omega}^{+}/\Omega^{-}$	π^{+}/π^{-}	$\overline{\mathrm{p}}/\mathrm{p}$	$^{3}_{\overline{\Lambda}}\overline{\mathrm{H}}/^{3}_{\Lambda}\mathrm{H}$	$^{3}\overline{\mathrm{H}}/^{3}\mathrm{H}$	$^{3}\overline{\mathrm{He}}/^{3}\mathrm{He}$
Candidate selection + signal extract.	0.5%	0.05%	0.05%	10%	3%	0.5%
Monte Carlo precision	0.5%	0.1%	0.1%	1%	1%	1%
Material budget	–	0.1%	0.5%	–	–	–
Absorption cross section	–	0.7%	0.5%	1%	10%	1%
Magnetic field polarity	–	0.2–0.3%	0.2–0.3%	–	–	–

1.5 Results for the antiparticle-to-particle ratios

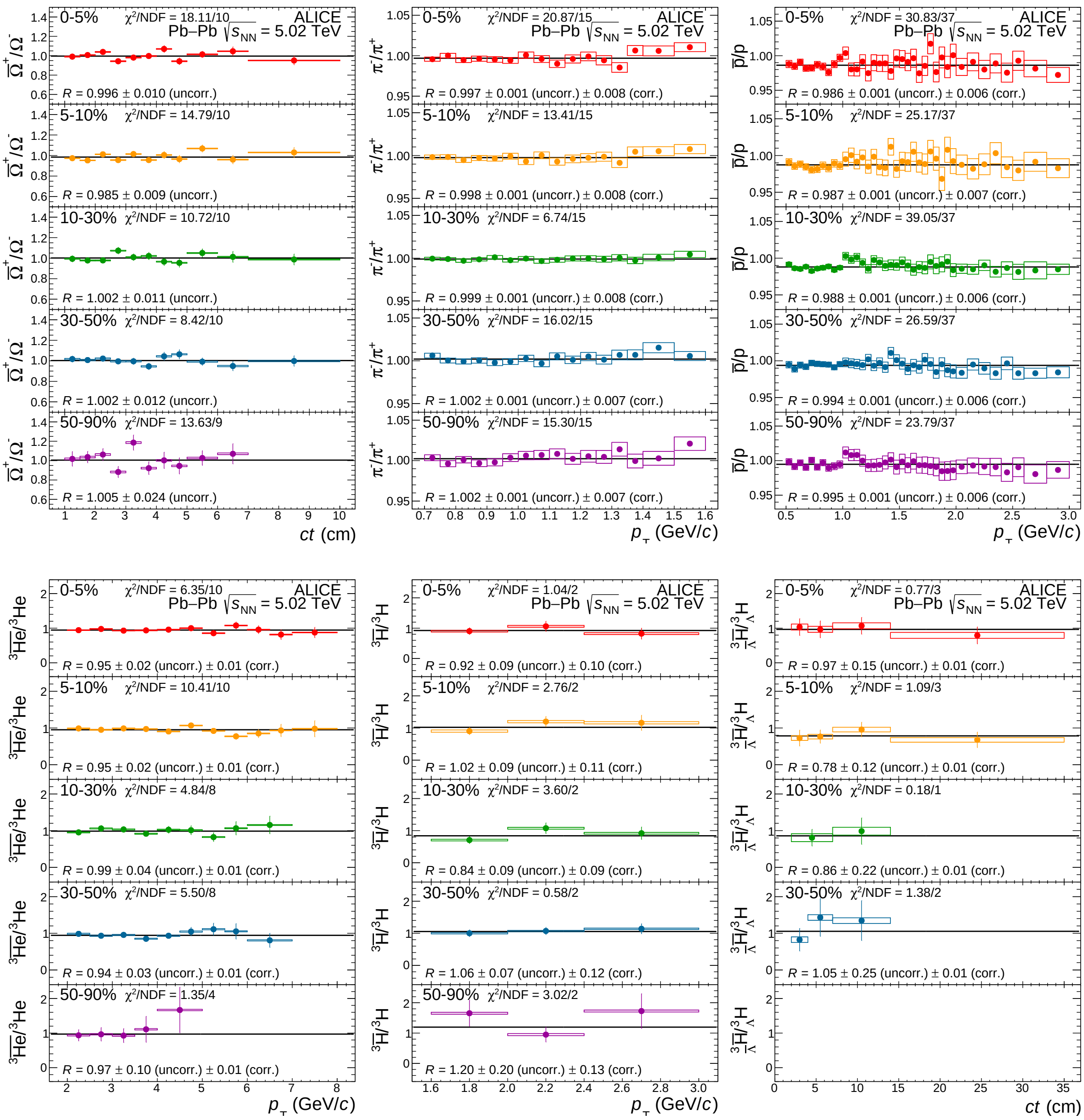

Figure 1: p_T- and ct-differential ratios of the species used for the chemical potential measurement in the various centrality intervals. Error bars show statistical uncertainties, while boxes represent centrality-uncorrelated uncertainties. The value of R represents the averages weighted with the total uncorrelated uncertainties of the differential measurements. The correlated uncertainties are not shown in the plots.

2 Covariance matrices

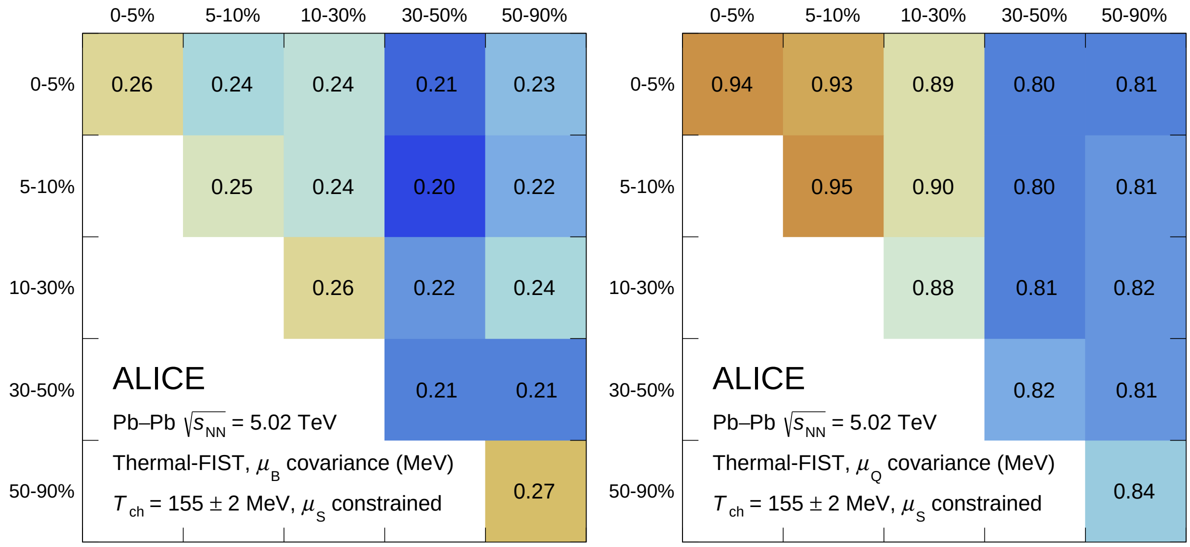

Figure 2: Covariance matrices of $\mu_{\rm B}$ (left) and $\mu_{\rm Q}$ (right) obtained with Thermal-FIST [22] in the different centrality intervals.

3 χ^2 profiles of chemical potential fits

3.1 Thermal-FIST model

Table 2: Confidence intervals (C.I.) at 1σ, 2σ, and 3σ levels for μ_B and μ_Q.

Observable	1σ C.I. (MeV)	2σ C.I. (MeV)	3σ C.I. (MeV)
μ_B	$[0.26, 1.16]$	$[-0.20, 1.61]$	$[-0.65, 2.07]$
μ_Q	$[-1.08, 0.73]$	$[-1.98, 1.63]$	$[-2.89, 2.54]$

3.2 GSI-Heidelberg model

Table 3: Confidence intervals (C.I.) at 1σ, 2σ, and 3σ levels for μ_B and μ_Q.

Observable	1σ C.I. (MeV)	2σ C.I. (MeV)	3σ C.I. (MeV)
μ_B	$[0.47, 1.33]$	$[0.05, 1.75]$	$[-0.38, 2.18]$

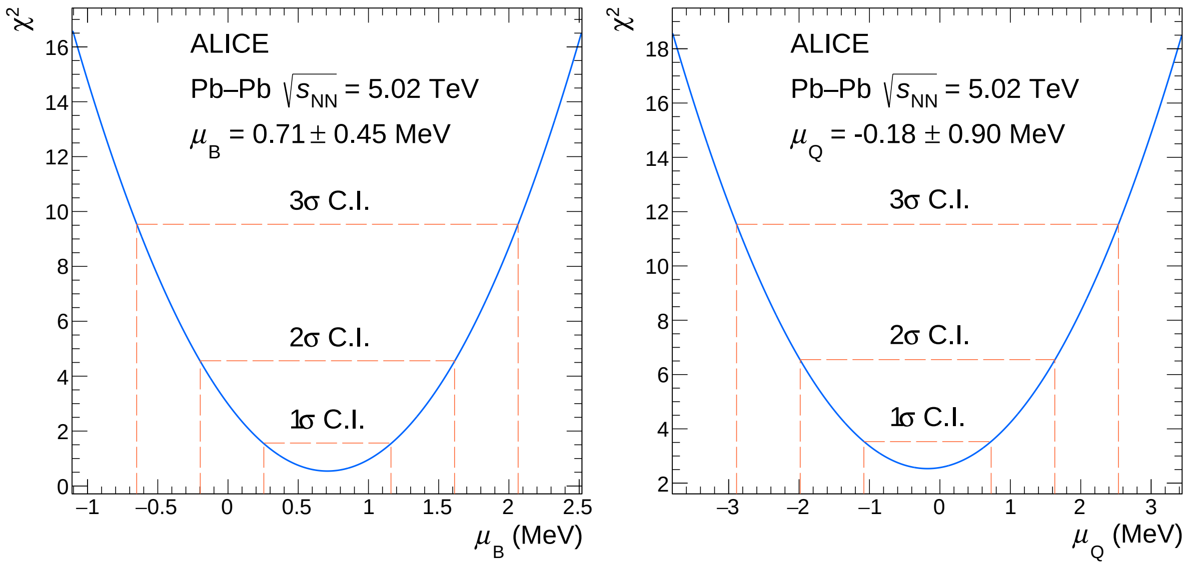

Figure 3: Profiles of the χ^2 variable minimized in the fit of μ_B (left) and μ_Q (right) obtained with the Thermal-FIST model [22]. The values obtained from the minimization, as well as the 1σ, 2σ, and 3σ confidence intervals, are reported in the figures.

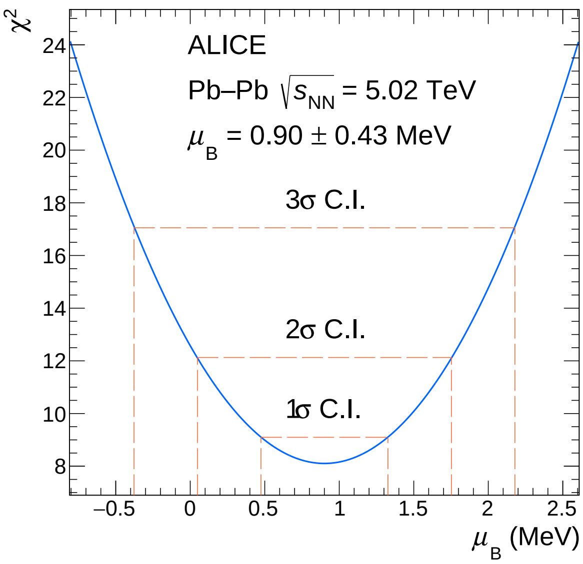

Figure 4: Profiles of the χ^2 variable minimized in the fit of μ_B obtained with the GSI-Heidelberg model [23–25]. The values obtained from the minimization, as well as the 1σ, 2σ, and 3σ confidence intervals, are reported in the figures.

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: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; 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) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Bulgarian Ministry of Education and Science, within the National Roadmap for Research Infrastructures 2020-2027 (object CERN), Bulgaria; Ministry of Education of China (MOEC) , Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; National Research and Innovation Agency - BRIN, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Academico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Education and Science, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics, Ministry of Research and Innovation and Institute of Atomic Physics and Universitatea Nationala de Stiinta si Tehnologie Politehnica Bucuresti, Romania; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSTDA) and National Science, Research and Innovation Fund (NSRF via PMU-B B05F650021), Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America. In addition, individual groups or members have received support from: Czech Science Foundation (grant no. 23-07499S), Czech Republic; European Research Council, Strong 2020 - Horizon 2020 (grant nos. 950692, 824093), European Union; ICSC - Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, European Union - NextGenerationEU; Academy of Finland (Center of Excellence in Quark Matter) (grant nos. 346327, 346328), Finland.

References

[1] E. Schnedermann, J. Sollfrank, and U. W. Heinz, "Thermal phenomenology of hadrons from 200-A/GeV S+S collisions", *Phys. Rev. C* **48** (1993) 2462–2475, `arXiv:nucl-th/9307020`.

[2] **ALICE** Collaboration, S. Acharya *et al.*, "Production of charged pions, kaons, and (anti-)protons in Pb-Pb and inelastic *pp* collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV", *Phys. Rev. C* **101** (2020) 044907, `arXiv:1910.07678 [nucl-ex]`.

[3] **ALICE** Collaboration, S. Acharya *et al.*, "Light (anti)nuclei production in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV", *Phys. Rev. C* **107** (2023) 064904, `arXiv:2211.14015 [nucl-ex]`.

[4] **ALICE** Collaboration, S. Acharya *et al.*, "Hypertriton Production in p-Pb Collisions at $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV", *Phys. Rev. Lett.* **128** (2022) 252003, `arXiv:2107.10627 [nucl-ex]`.

[5] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of the Lifetime and Λ Separation Energy of ${}^{3}_{\Lambda}$H", *Phys. Rev. Lett.* **131** (2023) 102302, `arXiv:2209.07360 [nucl-ex]`.

[6] F. F. Chen, C. P. Leavitt, and A. M. Shapiro, "Attenuation Cross Sections for 860-Mev Protons", *Physical Review* **99** (1955) 857.

[7] N. E. Booth, B. Ledley, D. Walker, and D. H. White, "Nuclear cross sections for 900 MeV protons.", *Proc.Physical Society (London), Section A* **70** (1957) 209.

[8] N. T. Porile, "Simple Nuclear Reactions of Indium with 30 and 2.9 GeV Protons", *Physical Review* **128** (1962) 1916.

[9] O. Artun, *et al.*, "Multinucleon Removal Induced by High-Energy Protons", *Phys. Rev. Lett.* **35** (1975) 773.

[10] M. E. Sadler, P. P. Singh, J. Jastrzebski, L. L. Rutledge, J. , and R. E. Segel, "Interaction of 80-164 MeV Protons with Nickel Isotopes", *Phys. Rev. C* **21** (1980) 2303.

[11] D. Ashery, I. Navon, G. Azuelos, H. K. Walter, H. J. Pfeiffer, and F. W. Schleputz, "True Absorption and Scattering of Pions on Nuclei", *Phys. Rev. C* **23** (1981) 2173–2185.

[12] K. Nakamura, J. Chiba, T. Fujii, H. Iwasaki, T. Kageyama, S. Kuribayashi, T. Sumiyoshi, T. Takeda, H. Ikeda, and Y. Takada, "Absorption and Forward Scattering of Antiprotons by C, Al, and Cu Nuclei in the Region 470-880 MeV/c", *Phys. Rev. Lett.* **52** (1984) 731–734.

[13] J. A. McGill, G. W. Hoffmann, M. L. Barlett, R. W. Fergerson, E. C. Milner, R. E. Chrien, R. J. Sutter, T. Kozlowski, and R. L. Stearns, "Proton + Nucleus Inclusive (p,p‘) Scattering at 800 MeV", *Phys. Rev. C* **29** (1984) 204.

[14] N. G. Zaitseva, E. Rurarz, M. Vobecky, K. H. Hwan, K. Nowak, T. Tethal, V. A. Khalkin, and L. M. Popinenkova, "Excitation Function and Yield for ^{97}Ru Production in ^{99}Tc(p,3n)^{97}Ru Reaction in 20-100 MeV Proton Energy Range", *Radiochimica Acta* **56** (1992) 59.

[15] V. F. Kuzichev, Y. B. Lepikhin, and V. A. Smirnitsky, "The Anti-proton - nuclei annihilation cross-section at the momentum range from 0.70 GeV/c to 2.5 GeV/c", *Nucl. Phys. A* **576** (1994) 581–602.

[16] C. M. Herbach, *et al.*, "Systematic investigation of 1.2 GeV proton-induced spallation reactions on targets between Al and U", *Nucl. Instrum. Methods in Physics Res., Sect.A* **562** (2006) 729.

[17] M. Zamani, S. Stoulos, M. Fragopoulou, M. Manolopoulou, and M. Krivopustov, "Indirect measurement of inelastic cross section of relativistic protons in Pb target", *Annals of Nuclear Energy* **37** (2010) 923.

[18] D. W. Bardayan, *et al.*, "Inelastic ^{17}F(p,p)^{17}F scattering at $E_{c.m.}$=3 MeV and the ^{14}O(|a,p)^{17}F reaction rate", *Phys. Rev. C* **81** (2010) 065802.

[19] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy", *Nature Phys.* **19** (2023) 61–71, `arXiv:2202.01549 [nucl-ex]`.

[20] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of the low-energy antitriton inelastic cross section", `arXiv:2307.03603 [nucl-ex]`.

[21] **ALICE** Collaboration, B. B. Abelev *et al.*, "Performance of the ALICE Experiment at the CERN LHC", *Int. J. Mod. Phys. A* **29** (2014) 1430044, `arXiv:1402.4476 [nucl-ex]`.

[22] V. Vovchenko and H. Stoecker, "Thermal-FIST: A package for heavy-ion collisions and hadronic equation of state", *Comput. Phys. Commun.* **244** (2019) 295–310, `arXiv:1901.05249 [nucl-th]`.

[23] P. Braun-Munzinger, K. Redlich, and J. Stachel, "Particle production in heavy ion collisions", in *Quark–Gluon Plasma 3*, pp. 491–599. World Scientific, 2004. `arXiv:nucl-th/0304013`.

[24] A. Andronic, P. Braun-Munzinger, and J. Stachel, "Hadron production in central nucleus-nucleus collisions at chemical freeze-out", *Nucl. Phys. A* **772** (2006) 167–199, `arXiv:nucl-th/0511071`.

[25] A. Andronic, P. Braun-Munzinger, B. Friman, P. M. Lo, K. Redlich, and J. Stachel, "The thermal proton yield anomaly in Pb-Pb collisions at the LHC and its resolution", *Phys. Lett. B* **792** (2019) 304–309, `arXiv:1808.03102 [hep-ph]`.

A The ALICE Collaboration

S. Acharya [128], D. Adamová [87], G. Aglieri Rinella [33], L. Aglietta[25], M. Agnello [30], N. Agrawal [26], Z. Ahammed [136], S. Ahmad [16], S.U. Ahn [72], I. Ahuja [38], A. Akindinov [142], M. Al-Turany [98], D. Aleksandrov [142], B. Alessandro [57], H.M. Alfanda [6], R. Alfaro Molina [68], B. Ali [16], A. Alici [26], N. Alizadehvandchali [117], A. Alkin [33], J. Alme [21], G. Alocco [53], T. Alt [65], A.R. Altamura [51], I. Altsybeev [96], J.R. Alvarado [45], M.N. Anaam [6], C. Andrei [46], N. Andreou [116], A. Andronic [127], E. Andronov [142], V. Anguelov [95], F. Antinori [55], P. Antonioli [52], N. Apadula [75], L. Aphecetche [104], H. Appelshäuser [65], C. Arata [74], S. Arcelli [26], M. Aresti [23], R. Arnaldi [57], J.G.M.C.A. Arneiro [111], I.C. Arsene [20], M. Arslandok [139], A. Augustinus [33], R. Averbeck [98], M.D. Azmi [16], H. Baba[125], A. Badalà [54], J. Bae [105], Y.W. Baek [41], X. Bai [121], R. Bailhache [65], Y. Bailung [49], R. Bala [92], A. Balbino [30], A. Baldisseri [131], B. Balis [2], D. Banerjee [4], Z. Banoo [92], F. Barile [32], L. Barioglio [57], M. Barlou[79], B. Barman[42], G.G. Barnaföldi [47], L.S. Barnby [86], E. Barreau [104], V. Barret [128], L. Barreto [111], C. Bartels [120], K. Barth [33], E. Bartsch [65], N. Bastid [128], S. Basu [76], G. Batigne [104], D. Battistini [96], B. Batyunya [143], D. Bauri[48], J.L. Bazo Alba [102], I.G. Bearden [84], C. Beattie [139], P. Becht [98], D. Behera [49], I. Belikov [130], A.D.C. Bell Hechavarria [127], F. Bellini [26], R. Bellwied [117], S. Belokurova [142], L.G.E. Beltran [110], Y.A.V. Beltran [45], G. Bencedi [47], S. Beole [25], Y. Berdnikov [142], A. Berdnikova [95], L. Bergmann [95], M.G. Besoiu [64], L. Betev [33], P.P. Bhaduri [136], A. Bhasin [92], M.A. Bhat [4], B. Bhattacharjee [42], L. Bianchi [25], N. Bianchi [50], J. Bielčík [36], J. Bielčíková [87], A.P. Bigot [130], A. Bilandzic [96], G. Biro [47], S. Biswas [4], N. Bize [104], J.T. Blair [109], D. Blau [142], M.B. Blidaru [98], N. Bluhme[39], C. Blume [65], G. Boca [22,56], F. Bock [88], T. Bodova [21], S. Boi [23], J. Bok [17], L. Boldizsár [47], M. Bombara [38], P.M. Bond [33], G. Bonomi [135,56], H. Borel [131], A. Borissov [142], A.G. Borquez Carcamo [95], H. Bossi [139], E. Botta [25], Y.E.M. Bouziani [65], L. Bratrud [65], P. Braun-Munzinger [98], M. Bregant [111], M. Broz [36], G.E. Bruno [97,32], M.D. Buckland [24], D. Budnikov [142], H. Buesching [65], S. Bufalino [30], P. Buhler [103], N. Burmasov [142], Z. Buthelezi [69,124], A. Bylinkin [21], S.A. Bysiak[108], J.C. Cabanillas Noris [110], M. Cai [6], H. Caines [139], A. Caliva [29], E. Calvo Villar [102], J.M.M. Camacho [110], P. Camerini [24], F.D.M. Canedo [111], S.L. Cantway [139], M. Carabas [114], A.A. Carballo [33], F. Carnesecchi [33], R. Caron [129], L.A.D. Carvalho [111], J. Castillo Castellanos [131], F. Catalano [33,25], S. Cattaruzzi [24], C. Ceballos Sanchez [143], R. Cerri[25], I. Chakaberia [75], P. Chakraborty [48], S. Chandra [136], S. Chapeland [33], M. Chartier [120], S. Chattopadhyay [136], S. Chattopadhyay [100], T. Cheng [98,6], C. Cheshkov [129], V. Chibante Barroso [33], D.D. Chinellato [112], E.S. Chizzali [II,96], J. Cho [59], S. Cho [59], P. Chochula [33], D. Choudhury[42], P. Christakoglou [85], C.H. Christensen [84], P. Christiansen [76], T. Chujo [126], M. Ciacco [30], C. Cicalo [53], M.R. Ciupek[98], G. Clai[III,52], F. Colamaria [51], J.S. Colburn[101], D. Colella [97,32], M. Colocci [26], M. Concas [33], G. Conesa Balbastre [74], Z. Conesa del Valle [132], G. Contin [24], J.G. Contreras [36], M.L. Coquet [131], P. Cortese [134,57], M.R. Cosentino [113], F. Costa [33], S. Costanza [22,56], C. Cot [132], J. Crkovská [95], P. Crochet [128], R. Cruz-Torres [75], P. Cui [6], A. Dainese [55], M.C. Danisch [95], A. Danu [64], P. Das [81], P. Das [4], S. Das [4], A.R. Dash [127], S. Dash [48], A. De Caro [29], G. de Cataldo [51], J. de Cuveland[39], A. De Falco [23], D. De Gruttola [29], N. De Marco [57], C. De Martin [24], S. De Pasquale [29], R. Deb [135], R. Del Grande [96], L. Dello Stritto [33,29], W. Deng [6], P. Dhankher [19], D. Di Bari [32], A. Di Mauro [33], B. Diab [131], R.A. Diaz [143,7], T. Dietel [115], Y. Ding [6], J. Ditzel [65], R. Divià [33], D.U. Dixit [19], Ø. Djuvsland[21], U. Dmitrieva [142], A. Dobrin [64], B. Dönigus [65], J.M. Dubinski [137], A. Dubla [98], S. Dudi [91], P. Dupieux [128], M. Durkac[107], N. Dzalaiova[13], T.M. Eder [127], R.J. Ehlers [75], F. Eisenhut [65], R. Ejima[93], D. Elia [51], B. Erazmus [104], F. Ercolessi [26], B. Espagnon [132], G. Eulisse [33], D. Evans [101], S. Evdokimov [142], L. Fabbietti [96], M. Faggin [28], J. Faivre [74], F. Fan [6], W. Fan [75], A. Fantoni [50], M. Fasel [88], A. Feliciello [57], G. Feofilov [142], A. Fernández Téllez [45], L. Ferrandi [111], M.B. Ferrer [33], A. Ferrero [131], C. Ferrero [IV,57], A. Ferretti [25], V.J.G. Feuillard [95], V. Filova [36], D. Finogeev [142], F.M. Fionda [53], E. Flatland[33], F. Flor [117], A.N. Flores [109], S. Foertsch [69], I. Fokin [95], S. Fokin [142], E. Fragiacomo [58], E. Frajna [47], U. Fuchs [33], N. Funicello [29], C. Furget [74], A. Furs [142], T. Fusayasu [99], J.J. Gaardhøje [84], M. Gagliardi [25], A.M. Gago [102], T. Gahlaut[48], C.D. Galvan [110], D.R. Gangadharan [117], P. Ganoti [79], C. Garabatos [98], T. García Chávez [45], E. Garcia-Solis [9], C. Gargiulo [33], P. Gasik [98], A. Gautam [119], M.B. Gay Ducati [67], M. Germain [104], A. Ghimouz[126], C. Ghosh[136], M. Giacalone [52], G. Gioachin [30], P. Giubellino [98,57], P. Giubilato [28], A.M.C. Glaenzer [131], P. Glässel [95], E. Glimos [123], D.J.Q. Goh[77], V. Gonzalez [138], P. Gordeev [142], M. Gorgon [2], K. Goswami [49], S. Gotovac[34], V. Grabski [68], L.K. Graczykowski [137], E. Grecka [87], A. Grelli [60], C. Grigoras [33], V. Grigoriev [142], S. Grigoryan [143,1], F. Grosa [33], J.F. Grosse-Oetringhaus [33], R. Grosso [98], D. Grund [36], N.A. Grunwald[95], G.G. Guardiano [112], R. Guernane [74], M. Guilbaud [104], K. Gulbrandsen [84], T. Gündem [65], T. Gunji [125],

W. Guo [6], A. Gupta [92], R. Gupta [92], R. Gupta [49], K. Gwizdziel [137], L. Gyulai [47], C. Hadjidakis [132], F.U. Haider [92], S. Haidlova [36], M. Haldar[4], H. Hamagaki [77], A. Hamdi [75], Y. Han [140], B.G. Hanley [138], R. Hannigan [109], J. Hansen [76], J.W. Harris [139], A. Harton [9], M.V. Hartung [65], H. Hassan [118], D. Hatzifotiadou [52], P. Hauer [43], L.B. Havener [139], E. Hellbär [98], H. Helstrup [35], M. Hemmer [65], T. Herman [36], G. Herrera Corral [8], F. Herrmann[127], S. Herrmann [129], K.F. Hetland [35], B. Heybeck [65], H. Hillemanns [33], B. Hippolyte [130], F.W. Hoffmann [71], B. Hofman [60], G.H. Hong [140], M. Horst [96], A. Horzyk [2], Y. Hou [6], P. Hristov [33], P. Huhn[65], L.M. Huhta [118], T.J. Humanic [89], A. Hutson [117], D. Hutter [39], M.C. Hwang [19], R. Ilkaev[142], H. Ilyas [14], M. Inaba [126], G.M. Innocenti [33], M. Ippolitov [142], A. Isakov [85], T. Isidori [119], M.S. Islam [100], M. Ivanov [98], M. Ivanov[13], V. Ivanov [142], K.E. Iversen [76], M. Jablonski [2], B. Jacak [19,75], N. Jacazio [26], P.M. Jacobs [75], S. Jadlovska[107], J. Jadlovsky[107], S. Jaelani [83], C. Jahnke [111], M.J. Jakubowska [137], M.A. Janik [137], T. Janson[71], S. Ji [17], S. Jia [10], A.A.P. Jimenez [66], F. Jonas [75,88,127], D.M. Jones [120], J.M. Jowett [33,98], J. Jung [65], M. Jung [65], A. Junique [33], A. Jusko [101], J. Kaewjai[106], P. Kalinak [61], A.S. Kalteyer [98], A. Kalweit [33], A. Karasu Uysal [V,73], D. Karatovic [90], O. Karavichev [142], T. Karavicheva [142], P. Karczmarczyk [137], E. Karpechev [142], M.J. Karwowska [33,137], U. Kebschull [71], R. Keidel [141], D.L.D. Keijdener[60], M. Keil [33], B. Ketzer [43], S.S. Khade [49], A.M. Khan [121], S. Khan [16], A. Khanzadeev [142], Y. Kharlov [142], A. Khatun [119], A. Khuntia [36], Z. Khuranova [65], B. Kileng [35], B. Kim [105], C. Kim [17], D.J. Kim [118], E.J. Kim [70], J. Kim [140], J. Kim [59], J. Kim [70], M. Kim [19], S. Kim [18], T. Kim [140], K. Kimura [93], S. Kirsch [65], I. Kisel [39], S. Kiselev [142], A. Kisiel [137], J.P. Kitowski [2], J.L. Klay [5], J. Klein [33], S. Klein [75], C. Klein-Bösing [127], M. Kleiner [65], T. Klemenz [96], A. Kluge [33], C. Kobdaj [106], T. Kollegger[98], A. Kondratyev [143], N. Kondratyeva [142], J. Konig [65], S.A. Konigstorfer [96], P.J. Konopka [33], G. Kornakov [137], M. Korwieser [96], S.D. Koryciak [2], A. Kotliarov [87], N. Kovacic[90], V. Kovalenko [142], M. Kowalski [108], V. Kozhuharov [37], I. Králik [61], A. Kravčáková [38], L. Krcal [33,39], M. Krivda [101,61], F. Krizek [87], K. Krizkova Gajdosova [33], M. Kroesen [95], M. Krüger [65], D.M. Krupova [36], E. Kryshen [142], V. Kučera [59], C. Kuhn [130], P.G. Kuijer [85], T. Kumaoka[126], D. Kumar[136], L. Kumar [91], N. Kumar[91], S. Kumar [32], S. Kundu [33], P. Kurashvili [80], A. Kurepin [142], A.B. Kurepin [142], A. Kuryakin [142], S. Kushpil [87], V. Kuskov [142], M. Kutyla[137], M.J. Kweon [59], Y. Kwon [140], S.L. La Pointe [39], P. La Rocca [27], A. Lakrathok[106], M. Lamanna [33], A.R. Landou [74], R. Langoy [122], P. Larionov [33], E. Laudi [33], L. Lautner [33,96], R. Lavicka [103], R. Lea [135,56], H. Lee [105], I. Legrand [46], G. Legras [127], J. Lehrbach [39], T.M. Lelek[2], R.C. Lemmon [86], I. León Monzón [110], M.M. Lesch [96], E.D. Lesser [19], P. Lévai [47], X. Li[10], B.E. Liang-gilman [19], J. Lien [122], R. Lietava [101], I. Likmeta [117], B. Lim [25], S.H. Lim [17], V. Lindenstruth [39], A. Lindner[46], C. Lippmann [98], D.H. Liu [6], J. Liu [120], G.S.S. Liveraro [112], I.M. Lofnes [21], C. Loizides [88], S. Lokos [108], J. Lömker [60], P. Loncar [34], X. Lopez [128], E. López Torres [7], P. Lu [98,121], F.V. Lugo [68], J.R. Luhder [127], M. Lunardon [28], G. Luparello [58], Y.G. Ma [40], M. Mager [33], A. Maire [130], E.M. Majerz[2], M.V. Makariev [37], M. Malaev [142], G. Malfattore [26], N.M. Malik [92], Q.W. Malik[20], S.K. Malik [92], L. Malinina [I,VIII,143], D. Mallick [132], N. Mallick [49], G. Mandaglio [31,54], S.K. Mandal [80], V. Manko [142], F. Manso [128], V. Manzari [51], Y. Mao [6], R.W. Marcjan [2], G.V. Margagliotti [24], A. Margotti [52], A. Marín [98], C. Markert [109], P. Martinengo [33], M.I. Martínez [45], G. Martínez García [104], M.P.P. Martins [111], S. Masciocchi [98], M. Masera [25], A. Masoni [53], L. Massacrier [132], O. Massen [60], A. Mastroserio [133,51], O. Matonoha [76], S. Mattiazzo [28], A. Matyja [108], C. Mayer [108], A.L. Mazuecos [33], F. Mazzaschi [25], M. Mazzilli [33], J.E. Mdhluli [124], Y. Melikyan [44], A. Menchaca-Rocha [68], J.E.M. Mendez [66], E. Meninno [103], A.S. Menon [117], M. Meres [13], Y. Miake[126], L. Micheletti [33], D.L. Mihaylov [96], K. Mikhaylov [143,142], D. Miśkowiec [98], A. Modak [4], B. Mohanty[81], M. Mohisin Khan [VI,16], M.A. Molander [44], S. Monira [137], C. Mordasini [118], D.A. Moreira De Godoy [127], I. Morozov [142], A. Morsch [33], T. Mrnjavac [33], V. Muccifora [50], S. Muhuri [136], J.D. Mulligan [75], A. Mulliri [23], M.G. Munhoz [111], R.H. Munzer [65], H. Murakami [125], S. Murray [115], L. Musa [33], J. Musinsky [61], J.W. Myrcha [137], B. Naik [124], A.I. Nambrath [19], B.K. Nandi [48], R. Nania [52], E. Nappi [51], A.F. Nassirpour [18], A. Nath [95], C. Nattrass [123], M.N. Naydenov [37], A. Neagu[20], A. Negru[114], E. Nekrasova[142], L. Nellen [66], R. Nepeivoda [76], S. Nese [20], G. Neskovic [39], N. Nicassio [51], B.S. Nielsen [84], E.G. Nielsen [84], S. Nikolaev [142], S. Nikulin [142], V. Nikulin [142], F. Noferini [52], S. Noh [12], P. Nomokonov [143], J. Norman [120], N. Novitzky [88], P. Nowakowski [137], A. Nyanin [142], J. Nystrand [21], S. Oh [18], A. Ohlson [76], V.A. Okorokov [142], J. Oleniacz [137], A. Onnerstad [118], C. Oppedisano [57], A. Ortiz Velasquez [66], J. Otwinowski [108], M. Oya[93], K. Oyama [77], Y. Pachmayer [95], S. Padhan [48], D. Pagano [135,56], G. Paić [66], S. Paisano-Guzmán [45], A. Palasciano [51], S. Panebianco [131], H. Park [126], H. Park [105], J. Park [59], J.E. Parkkila [33], Y. Patley [48], B. Paul [23], M.M.D.M. Paulino [111], H. Pei [6], T. Peitzmann [60], X. Peng [11], M. Pennisi [25], S. Perciballi [25], D. Peresunko [142], G.M. Perez [7], Y. Pestov[142], V. Petrov [142], M. Petrovici [46], R.P. Pezzi [104,67], S. Piano [58], M. Pikna [13], P. Pillot [104], O. Pinazza [52,33], L. Pinsky[117], C. Pinto [96], S. Pisano [50], M. Płoskoń [75], M. Planinic[90], F. Pliquett[65], M.G. Poghosyan [88], B. Polichtchouk [142], S. Politano [30], N. Poljak [90], A. Pop [46], S. Porteboeuf-Houssais [128], V. Pozdniakov [143], I.Y. Pozos [45], K.K. Pradhan [49], S.K. Prasad [4], S. Prasad [49], R. Preghenella [52], F. Prino [57], C.A. Pruneau [138], I. Pshenichnov [142], M. Puccio [33], S. Pucillo [25], Z. Pugelova[107], S. Qiu [85], L. Quaglia [25], S. Ragoni [15], A. Rai [139], A. Rakotozafindrabe [131], L. Ramello [134,57], F. Rami [130], T.A. Rancien[74], M. Rasa [27], S.S. Räsänen [44], R. Rath [52], M.P. Rauch [21], I. Ravasenga [33], K.F. Read [88,123], C. Reckziegel [113], A.R. Redelbach [39], K. Redlich [VII,80], C.A. Reetz [98], H.D. Regules-Medel[45], A. Rehman[21], F. Reidt [33], H.A. Reme-Ness [35], Z. Rescakova[38], K. Reygers [95], A. Riabov [142], V. Riabov [142], R. Ricci [29], M. Richter [20], A.A. Riedel [96], W. Riegler [33], A.G. Riffero [25], C. Ristea [64], M.V. Rodriguez [33], M. Rodríguez Cahuantzi [45], S.A. Rodríguez Ramírez [45], K. Røed [20], R. Rogalev [142], E. Rogochaya [143], T.S. Rogoschinski [65], D. Rohr [33], D. Röhrich [21], P.F. Rojas[45], S. Rojas Torres [36], P.S. Rokita [137], G. Romanenko [26], F. Ronchetti [50], A. Rosano [31,54], E.D. Rosas[66], K. Roslon [137], A. Rossi [55], A. Roy [49], S. Roy [48], N. Rubini [26], D. Ruggiano [137], R. Rui [24], P.G. Russek [2], R. Russo [85], A. Rustamov [82], E. Ryabinkin [142], Y. Ryabov [142], A. Rybicki [108], H. Rytkonen [118], J. Ryu [17], W. Rzesa [137], O.A.M. Saarimaki [44], S. Sadhu [32], S. Sadovsky [142], J. Saetre [21], K. Šafařík [36], P. Saha[42], S.K. Saha [4], S. Saha [81], B. Sahoo [49], R. Sahoo [49], S. Sahoo[62], D. Sahu [49], P.K. Sahu [62], J. Saini [136], K. Sajdakova[38], S. Sakai [126], M.P. Salvan [98], S. Sambyal [92], D. Samitz [103], I. Sanna [33,96], T.B. Saramela[111], D. Sarkar [84], P. Sarma [42], V. Sarritzu [23], V.M. Sarti [96], M.H.P. Sas [33], S. Sawan [81], E. Scapparone [52], J. Schambach [88], H.S. Scheid [65], C. Schiaua [46], R. Schicker [95], F. Schlepper [95], A. Schmah[98], C. Schmidt [98], H.R. Schmidt[94], M.O. Schmidt [33], M. Schmidt[94], N.V. Schmidt [88], A.R. Schmier [123], R. Schotter [130], A. Schröter [39], J. Schukraft [33], K. Schweda [98], G. Scioli [26], E. Scomparin [57], J.E. Seger [15], Y. Sekiguchi[125], D. Sekihata [125], M. Selina [85], I. Selyuzhenkov [98], S. Senyukov [130], J.J. Seo [95], D. Serebryakov [142], L. Serkin [66], L. Šerkšnytė [96], A. Sevcenco [64], T.J. Shaba [69], A. Shabetai [104], R. Shahoyan[33], A. Shangaraev [142], B. Sharma [92], D. Sharma [48], H. Sharma [55], M. Sharma [92], S. Sharma [77], S. Sharma [92], U. Sharma [92], A. Shatat [132], O. Sheibani[117], K. Shigaki [93], M. Shimomura[78], J. Shin[12], S. Shirinkin [142], Q. Shou [40], Y. Sibiriak [142], S. Siddhanta [53], T. Siemiarczuk [80], T.F. Silva [111], D. Silvermyr [76], T. Simantathammakul[106], R. Simeonov [37], B. Singh[92], B. Singh [96], K. Singh [49], R. Singh [81], R. Singh [92], R. Singh [98,49], S. Singh [16], V.K. Singh [136], V. Singhal [136], T. Sinha [100], B. Sitar [13], M. Sitta [134,57], T.B. Skaali[20], G. Skorodumovs [95], M. Slupecki [44], N. Smirnov [139], R.J.M. Snellings [60], E.H. Solheim [20], J. Song [17], C. Sonnabend [33,98], J.M. Sonneveld [85], F. Soramel [28], A.B. Soto-hernandez [89], R. Spijkers [85], I. Sputowska [108], J. Staa [76], J. Stachel [95], I. Stan [64], P.J. Steffanic [123], S.F. Stiefelmaier [95], D. Stocco [104], I. Storehaug [20], P. Stratmann [127], S. Strazzi [26], A. Sturniolo [31,54], C.P. Stylianidis[85], A.A.P. Suaide [111], C. Suire [132], M. Sukhanov [142], M. Suljic [33], R. Sultanov [142], V. Sumberia [92], S. Sumowidagdo [83], I. Szarka [13], M. Szymkowski [137], S.F. Taghavi [96], G. Taillepied [98], J. Takahashi [112], G.J. Tambave [81], S. Tang [6], Z. Tang [121], J.D. Tapia Takaki [119], N. Tapus[114], L.A. Tarasovicova [127], M.G. Tarzila [46], G.F. Tassielli [32], A. Tauro [33], A. Tavira García [132], G. Tejeda Muñoz [45], A. Telesca [33], L. Terlizzi [25], C. Terrevoli [117], S. Thakur [4], D. Thomas [109], A. Tikhonov [142], N. Tiltmann [33,127], A.R. Timmins [117], M. Tkacik[107], T. Tkacik [107], A. Toia [65], R. Tokumoto[93], K. Tomohiro[93], N. Topilskaya [142], M. Toppi [50], T. Tork [132], V.V. Torres [104], A.G. Torres Ramos [32], A. Trifiró [31,54], A.S. Triolo [33,31,54], S. Tripathy [52], T. Tripathy [48], S. Trogolo [33], V. Trubnikov [3], W.H. Trzaska [118], T.P. Trzcinski [137], A. Tumkin [142], R. Turrisi [55], T.S. Tveter [20], K. Ullaland [21], B. Ulukutlu [96], A. Uras [129], M. Urioni [135], G.L. Usai [23], M. Vala[38], N. Valle [22], L.V.R. van Doremalen[60], M. van Leeuwen [85], C.A. van Veen [95], R.J.G. van Weelden [85], P. Vande Vyvre [33], D. Varga [47], Z. Varga [47], P. Vargas Torres[66], M. Vasileiou [79], A. Vasiliev [142], O. Vázquez Doce [50], O. Vazquez Rueda [117], V. Vechernin [142], E. Vercellin [25], S. Vergara Limón[45], R. Verma[48], L. Vermunt [98], R. Vértesi [47], M. Verweij [60], L. Vickovic[34], Z. Vilakazi[124], O. Villalobos Baillie [101], A. Villani [24], A. Vinogradov [142], T. Virgili [29], M.M.O. Virta [118], V. Vislavicius[76], A. Vodopyanov [143], B. Volkel [33], M.A. Völkl [95], S.A. Voloshin [138], G. Volpe [32], B. von Haller [33], I. Vorobyev [33], N. Vozniuk [142], J. Vrláková [38], J. Wan[40], C. Wang [40], D. Wang[40], Y. Wang [40], Y. Wang [6], A. Wegrzynek [33], F.T. Weiglhofer[39], S.C. Wenzel [33], J.P. Wessels [127], J. Wiechula [65], J. Wikne [20], G. Wilk [80], J. Wilkinson [98], G.A. Willems [127], B. Windelband [95], M. Winn [131], J.R. Wright [109], W. Wu[40], Y. Wu [121], Z. Xiong[121], R. Xu [6], A. Yadav [43], A.K. Yadav [136], S. Yalcin [73], Y. Yamaguchi [93], S. Yang[21], S. Yano [93], E.R. Yeats[19], Z. Yin [6], I.-K. Yoo [17], J.H. Yoon [59],

H. Yu[12], S. Yuan[21], A. Yuncu[95], V. Zaccolo[24], C. Zampolli[33], F. Zanone[95], N. Zardoshti[33], A. Zarochentsev[142], P. Závada[63], N. Zaviyalov[142], M. Zhalov[142], B. Zhang[6], C. Zhang[131], L. Zhang[40], M. Zhang[6], S. Zhang[40], X. Zhang[6], Y. Zhang[121], Z. Zhang[6], M. Zhao[10], V. Zherebchevskii[142], Y. Zhi[10], C. Zhong[40], D. Zhou[6], Y. Zhou[84], J. Zhu[55,6], Y. Zhu[6], S.C. Zugravel[57], N. Zurlo[135,56]

Affiliation Notes

[I] Deceased
[II] Also at: Max-Planck-Institut fur Physik, Munich, Germany
[III] Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy
[IV] Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy
[V] Also at: Yildiz Technical University, Istanbul, Türkiye
[VI] Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India
[VII] Also at: Institute of Theoretical Physics, University of Wroclaw, Poland
[VIII] Also at: An institution covered by a cooperation agreement with CERN

Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] AGH University of Krakow, Cracow, Poland
[3] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[4] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[5] California Polytechnic State University, San Luis Obispo, California, United States
[6] Central China Normal University, Wuhan, China
[7] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[8] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[9] Chicago State University, Chicago, Illinois, United States
[10] China Institute of Atomic Energy, Beijing, China
[11] China University of Geosciences, Wuhan, China
[12] Chungbuk National University, Cheongju, Republic of Korea
[13] Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovak Republic
[14] COMSATS University Islamabad, Islamabad, Pakistan
[15] Creighton University, Omaha, Nebraska, United States
[16] Department of Physics, Aligarh Muslim University, Aligarh, India
[17] Department of Physics, Pusan National University, Pusan, Republic of Korea
[18] Department of Physics, Sejong University, Seoul, Republic of Korea
[19] Department of Physics, University of California, Berkeley, California, United States
[20] Department of Physics, University of Oslo, Oslo, Norway
[21] Department of Physics and Technology, University of Bergen, Bergen, Norway
[22] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[25] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[26] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[28] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[29] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[30] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[31] Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
[32] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[33] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[34] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia

[35] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[36] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[37] Faculty of Physics, Sofia University, Sofia, Bulgaria
[38] Faculty of Science, P.J. Šafárik University, Košice, Slovak Republic
[39] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[40] Fudan University, Shanghai, China
[41] Gangneung-Wonju National University, Gangneung, Republic of Korea
[42] Gauhati University, Department of Physics, Guwahati, India
[43] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[44] Helsinki Institute of Physics (HIP), Helsinki, Finland
[45] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[46] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[47] HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[48] Indian Institute of Technology Bombay (IIT), Mumbai, India
[49] Indian Institute of Technology Indore, Indore, India
[50] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[51] INFN, Sezione di Bari, Bari, Italy
[52] INFN, Sezione di Bologna, Bologna, Italy
[53] INFN, Sezione di Cagliari, Cagliari, Italy
[54] INFN, Sezione di Catania, Catania, Italy
[55] INFN, Sezione di Padova, Padova, Italy
[56] INFN, Sezione di Pavia, Pavia, Italy
[57] INFN, Sezione di Torino, Turin, Italy
[58] INFN, Sezione di Trieste, Trieste, Italy
[59] Inha University, Incheon, Republic of Korea
[60] Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
[61] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovak Republic
[62] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[63] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[64] Institute of Space Science (ISS), Bucharest, Romania
[65] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[66] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[67] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[68] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[69] iThemba LABS, National Research Foundation, Somerset West, South Africa
[70] Jeonbuk National University, Jeonju, Republic of Korea
[71] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
[72] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[73] KTO Karatay University, Konya, Turkey
[74] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[75] Lawrence Berkeley National Laboratory, Berkeley, California, United States
[76] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[77] Nagasaki Institute of Applied Science, Nagasaki, Japan
[78] Nara Women's University (NWU), Nara, Japan
[79] National and Kapodistrian University of Athens, School of Science, Department of Physics , Athens, Greece
[80] National Centre for Nuclear Research, Warsaw, Poland
[81] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[82] National Nuclear Research Center, Baku, Azerbaijan
[83] National Research and Innovation Agency - BRIN, Jakarta, Indonesia
[84] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[85] Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
[86] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom

[87] Nuclear Physics Institute of the Czech Academy of Sciences, Husinec-Řež, Czech Republic
[88] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
[89] Ohio State University, Columbus, Ohio, United States
[90] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[91] Physics Department, Panjab University, Chandigarh, India
[92] Physics Department, University of Jammu, Jammu, India
[93] Physics Program and International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM2), Hiroshima University, Hiroshima, Japan
[94] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[95] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[96] Physik Department, Technische Universität München, Munich, Germany
[97] Politecnico di Bari and Sezione INFN, Bari, Italy
[98] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[99] Saga University, Saga, Japan
[100] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[101] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[102] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[103] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[104] SUBATECH, IMT Atlantique, Nantes Université, CNRS-IN2P3, Nantes, France
[105] Sungkyunkwan University, Suwon City, Republic of Korea
[106] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[107] Technical University of Košice, Košice, Slovak Republic
[108] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[109] The University of Texas at Austin, Austin, Texas, United States
[110] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[111] Universidade de São Paulo (USP), São Paulo, Brazil
[112] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[113] Universidade Federal do ABC, Santo Andre, Brazil
[114] Universitatea Nationala de Stiinta si Tehnologie Politehnica Bucuresti, Bucharest, Romania
[115] University of Cape Town, Cape Town, South Africa
[116] University of Derby, Derby, United Kingdom
[117] University of Houston, Houston, Texas, United States
[118] University of Jyväskylä, Jyväskylä, Finland
[119] University of Kansas, Lawrence, Kansas, United States
[120] University of Liverpool, Liverpool, United Kingdom
[121] University of Science and Technology of China, Hefei, China
[122] University of South-Eastern Norway, Kongsberg, Norway
[123] University of Tennessee, Knoxville, Tennessee, United States
[124] University of the Witwatersrand, Johannesburg, South Africa
[125] University of Tokyo, Tokyo, Japan
[126] University of Tsukuba, Tsukuba, Japan
[127] Universität Münster, Institut für Kernphysik, Münster, Germany
[128] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[129] Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France
[130] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[131] Université Paris-Saclay, Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[132] Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[133] Università degli Studi di Foggia, Foggia, Italy
[134] Università del Piemonte Orientale, Vercelli, Italy
[135] Università di Brescia, Brescia, Italy
[136] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[137] Warsaw University of Technology, Warsaw, Poland
[138] Wayne State University, Detroit, Michigan, United States
[139] Yale University, New Haven, Connecticut, United States

[140] Yonsei University, Seoul, Republic of Korea
[141] Zentrum für Technologie und Transfer (ZTT), Worms, Germany
[142] Affiliated with an institute covered by a cooperation agreement with CERN
[143] Affiliated with an international laboratory covered by a cooperation agreement with CERN.