



CERN-EP-2022-040

11 March 2022

First measurement of antideuteron number fluctuations at energies available at the Large Hadron Collider

ALICE Collaboration*

Abstract

The first measurement of event-by-event antideuteron number fluctuations in high energy heavy-ion collisions is presented. The measurements are carried out at midrapidity ($|\eta| < 0.8$) as a function of collision centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the ALICE detector. A significant negative correlation between the produced antiprotons and antideuterons is observed in all collision centralities. The results are compared with a state-of-the-art coalescence calculation. While it describes the ratio of higher order cumulants of the antideuteron multiplicity distribution, it fails to describe quantitatively the magnitude of the correlation between antiproton and antideuteron production. On the other hand, thermal-statistical model calculations describe all the measured observables within uncertainties only for correlation volumes that are different with respect to those describing proton yields and a similar measurement of net-proton number fluctuations.

arXiv:2204.10166v2 [nucl-ex] 5 Oct 2023

*See Appendix A for the list of collaboration members

The production of nuclei and antinuclei in heavy-ion collisions has been extensively studied in the last two decades. Nevertheless, this wealth of results is still not able to clarify the mechanism behind nuclei and antinuclei formation in heavy-ion collisions. Indeed, the two best fitting models, the coalescence [1–3] and the statistical hadronisation models (SHM) [4, 5], give very similar predictions for the production rates of nuclei and antinuclei in heavy-ion collisions. This similarity calls for new observables to decisively discriminate between these two approaches.

The SHM describes the system as a hadron-resonance gas in thermal equilibrium at hadron emission, hence it predicts particle yields starting from the volume (V) and the temperature of the system at chemical freeze-out (T_{chem}). The Grand Canonical Ensemble (GCE) formulation of the SHM fits the measured production yields of light hadrons and nuclei in central Pb–Pb collisions at center-of-mass energy ($\sqrt{s_{\text{NN}}}$) of 2.76 TeV with $T_{\text{chem}} = 156.5$ MeV [6]. The coalescence model uses a different approach to explain the production of nuclei: the size of the nucleon-emitting source, accessible through the analysis of femtoscopic correlations [7], the momentum distribution of the nucleons, as well as the nuclear wave function, are inputs that determine the formation probability of bound states [3, 8]. While using statistical hadronisation it is possible to compute directly the absolute yields of particles, in the hadron coalescence model the yield of bound states can be computed only relative to the production of its components and as a function of system size.

In a recent model study [9], it is shown that the higher order cumulants of the deuteron yield distribution and correlation between proton (p) and deuteron (d) production can be used to distinguish between coalescence and SHM. Higher order cumulants κ_m of the multiplicity distribution for $m < 4$ and the Pearson correlation coefficient (ρ_{ab}) between different identified particles a and b can be expressed as

$$\kappa_1 = \langle n \rangle, \quad (1)$$

$$\kappa_m = \langle (n - \langle n \rangle)^m \rangle, \quad (2)$$

$$\rho_{\text{ab}} = \langle (n_a - \langle n_a \rangle)(n_b - \langle n_b \rangle) \rangle / \sqrt{\kappa_{2a} \kappa_{2b}}, \quad (3)$$

where n , $\langle n \rangle$, and m are the event-by-event particle numbers, event average of particle numbers and order of the cumulants, respectively. The $\langle n_a \rangle$ ($\langle n_b \rangle$) and κ_{2a} (κ_{2b}) are the first and second order cumulants of the multiplicity distribution of particle a (b). In the GCE formulation of the SHM, the event-by-event deuteron multiplicity distribution is expected to follow the Poisson distribution [10]. Therefore various ratios between cumulants of different order of the deuteron multiplicity distribution such as κ_2/κ_1 , κ_3/κ_2 are equal to unity in the GCE SHM. In a simple coalescence scenario, if deuterons are produced by the coalescence of thermally produced protons and neutrons, then the event-by-event deuteron distribution is expected to deviate from the Poisson baseline [9]. By definition, the coalescence model also introduces a negative correlation between the measured proton and deuteron numbers in the absence of any initial correlation between proton and neutron. On the other hand, one does not expect any correlation between the measured p and d in the GCE SHM as the baryon productions from a thermal source are independent from each other. However, in the Canonical Ensemble (CE) formulation of the SHM, particle production is constrained by the conservation of the net baryon numbers on an event-by-event basis, which can also introduce a negative correlation between measured proton and deuteron in SHM and a deviation of cumulant ratios from the Poisson baseline [10, 11].

In this Letter, the first measurements of the κ_2/κ_1 ratio of antideuteron (antiparticles are used throughout the analysis to avoid the contamination from secondary deuterons coming from spallation processes in the beam pipe) multiplicity distribution and correlation ($\rho_{\bar{p}\bar{d}}$) between measured antideuterons (\bar{d}) and antiprotons (\bar{p}) are presented. Measurements are compared with predictions from the SHM and coalescence model in order to shed light on the deuteron synthesis mechanism. The results presented in this letter are obtained using data collected during the 2015 Pb–Pb LHC run at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

The ALICE detector and its performance are described in detail in Refs. [12, 13]. Collision events are selected by using the information from the V0C and V0A scintillator arrays [14], located on both

sides of the interaction point, covering the pseudorapidity intervals $-3.7 < \eta < -1.6$ and $2.8 < \eta < 5.1$, respectively. Events are selected with a minimum-bias (MB) trigger which requires at least one hit in both the V0A and the V0C detectors. In addition, only events with the primary vertex position within 10 cm along the beam axis to the nominal interaction point are selected to benefit from the full acceptance of the detector. Furthermore, to ensure the best possible performance of the detector and proper normalisation of the results, events with more than one reconstructed primary interaction vertex (pile-up events) are rejected. In total, about 100 million MB events are selected for analysis. Furthermore, the selected events are divided into centrality classes based on the measured amplitude distribution in the V0A and V0C counters as described in Ref. [15]. Central Pb–Pb collisions (head-on collisions) are obtained from the top 10% of the amplitude distribution corresponding to hadronic interactions and peripheral Pb–Pb collisions are obtained from the 70–80% region of the same distribution.

The charged-particle tracks are reconstructed in the ALICE central barrel with the Inner Tracking System (ITS) [13] and the Time Projection Chamber (TPC) [16], which are located within a solenoid that provides a homogeneous magnetic field of up to 0.5 T in the direction of the beam axis. These two subsystems provide full azimuthal coverage for charged-particle trajectories in the pseudorapidity interval $|\eta| < 0.8$. The transverse momentum range is restricted to $0.4 < p_T < 1.8$ GeV/c to select the \bar{p} and \bar{d} with high purity. Moreover, to guarantee a track-momentum resolution of 2% in the relevant p_T range and an energy loss (dE/dx) resolution in the TPC of 5%, the selected tracks are required to have at least 70 out of a maximum possible 159 reconstructed space points in the TPC, and at least one hit in the two innermost layers of the ITS. This selection also assures a resolution better than 300 μm [13] on the distance of the closest approach to the primary vertex in the plane perpendicular (DCA_{xy}) and parallel (DCA_z) to the beam axis for the selected tracks. In addition, the χ^2 per space point in the TPC and the ITS from the track fit are required to be less than 4 and 36, respectively. Daughter tracks from reconstructed secondary weak-decay kink topologies were rejected and a suppression of the weak-decay particles are obtained by selecting tracks with $|DCA_z|$ and $|DCA_{xy}|$ less than 1.0 and 0.1 cm, respectively.

The \bar{d} and \bar{p} are identified via the specific energy loss dE/dx in the gas volume of the TPC and the flight time of a particle from the primary vertex of the collision to the Time-of-Flight (TOF) detector. The $n(\sigma_i^{\text{TPC}})$ variable represents the particle identification (PID) response in the TPC expressed in terms of the deviation between the measured and the expected dE/dx for a particle species i , normalized by the detector resolution σ . The expected dE/dx is computed with a parameterised Bethe–Bloch function [13]. The \bar{p} and \bar{d} are identified using $-2 < |n(\sigma_i^{\text{TPC}})| < 4$ in the range $0.4 < p_T < 0.6$ GeV/c and $0.8 < p_T < 1.0$ GeV/c, respectively. Particle identification on a track-by-track basis using the TPC is limited to low momenta. Therefore, to identify \bar{d} (\bar{p}) in the range $1.0 < p_T < 1.8$ GeV/c ($0.6 < p_T < 0.9$ GeV/c), an additional selection of $3.0 < m^2 < 4.2$ GeV²/c⁴ ($0.6 < m^2 < 1.2$ GeV²/c⁴) using the Time-of-Flight (TOF) [17] detector is applied, where the square of the particle mass, m^2 , is obtained by combining the information of the flight time with the trajectory length of the particle. The selection of \bar{d} is restricted to the range $0.8 < p_T < 1.8$ GeV/c in order to keep the overall \bar{d} purity above 90%. The \bar{p} selection is restricted to exactly half of the p_T range of \bar{d} according to the coalescence mechanism. This selection results in a purity of the selected \bar{p} sample above 95%. The impurity in \bar{d} selection can lead to an autocorrelation with the selected \bar{p} and affect the $\rho_{\bar{p}\bar{d}}$. The effect is negligible in our measurement as the \bar{d} and \bar{p} are mostly selected in separated p_T regions and in the common p_T interval the \bar{d} purity is $\sim 99\%$. Selected \bar{d} and \bar{p} numbers in each event are further used to obtain the higher order cumulants and correlation.

Measured cumulants are corrected for the \bar{d} and \bar{p} efficiencies assuming a binomial response of the detectors. The binomial-based method of efficiency correction [18] is a two-step method. First, the efficiency of \bar{d} and \bar{p} reconstruction in the ALICE detector is obtained using a simulation based on GEANT4, which correctly describes the interaction of \bar{p} and \bar{d} with the material of the detectors [19]. Then, the cumulants and correlation coefficient are corrected for the reconstruction efficiencies using

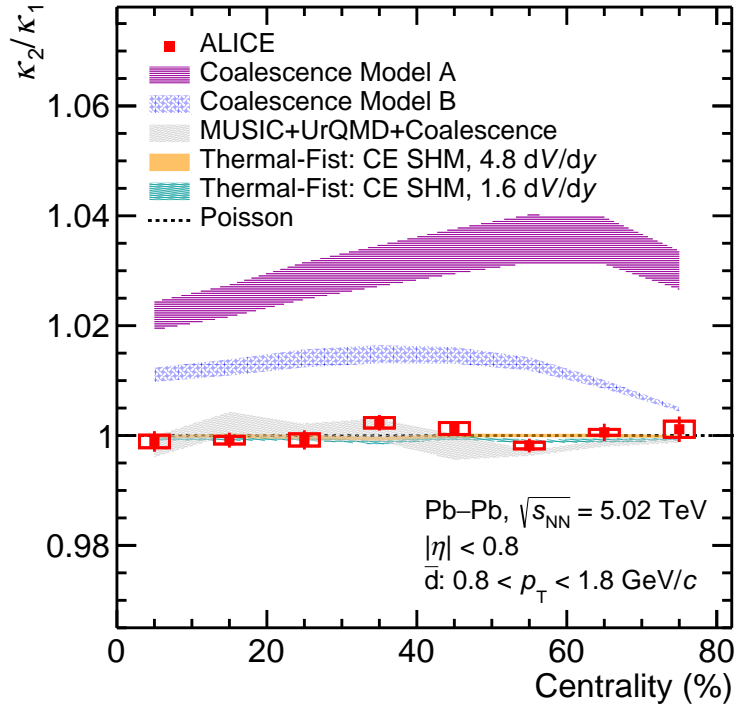


Figure 1: Second order to first order cumulant ratio of the \bar{d} multiplicity distribution as a function of collision centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical and systematic uncertainties are shown by the bars and boxes, respectively. Measured cumulant ratios are compared with estimations from the CE version of the SHM, from a simple coalescence model and from a MUSIC+UrQMD+Coalescence simulation. The width of the SHM model and MUSIC+UrQMD+Coalescence bands corresponds to the statistical uncertainty of the model estimation, whereas the width of the bands for the coalescence model corresponds to the uncertainty coming from the variation of the coalescence parameters.

analytic expressions as discussed in Ref. [18]. Typical reconstruction efficiencies of both \bar{p} and \bar{d} in the studied p_T ranges are about 70% and 25% in the TPC and TOF, respectively. The efficiency-corrected cumulants and correlation are further corrected for the centrality bin width effect [20] to suppress the initial volume fluctuations which arise from the initial state (size and shape) fluctuations.

The statistical uncertainties on the efficiency corrected κ_2/κ_1 ratio and $\rho_{\bar{p}\bar{d}}$ are obtained by the subsample method [21]. The systematic uncertainties on the observables are estimated by varying the track selection and PID criteria. The systematic uncertainties due to track selection include the variation of the selection criteria on DCA_{xy} , DCA_z , the number of reconstructed space points in the TPC, and the quality of the track fit from their nominal values. The systematic uncertainties due to PID are calculated by varying the default $n(\sigma^{TPCi})$ and m^2 criteria. Systematic uncertainties due to each of these sources are considered as uncorrelated and the total systematic uncertainty on the observables is obtained by adding all the contributions in quadrature.

The resulting ratio of the second to first order cumulant for \bar{d} is shown in Fig. 1 for different centrality classes. The data is found to be consistent with unity within uncertainties as expected from a Poisson distribution and does not exhibit a significant centrality dependence. Measurements are also compared with estimations from the CE version of the SHM [22] for two different correlation volumes (V_c) for baryon number conservation, $V_c = 4.8$ dV/dy (orange band in figures) and $V_c = 1.6$ dV/dy (green band in figures). The choice of two different V_c is discussed below. In the SHM model the temperature is fixed to $T = 155$ MeV [5], the volume fitted to the published pion, kaon, and proton yields at midrapidity [23], and the net-baryon number set to 0. Measurements are found to be consistent with the SHM model for both of the V_c . In contrast to the corresponding ratio for p and \bar{p} [24, 25], no strong dependence on the V_c

is seen due to the fact that only a small fraction of the total antibaryon number is carried by \bar{d} [10, 26]. Remarkably, the data differs from the calculations of the coalescence model, which predicts a deviation larger than 1% from the Poisson baseline as explained in Ref. [9]. Two shaded bands are shown for the coalescence model: the purple one assumes full correlation among protons and neutrons produced in the collision (Model A), while the blue one assumes completely independent proton and neutron production fluctuations (Model B). On the other hand, a state of art model calculation coupling coalescence to a hydrodynamical model with hadronic interactions in the final state (MUSIC+UrQMD+COAL) [27] predicts κ_2/κ_1 ratio ~ 1 , in agreement with the experimental data (note that these predictions were updated after acceptance of this Letter). As discussed in [27], the main difference between the coalescence predictions in Fig. 1 and the MUSIC+UrQMD+COAL calculation is due to the different method of implementing baryon number conservation.

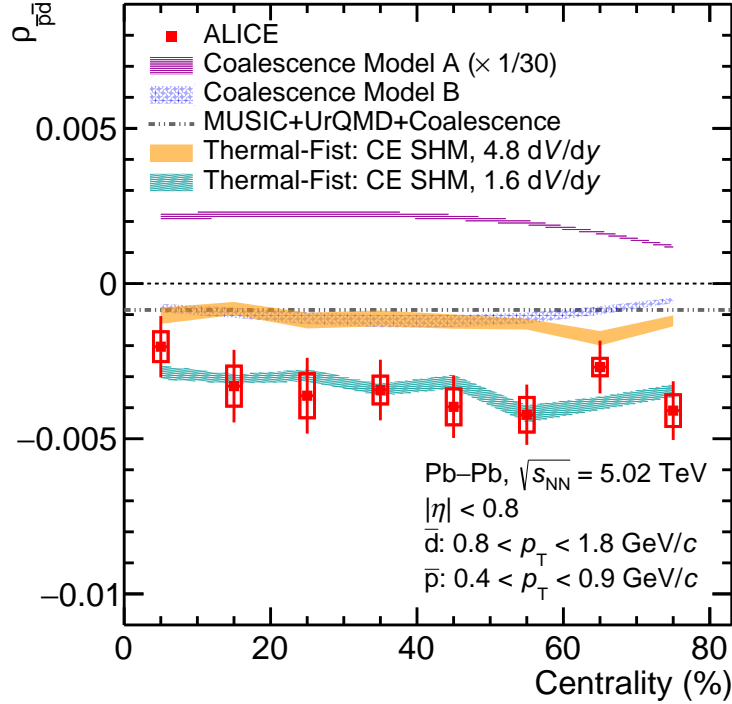


Figure 2: Pearson correlation between the measured \bar{p} and \bar{d} as a function of collision centrality in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Bars and boxes represent statistical and systematic uncertainties, respectively. Measured correlations are compared with estimations from the CE version of the SHM for two different baryon number conservation volumes, from coalescence model and from MUSIC+UrQMD+COAL.

Figure 2 shows $\rho_{\bar{p}\bar{d}}$ as a function of the collision centrality. A small negative correlation of $O(0.1\%)$ is observed, i.e. in events with at least one \bar{d} , there are $O(0.1\%)$ less \bar{p} observed than in an average event. A negative correlation as observed in data is expected by the coalescence model (shown by the blue band in Fig. 2) where \bar{p} and \bar{n} from two independent sources coalesce to produce \bar{d} . The same behaviour is observed for the MUSIC+UrQMD+COAL calculation. It has to be noted that models based on fully correlated proton and neutron fluctuations (Model A in Ref. [9]) predict values of ρ around 6% and are ruled out by data. On the other hand, the measured negative correlation between \bar{p} and \bar{d} is also expected by the CE version of the SHM which introduces a negative correlation between \bar{p} and \bar{d} through the conservation of a fixed net-baryon number. The predicted correlation in the SHM increases with decreasing correlation volume V_c for baryon number conservation which is used in the following for a determination of V_c . In order to determine the correlation volume for the baryon quantum number, a χ^2 minimization is performed by varying the V_c parameter in the SHM model and comparing the result to the measured correlation as a function of centrality. The V_c interval probed in this case spans from 1 to 5 units of rapidity, and the value that describes best the measurement is $V_c = 1.6 \pm 0.3$ dV/dy

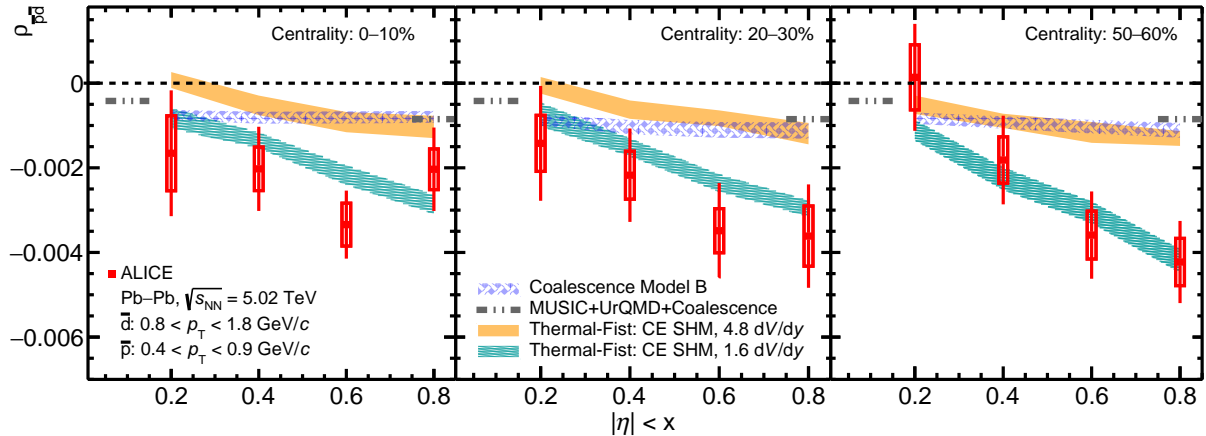


Figure 3: Dependence of \bar{p} - \bar{d} correlation on pseudorapidity acceptance of \bar{p} and \bar{d} selection in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for three different centrality classes. Measurements are compared with calculations from the CE version of the SHM, coalescence model and MUSIC+UrQMD+COAL.

with a fit probability of 85%. The SHM configuration with $V_c = 4.8$ dV/dy that correctly describes the net-proton number fluctuations in central Pb-Pb collisions [26, 28] is compatible within uncertainties with the measured $\rho_{\bar{p}\bar{d}}$ only in central collisions. Conversely, this configuration is excluded with a 4σ confidence level when compared with the measurements in all centrality classes.

Several consistency checks such as the correlation between \bar{p} and \bar{d} from different events, the correlation between antibaryon (\bar{d}) and baryon (p) were performed for a better understanding of the observed correlation. The correlation between \bar{p} and \bar{d} from mixed events is served as a null hypothesis test of the measurements and the obtained results are consistent with zero as expected. However, a positive correlation is observed between antibaryon and baryon. This positive correlation is expected due to baryon number conservation [10], whereas in simple coalescence model no correlation between baryon and antibaryon is expected as \bar{d} is not produced from the coalescence of p .

Figure 3 shows the same Pearson correlation coefficient in three centrality intervals as a function of the η acceptance of \bar{p} and \bar{d} selection. The observed anticorrelation is increasing with acceptance, and the effect is more pronounced for peripheral collisions. Simple coalescence calculations do not capture this trend. On the other hand, this measurement should motivate further calculations with more refined coalescence models. The decreasing trend seen in the SHM with $V_c = 1.6$ dV/dy describes the experimental data. In the CE version of SHM model, anticorrelation between antibaryons depends on the fraction of antibaryon number in the acceptance out of the total conserved antibaryon numbers [10, 11, 25, 28]. Therefore, the increased negative correlation magnitude with increasing acceptance can be understood as a consequence of baryon number conservation.

In summary, the measurement of \bar{d} production fluctuation is a valuable tool to challenge the nucleosynthesis models used for hadronic collisions. Simple coalescence models, as well as state-of-the-art MUSIC+UrQMD+COAL calculations, fail to fit simultaneously the measurement of the cumulant ratios and the correlation coefficient $\rho_{\bar{p}\bar{d}}$. These models show a great sensitivity to the initial correlation between the proton and the neutron production, hence further theoretical developments might improve the comparison with the measurement. In recent studies, state-of-the-art CE SHM models are describing simultaneously proton yields and net-proton fluctuation measurements finding large $V_c \approx 3-5$ dV/dy [26, 28, 29]. Surprisingly, deuteron production measurements [5] as well as the fluctuation measurements presented here indicate a significantly smaller correlation volume for the baryon number. Under the assumption that V_c is independent of collision centrality, the value $V_c = 1.6 \pm 0.3$ dV/dy is obtained. This discrepancy might indicate a different production mechanism for light flavored hadrons and light nuclei. However, more sophisticated approaches including partial chemical equilibrium [30] or the implementation of the

interaction of hadrons through phase shift [31, 32] could help in resolving this conundrum. The results of this Letter present a severe challenge to the current understanding of nuclei production in heavy-ion collisions at the LHC energies.

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; 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 Académico (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 University Politehnica of Bucharest, 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), Thailand Science Research and Innovation (TSRI) and National Science, Research and Innovation Fund (NSRF), 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 Sci-

ence 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: Marie Skłodowska Curie, Strong 2020 - Horizon 2020 (grant nos. 824093, 896850), European Union; Academy of Finland (Center of Excellence in Quark Matter) (grant nos. 346327, 346328), Finland; Programa de Apoyos para la Superación del Personal Académico, UNAM, Mexico.

References

- [1] S. Mrowczynski, “Deuteron formation mechanism”, *J. Phys. G* **13** (1987) 1089–1097.
- [2] R. Scheibl and U. W. Heinz, “Coalescence and flow in ultrarelativistic heavy ion collisions”, *Phys. Rev. C* **59** (1999) 1585–1602, arXiv:nucl-th/9809092.
- [3] K.-J. Sun, C. M. Ko, and B. Dönigus, “Suppression of light nuclei production in collisions of small systems at the Large Hadron Collider”, *Phys. Lett. B* **792** (2019) 132–137, arXiv:1812.05175 [nucl-th].
- [4] A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stoecker, “Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions”, *Phys. Lett. B* **697** (2011) 203–207, arXiv:1010.2995 [nucl-th].
- [5] V. Vovchenko, B. Dönigus, and H. Stoecker, “Multiplicity dependence of light nuclei production at LHC energies in the canonical statistical model”, *Phys. Lett. B* **785** (2018) 171–174, arXiv:1808.05245 [hep-ph].
- [6] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, “Decoding the phase structure of QCD via particle production at high energy”, *Nature* **561** (2018) 321–330, arXiv:1710.09425 [nucl-th].
- [7] ALICE Collaboration, S. Acharya *et al.*, “Search for a common baryon source in high-multiplicity pp collisions at the LHC”, *Phys. Lett. B* **811** (2020) 135849, arXiv:2004.08018 [nucl-ex].
- [8] K. Blum, K. C. Y. Ng, R. Sato, and M. Takimoto, “Cosmic rays, antihelium, and an old navy spotlight”, *Phys. Rev. D* **96** (2017) 103021, arXiv:1704.05431 [astro-ph.HE].
- [9] Z. Fecková, J. Steinheimer, B. Tomášik, and M. Bleicher, “Formation of deuterons by coalescence: Consequences for deuteron number fluctuations”, *Phys. Rev. C* **93** (2016) 054906, arXiv:1603.05854 [nucl-th].
- [10] P. Braun-Munzinger, B. Friman, K. Redlich, A. Rustamov, and J. Stachel, “Relativistic nuclear collisions: Establishing a non-critical baseline for fluctuation measurements”, *Nucl. Phys. A* **1008** (2021) 122141, arXiv:2007.02463 [nucl-th].
- [11] M. Barej and A. Bzdak, “Factorial cumulants from global baryon number conservation”, *Phys. Rev. C* **102** (2020) 064908, arXiv:2006.02836 [nucl-th].
- [12] ALICE Collaboration, K. Aamodt *et al.*, “The ALICE experiment at the CERN LHC”, *JINST* **3** (2008) S08002.
- [13] 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].
- [14] ALICE Collaboration, E. Abbas *et al.*, “Performance of the ALICE VZERO system”, *JINST* **8** (2013) P10016, arXiv:1306.3130 [nucl-ex].

- [15] **ALICE** Collaboration, B. Abelev *et al.*, “Centrality determination of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE”, *Phys. Rev. C* **88** (2013) 044909, arXiv:1301.4361 [nucl-ex].
- [16] J. Alme *et al.*, “The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events”, *Nucl. Instrum. Meth. A* **622** (2010) 316–367, arXiv:1001.1950 [physics.ins-det].
- [17] A. Akindinov *et al.*, “Performance of the ALICE Time-Of-Flight detector at the LHC”, *Eur. Phys. J. Plus* **128** (2013) 44.
- [18] T. Nonaka, M. Kitazawa, and S. Esumi, “More efficient formulas for efficiency correction of cumulants and effect of using averaged efficiency”, *Phys. Rev. C* **95** (2017) 064912, arXiv:1702.07106 [physics.data-an]. [Erratum: *Phys.Rev.C* 103, 029901 (2021)].
- [19] **ALICE** Collaboration, S. Acharya *et al.*, “Measurement of the low-energy antideuteron inelastic cross section”, *Phys. Rev. Lett.* **125** (2020) 162001, arXiv:2005.11122 [nucl-ex].
- [20] X. Luo, J. Xu, B. Mohanty, and N. Xu, “Volume fluctuation and auto-correlation effects in the moment analysis of net-proton multiplicity distributions in heavy-ion collisions”, *J. Phys. G* **40** (2013) 105104, arXiv:1302.2332 [nucl-ex].
- [21] **ALICE** Collaboration, S. Acharya *et al.*, “Relative particle yield fluctuations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Eur. Phys. J. C* **79** (2019) 236, arXiv:1712.07929 [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] **ALICE** Collaboration, S. Acharya *et al.*, “Production of charged pions, kaons, and (anti-)protons in Pb-Pb and inelastic *pp* collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Rev. C* **101** (2020) 044907, arXiv:1910.07678 [nucl-ex].
- [24] **STAR** Collaboration, M. Abdallah *et al.*, “Cumulants and correlation functions of net-proton, proton, and antiproton multiplicity distributions in Au+Au collisions at energies available at the BNL Relativistic Heavy Ion Collider”, *Phys. Rev. C* **104** (2021) 024902, arXiv:2101.12413 [nucl-ex].
- [25] V. Vovchenko, V. Koch, and C. Shen, “Proton number cumulants and correlation functions in Au-Au collisions at $s_{NN}=7.7$ –200 GeV from hydrodynamics”, *Phys. Rev. C* **105** (2022) 014904, arXiv:2107.00163 [hep-ph].
- [26] **ALICE** Collaboration, S. Acharya *et al.*, “Global baryon number conservation encoded in net-proton fluctuations measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Lett. B* **807** (2020) 135564, arXiv:1910.14396 [nucl-ex].
- [27] K.-J. Sun and C. M. Ko, “Event-by-event anti-deuteron multiplicity fluctuation in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Lett. B* **840** (2023) 137864, arXiv:2204.10879 [nucl-th].
- [28] V. Vovchenko and V. Koch, “Particlization of an interacting hadron resonance gas with global conservation laws for event-by-event fluctuations in heavy-ion collisions”, *Phys. Rev. C* **103** (2021) 044903, arXiv:2012.09954 [hep-ph].
- [29] V. Vovchenko, B. Dönigus, and H. Stoecker, “Canonical statistical model analysis of p-p, p-Pb, and Pb-Pb collisions at energies available at the CERN Large Hadron Collider”, *Phys. Rev. C* **100** (2019) 054906, arXiv:1906.03145 [hep-ph].

- [30] T. Neidig, K. Gallmeister, C. Greiner, M. Bleicher, and V. Vovchenko, “Towards solving the puzzle of high temperature light (anti)-nuclei production in ultra-relativistic heavy ion collisions”, *Phys. Lett. B* **827** (2022) 136891, arXiv:2108.13151 [hep-ph].
- [31] 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].
- [32] J. Cleymans, P. M. Lo, K. Redlich, and N. Sharma, “Multiplicity dependence of (multi)strange baryons in the canonical ensemble with phase shift corrections”, *Phys. Rev. C* **103** (2021) 014904, arXiv:2009.04844 [hep-ph].

A The ALICE Collaboration

S. Acharya ^{123,130}, D. Adamová ⁸⁵, A. Adler⁶⁸, G. Aglieri Rinella ³², M. Agnello ²⁹, N. Agrawal ⁴⁹, Z. Ahammed ¹³⁰, S. Ahmad ¹⁵, S.U. Ahn ⁶⁹, I. Ahuja ³⁶, A. Akindinov ¹³⁸, M. Al-Turany ⁹⁷, D. Aleksandrov ¹³⁸, B. Alessandro ⁵⁴, H.M. Alfanda ⁶, R. Alfaro Molina ⁶⁵, B. Ali ¹⁵, Y. Ali¹³, A. Alici ²⁵, N. Alizadehvandchali ¹¹², A. Alkin ³², J. Alme ²⁰, G. Alocco ⁵⁰, T. Alt ⁶², I. Altsybeev ¹³⁸, M.N. Anaam ⁶, C. Andrei ⁴⁴, A. Andronic ¹³³, V. Angelov ⁹⁴, F. Antinori ⁵², P. Antonioli ⁴⁹, C. Anuj ¹⁵, N. Apadula ⁷³, L. Aphecetche ¹⁰², H. Appelshäuser ⁶², S. Arcelli ²⁵, R. Arnaldi ⁵⁴, I.C. Arsene ¹⁹, M. Arslanok ¹³⁵, A. Augustinus ³², R. Averbeck ⁹⁷, S. Aziz ⁷¹, M.D. Azmi ¹⁵, A. Badalà ⁵¹, Y.W. Baek ³⁹, X. Bai ⁹⁷, R. Bailhache ⁶², Y. Bailung ⁴⁶, R. Bala ⁹⁰, A. Balbino ²⁹, A. Baldisseri ¹²⁶, B. Balis ², D. Banerjee ⁴, Z. Banoo ⁹⁰, R. Barbera ²⁶, L. Barioglio ⁹⁵, M. Barlou⁷⁷, G.G. Barnaföldi ¹³⁴, L.S. Barnby ⁸⁴, V. Barret ¹²³, L. Barreto ¹⁰⁸, C. Bartels ¹¹⁵, K. Barth ³², E. Bartsch ⁶², F. Baruffaldi ²⁷, N. Bastid ¹²³, S. Basu ⁷⁴, G. Batigne ¹⁰², D. Battistini ⁹⁵, B. Batyunya ¹³⁹, D. Bauri⁴⁵, J.L. Bazo Alba ¹⁰⁰, I.G. Bearden ⁸², C. Beattie ¹³⁵, P. Becht ⁹⁷, D. Behera ⁴⁶, I. Belikov ¹²⁵, A.D.C. Bell Hechavarria ¹³³, R. Bellwied ¹¹², S. Belokurova ¹³⁸, V. Belyaev ¹³⁸, G. Bencedi ^{134,63}, S. Beole ²⁴, A. Bercuci ⁴⁴, Y. Berdnikov ¹³⁸, A. Berdnikova ⁹⁴, L. Bergmann ⁹⁴, M.G. Besoiu ⁶¹, L. Betev ³², P.P. Bhaduri ¹³⁰, A. Bhasin ⁹⁰, I.R. Bhat⁹⁰, M.A. Bhat ⁴, B. Bhattacharjee ⁴⁰, L. Bianchi ²⁴, N. Bianchi ⁴⁷, J. Bielčik ³⁵, J. Bielčíková ⁸⁵, J. Biernat ¹⁰⁵, A. Bilandzic ⁹⁵, G. Biro ¹³⁴, S. Biswas ⁴, J.T. Blair ¹⁰⁶, D. Blau ¹³⁸, M.B. Blidaru ⁹⁷, N. Bluhme³⁷, C. Blume ⁶², G. Boca ^{21,53}, F. Bock ⁸⁶, T. Bodova ²⁰, A. Bogdanov¹³⁸, S. Boi ²², J. Bok ⁵⁶, L. Boldizsár ¹³⁴, A. Bolozdynya ¹³⁸, M. Bombara ³⁶, P.M. Bond ³², G. Bonomi ^{129,53}, H. Borel ¹²⁶, A. Borissov ¹³⁸, H. Bossi ¹³⁵, E. Botta ²⁴, L. Bratrud ⁶², P. Braun-Munzinger ⁹⁷, M. Bregant ¹⁰⁸, M. Broz ³⁵, G.E. Bruno ^{96,31}, M.D. Buckland ¹¹⁵, D. Budnikov ¹³⁸, H. Buesching ⁶², S. Bufalino ²⁹, O. Bugnon¹⁰², P. Buhler ¹⁰¹, Z. Buthelezi ^{66,119}, J.B. Butt¹³, A. Bylinkin ¹¹⁴, S.A. Bysiak¹⁰⁵, M. Cai ^{27,6}, H. Caines ¹³⁵, A. Caliva ⁹⁷, E. Calvo Villar ¹⁰⁰, J.M.M. Camacho ¹⁰⁷, R.S. Camacho⁴³, P. Camerini ²³, F.D.M. Canedo ¹⁰⁸, M. Carabas ¹²², F. Carnesecchi ²⁵, R. Caron ^{124,126}, J. Castillo Castellanos ¹²⁶, F. Catalano ²⁹, C. Ceballos Sanchez ¹³⁹, I. Chakaberia ⁷³, P. Chakraborty ⁴⁵, S. Chandra ¹³⁰, S. Chapeland ³², M. Chartier ¹¹⁵, S. Chattopadhyay ¹³⁰, S. Chattopadhyay ⁹⁸, T.G. Chavez ⁴³, T. Cheng ⁶, C. Cheshkov ¹²⁴, B. Cheynis ¹²⁴, V. Chibante Barroso ³², D.D. Chinellato ¹⁰⁹, E.S. Chizzali ^{11,95}, S. Cho ⁵⁶, P. Chochula ³², P. Christakoglou ⁸³, C.H. Christensen ⁸², P. Christiansen ⁷⁴, T. Chujo ¹²¹, M. Ciacco ²⁹, C. Cicalo ⁵⁰, L. Cifarelli ²⁵, F. Cindolo ⁴⁹, M.R. Ciupek⁹⁷, G. Clai^{III,49}, F. Colamaria ⁴⁸, J.S. Colburn⁹⁹, D. Colella ^{96,31}, A. Collu⁷³, M. Colocci ³², M. Concas ^{IV,54}, G. Conesa Balbastre ⁷², Z. Conesa del Valle ⁷¹, G. Contin ²³, J.G. Contreras ³⁵, M.L. Coquet ¹²⁶, T.M. Cormier^{I,86}, P. Cortese ^{128,54}, M.R. Cosentino ¹¹⁰, F. Costa ³², S. Costanza ^{21,53}, P. Crochet ¹²³, R. Cruz-Torres ⁷³, E. Cuautle⁶³, P. Cui ⁶, L. Cunqueiro⁸⁶, A. Dainese ⁵², M.C. Danisch ⁹⁴, A. Danu ⁶¹, P. Das ⁷⁹, P. Das ⁴, S. Das ⁴, S. Dash ⁴⁵, A. De Caro ²⁸, G. de Cataldo ⁴⁸, L. De Cilladi ²⁴, J. de Cuveland³⁷, A. De Falco ²², D. De Gruttola ²⁸, N. De Marco ⁵⁴, C. De Martin ²³, S. De Pasquale ²⁸, S. Deb ⁴⁶, H.F. Degenhardt¹⁰⁸, K.R. Deja ¹³¹, R. Del Grande ⁹⁵, L. Dello Stritto ²⁸, W. Deng ⁶, P. Dhankher ¹⁸, D. Di Bari ³¹, A. Di Mauro ³², R.A. Diaz ^{139,7}, T. Dietel ¹¹¹, Y. Ding ^{124,6}, R. Divià ³², D.U. Dixit ¹⁸, Ø. Djuvsland²⁰, U. Dmitrieva ¹³⁸, A. Dobrin ⁶¹, B. Dönigus ⁶², A.K. Dubey ¹³⁰, J.M. Dubinski¹³¹, A. Dubla ⁹⁷, S. Dudi ⁸⁹, P. Dupieux ¹²³, M. Durkac¹⁰⁴, N. Dzalaiova¹², T.M. Eder ¹³³, R.J. Ehlers ⁸⁶, V.N. Eikeland²⁰, F. Eisenhut ⁶², D. Elia ⁴⁸, B. Erasmus ¹⁰², F. Ercolessi ²⁵, F. Erhardt ⁸⁸, A. Erokhin¹³⁸, M.R. Ersdal²⁰, B. Espagnon ⁷¹, G. Eulisse ³², D. Evans ⁹⁹, S. Evdokimov ¹³⁸, L. Fabbietti ⁹⁵, M. Faggin ²⁷, J. Faivre ⁷², F. Fan ⁶, W. Fan ⁷³, A. Fantoni ⁴⁷, M. Fasel ⁸⁶, P. Fedchio²⁹, A. Feliciello ⁵⁴, G. Feofilov ¹³⁸, A. Fernández Téllez ⁴³, M.B. Ferrer ³², A. Ferrero ¹²⁶, A. Ferretti ²⁴, V.J.G. Feuillard ⁹⁴, J. Figiel ¹⁰⁵, V. Filova³⁵, D. Finogeev ¹³⁸, G. Fiorenza ⁹⁶, F. Flor ¹¹², A.N. Flores ¹⁰⁶, S. Foertsch ⁶⁶, I. Fokin ⁹⁴, S. Fokin ¹³⁸, E. Fragiaco ⁵⁵, E. Frajna ¹³⁴, U. Fuchs ³², N. Funicello ²⁸, C. Furget ⁷², A. Furs ¹³⁸, J.J. Gaardhøje ⁸², M. Gagliardi ²⁴, A.M. Gago ¹⁰⁰, A. Gal¹²⁵, C.D. Galvan ¹⁰⁷, P. Ganoti ⁷⁷, C. Garabatos ⁹⁷, J.R.A. Garcia ⁴³, E. Garcia-Solis ⁹, K. Garg ¹⁰², C. Gargiulo ³², A. Garibli⁸⁰, K. Garner¹³³, E.F. Gauger ¹⁰⁶, A. Gautam ¹¹⁴, M.B. Gay Ducati ⁶⁴, M. Germain ¹⁰², S.K. Ghosh⁴, M. Giacalone ²⁵, P. Gianotti ⁴⁷, P. Giubellino ^{97,54}, P. Giubilato ²⁷, A.M.C. Glaenger ¹²⁶, P. Glässel ⁹⁴, E. Glimos¹¹⁸, D.J.Q. Goh⁷⁵, V. Gonzalez ¹³², L.H. González-Trueba ⁶⁵, S. Gorbunov³⁷, M. Gorgon ², L. Görlich ¹⁰⁵, S. Gotovac³³, V. Grabski ⁶⁵, L.K. Graczykowski ¹³¹, E. Grecka ⁸⁵, L. Greiner ⁷³, A. Grelli ⁵⁷, C. Grigoras ³², V. Grigoriev ¹³⁸, S. Grigoryan ^{139,1}, F. Grosa ⁵⁴, J.F. Grosse-Oetringhaus ³², R. Grosso ⁹⁷, D. Grund ³⁵, G.G. Guardiano ¹⁰⁹, R. Guernane ⁷², M. Guilbaud ¹⁰², K. Gulbrandsen ⁸², T. Gunji ¹²⁰, W. Guo ⁶,

A. Gupta ⁹⁰, R. Gupta ⁹⁰, S.P. Guzman ⁴³, L. Gyulai ¹³⁴, M.K. Habib⁹⁷, C. Hadjidakis ⁷¹,
 H. Hamagaki ⁷⁵, M. Hamid⁶, Y. Han ¹³⁶, R. Hannigan ¹⁰⁶, M.R. Haque ¹³¹, A. Harlanderova⁹⁷,
 J.W. Harris ¹³⁵, A. Harton ⁹, J.A. Hasenbichler³², H. Hassan ⁸⁶, D. Hatzifotiadou ⁴⁹, P. Hauer ⁴¹,
 L.B. Havener ¹³⁵, S.T. Heckel ⁹⁵, E. Hellbär ⁹⁷, H. Helstrup ³⁴, T. Herman ³⁵, G. Herrera Corral ⁸,
 F. Herrmann¹³³, K.F. Hetland ³⁴, B. Heybeck ⁶², H. Hillemanns ³², C. Hills ¹¹⁵, B. Hippolyte ¹²⁵,
 B. Hofman ⁵⁷, B. Hohlweger ⁸³, J. Honermann ¹³³, G.H. Hong ¹³⁶, D. Horak ³⁵, A. Horzyk ²,
 R. Hosokawa¹⁴, Y. Hou ⁶, P. Hristov ³², C. Hughes ¹¹⁸, P. Huhn⁶², L.M. Huhta ¹¹³, C.V. Hulse ⁷¹,
 T.J. Humanic ⁸⁷, H. Hushnud⁹⁸, A. Hutson ¹¹², D. Hutter ³⁷, J.P. Iddon ¹¹⁵, R. Ilkaev¹³⁸, H. Ilyas ¹³,
 M. Inaba ¹²¹, G.M. Innocenti ³², M. Ippolitov ¹³⁸, A. Isakov ⁸⁵, T. Isidori ¹¹⁴, M.S. Islam ⁹⁸,
 M. Ivanov ⁹⁷, V. Ivanov ¹³⁸, V. Izucheev¹³⁸, M. Jablonski ², B. Jacak ⁷³, N. Jacazio ³², P.M. Jacobs ⁷³,
 S. Jadlovská¹⁰⁴, J. Jadlovsky¹⁰⁴, L. Jaffe³⁷, C. Jahnke¹⁰⁹, M.A. Janik ¹³¹, T. Janson⁶⁸, M. Jercic⁸⁸, O. Jevons⁹⁹,
 A.A.P. Jimenez ⁶³, F. Jonas ^{86,133}, P.G. Jones⁹⁹, J.M. Jowett ^{32,97}, J. Jung ⁶², M. Jung ⁶²,
 A. Junique ³², A. Jusko ⁹⁹, M.J. Kabus ¹³¹, J. Kaewjai¹⁰³, P. Kalinak ⁵⁸, A.S. Kalteyer ⁹⁷,
 A. Kalweit ³², V. Kaplin ¹³⁸, A. Karasu Uysal ⁷⁰, D. Karatovic ⁸⁸, O. Karavichev ¹³⁸,
 T. Karavicheva ¹³⁸, P. Karczmarczyk ¹³¹, E. Karpechev ¹³⁸, V. Kashyap⁷⁹, A. Kazantsev¹³⁸,
 U. Keschull ⁶⁸, R. Keidel ¹³⁷, D.L.D. Keijdener⁵⁷, M. Keil ³², B. Ketzer ⁴¹, A.M. Khan ⁶, S. Khan ¹⁵,
 A. Khanzadeev ¹³⁸, Y. Kharlov ¹³⁸, A. Khatun ¹⁵, A. Khuntia ¹⁰⁵, B. Kileng ³⁴, B. Kim ¹⁶,
 C. Kim ¹⁶, D.J. Kim ¹¹³, E.J. Kim ⁶⁷, J. Kim ¹³⁶, J.S. Kim ³⁹, J. Kim ⁹⁴, J. Kim ⁶⁷, M. Kim ⁹⁴,
 S. Kim ¹⁷, T. Kim ¹³⁶, S. Kirsch ⁶², I. Kisel ³⁷, S. Kiselev ¹³⁸, A. Kisiel ¹³¹, J.P. Kitowski ²,
 J.L. Klay ⁵, J. Klein ³², S. Klein ⁷³, C. Klein-Bösing ¹³³, M. Kleiner ⁶², T. Klemenz ⁹⁵, A. Kluge ³²,
 A.G. Knospe ¹¹², C. Kobdaj ¹⁰³, T. Kollegger⁹⁷, A. Kondratyev ¹³⁹, N. Kondratyeva ¹³⁸,
 E. Kondratyuk ¹³⁸, J. Konig ⁶², S.A. Konigstorfer ⁹⁵, P.J. Konopka ³², G. Kornakov ¹³¹,
 S.D. Koryciak ², A. Kotliarov ⁸⁵, O. Kovalenko ⁷⁸, V. Kovalenko ¹³⁸, M. Kowalski ¹⁰⁵, I. Králík ⁵⁸,
 A. Kravčáková ³⁶, L. Kreis⁹⁷, M. Krivda ^{99,58}, F. Krizek ⁸⁵, K. Krizkova Gajdosova ³⁵, M. Kroesen ⁹⁴,
 M. Krüger ⁶², D.M. Krupova ³⁵, E. Kryshen ¹³⁸, M. Krzewicki³⁷, V. Kučera ³², C. Kuhn ¹²⁵,
 P.G. Kuijjer ⁸³, T. Kumaoka¹²¹, D. Kumar¹³⁰, L. Kumar ⁸⁹, N. Kumar⁸⁹, S. Kundu ³², P. Kurashvili ⁷⁸,
 A. Kurepin ¹³⁸, A.B. Kurepin ¹³⁸, A. Kuryakin ¹³⁸, S. Kushpil ⁸⁵, J. Kvapil ⁹⁹, M.J. Kweon ⁵⁶,
 J.Y. Kwon ⁵⁶, Y. Kwon ¹³⁶, S.L. La Pointe ³⁷, P. La Rocca ²⁶, Y.S. Lai⁷³, A. Lakrathok¹⁰³,
 M. Lamanna ³², R. Langoy ¹¹⁷, P. Larionov ⁴⁷, E. Laudi ³², L. Lautner ^{32,95}, R. Lavicka ¹⁰¹,
 T. Lazareva ¹³⁸, R. Lea ^{129,53}, J. Lehrbach ³⁷, R.C. Lemmon ⁸⁴, I. León Monzón ¹⁰⁷, M.M. Lesch ⁹⁵,
 E.D. Lesser ¹⁸, M. Lettrich⁹⁵, P. Lévai ¹³⁴, X. Li¹⁰, X.L. Li⁶, J. Lien ¹¹⁷, R. Lietava ⁹⁹, B. Lim ¹⁶,
 S.H. Lim ¹⁶, V. Lindenstruth ³⁷, A. Lindner⁴⁴, C. Lippmann ⁹⁷, A. Liu ¹⁸, D.H. Liu ⁶, J. Liu ¹¹⁵,
 I.M. Lofnes ²⁰, V. Loginov¹³⁸, C. Loizides ⁸⁶, P. Loncar ³³, J.A. Lopez ⁹⁴, X. Lopez ¹²³, E. López
 Torres ⁷, P. Lu ^{97,116}, J.R. Luhder ¹³³, M. Lunardon ²⁷, G. Luparello ⁵⁵, Y.G. Ma ³⁸, A. Maevskaya¹³⁸,
 M. Mager ³², T. Mahmoud⁴¹, A. Maire ¹²⁵, M. Malaev ¹³⁸, N.M. Malik ⁹⁰, Q.W. Malik¹⁹, S.K. Malik ⁹⁰,
 L. Malinina ^{VII,139}, D. Mal'Kevich ¹³⁸, D. Mallick ⁷⁹, N. Mallick ⁴⁶, G. Mandaglio ^{30,51}, V. Manko ¹³⁸,
 F. Manso ¹²³, V. Manzari ⁴⁸, Y. Mao ⁶, G.V. Margagliotti ²³, A. Margotti ⁴⁹, A. Marín ⁹⁷,
 C. Markert ¹⁰⁶, M. Marquard⁶², N.A. Martin⁹⁴, P. Martinengo ³², J.L. Martinez¹¹², M.I. Martínez ⁴³,
 G. Martínez García ¹⁰², S. Masciocchi ⁹⁷, M. Masera ²⁴, A. Masoni ⁵⁰, L. Massacrier ⁷¹,
 A. Mastroserio ^{127,48}, A.M. Mathis ⁹⁵, O. Matonoha ⁷⁴, P.F.T. Matuoka¹⁰⁸, A. Matyja ¹⁰⁵, C. Mayer ¹⁰⁵,
 A.L. Mazuecos ³², F. Mazzaschi ²⁴, M. Mazzilli ³², J.E. Mdhuli ¹¹⁹, A.F. Mechler⁶², Y. Melikyan ¹³⁸,
 A. Menchaca-Rocha ⁶⁵, E. Meninno ^{101,28}, A.S. Menon ¹¹², M. Meres ¹², S. Mhlanga^{111,66}, Y. Miake¹²¹,
 L. Micheletti ⁵⁴, L.C. Migliorin¹²⁴, D.L. Mihaylov ⁹⁵, K. Mikhaylov ^{139,138}, A.N. Mishra ¹³⁴,
 D. Miśkowiec ⁹⁷, A. Modak ⁴, A.P. Mohanty ⁵⁷, B. Mohanty ⁷⁹, M. Mohisin Khan ^{V,15},
 M.A. Molander ⁴², Z. Moravcova ⁸², C. Mordasini ⁹⁵, D.A. Moreira De Godoy ¹³³, I. Morozov ¹³⁸,
 A. Morsch ³², T. Mrnjavac ³², V. Muccifora ⁴⁷, E. Mudnic³³, S. Muhuri ¹³⁰, J.D. Mulligan ⁷³,
 A. Mulliri²², M.G. Munhoz ¹⁰⁸, R.H. Munzer ⁶², H. Murakami ¹²⁰, S. Murray ¹¹¹, L. Musa ³²,
 J. Musinsky ⁵⁸, J.W. Myrcha ¹³¹, B. Naik ¹¹⁹, R. Nair ⁷⁸, B.K. Nandi ⁴⁵, R. Nania ⁴⁹, E. Nappi ⁴⁸,
 A.F. Nassirpour ⁷⁴, A. Nath ⁹⁴, C. Nattrass ¹¹⁸, T.K. Nayak ⁷⁹, A. Neagu¹⁹, A. Negru¹²², L. Nellen ⁶³,
 S.V. Nesbo³⁴, G. Neskovic ³⁷, D. Nesterov ¹³⁸, B.S. Nielsen ⁸², E.G. Nielsen ⁸², S. Nikolaev ¹³⁸,
 S. Nikulin ¹³⁸, V. Nikulin ¹³⁸, F. Noferini ⁴⁹, S. Noh ¹¹, P. Nomokonov ¹³⁹, J. Norman ¹¹⁵,
 N. Novitzky ¹²¹, P. Nowakowski ¹³¹, A. Nyanin ¹³⁸, J. Nystrand ²⁰, M. Ogino ⁷⁵, A. Ohlson ⁷⁴,
 V.A. Okorokov ¹³⁸, J. Oleniacz ¹³¹, A.C. Oliveira Da Silva ¹¹⁸, M.H. Oliver ¹³⁵, A. Onnerstad ¹¹³,
 C. Oppedisano ⁵⁴, A. Ortiz Velasquez ⁶³, A. Oskarsson⁷⁴, J. Otwinowski ¹⁰⁵, M. Oya⁹², K. Oyama ⁷⁵,
 Y. Pachmayer ⁹⁴, S. Padhan ⁴⁵, D. Pagano

X. Peng⁶, L.G. Pereira⁶⁴, H. Pereira Da Costa¹²⁶, D. Peresunko¹³⁸, G.M. Perez⁷, S. Perrin¹²⁶, Y. Pestov¹³⁸, V. Petráček³⁵, V. Petrov¹³⁸, M. Petrovici⁴⁴, R.P. Pezzi⁶⁴, S. Piano⁵⁵, M. Pikna¹², P. Pillot¹⁰², O. Pinazza^{49,32}, L. Pinsky¹¹², C. Pinto^{95,26}, S. Pisano⁴⁷, M. Płoskoń⁷³, M. Planinic⁸⁸, F. Pliquett⁶², M.G. Poghosyan⁸⁶, B. Polichtchouk¹³⁸, S. Politano²⁹, N. Poljak⁸⁸, A. Pop⁴⁴, S. Porteboeuf-Houssais¹²³, J. Porter⁷³, V. Pozdniakov¹³⁹, S.K. Prasad⁴, S. Prasad⁴⁶, R. Preghenella⁴⁹, F. Prino⁵⁴, C.A. Pruneau¹³², I. Pshenichnov¹³⁸, M. Puccio³², S. Qiu⁸³, L. Quaglia²⁴, R.E. Quishpe¹¹², S. Ragoni⁹⁹, A. Rakotozafindrabe¹²⁶, L. Ramello^{128,54}, F. Rami¹²⁵, S.A.R. Ramirez⁴³, T.A. Rancien⁷², R. Raniwala⁹¹, S. Raniwala⁹¹, S.S. Räsänen⁴², R. Rath⁴⁶, I. Ravasenga⁸³, K.F. Read^{86,118}, A.R. Redelbach³⁷, K. Redlich^{VI,78}, A. Rehman²⁰, P. Reichelt⁶², F. Reidt³², H.A. Reme-Ness³⁴, Z. Rescakova³⁶, K. Reygers⁹⁴, A. Riabov¹³⁸, V. Riabov¹³⁸, R. Ricci²⁸, T. Richert⁷⁴, M. Richter¹⁹, W. Riegler³², F. Riggi²⁶, C. Ristea⁶¹, M. Rodríguez Cahuantzi⁴³, K. Røed¹⁹, R. Rogalev¹³⁸, E. Rogochaya¹³⁹, T.S. Rogoschinski⁶², D. Rohr³², D. Röhrich²⁰, P.F. Rojas⁴³, S. Rojas Torres³⁵, P.S. Rokita¹³¹, F. Ronchetti⁴⁷, A. Rosano^{30,51}, E.D. Rosas⁶³, A. Rossi⁵², A. Roy⁴⁶, P. Roy⁹⁸, S. Roy⁴⁵, N. Rubini²⁵, O.V. Rueda⁷⁴, D. Ruggiano¹³¹, R. Rui²³, B. Rumyantsev¹³⁹, P.G. Russek², R. Russo⁸³, A. Rustamov⁸⁰, E. Ryabinkin¹³⁸, Y. Ryabov¹³⁸, A. Rybicki¹⁰⁵, H. Rytönen¹¹³, W. Rzesza¹³¹, O.A.M. Saari⁴², R. Sadek¹⁰², S. Sadovsky¹³⁸, J. Saetre²⁰, K. Šafařík³⁵, S.K. Saha¹³⁰, S. Saha⁷⁹, B. Sahoo⁴⁵, P. Sahoo⁴⁵, R. Sahoo⁴⁶, S. Sahoo⁵⁹, D. Sahu⁴⁶, P.K. Sahu⁵⁹, J. Saini¹³⁰, S. Sakai¹²¹, M.P. Salvan⁹⁷, S. Sambyal⁹⁰, T.B. Saramela¹⁰⁸, D. Sarkar¹³², N. Sarkar¹³⁰, P. Sarma⁴⁰, V.M. Sarti⁹⁵, M.H.P. Sas¹³⁵, J. Schambach⁸⁶, H.S. Scheid⁶², C. Schiaua⁴⁴, R. Schicker⁹⁴, A. Schmah⁹⁴, C. Schmidt⁹⁷, H.R. Schmidt⁹³, M.O. Schmidt³², M. Schmidt⁹³, N.V. Schmidt^{86,62}, A.R. Schmier¹¹⁸, R. Schotter¹²⁵, J. Schukraft³², K. Schwarz⁹⁷, K. Schweda⁹⁷, G. Scioli²⁵, E. Scapparini⁵⁴, J.E. Seger¹⁴, Y. Sekiguchi¹²⁰, D. Sekihata¹²⁰, I. Selyuzhenkov^{97,138}, S. Senyukov¹²⁵, J.J. Seo⁵⁶, D. Serebryakov¹³⁸, L. Šerkšnytė⁹⁵, A. Sevcenco⁶¹, T.J. Shaba⁶⁶, A. Shabanov¹³⁸, A. Shabetai¹⁰², R. Shahoyan³², W. Shaikh⁹⁸, A. Shangaraev¹³⁸, A. Sharma⁸⁹, D. Sharma⁴⁵, H. Sharma¹⁰⁵, M. Sharma⁹⁰, N. Sharma⁸⁹, S. Sharma⁹⁰, U. Sharma⁹⁰, A. Shatat⁷¹, O. Sheibani¹¹², K. Shigaki⁹², M. Shimomura⁷⁶, S. Shirinkin¹³⁸, Q. Shou³⁸, Y. Sibiriak¹³⁸, S. Siddhanta⁵⁰, T. Siemiarzuk⁷⁸, T.F. Silva¹⁰⁸, D. Silvermyr⁷⁴, T. Simantathammakul¹⁰³, G. Simonetti³², B. Singh⁹⁰, B. Singh⁹⁵, R. Singh⁷⁹, R. Singh⁹⁰, R. Singh⁴⁶, V.K. Singh¹³⁰, V. Singhal¹³⁰, T. Sinha⁹⁸, B. Sitar¹², M. Sitta^{128,54}, T.B. Skaali¹⁹, G. Skorodumovs⁹⁴, M. Slupecki⁴², N. Smirnov¹³⁵, R.J.M. Snellings⁵⁷, E.H. Solheim¹⁹, C. Soncco¹⁰⁰, J. Song¹¹², A. Songmoolnak¹⁰³, F. Soramel²⁷, S. Sorensen¹¹⁸, R. Spijkers⁸³, I. Sputowska¹⁰⁵, J. Staa⁷⁴, J. Stachel⁹⁴, I. Stan⁶¹, P.J. Steffanic¹¹⁸, S.F. Stiefelmaier⁹⁴, D. Stocco¹⁰², I. Storehaug¹⁹, M.M. Storetvedt³⁴, P. Stratmann¹³³, S. Strazzi²⁵, C.P. Stylianidis⁸³, A.A.P. Suaide¹⁰⁸, C. Suire⁷¹, M. Sukhanov¹³⁸, M. Suljic³², V. Sumberia⁹⁰, S. Sumowidagdo⁸¹, S. Swain⁵⁹, A. Szabo¹², I. Szarka¹², U. Tabassam¹³, S.F. Taghavi⁹⁵, G. Taillepie^{97,123}, J. Takahashi¹⁰⁹, G.J. Tambave²⁰, S. Tang^{123,6}, Z. Tang¹¹⁶, J.D. Tapia Takaki¹¹⁴, N. Tapus¹²², L.A. Tarasovicova¹³³, M.G. Tartzila⁴⁴, A. Tauro³², G. Tejeda Muñoz⁴³, A. Telesca³², L. Terlizzi²⁴, C. Terrevoli¹¹², G. Tersimonov³, S. Thakur¹³⁰, D. Thomas¹⁰⁶, R. Tieulent¹²⁴, A. Tikhonov¹³⁸, A.R. Timmins¹¹², M. Tkacik¹⁰⁴, T. Tkacik¹⁰⁴, A. Toia⁶², N. Topilskaya¹³⁸, M. Toppi⁴⁷, F. Torres-Acosta¹⁸, T. Tork⁷¹, A.G. Torres Ramos³¹, A. Trifiró^{30,51}, A.S. Triolo^{30,51}, S. Tripathy⁴⁹, T. Tripathy⁴⁵, S. Trogolo³², V. Trubnikov³, W.H. Trzaska¹¹³, T.P. Trzcinski¹³¹, A. Tumkin¹³⁸, R. Turrisi⁵², T.S. Tveter¹⁹, K. Ullaland²⁰, B. Ulukutlu⁹⁵, A. Uras¹²⁴, M. Urioni^{53,129}, G.L. Usai²², M. Vala³⁶, N. Valle²¹, S. Vallero⁵⁴, L.V.R. van Doremalen⁵⁷, M. van Leeuwen⁸³, C.A. van Veen⁹⁴, R.J.G. van Weelden⁸³, P. Vande Vyvre³², D. Varga¹³⁴, Z. Varga¹³⁴, M. Varga-Kofarago¹³⁴, M. Vasileiou⁷⁷, A. Vasiliev¹³⁸, O. Vázquez Doce⁹⁵, V. Veckernin¹³⁸, E. Vercellin²⁴, S. Vergara Limón⁴³, L. Vermunt⁵⁷, R. Vértesi¹³⁴, M. Verweij⁵⁷, L. Vickovic³³, Z. Vilakazi¹¹⁹, O. Villalobos Baillie⁹⁹, G. Vino⁴⁸, A. Vinogradov¹³⁸, T. Virgili²⁸, V. Vislavicius⁸², A. Vodopyanov¹³⁹, B. Volkel³², M.A. Völkl⁹⁴, K. Voloshin¹³⁸, S.A. Voloshin¹³², G. Volpe³¹, B. von Haller³², I. Vorobyev⁹⁵, N. Vozniuk¹³⁸, J. Vrláková³⁶, B. Wagner²⁰, C. Wang³⁸, D. Wang³⁸, M. Weber¹⁰¹, A. Wegrzynek³², F.T. Weiglhofer³⁷, S.C. Wenzel³², J.P. Wessels¹³³, S.L. Weyhmler¹³⁵, J. Wiechula⁶², J. Wikne¹⁹, G. Wilk⁷⁸, J. Wilkinson⁹⁷, G.A. Willems¹³³, B. Windelband⁹⁴, M. Winn¹²⁶, J.R. Wright¹⁰⁶, W. Wu³⁸, Y. Wu¹¹⁶, R. Xu⁶, A.K. Yadav¹³⁰, S. Yalcin⁷⁰, Y. Yamaguchi⁹², K. Yamakawa⁹², S. Yang²⁰, S. Yano⁹², Z. Yin⁶, I.-K. Yoo¹⁶, J.H. Yoon⁵⁶, S. Yuan²⁰, A. Yuncu⁹⁴, V. Zaccolo²³, C. Zampolli³², H.J.C. Zanoli⁵⁷, F. Zanone⁹⁴, N. Zardoshti^{32,99}, A. Zarochentsev¹³⁸, P. Závada⁶⁰, N. Zaviyalov¹³⁸, M. Zhalov¹³⁸, B. Zhang⁶, S. Zhang³⁸, X. Zhang⁶, Y. Zhang¹¹⁶, M. Zhao¹⁰, V. Zhrebchevskii¹³⁸, Y. Zhi¹⁰, N. Zhigareva¹³⁸, D. Zhou⁶, Y. Zhou⁸², J. Zhu^{97,6}, Y. Zhu⁶, G. Zinovjev^{1,3}, N. Zurlo^{129,53}

Affiliation Notes

- ^I Deceased
^{II} Also at: Max-Planck-Institut für 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: Department of Applied Physics, Aligarh Muslim University, Aligarh, India
^{VI} Also at: Institute of Theoretical Physics, University of Wrocław, Poland
^{VII} 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 Science and Technology, 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 Chungbuk National University, Cheongju, Republic of Korea
¹² Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovak Republic
¹³ COMSATS University Islamabad, Islamabad, Pakistan
¹⁴ Creighton University, Omaha, Nebraska, United States
¹⁵ Department of Physics, Aligarh Muslim University, Aligarh, India
¹⁶ Department of Physics, Pusan National University, Pusan, Republic of Korea
¹⁷ Department of Physics, Sejong University, Seoul, Republic of Korea
¹⁸ Department of Physics, University of California, Berkeley, California, United States
¹⁹ Department of Physics, University of Oslo, Oslo, Norway
²⁰ Department of Physics and Technology, University of Bergen, Bergen, Norway
²¹ Dipartimento di Fisica, Università di Pavia, Pavia, Italy
²² Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
²³ Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
²⁴ Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
²⁵ Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
²⁶ Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
²⁷ Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
²⁸ Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
²⁹ Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
³⁰ Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
³¹ Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
³² European Organization for Nuclear Research (CERN), Geneva, Switzerland
³³ Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
³⁴ Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
³⁵ Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
³⁶ Faculty of Science, P.J. Šafárik University, Košice, Slovak Republic
³⁷ Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
³⁸ Fudan University, Shanghai, China
³⁹ Gangneung-Wonju National University, Gangneung, Republic of Korea
⁴⁰ Gauhati University, Department of Physics, Guwahati, India
⁴¹ Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn,

Germany

- 42 Helsinki Institute of Physics (HIP), Helsinki, Finland
- 43 High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
- 44 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- 45 Indian Institute of Technology Bombay (IIT), Mumbai, India
- 46 Indian Institute of Technology Indore, Indore, India
- 47 INFN, Laboratori Nazionali di Frascati, Frascati, Italy
- 48 INFN, Sezione di Bari, Bari, Italy
- 49 INFN, Sezione di Bologna, Bologna, Italy
- 50 INFN, Sezione di Cagliari, Cagliari, Italy
- 51 INFN, Sezione di Catania, Catania, Italy
- 52 INFN, Sezione di Padova, Padova, Italy
- 53 INFN, Sezione di Pavia, Pavia, Italy
- 54 INFN, Sezione di Torino, Turin, Italy
- 55 INFN, Sezione di Trieste, Trieste, Italy
- 56 Inha University, Incheon, Republic of Korea
- 57 Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
- 58 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovak Republic
- 59 Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
- 60 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
- 61 Institute of Space Science (ISS), Bucharest, Romania
- 62 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- 63 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
- 64 Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
- 65 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
- 66 iThemba LABS, National Research Foundation, Somerset West, South Africa
- 67 Jeonbuk National University, Jeonju, Republic of Korea
- 68 Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
- 69 Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
- 70 KTO Karatay University, Konya, Turkey
- 71 Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France
- 72 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
- 73 Lawrence Berkeley National Laboratory, Berkeley, California, United States
- 74 Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
- 75 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 76 Nara Women's University (NWU), Nara, Japan
- 77 National and Kapodistrian University of Athens, School of Science, Department of Physics, Athens, Greece
- 78 National Centre for Nuclear Research, Warsaw, Poland
- 79 National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
- 80 National Nuclear Research Center, Baku, Azerbaijan
- 81 National Research and Innovation Agency - BRIN, Jakarta, Indonesia
- 82 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- 83 Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
- 84 Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
- 85 Nuclear Physics Institute of the Czech Academy of Sciences, Husinec-Řež, Czech Republic
- 86 Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
- 87 Ohio State University, Columbus, Ohio, United States
- 88 Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
- 89 Physics Department, Panjab University, Chandigarh, India
- 90 Physics Department, University of Jammu, Jammu, India
- 91 Physics Department, University of Rajasthan, Jaipur, India
- 92 Physics Program and International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM2), Hiroshima University, Hiroshima, Japan
- 93 Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany

- ⁹⁴ Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁹⁵ Physik Department, Technische Universität München, Munich, Germany
- ⁹⁶ Politecnico di Bari and Sezione INFN, Bari, Italy
- ⁹⁷ Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
- ⁹⁸ Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
- ⁹⁹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ¹⁰⁰ Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
- ¹⁰¹ Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
- ¹⁰² SUBATECH, IMT Atlantique, Nantes Université, CNRS-IN2P3, Nantes, France
- ¹⁰³ Suranaree University of Technology, Nakhon Ratchasima, Thailand
- ¹⁰⁴ Technical University of Košice, Košice, Slovak Republic
- ¹⁰⁵ The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
- ¹⁰⁶ The University of Texas at Austin, Austin, Texas, United States
- ¹⁰⁷ Universidad Autónoma de Sinaloa, Culiacán, Mexico
- ¹⁰⁸ Universidade de São Paulo (USP), São Paulo, Brazil
- ¹⁰⁹ Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
- ¹¹⁰ Universidade Federal do ABC, Santo Andre, Brazil
- ¹¹¹ University of Cape Town, Cape Town, South Africa
- ¹¹² University of Houston, Houston, Texas, United States
- ¹¹³ University of Jyväskylä, Jyväskylä, Finland
- ¹¹⁴ University of Kansas, Lawrence, Kansas, United States
- ¹¹⁵ University of Liverpool, Liverpool, United Kingdom
- ¹¹⁶ University of Science and Technology of China, Hefei, China
- ¹¹⁷ University of South-Eastern Norway, Kongsberg, Norway
- ¹¹⁸ University of Tennessee, Knoxville, Tennessee, United States
- ¹¹⁹ University of the Witwatersrand, Johannesburg, South Africa
- ¹²⁰ University of Tokyo, Tokyo, Japan
- ¹²¹ University of Tsukuba, Tsukuba, Japan
- ¹²² University Politehnica of Bucharest, Bucharest, Romania
- ¹²³ Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
- ¹²⁴ Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France
- ¹²⁵ Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
- ¹²⁶ Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Département de Physique Nucléaire (DPHN), Saclay, France
- ¹²⁷ Università degli Studi di Foggia, Foggia, Italy
- ¹²⁸ Università del Piemonte Orientale, Vercelli, Italy
- ¹²⁹ Università di Brescia, Brescia, Italy
- ¹³⁰ Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
- ¹³¹ Warsaw University of Technology, Warsaw, Poland
- ¹³² Wayne State University, Detroit, Michigan, United States
- ¹³³ Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
- ¹³⁴ Wigner Research Centre for Physics, Budapest, Hungary
- ¹³⁵ Yale University, New Haven, Connecticut, United States
- ¹³⁶ Yonsei University, Seoul, Republic of Korea
- ¹³⁷ Zentrum für Technologie und Transfer (ZTT), Worms, Germany
- ¹³⁸ Affiliated with an institute covered by a cooperation agreement with CERN
- ¹³⁹ Affiliated with an international laboratory covered by a cooperation agreement with CERN.