First Measurement of Antideuteron Number Fluctuations at Energies Available at the Large Hadron Collider

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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 $\sqrt{s_{\mathrm{NN}}}$ = 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.

*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 ($\sqrt{s_{\mathrm{NN}}}$) of 2.76 TeV with $T_{\mathrm{chem}} = 156.5$ 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

$$\kappa_1 = \langle n \rangle, \tag{1}$$

$$\kappa_m = \langle (n - \langle n \rangle)^m \rangle, \tag{2}$$

$$\rho_{\mathrm{ab}} = \langle (n_{\mathrm{a}} - \langle n_{\mathrm{a}} \rangle)(n_{\mathrm{b}} - \langle n_{\mathrm{b}} \rangle) \rangle / \sqrt{\kappa_{2\mathrm{a}} \kappa_{2\mathrm{b}}}, \tag{3}$$

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 $\langle n_{\mathrm{a}} \rangle$ ($\langle n_{\mathrm{b}} \rangle$) 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 ($\rho_{\overline{\mathrm{p}}\,\overline{\mathrm{d}}}$) between measured antideuterons ($\overline{\mathrm{d}}$) and antiprotons ($\overline{\mathrm{p}}$) 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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 $0.4 < p_{\mathrm{T}} < 1.8$ GeV/c to select the $\overline{\mathrm{p}}$ and $\overline{\mathrm{d}}$ with high purity. Moreover, to guarantee a track-momentum resolution of 2% in the relevant p_{T} range and an energy loss ($\mathrm{d}E/\mathrm{d}x$) 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 $|\mathrm{DCA}_{z}|$ and $|\mathrm{DCA}_{xy}|$ less than 1.0 and 0.1 cm, respectively.

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

Measured cumulants are corrected for the $\overline{\mathrm{d}}$ and $\overline{\mathrm{p}}$ 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 $\overline{\mathrm{d}}$ and $\overline{\mathrm{p}}$ reconstruction in the ALICE detector is obtained using a simulation based on GEANT4, which correctly describes the interaction of $\overline{\mathrm{p}}$ and $\overline{\mathrm{d}}$ with the material of the detectors [19]. Then, the cumulants and correlation coefficient are corrected for the reconstruction efficiencies using

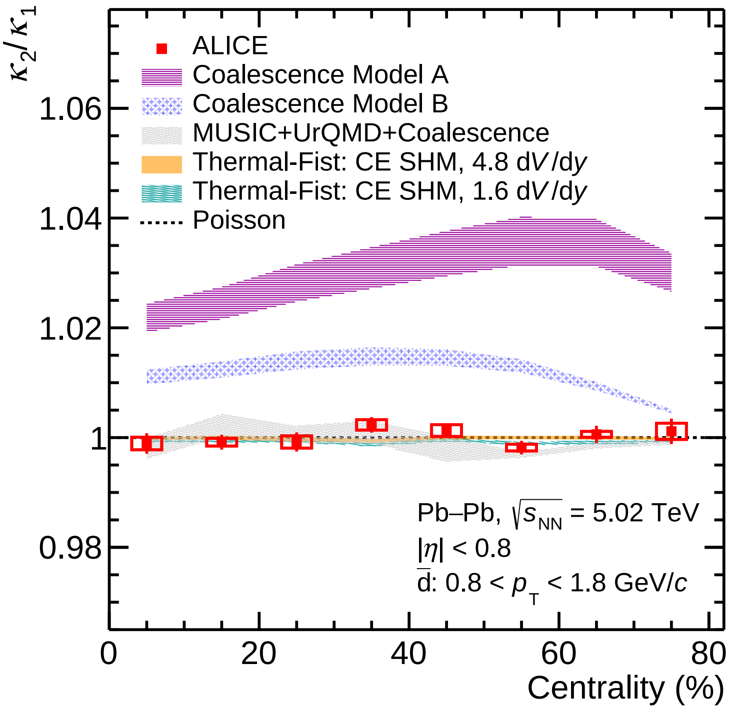

Figure 1: Second order to first order cumulant ratio of the $\bar{\mathrm{d}}$ multiplicity distribution as a function of collision centrality in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Statistical and systematic uncertainties are shown by the bars and boxes, respectively. Measured cumulant 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 $\bar{\mathrm{p}}$ and $\bar{\mathrm{d}}$ 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 $\rho_{\bar{\mathrm{p}}\,\bar{\mathrm{d}}}$ 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 $n(\sigma^{\mathrm{TPC_i}})$ 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 $\bar{\mathrm{d}}$ 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, $V_{\mathrm{c}} = 4.8\ \mathrm{d}V/\mathrm{d}y$ (orange band in figures) and $V_{\mathrm{c}} = 1.6\ \mathrm{d}V/\mathrm{d}y$ (green band in figures). The choice of two different V_{c} is discussed below. In the SHM model the temperature is fixed to $\mathrm{T} = 155$ 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 $\bar{\mathrm{p}}$ [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 $\overline{\mathrm{d}}$ [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.

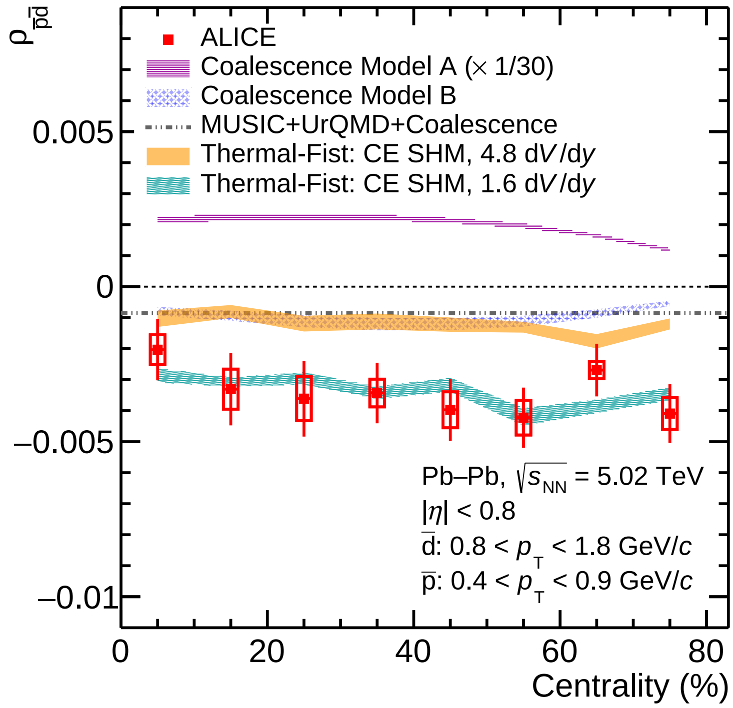

Figure 2: Pearson correlation between the measured $\overline{\mathrm{p}}$ and $\overline{\mathrm{d}}$ as a function of collision centrality in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Bars and boxes represent statistical and systematic uncertainties, respectively. Measured correlations 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 $\rho_{\overline{\mathrm{p}}\overline{\mathrm{d}}}$ 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 $\overline{\mathrm{d}}$, there are $O(0.1\%)$ less $\overline{\mathrm{p}}$ 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 $\overline{\mathrm{p}}$ and $\overline{\mathrm{n}}$ from two independent sources coalesce to produce $\overline{\mathrm{d}}$. 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 $\overline{\mathrm{p}}$ and $\overline{\mathrm{d}}$ is also expected by the CE version of the SHM which introduces a negative correlation between $\overline{\mathrm{p}}$ and $\overline{\mathrm{d}}$ 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 $V_{\mathrm{c}} = 1.6 \pm 0.3\ \mathrm{d}V/\mathrm{d}y$

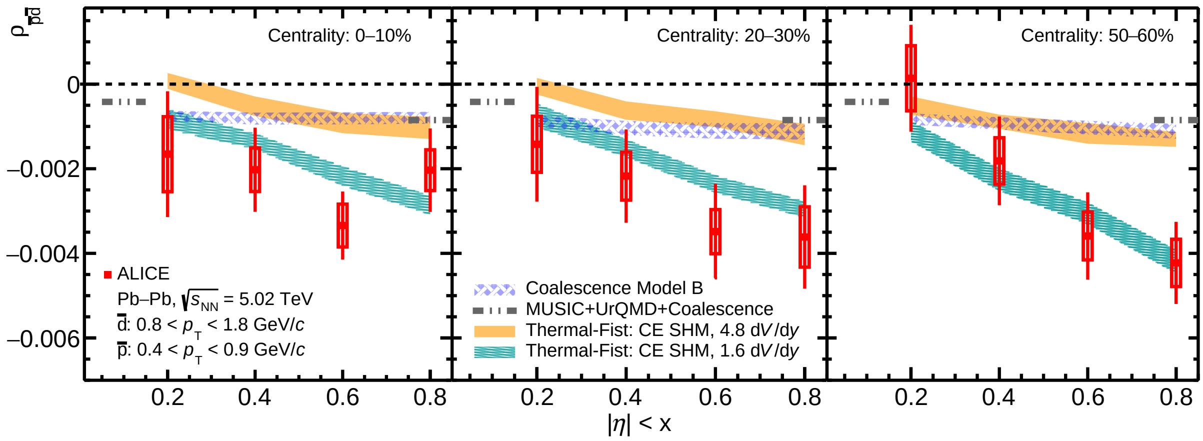

Figure 3: Dependence of $\bar{p}$–$\bar{d}$ correlation on pseudorapidity acceptance of $\bar{p}$ and $\bar{d}$ selection in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for three different centrality classes. Measurements are compared with calculations from the CE version of the SHM, coalescence model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

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A The ALICE Collaboration

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