

Production of Nuclei, Hyper-Nuclei and Exotics in the ALICE Detector

Benjamin Dönigus (for the ALICE Collaboration)

Institut für Kernphysik, Goethe-Universität Frankfurt, Max-von-Laue-Str. 1, 60438 Frankfurt, Germany

E-mail: benjamin.doenigus@cern.ch

Abstract. Measurements of light (anti-)nuclei and (anti-)hypernuclei have been performed in different collision systems, namely pp, p-Pb and Pb-Pb, covering a large range of physics topics at the LHC using the ALICE detector setup. The results of the production of in Pb-Pb collisions is following the expectation of thermal models, whereas the production of nuclei in p-Pb collisions is tending to closer follow the expectations from coalescence models. Both models can give predictions for the production of hypothetical states such as bound states of two Λ hyperons or of a Λ and a neutron, which are expected to decay weakly. The states are searched for and no signal is found, thus upper limits are set which are significantly below the model expectations. Further, the measurement of the lifetime of the hypertriton determined in Pb-Pb collisions at the LHC gives a value significantly below the expectations of the most recent theoretical calculation. Instead this measurement is in agreement with other recent measurements in heavy-ion collisions. The combination of all measurements gives a tension of more than 2σ between the experimental lifetime and the most recent model calculation.

1. Introduction

The ALICE Collaboration has, among others, a program to investigate many different kinds of (multi-)baryon states predicted and expected by QCD and QCD inspired models [1]. One way of approaching this research topic is to start by measuring rarely observed anti- and hypermatter, which is produced copiously in Pb-Pb collisions at the LHC. With these data the model predictions, e.g. the thermal (statistical) model and coalescence approaches are tested. Ultimately, the aim is to understand the production mechanisms acting in these collisions and resulting in large production yields for (anti-)nuclei, (anti-)hypernuclei and exotica still to be discovered or excluded by setting strong upper limits.

The thermal model at the LHC has basically only one key parameter: the chemical freeze-out temperature T_{ch} . This statement is valid because the baryo-chemical potential μ_B is close to zero, and therefore often treated as being zero in thermal model fits. The nuclei themselves are subject to a strong sensitivity on T_{ch} , because of their large mass and the exponential behaviour of the expected particle yields dN/dy on the particle mass m ($dN/dy \propto \exp(-m/T_{ch})$). The interesting fact to mention here, is that the binding energies of these objects are very small compared to the chemical freeze-out temperature T_{ch} [2].

Another model approach expects the constituents of a (hyper-)nucleus produced from the fireball to come close in phase space and form the (hyper-)nucleus through coalescence. In this model the produced nuclei could break apart and be created again by final-state coalescence.



2. (Anti-)nuclei

The measurement of (anti-)nuclei is performed using the time projection chamber (TPC) and the time-of-flight detector (TOF). The TOF is used in addition where the TPC is no longer sufficient to separate the different nuclei from other hadrons using the specific energy-loss dE/dx . One way to combine the information of both detectors is the measurement of the mass of the investigated particle. This is using the $\beta = v/c$ from the TOF and the measured momentum, strongly constrained after a pre-selection based on the TPC measurement. A result for the measured $(m/z)^2$ for deuteron, ${}^3\text{He}$ and the corresponding anti-particles in Pb–Pb collisions is shown in Fig. 1. From this measurement, one can deduce a mass difference and the binding energy difference between particle and anti-particle. This test of the CPT invariance in the nuclei sector shows no hint of any violation [3].

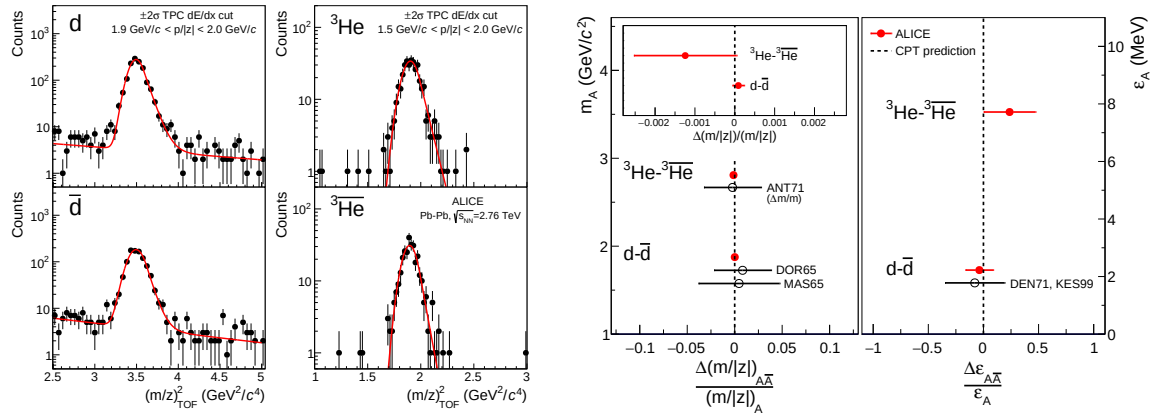


Figure 1. The left panel shows the squared ratio of mass and charge number $(m/z)^2$, distributions for d , $\bar{d}$, ${}^3\text{He}$ and $\bar{{}^3\text{He}}$. The right panel depicts the normalised mass difference $\frac{\Delta(m/z)}{(m/z)_A}$ and the normalised binding energy difference $\frac{\Delta\epsilon_{A\bar{A}}}{\epsilon_A}$. Both figures from [3].

Furthermore, spectra are extracted dividing the signal in p_T slices and correcting for acceptance and efficiency. The result for deuterons in pp collisions and for five different centralities in Pb–Pb is displayed in Fig. 2, together with the ratios of the anti-nuclei to nuclei in the same centrality classes. In addition, the ratio is also shown for ${}^3\text{He}$. All ratios are compatible with unity as a function of transverse momentum which is expected by thermal and coalescence models.

The spectra in Pb–Pb show a clear hardening with increasing centrality and are fitted with blast-wave distributions [4], mainly to extrapolate to the unmeasured region of the spectra and thus to extract the integrated production yield. A combined blast-wave fit (resulting in one common set of T_{kin} , $\langle\beta\rangle$ and n) to π , K, p, d and ${}^3\text{He}$, shown in Fig. 3, gives a good fit for all particles (the deviation of pions at low p_T is due to feed-down from resonances mainly contributing in this region). This shows that nuclei are following the same radial expansion as the lighter hadrons in central Pb–Pb collisions.

The ratio of the production yields of deuterons to protons in pp, p–Pb and Pb–Pb collisions as a function of the mean multiplicity $\langle dN_{ch}/d\eta \rangle$ is depicted in Fig. 4. It shows an increase going from pp multiplicities over p–Pb multiplicities until a saturation seems to be reached in peripheral Pb–Pb collisions. The increase with multiplicity is expected from coalescence models whereas the basically constant behaviour at higher multiplicities is expected by the thermal model.

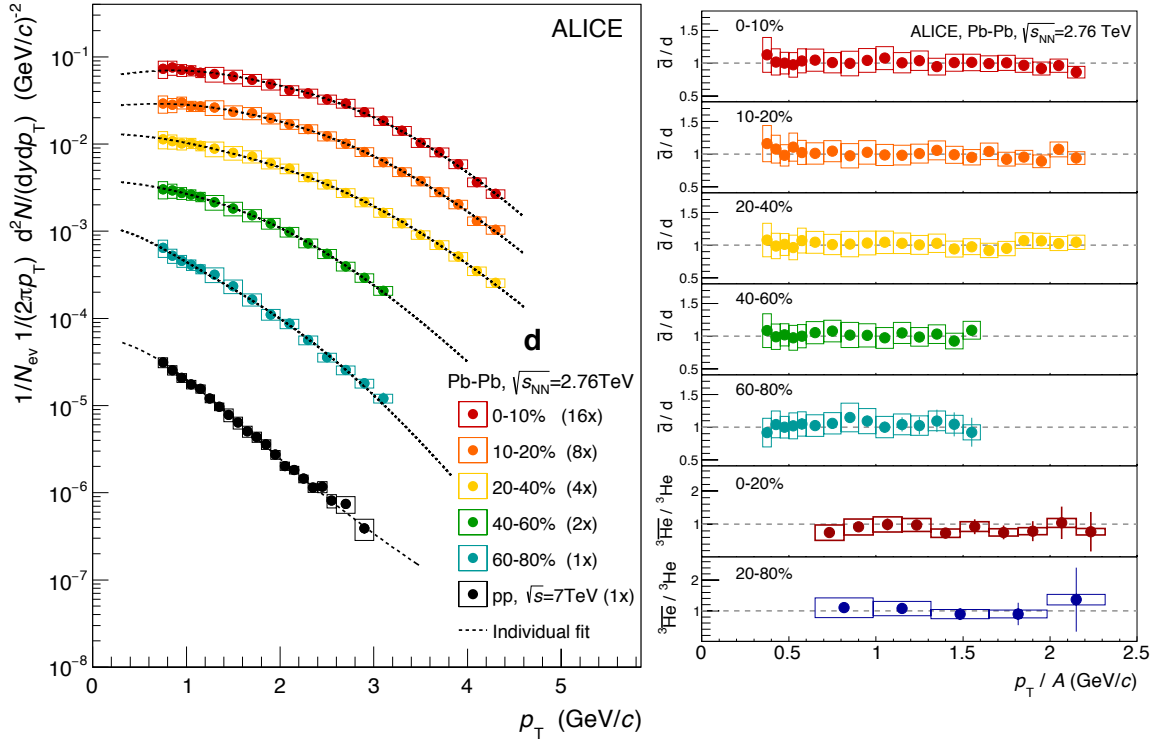


Figure 2. Invariant transverse momentum spectra for deuterons in pp and five centrality classes in Pb-Pb (left panel) and ratio between anti-nuclei and nuclei ($\bar{d}/d$ and ${}^3\bar{\text{He}}$) for the different centrality classes in the lower panel. Figures taken from [5].

Figure 5 is showing the production yield of nuclei in Pb-Pb and p-Pb collisions as a function of their mass together with exponential fits. As mentioned above an exponential decrease with mass is expected from the thermal model. The penalty factor for adding a baryon to the system is about 300 in Pb-Pb and around 600 in p-Pb, which means the suppression when going from d to ${}^3\text{He}$ is 300 in Pb-Pb and 600 in p-Pb.

A non-central collision is creating an almond shape fireball which is basically a spatial anisotropy. This spacial anisotropy (eccentricity) will be transformed into a momentum anisotropy from the pressure gradients inside the fireball. Therefore the spectra are usually expanded into a Fourier series in azimuth and the main contribution is given by the so-called elliptic term v_2 , the Fourier coefficient of the second order. The measured v_2 is displayed in Fig. 6 for π , K, p and d, which follows the mass ordering expected from hydrodynamic models. The full lines represent a blast-wave fit to π , K and p, and a prediction using this fit for the deuteron. This is describing the v_2 of deuterons rather well, whereas a simple coalescence model (dashed magenta region), scaling the v_2 of protons accordingly, fails in the description.

3. (Anti-)hypernuclei

The hypertriton is the lightest hypernucleus, consisting of a proton, a neutron and a Λ hyperon. It decays weakly, for instance into a ${}^3\text{He}$ and a π^- , with a lifetime close to the one of the Λ hyperon. The separation energy of the Λ is only 130 keV, which gives from simple quantum mechanical calculations a size of about 10 fm of the hypertriton. This already indicates that the

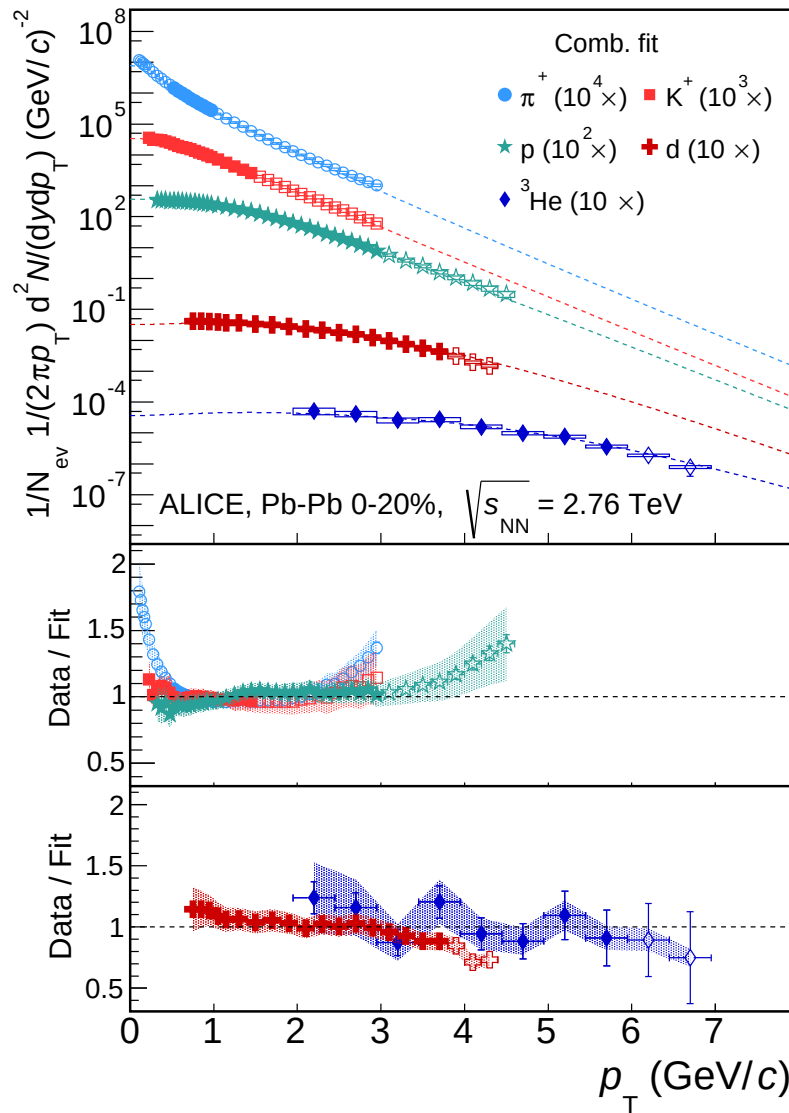
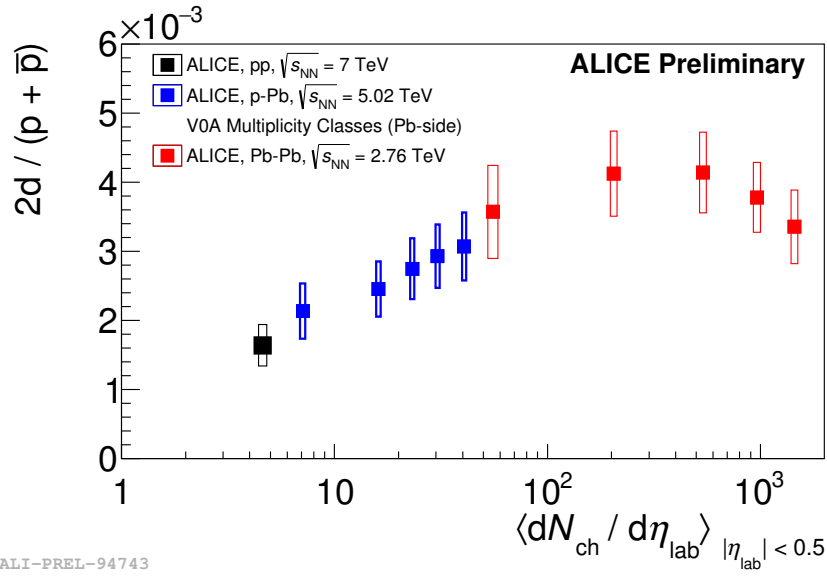


Figure 3. Invariant transverse momentum spectra for π^+ , K^+ , p , d , ${}^3\text{He}$ in 0-20% fitted with one global blast-wave function. The lower panels show the comparison of the model with the data. From [5].

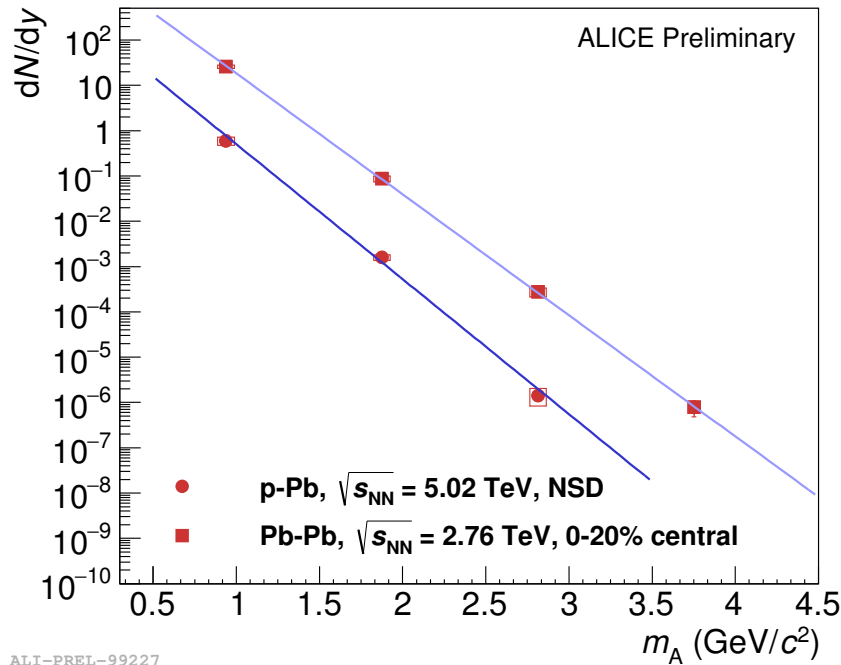
lifetime should be very close to the one of the free Λ . A more sophisticated model involving also three-body forces also expects it to be close to it [6]. In addition, this model gives a branching ratio of the hypertriton into the ${}^3\text{He}+\pi^-$ of about 25%. The branching ratios (B.R.) of the hypertriton decay modes are not well known because many channels involve neutral particles such as neutrons and π^0 which are not accessible by the production experiments.

The measured $dN/dy \times \text{B.R.}$ of the hypertriton in 0-10% central Pb-Pb collisions as a function of the branching ratio is depicted in Fig. 7, together with models describing its production. The thermal model describing the production of light hadrons and nuclei well, is in agreement with the measurement around the 25% branching ratio expected from the previously mentioned



ALI-PREL-94743

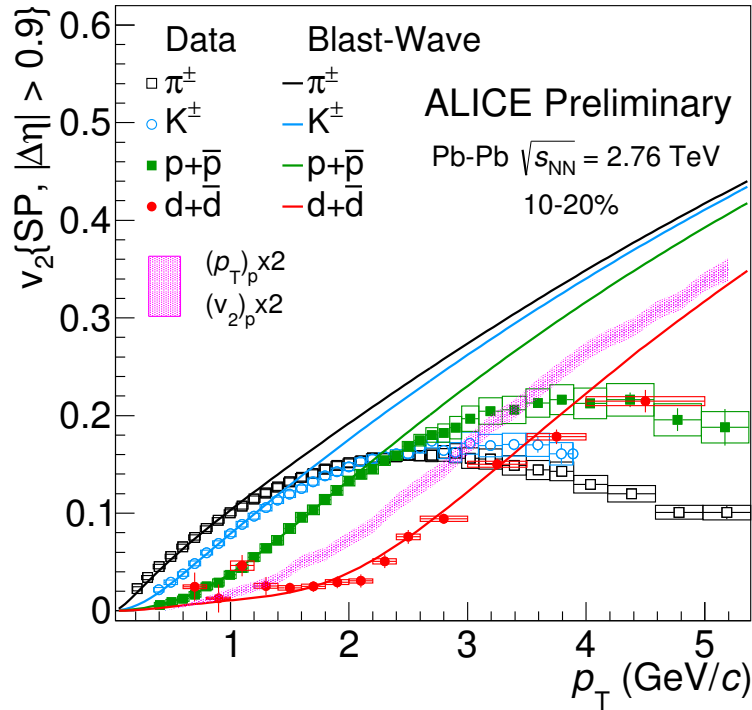
Figure 4. Ratio of the production yields of deuterons to protons ($2d/(p+\bar{p})$) as a function of the mean multiplicity $\langle dN_{ch}/d\eta \rangle$. The black point is extracted from the minimum bias pp measurement, the p-Pb results are preliminary results from a multiplicity dependent study and the Pb-Pb corresponds to the five centrality classes discussed before.



ALI-PREL-99227

Figure 5. Production yield of different nuclei as a function of their mass. The lines indicate exponential fits through the data points at the two energies.

model.



ALI-PREL-97047

Figure 6. Elliptic flow coefficient v_2 for pions, kaons, protons and deuterons. The measured data points are compared with a blast-wave fit of pions, kaons and protons which is used as a prediction for deuterons, full lines. The dashed region indicates the prediction of a naïve coalescence model assuming a simple scaling of the v_2 of protons by a factor of 2 to get the v_2 of deuterons.

The extracted lifetime is displayed in Fig. 8 and compared with previous measurements. An average calculated following the PDG description is also shown which deviates from the free Λ hyperon lifetime by more than 2σ . The measurements before 2010 are done with emulsions whereas the latest ones are all from heavy-ion collisions. This lead to the discussion in the hyper-nuclei community that the measurements in heavy-ions might be biased because of the more rough collision environment there, which could influence the observed lifetime of the hypertriton. Therefore measurements of the lifetime in elementary collisions are desirable.

4. Exotica searches

Since the production yields of composite objects (such as light (anti-)(hyper-)nuclei) are rather well described by both production models they can be used to predict the production of exotic objects such as bound states among hyperons or hyperons and nucleons. Of particular interest is the so-called H-dibaryon, a hexaquark state composed of $uuddss$ ($\Lambda\Lambda$) predicted by R. Jaffe in a bag model calculation in 1977 [8]. It is investigated in the weak decay mode $\Lambda + p + \pi^-$. Another investigated bound state is a possible bound state of Λn which would decay into $d + \pi^-$. Since no signal was observed, upper limits have been extracted in a wide phase space of lifetime and branching ratio.

The upper limits of the investigated bound states are depicted in Fig. 9 as function of the

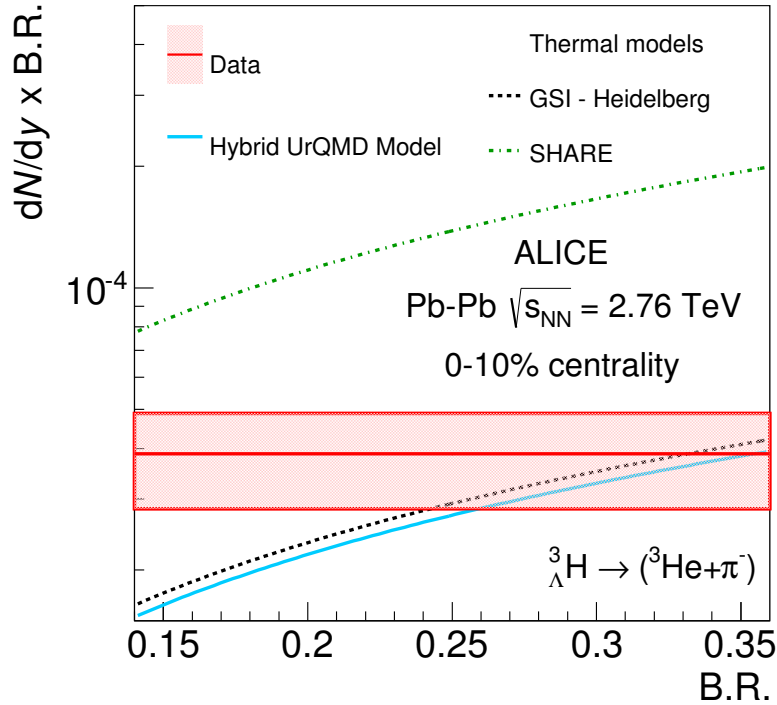


Figure 7. p_T -integrated rapidity density times branching ratio as a function of branching ratio ($dN/dy \times B.R.$ vs $B.R.$). The horizontal line is the measured $dN/dy \times B.R.$ and the band around it represents the quadratic sum of statistical and systematic uncertainties. The dashed lines indicate different theoretical expectations. Taken from [7].

branching ratio assuming a lifetime of the free Λ hyperon. All production models are far away from the extracted upper limits in reasonable regions of the branching ratio. Only if the branching ratios are very small, the model predictions reach down to the upper limit value.

The dependency of the upper limit on the lifetime is displayed in Fig. 10 and shows that only at very long lifetimes (about 3 m) the upper limit of the H-dibaryon comes close to the thermal model expectation. For the Λn bound state the upper limits are for all configurations under study below the model expectation.

5. Summary and outlook

The results from the production of (anti-)nuclei (in pp, p-Pb and Pb-Pb collisions) and (anti-)hypernuclei (in Pb-Pb collisions) are described rather well by the thermal and the coalescence models, but a simple coalescence model fails in describing the v_2 of the deuteron. Both models can make predictions for the production of exotic objects, such as the H-dibaryon and a Λn bound state. These exotica were searched for and no signals were observed, thus upper limits were set which are significantly below the expectations of both models. A comparison of the thermal model involving all discussed states is displayed in Fig. 11. It shows that the thermal model describes the yields of the known states very well, even the hypertriton having a Λ separation energy of only 130 keV is in good agreement. Instead, the upper limits of the exotic states are more than a factor 25 below the expectation. This makes it rather hard to accept

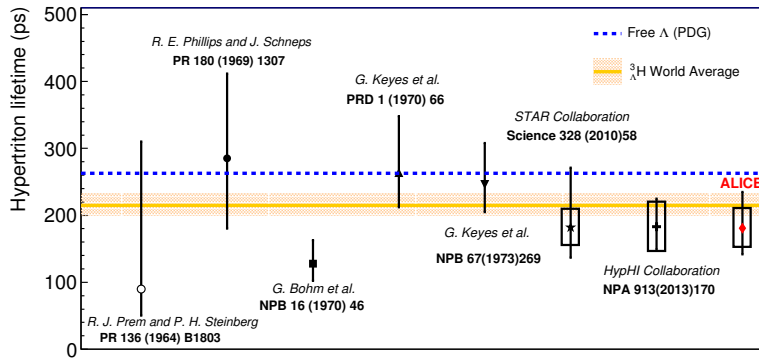


Figure 8. Measured hypertriton lifetime (red symbol) compared with previously published results. The band represents the world average of the hypertriton lifetime measurements. The dashed line indicates the lifetime of the Λ hyperon as reported by the Particle Data Group. Taken from [7].

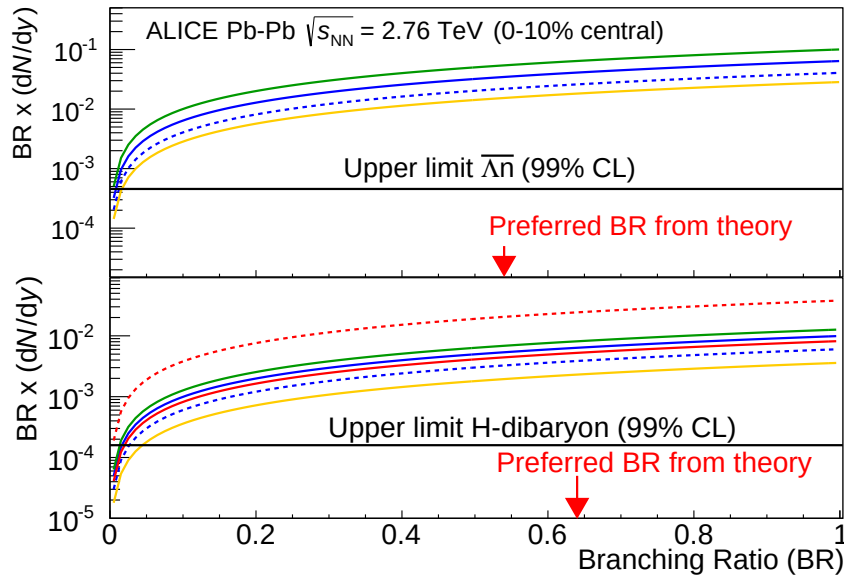


Figure 9. Extracted upper limit dN/dy as function of the branching ratio compared with different models. For details see [9].

that these particles exist in the investigated phase space.

Further, the measurement of the lifetime of the hypertriton determined in Pb–Pb collisions at the LHC gives a value significantly below the expectations of the most recent calculation. This measurement is in agreement with other recent measurements in heavy-ion collisions and in emulsions. The combination of all measurements gives a tension of more than 2σ between the experimental lifetime and the most recent model calculation. The repetition of this measurement in more elementary collisions is one aim of run 2, which has started in 2015 and will deliver significantly larger data sets in higher collision energies as before ($\sqrt{s} = 13$ TeV in pp, $\sqrt{s_{NN}} = 8$ TeV in p–Pb and $\sqrt{s_{NN}} = 5$ TeV in Pb–Pb). This data will allow also to complement the

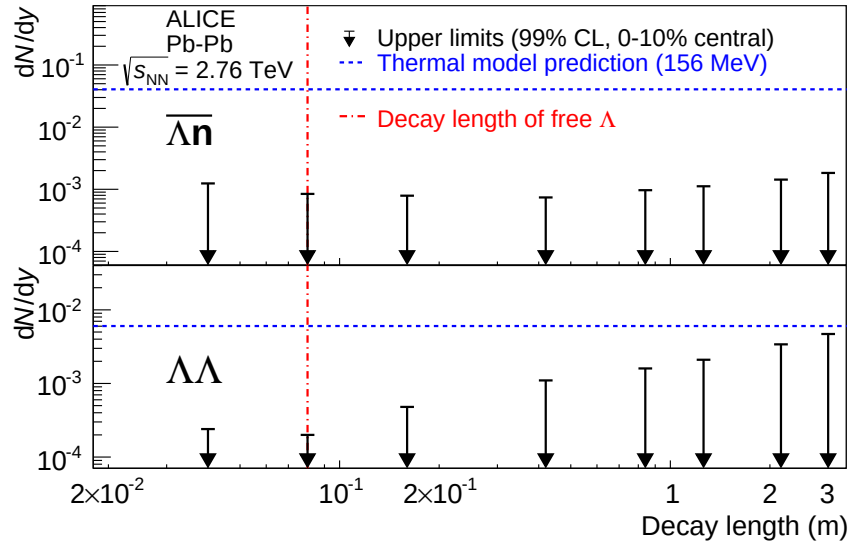


Figure 10. Upper limit dN/dy as function of the decay length compared with different models. For details see [9].

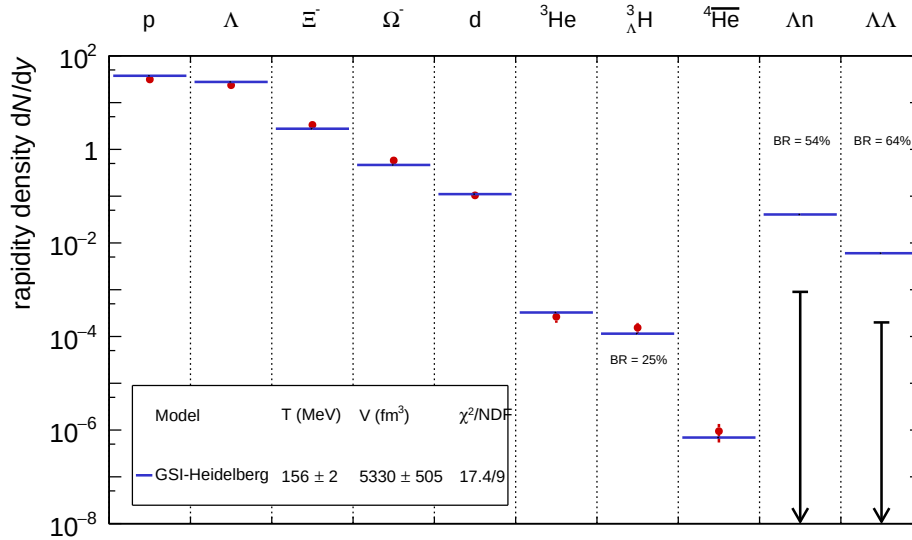


Figure 11. Comparison of production yields dN/dy of baryons, light (hyper-)nuclei and exotica with thermal model predictions. Hypertriton was corrected by 25% for the branching ratio, Λn by 54% and $\Lambda\Lambda$ by 64%. As shown in [10].

measurements reported here and perform more systematic studies, for instance to measure the production of deuterons in pp collisions as a function of multiplicity and in particular at high multiplicities.

After 2018 in the so-called long shutdown 2 (LS2) two main detectors will be upgraded. The current silicon detectors of different technology will be replaced by pixel layers which will increase the (secondary) vertex resolution significantly [11]. The multi-wire proportional chambers of the TPC will be replaced by four layers of GEM detectors which will allow for continuous readout

at rates of 50 kHz [12]. These upgrades will allow the ALICE detector to cope with the high luminosity expected in run 3 (starting in 2021). In run 3, a data sample of 10^{10} central events is expected to be collected, which gives the possibility to study the production of the presented particles with high precision and will allow to study also hyper-nuclei with $A=4$ [1,11].

6. Acknowledgments

The author acknowledges the support from the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) through the project grant 05P2015 - ALICE at High Rate (BMBF-FSP202).

7. References

- [1] Abelev B et al. (ALICE Collaboration), 2014 *J. Phys. G: Nucl. Part. Phys.* **41** 087001
- [2] Andronic A et al., 2011 *Phys. Lett. B* **697** 203
- [3] Adam J et al. (ALICE Collaboration), 2015 *Nature Phys.* **11** 811
- [4] Schnedermann E et al., 1993 *Phys. Rev. C* **48** 2462
- [5] Adam J et al. (ALICE Collaboration), 2016 *Phys. Rev. C* **93** 02491
- [6] Kamada H et al., 1998 *Phys. Rev. C* **57** 1595
- [7] Adam J et al. (ALICE Collaboration), 2016 *Phys. Lett. B* **754** 360
- [8] Jaffe R L, 1977 *Phys. Rev. Lett.* **38** 195 and 617
- [9] Adam J et al. (ALICE Collaboration), 2016 *Phys. Lett. B* **752** 267
- [10] Braun-Munzinger P, Dönigus B, Löhner N, 2015 *CERN Courier* **September**
- [11] Abelev B et al. (ALICE Collaboration), 2014 *J. Phys. G* **41** 087002
- [12] Adam J et al. (ALICE Collaboration), 2014 *CERN-LHCC-2013-020, ALICE-TDR-016*