Light (Hyper)Nuclei production at the LHC with ALICE

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The excellent particle identification and momentum measurement capabilities of the ALICE detector allows for the identification of dueterons and ^{3}He and and their corresponding anti-nuclei. This is achieved via the measurement of their specific energy loss in the Time Projection Chamber and the velocity measurement by the Time Of Flight detector. Moreover, thanks to the Inner Tracking System capability to separate primary from secondary vertices, it is possible to identify (anti-)hypertritons exploiting their mesonic weak decay ($^3_\Lambda$H $\rightarrow$ ^{3}He + π^-). Results on the production yields of light nuclei and anti-nuclei in Pb–Pb and p–Pb are presented, together with the measurement of hypertriton production rates in Pb–Pb and upper limits for the production of lighter exotica candidates. The experimental results are compared with the predictions of both thermal (statistical) and coalescence models.

1 Introduction

High energy heavy-ion collisions offer the opportunity to measure light anti-nuclei and search for hypermatter. In fact, although the measurement is challenging as the production probability decreases with increasing mass, the data collected at the LHC allows for the measurement of such particles. Thanks to its unique performance for particle identification, the ALICE detector [1, 2] allows for the identification and the measurements of (anti-)nuclei (deuterons and ^{3}He and their corresponding anti-nuclei) and (anti-)hypertriton and gives the opportunity to search for predicted particles such as the H-Dibaryon and the Λn bound state. Usually two different approaches are used to describe the production yield of these particles: they can be formed at the kinetic freeze-out via the coalescence of nucleons (hyperons) close in phase-space, or their can born in thermal equilibrium [3, 4, 5]. In the thermal models the chemical freeze-out temperature T_{chem} is the key parameter at LHC energies: the production yields depend exponentially on this temperature and on the mass of the particle m ($\mathrm{d}N/\mathrm{d}y \sim \exp(-m/T_{\mathrm{chem}})$).
For the present analysis, the data of Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV recorded in two periods during the years 2010 and 2011 and the data of p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV recorded at the beginning of 2013 were used.

2 (Anti-)Nuclei

Nuclei and anti-nuclei are identified over a wide range of momentum using the combined information of the specific energy loss ($\mathrm{d}E/\mathrm{d}x$) measurement in the Time Projection Chamber (TPC) [6], the velocity measured by the Time Of Flight detector (TOF) [7] and the measurement of the Cherenkov radiation angle measured with the High Momentum Particle Identification Detector (HMPID) [7]. The measured energy loss signal in the TPC of a track is required to be within a 3σ region around the expected value for a given mass hypothesis: with this method it possible to provide a pure sample of ^{3}He in the (2-8) GeV/c transverse momentum interval, while it is limited to 1.4 GeV/c for deuterons. In order to extend deuteron identification, the measured time-of-flight and Cherenkov radiation allows for deuteron identification up to 8 GeV/c. The measured raw spectra were corrected for efficiency and acceptance. Figure 1 shows the deuteron transverse momentum p_{T} spectra in different centrality (multiplicity) classes in Pb–Pb (left panel) and p–Pb (right panel) collisions. In both colliding systems, a hardening of the spectrum with increasing centrality is observed as expected in a hydrodynamic description of the fireball as a radially expanding source. In order to extrapolate the yield in the regions where it is not measured, the spectra were fitted with a Blast-Wave function [8].

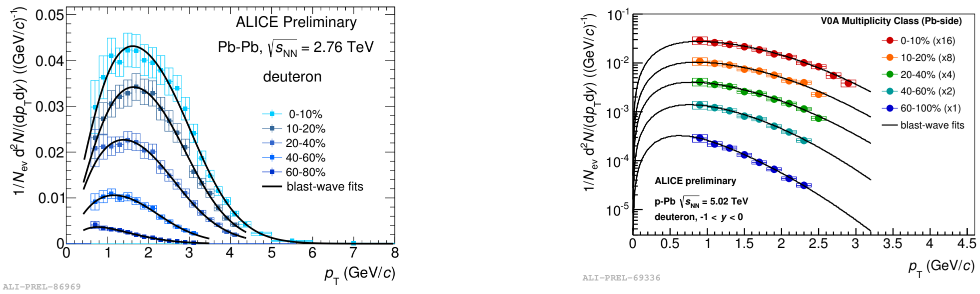

Figure 1: Transverse momentum spectra in different centrality (multiplicity) classes for deuterons in Pb–Pb (left) and in p–Pb (right) collisions at LHC energies.

Figure 2 shows the coalescence parameter $\mathrm{B}_2 = E_{\mathrm{deuteron}} \frac{d^3N_{\mathrm{deuteron}}}{dp^3_{\mathrm{deuteron}}} / \left(E_{\mathrm{proton}} \frac{d^3N_{\mathrm{proton}}}{dp^3_{\mathrm{proton}}}\right)^2$, for Pb–Pb (left) and p–Pb (right) collisions. In a simple coalescence model the B_2 parameter is independent of p_{T}: this is observed in peripheral Pb–Pb and p–Pb. More sophisticated models show that B_2 scales like the HBT radii [9]: the decrease with centrality in Pb–Pb can be explained as an increase in the source volume and the increasing with p_{T} in central Pb–Pb reflects the k_{T}-dependence of the homogeneity volume in HBT.

3 (Anti-)Hypertriton

The hypertriton $^3_\Lambda$H is the lightest known hypernucleus and is formed by a proton, a neutron and a Λ. Its mass is 2.991 ± 0.002 GeV/c^2 and it has a lifetime comparable with the free Λ one (few hundreds of picoseconds) [10]. The ($^3_\Lambda\overline{\mathrm{H}}$) $^3_\Lambda$H production yield was measured in Pb–Pb by exploiting its weak mesonic decay ($^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$) (($^3_\Lambda\overline{\mathrm{H}} \rightarrow {}^3\overline{\mathrm{He}} + \pi^+$)), via the topological identification of secondary vertices and the analysis of the invariant mass distributions of the

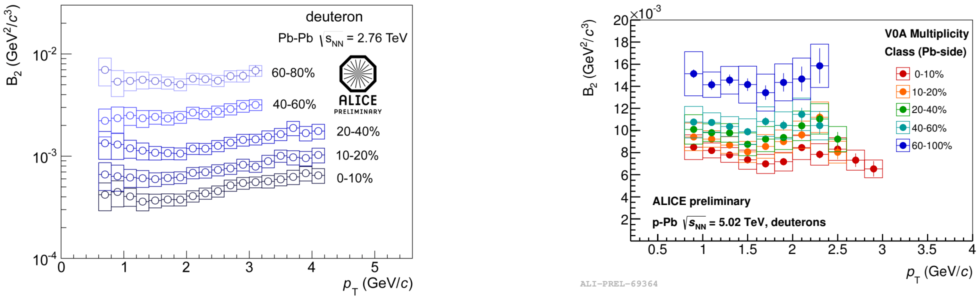

Figure 2: Coalescence parameter B_2 as a function of p_T for deuterons in in Pb–Pb (left) and p–Pb (right) collisions.

decay daughters. The measured $^3_\Lambda$H production yield dN/dy is compared to different models as a function of the branching ratio ($B.R.$) in Figure 3 (left panel). At the theoretical value ($B.R.$ = 25 %) [11], the model which describes better the obtained value is the equilibrium thermal model [3] with a temperature T_{chem} =156 MeV. This temperature is the one which best describes all the particle yields measured at LHC.

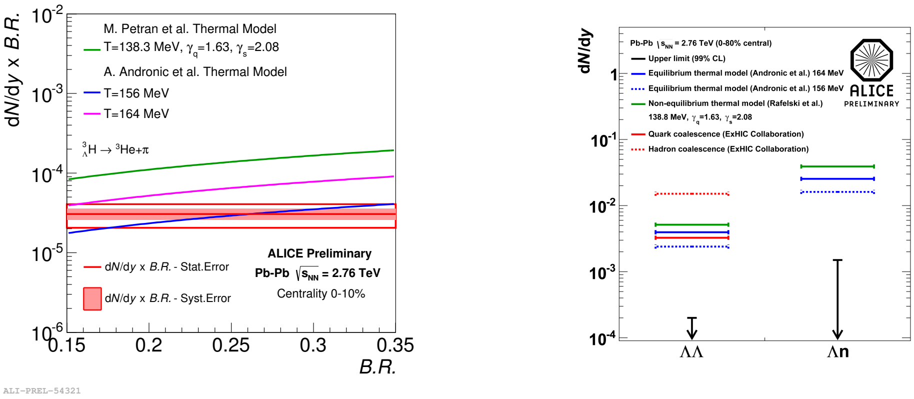

Figure 3: Left: dN/dy comparison to different models for the hypertriton measurement. Right: upper limits for H-Dibaryon and Λn dN/dy compared with several theoretical models.

4 Exotic Bound State

The H-Dibaryon is a hypothetical *uuddss* bound state (ΛΛ) first predicted by Jaffe in a bag model calculation [12]. Recent lattice calculations [13, 14, 15, 16] suggest that H-Dibaryon should be a bound state, with a binding energy of around 1 MeV/c^2. The same binding energy is also favored from the observed double-Λ hypernuclei, which gives the current constraints on the ΛΛ interaction (for a recent review see [17] and the references therein). In this analysis the decay of the H-Dibaryon into Λpπ was investigated. In the measured invariant mass distribution no evidence of a signal for the H-Dibaryon was found [18], and an upper limit of dN/dy $2{\times}10^{-4}$ (99 %CL) was obtained. The HypHI collaboration at GSI found evidence for a possible Λn bound state with a mass of 2.054 GeV/c^2, decaying into a deuteron and a pion [19]. The invariant mass distribution of deuterons and pions from displaced vertices, where a possible Λn bound state is expected to be visible, was studied but no signal was observed [18]. This led to an upper limit of dN/dy $1.5{\times}10^3$ (99 %CL). The extracted limits are a factor of 10 lower than the thermal model predictions used to estimate the expected signal while this successfully describes the measured yields of deuterons, ^{3}He and $^3_\Lambda$H nuclei. Figure3 (right) shows the upper limits on the dN/dy of H-Dibaryon and Λn and are compared with several theoretical models.

5 Summary and Conclusions

The p_{T} spectra of deuteron and ^{3}He (not shown here) were measured in p–Pb and Pb–Pb collisions: a hardening of the spectra with increasing centrality is observed in both the colliding systems. The coalescence parameter B_2 was also determined; it was found to be independent from p_{T} in p–Pb and peripheral Pb–Pb collisions, while it increases with p_{T} in central Pb–Pb collisions. A decrease with centrality is also observed in Pb–Pb collisions. The production yield of deuterons, ^{3}He and $^3_\Lambda$H nuclei is in agreement with the current best thermal fit from equilibrium thermal model with a $T_{\mathrm{chem}} = 156$ MeV. On the other hand, the upper limits for exotica (H-Dibaryon and Λn) are lower than the thermal model expectation by at least an order of magnitude, therefore the existence of such states with the assumed decay branching fraction, mass and lifetime is questionable.

Acknowledgments

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