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Investigating the system size dependence of hypernuclei production with A < 5 using the ALICE detector

Yuanzhe Wang[1,*] for the ALICE Collaboration

[1]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, 200433, Shanghai, China

Abstract. The production of (anti)hypernuclei is among the most promising probes for studying the production mechanism of light nuclei in high-energy hadronic collisions. According to coalescence predictions, the production of ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, and ${}^{4}_{\Lambda}$He is sensitive to their internal wave function. In contrast, the yields predicted with the Statistical Hadronitazion Models (SHM) are based on the mass of the (hyper)nuclei and the freeze-out temperature, with no explicit dependence on the nuclear structure. In these proceedings, the measurements of ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, and ${}^{4}_{\Lambda}$He from pp to central Pb–Pb collisions are presented. The results are based on the data samples collected by ALICE during the LHC Run 2 and Run 3. For the ${}^{3}_{\Lambda}$H, in addition, an innovative method to extract its properties based on the system size dependency of its production yield is also presented.

1 Introduction

Hypernuclei are nuclei that contain at least one hyperon. Since this unique system was first discovered in the 1950s, hypernuclei have gathered substantial interests as natural probes to study the hyperon-nucleon (Y-N) interaction, which is expected to play an important role in the innermost core of neutron stars [1]. Relativistic hadronic collisions provide a favourable environment for the formation of hypernuclei and antihypernuclei. A basic understanding of the physical properties of hypernuclei has already been established by experimental measurements. The ${}^{3}_{\Lambda}$H is found to be a loosely bound structure with a size around 10 fm due to the small Λ separation energy (B_{Λ}) about one hundred keV [2]. Moreover, the B_{Λ} of both ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He are of the order of several MeV [3], which is similar to the binding energy per nucleon of ordinary nucleus.

Recently, the production of hypernuclei is proposed as an effective method to study the nucleosynthesis mechanism in hadronic collisions. The coalescence model [4] suggests that the probability to produce a nucleus relies on the overlap of the nucleus Wigner function and the nucleon distribution function in the emission source. On the other hand, the Statistical hadronization Model (SHM) [5] assumes that the yield of particles is mainly dominated by their mass and the chemical freeze-out temperature but do not depend on their internal structure. Furthermore, it is also possible that the elliptic flow of hypernuclei could distinguish between SHM and the coalescence models, because the emission source of fireball differs in different directions in non-central collisions [6].

*e-mail: yuanzhe.wang@cern.ch

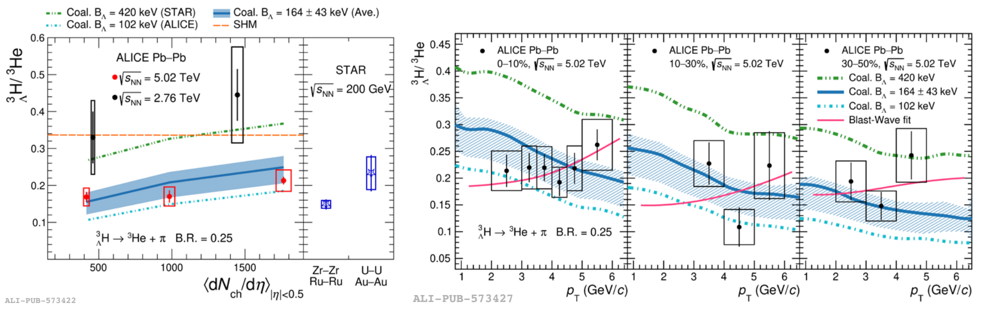

Figure 1. Yield ratio of ${}^{3}_{\Lambda}$H to ^{3}He in Pb–Pb collisions together with theoretical predictions. Left panel: ${}^{3}_{\Lambda}$H/ ^{3}He as a function of charged-particle multiplicity density $\langle dN_{ch}/d\eta \rangle$. The recent experimental results of STAR are shown alongside for comparison. Right panel: ${}^{3}_{\Lambda}$H/ ^{3}He versus p_T in different centrality intervals.

In these proceedings, we present the measurements of hypernuclei production (${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He and their charge conjugates) obtained by analysing the data sample collected by ALICE during the LHC Run 2 and Run 3. In the following, we use the notation ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, and ${}^{4}_{\Lambda}$He for both particles and antiparticles.

2 Results

2.1 Production of ${}^{3}_{\Lambda}$H in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

In order to test the two nuclear production models, namely the SHM and the coalescence models, the yield ratio of ${}^{3}_{\Lambda}$H to ^{3}He was calculated based on the p_T differential measurements of ${}^{3}_{\Lambda}$H in different centrality intervals [7]. The ${}^{3}_{\Lambda}$H candidates are reconstructed in Pb–Pb collisions via its two-body decay channel ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$ using 210 million collision events collected by ALICE in 2018. Fig. 1 shows measured ${}^{3}_{\Lambda}$H/^{3}He yield ratios with theoretical predictions [8, 9] and experimental results from STAR Collaboration [10] for comparison. The multiplicity dependence of ${}^{3}_{\Lambda}$H/^{3}He, shown in left the panel reflects the dependence on the size of the emission source. The expectation of SHM stays constant at large multiplicities, while all the three coalescence predictions with different B_Λ hypotheses are more sensitive to the system size. Compared with the prior results which were measured at $\sqrt{s_{NN}}$ = 2.76 TeV, the uncertainties of this work have been improved due to larger statistics, further understanding of properties of ${}^{3}_{\Lambda}$H, and the new Machine Learning analysis method [11] with a gradient-boosted decision tree classifier (BDT). These two results are consistent within a 2σ confidence interval. T or the one measured by ALICE [2]. In addition, the suppression of ${}^{3}_{\Lambda}$H yield in smaller collision systems has also been measured by STAR [10]. This approach offers a novel method to probe properties of ${}^{3}_{\Lambda}$H through its production dependence on system size. The right panel of Fig. 1 presents the transverse momentum (p_T) dependence of the ${}^{3}_{\Lambda}$H/^{3}He yield ratio, together with the coalescence predictions and a hydrodynamic description of the observable based on the Blast-Wave model [12]. The coalescence predicts larger suppression of ${}^{3}_{\Lambda}$H production at higher p_T, while the Blast-Wave picture provides an increasing trend of ${}^{3}_{\Lambda}$H/^{3}He. However, the current experimental uncertainties do not support drawing any conclusion.

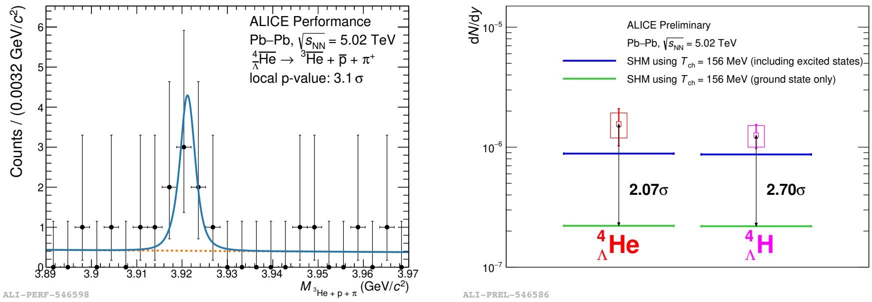

Figure 2. Left panel: Invariant mass distribution of the ${}^{4}_{\bar{\Lambda}}\overline{\mathrm{He}}$ in 0–10% most central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The data points are fitted with a function which is a combination of KDE signal and an exponential background. Right panel: Integrated yields of ${}^{4}_{\Lambda}$He and ${}^{4}_{\Lambda}$H in 0–10% most central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with SHM predictions.

2.2 Production of A = 4 hypernuclei in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

The search of A = 4 hypernuclei (${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He) was also performed in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He are reconstructed via the decay channels ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$ and ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$ respectively. The first evidence of ${}^{4}_{\bar{\Lambda}}\overline{\mathrm{He}}$ is shown in the left panel of Fig. 2. The right panel presents the integrated yield of A = 4 hypernuclei, where both production yields deviate by at least 2σ from the SHM prediction which only includes ground states. However, the effect of the excited states is observed as an enhancement in the yields of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He. Additionally, taking into account the spin degeneracy, the feed-down effects originating from these excited states can increase the expected yields by a factor up to 4 in total. With the contribution from the excited states, the yields of both ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He are consistent with the SHM predictions. It appears that the SHM works well for compact states such as ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He, but it becomes less effective when the structure is larger, as in the case of ${}^{3}_{\Lambda}$H.

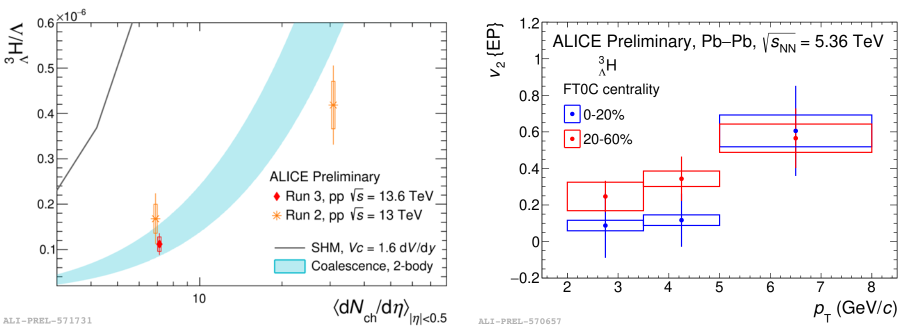

Figure 3. Left panel: Yield ratio of ${}^{3}_{\Lambda}$H to Λ in pp collisions with theoretical predictions. The results of ${}^{3}_{\Lambda}$H are obtained from antimatter only. Right panel: v_2 of ${}^{3}_{\Lambda}$H in Pb–Pb collision at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV in different centrality classes.

2.3 Measurement of ${}^{3}_{\Lambda}$H in Run3

As previously discussed, there is a notable discrepancy between the SHM and the coalescence model in their predictions regarding the yield of ${}^{3}_{\Lambda}$H. In the small collision systems where the emission size is comparable to that of ${}^{3}_{\Lambda}$H, the ${}^{3}_{\Lambda}$H yield is expected to be more significantly suppressed in the coalescence picture. Therefore, it would be more decisive to test these two models at low multiplicities. Such studies are also performed during the LHC Run3 period. The ${}^{3}_{\Lambda}$H p_{T} differential production in pp collision at $\sqrt{s}$ = 13.6 TeV was measured using the data collected in 2022. The left panel of Fig. 3 shows the p_{T} integrated yield ratio of ${}^{3}_{\Lambda}$H to Λ. The new results obtained in Run3 is compatible with the ones from Run2. From a comparison with the model predictions, the SHM [5] is found to be inconsistent with the results, while the Run3 ${}^{3}_{\Lambda}$H/ Λ ratio aligns well with the 2-body coalescence model [4] which assumes that ${}^{3}_{\Lambda}$H is formed from the coalescence of d and Λ.

The elliptic flow of ${}^{3}_{\Lambda}$H was measured for the first time in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV, using the dataset collected by ALICE in 2023. The results are shown in the right panel of Fig. 3. In general, the v_2 of ${}^{3}_{\Lambda}$H increases with both centrality and p_{T}. In future, uncertainties on the measurement will be improved from the full event statistics of LHC Run 3.

3 Summary

The production of A < 5 hypernuclei has been investigated by ALICE. The ${}^{3}_{\Lambda}$H yield is measured among different collision systems and appears to be in favor of the coalescence picture. Notably, based on the predictions of the coalescence model, the system size dependence of ${}^{3}_{\Lambda}$H production is sensitive to its B_{Λ}. However, in the case of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He where the Λ separation energy is larger, SHM is found to be effective while taking into account the feed-down effects from the excited states, while no coalescence prediction is currently available for them. It indicates that there may still be unknown factors in nuclear production. The extensive data sample collected during the ongoing LHC Run3 period will enable more precise measurements and differential analyses of hypernuclei.

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