

2 Testing production scenarios for (anti-)(hyper-)nuclei with
3 multiplicity-dependent measurements at the LHC

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6 The production of light anti- and hyper-nuclei provides unique observ-
7 ables to characterise the system created in high energy proton-proton (pp),
8 proton-nucleus (pA) and nucleus-nucleus (AA) collisions. In particular,
9 nuclei and hyper-nuclei are special objects with respect to non-composite
10 hadrons (such as pions, kaons, protons, etc.), because their size is com-
11 parable to a fraction or the whole system created in the collision. Their
12 formation is typically described within the framework of coalescence and
13 thermal-statistical production models. In order to distinguish between the
14 two production scenarios, we propose to measure the coalescence parameter
15 B_A for different anti- and hyper-nuclei (that differ by mass, size and inter-
16 nal wave-function) as a function of the size of the particle emitting source.
17 The latter can be controlled by performing systematic measurements of
18 light anti- hyper- nuclei in different collision systems (pp, pA, AA) and as
19 a function of the multiplicity of particles created in the collision. While
20 it is often argued that the coalescence and the thermal model approach
21 give very similar predictions for the production of light nuclei in heavy-ion
22 collisions, our study shows that large differences can be expected for hyper-
23 nuclei with extended wave-functions, as the hyper-triton. We compare the
24 model predictions with data from the ALICE experiment and we discuss
25 perspectives for future measurements with the upgraded detectors during
26 the High-Luminosity LHC phase in the next decade.

27 **1. Introduction: the “anti-nuclei” puzzle**

28 The formation of light anti- and hyper-nuclei in high energy proton-
29 proton (pp), proton-nucleus (pA) and nucleus-nucleus (AA) collisions pro-
30 vides unique observables for the study of the system created in these reac-
31 tions, and can be used to understand both the internal structure and the
32 formation mechanisms of loosely-bound composite objects. The produc-
33 tion of (anti-)(hyper-)nuclei in high-energy collisions is commonly described

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by following two distinct approaches: formation by nucleon coalescence at the system (kinetic) freeze-out [1–4] or thermal-statistical production at the chemical freeze-out [5,6]. Thanks to the large data samples of pp, p–Pb and Pb–Pb collisions collected during the first ten years of operations of the CERN Large Hadron Collider (LHC), A Large Ion Collider Experiment (ALICE) Collaboration has measured the production of light nuclei and anti-nuclei at several centre-of-mass energies [7–12], thus providing a crucial experimental input and a boost to theoretical and phenomenological investigations [13–19]. In small collision systems, the experimental results seem to confirm the validity of the coalescence picture, with the most recent multiplicity-differential measurements pointing toward a dependence of the coalescence process on the volume of the particle-emitting source (“source size” hereafter). In heavy-ion collisions, coalescence approaches that do not take into account the source size are not able to reproduce the data. At the same time, the production of light nuclei, anti-nuclei and hypertriton as measured in Pb–Pb collisions is found to be consistent with statistical-thermal model predictions and a non-zero deuteron elliptic flow is observed. This is surprising as (anti-)nuclei produced at chemical freeze-out are not expected to survive the hadronic phase: the deuteron is a “fragile object” when surrounded by the fireball created in heavy-ion collisions, because its binding energy ($B_E = 2.2$ MeV) is much lower than the characteristic temperatures of the system ($T_{chem} \approx 153$ MeV, $T_{kin} \approx 100$ MeV). Moreover, the cross-section for pion-induced deuteron breakup is significantly larger than the typical (pseudo)-elastic cross-sections for the re-scattering of hadronic resonance decay products [19–22]. These observations pose the “(anti-)nuclei puzzle”: how can loosely-bound composite objects survive in the dense and hot fireball, freeze-out and develop collective flow like the other light-flavour non-composite hadrons?

In our study [14] we have extended and combined known formalisms used to describe (anti-)(hyper-)nuclei production in order to allow, for the first time, a direct comparison of the thermal and coalescence models as well as a direct comparison to the ALICE data. Identifying the coalescence parameter (B_A) as the key observable, we present a consistent picture across different collision systems (pp, p–Pb, Pb–Pb) for light (anti-)(hyper-)nuclei with mass number $A = 2, 3$ and 4. We also suggest to address the open questions by looking at the production of nuclei and hyper-nuclei up to $A = 4$ that differ by size and properties, measured as a function of multiplicity used as a proxy for the source size. Whereas the (anti-)deuteron production has been measured multi-differentially and quite precisely with the LHC Run 1 and 2 data, the study of heavier objects with $A = 3$ and 4 will greatly profit from the increase in integrated luminosity foreseen at the LHC Runs 3 and 4 in all collision systems [23]. A comprehension of (anti-)nuclei production

mechanisms is not only relevant for nuclear and hadronic physics, but has applications in astrophysics and indirect Dark Matter searches [24]. In recent years, it has been suggested that the detection of light anti-nuclei in space could provide a signature for the presence of Dark Matter in the Cosmos, see for instance [25, 26]. Anti-deuterons and ${}^3\overline{\text{He}}$ might indeed be produced by coalescence of antiprotons and antineutrons coming from the annihilation of Weakly Interacting Massive Particles into Standard Model particles, for which anti-nuclei created in reactions between primary cosmic ray protons and interstellar matter (pp, pA collisions) represent a source of background.

The main features of the theoretical frameworks employed for our study are briefly summarised in Sec. 2, while we address the reader to [14] for the full details. Section 3 presents the main results and conclusions follow.

2. Modelling light (anti-)(hyper-)nuclei production

For our study, we consider nuclei and hyper-nuclei with mass number $A = 2, 3$ and 4, whose properties are summarised in Tab. 1. Those properties are the same as for their anti-matter counterparts and we assume that the same formation mechanisms are at play for matter and anti-matter¹. Nuclei and hyper-nuclei are special objects with respect to non-composite hadrons (pions, protons, etc.), because their size is comparable to a fraction or the whole system created in pp, p-Pb and Pb-Pb collisions. The size is typically defined in two ways: a) as the rms of the (charge) distribution (λ_A), typically measured in electron scattering experiments, or b) as the size parameter of the object wave-function (r_A), typically taken as the gaussian solution of an isotropic harmonic oscillator potential in coalescence calculations. For light nuclei, $\lambda_A \approx 2$ fm. For the hyper-triton, theoretical calculations indicate a charge rms radius $\lambda_A \approx 5$ fm [27], driven by the average separation of the Λ relative to the two other nucleons. Assuming a similar structure (e.g. a s-wave interaction for a bound state of a n or a Λ with a deuteron), the hypertriton results in a much larger object than the other non-strange nuclei with $A = 3$. A simple relation holds between λ_A and r_A , see [14]. In Tab. 1 the binding energy (B_E) is also reported. The most tightly bound nucleus is ${}^4\text{He}$, whereas the most loosely bound object is ${}^3_{\Lambda}\text{H}$, that is also the largest one. For the latter, we report the separation energy of the Λ baryon from the deuteron ($B_{\Lambda} = 0.13$ MeV). The large size and the low binding energy of the ${}^3_{\Lambda}\text{H}$ with respect to the other (hyper-)nuclei has important consequences on its production, as discussed in what follows.

¹ For brevity, in the following we refer to “nuclei” and “hyper-nuclei” but we imply both matter and anti-matter.

Mass number	Nucleus	Compo- sition	B_E (MeV)	Spin J_A	(Charge) rms radius λ_A^{meas} (fm)	Harmonic oscillator size parameter r_A (fm)	Refs.
A = 2	d	pn	2.224575 (9)	1	2.1413 ± 0.0025	3.2	[28, 29]
A = 3	^3H	pnn	8.4817986 (20)	1/2	1.755 ± 0.086	2.15	[30]
	^3He	ppn	7.7180428 (23)	1/2	1.959 ± 0.030	2.48	[30]
	$^3_\Lambda\text{H}$	p Λ n	0.13 ± 0.05	1/2	4.9 – 10.0	6.8 – 14.1	[27, 31]
A = 4	^4He	ppnn	28.29566 (20)	0	1.6755 ± 0.0028	1.9	[32, 33]
	$^4_\Lambda\text{H}$	p Λ nn	2.04 ± 0.04	0	2.0 – 3.8	2.4 – 4.9	[27, 31]
	$^4_{\Lambda\Lambda}\text{H}$	p $\Lambda\Lambda$ n	0.39 – 0.51	1	4.2 – 7.1	5.5 – 9.4	[27]
	$^4_\Lambda\text{He}$	pp Λ n	2.39 ± 0.03	0	2.0 – 3.8	2.4 – 4.9	[27, 31]

Table 1. Properties of nuclei and hyper-nuclei with mass number $A \leq 4$. B_E is the binding energy in MeV. The size parameter r_A , is chosen to approximately reproduce the measured/expected rms, λ_A^{meas} (fm). The proton rms charge radius $\lambda_p = 0.879(8)$ fm is subtracted quadratically from the measured rms charge radius λ_A^{meas} of the nucleus $\lambda_A = \sqrt{(\lambda_A^{meas})^2 - \lambda_p^2}$ to account for the finite extension of the constituents. Implicitly we assume here that $\lambda_\Lambda \approx \lambda_n \approx \lambda_p$.

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2.1. The coalescence approach

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In the coalescence picture, nucleons produced in the collision coalesce into nuclei if they are close in space and have similar velocities [1–3]. The coalescence probability is encoded in the coalescence parameter, B_A . Considering that at LHC energies the number of produced protons and neutrons at midrapidity as well as their momentum distributions are expected to be equal, B_A is defined as

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$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Big|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}, \quad (1)$$

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where $p_{p,n}$ are the proton and neutron momenta and $E_{p,n}$ their energies. Equation 1 represents also the operative definition of B_A that is used by experiments like ALICE to extract the coalescence probability starting from the measured nucleus and nucleon (proton) distributions. Starting from the model described in [3, 4], we have obtained in [14] a generalised expression for B_A

$$B_A = \frac{2J_A + 1}{2^A} \frac{1}{\sqrt{A}} \frac{1}{m_T^{A-1}} \left(\frac{2\pi}{R^2 + (\frac{r_A}{2})^2} \right)^{\frac{3}{2}(A-1)}, \quad (2)$$

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which is a function of the spin of the particle J_A , its transverse mass m_T , its size parameter r_A and the source radius R . Very importantly, Eq. 2

127 takes explicitly into account the source size (R), as the coalescence proba-
 128 bility naturally decreases for nucleons with similar momenta that are pro-
 129 duced far apart in configuration space. Moreover, the source size is identified
 130 with the effective sub-volume of the whole system that is governed by the
 131 (momentum-dependent) homogeneity length of the interacting nucleons and
 132 experimentally accessible with Hanbury-Brown-Twiss (HBT) interferome-
 133 try [3,4]. Figure 1 shows the source radius dependence of B_A for nuclei and
 134 hyper-nuclei with $A = 2, 3$ and 4 whose properties are reported in Tab. 1.
 135 For the cases in which more than one estimate for r_A is available, we have
 adopted the lowest value for the calculations in Fig. 1. We observe that the

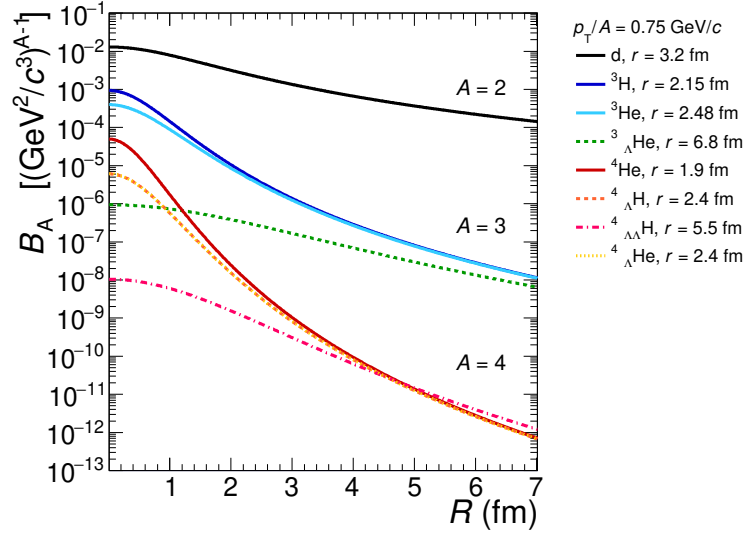


Fig. 1. (Color online) Coalescence parameter B_A as a function of the source radius R as predicted from the coalescence model (Eq. 2) for various composite objects with $p_T/A = 0.75$ GeV/ c . For each (hyper-)nucleus, the radius r used for the calculation is reported in the legend.

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 137 coalescence probability decreases with increasing mass number and B_A de-
 138 creases with increasing volume. For a given A , the larger the object radius,
 139 the lower is B_A , as clearly visible by comparing ${}^3\text{He}$ and ${}^3_\Lambda\text{H}$. For objects
 140 with same A , mass and spin (e.g. the isobars ${}^3\text{H}$ and ${}^3\text{He}$), B_A differs only
 141 due to the different radius r_A . This difference is more relevant in small sys-
 142 tems, because in large systems the difference between nucleus radii is much
 143 smaller than the size of the source. Incidentally, this could be experimentally
 144 verified with high precision measurements of the production of ${}^3\text{H}$ relative

145 to ${}^3\text{He}$ in pp collisions. The production of objects with radius larger than
 146 the source is strongly suppressed, indicating that the process is driven by
 147 the length scale defined by the object radius relative to the source radius.

148 2.2. Thermal + blast-wave model

149 Thermal-statistical models [5, 6] have been successful in describing the
 150 production of light (anti-)(hyper-)nuclei across a wide range of energies in
 151 AA collisions, including production at the LHC. In this approach, par-
 152 ticles are produced from a fireball in thermal equilibrium with tempera-
 153 tures of $T_{\text{chem}} \approx 156$ MeV. Particle yields are derived from the partition
 154 function assuming a Grand Canonical ensemble² and they depend only
 155 on the mass of the particle and the temperature of chemical freeze-out,
 156 $dN/dy \propto \exp(-m/T_{\text{chem}})$. The thermal model cannot – alone – be com-
 157 pared to the p_{T} -dependent coalescence description because it provides only
 158 predictions for p_{T} -integrated yields. A thermal particle production implies
 159 a Boltzmann distribution of the momenta only for a static source, which
 160 is not the case of the rapidly expanding system produced in heavy-ion col-
 161 lisions. The thermal model (i.e. the GSI-Heidelberg implementation we
 162 have considered here) needs to be complemented by a hydrodynamic de-
 163 scription of the rapidly expanding source. To that end, we use the Blast-
 164 Wave model [35], which has been proven to describe reasonably well the
 165 measured momentum distributions of protons [36]. Our “thermal+blast-
 166 wave” approach results from the combination of the two models: the p_{T} -
 167 dependence is modelled by the blast-wave whereas the normalisation (i.e.
 168 the p_{T} -integrated yield) is taken from the thermal model predictions. In
 169 particular, to shape the (hyper-)nucleus transverse momentum distributions
 170 we use the blast-wave parameters obtained from the simultaneous fit to
 171 pion, kaon and proton spectra measured in Pb–Pb collisions by ALICE
 172 for several centralities/multiplicities and reported in [36]. We therefore in-
 173 herit the multiplicity-dependence of the radial expansion of the system from
 174 the measurements. The object size does not enter in the formulation of
 175 the blast-wave model. In our thermal+blast-wave model, for each central-
 176 ity/multiplicity class, the coalescence parameter is extracted according to
 177 Eq. 1 (as done for data) from the predicted (hyper-)nucleus spectrum and
 178 the proton spectrum measured by ALICE [36].

² Extensions to small systems employ a canonical ensemble partition function to ac-
 count for the exact conservation of quantum numbers in a finite size system, see for
 instance [34].

3. Results and discussion

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180 As discussed in the previous sections, the coalescence model describe the
 181 coalescence parameter

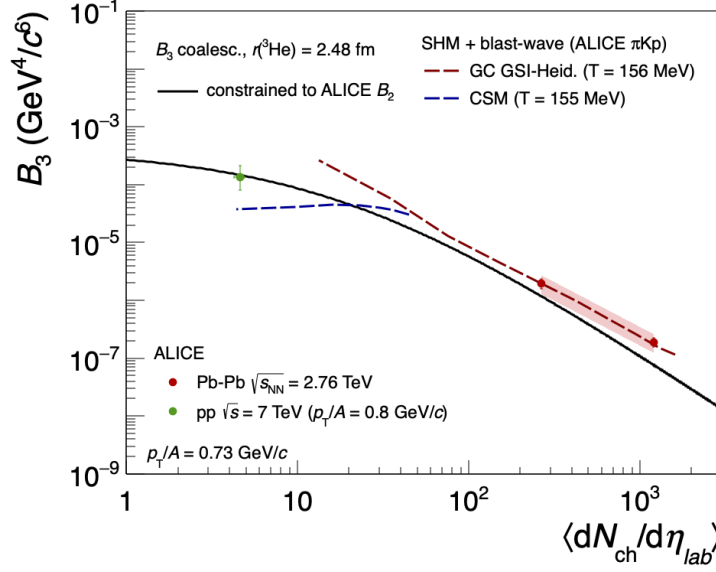


Fig. 2. (Color online) Coalescence parameter B_3 for ^3He as a function of the average charged particle multiplicity density. The coalescence calculation (continuous black line) is compared to two thermal+blast-wave predictions (dashed lines), obtained by using the Grand Canonical (GC, red) [6] and Canonical Statistical Model (CSM, blue) [34] expectations for the ^3He yield, respectively. ALICE data from pp (green circles) and Pb-Pb (red circles) collisions [7,9] are reported.

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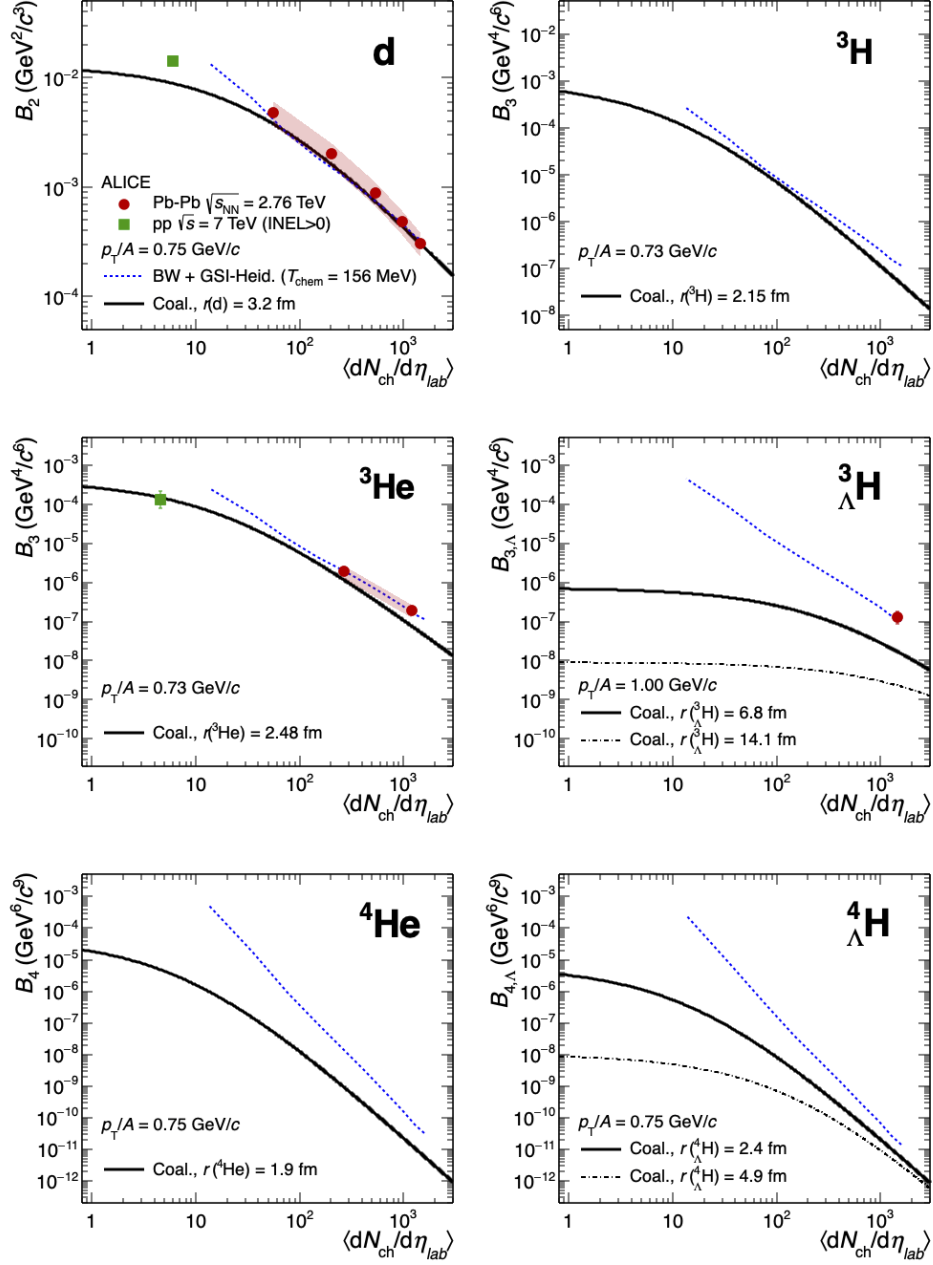


Fig. 3. (Color online) Coalescence parameter B_A as a function of the average charged particle multiplicity density for various (hyper-)nuclei, up to $A = 4$. The coalescence calculations (continuous or dashed-dotted black lines) are compared to the thermal+blast-wave predictions (dashed blue line), as well as to pp (green square) and Pb-Pb (red circles) collision data from ALICE [7–9].