



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 [1–6] or thermal-statistical production at the chemical freeze-out [7, 8]. 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 [9–15], thus providing a crucial experimental input and a boost to theoretical and phenomenological investigations [16–22]. 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 [22–25]. 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 [17] 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 [26]. 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 [27]. 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 [28, 29]. 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 [17] 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-matter<sup>1</sup>. 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 ( $\lambda_A$ ), 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 [31], driven by the average separation of the  $\Lambda$  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  $\Lambda$  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  $\lambda_A$  and  $r_A$ , see [17]. 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  $\Lambda$  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.

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

| Mass<br>number | Nucleus                       | Compo-<br>sition     | $B_E$ (MeV)     | Spin<br>$J_A$ | (Charge)<br>rms radius<br>$\lambda_A^{meas}$ (fm) | Harmonic<br>oscillator<br>size<br>parameter<br>$r_A$ (fm) | Refs.    |
|----------------|-------------------------------|----------------------|-----------------|---------------|---|---|----------|
| A = 2          | d                             | pn                   | 2.224575 (9)    | 1             | $2.1413 \pm 0.0025$                               | 3.2   | [32, 33] |
| A = 3          | $^3\text{H}$                  | pnn                  | 8.4817986 (20)  | 1/2           | $1.755 \pm 0.086$                                 | 2.15  | [34]     |
|                | $^3\text{He}$                 | ppn                  | 7.7180428 (23)  | 1/2           | $1.959 \pm 0.030$                                 | 2.48  | [34]     |
|                | $^3_\Lambda\text{H}$          | p $\Lambda$ n        | $0.13 \pm 0.05$ | 1/2           | 4.9 – 10.0  | 6.8 – 14.1  | [31, 35] |
| A = 4          | $^4\text{He}$                 | ppnn                 | 28.29566 (20)   | 0             | $1.6755 \pm 0.0028$                               | 1.9   | [36, 37] |
|                | $^4_\Lambda\text{H}$          | p $\Lambda$ nn       | $2.04 \pm 0.04$ | 0             | 2.0 – 3.8   | 2.4 – 4.9   | [31, 35] |
|                | $^4_{\Lambda\Lambda}\text{H}$ | p $\Lambda\Lambda$ n | 0.39 – 0.51     | 1             | 4.2 – 7.1   | 5.5 – 9.4   | [31]     |
|                | $^4_\Lambda\text{He}$         | pp $\Lambda$ n       | $2.39 \pm 0.03$ | 0             | 2.0 – 3.8   | 2.4 – 4.9   | [31, 35] |

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,  $\lambda_A^{meas}$  (fm). The proton rms charge radius  $\lambda_p = 0.879(8)$  fm is subtracted quadratically from the measured rms charge radius  $\lambda_A^{meas}$  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 [1–5]. 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 [5, 6], we have obtained in [17] 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 [5,6]. 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

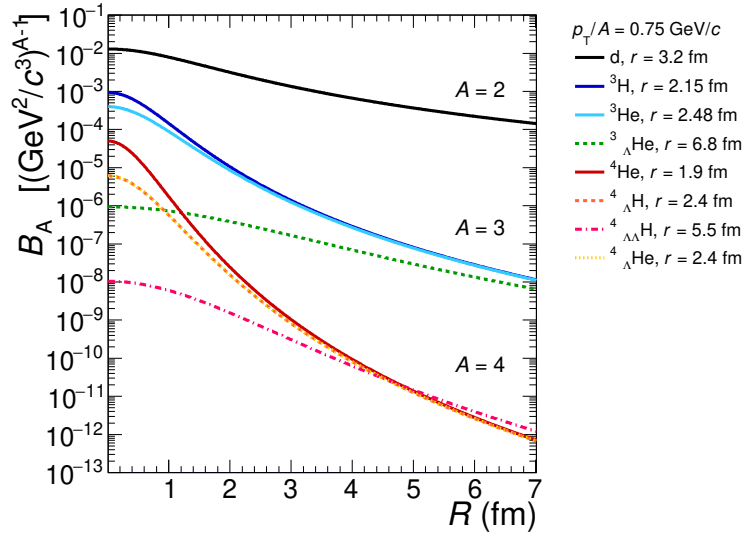


Fig. 1. (Color online) Coalescence parameter  $B_A$  as a function of the source radius  $R$  as predicted from the coalescence model (Eq. 2) for various composite objects with  $p_T/A = 0.75$  GeV/ $c$ . For each (hyper-)nucleus, the radius  $r$  used for the calculation is reported in the legend.

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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.

144 The production of objects with radius larger than the source is strongly

145 suppressed, indicating that the process is driven by the lenght scale defined  
 146 by the object radius relative to the source radius.

## 147 2.2. Thermal + blast-wave model

148 Thermal-statistical models [7,8] have been successful in describing the  
 149 production of light (anti-)(hyper-)nuclei across a wide range of energies in  
 150 AA collisions, including production at the LHC. In this approach, particles  
 151 are produced from a fireball in thermal equilibrium with temperatures of  
 152  $T_{chem} \approx 156$  MeV. The thermal model cannot – alone – be compared to the  
 153  $p_T$ -dependent coalescence description because it provides only predictions  
 154 for  $p_T$ -integrated yields. A thermal particle production implies a Boltzmann  
 155 distribution of the momenta only for a static source, which is not the case of  
 156 the rapidly expanding system produced in heavy-ion collisions. The thermal  
 157 model (i.e. the GSI-Heidelberg implementation we have considered) needs to  
 158 be complemented by a hydrodynamic description of the rapidly expanding  
 159 source. To that end, we chose to use the Blast-Wave model, which has been  
 160 proven to describe reasonably well the measured momentum distributions of  
 161 protons. Our “thermal+blast-wave” approach results from the combination  
 162 of the two models: the  $p_T$ -dependence is modelled by the blast-wave whereas  
 163 the normalisation (i.e. the  $p_T$ -integrated yield) is taken from the thermal  
 164 model predictions.

## 165 3. Comparison with data

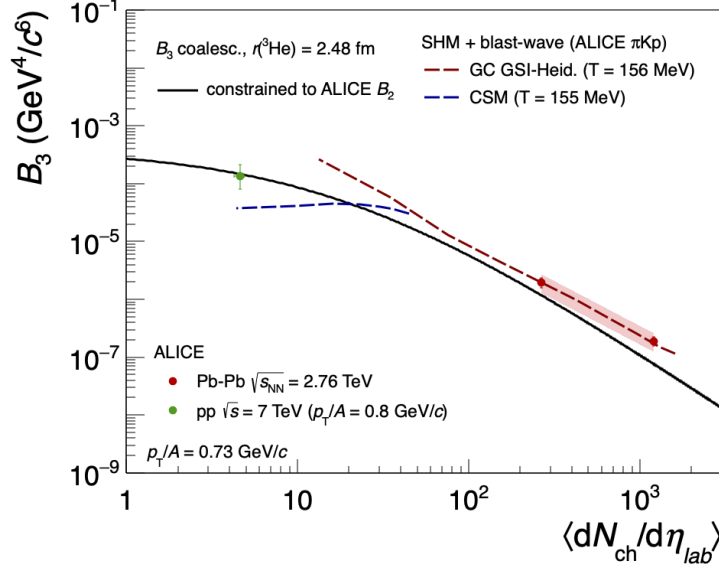


Fig. 2. (Color online) Coalescence parameter  $B_3$  for  $^3\text{He}$  as a function of the average charged particle multiplicity density. The coalescence calculation (continuous black line) is compared to two thermal+blast-wave predictions (dashed lines), obtained by using the Grand Canonical (GC, red) [8] and Canonical Statistical Model (CSM, blue) [39] expectations for the  $^3\text{He}$  yield, respectively. ALICE data from pp (green circles) and Pb-Pb (red circles) collisions [9, 13] are reported.

## REFERENCES

- 166 [1] S. T. Butler and C. A. Pearson *Phys. Rev.* **129** (1963) 836–842.
- 167 [2] J. I. Kapusta *Phys. Rev.* **C21** (1980) 1301–1310.
- 168 [3] H. Sato and K. Yazaki *Phys. Lett.* **B98** (1981) 153–157.
- 169 [4] J. L. Nagle, B. S. Kumar, D. Kusnezov, H. Sorge, and R. Mattiello *Phys.*  
170 *Rev.* **C53** (1996) 367–376.
- 171 [5] R. Scheibl and U. W. Heinz *Phys. Rev.* **C59** (1999) 1585–1602,  
172 [arXiv:nuc1-th/9809092](#) [nucl-th].
- 173 [6] K. Blum, K. C. Y. Ng, R. Sato, and M. Takimoto *Phys. Rev.* **D96** no. 10,  
174 (2017) 103021, [arXiv:1704.05431](#) [astro-ph.HE].
- 175 [7] A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stocker *Physics Letters*  
176 *B* **697** no. 3, (2011) 203 – 207.
- 177 [8] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel *Nature* **561**  
178 no. 7723, (2018) 321–330, [arXiv:1710.09425](#) [nucl-th].



- 179 [9] **ALICE** Collaboration, J. Adam *et al.* *Phys. Rev.* **C93** no. 2, (2016) 024917,  
180 arXiv:1506.08951 [nucl-ex].
- 181 [10] **ALICE** Collaboration, J. Adam *et al.* *Phys. Lett.* **B754** (2016) 360–372,  
182 arXiv:1506.08453 [nucl-ex].
- 183 [11] Anielski, Jonas *J. Phys. Conf. Ser.* **612** no. 1, (2015) 012014.
- 184 [12] **ALICE** Collaboration, M. Puccio *Nucl. Phys.* **A982** (2019) 447–450.
- 185 [13] **ALICE** Collaboration, S. Acharya *et al.* *Phys. Rev.* **C97** no. 2, (2018)  
186 024615, arXiv:1709.08522 [nucl-ex].
- 187 [14] **ALICE** Collaboration, S. Acharya *et al.* *Eur. Phys. J.* **C77** no. 10, (2017)  
188 658, arXiv:1707.07304 [nucl-ex].
- 189 [15] **ALICE** Collaboration, S. Acharya *et al.* arXiv:1902.09290 [nucl-ex].
- 190 [16] S. Mrowczynski *Acta Phys. Polon.* **B48** (2017) 707, arXiv:1607.02267  
191 [nucl-th].
- 192 [17] F. Bellini and A. P. Kalweit arXiv:1807.05894 [hep-ph].
- 193 [18] S. Bazak and S. Mrowczynski *Mod. Phys. Lett.* **A33** no. 25, (2018) 1850142,  
194 arXiv:1802.08212 [nucl-th].
- 195 [19] W. Zhao, L. Zhu, H. Zheng, C. M. Ko, and H. Song *Phys. Rev.* **C98** no. 5,  
196 (2018) 054905, arXiv:1807.02813 [nucl-th].
- 197 [20] K.-J. Sun, C. M. Ko, and B. Doenigus arXiv:1812.05175 [nucl-th].
- 198 [21] X. Xu and R. Rapp arXiv:1809.04024 [nucl-th].
- 199 [22] D. Oliinychenko, L.-G. Pang, H. Elfner, and V. Koch arXiv:1809.03071  
200 [hep-ph].
- 201 [23] H. Garcilazo *Phys. Rev. Lett.* **48** (1982) 577–580.
- 202 [24] S. A. Bass *et al.* *Prog. Part. Nucl. Phys.* **41** (1998) 255–369,  
203 arXiv:nucl-th/9803035 [nucl-th].
- 204 [25] J. Schukraft *Nucl. Phys.* **A967** (2017) 1–10, arXiv:1705.02646 [hep-ex].
- 205 [26] Z. Citron *et al.* in *HL/HE-LHC Workshop: Workshop on the Physics of*  
206 *HL-LHC, and Perspectives at HE-LHC Geneva, Switzerland, June 18-20,*  
207 *2018.* 2018. arXiv:1812.06772 [hep-ph].
- 208 [27] T. Aramaki *et al.* *Phys. Rept.* **618** (2016) 1–37, arXiv:1505.07785  
209 [hep-ph].
- 210 [28] M. Cirelli, N. Fornengo, M. Taoso, and A. Vittino *JHEP* **08** (2014) 009,  
211 arXiv:1401.4017 [hep-ph].
- 212 [29] M. Korsmeier, F. Donato, and N. Fornengo *Phys. Rev.* **D97** no. 10, (2018)  
213 103011, arXiv:1711.08465 [astro-ph.HE].
- 214 [30] **ALICE** Collaboration, J. Adam *et al.* *Phys. Rev.* **C93** no. 2, (2016) 024905,  
215 arXiv:1507.06842 [nucl-ex].
- 216 [31] H. Nemura, Y. Suzuki, Y. Fujiwara, and C. Nakamoto *Prog. Theor. Phys.*  
217 **103** (2000) 929–958, arXiv:nucl-th/9912065 [nucl-th].
- 218 [32] C. Van Der Leun and C. Alderliesten *Nucl. Phys.* **A380** (1982) 261–269.
- 219 [33] P. J. Mohr, D. B. Newell, and B. N. Taylor *Rev. Mod. Phys.* **88** no. 3, (2016)  
220 035009, arXiv:1507.07956 [physics.atom-ph].

- 221 [34] J. E. Purcell and C. G. Sheu *Nucl. Data Sheets* **130** (2015) 1–20.
- 222 [35] D. H. Davis *Nucl. Phys.* **A754** (2005) 3–13.
- 223 [36] M. Wang, G. Audi, F. Kondev, W. Huang, S. Naimi, and X. Xu *Chinese*  
224 *Physics C* **41** no. 3, (2017) 030003.
- 225 [37] I. Angeli and K. P. Marinova *Atom. Data Nucl. Data Tabl.* **99** no. 1, (2013)  
226 69–95.
- 227 [38] **A1** Collaboration, J. C. Bernauer *et al. Phys. Rev. Lett.* **105** (Dec, 2010)  
228 242001.
- 229 [39] V. Vovchenko, B. Doenigus, and H. Stoecker *Phys. Lett.* **B785** (2018)  
230 171–174, [arXiv:1808.05245](#) [hep-ph].

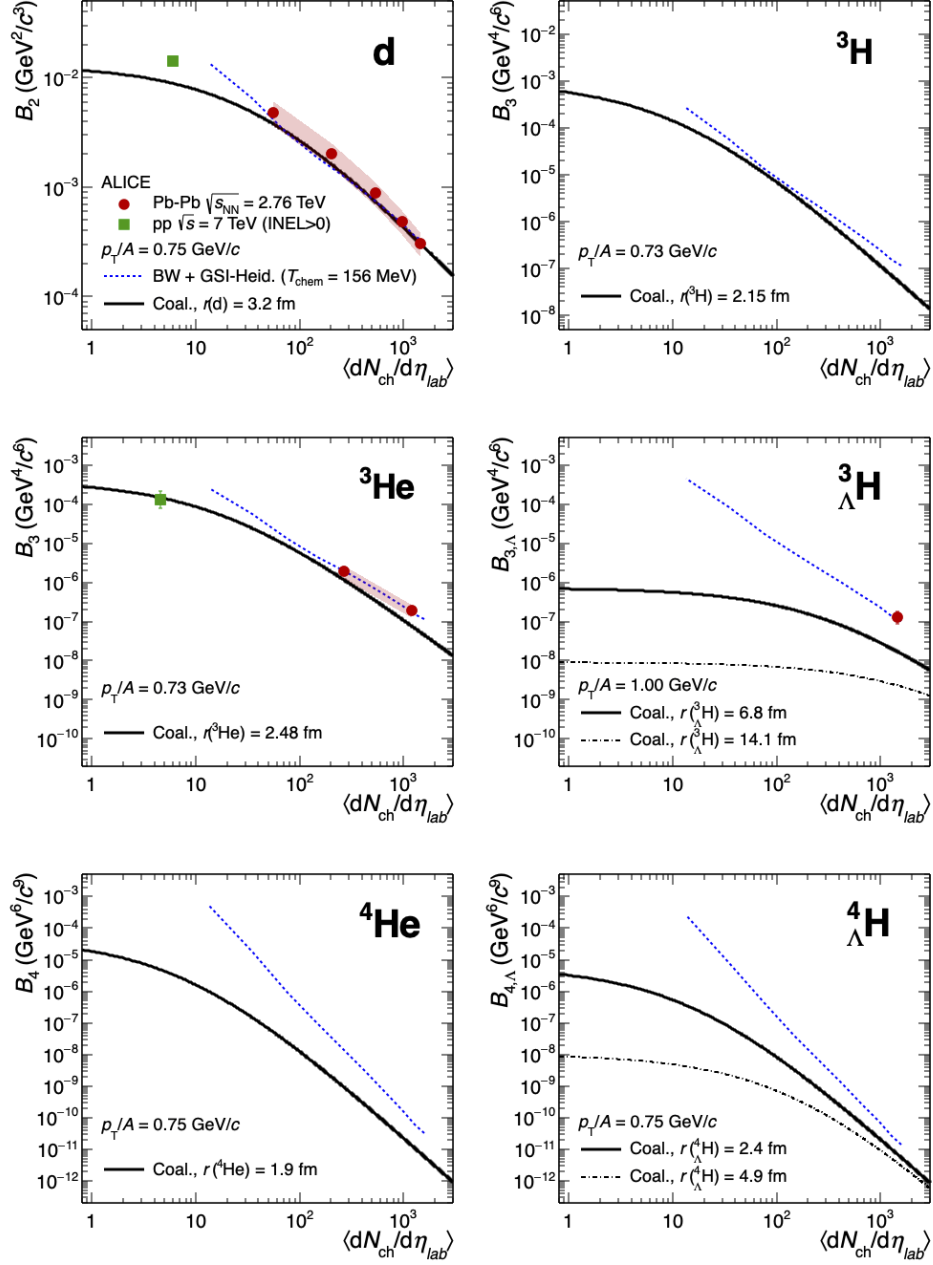


Fig. 3. (Color online) Coalescence parameter  $B_A$  as a function of the average charged particle multiplicity density for various (hyper-)nuclei, up to  $A = 4$ . The coalescence calculations (continuous or dashed-dotted black lines) are compared to the thermal+blast-wave predictions (dashed blue line), as well as to pp (green square) and Pb-Pb (red circles) collision data from ALICE [9, 10, 13].