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

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XXV Cracow EPIPHANY Conference
on Advances in Heavy Ion Physics
Cracow, 10th January 2019

Based on the work with A.Kalweit, arXiv:1807.05894

(Anti-)nuclei and hyper-nuclei production measured by ALICE in all collision systems

ALICE, NPA 971 (2018) 1-20; PRC 97 (2018) 024615; EPJ. C 77 (2017) 658; PRC 93 (2015) 024917; multiplicity dependence of d production in pp and p-Pb: in preparation

Two main approaches to describe (anti-)(hyper-)nuclei production:

Thermal production at chemical freeze-out/phase boundary

works in Pb-Pb collisions

→ how can loosely-bound states survive the hadronic phase?

Coalescence of nucleons at kinetic freeze-out

works in small systems

→ how can ''large'' objects be created in the system?

We propose a **direct comparison** of the coalescence and thermal model approach based on the **coalescence parameter B_A as the key observable:**

$$E_A \frac{dN_A}{d^3P_A} = \underline{B_A} \left(E_p \frac{dN_p}{d^3P_p} \right)^Z \left(E_n \frac{dN_n}{d^3P_n} \right)^N \Bigg|_{P_p = P_n = P_A/A}$$

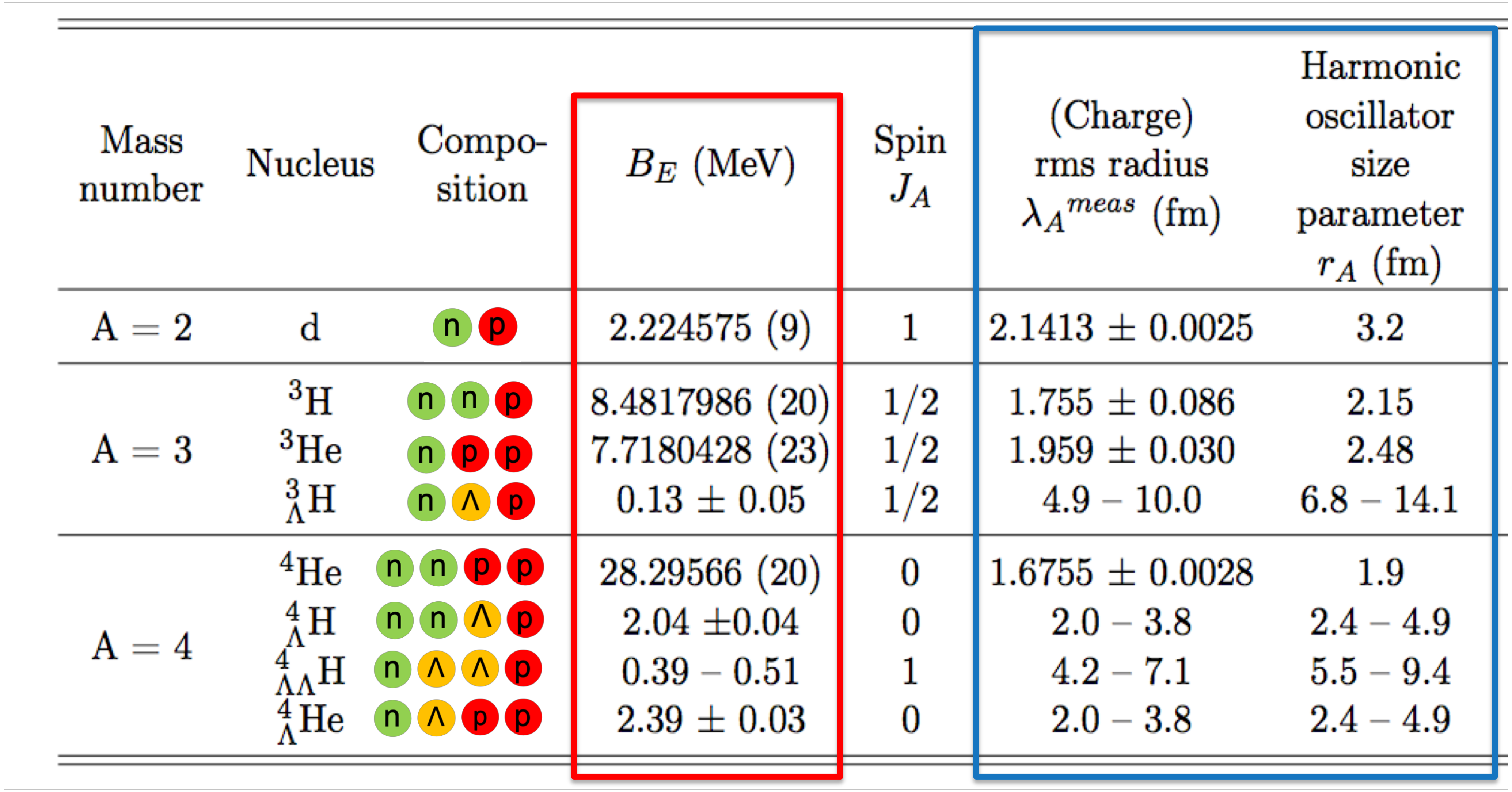
measure **different nuclei and hyper-nuclei up to A = 4**

as a function of the **source size**

sampled via **multiplicity-differential measurements**

that appear to be feasible at the LHC Runs 3+4.

Properties of (anti-)(hyper-)nuclei with A ≤ 4

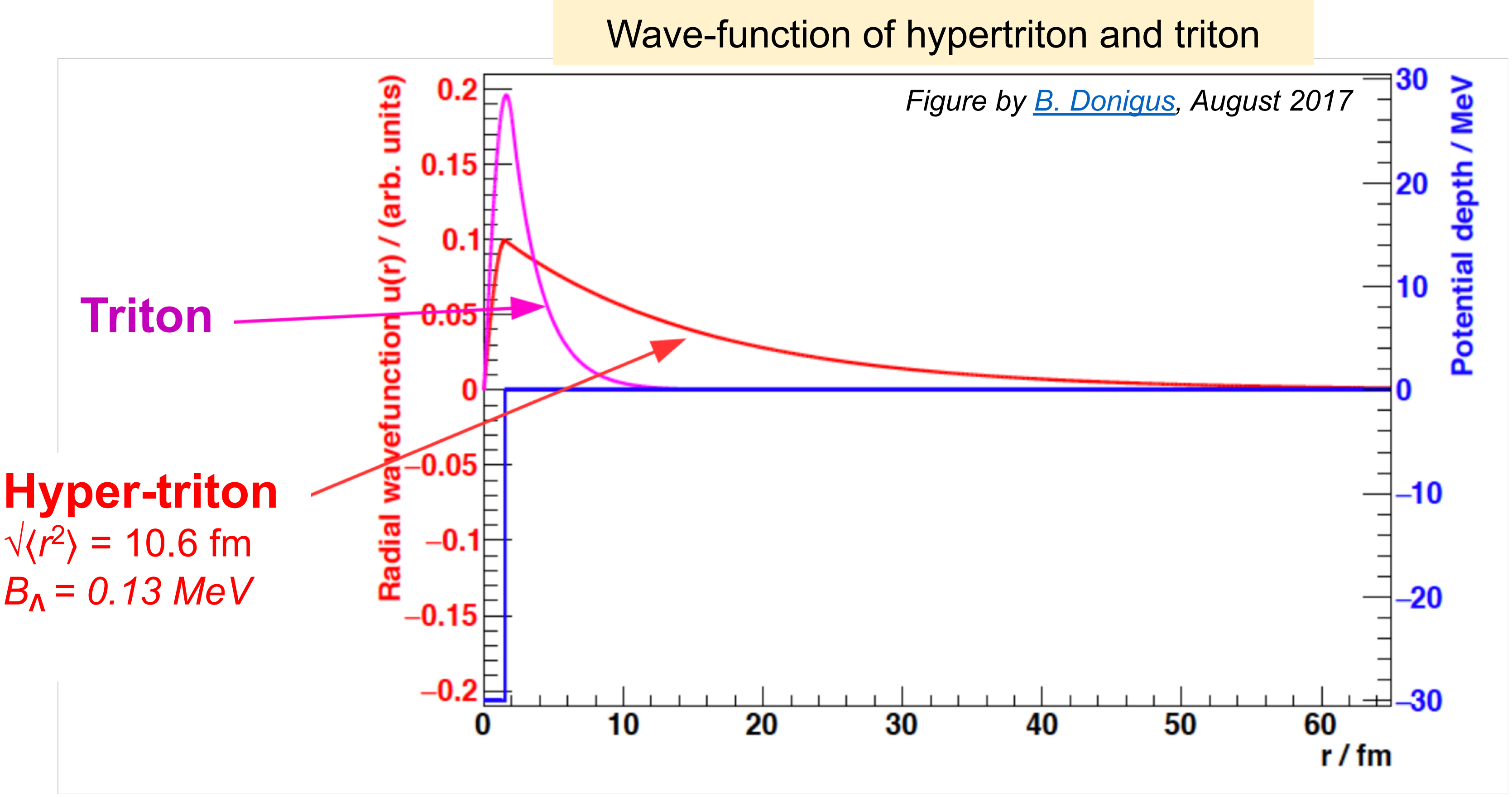


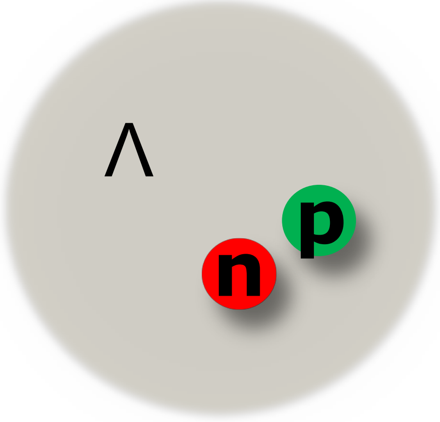
Mass number	Nucleus	Composition	B_E (MeV)	Spin J_A	(Charge) rms radius $\lambda_A{}^{meas}$ (fm)	Harmonic oscillator size parameter r_A (fm)
A = 2	d	n p	2.224575 (9)	1	2.1413 ± 0.0025	3.2
A = 3	^{3}H	n n p	8.4817986 (20)	1/2	1.755 ± 0.086	2.15
	^{3}He	n p p	7.7180428 (23)	1/2	1.959 ± 0.030	2.48
	$^3_\Lambda$H	n Λ p	0.13 ± 0.05	1/2	4.9 – 10.0	6.8 – 14.1
A = 4	^{4}He	n n p p	28.29566 (20)	0	1.6755 ± 0.0028	1.9
	$^4_\Lambda$H	n n Λ p	2.04 ±0.04	0	2.0 – 3.8	2.4 – 4.9
	$^4_{\Lambda\Lambda}$H	n Λ Λ p	0.39 – 0.51	1	4.2 – 7.1	5.5 – 9.4
	$^4_\Lambda$He	n Λ p p	2.39 ± 0.03	0	2.0 – 3.8	2.4 – 4.9

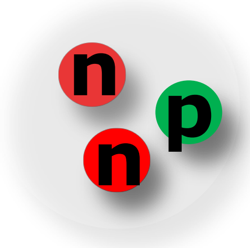
“Fragile” objects in HIC

Different sizes

Hyper-triton wave-function





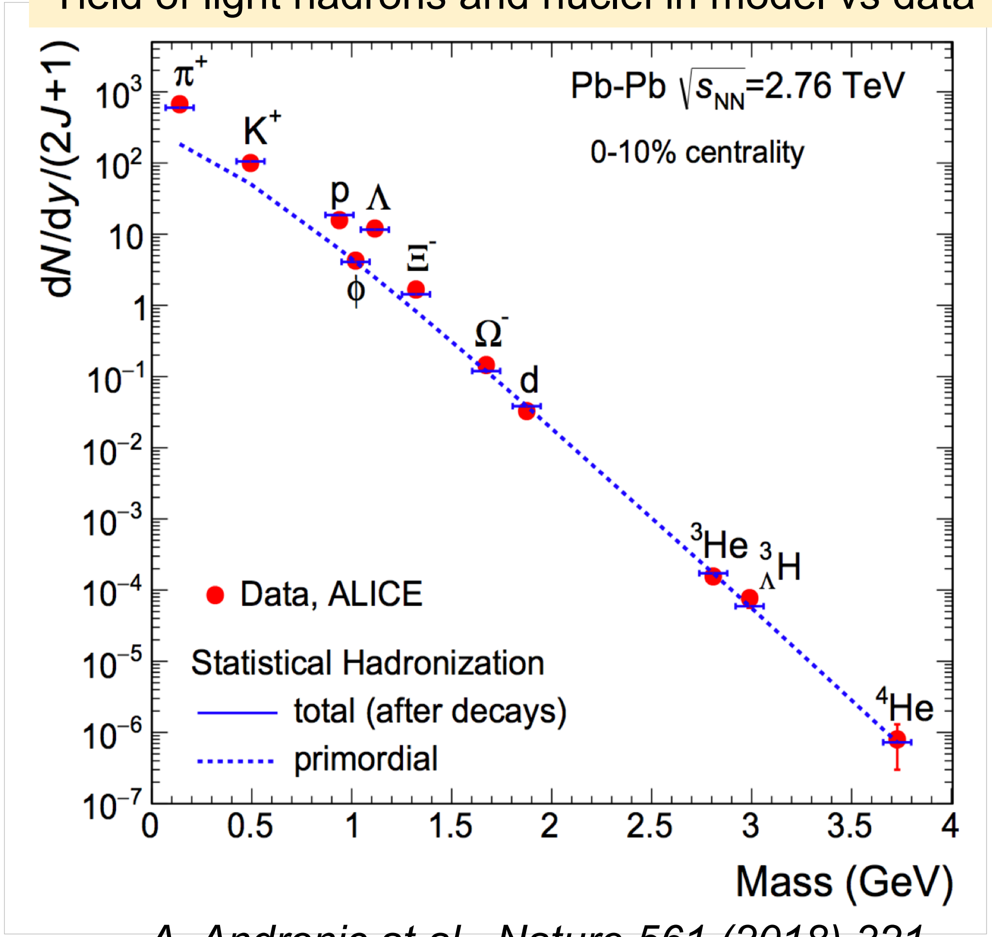


Assuming a similar structure (s-wave interaction for a bound state of a n or **Λ** with a deuteron), the hypertriton results in a much larger object than the triton.

Thermal-statistical hadronisation model

- (Hyper-)nuclei produced with light-flavor hadrons from a fireball in chemical equilibrium
- Yields are determined only by mass and chemical freeze-out temperature: **$dN/dy \sim \exp(-m/T_{ch})$**
  - Derived from partition function
  - Nuclei not considered as composite objects (B_E does not enter)
  - Does not predict p_T dependence
- Due to their large mass, (hyper-)nuclei are particularly sensitive to the temperature T_{ch}
- (Hyper-)nuclei are not affected by feeddown from higher-mass states, contrary to light hadrons (hadronic resonance decays)

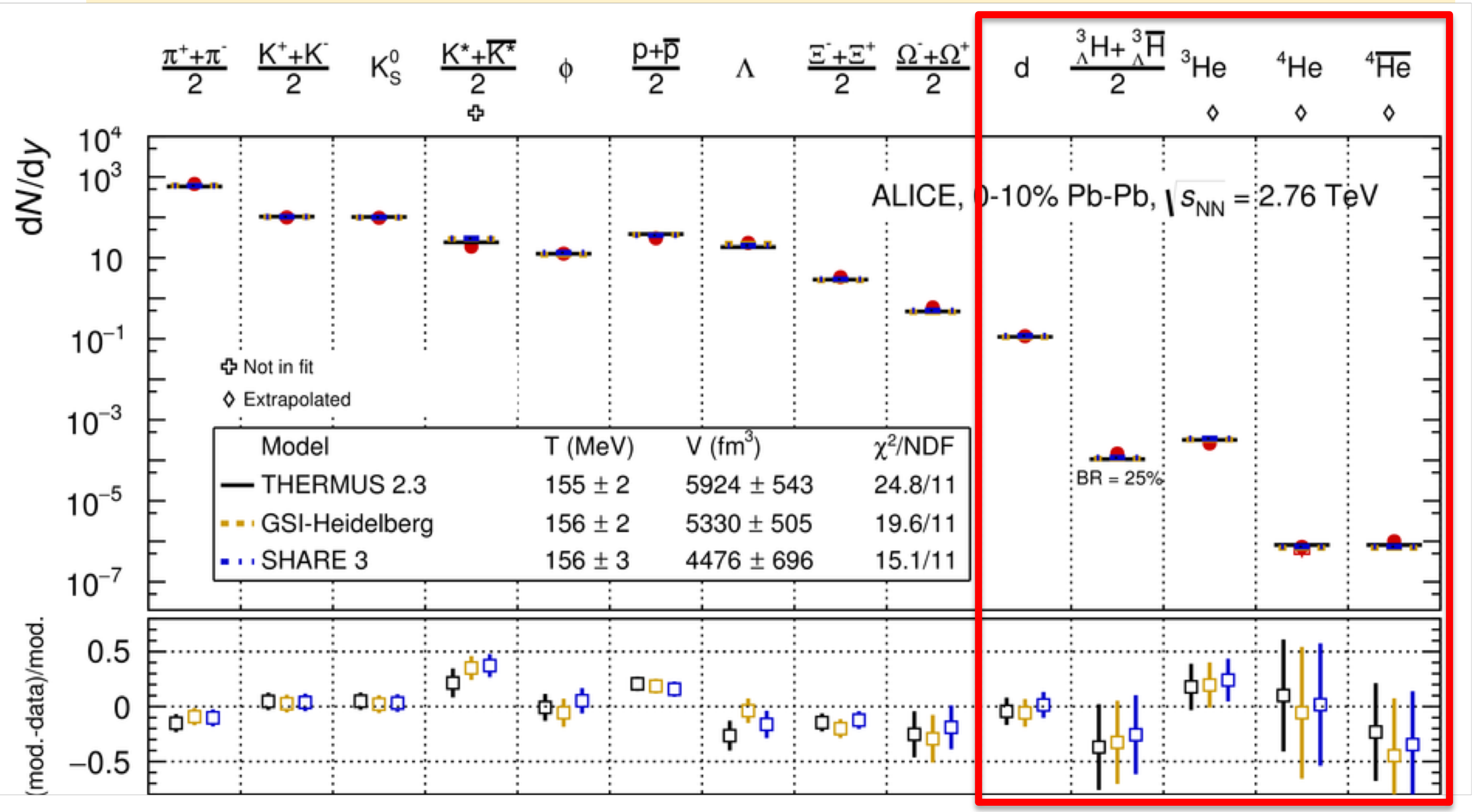
Yield of light hadrons and nuclei in model vs data



A. Andronic at al., Nature 561 (2018) 321
Phys. Lett. B 697, 203 (2011)]

Thermal fit to ALICE data

Thermal model fit to the measured p_T-integrated yields of light flavor hadrons and (anti-)(hyper-)nuclei in central Pb-Pb collisions

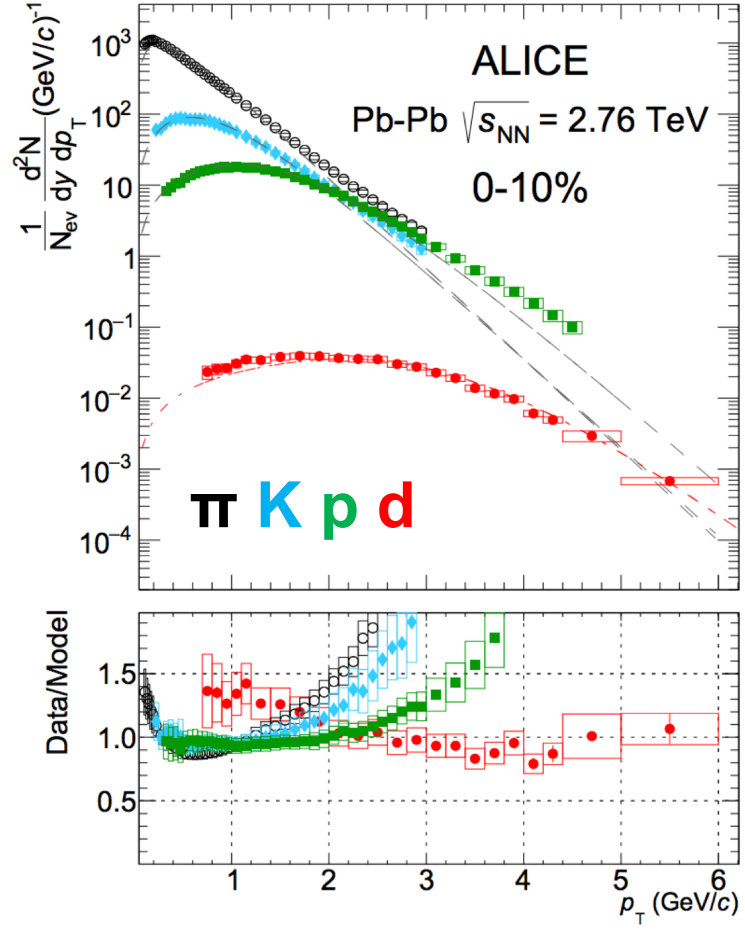


Production of light (anti-)(hyper-) nuclei is described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out** temperature, **T_{ch} ≈ 156 MeV** with other light-flavour hadrons **despite their low binding energy**!

Figure from ALICE, Nucl. Phys. A 971 (2018) 1-20
THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, arXiv:1310.5108

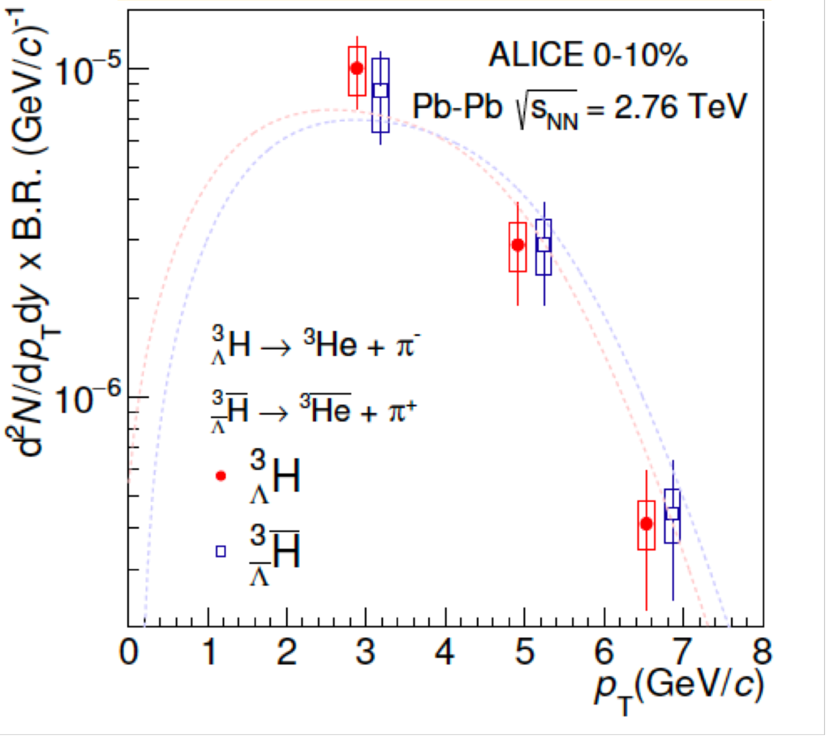
(Anti-)nuclei survival puzzle

Simultaneous Blast-wave model fit to π,K,p,d spectra and v_2



ALICE, Eur. Phys. J. C77 (2017) 658

Blast-wave model compared to hypertriton spectrum



ALICE, Phys. Lett. B 754 (2016) 360-372

The deuteron is observed to participate in the collective expansion (radial flow) of the fireball with **the same radial velocity as other hadrons**

If produced at chemical freeze-out, how can (anti-)(hyper-) nuclei survive the hadronic phase?

R. Scheibl, U. Heinz, (1999) PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

Coalescence

- Nuclei form at kinetic freeze-out by coalescence of nucleons close enough in phase-space

- Production depends on **coalescence probability *B*$_A$**

$$\underbrace{E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3}}_{\text{Nucleus distributions}} = \boxed{B_A} \left(\underbrace{E_{\mathrm{p,n}} \frac{\mathrm{d}^3 N_{\mathrm{p,n}}}{\mathrm{d}p_{\mathrm{p,n}}^3}}_{\text{Nucleon distributions}} \right)^A \Bigg|_{\vec{p}_{\mathrm{p}} = \vec{p}_{\mathrm{n}} = \frac{\vec{p}_A}{A}}$$

R. Scheibl, U. Heinz, (1999) PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

Coalescence

- Nuclei form at kinetic freeze-out by coalescence of nucleons close enough in phase-space

- Production depends on **coalescence probability B_A**, i.e. on the **overlap of the nucleus Wigner function with the phase-space distributions of the constituents**

- Calculated with density matrix approach, assuming
  - source rapidly **expanding under radial flow** (blast wave in Scheibl-Heinz)
  - **Gaussian wave-functions** (size parameter = r_A) **for (hyper-)nuclei**

Spin

$$B_A = \frac{2J_A + 1}{2^A} \frac{1}{\sqrt{A}} \langle C_A \rangle \left(\frac{(2\pi)^{3/2}}{m_T \prod_{i=1,2,3} R_i} \right)^{A-1}$$

Source radii

Quantum-mechanical correction factor

Nucleus transverse mass
$m_T = \sqrt{(p_T^2 + m^2)}$

R. Scheibl, U. Heinz, (1999) PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

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    - **Gaussian wave-functions** (size parameter = r_A) **for (hyper-)nuclei**
    - $\langle C_A \rangle$ introduces a length scale defined by the **size of the object** being produced (r_A) **relative to the size of the source** (R_i)

$$\langle C_A \rangle = \prod_{i=1,2,3} \left(1 + \frac{r^2}{4R_i^2}\right)^{-\frac{1}{2}(A-1)}$$

R. Scheibl, U. Heinz, (1999) PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021
FB, A. Kalweit, arXiv:1807.05894v2

Coalescence

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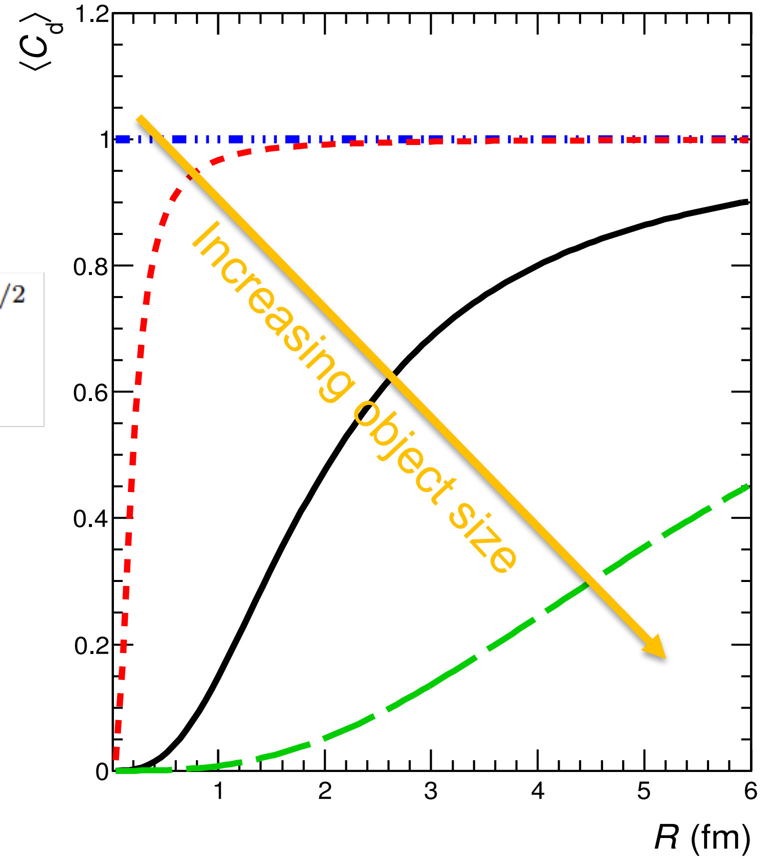
  - $\langle C_A \rangle$ introduces a length scale defined by the **size of the object** being produced (r_A) **relative to the size of the source** (R_i)
  - The coalescence process is governed by the same **correlation volume** which can be extracted from **Hanbury-Brown-Twiss interferometry**
  - For the source, $R_\perp \approx R_\parallel \approx R$ is assumed

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

Coalescence probability for deuteron

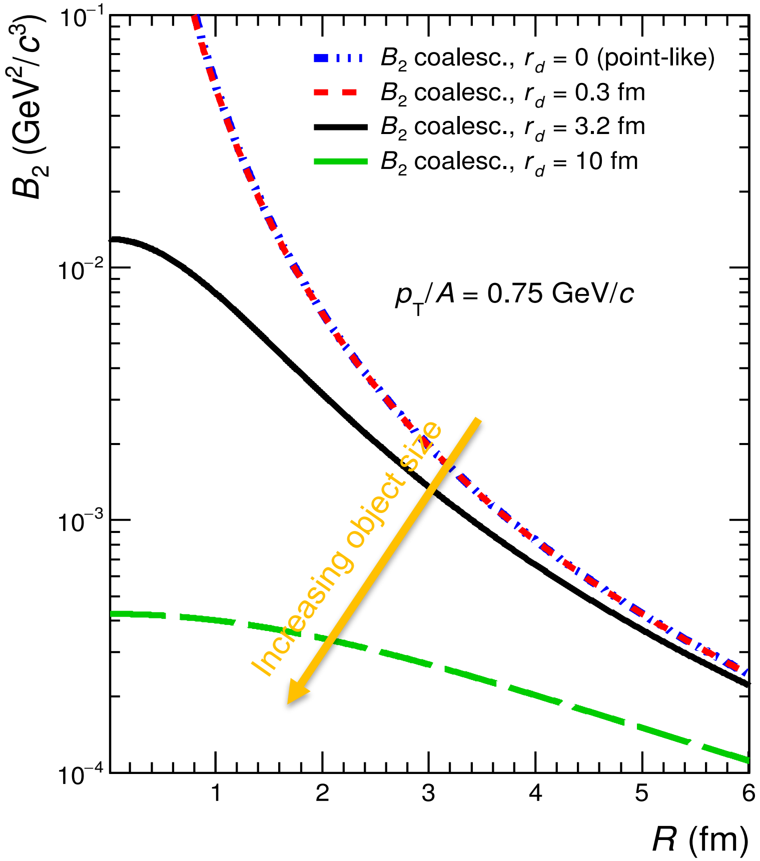
$$\langle C_d \rangle \approx \left[1 + \left(\frac{r_d}{2R(m_T)}\right)^2\right]^{-3/2}$$

Quantum-mechanical factor



Increasing source size

Coalescence parameter



$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2m_T R^3(m_T)}$$

FB, A. Kalweit, arXiv:1807.05894

Comparing production models

Coalescence model

- derives **analytic expression** for B_A
- explicit dependence on R, A, r_A, m_T

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

Data:

- B_A from **measured** (hyper-)nuclei and proton spectra
- Multiplicity ⟶ source radius mapping from parameterization of HBT data

$$E_A\frac{\mathrm{d}^3N_A}{\mathrm{d}p_A^3} = B_A\left(E_{\mathrm{p,n}}\frac{\mathrm{d}^3N_{\mathrm{p,n}}}{\mathrm{d}p_{\mathrm{p,n}}^3}\right)^A\Bigg|_{\vec{p}_\mathrm{p}=\vec{p}_\mathrm{n}=\frac{\vec{p}_A}{A}}$$

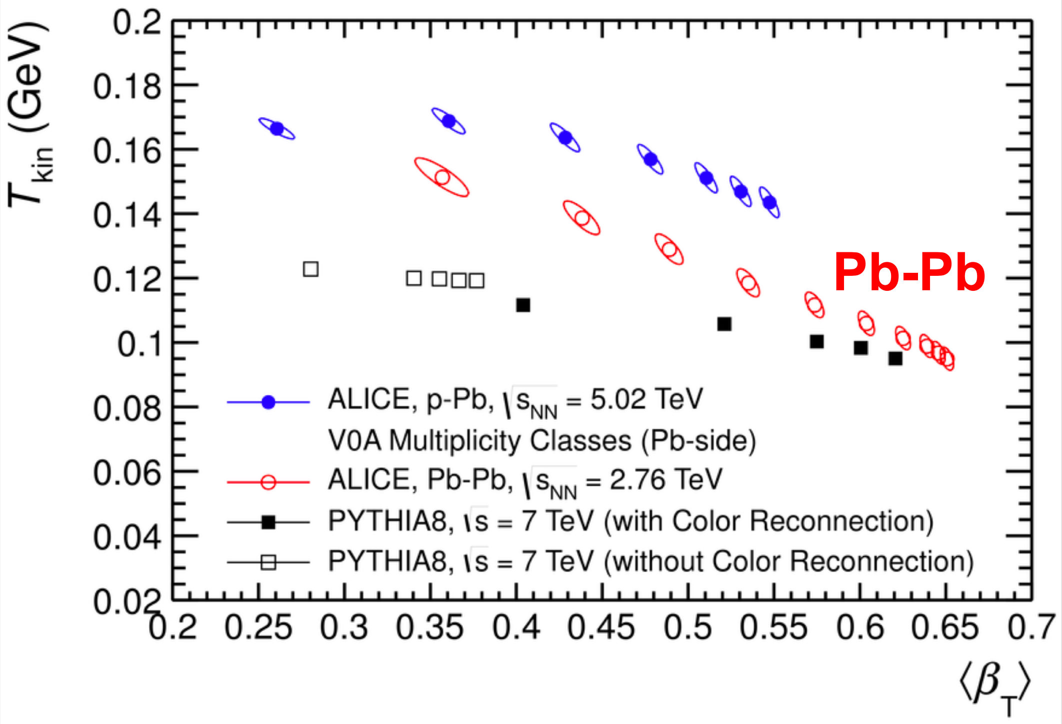
Thermal model + blast-wave:

- B_A from **predicted** (hyper-)nuclei and proton spectra
    - p_T shape of (hyper-)nuclei and protons from Blast-wave model
    - Yields / normalisation from thermal model
- Multiplicity ⟶ source radius mapping from parameterization of HBT data

Thermal model + blast-wave

- p_T spectra modeled with a **blast-wave** parameterization, with parameters **fixed by fit to measured π,K,p**

Centrality dependent blast-wave parameters from fit to measured πKp



ALICE, Phys. Lett. B 728 (2014) 25-38
Phys. Rev. C 88 (2013) 044910

Thermal model + blast-wave

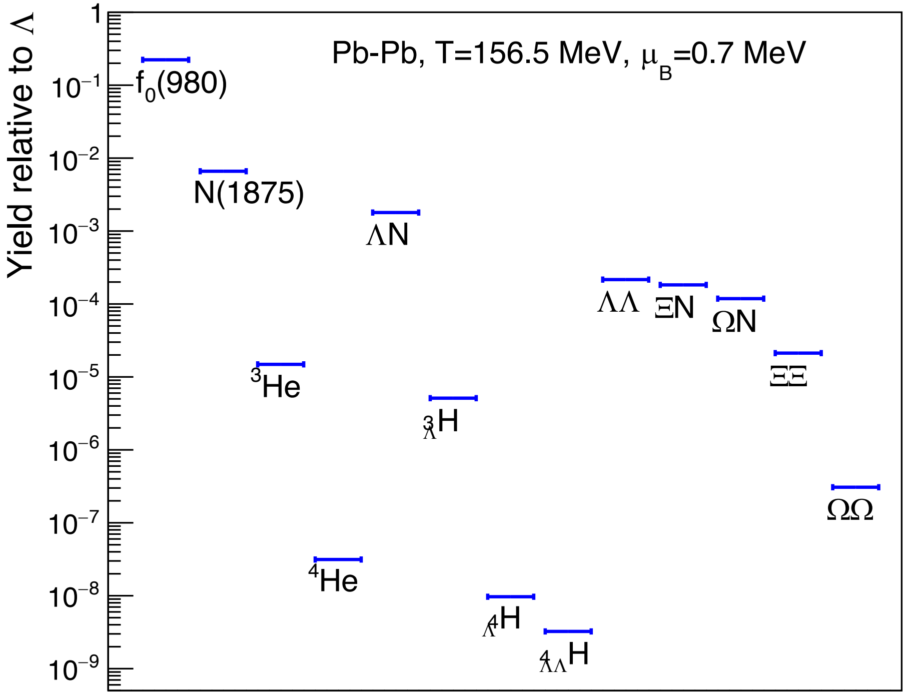
- p_T spectra modeled with a **blast-wave** parameterization, with parameters **fixed by fit to measured π,K,p**

- Normalisation using predictions from **GSI-Heidelberg thermal model with T = 156 MeV** for Pb-Pb collisions
    - for nuclei: $(dN_A^{th}/dy \,/\, dN_\pi^{th}/dy) \times dN_\pi^{exp}/dy$
    - for $^3_\Lambda$H fixed to the thermal model prediction for S_3 times the measured ^{3}He yield

- Coalescence parameter from

$$E_i \frac{d^3 N_i}{dp_i^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

Predictions of GSI-Heidelberg model



A.Andronic, priv. comm.
based on Nature 561 (2018) 321

Size of the source

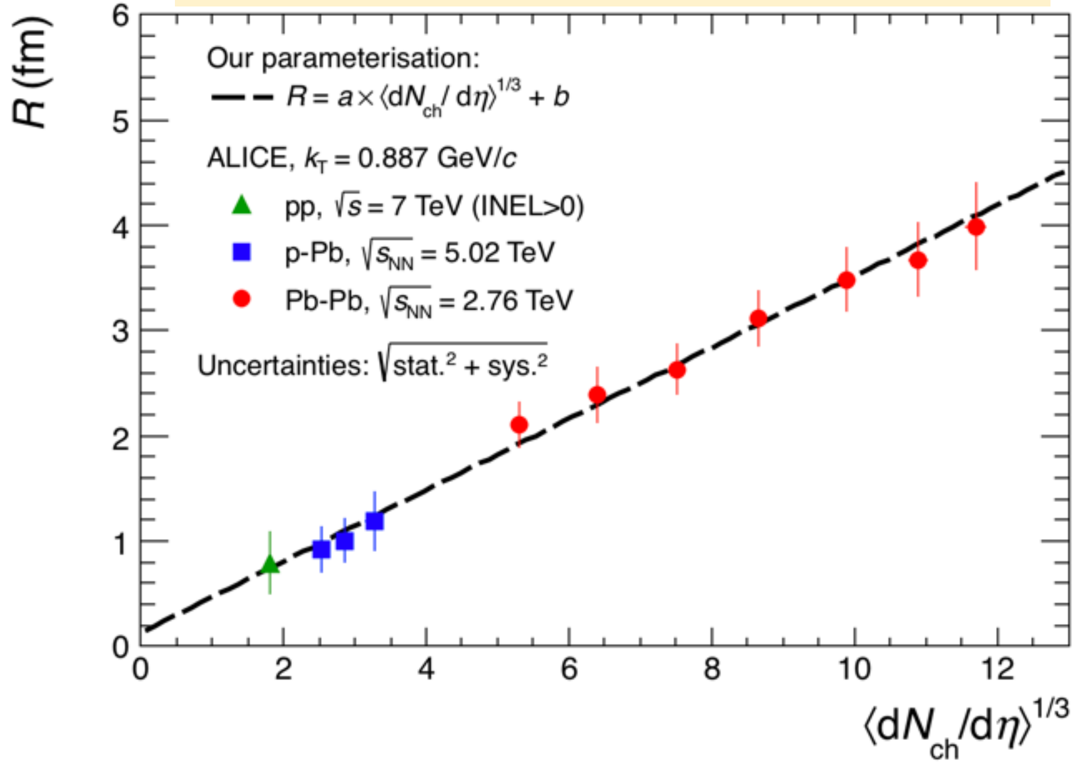
The size of the source is **sampled with multiplicity/centrality-dependent measurements**

→ Need to map ⟨dN/dη⟩ into system radius to compare data to model

Source radius measured by ALICE with HBT interferometry.

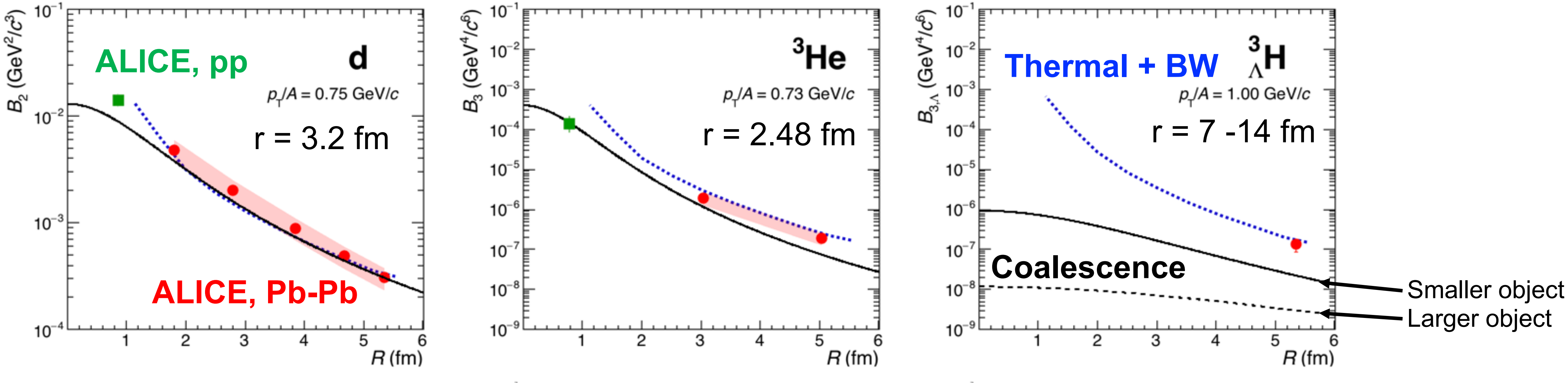
- Assuming scaling with $\langle dN/d\eta \rangle^{1/3}$ approximately holds across collision systems
- Assuming m_T-scaling holds
- Linear parameterization of R vs $\langle dN/d\eta \rangle^{1/3}$
- *a* and *b* such that the ALICE Pb-Pb B_2 data fall onto the coalescence prediction

Mapping of ⟨dN/dη⟩ into system radius



ALICE data: PLB 696 (2011) 328-337, PRC 91 (2015) 034906

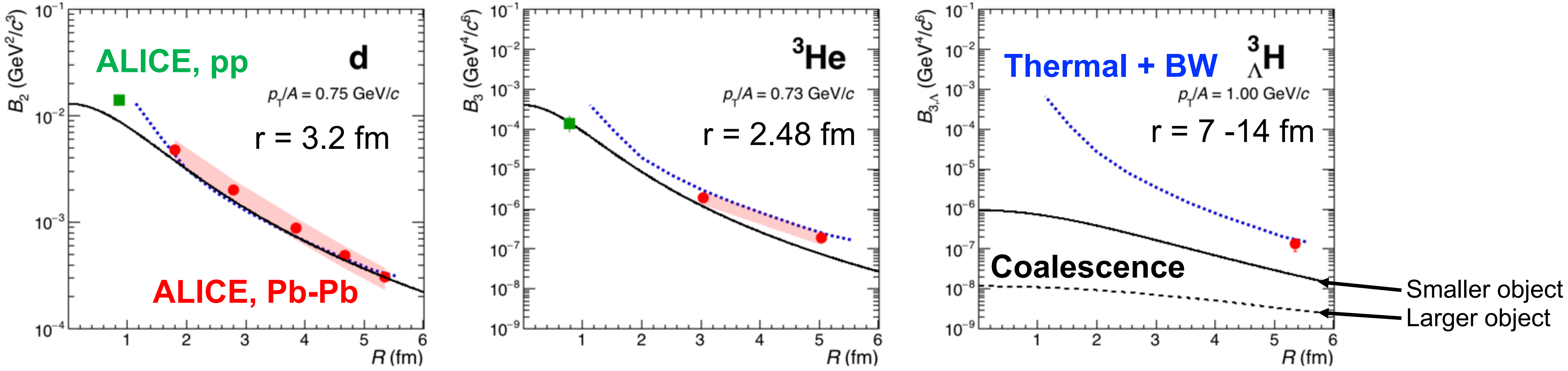
B_A vs source size R

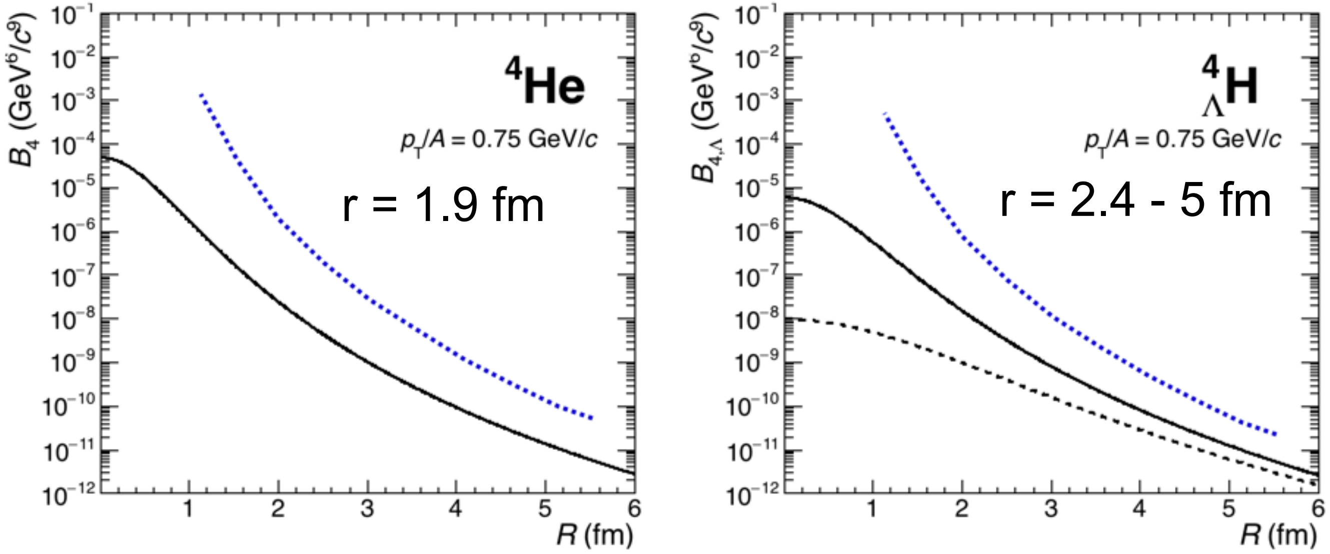


- Difference between data and coalescence for ^{3}He and $^3_\Lambda$H
  - *Wave function?*
  - *Two-steps coalescence?*

- *$^3_\Lambda$H suppressed by about 2 orders of magnitude wrt ^{3}He in pp*
  - *Size of $^3_\Lambda$H relative to the size of the emitting source*
    → see also K.-J.Sun, C.M.Ko, B.Dönigus, arXiv:1812.05175

B_A vs source size R

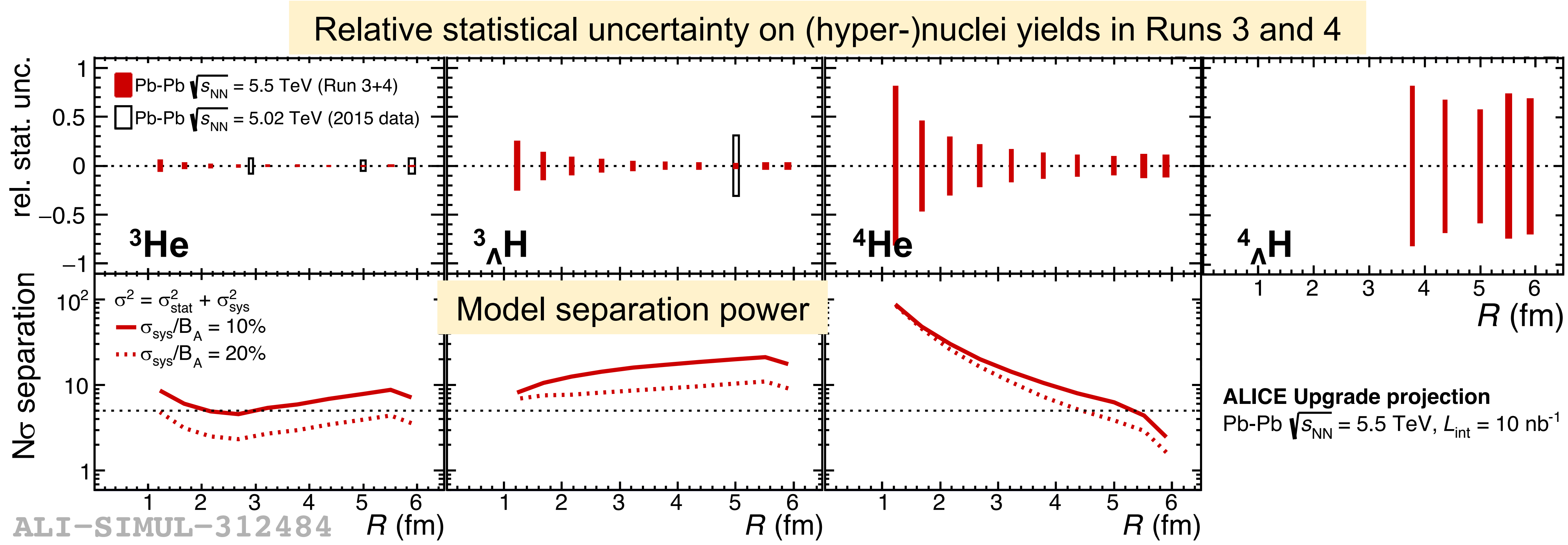




Update since arXiv:
- ✻ extension to A = 4 objects

Next:
- p_T dependence
- other exotic states
- Realistic wave-functions
- …

Test production models with L = 10 nb^{-1} at LHC Run 3+4



Relative statistical uncertainty on (hyper-)nuclei yields in Runs 3 and 4

Model separation power

Report from the HL-LHC Workshop, arXiv:1812.06772

At the LHC Runs 3+4 (2021-2029), Pb-Pb integrated luminosity will be 100x larger than Run 1+2.
Nuclei with A = 3 and A = 4 will be measurable more differentially
→ **Hyper-triton** will allow for a ~10σ discrimination between models

Summary

A direct comparison of the thermal model and coalescence production scenarios for light (anti-)(hyper-)nuclei is presented:

- ✻ Plan to improve and extend this first study further
- ✻ Numerical calculations for realistic (hyper)nuclei wave-functions are needed from theory side

To clarify the production mechanism of composite loosely-bound QCD objects, measure light (anti-)(hyper-)nuclei production as a function of multiplicity in different collision systems:

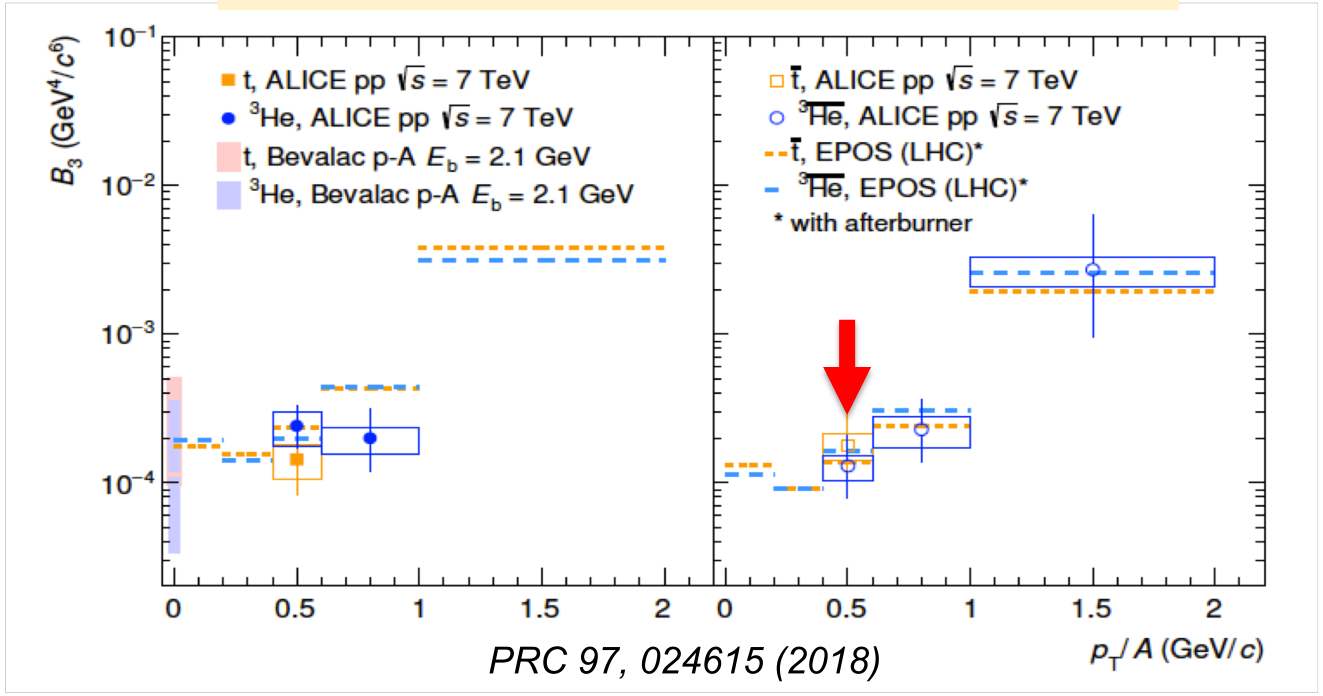
⟶ exploit the sensitivity of production mechanisms to the size of the object relative to the size of the source

- ✻ Particularly sensitive to production mechanisms is the **hyper-triton**, with its large size
- ✻ **Major opportunity** to perform measurements with the 100x larger Pb-Pb luminosity foreseen at the **LHC Runs 3 and 4 with upgraded ALICE detector**.

Thank you!

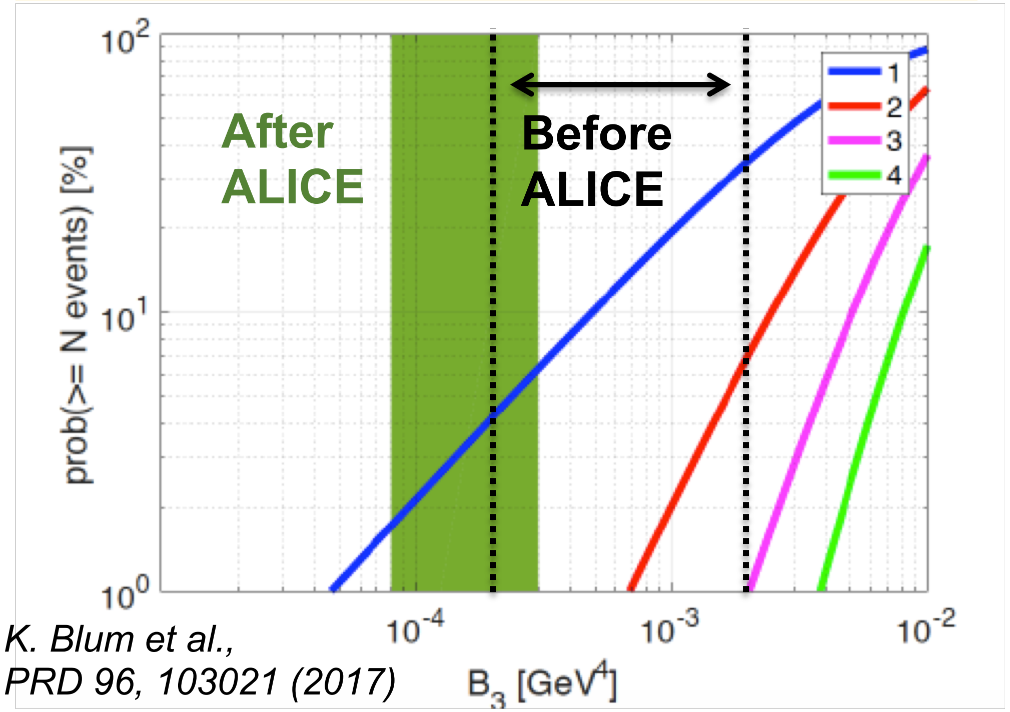
Measurements at LHC with impact on astrophysics

Coalescence parameter for A = 3 nuclei vs p_T-per-nucleon



PRC 97, 024615 (2018)

Poisson prob. for detecting N ≥ 1, 2, 3, 4 ^{3}He-bar events in a 5-yr analysis of AMS02

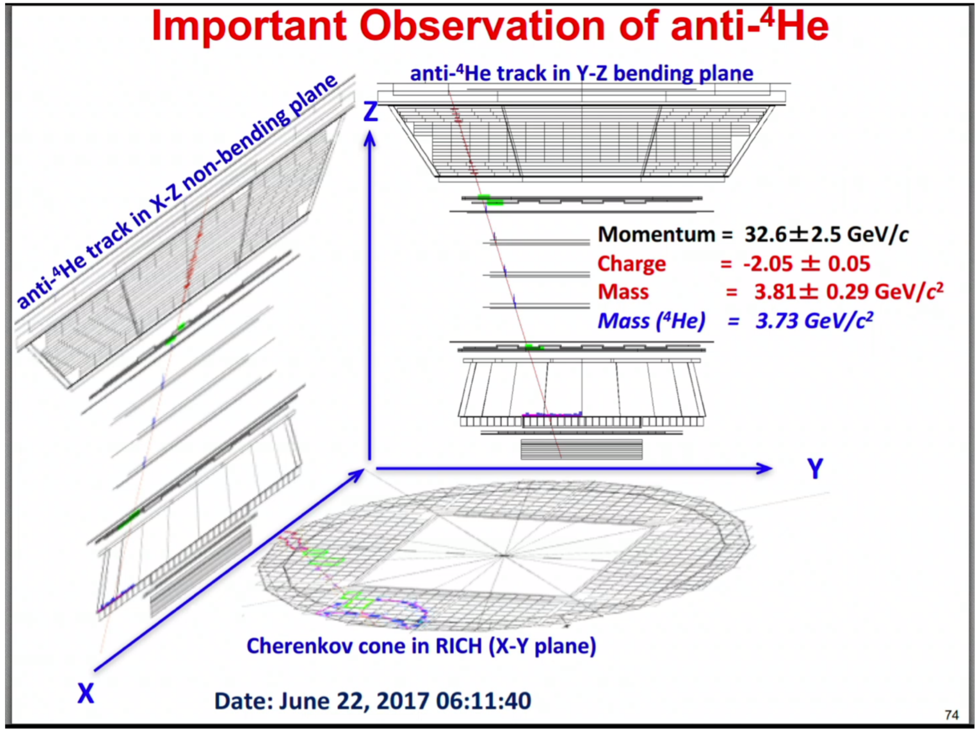


K. Blum et al., PRD 96, 103021 (2017)

Precise measurements of coalescence parameters at the LHC can be used to constrain the amount of secondary anti-nuclei produced in cosmic ray interactions with interstellar matter
→ Background estimate for Dark Matter searches in space-based experiments (e.g. AMS-02)

Anti-^{4}He in the Cosmos

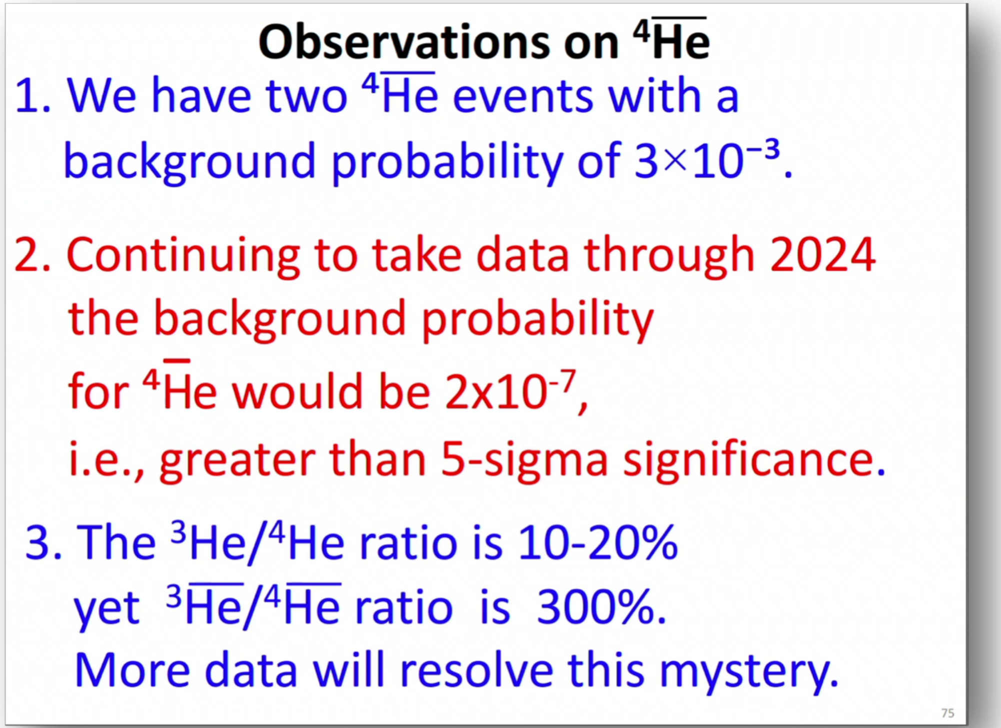
Anti-^{4}He candidate observed in AMS



Important Observation of anti-^{4}He

Momentum = 32.6±2.5 GeV/c
Charge = -2.05 ± 0.05
Mass = 3.81± 0.29 GeV/c^2
Mass (^{4}He) = 3.73 GeV/c^2

Date: June 22, 2017 06:11:40



Observations on $^4\overline{\text{He}}$

1. We have two $^4\overline{\text{He}}$ events with a background probability of 3×10^{-3}.
2. Continuing to take data through 2024 the background probability for $^4\overline{\text{He}}$ would be $2\text{x}10^{-7}$, i.e., greater than 5-sigma significance.
3. The ^{3}He/^{4}He ratio is 10-20% yet $^3\overline{\text{He}}/^4\overline{\text{He}}$ ratio is 300%. More data will resolve this mystery.

S. Ting (AMS), CERN Colloquium 24/05/2018

Anti-^{4}He measurement in pp collisions in reach with ALICE with the High-Luminosity LHC phase (Run3-4, 2021-2028) → measurement of production probability for *A* = *4*

References to models (a non-exhaustive list)

Several efforts to explain the experimental data from LHC in the last few months:

- R. Stock et al. arXiv:1811.07766 (thermal model + UrQMD)
- V. Vovchenko et al., PLB 785 (2018) 171-174 (canonical statistical hadronization model)
- W. Zhao et al., Phys. Rev. C 98, 054905 (2018) (hydrodynamics + coalescence)
- V. Koch et al. arXiv:1809.03071, 1812.06225 (hydrodynamics + hadronic afterburner)
- S. Bazak and S. Mrowczynski, Mod.Phys.Lett. A33 (2018), 1850142 (coalesce. vs thermal with ^{4}He and ^{4}Li)
- K.-J.Sun, C.M.Ko, B.Dönigus, arXiv:1812.05175 (coalescence)

Statistical-hadronization model:

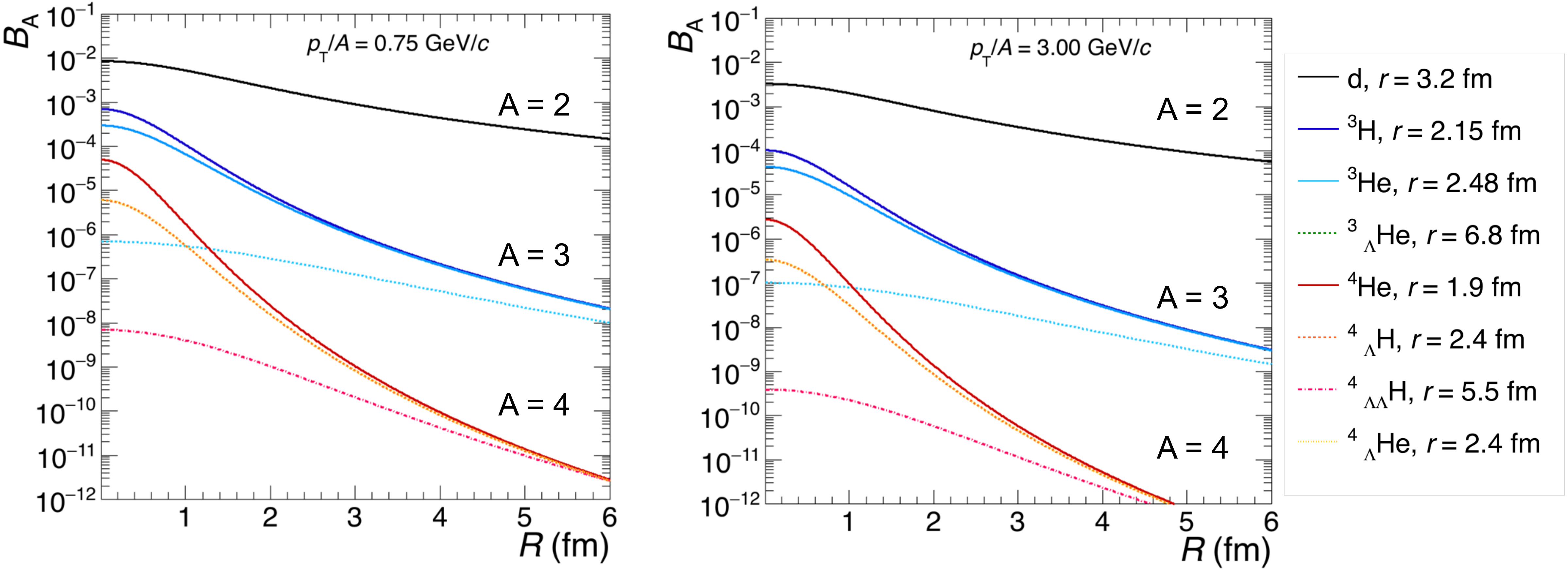
A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker, Phys. Lett. B 697, 203 (2011)
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nature 561 (2018) 321

Coalescence:

S.T. Butler and C. A. Pearson, Phys. Rev. 129, 836 (1963).
J. I. Kapusta, Phys. Rev. C21, 1301 (1980).
H. Sato and K. Yazaki, Phys. Lett. B98, 153 (1981).
J. L. Nagle, B. S. Kumar, D. Kusnezov, H. Sorge, and R. Mattiello, Phys. Rev. C53, 367 (1996).
R. Scheibl and U. W. Heinz, Phys. Rev. C59, 1585 (1999)
K. Blum, K. C. Y. Ng, R. Sato, and M. Takimoto, Phys. Rev. D96, 103021 (2017)
S. Mrowzcynski, Acta Phys.Polon. B48 (2017) 707

Additional material

Coalescence probability for (hyper-)nuclei with A≤4



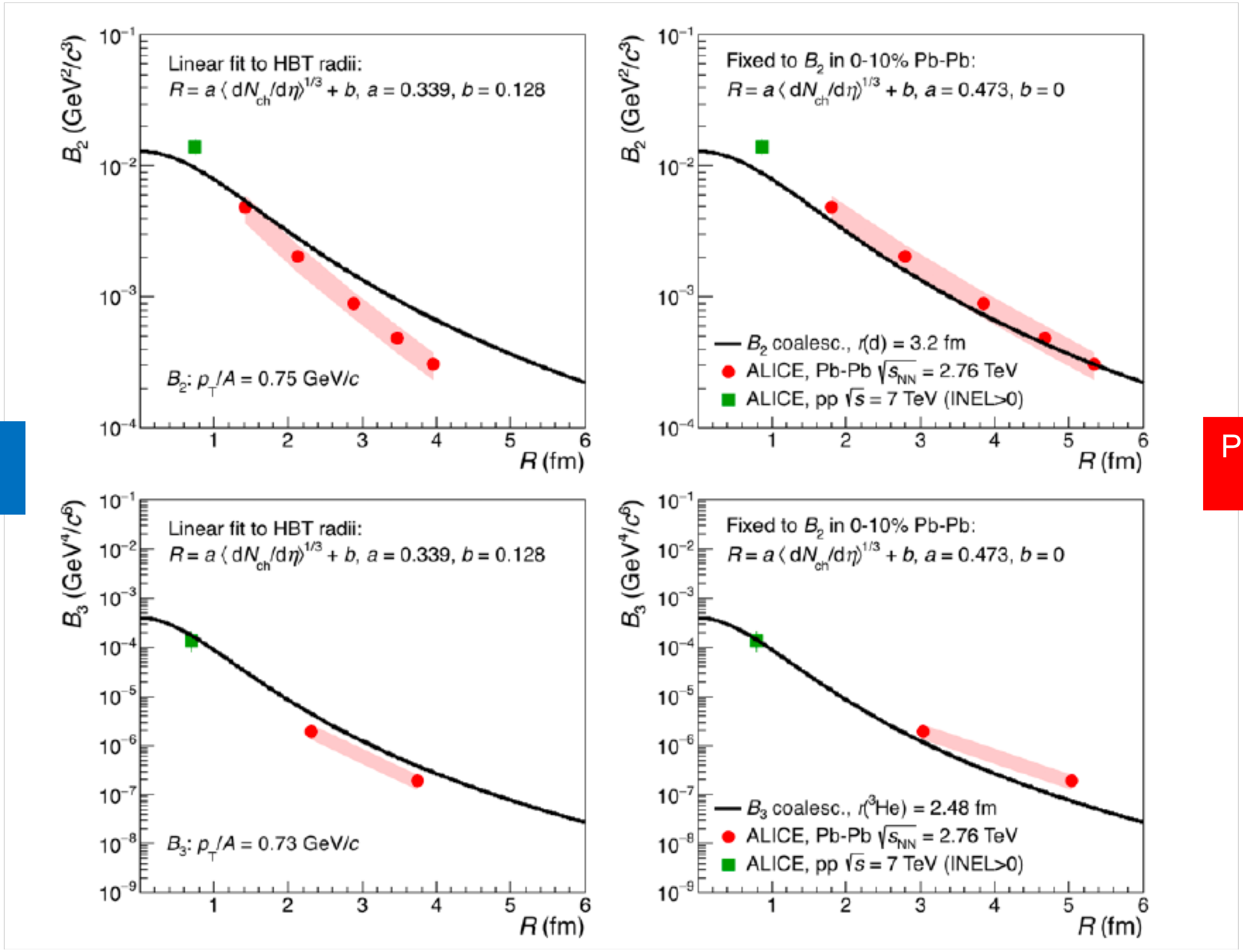
B_A from coalescence at $p_T/A = 0.75$ GeV/c

B_A from coalescence at $p_T/A = 3$ GeV/c

Coalescence probability decreases with transverse momentum for all A and R.

Multiplicity → *R* mapping

Parameterisation A: Fit to HBT radii



Parameterisation B: B_2 in Pb-Pb falls onto coalescence

Size of light (anti-)nuclei and wave-function

- Charge rms radius (λ_A):
  - rms of the nucleus charge distribution
  - Measurable via scattering experiments

- Size parameter of the wave-function (r_A):
  - Relevant for models of production via coalescence
  - Gaussian wave-function ⟶ treat problem analytically
  - For deuteron more realistic to use Hulthén wave-function *[J. L. Nagle et al., PRC53 (1996) 367]*
  - For A = 3, more realistic wave-functions need numerical calculations

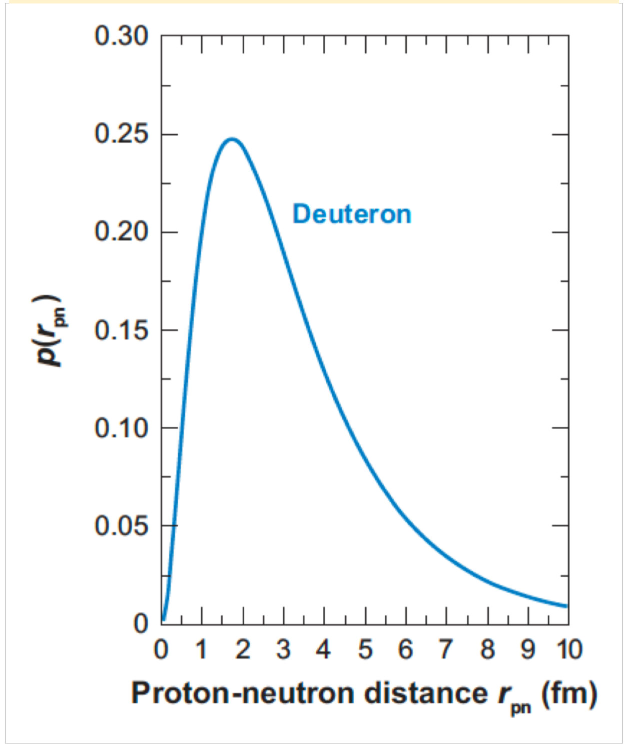
- Simple relations hold between the two for light (anti-)nuclei:

$$\lambda_A^2 = \frac{3}{2}\frac{A-1}{A}\frac{r_A^2}{2}$$

Example: *A* = 2, the deuteron
Gaussian wave-function:

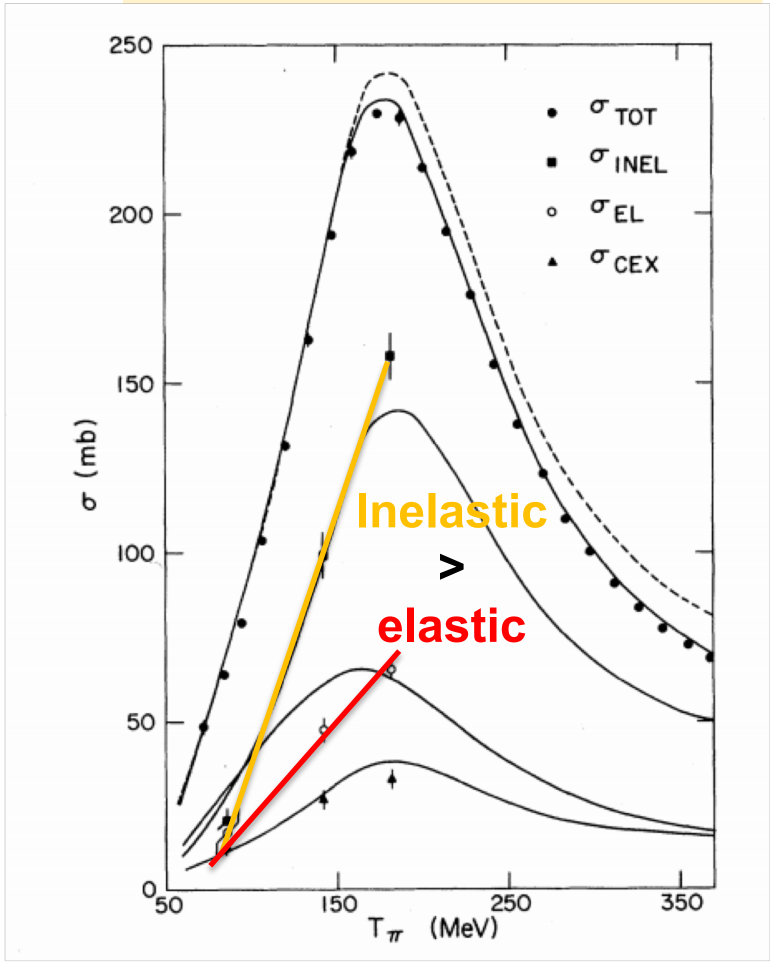
$$\varphi_d(\vec{r}) = (\pi r_d^2)^{-3/4} \exp\left(-\frac{r^2}{2r_d^2}\right)$$

Hulthén wave-function



(Anti-)nuclei survival puzzle

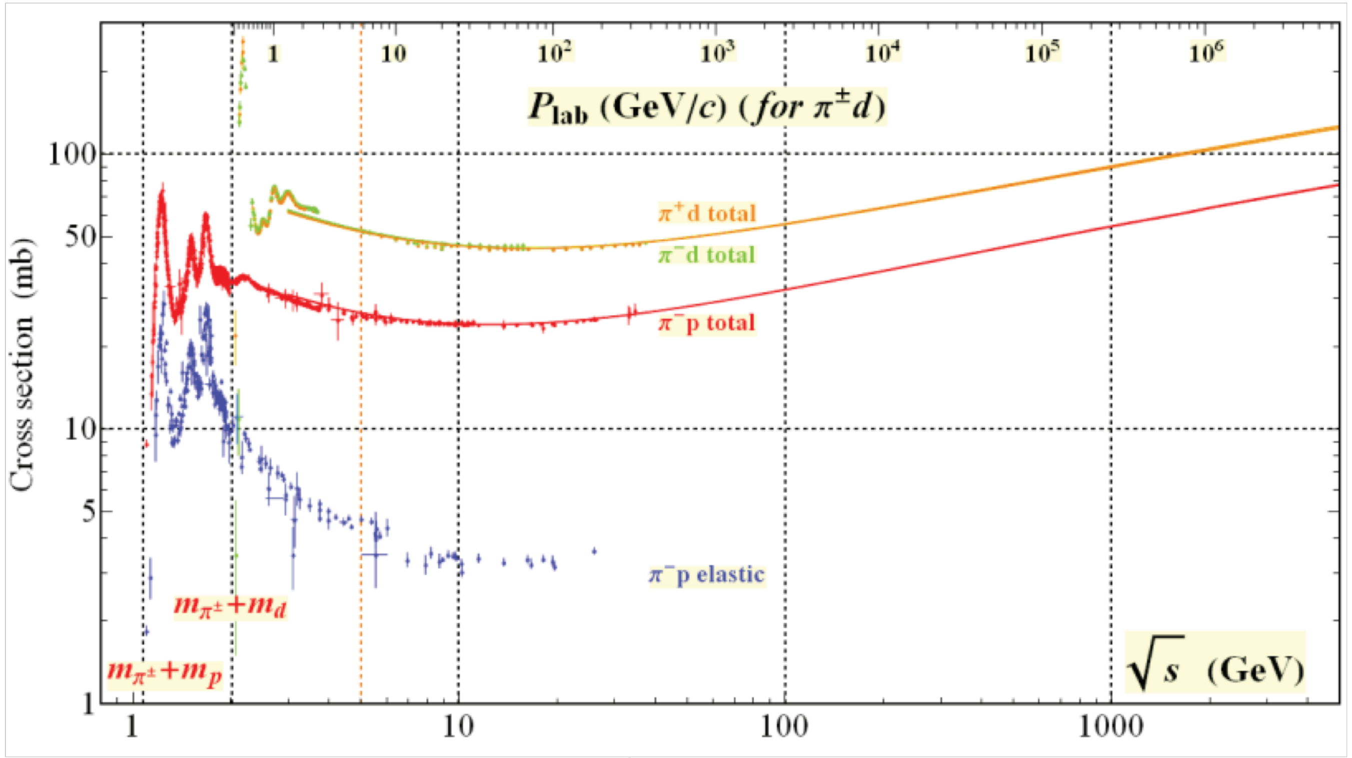
π-d deuteron cross-section vs π kinetic energy



H. Garcilazo, PRL 48, 577 (1982)

π-induced deuteron breakup cross section is larger than the elastic cross section that is responsible to drive the system to equilibrium

π-d, π-p hadronic cross section



Particle Data Group 2018

Femtoscopic radii

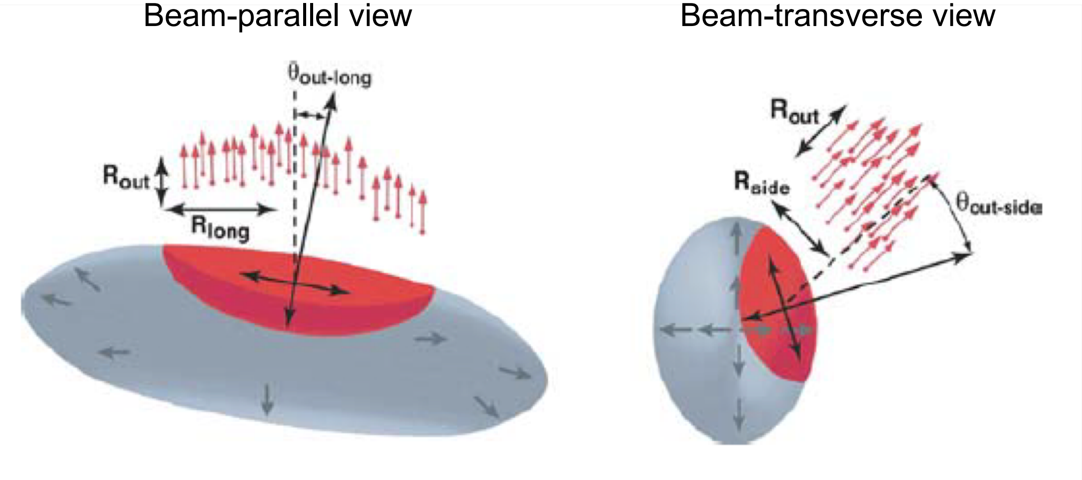
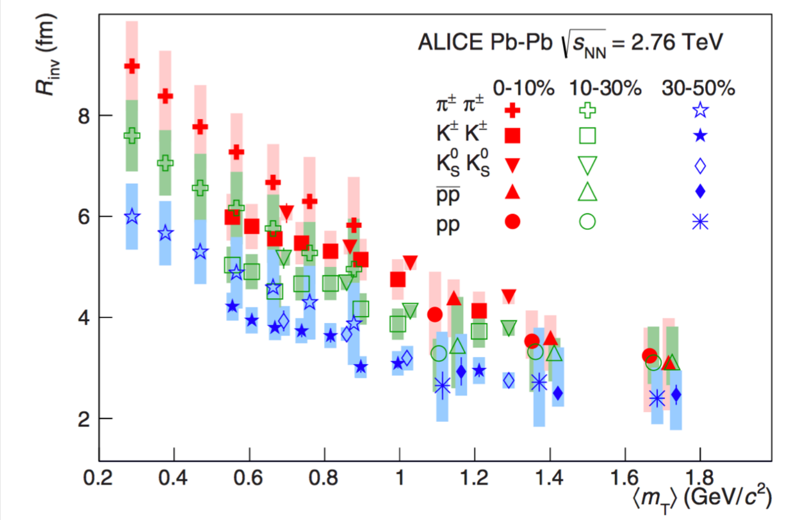
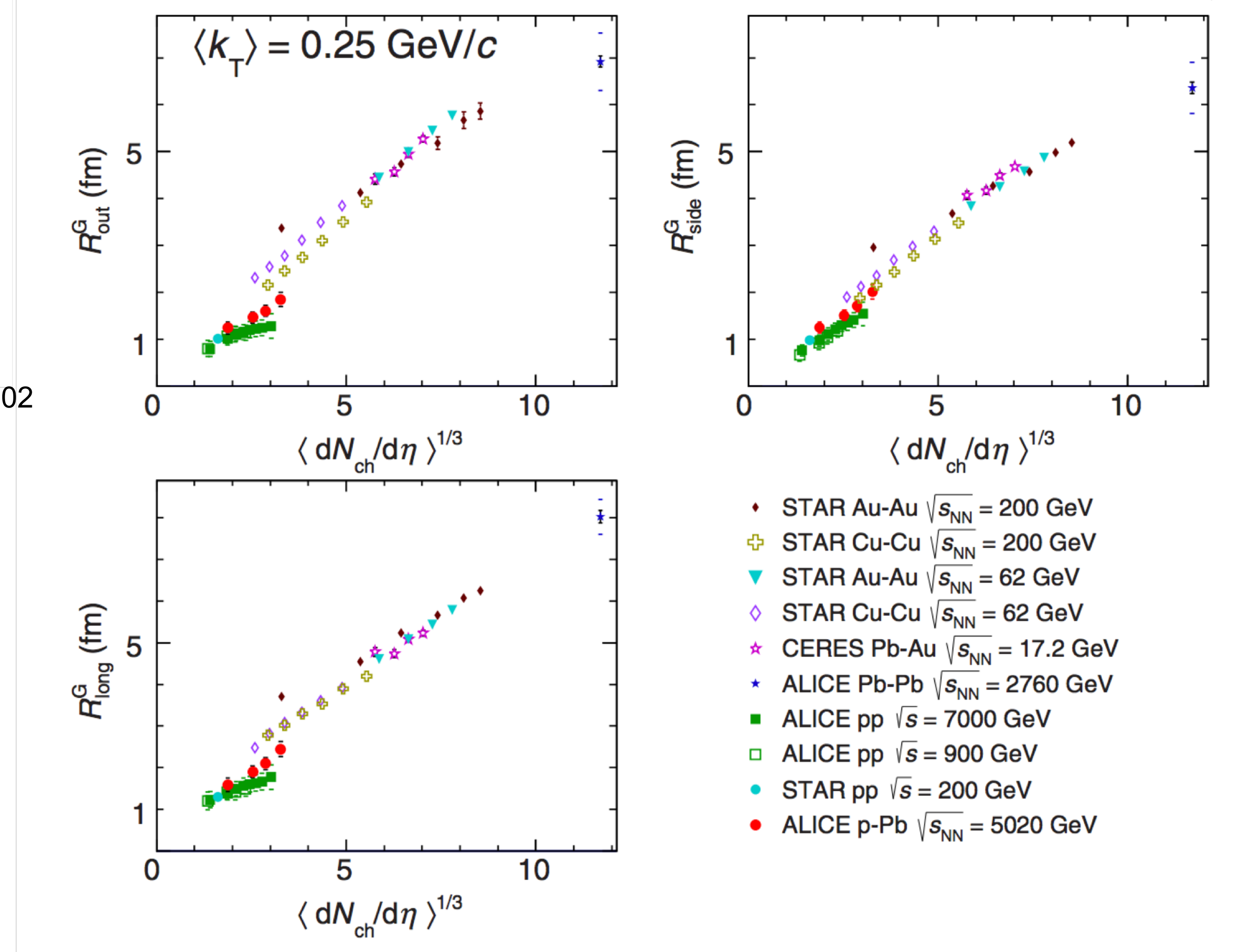


Illustration from M. Lisa et al., Annu. Rev. Nucl. Part. Sci. 2005.55:357-402

ALICE, PRC 92, 054908 (2015) 1-dimensional analysis



ALICE, PRC 91, 034906 (2015) - 3-dimensional analysis: R_{out}, R_{side}, R_{long}



Size of the source

The size of the source is sampled with multiplicity/centrality-dependent measurements

→ Need to map ⟨dN/dη⟩ into system radius to compare data to model

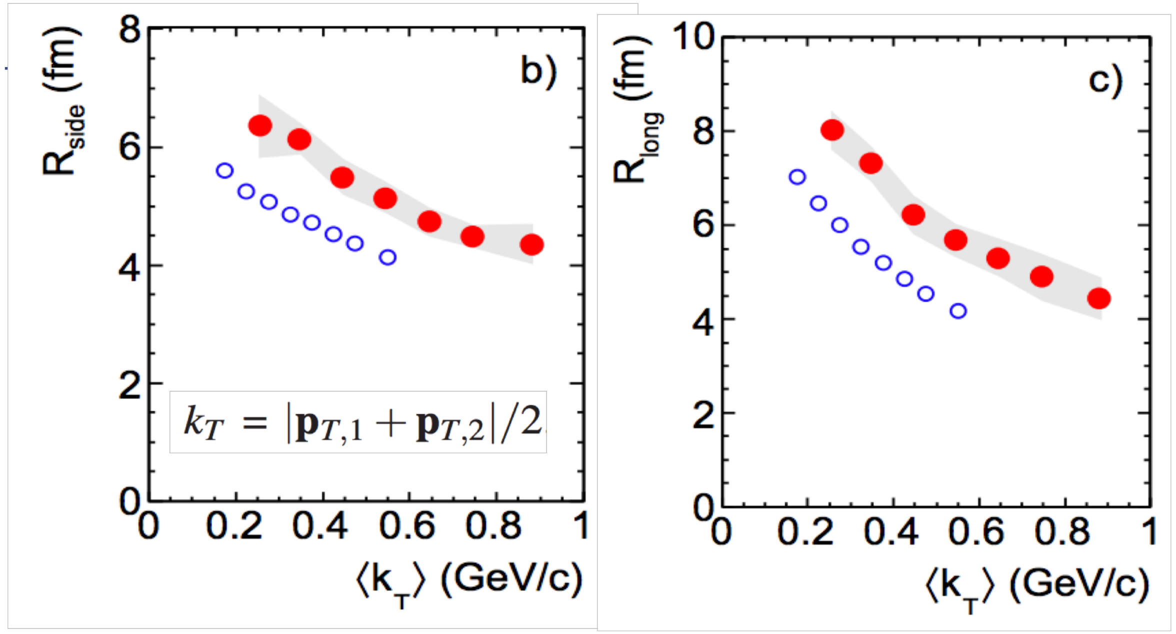
Our assumptions:

- Scaling with $\langle dN/d\eta \rangle^{1/3}$ approximately holds across collision systems
- $R = (R_\perp^2 R_\parallel)^{1/3} \approx (R_{side}^2 R_{long})^{1/3}$
- m_T-scaling holds
- Spectra and yields are measured in different multiplicity bins and estimators wrt HBT radii
  → we rely on a parameterization

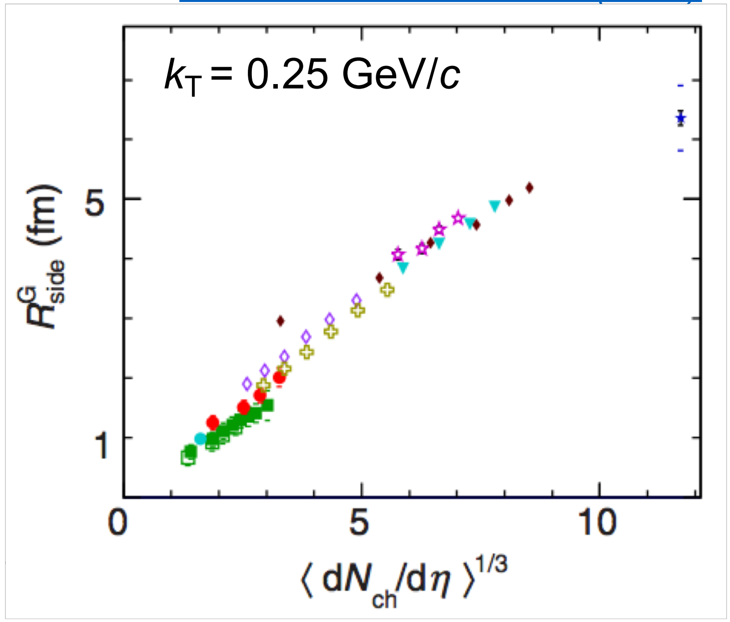
$$R = a \left\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \right\rangle^{1/3} + b$$

a and b such that the ALICE Pb-Pb B_2 data fall onto the coalescence prediction

ALICE, PLB 696 (2011) 328-337



ALICE, PRC 91, 034906 (2015)

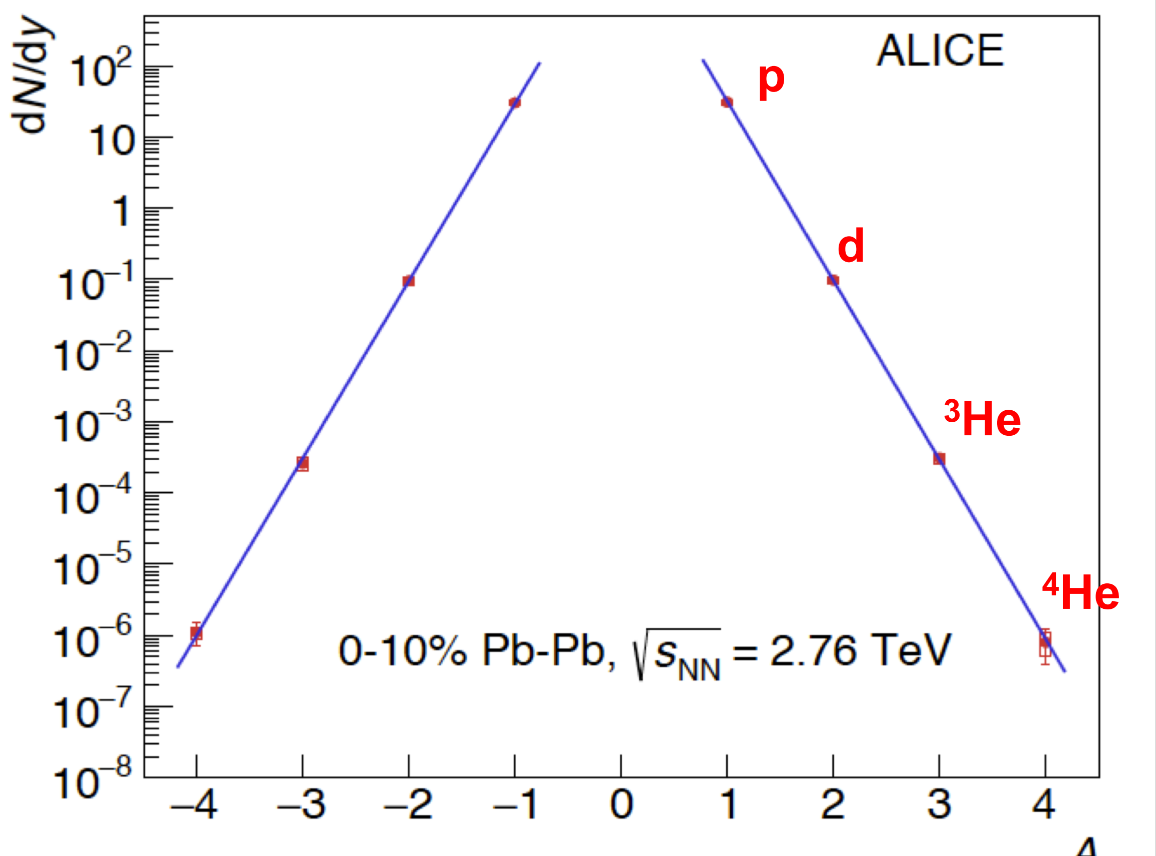


ALICE DATA

Nucl. Phys. A 971 (2018) 1-20, Phys. Rev. C 97 (2018) 024615
Eur. Phys. J. C 77 (2017) 658, Phys. Rev. C 93 (2015) 024917
Deuteron in pp vs multiplicity: in preparation

(Anti-)nuclei are rare objects

Yield of (anti-)nuclei vs A in central Pb-Pb collisions



ALICE, Nucl. Phys. A 971 (2018) 1-20

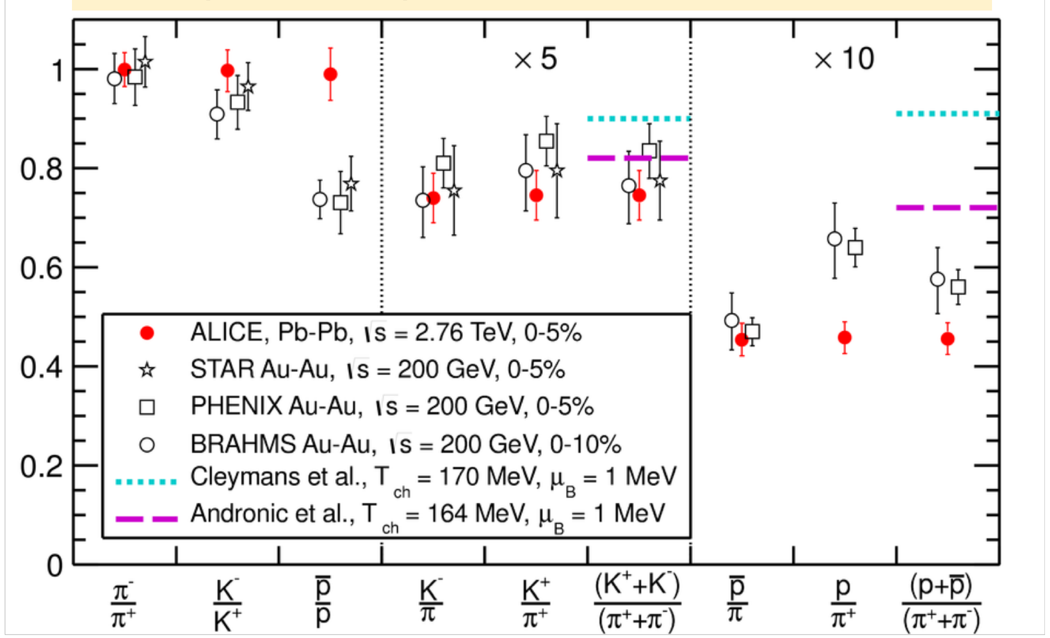
In central Pb-Pb collisions the "**penalty factor**" for increasing the mass number by adding one nucleon is **~350**

- Consistent with expectations from model of thermal production
- Penalty factor ~10^3 (600) in pp (p-Pb) collisions

Anti-matter / matter ~ 1 at the LHC

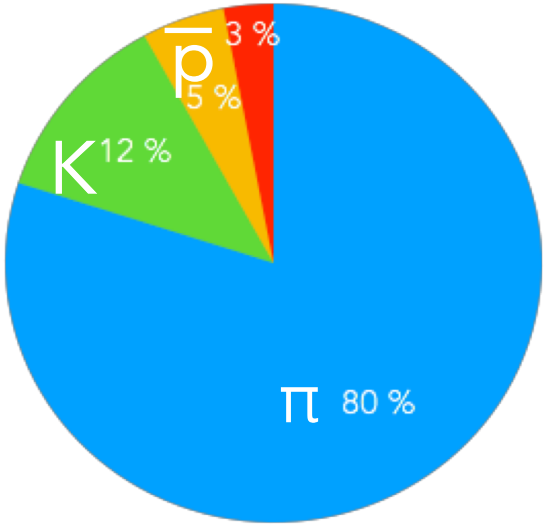
LHC as “anti-matter factory”

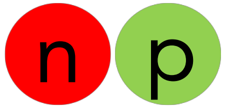
Anti-particle to particle ratio in central Pb-Pb



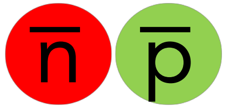
ALICE, Phys. Rev. Lett. 109 (2012) 252301

(negative particles)



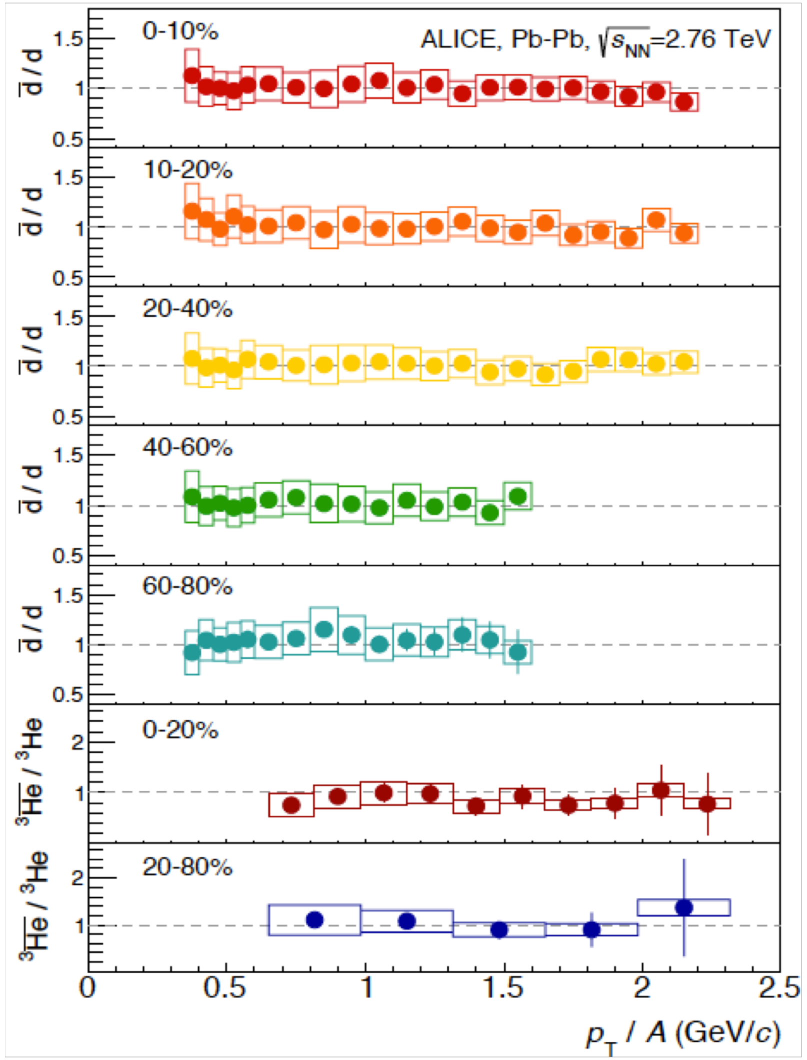


deuteron



anti-deuteron

Anti-nuclei to nuclei ratio

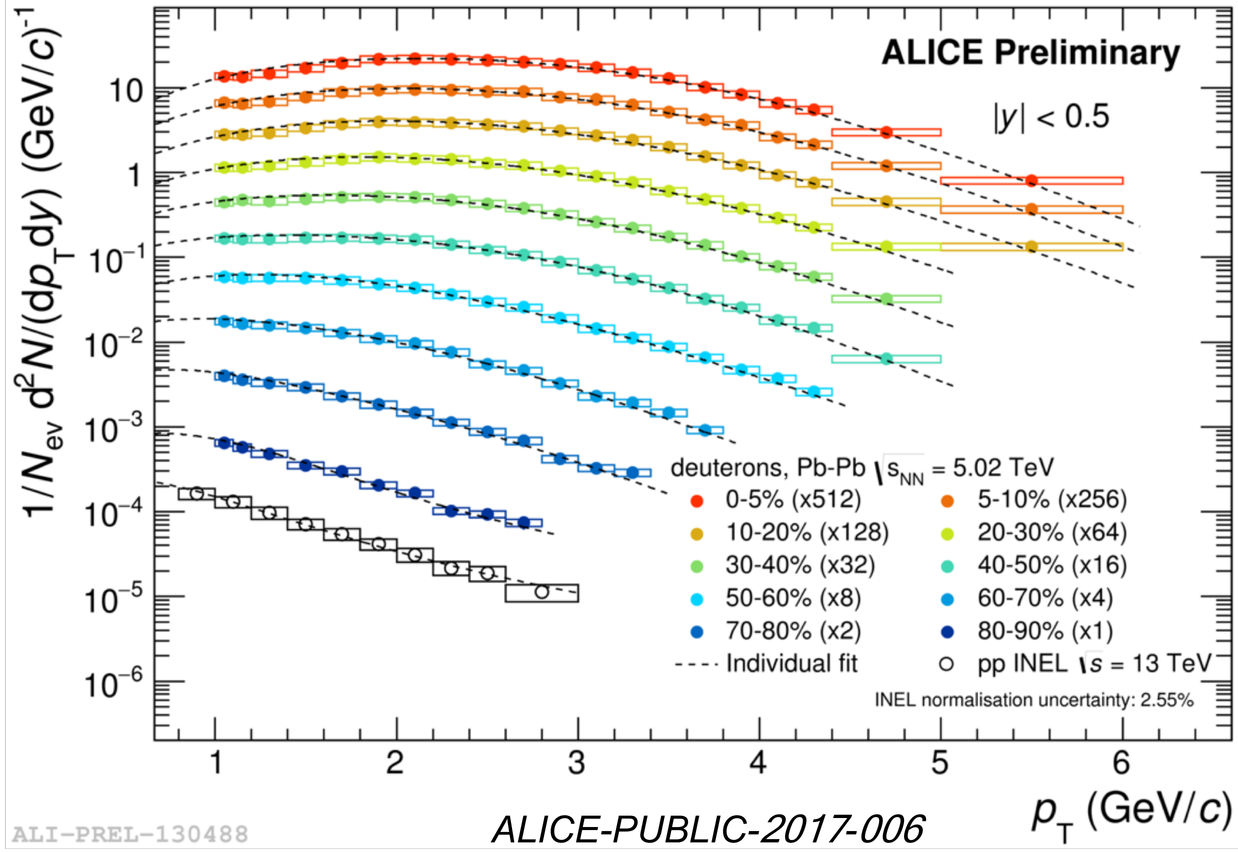


ALICE, Phys. Rev. C 93, 024917 (2016)

- Only ~5% of all negative particles are anti-protons (the “lightest anti-nucleus”).
- The production of composite anti-particles is **very rare**: ~ 0.005% are **anti-deuterons.**

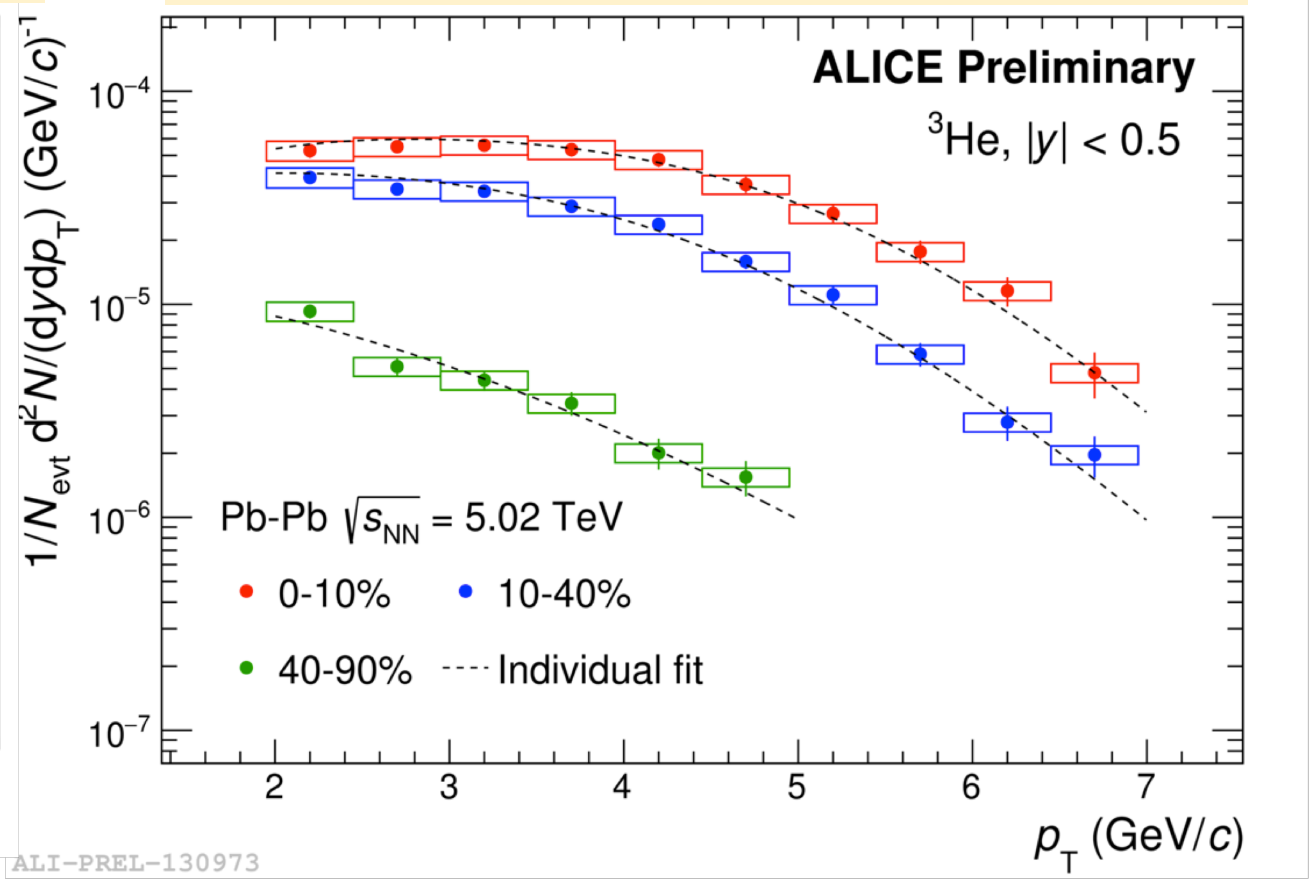
Production at the LHC

p_T – differential yield of deuteron in Pb-Pb vs centrality



ALICE-PUBLIC-2017-006

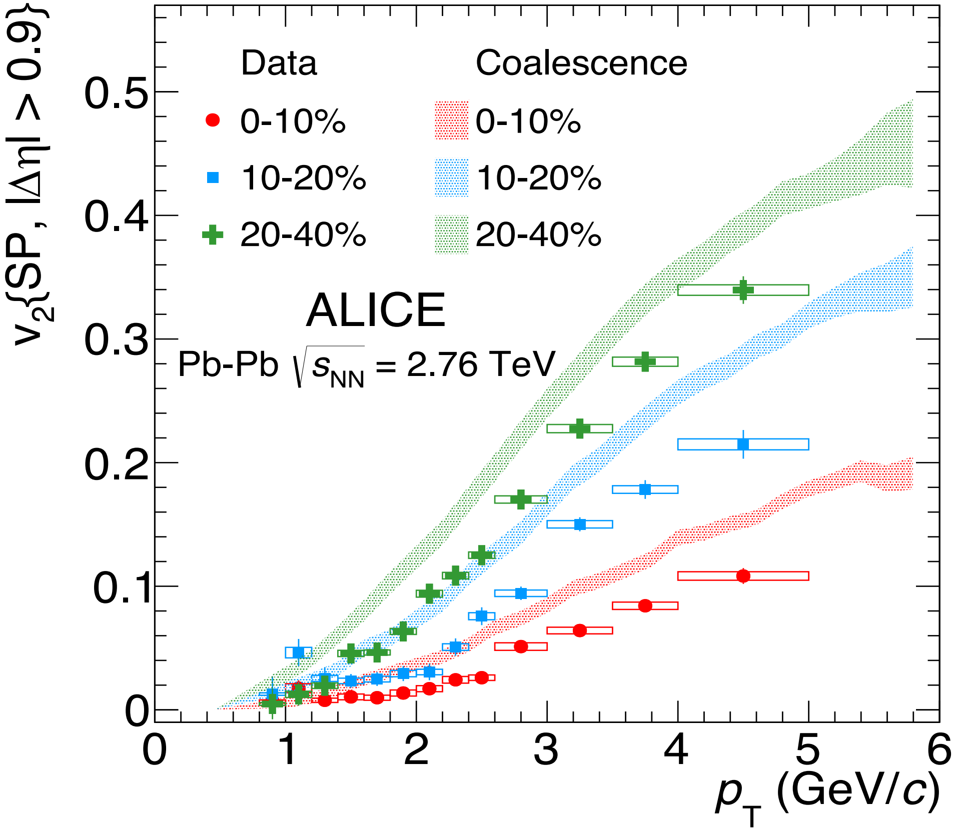
p_T – differential yield of ^{3}He in Pb-Pb vs centrality



RUN II (2015 sample), Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Deuteron v_2

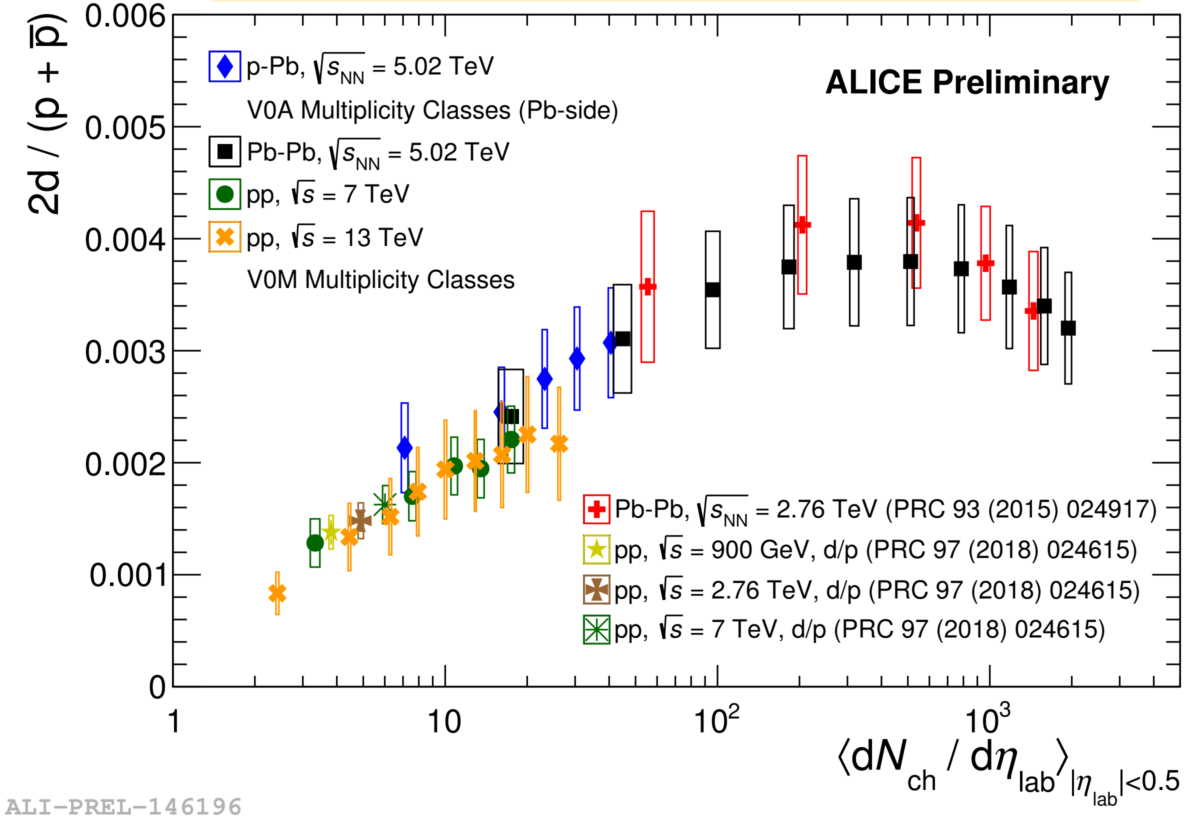
p_T – dependent deuteron v_2



ALICE Coll., arXiv:1707.07304

Smooth relative production across collision systems

d/p ratio vs multiplicity across systems



ALI-PREL-146196

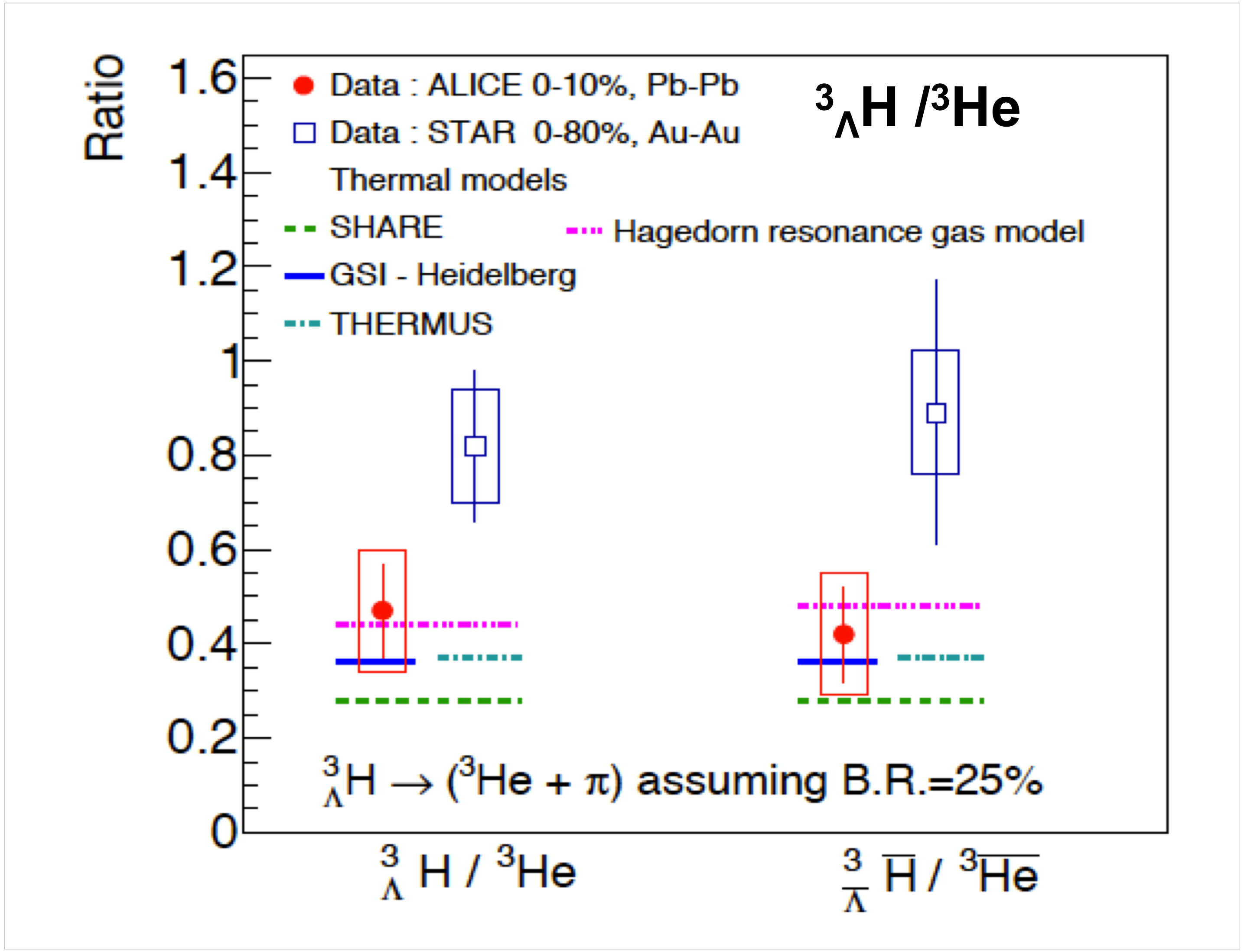
Smooth evolution of d/p ratio with multiplicity across systems

No significant centrality dependence in Pb-Pb

- indication for decrease of d/p ratio in most central collisions

No significant $\sqrt{s_{NN}}$ dependence

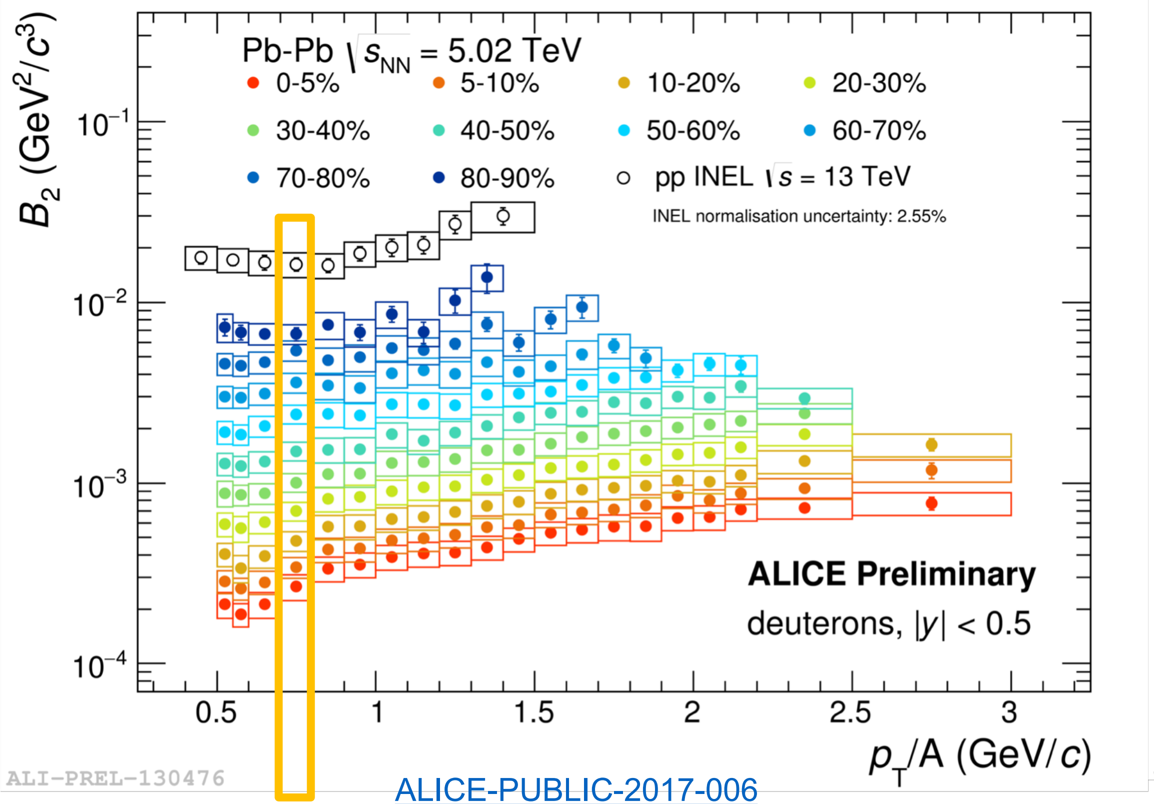
$^{3}_{\Lambda}H$ /^{3}He



Measured coalescence parameter

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

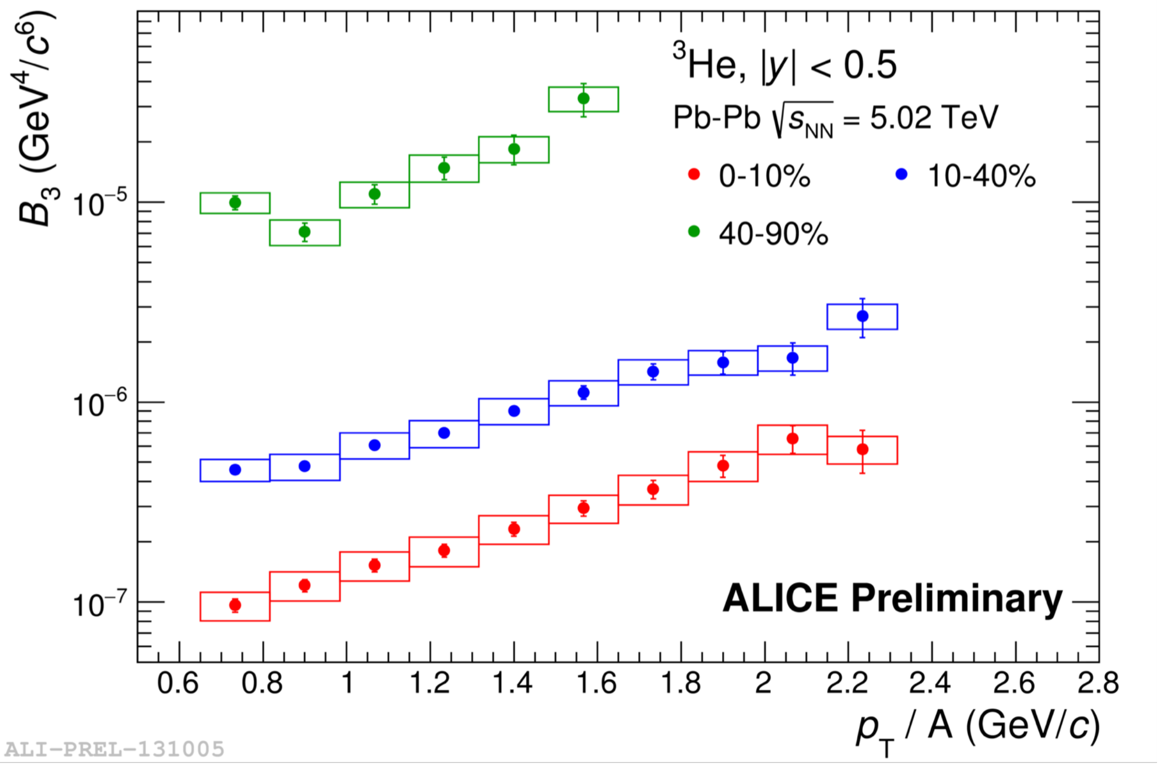
p_T – dependent coalescence parameter for deuteron



ALICE-PUBLIC-2017-006

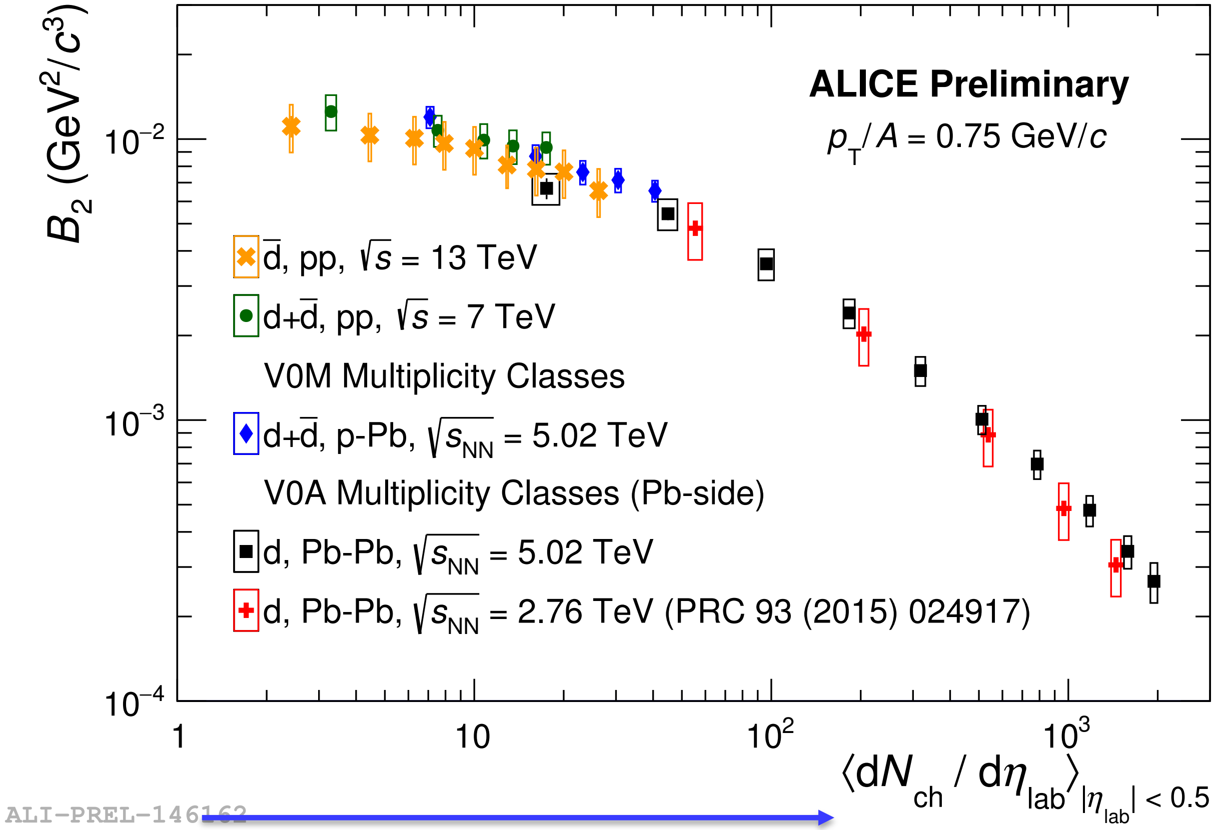
p_T/A = 0.75 GeV/c

p_T – dependent coalescence parameter for ^{3}He



Coalescence probability across collision systems

Coalescence parameter B_2 for deuterons vs multiplicity across systems



Increasing source size

The trend with multiplicity is explained as an increase in the source size (radius R) in coalescence models

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