Anti-nuclei at the LHC and in cosmic rays

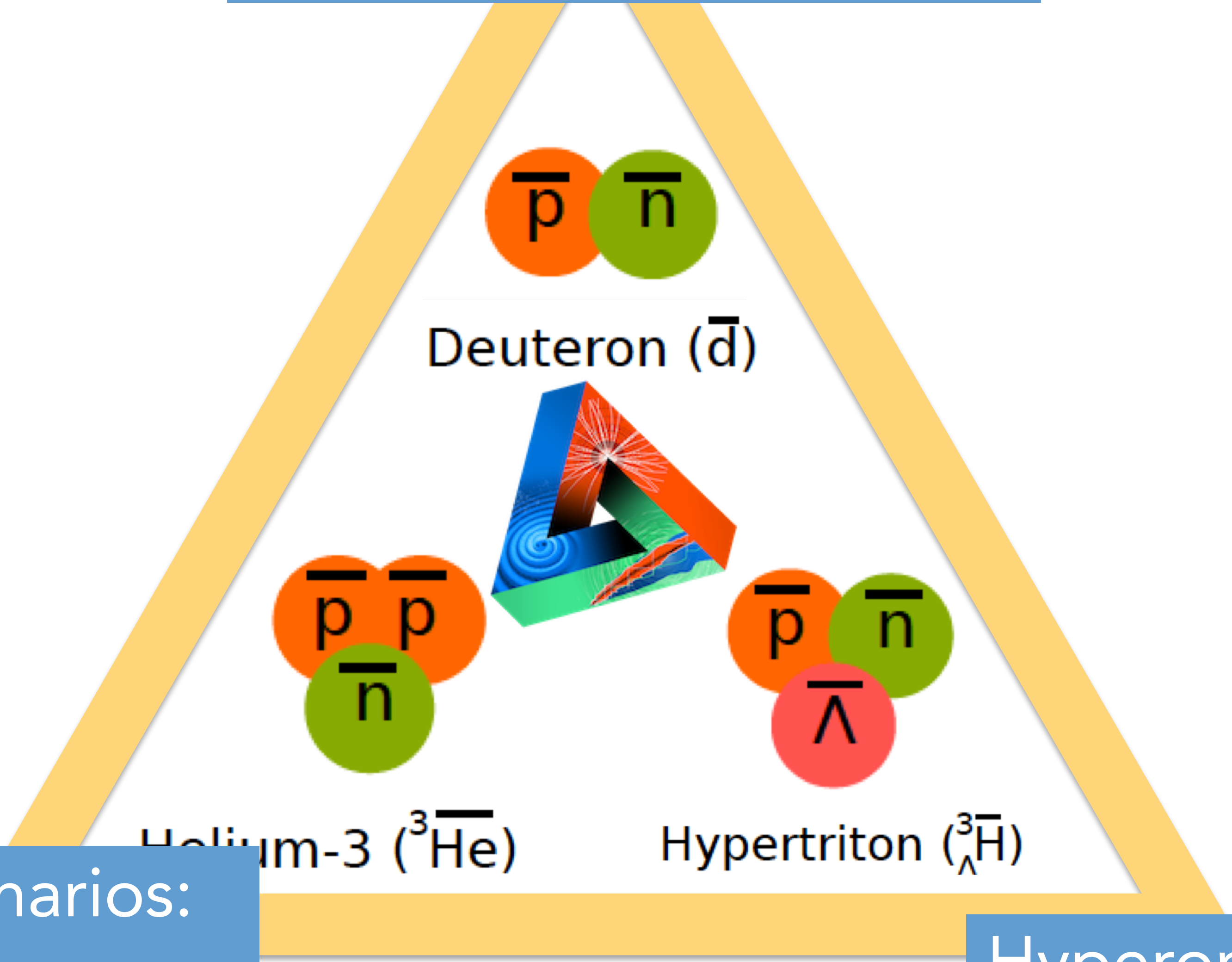
Nuclei@LHC expression of interest

Alexander Kalweit (CERN)

JENAA meeting 2^{nd} October 2020

JENAA
Joint ECFA-NuPECC-APPEC Activities

1. Search for anti-nuclei and dark matter in space



2. Production scenarios: thermal vs coalescence ("anti-nuclei puzzle")

3. Hyperon-nucleon interactions

Production of anti- and hyper-nuclei in the cosmos

Dark matter and anti-nuclei

Signal: anti-nuclei from dark matter

$$\chi + \bar{\chi} \leftrightharpoons f + \bar{f}, W^+ + W^-, \ldots$$
$$\leftrightharpoons \bar{p}, \bar{d}, \overline{He}, \gamma, \ldots$$

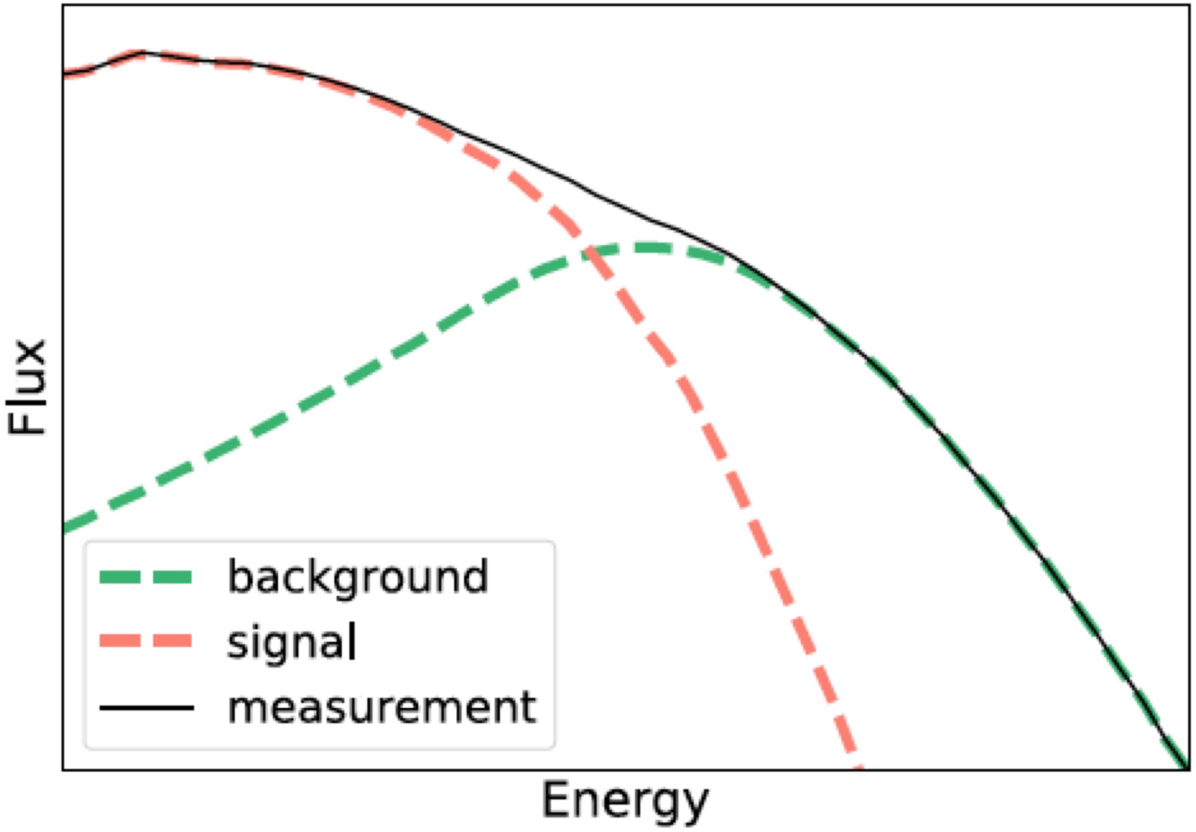
→ Measured by AMS, GAPS, BESS,…

Background: anti-nuclei from ordinary matter

$$p + p, p + He, He + He, \ldots$$
$$\leftrightharpoons \bar{p}, \bar{d}, \overline{He}, \gamma, \ldots$$

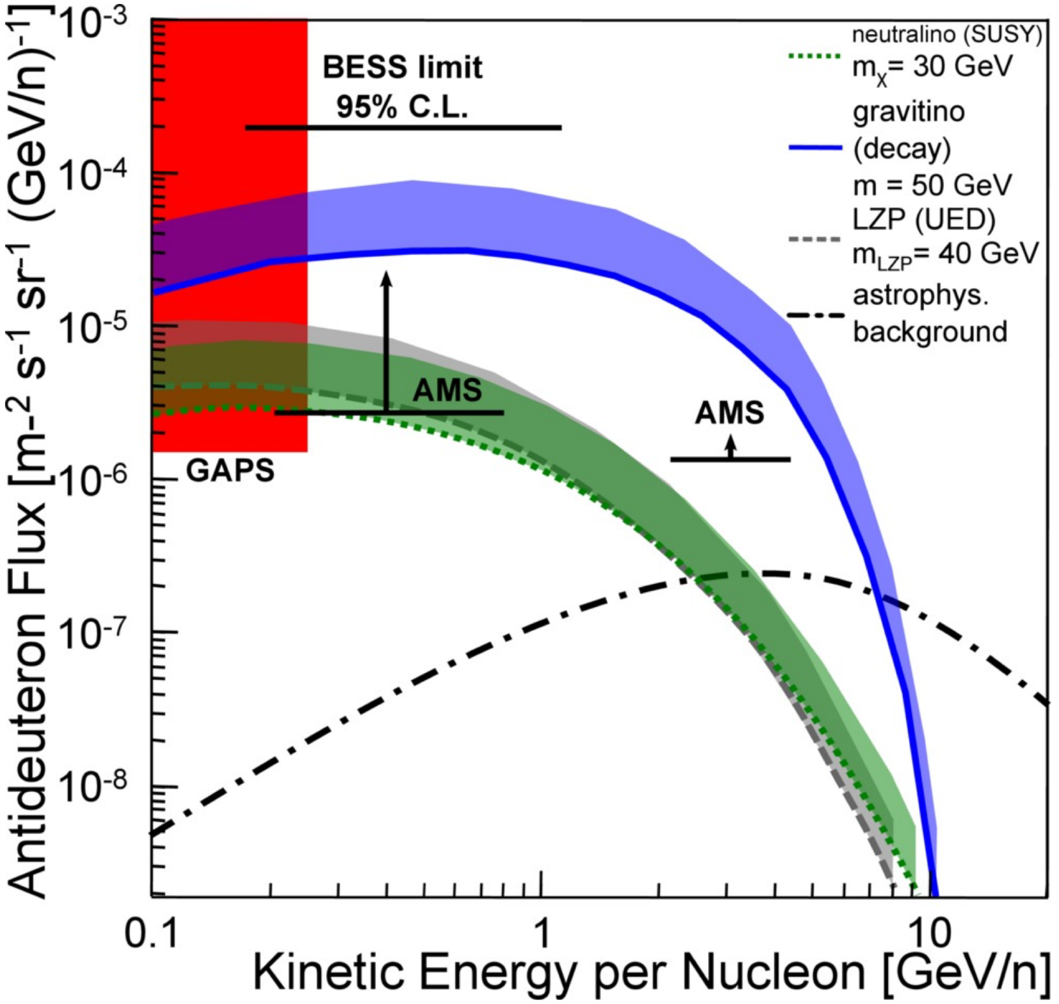
→ Measured at accelerators by ALICE, LHCb, NA-61,…

anti-nuclei cosmic ray flux near earth



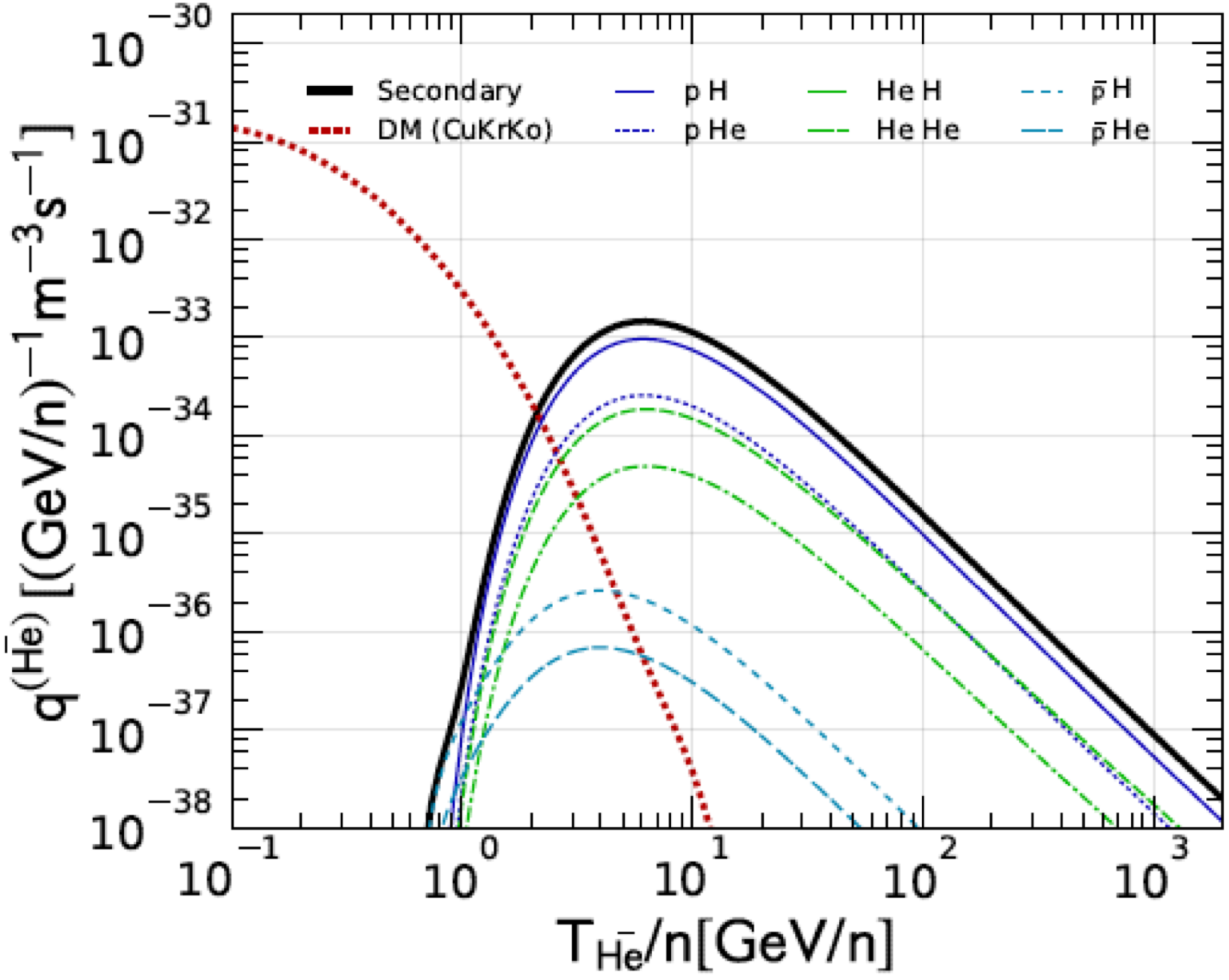
Examples of current predictions (1)

anti-deuteron



[https://antideuteron.com (GAPS)]

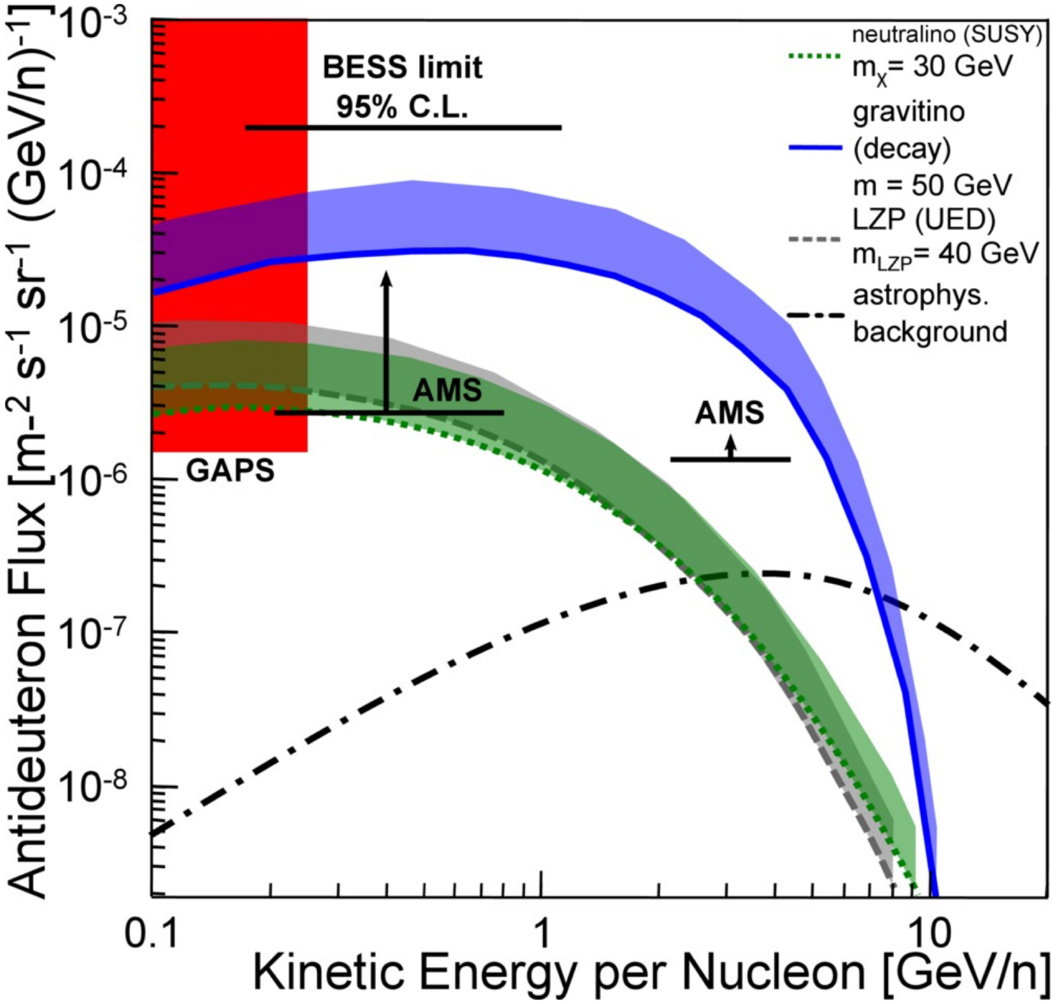
anti-^{3}He



[Phys. Rev. D 97, 103011 (2018)]

Examples of current predictions (2)

anti-deuteron



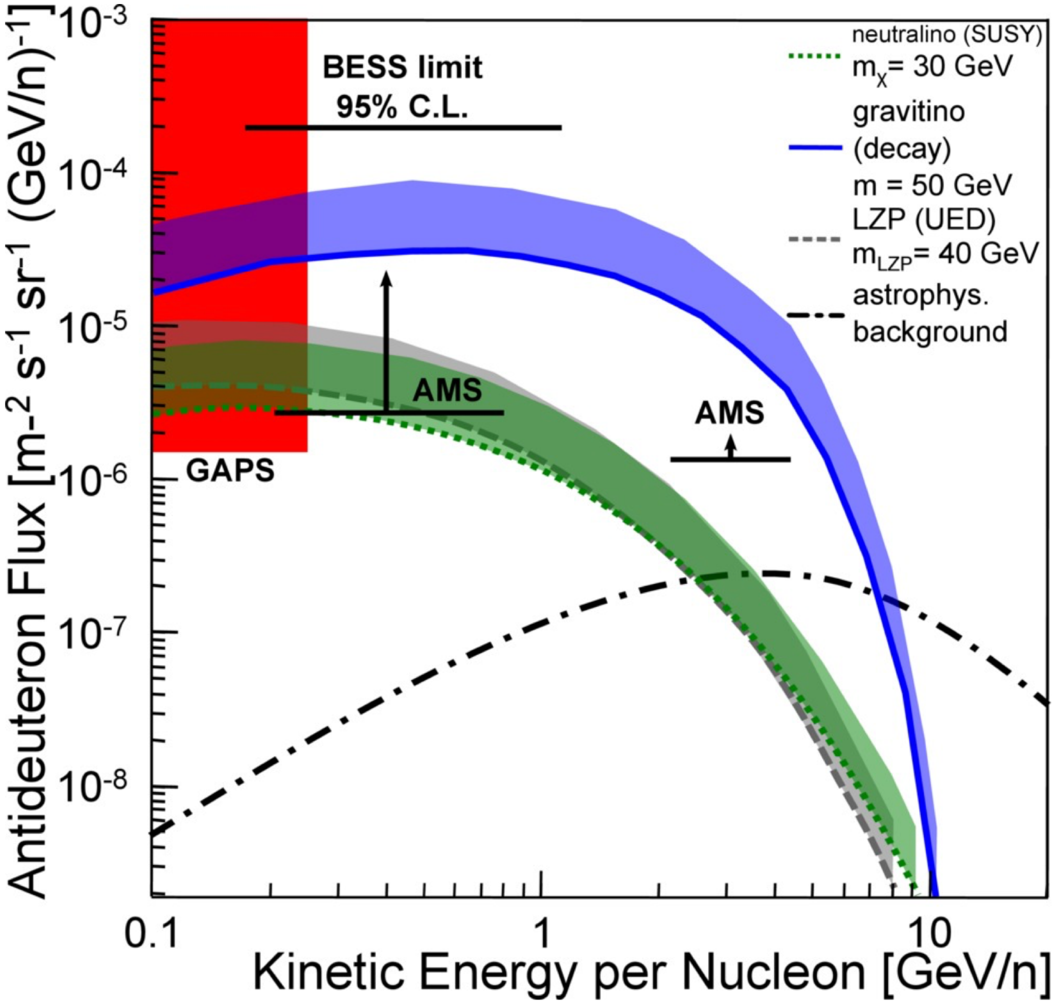
[https://antideuteron.com (GAPS)]

anti-^{3}He

[arXiv:2006.16251]

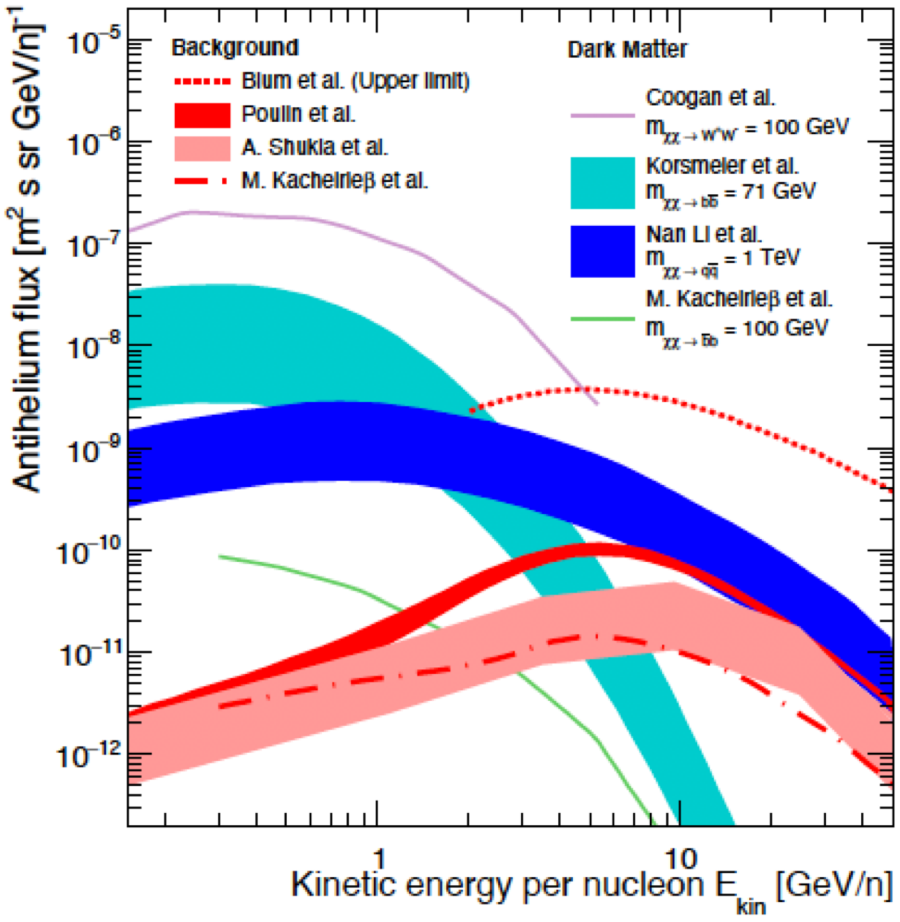
Examples of current predictions (2)

anti-deuteron



[https://antideuteron.com (GAPS)]

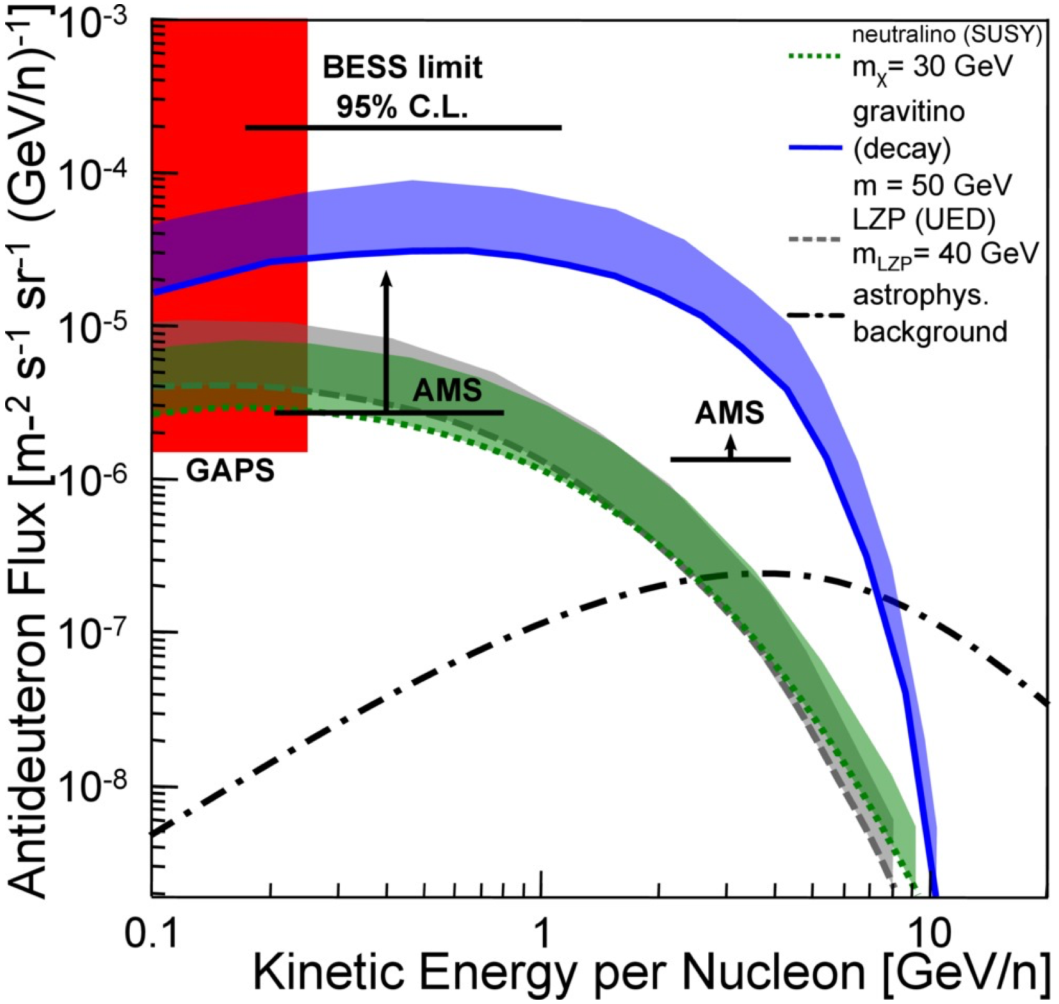
anti-^{3}He



[arXiv:2002.04163v2]

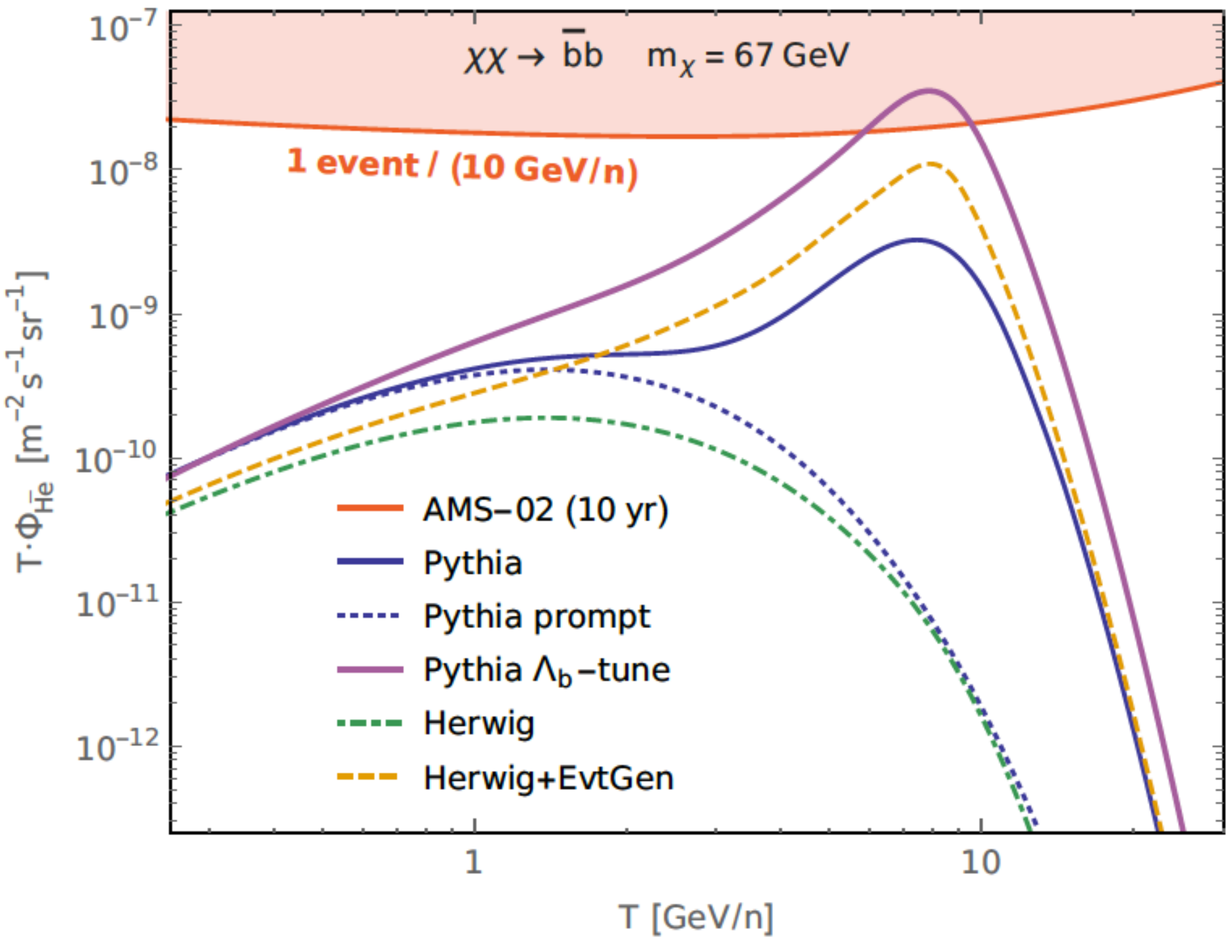
Examples of current predictions (3)

anti-deuteron



[https://antideuteron.com (GAPS)]

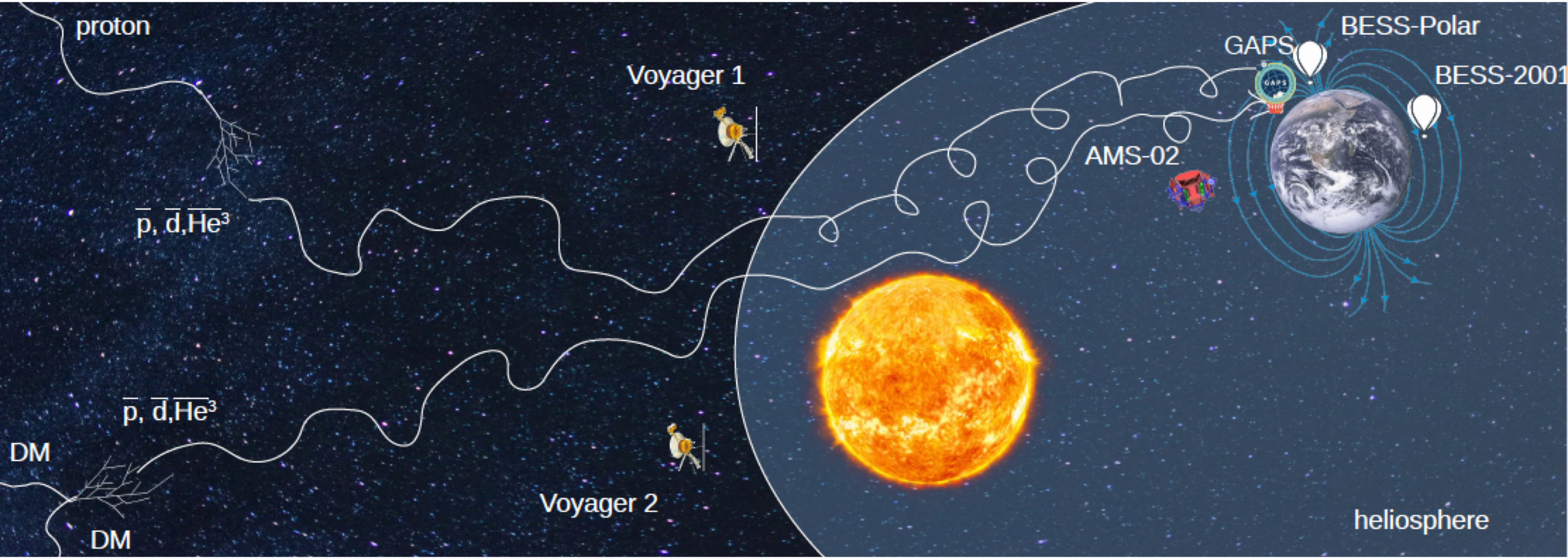
anti-^{3}He



[arXiv:2006.16251]

Slide taken form L. Serksnyte (TUM)

The path of anti-nuclei to Earth



$$\nabla \cdot (-K \nabla N_{\bar{d}} + V_c N_{\bar{d}}) + \partial_t (b_{tot} N_{\bar{d}} - K_{EE} \partial_t N_{\bar{d}}) + \Gamma_{ann} N_{\bar{d}} = q_{\bar{d}}$$

Propagation term:
Common to all antiparticles (propagation codes, e.g. GALPROP)

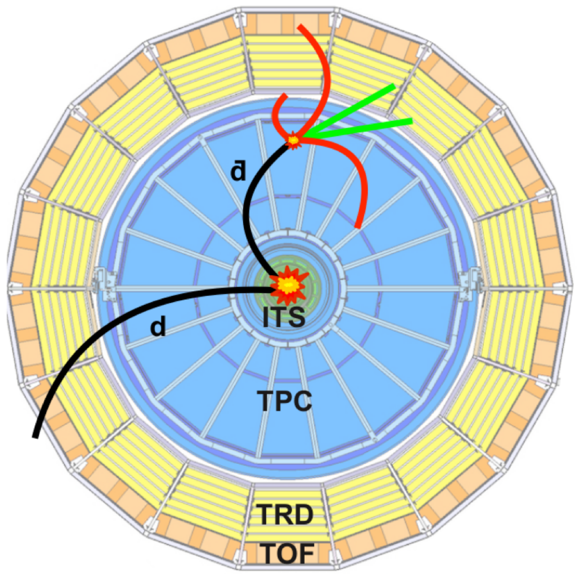
Annihilation term:
Known for antiprotons and can be **measured at the LHC**

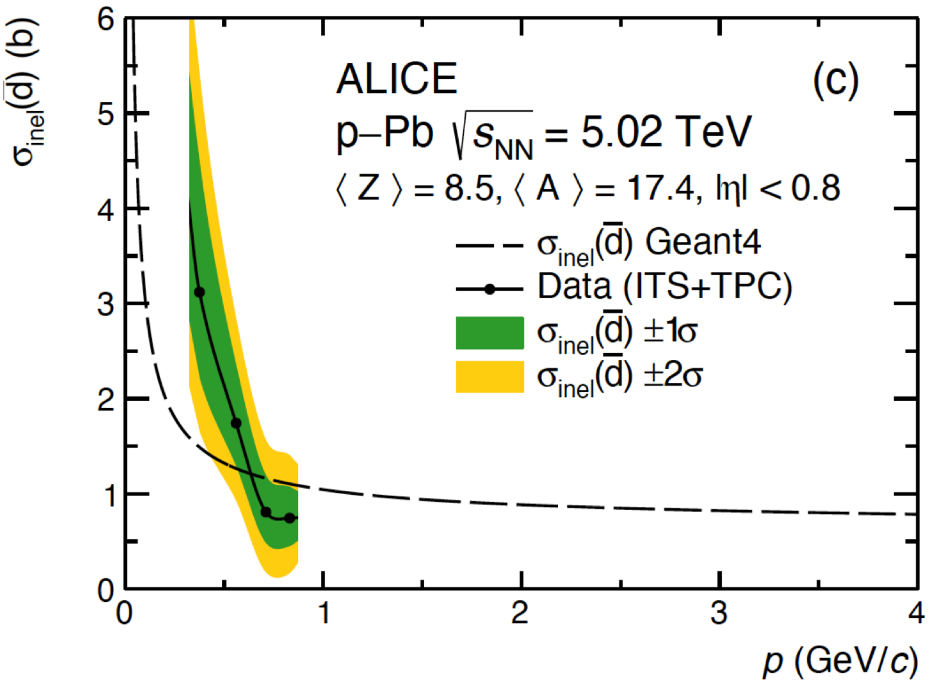
Source term:
Depends on coalescence models for anti-nuclei formation that can be **tested at accelerators**

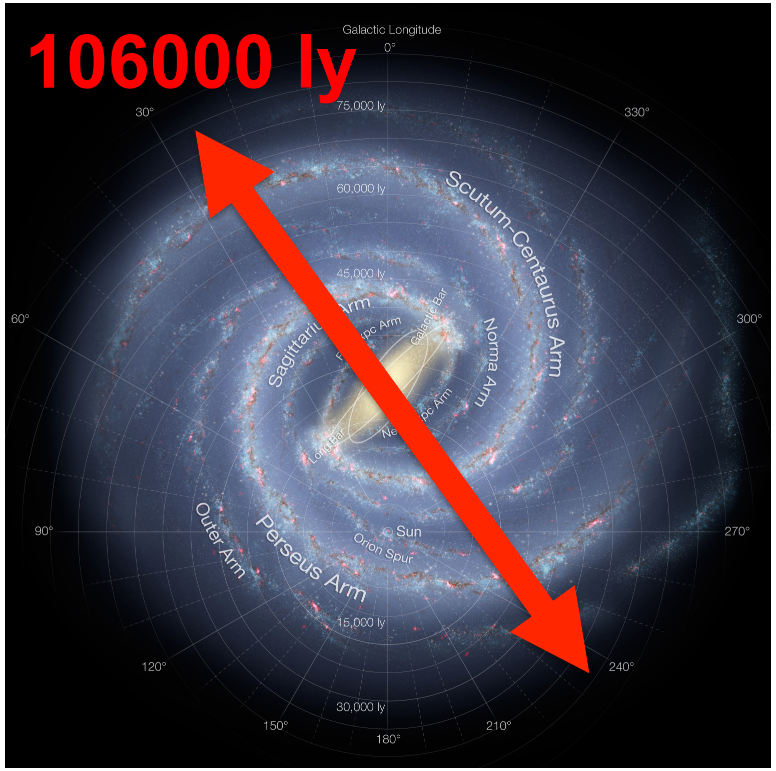
Hadronic interaction of anti-nuclei with interstellar matter

→ What is the mean free path of anti-nuclei in the galaxy?

[ALICE, 2005.11122]







→ Very rough estimate (for educational purposes):

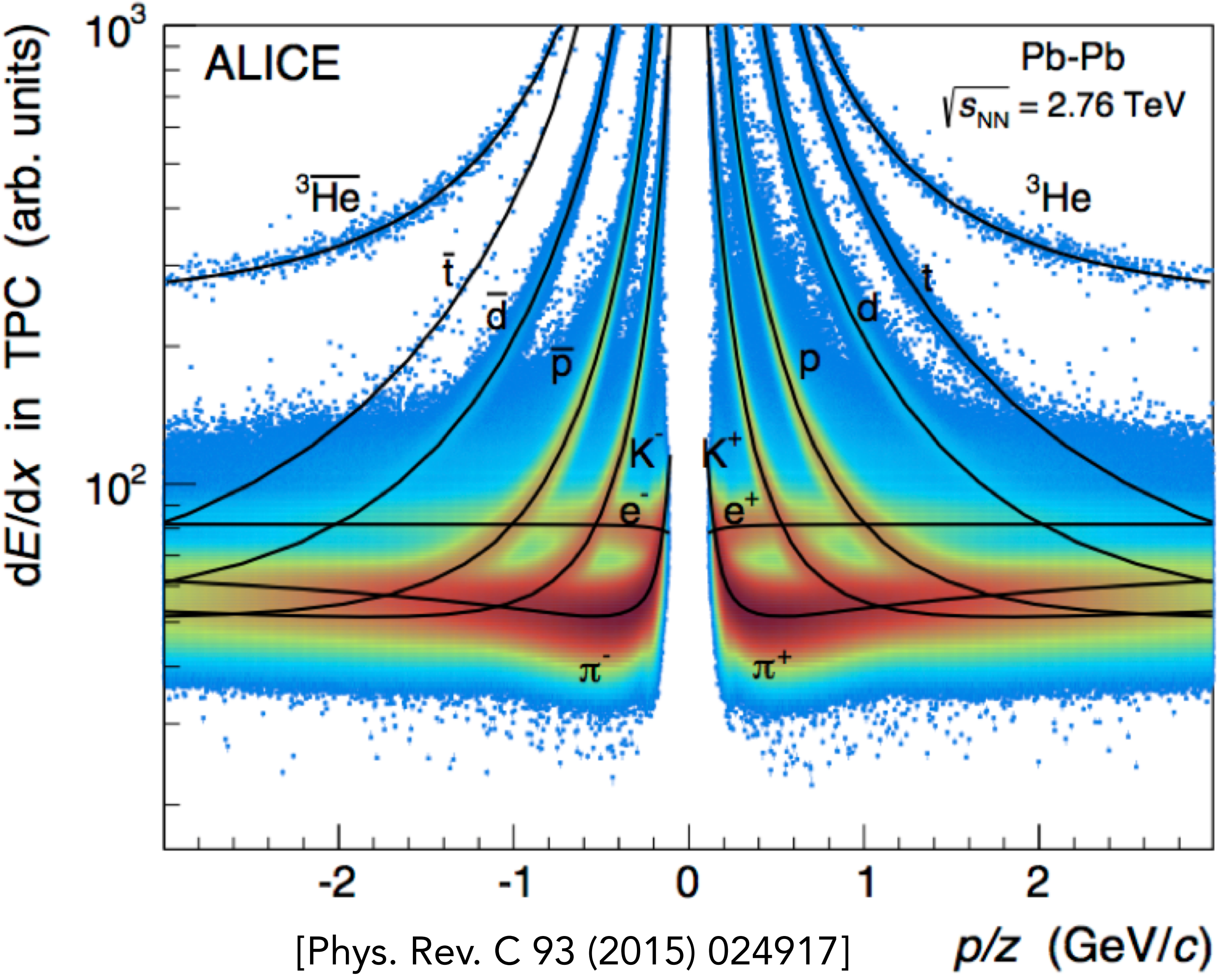
$$\lambda = \frac{1}{n \cdot \sigma} \qquad \lambda \approx \frac{1}{\frac{1}{\mathrm{cm}^{-3}} \cdot 6 \cdot 10^{-24}\,\mathrm{cm}^2} \approx 1.7 \cdot 10^{21}\,\mathrm{m} \approx \underline{180000\,\mathrm{ly}}$$

Cross section from ALICE measurement

Number density of hydrogen and He atoms in universe

Production of anti- and hyper-nuclei at accelerators

Anti-nuclei at the LHC

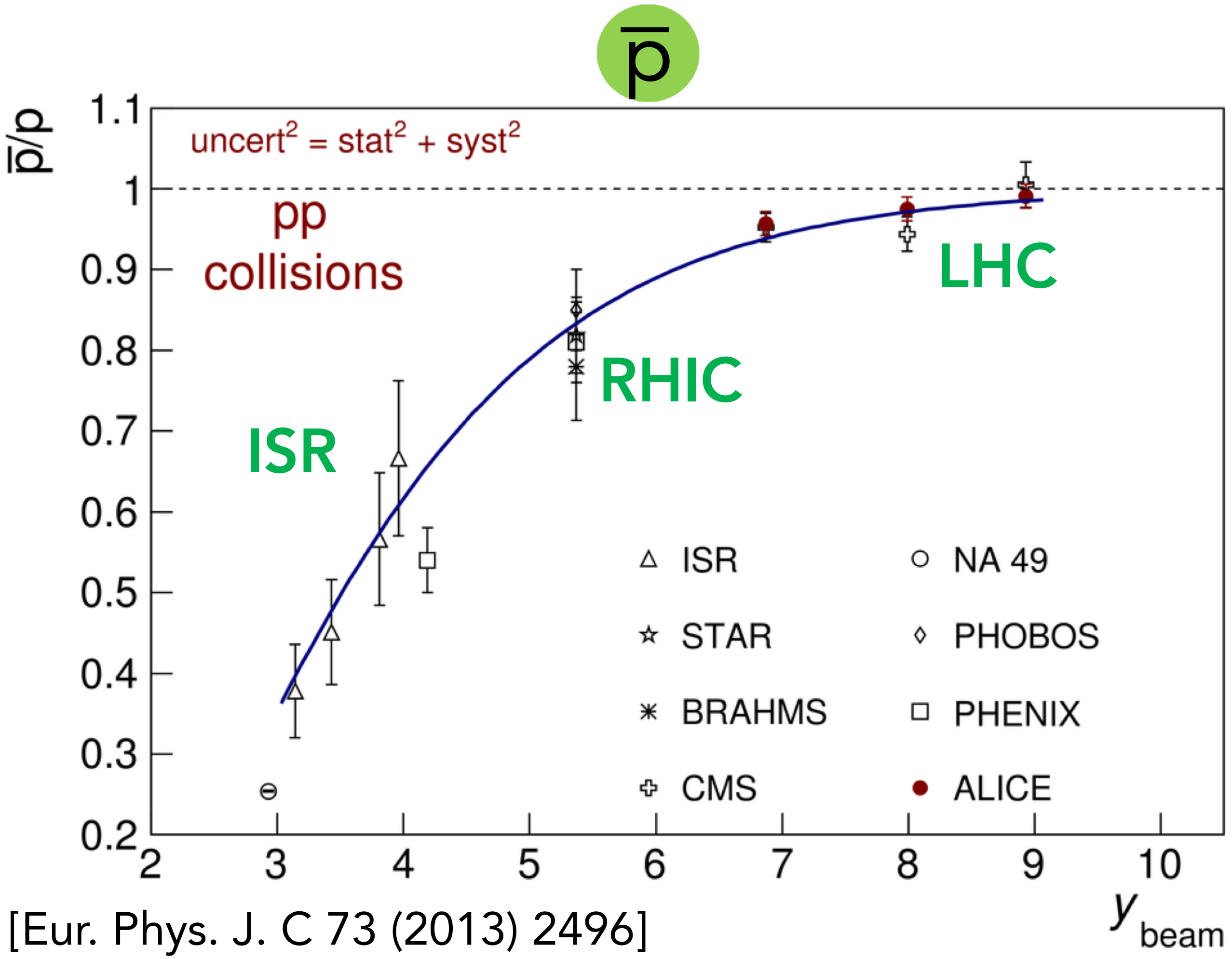


[Phys. Rev. C 93 (2015) 024917]

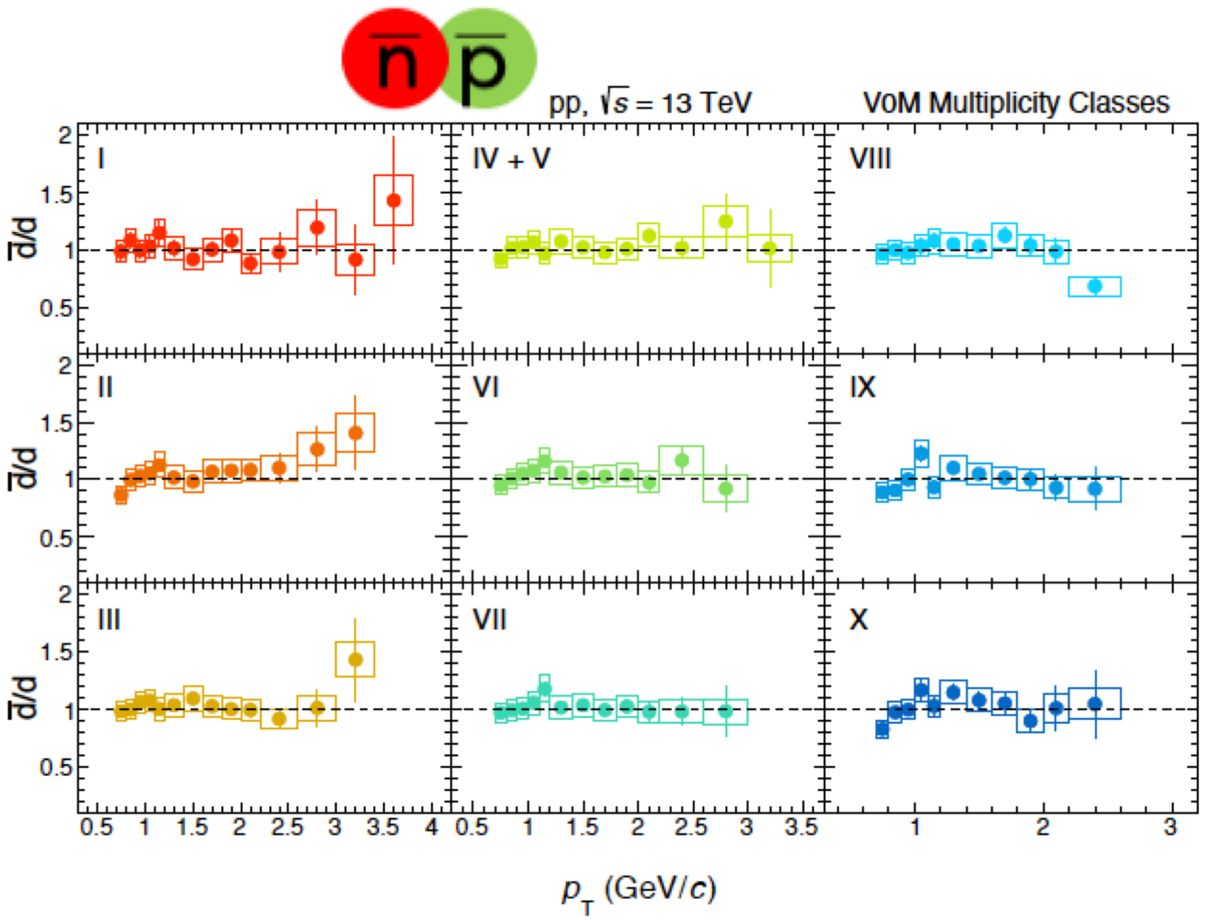
While anti-nuclei are still not seen in space, we see them abundantly at the LHC!

We can study their production and their properties in great detail.

The LHC as an antimatter factory

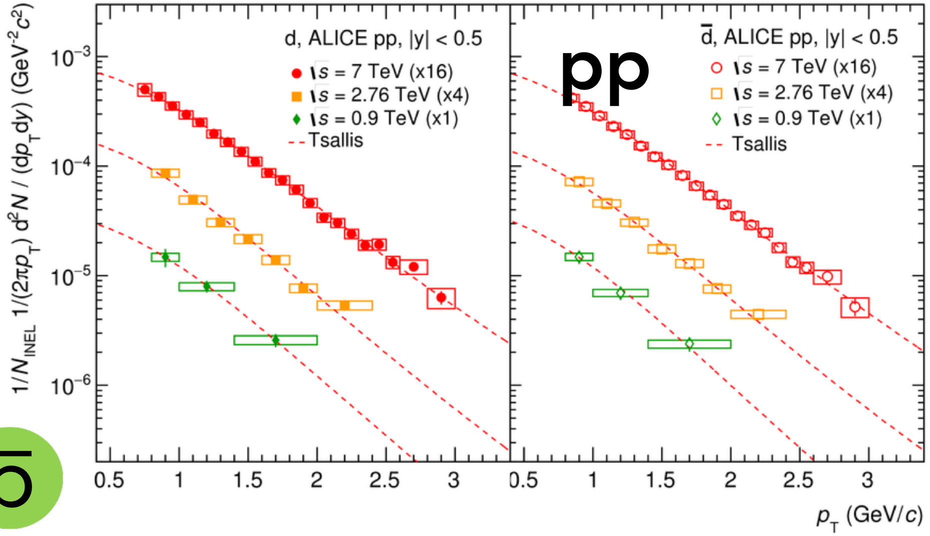


[Eur. Phys. J. C 73 (2013) 2496]



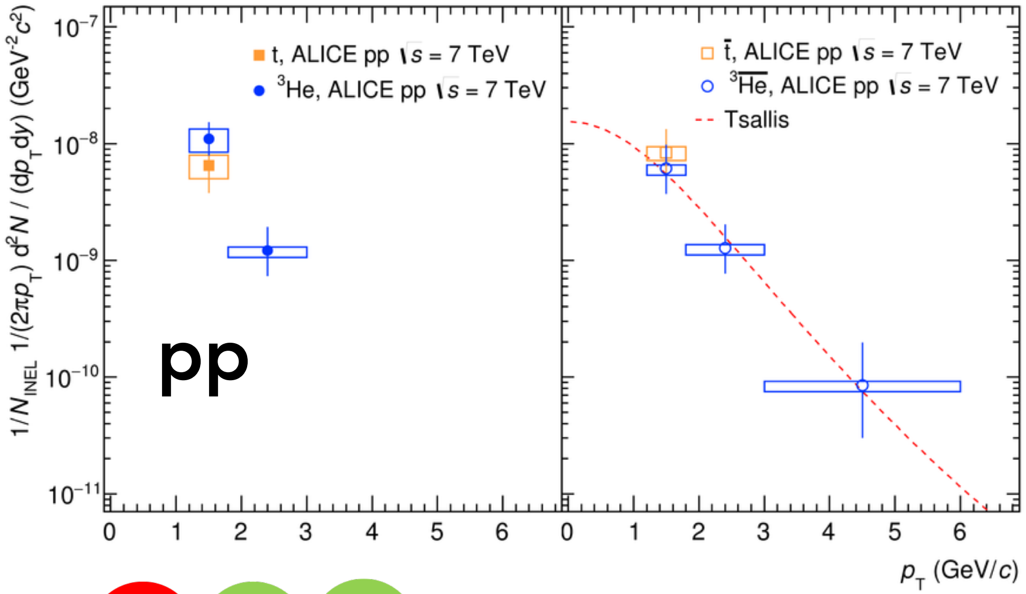
At LHC energies, particles and anti-particles are produced in equal abundance at mid-rapidity.

A wealth of existing data



n̄ p̄

anti-deuteron

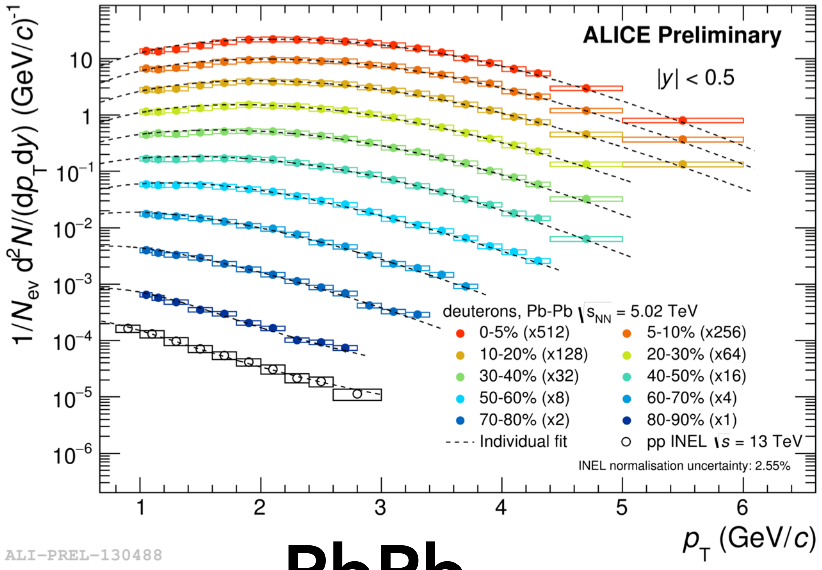


n̄ p̄ p̄

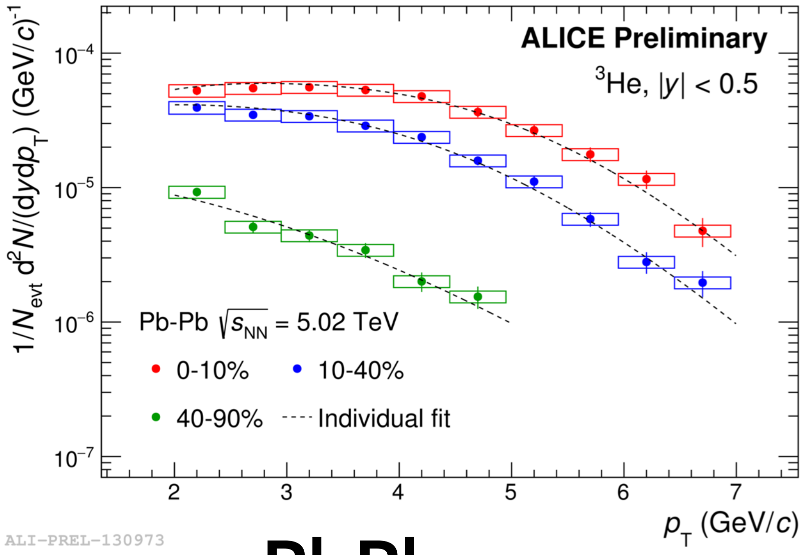
anti-helium3

n̄ Λ̄ p̄

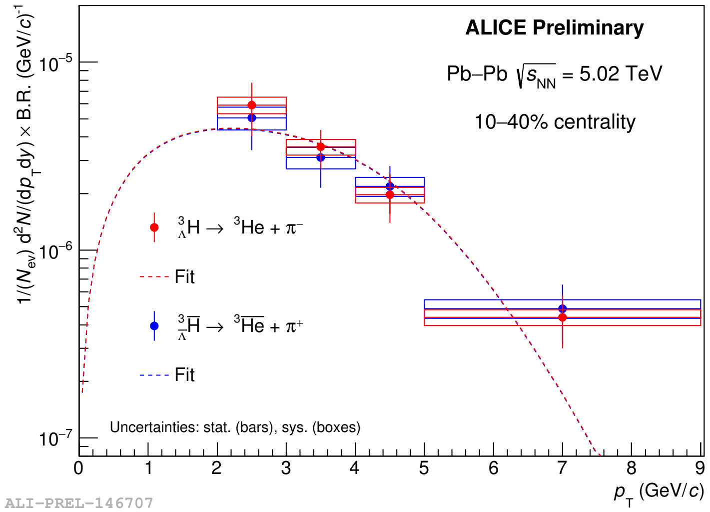
anti-hyper-triton



PbPb

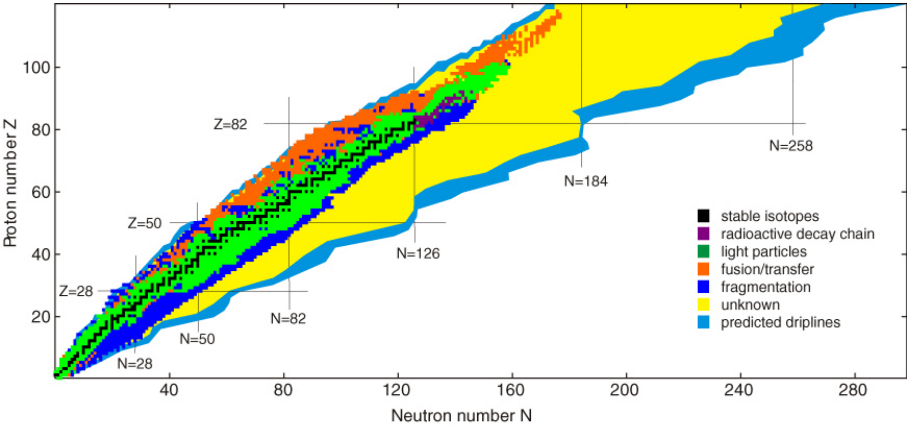


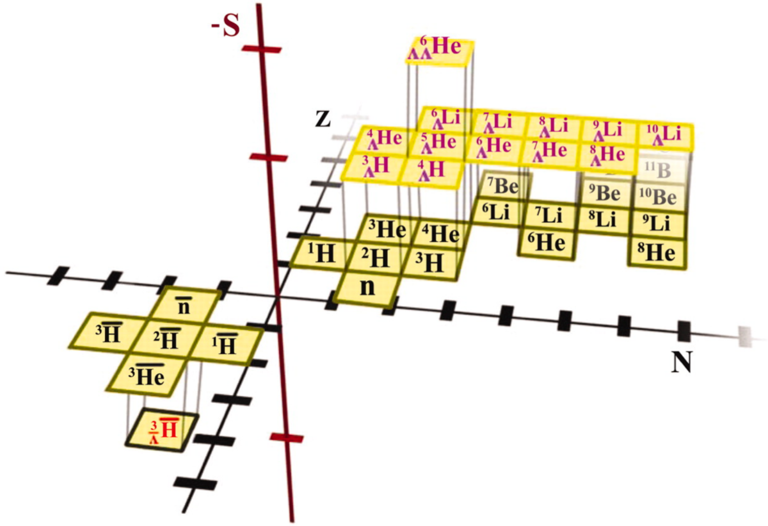
PbPb

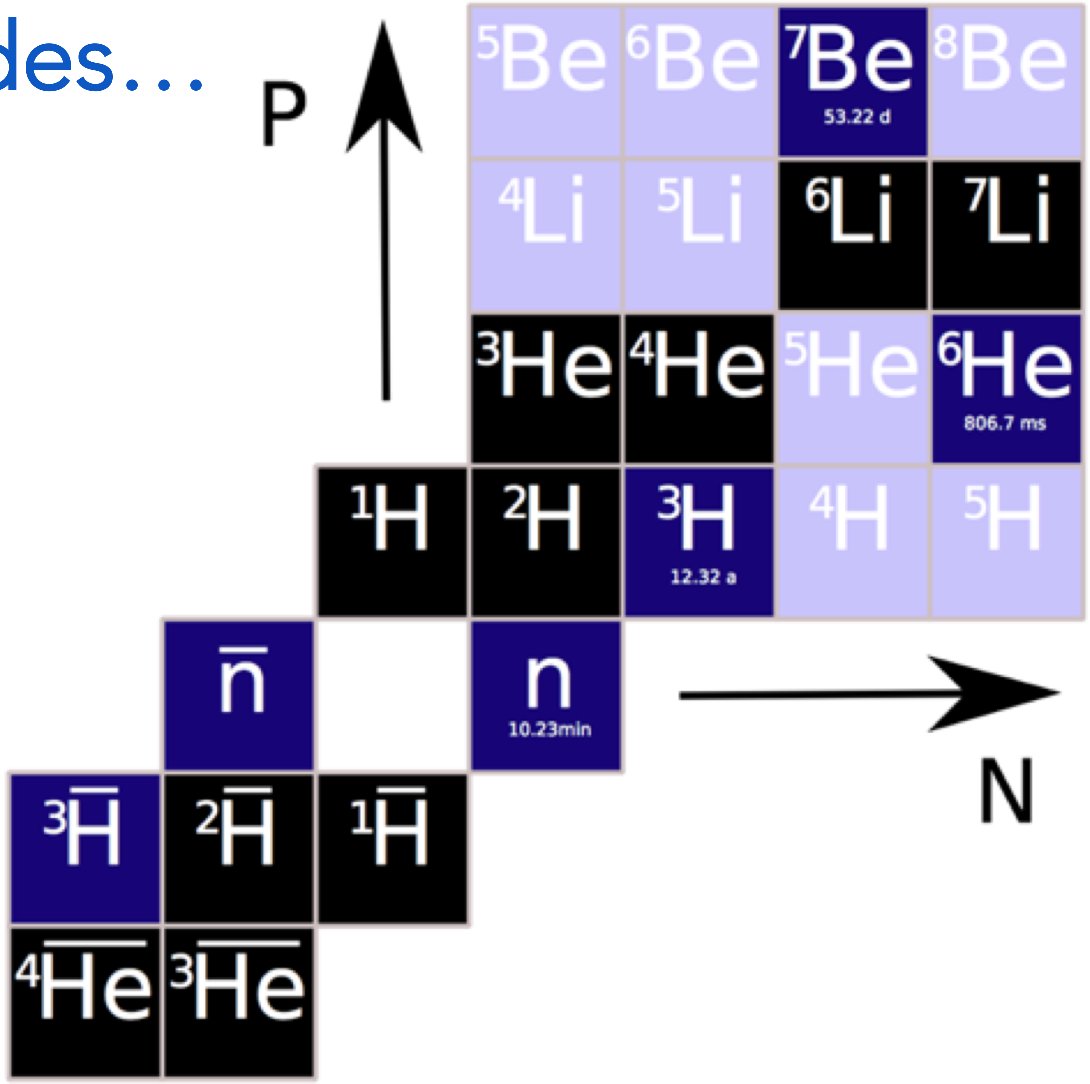


PbPb

Extending the table of nuclides…



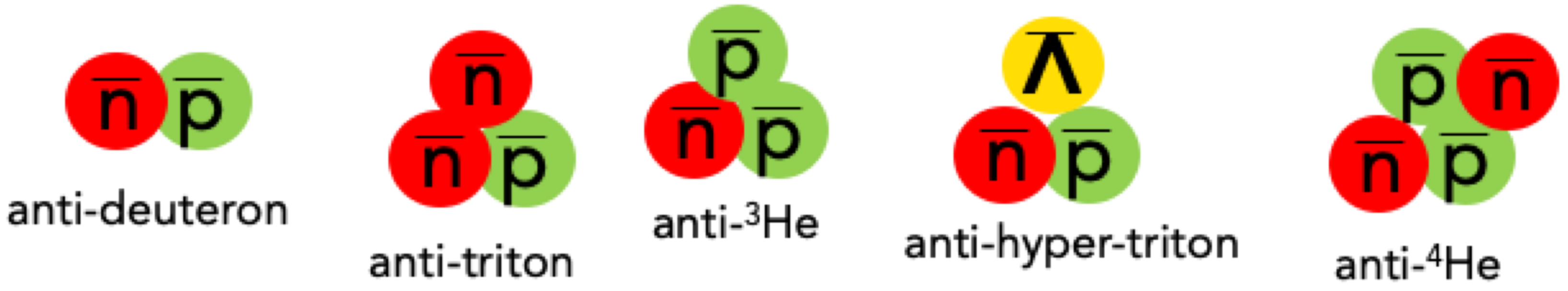




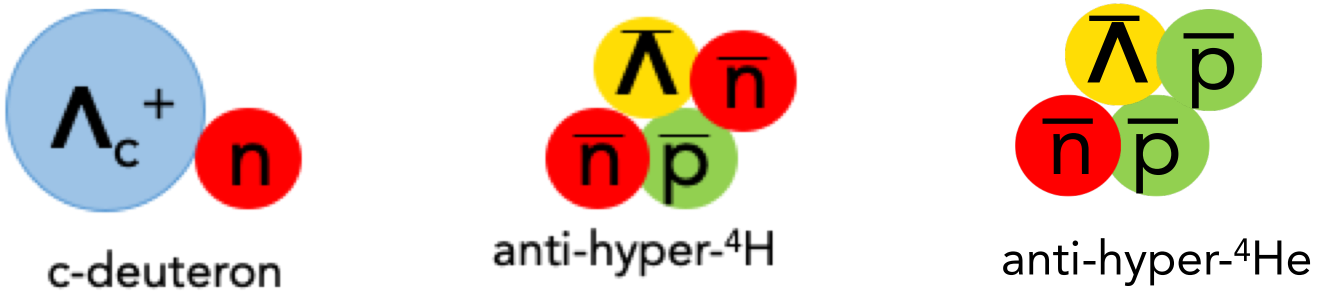
Anti-(hyper)-nuclei up to A=4 are currently in reach at accelerators. Anti-hyper-nuclei of mass A=5 and anti-nuclei of mass A=6 will become in reach in the long term future.

Zoo of exotic QCD bound states reachable at LHC

Run 1 & 2
(2010-2018)



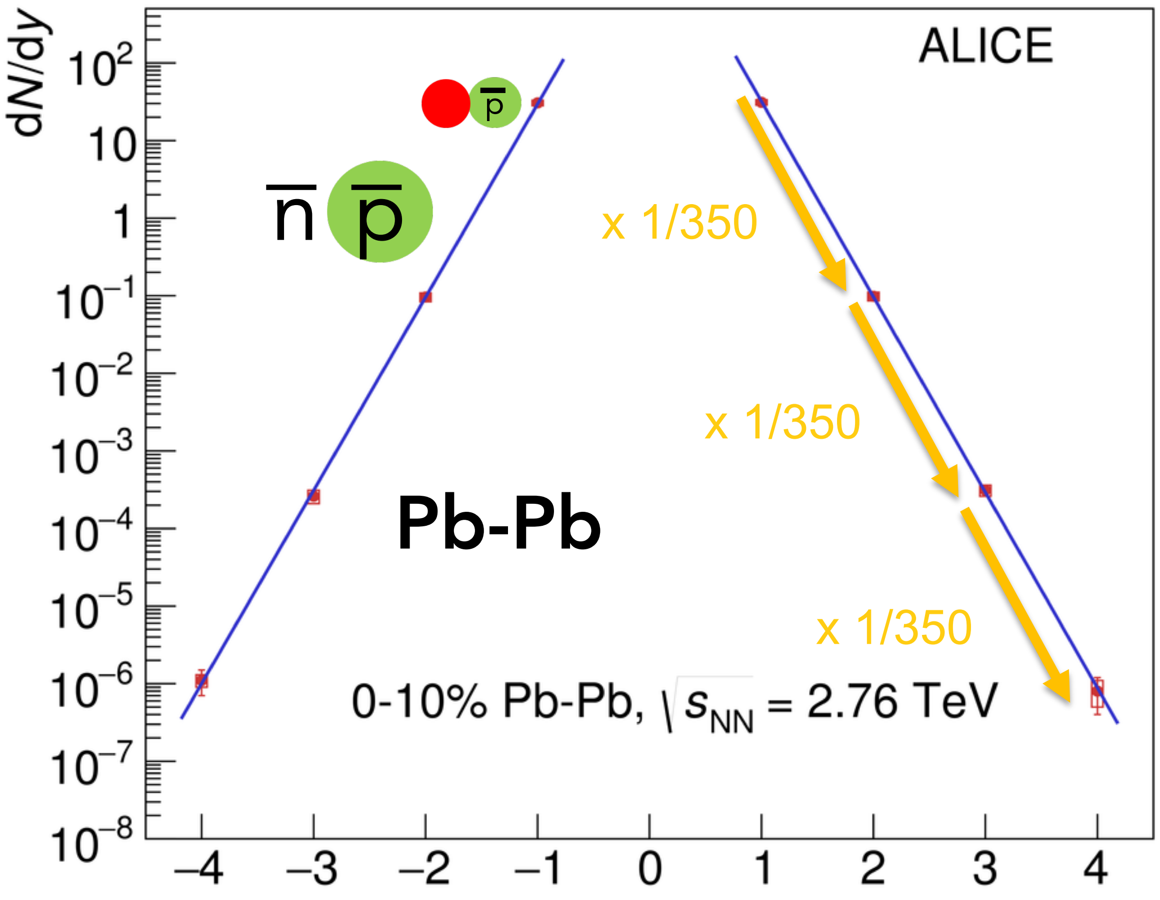
Run 3 & 4
(2021-2030)



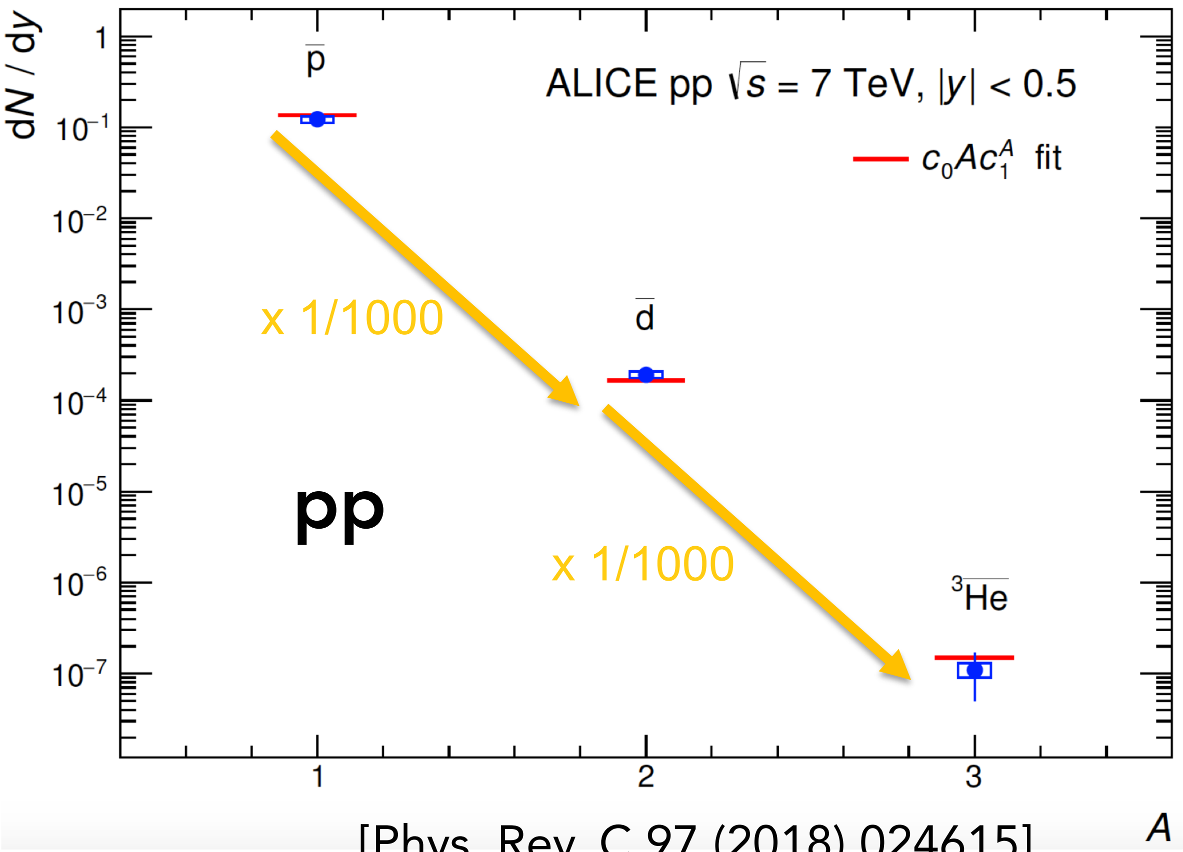
Run 5 & 6
(2032-2038)

→ new ALICE 3.0 experiment at LHC-P2

Understanding anti-nuclei production: penalty factor



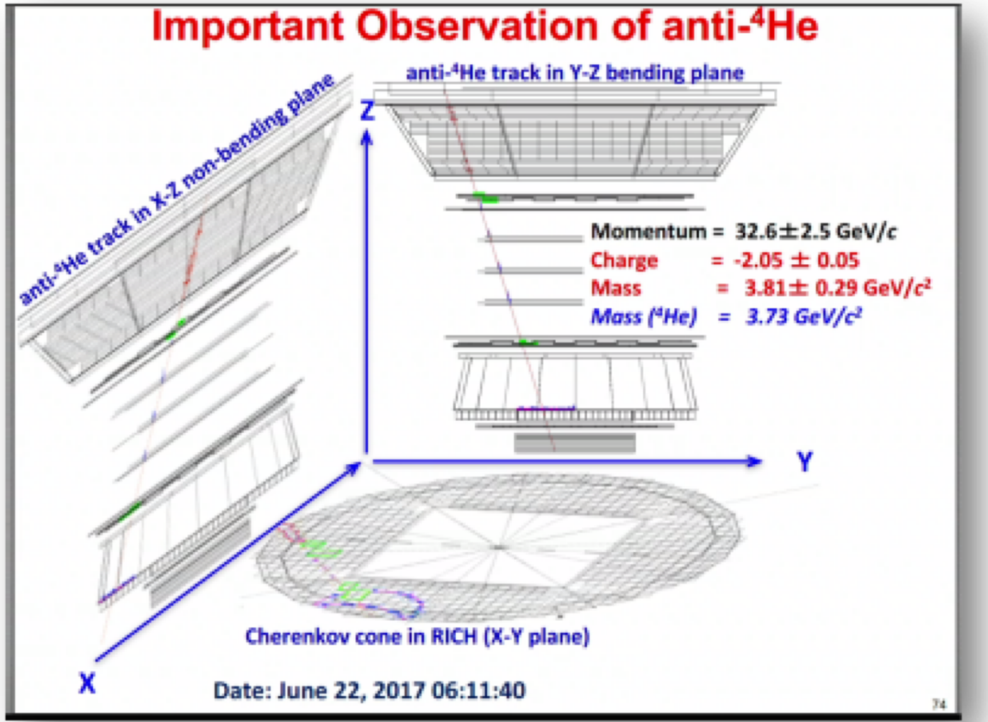
[Nucl. Phys. A 971 (2018) 1-20]



[Phys. Rev. C 97 (2018) 024615]

The production yield of (anti)-nuclei decreases at the LHC by a factor of about ~350 for each additional nucleon in Pb-Pb (~1000 in pp).

The penalty factor in the universe



Samuel Ting,
CERN Colloquium
24th May 2018

Observations on $^4\overline{He}$

1. We have two $^4\overline{He}$ events with a background probability of 3×10^{-3}.

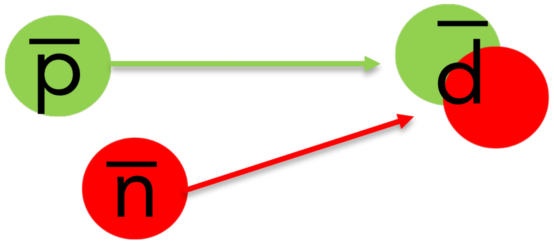
2. Continuing to take data through 2024 the background probability for $^4\overline{He}$ would be $2x10^{-7}$, i.e., greater than 5-sigma significance.

3. The $^3He/^4He$ ratio is 10-20% yet $^3\overline{He}/^4\overline{He}$ ratio is 300%. More data will resolve this mystery.

Coalescence parameters B_A

- (anti-)nuclei production by coalescence of (anti-)protons and (anti-)neutrons which are close by in momentum and configuration space. Roughly speaking:
  "deuteron ∝ proton x neutron => deuteron ∝ proton^2"

$$E_{\mathrm{d}} \frac{\mathrm{d}^3 N_{\mathrm{d}}}{\mathrm{d}p_{\mathrm{d}}^3} = B_2 \left(E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^2$$

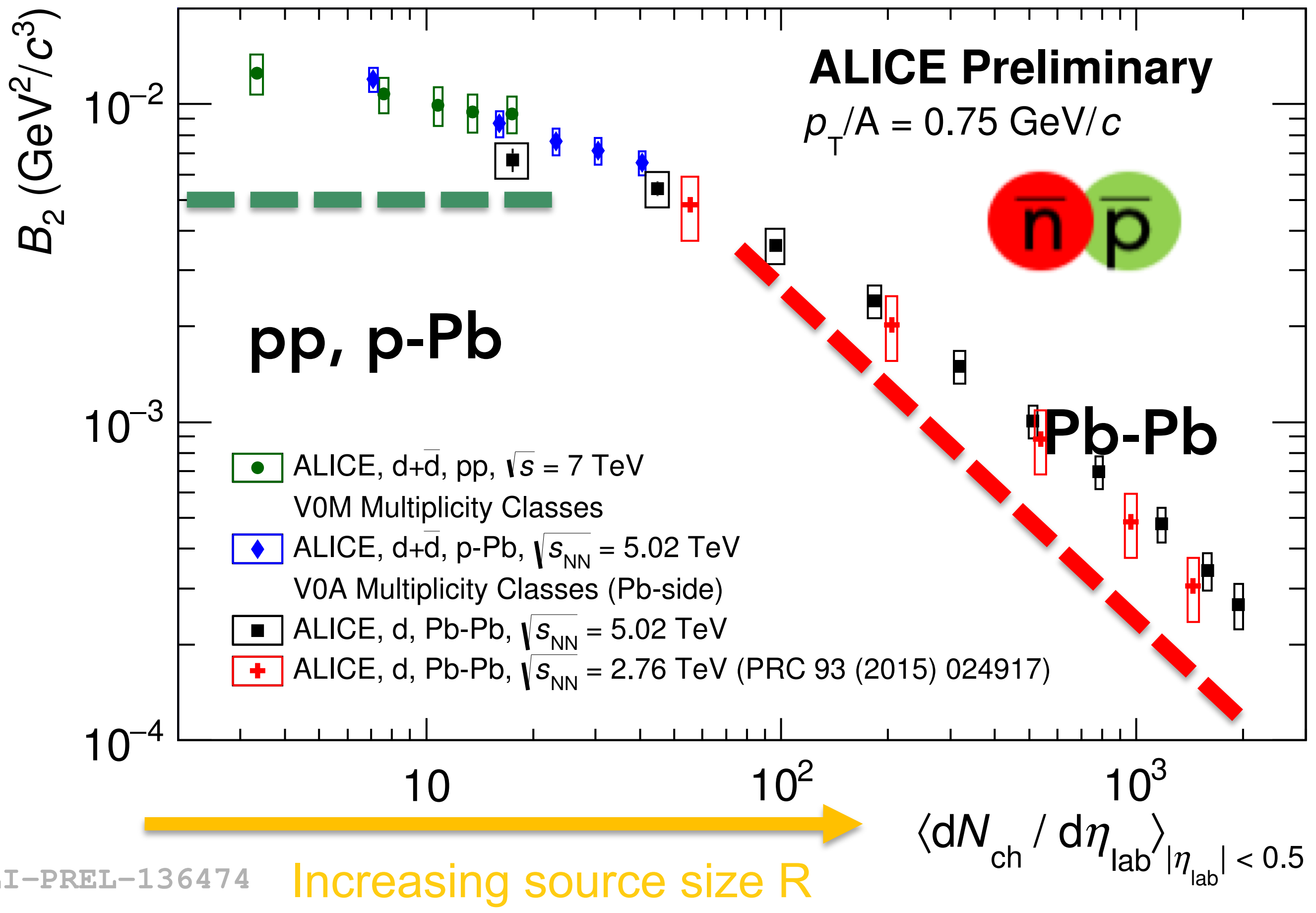


- Spherical approximation: maximum momentum difference (coalescence momentum p_0) is approx. 100 MeV (5.3 MeV kinetic energy of a nucleon in the rest frame of the other).
  → Can be implemented as an *afterburner* to standard event generators.

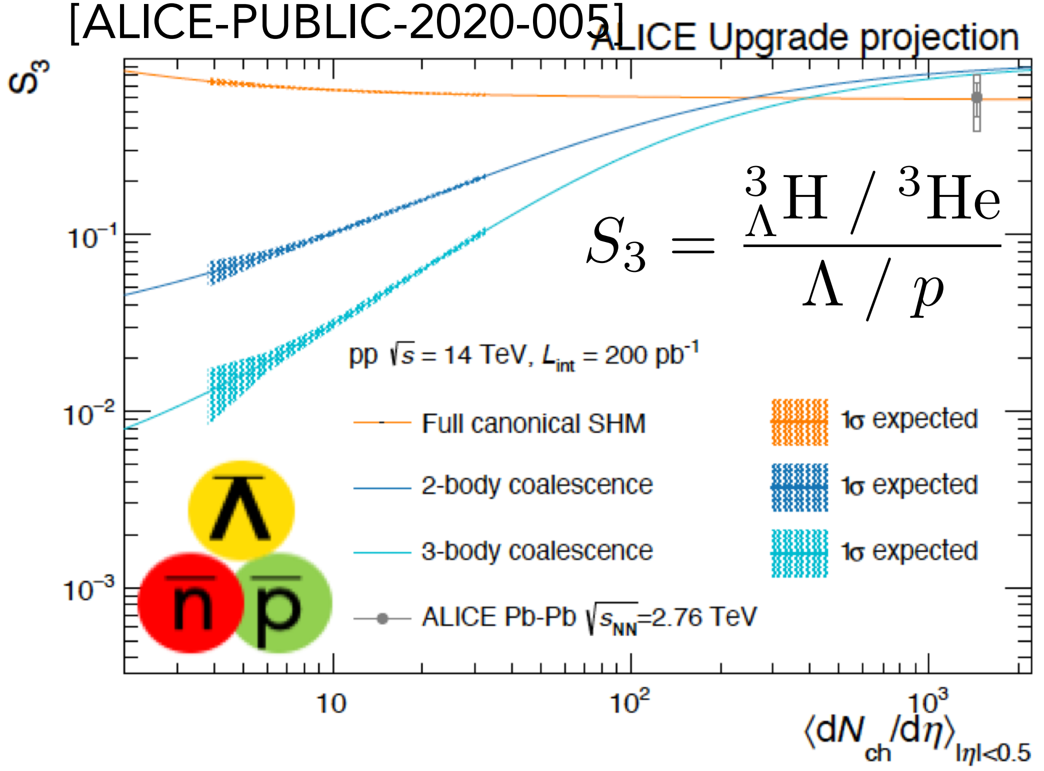
- Quantum-mechanically correct: overlap of the **source function** (e.g. pp collision) with the **Wigner-function** (and thus the wave-function) of the produced nucleus:

$$\gamma \frac{dN_{\mathrm{d}}}{d^3\mathbf{P}} = \frac{2s_d+1}{(2\pi)^3} \int d^4x_1 \int d^4x_2 \int d^4x_1' \int d^4x_2' \, \underline{\Psi^*_{d,P}(x_1',x_2')\,\Psi_{d,P}(x_1,x_2)}\; \underline{\rho_{p_1,p_2}(x_1,x_2;x_1',x_2')}$$

Understanding the details of the coalescence process

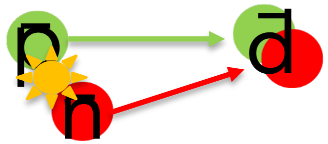


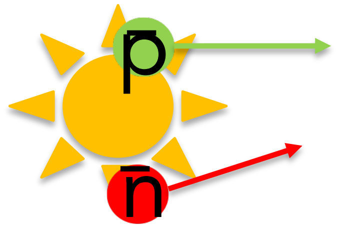
[ALICE-PUBLIC-2020-005]



Hyper-nuclei like the hyper-triton are very sensitive to details of the coalescence process due to their wide wave-function!

(a.) system size < deuteron size **(b.) system size > deuteron size**



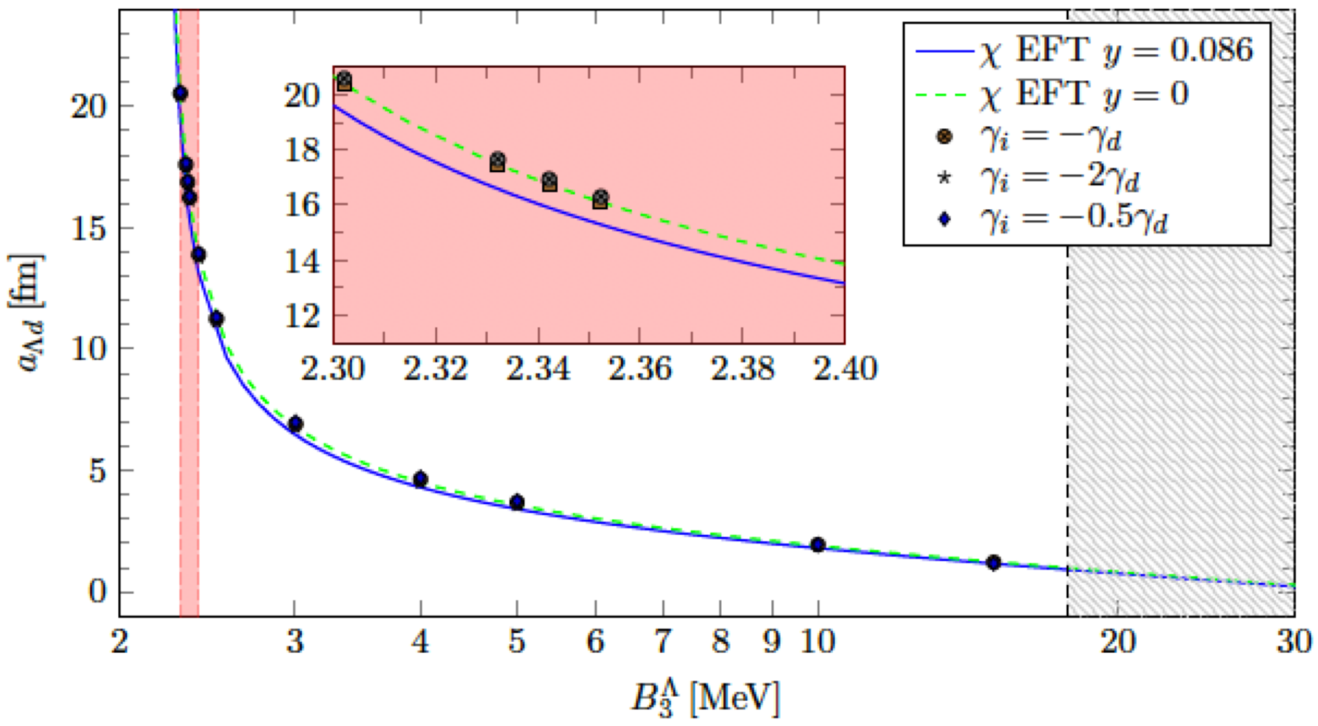


→ Their production yields are comparable to anti-nuclei in which they decay resulting in an additional background source in DM searches.

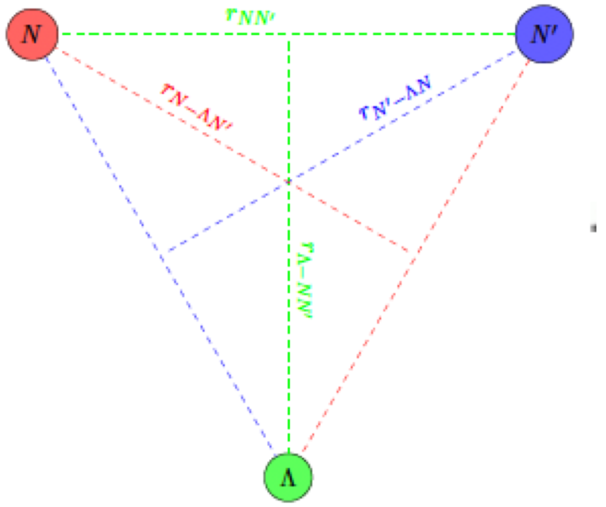
Hyper-nuclei and hyperon-nucleon interactions

Hyper-triton wave-function

→ Calculating the hyper-triton wave-function, a crucial input to coalescence studies, requires sophisticated nuclear structure calculations, e.g. based on pionless effective field theory.



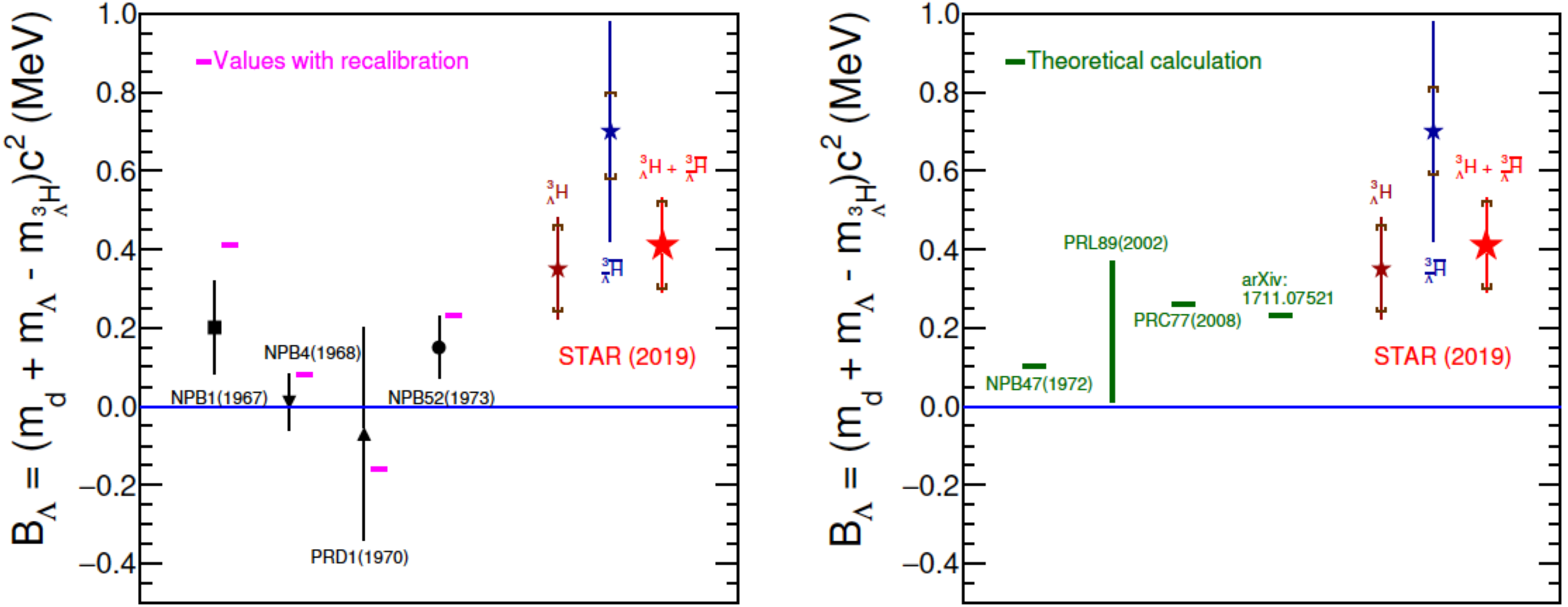
$\sqrt{\langle r^2_{\Lambda-NN'}\rangle}$[fm]	$\sqrt{\langle r^2_{N'-\Lambda N}\rangle}$[fm]	$\sqrt{\langle r^2_{N-N'\Lambda}\rangle}$[fm]	$\sqrt{\langle r^2_{NN'}\rangle}$[fm]
10.79	3.96	4.02	2.96
+3.04/−1.53	+0.40/−0.25	+0.41/−0.25	+0.06/−0.05
+0.03/−0.02	+0.03/−0.03	+0.03/−0.03	+0.03/−0.04



[Phys. Rev. C 100 (2019) 034002]

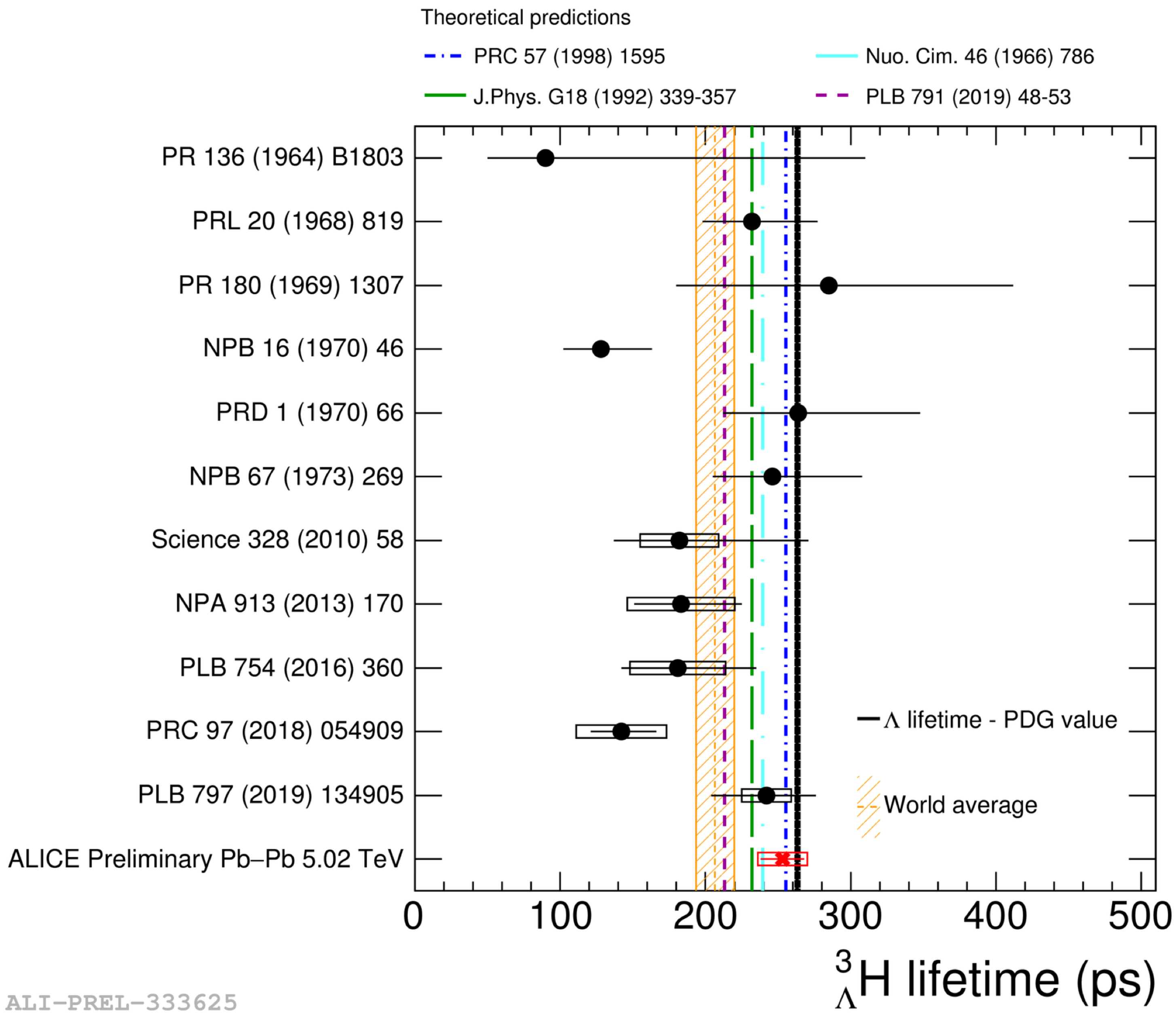
(anti-)Hyper-triton binding energy measurements

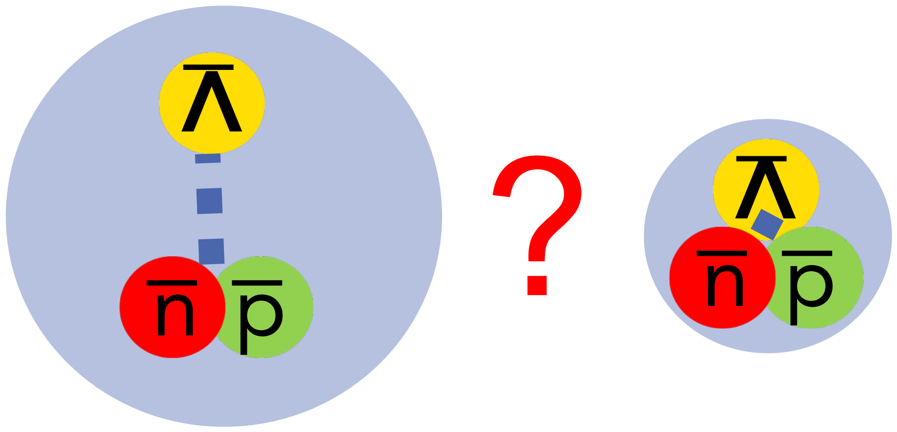
[*STAR, Nature Phys.* 16 (2020) 4]



How precisely do we really know the Lambda separation energy in the hyper-triton?
→ Homework for the experimentalists..

(Anti-)Hypertriton lifetime measurement from ALICE





m = 2.991 GeV/c^2, B_Λ = 130 keV

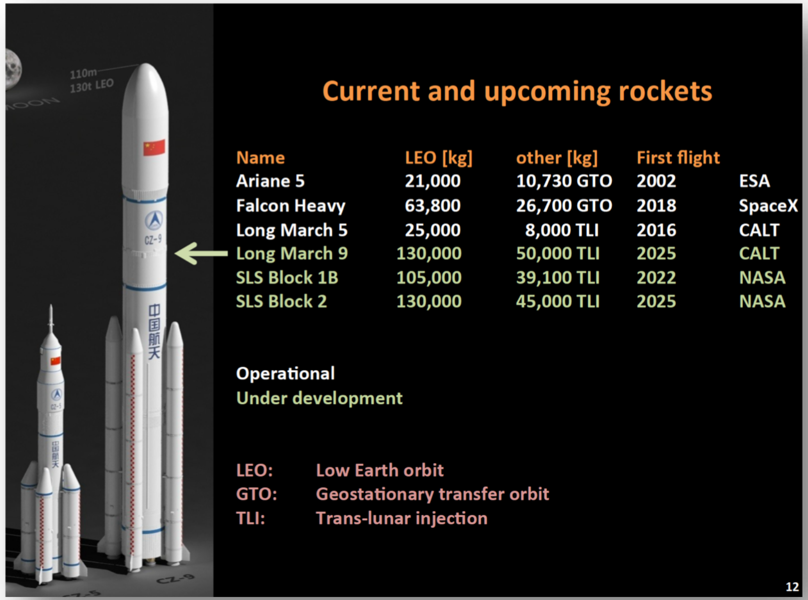
→rms-radius = 10.3 fm

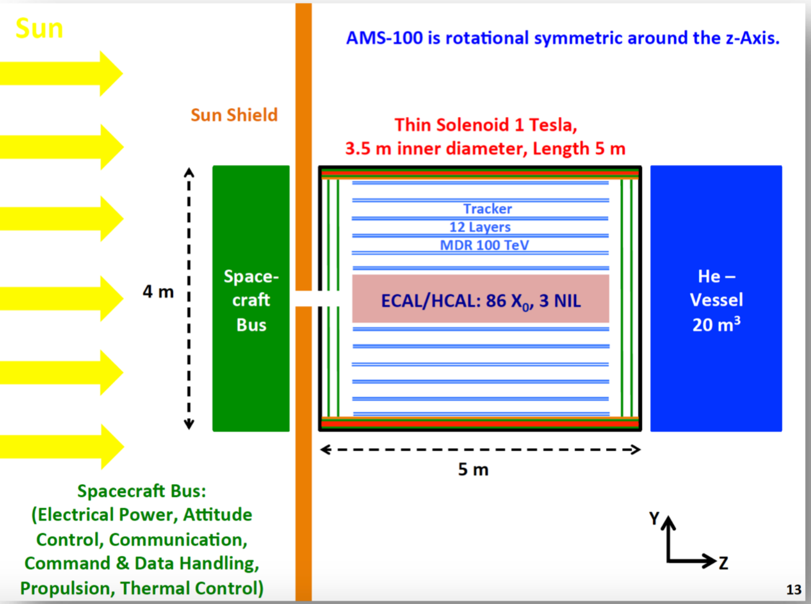
- Exclude large deviations from free **Λ** life time
- Test of different models with different Hypertriton structure and final state interaction

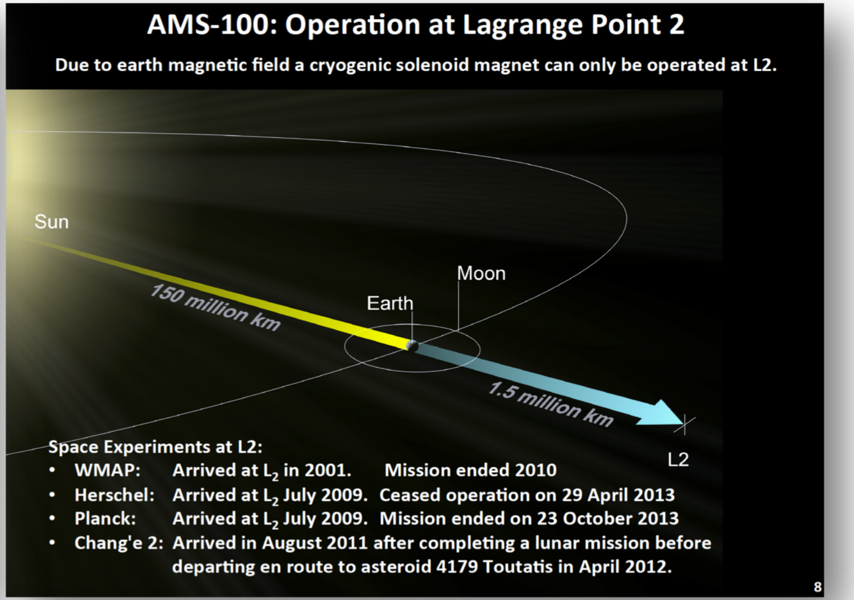
Outlook and summary

AMS-100

[Talk from Prof. S. Schael at AMS days La Palma: https://www1b.physik.rwth-aachen.de/~schael/AMS-100.html]







→As the only high energy hadron collider experiment for many years to come, the LHC community has the duty to measure and understand anti-nuclei production in an as comprehensive way as possible!

ALICE 3.0

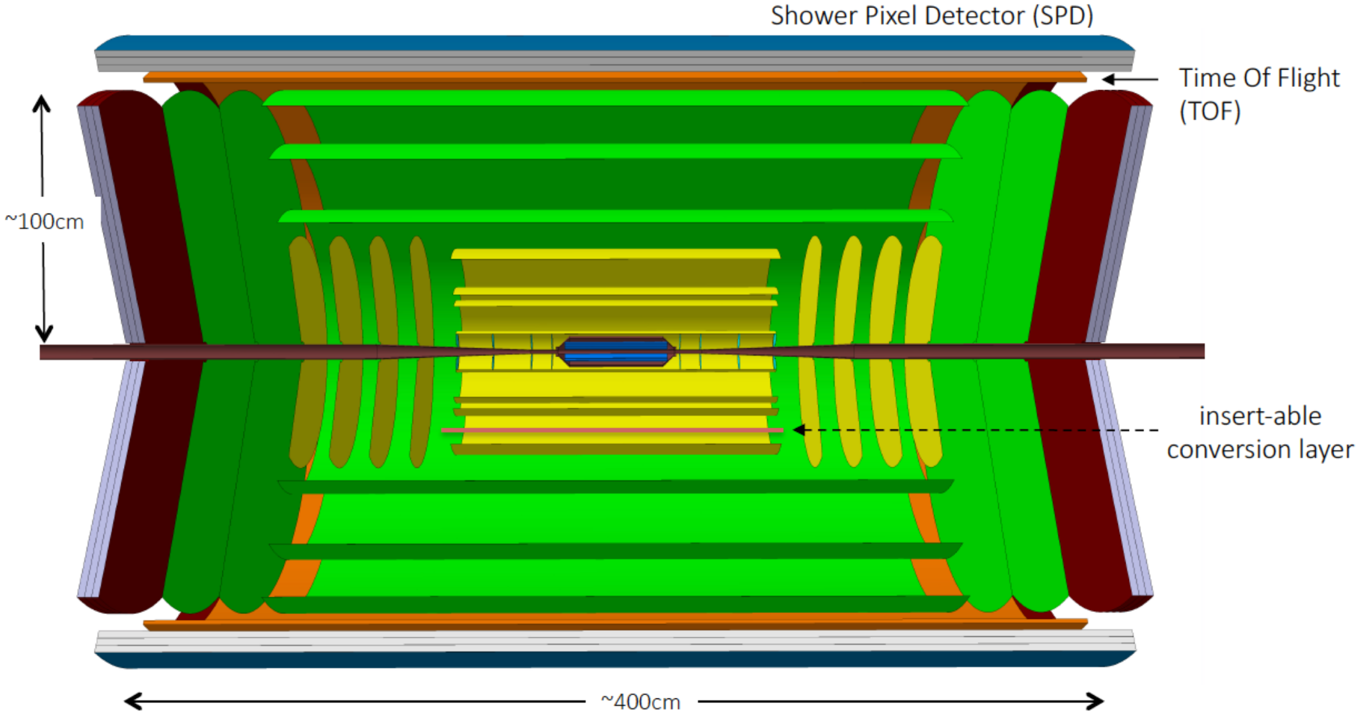
→ Complex QCD bound states like anti- and hyper-nuclei could be well studies with a future LHC experiment that is foreseen to replace ALICE in the 2030s.

Tracker: ~10 tracking barrel layers (blue, yellow and green) based on CMOS sensors

Particle ID:

- TOF with outer silicon layers (orange)
- Shower Pixel Detector (outermost blue layer)

Extended rapidity coverage: **up to 8 rapidity units**



Magnetic Field

- B = 0.5 or 1 T

Spatial resolution

- Innermost 3 layers: $\sigma < 3\mu m$
- Outer layers: $\sigma \sim 5\mu m$

Vertex material thickness

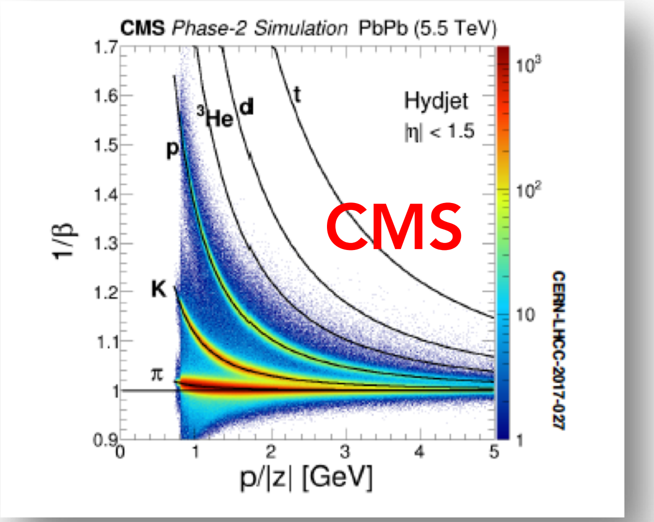
- X/X0 ~ 0.05% / layer

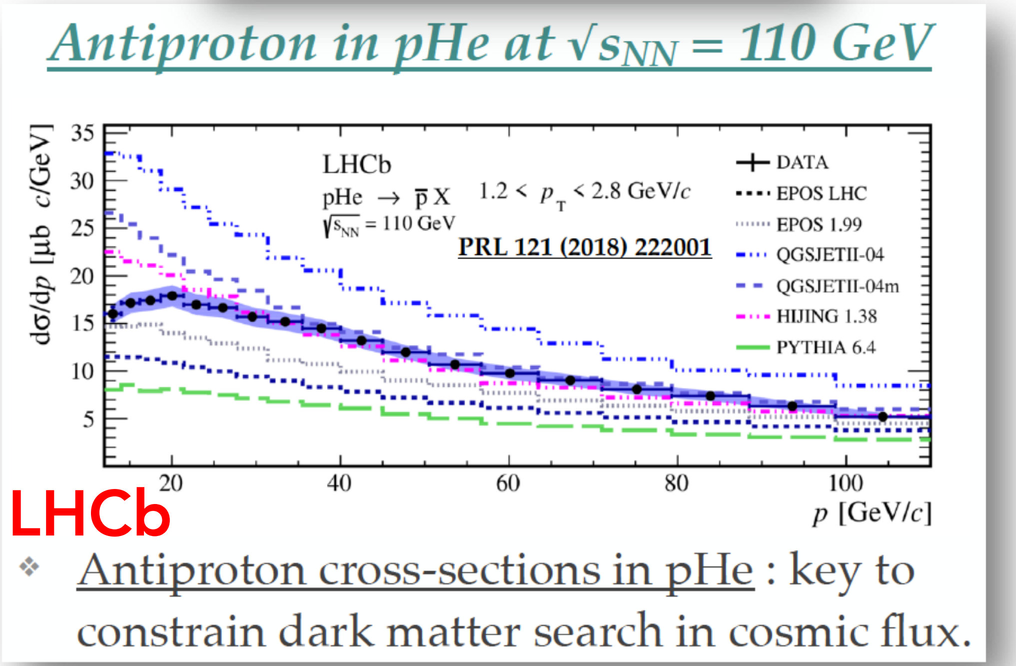
Time Measurement

Outermost layer integrates high precision time measurement ($\sigma_t \sim 20ps$)

Ongoing activities and future prospects

- A rich interdisciplinary physics program awaits us in the upcoming years at LHC (not only in ALICE)!
- A number of nice workshops combining two out of the three communities took already place, for instance:
  - CERN TH institute in May 2020 on anti- and hyper-nuclei bringing together nuclear physics and high energy physics [link].
  - Anti-deuteron workshop bringing together cosmic ray and high energy physics community [link].
  - XSCRC2019 [link]
- We now have to start to truly bring together all three communities simultaneously.
  - A starting point could be the MIAPP workshop in April-May 2021 in Munich [link].





Nuclear Physics at the LHC

- High energy LHC experiments provide a unique laboratory for nuclear and hadron physics studies that have a wide breadth of possible applications to astrophysics.

- A **very targeted** and **truly interdisciplinary** proposal focused on

1. High precision studies of hyperon-nucleon (Y-N) and hyperon-hyperon interactions → **fundamental to study the EoS of neutron stars**

2. Formation process and properties of light anti- and hyper-nuclei → **pivotal ingredient in searches for dark matter in cosmic rays**

- Web page: https://indico.ph.tum.de/event/4492/overview

Thank you!