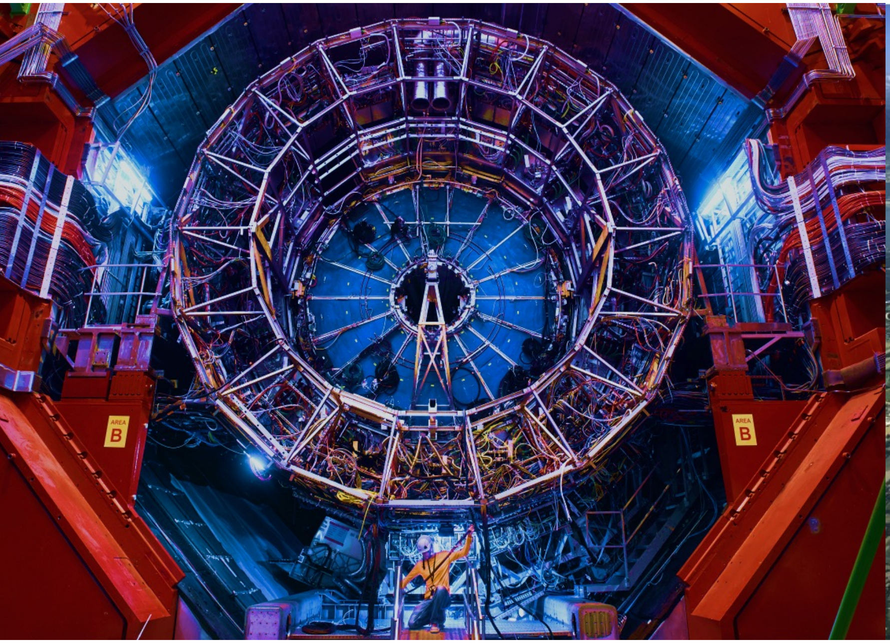
ALICE and the renaissance of nuclear physics at the LHC



Alexander Kalweit (CERN)

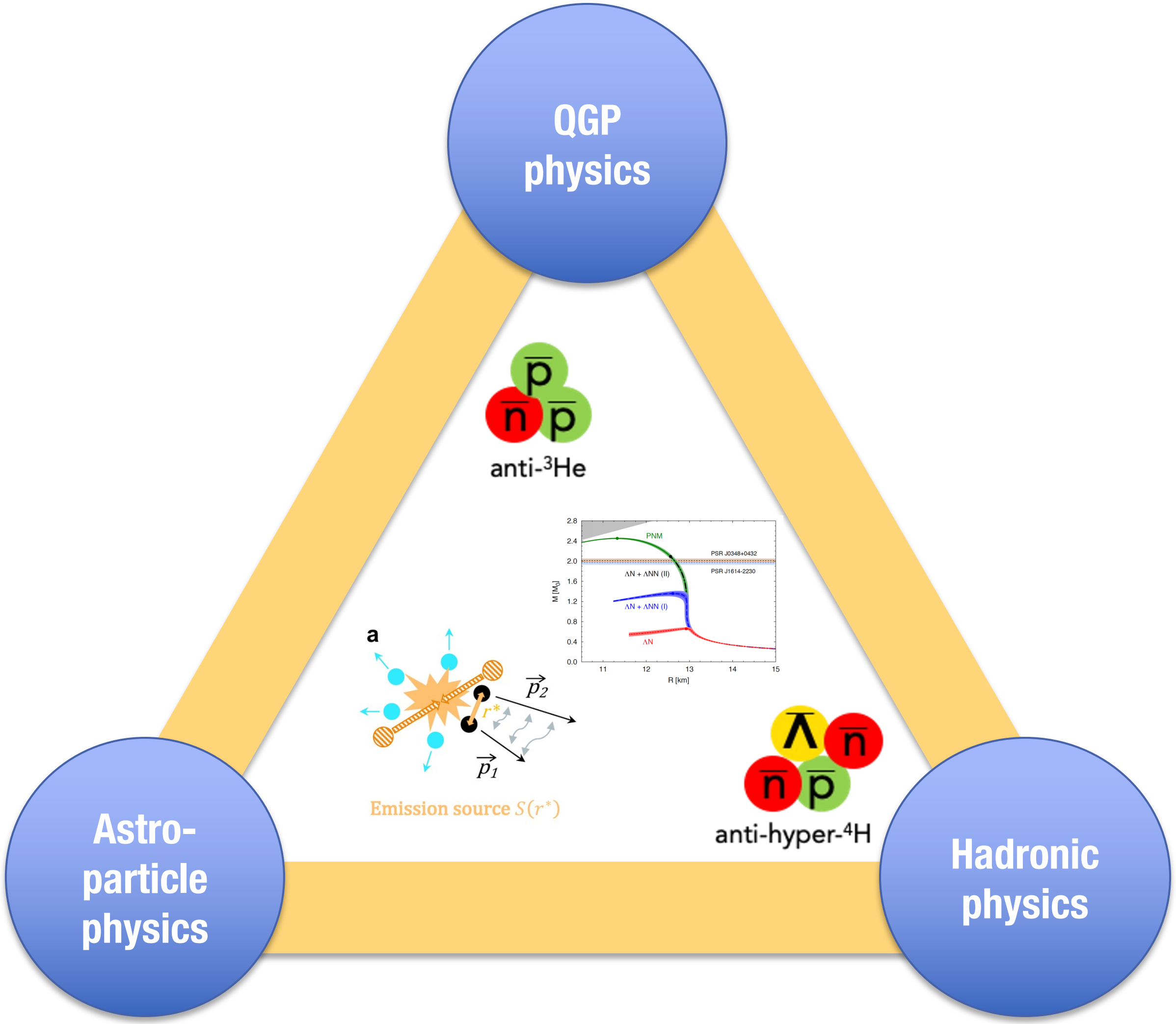
Saclay, 7th February 2023

Introduction

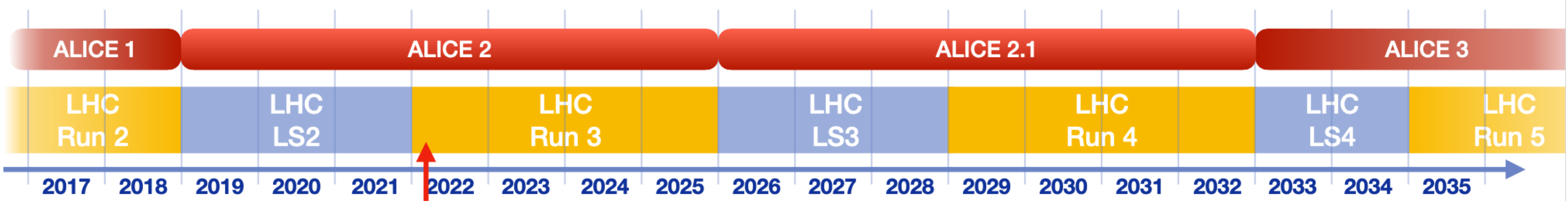
- The LHC is a TeV scale accelerator. Its primary goal is the study of high energy phenomena such as the Higgs Boson, Supersymmetry, Quark-Gluon Plasma, CP violation.

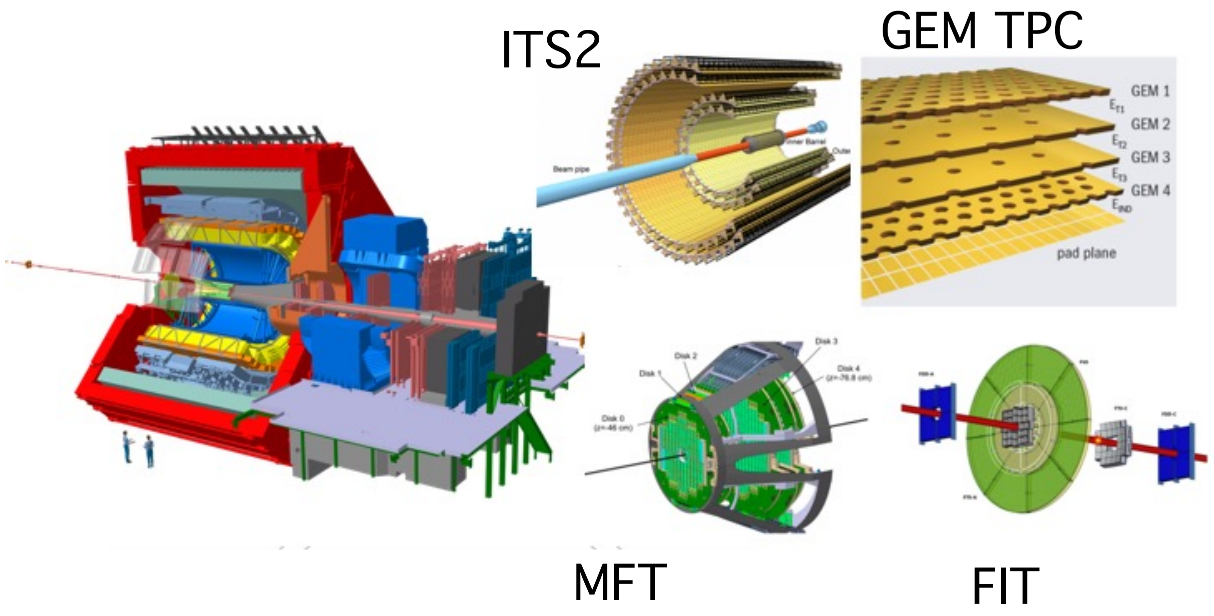
- At the same time, it delivers a plethora of groundbreaking measurements at the MeV (nuclear and hadronic physics) scale, e.g. precision studies on hyper-triton properties and measurements of the hyperon-nucleon strong interaction potential.

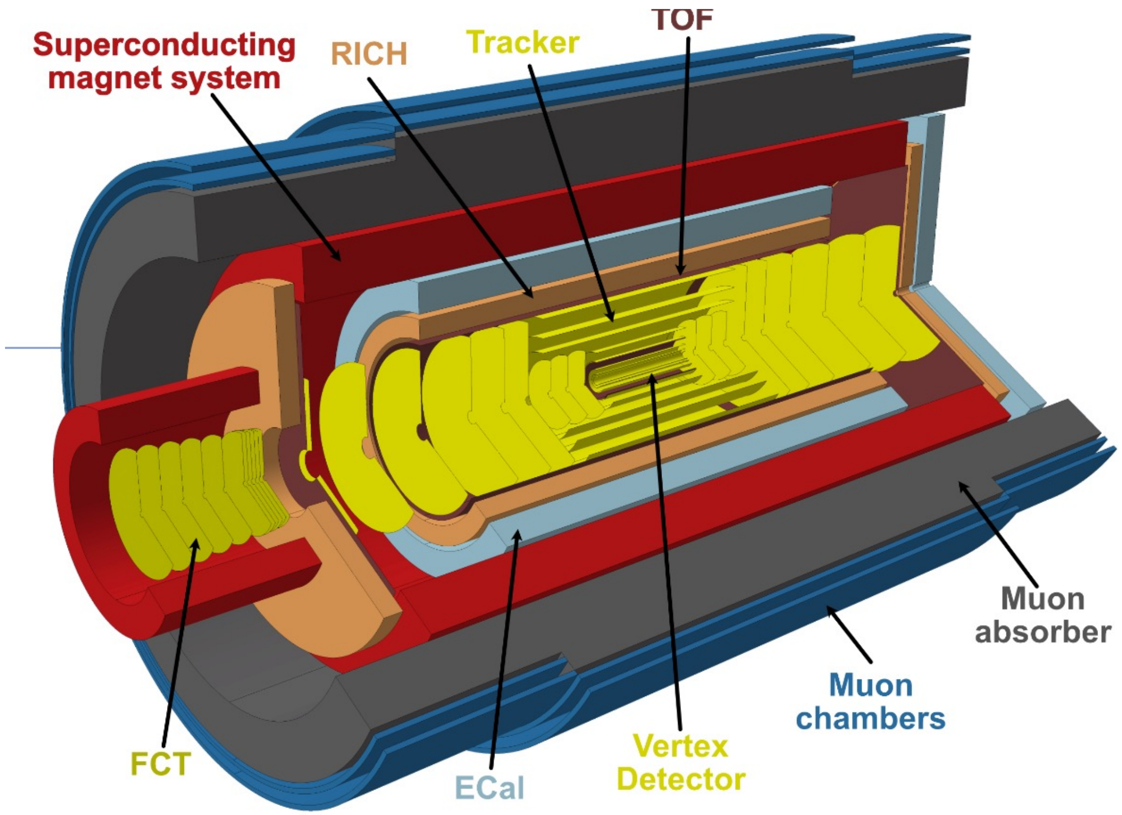
- Surprisingly, many of these results have strong implications for fundamental questions in astroparticle physics.



ALICE 1.. 2.. 3..


ALICE 1
ALICE 2
ALICE 2.1
ALICE 3
LHC Run 2
LHC LS2
LHC Run 3
LHC LS3
LHC Run 4
LHC LS4
LHC Run 5
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035

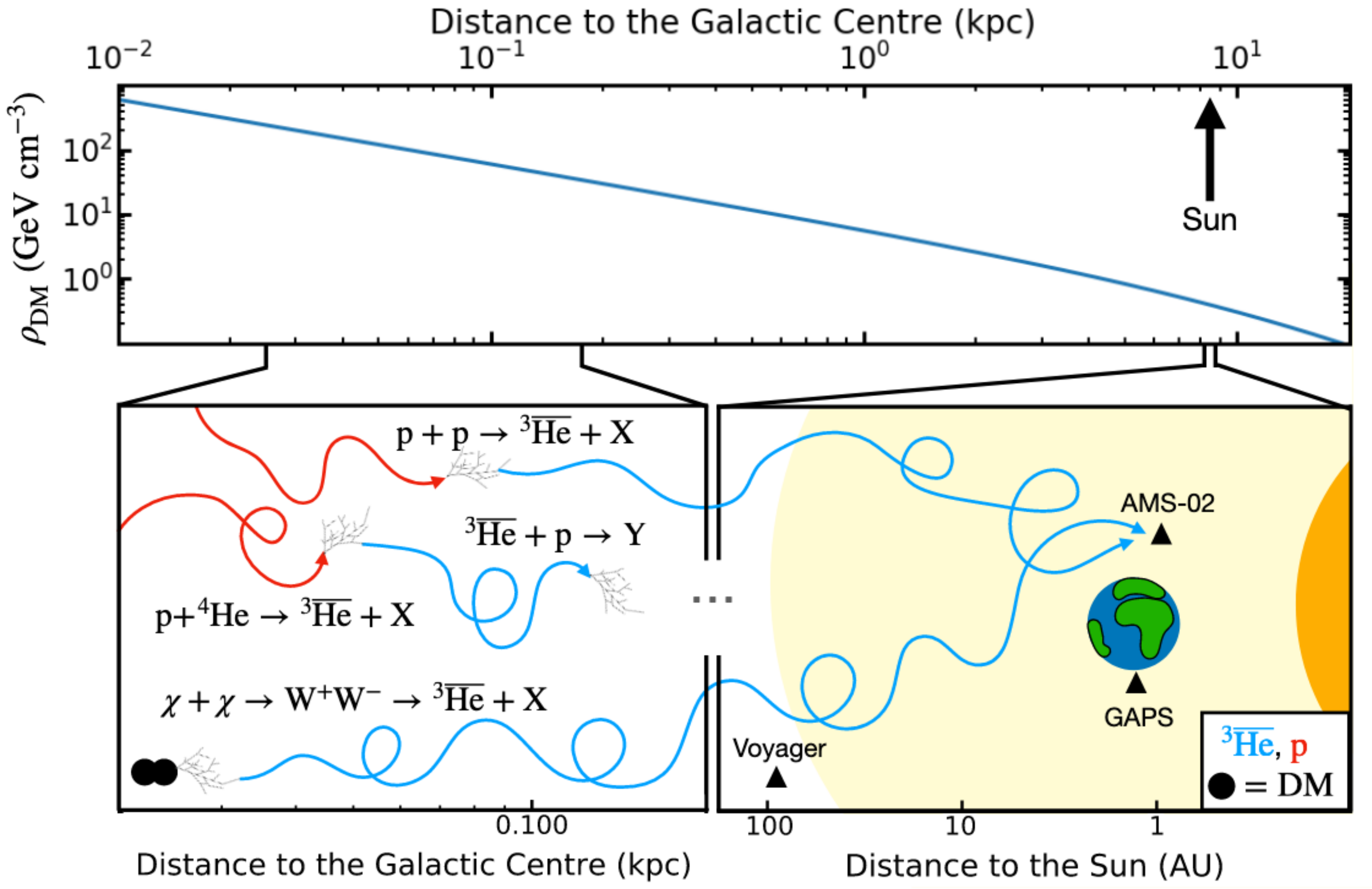

ITS2
GEM TPC
GEM 1
GEM 2
GEM 3
GEM 4
pad plane
MFT
FIT

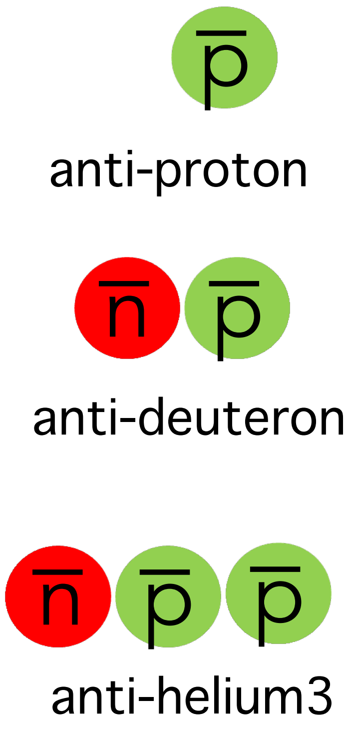

Superconducting magnet system
RICH
Tracker
TOF
Muon absorber
Muon chambers
Vertex Detector
ECal
FCT

Antinuclei at the LHC: a portal to astrophysics

[ALICE, *Nature Phys.* 19 (2023)]

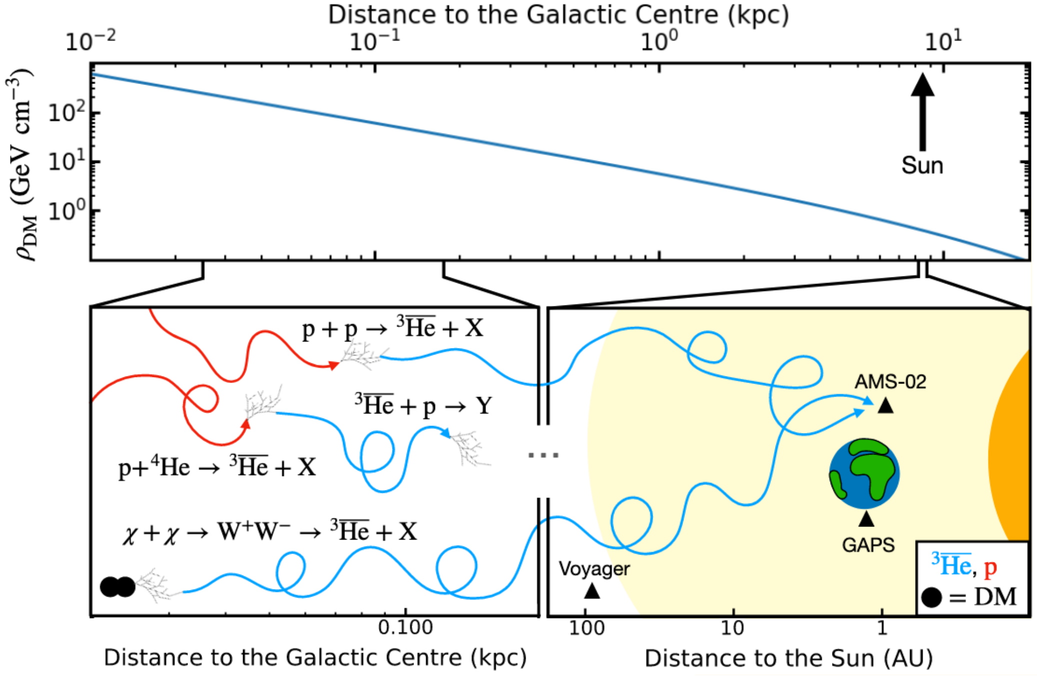
Search for antinuclei in space (1)





[ALICE, *Nature Phys.* 19 (2023)]

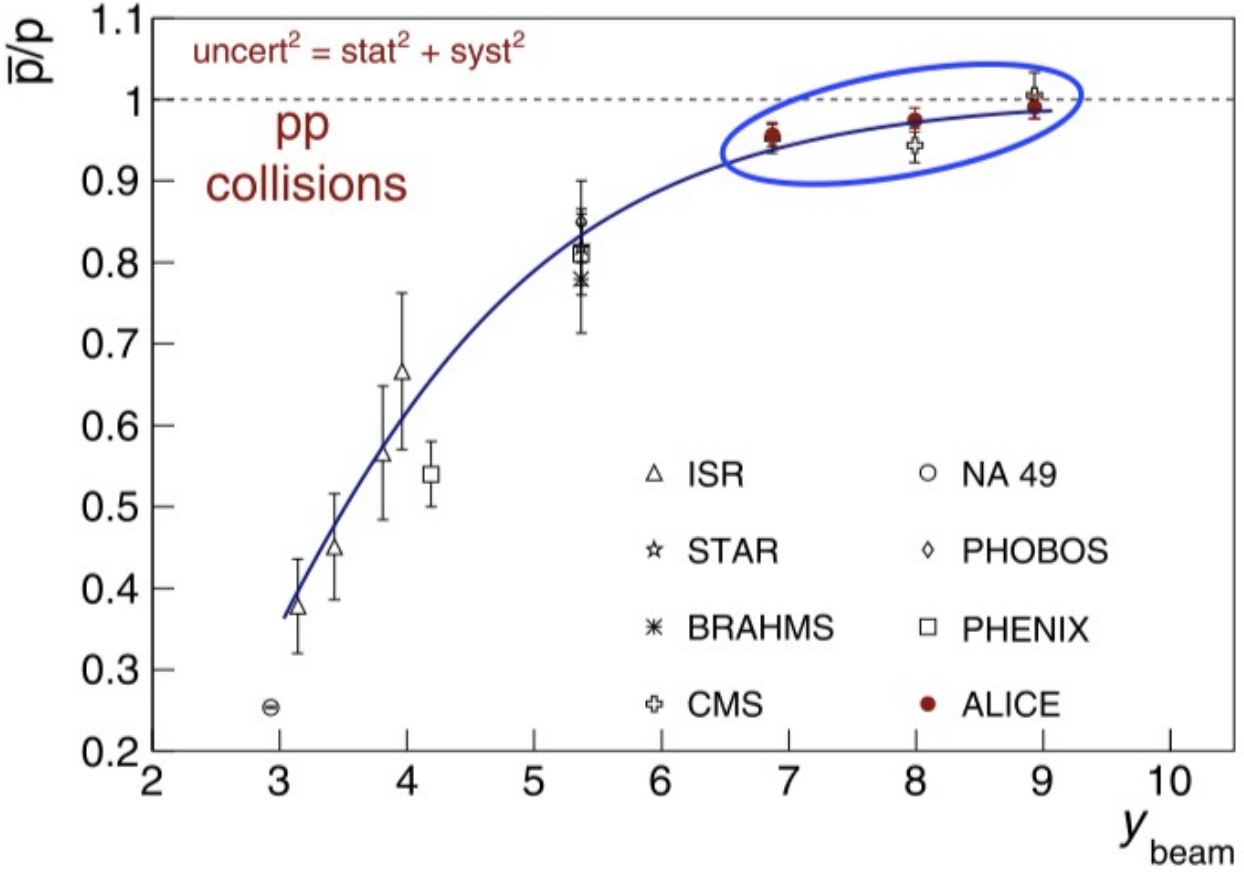
Search for antinuclei in space (2)



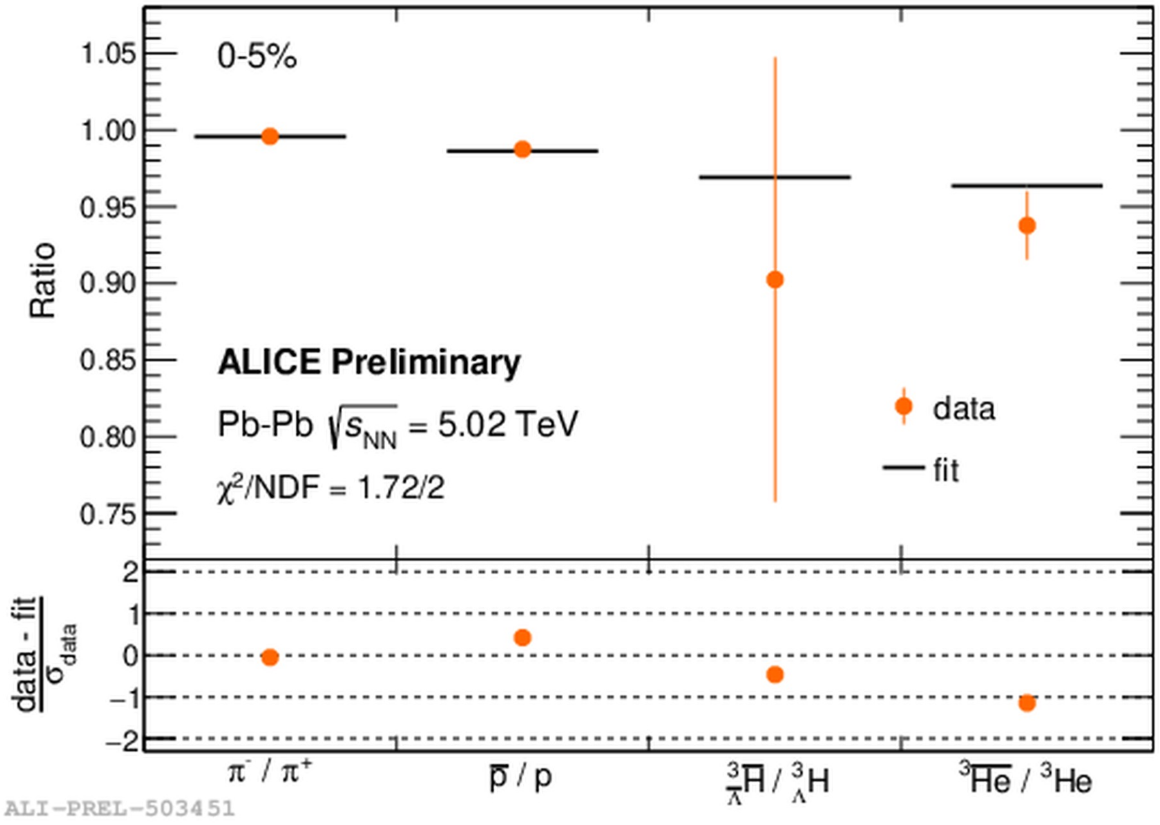
To-do list for collider based experiments:

- Understand antinuclei formation in DM decays
- Understand antinuclei formation in background reactions
- Understand interaction of antinuclei with matter to determine the transparency of the galaxy

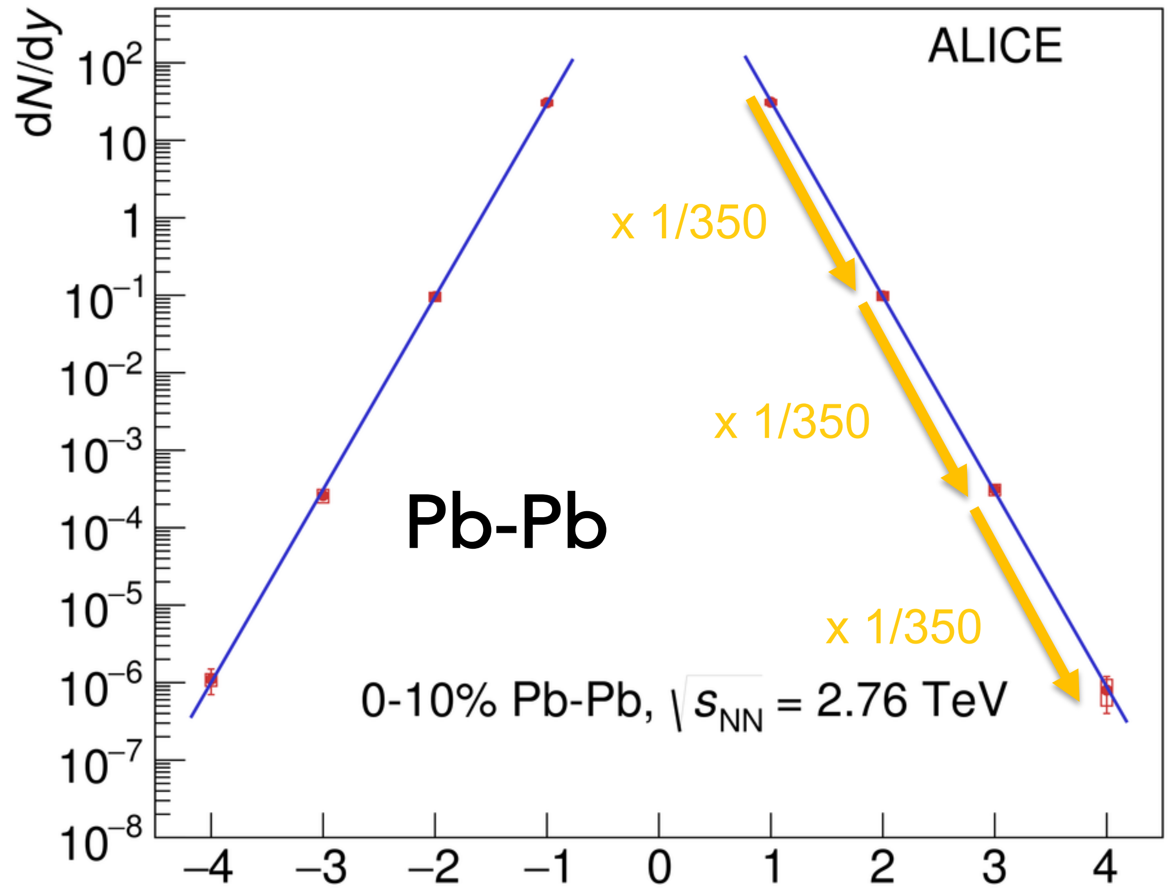
The LHC as an antimatter factory



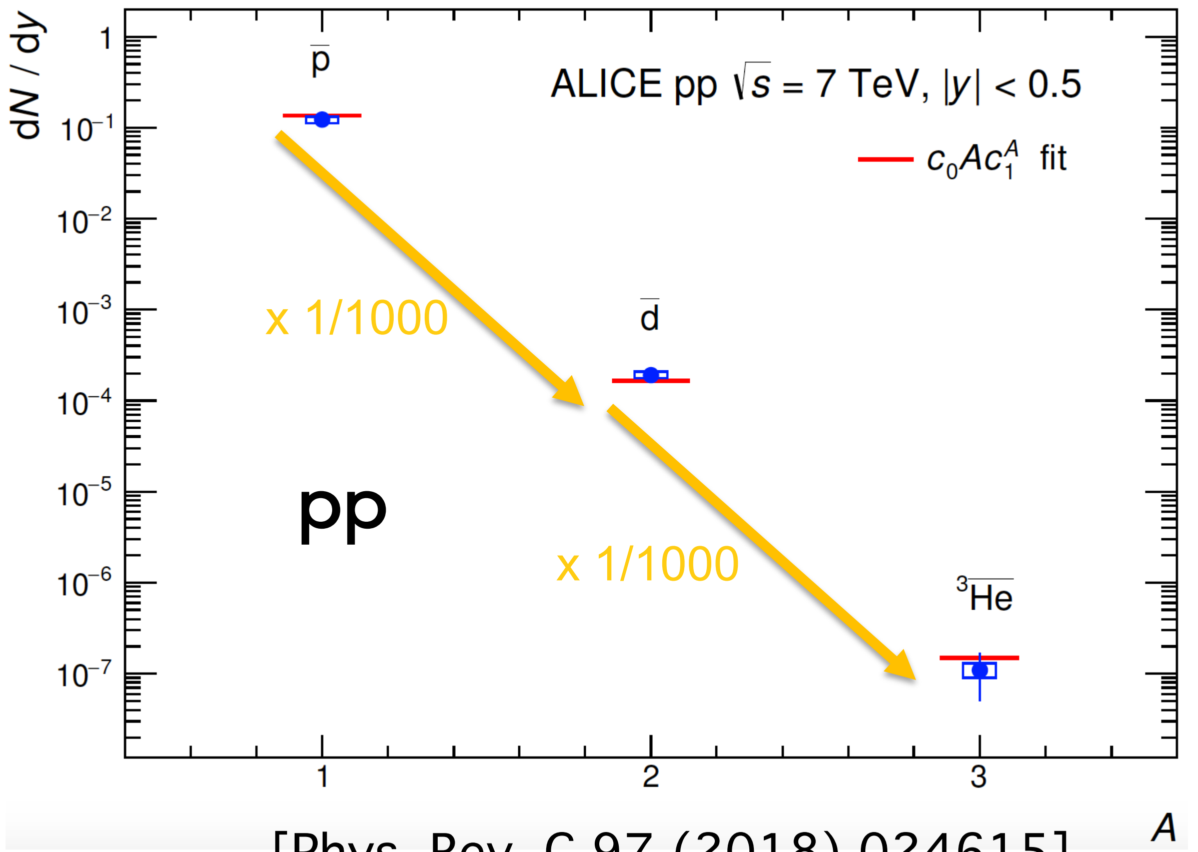
[Phys. Rev. C 97, 024615 (2018)]



Penalty factor at the LHC



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



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

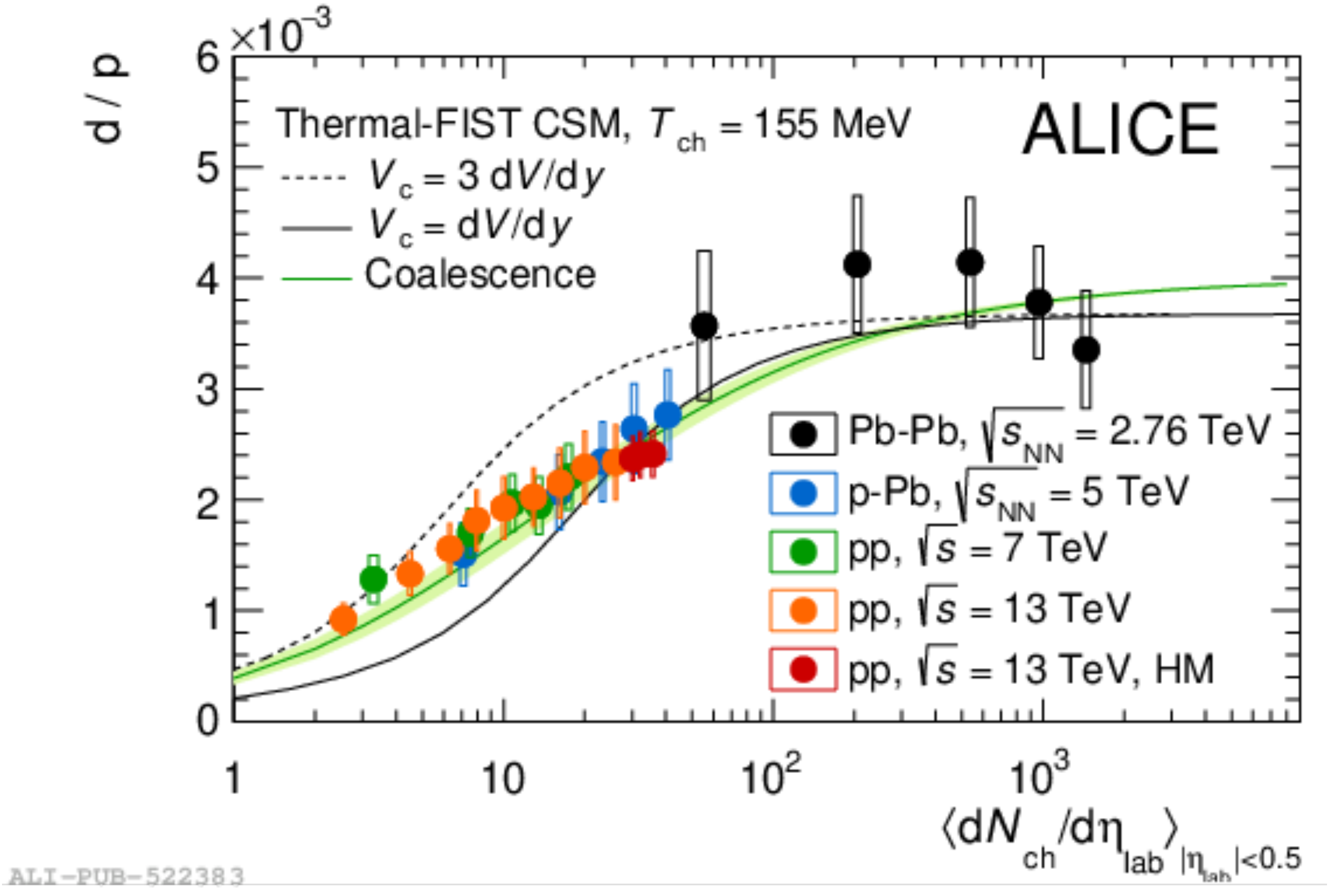
The production yield of (anti)-nuclei decreases by a factor of about ~350 for each additional nucleon in Pb-Pb (~1000 in pp).

Antinuclei at the LHC: a portal to astrophysics

antinuclei formation

Measurements of antinuclei production

→ Over the last years, ALICE delivered a unique set of high quality on anti-nuclei production for various collision systems.

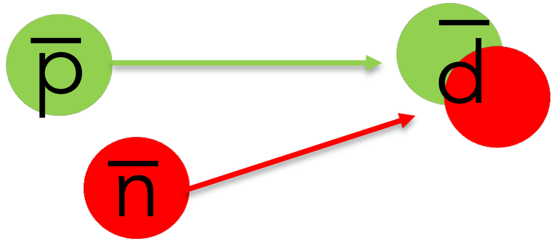


[JHEP 01 (2022) 106]

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 ∝ proton²"*

$$E_d \frac{d^3N_d}{dp_d^3} = B_2 \left(E_p \frac{d^3N_p}{dp_p^3} \right)^2$$



- 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.

Coalescence model parameters as input for astro

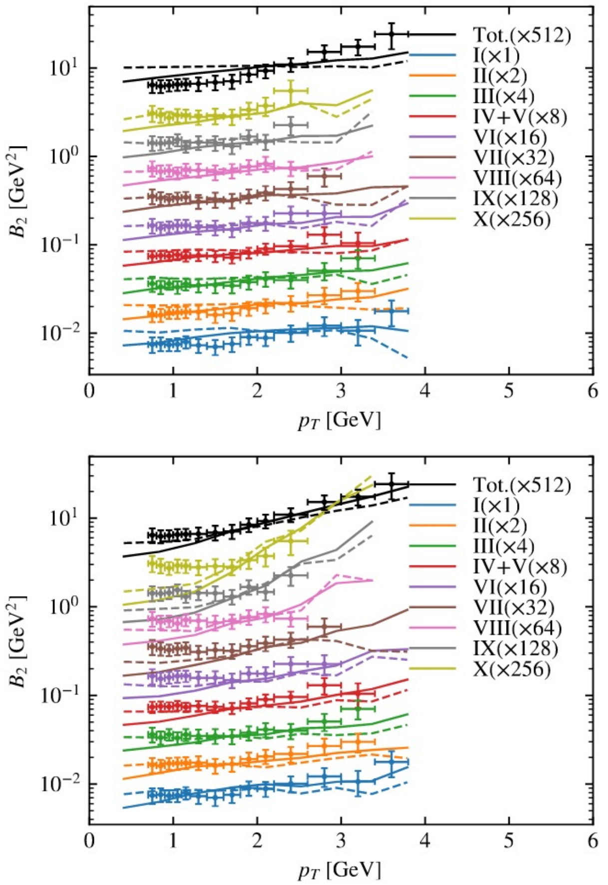


Fig. 2 The coalescence factor B_2 for different multiplicity classes measured by the ALICE collaboration is compared to the predictions by QGSJET II (above) and Pythia 8.2 (below) using the WiFunC model (solid lines). The results for the standard coalescence model (dashed lines) are shown for comparison. Class I corresponds to largest multiplicities, while the multiplicity decreases with increasing class.

[Kachelrieß et al., arXiv:2012.04352v2]

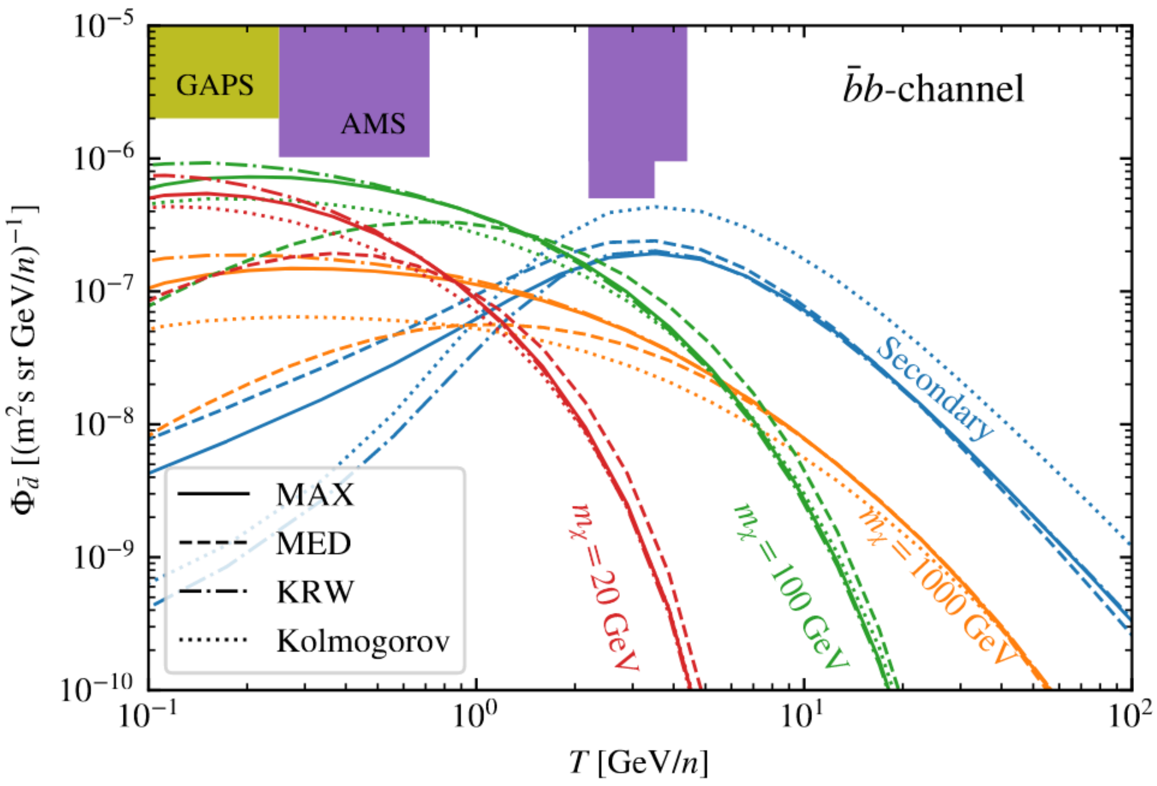


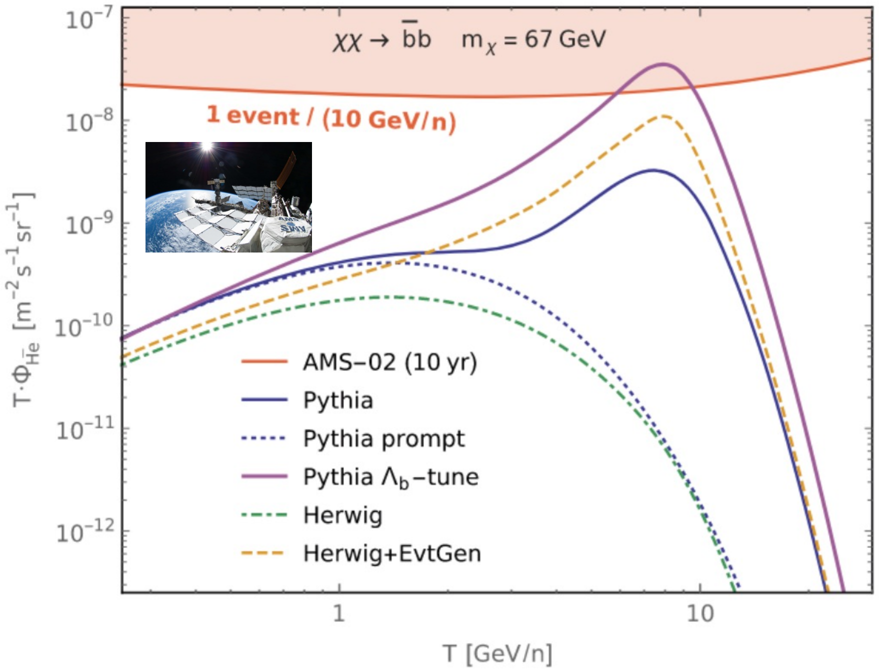
Figure 13. Estimated antideuteron flux on Earth from DM annihilations into $\bar{b}b$ pairs and from secondary production for the considered benchmark cases. The shaded areas on the top are the estimated AMS-02 and GAPS sensitivities.

[Kachelrieß et al., arXiv:2002.10481v2]

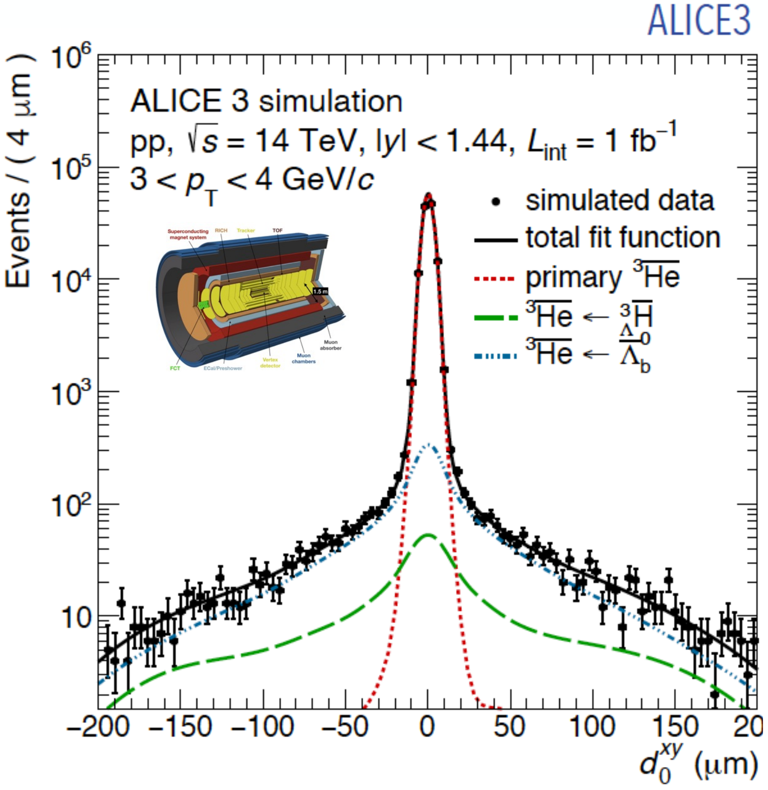
N.B.: Several groups perform these calculations, we show here the example of Kachelrieß et al.!

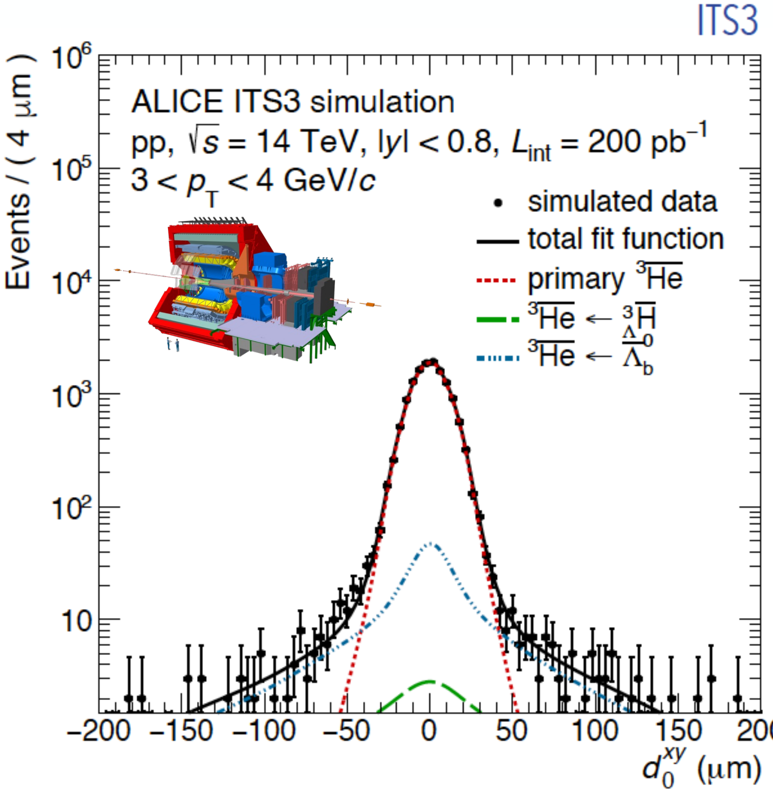
Antinuclei production in b-quark decays (1)

$$\chi\chi \rightarrow b\bar{b} \rightarrow \overline{\Lambda}_b^0 + X \rightarrow {}^3\overline{\mathrm{He}} + X$$



[M. Winkler, T. Linden, PRL 126 (2021)]





[ALICE 3 Letter of Intent]

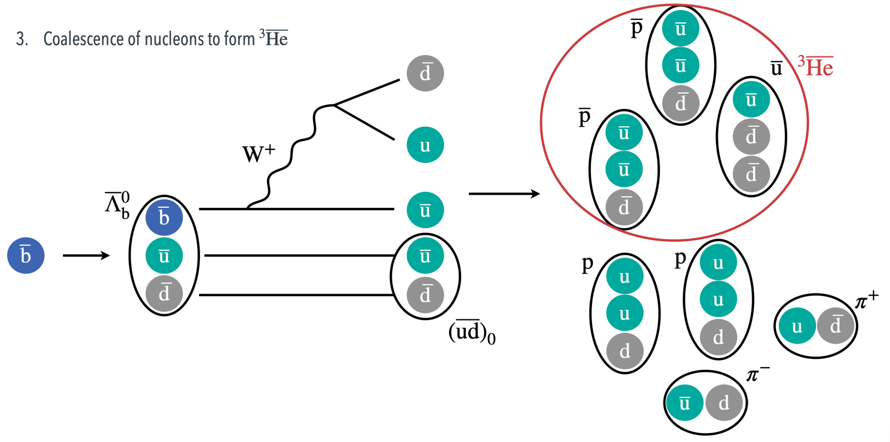
→ Anti-^{3}He originating from Λ_b decays from dark matter annihilation might lead to an enhanced flux of anti-^{3}He near earth.

→ Accelerator based experiments like ALICE are in the best position to determine the branching ratios of these rare decays.

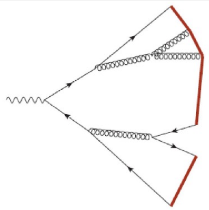
→ Precise dca-resolution of ALICE 3 is key to perform the measurement. First layer in beam-pipe removes all potential ambiguities from Moliere scattering that are difficult to simulate.

Antinuclei production in b-quark decays (2)

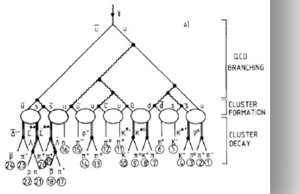
$$\chi\chi \rightarrow b\bar{b} \rightarrow \overline{\Lambda}_b^0 + X \rightarrow {}^3\overline{\mathrm{He}} + X$$

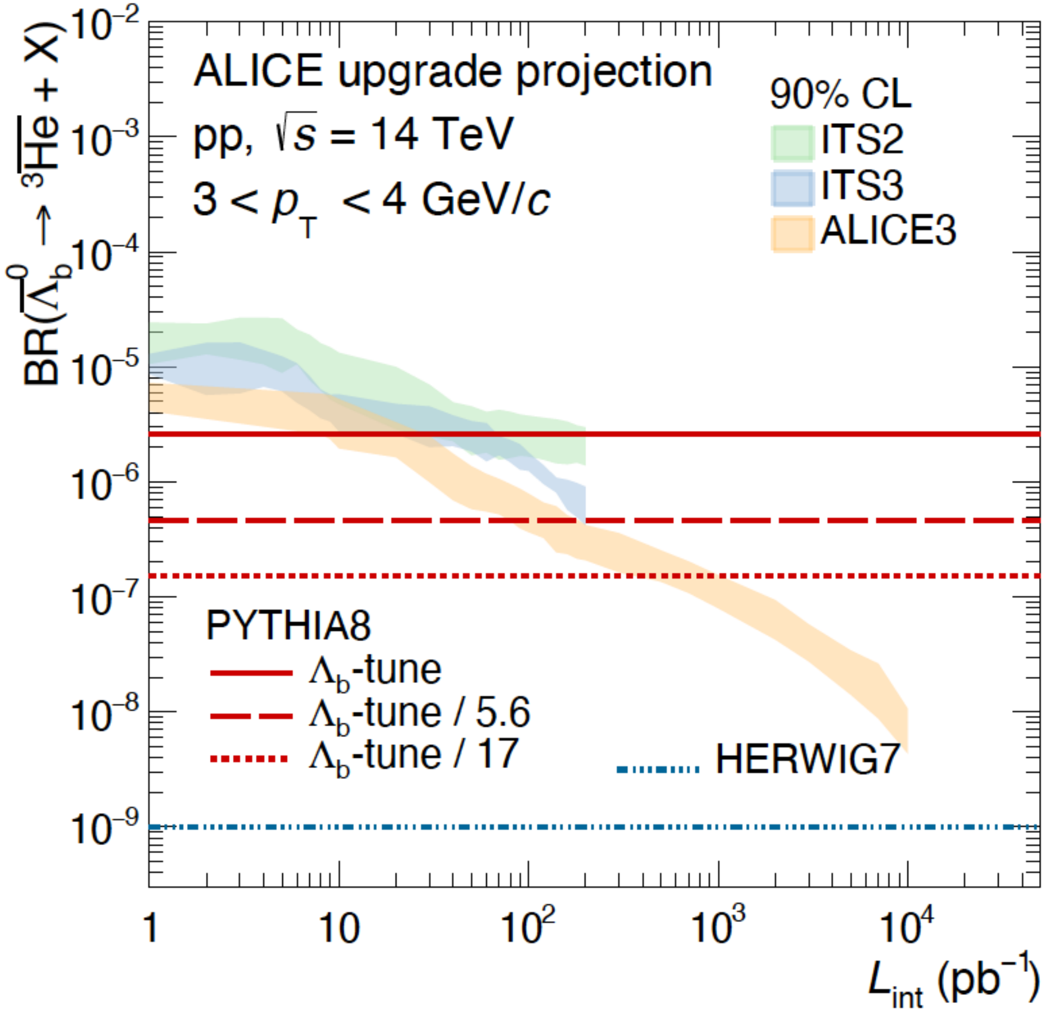


- **String fragmentation** (e.g. Lund model in PYTHIA)
  - Strings = colour-flux tubes between q and q̅ end-points
  - Gluons represent kinks along the string
  - Strings break via vacuum-tunneling of (di)quark-anti(di)quark pairs



- **Cluster decay** in HERWIG
  - Shower evolved up to a softer scale
  - All gluons forced to split into qq̅ pairs
  - Identify colour-singlet clusters of partons following color flow
  - Clusters decay into hadrons according to available phase space





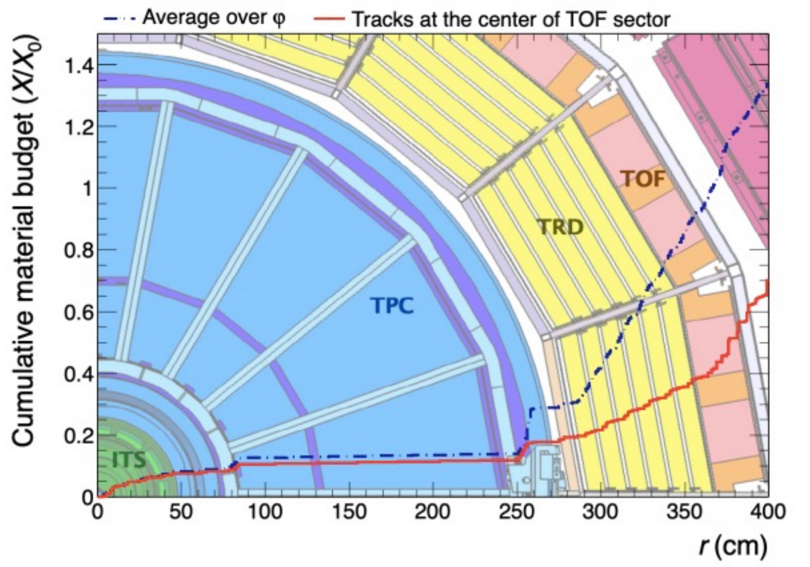
After LHC Run 3 & 4, we will have understood the formation mechanisms of A < 5 anti- and hyper-nuclei from collisions, but will only **start to probe** their production in b-quark decays. Run 5 & 6 will provide the **definitive answer**.

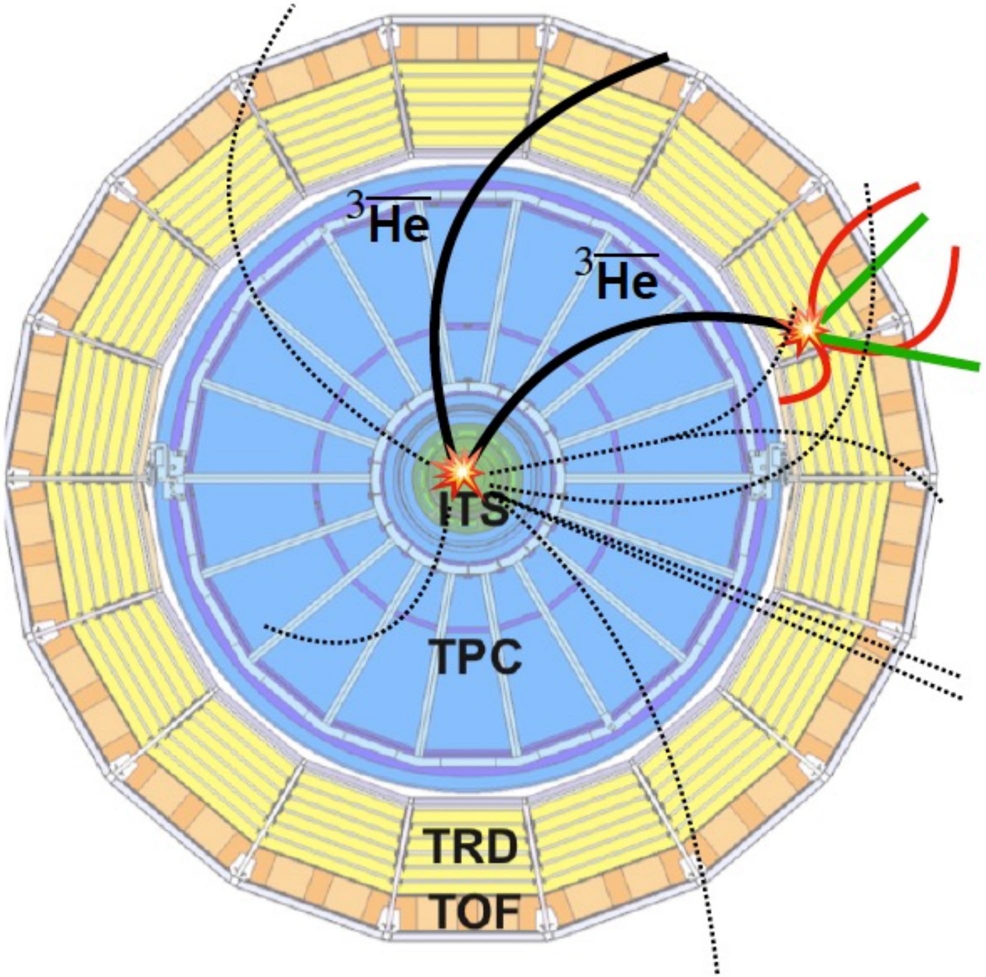
Antinuclei at the LHC: a portal to astrophysics

transparency of the galaxy to antinuclei

Annihilation of antinuclei in interactions with matter

- The inelastic interaction cross-sections of antinuclei with matter remained poorly known: since the 70s – only 2 papers on at high energies from '70, '71 [1-2].
- This is due to the fact that beams of heavier antinuclei are very difficult to obtain.
- Idea: we use the ALICE detector material as a target!

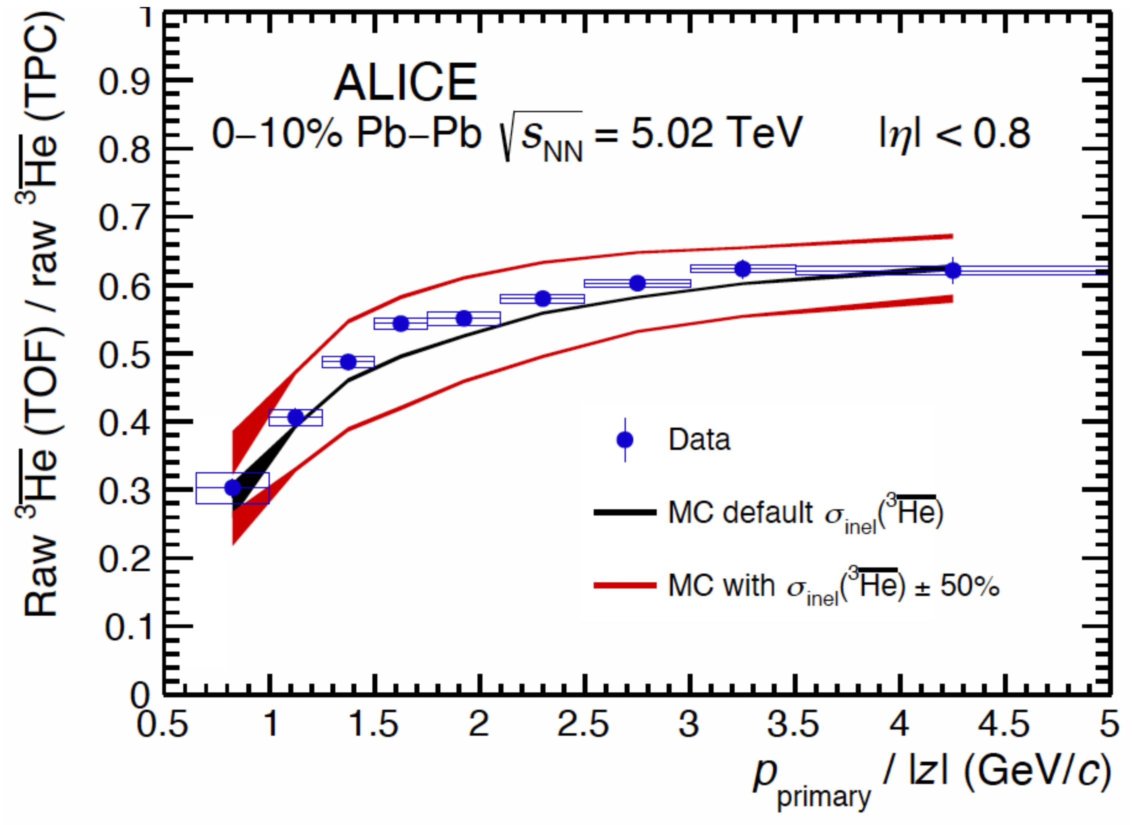


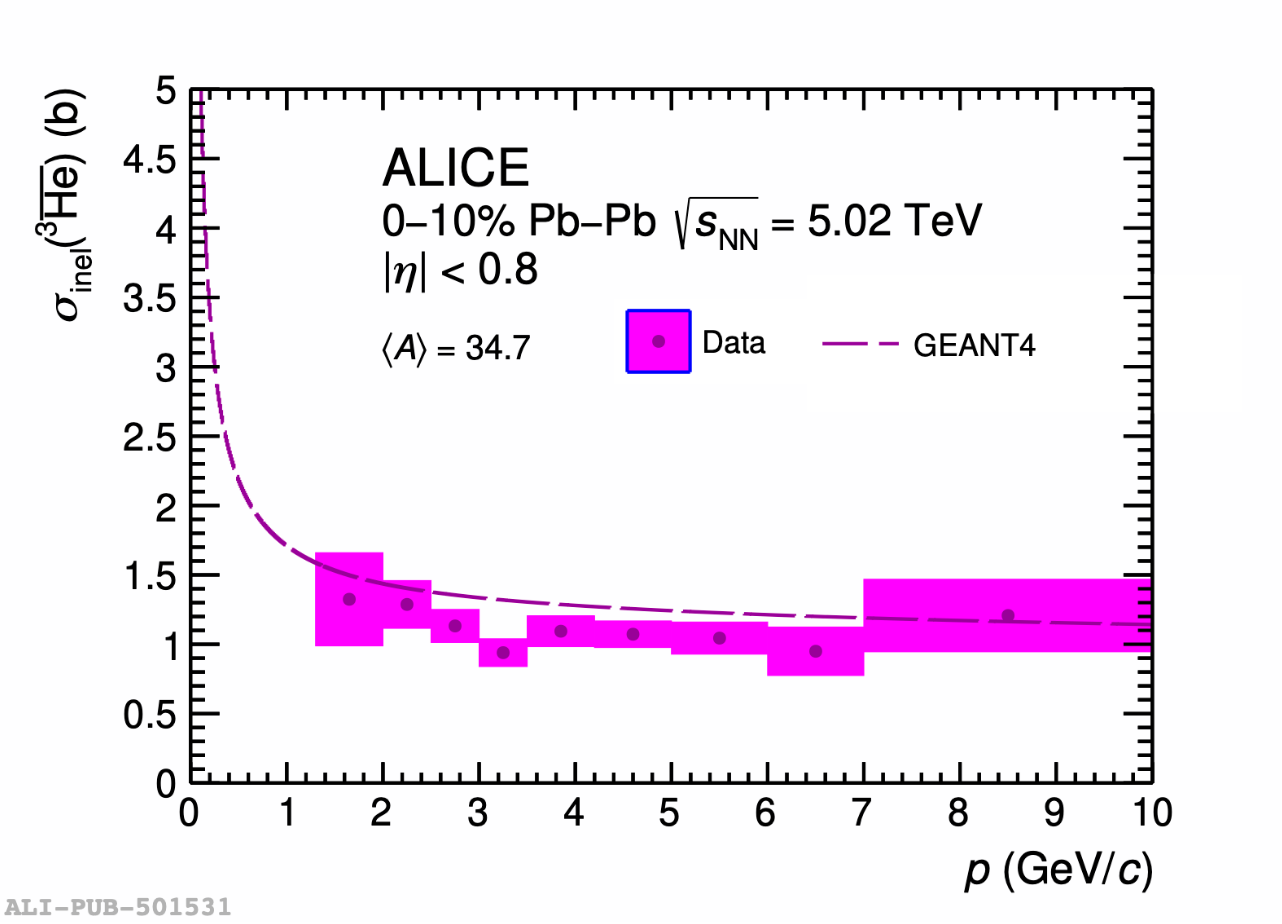


[1] Binon et al. PLB 31 (1970), [2] Denisov et. al. Nuc. Phys. B 31 (1971)

[ALICE, *Nature Phys.* 19 (2023)]

Anti-^{3}He inelastic cross-section



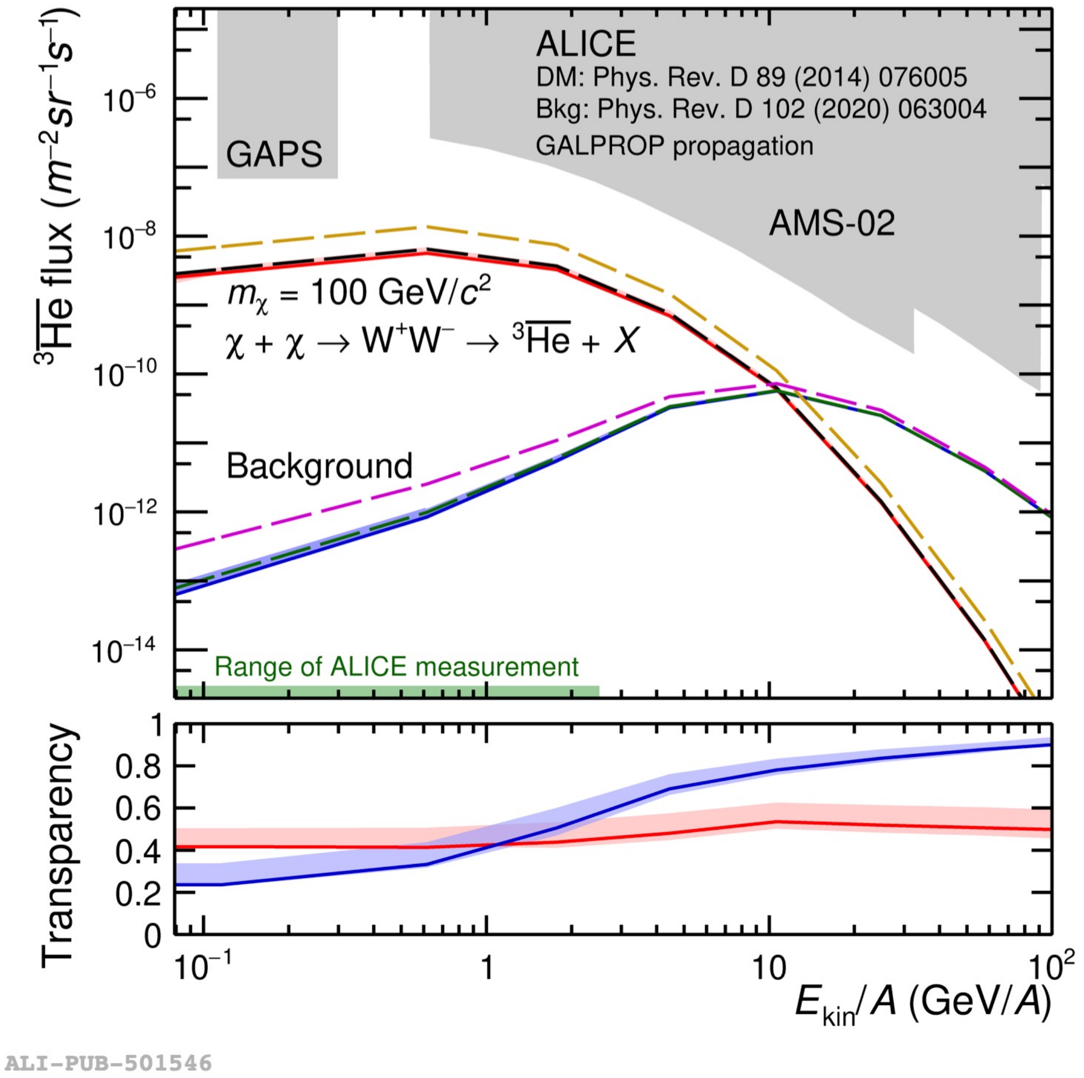


Putting it all together: anti-3He flux near earth

- → We calculate the effect of the inelastic cross sections on the anti-3He flux near earth
- → Uncertainties only from ALICE measurement are **small compared to other uncertainties in the field!**

$$\text{Transparency} = \frac{\mathrm{Flux}(\sigma_{\mathrm{inel}})}{\mathrm{Flux}(\sigma_{\mathrm{inel}} = 0)}$$

- → Rather constant transparency of 50% for typical DM scenario and 25%-90% for background
- → **High transparency of the galaxy to nuclei!**

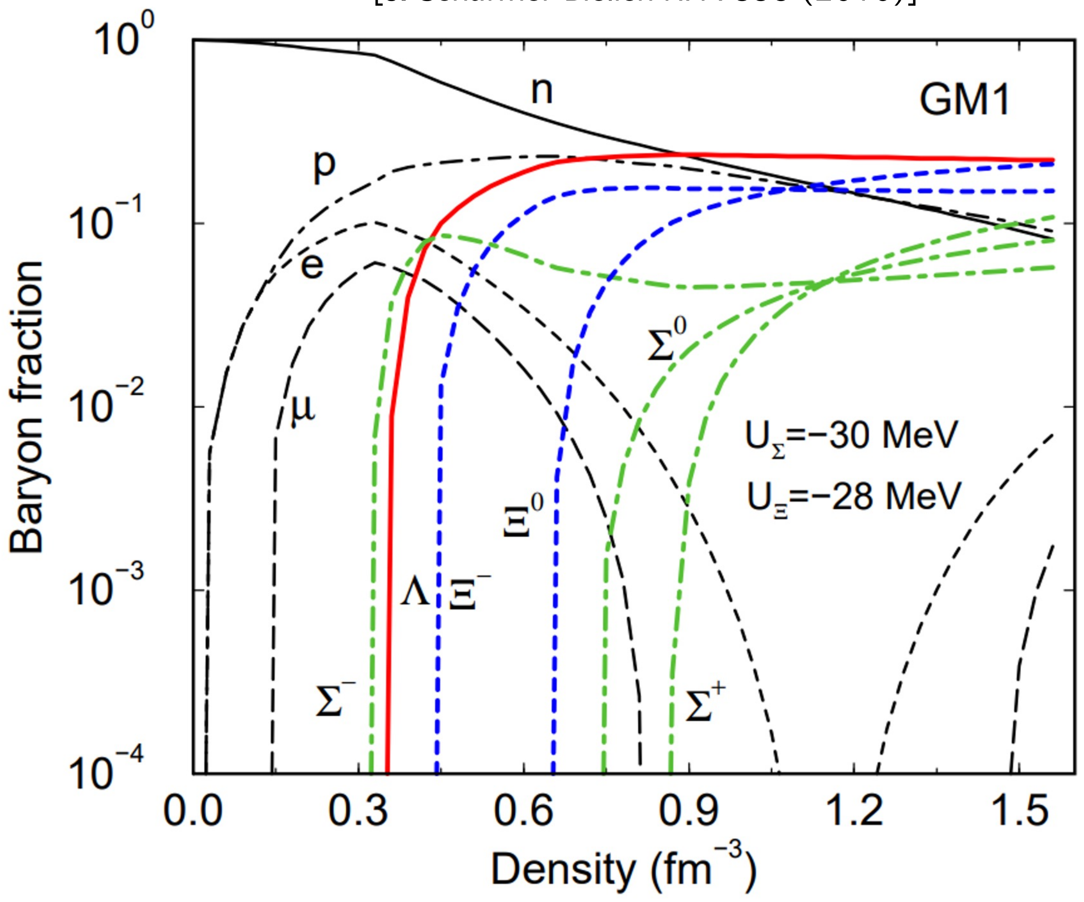


[ALICE, *Nature Phys.* 19 (2023)]

Strong interaction among hadrons and neutron stars

Hyperon appearance in neutron stars

[J. Schaffner-Bielich NPA 835 (2010)]

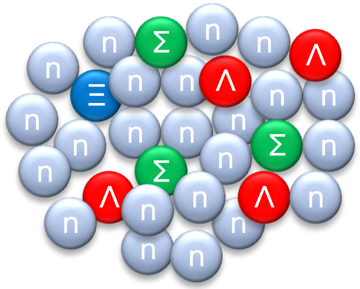


Neutron Stars: very dense, compact objects

→ What is the EoS?
  → What are the constituents to consider?
  → How do they interact?

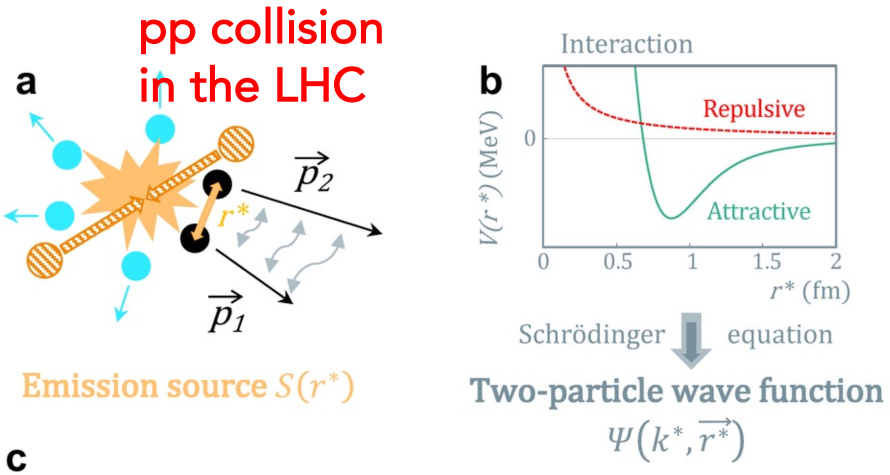
→ With increasing baryonic densities **hyperon** production becomes energetically favorable

→ Exact composition strongly depends on constituent interactions and couplings!



Correlation functions to study the strong interaction

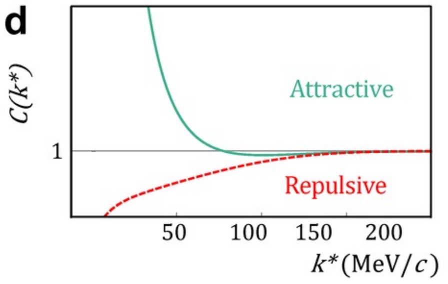
[Nature 588 (2020) 232-238]

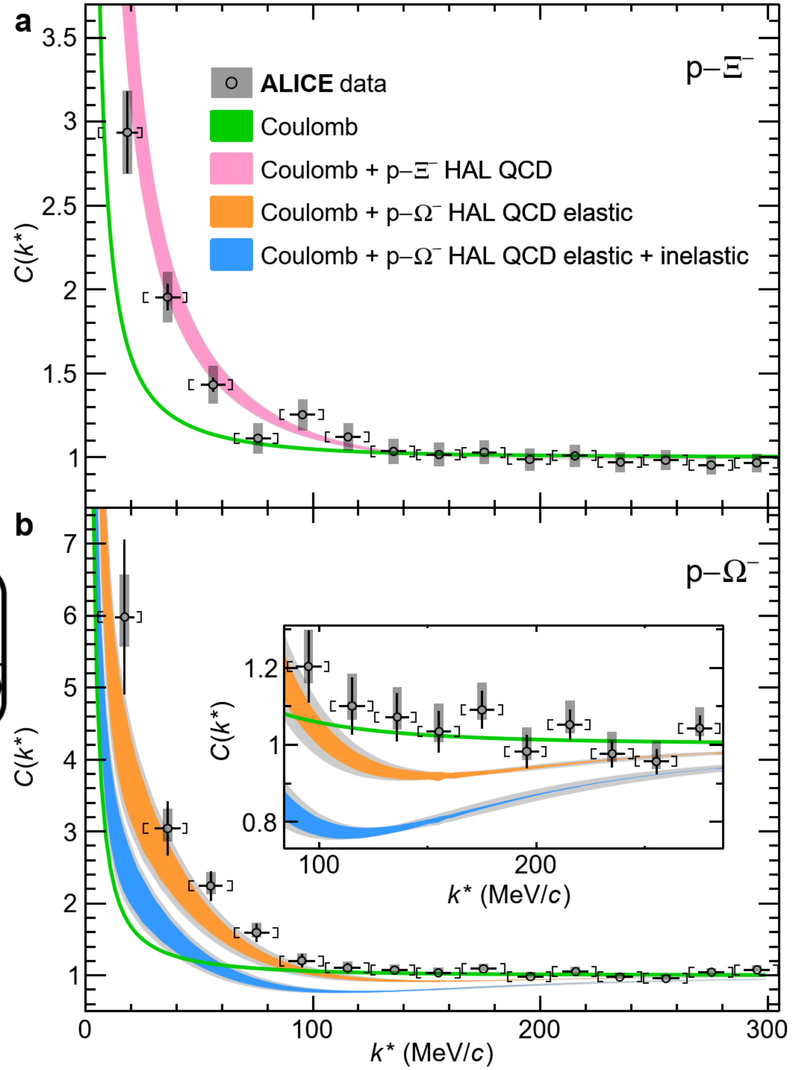


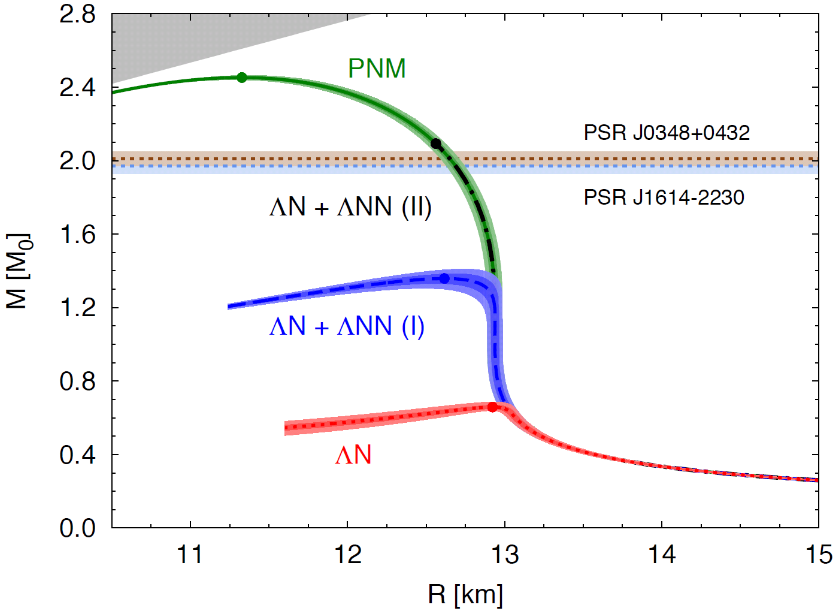
c

Correlation Function

$$C(k^*) = \int S(r^*) \left|\Psi(k^*, \vec{r^*})\right|^2 d^3r^* = \xi(k^*) \otimes \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$



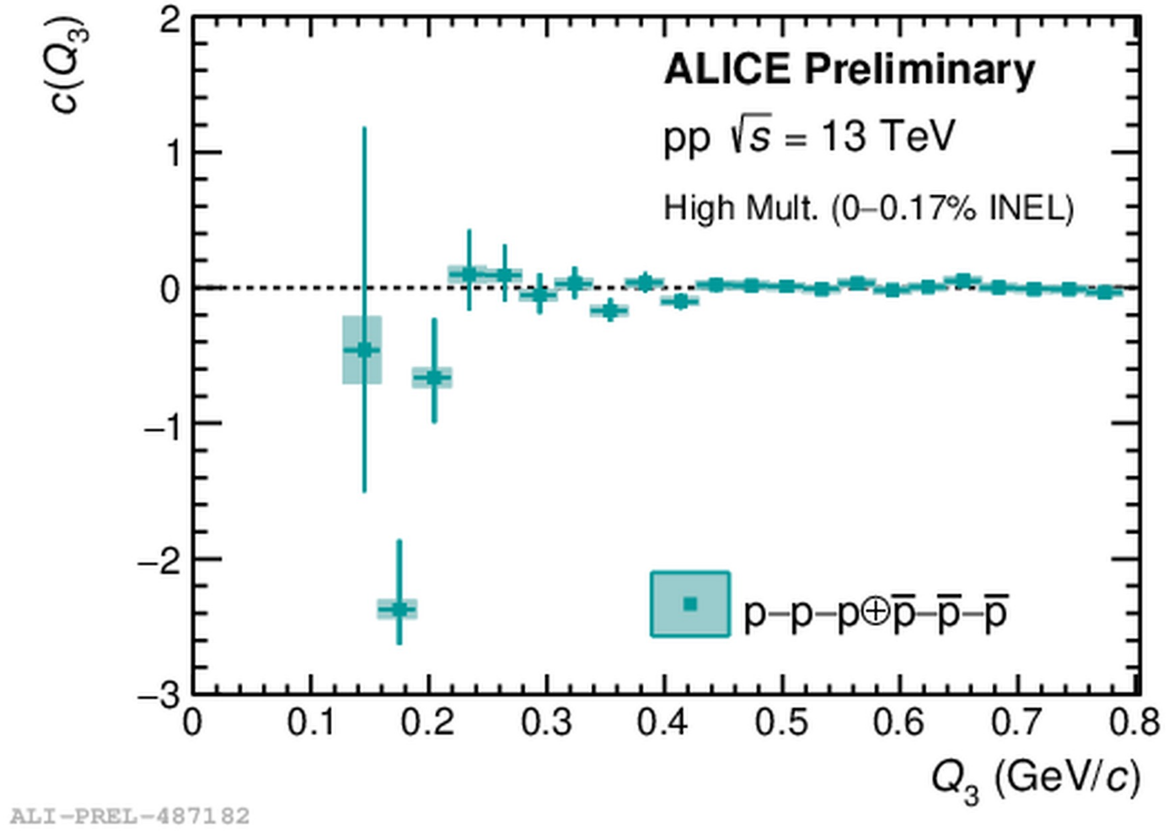


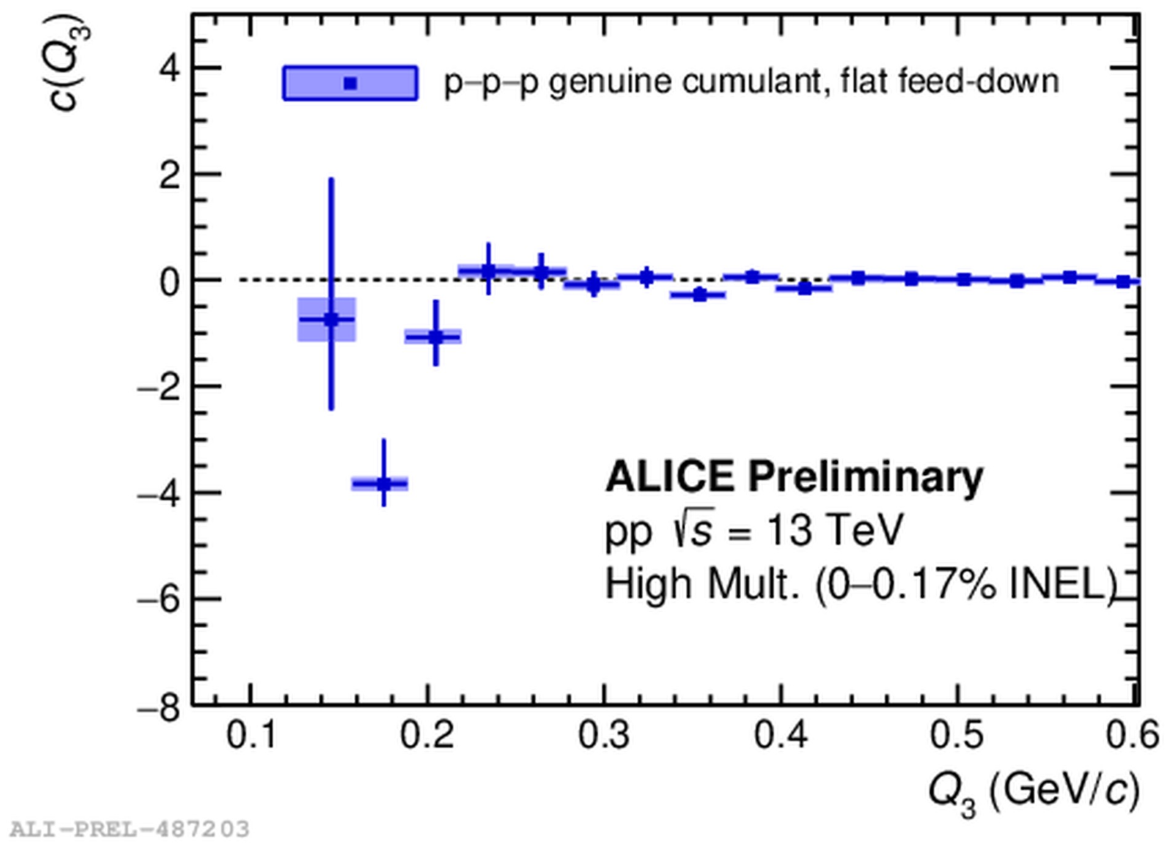


[D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)]

The novel results on hyperon-nucleon and hyperon-hyperon interactions provided by correlation studies at the LHC by ALICE are key to compute **more realistic equation of state for neutron stars containing hadrons with strange content.**

Access to genuine three-body interactions

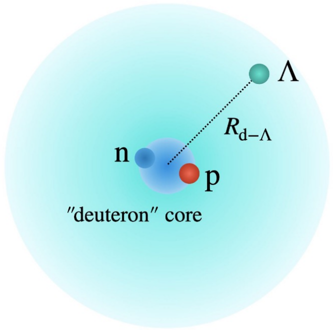


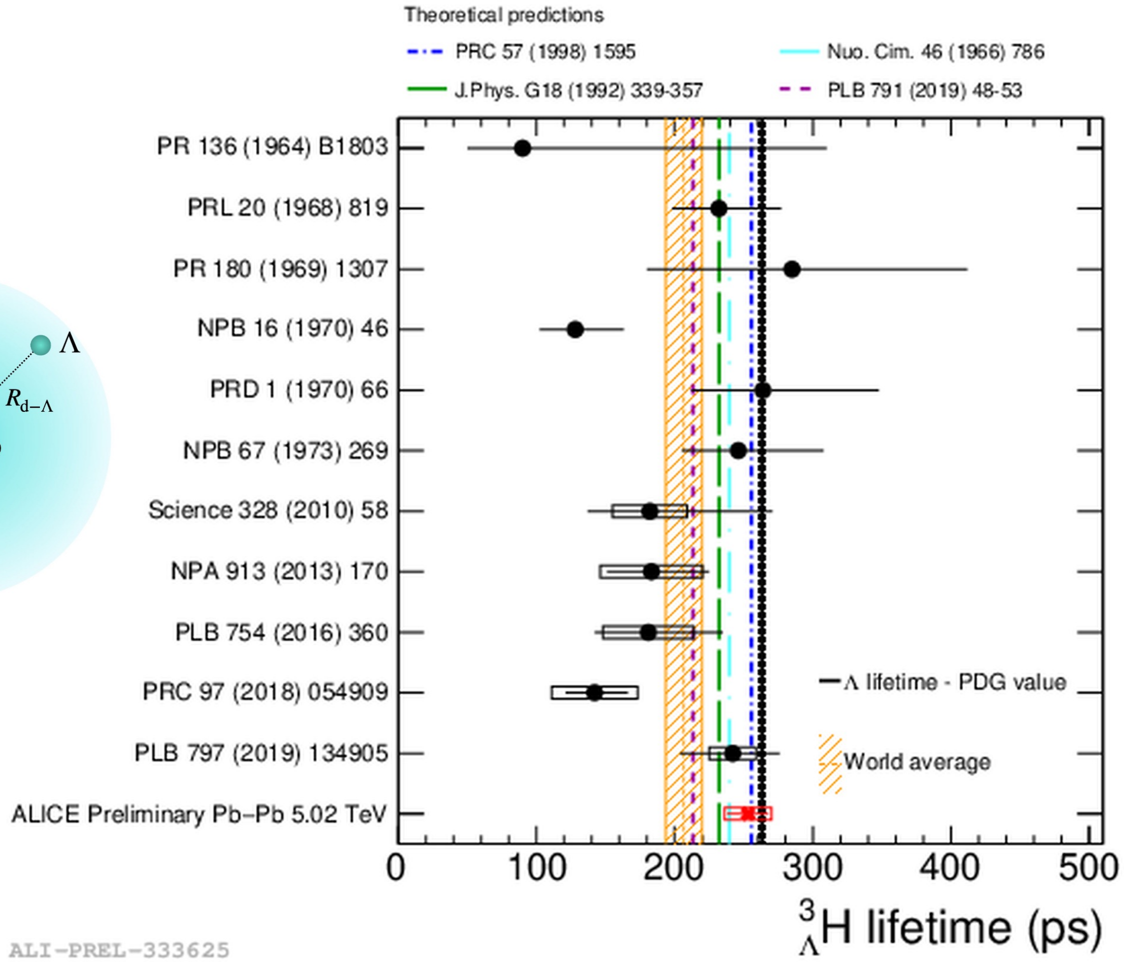


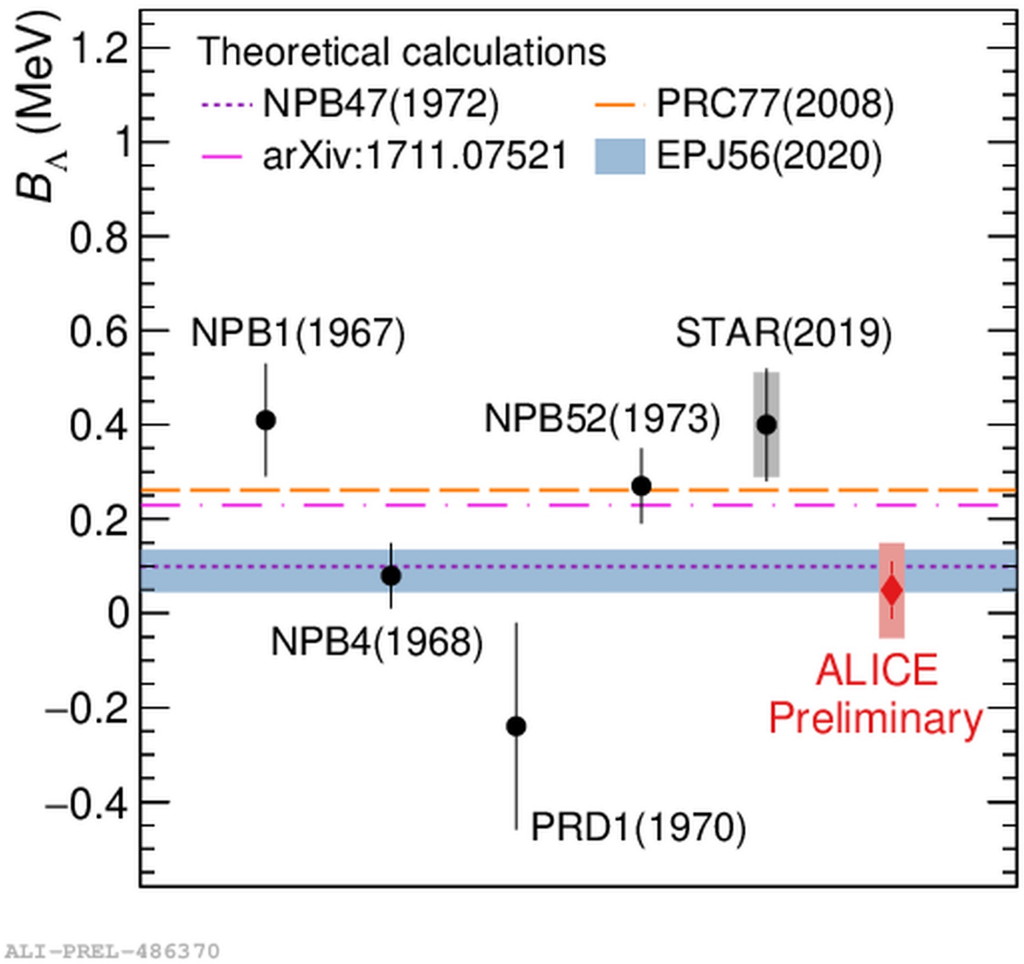
→ First look at three-body interactions looks promising. Precision results are awaited for LHC Run 3!

Nuclear structure, charm- and hyper-nuclei

Hypertriton lifetime and binding energy

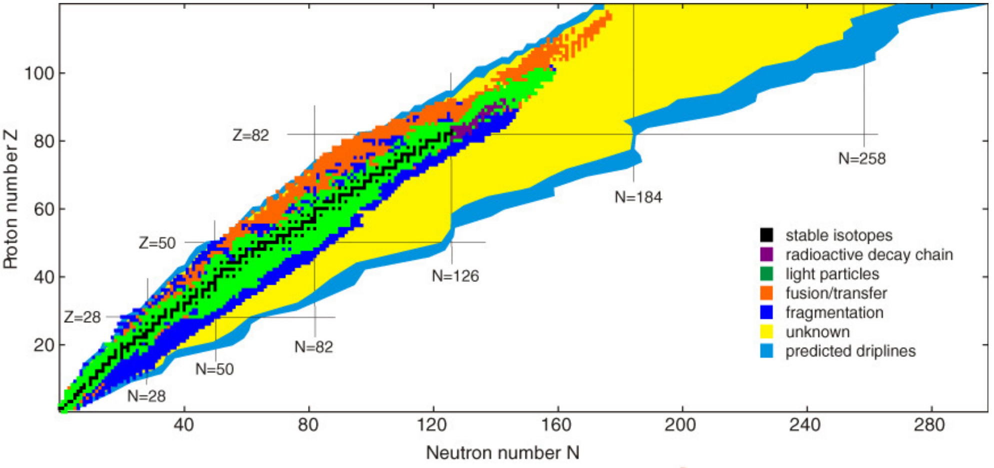




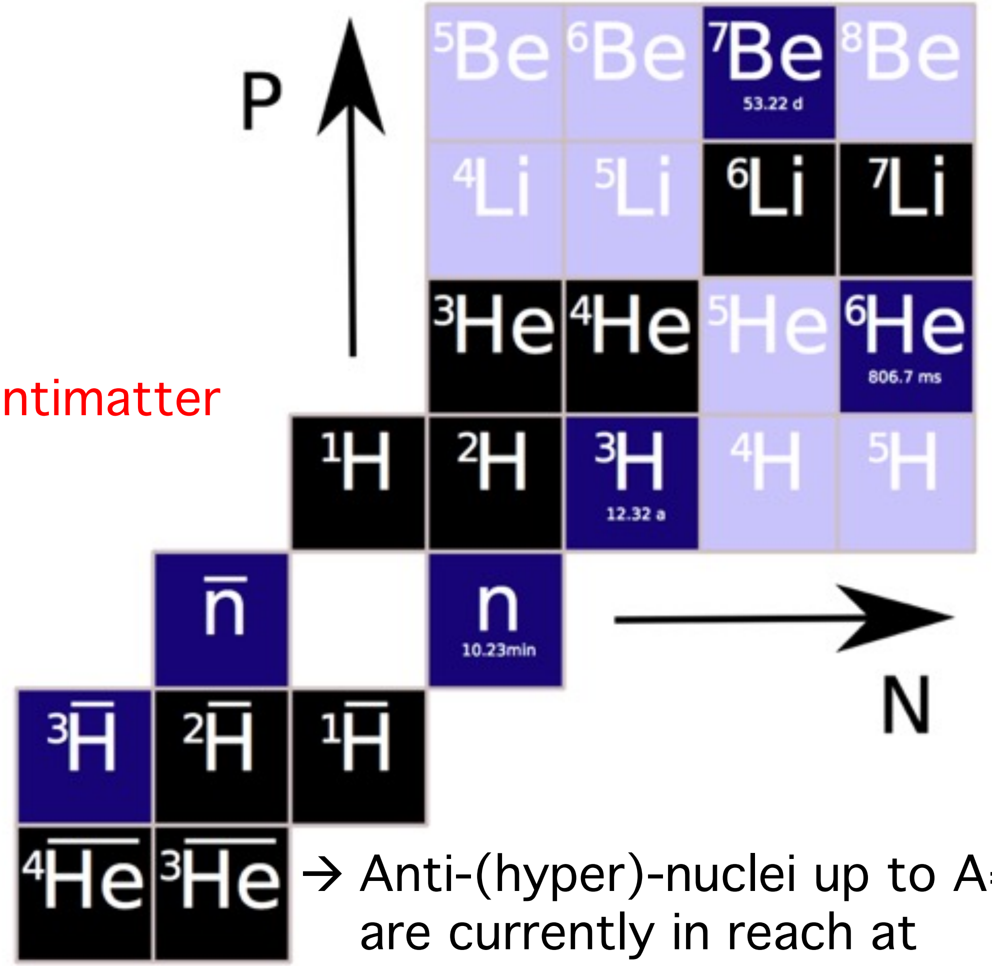


→ Most precise measurements are done at the LHC and not at dedicated low energy facilities!

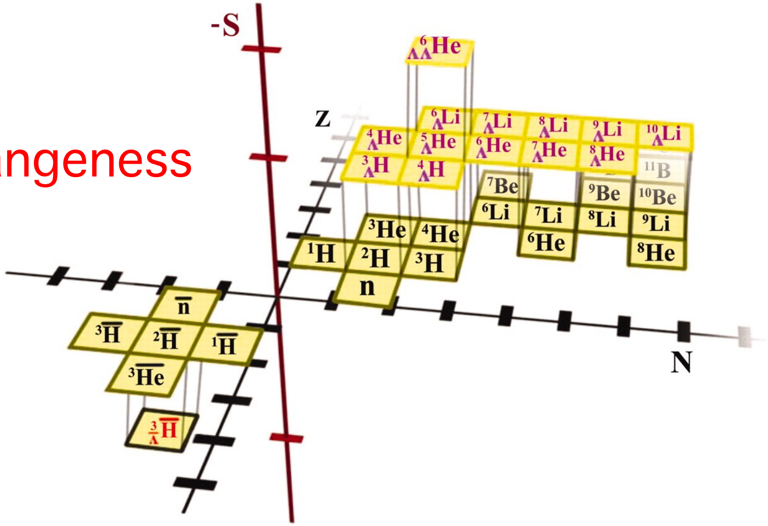
Extending the table of nuclides…



→ In the antimatter direction..



→ In the strangeness direction..



→ 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.

→ Can we also extend the table of nuclides in the charm direction in the next 15 years?

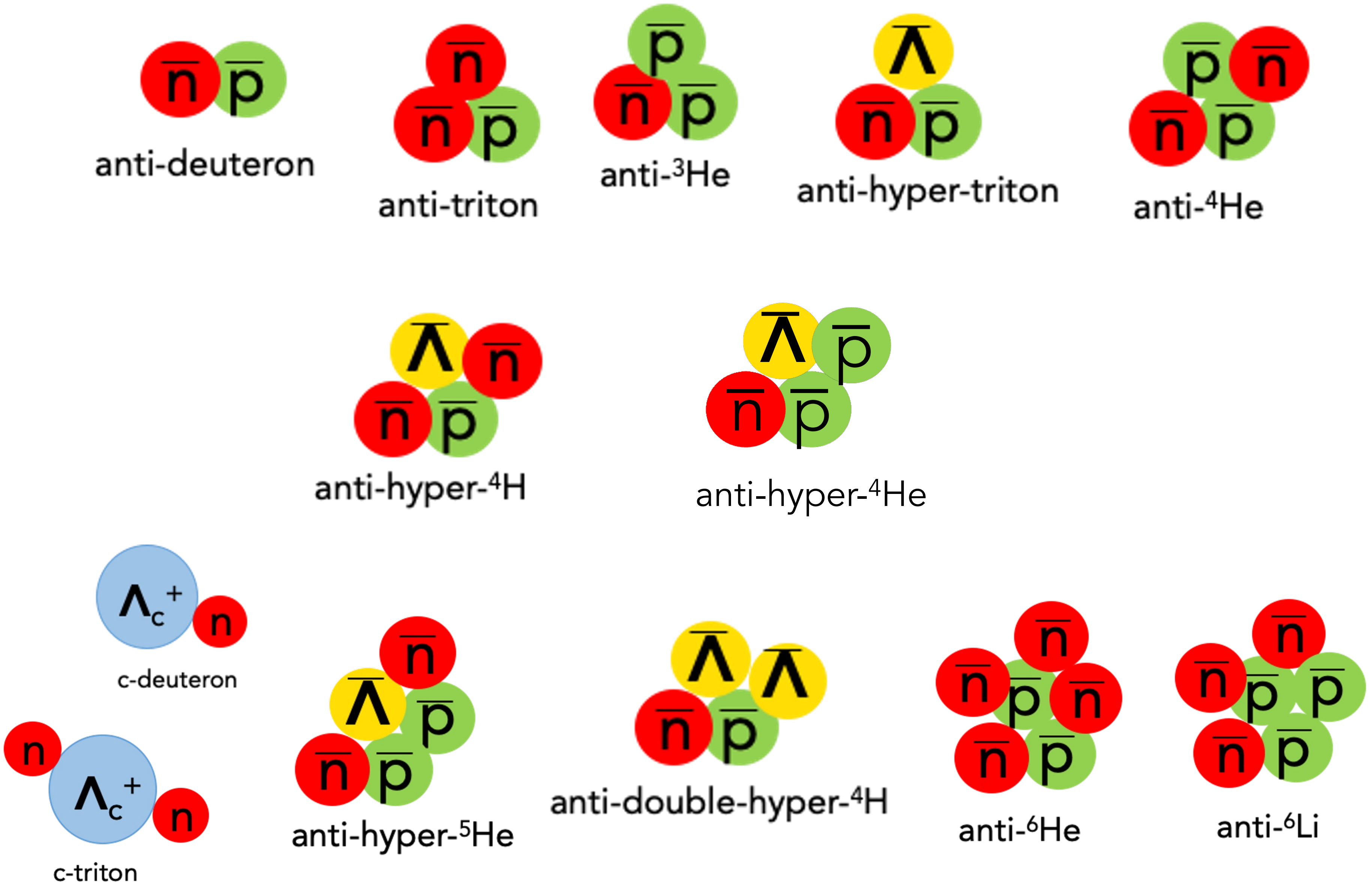
Zoo of exotic QCD bound states reachable at LHC

Run 1 & 2
(2010-2018)

Run 3 & 4
(2021-2030)

Run 5 & 6
(2032-2038)

→ new ALICE 3 experiment at LHC-P2

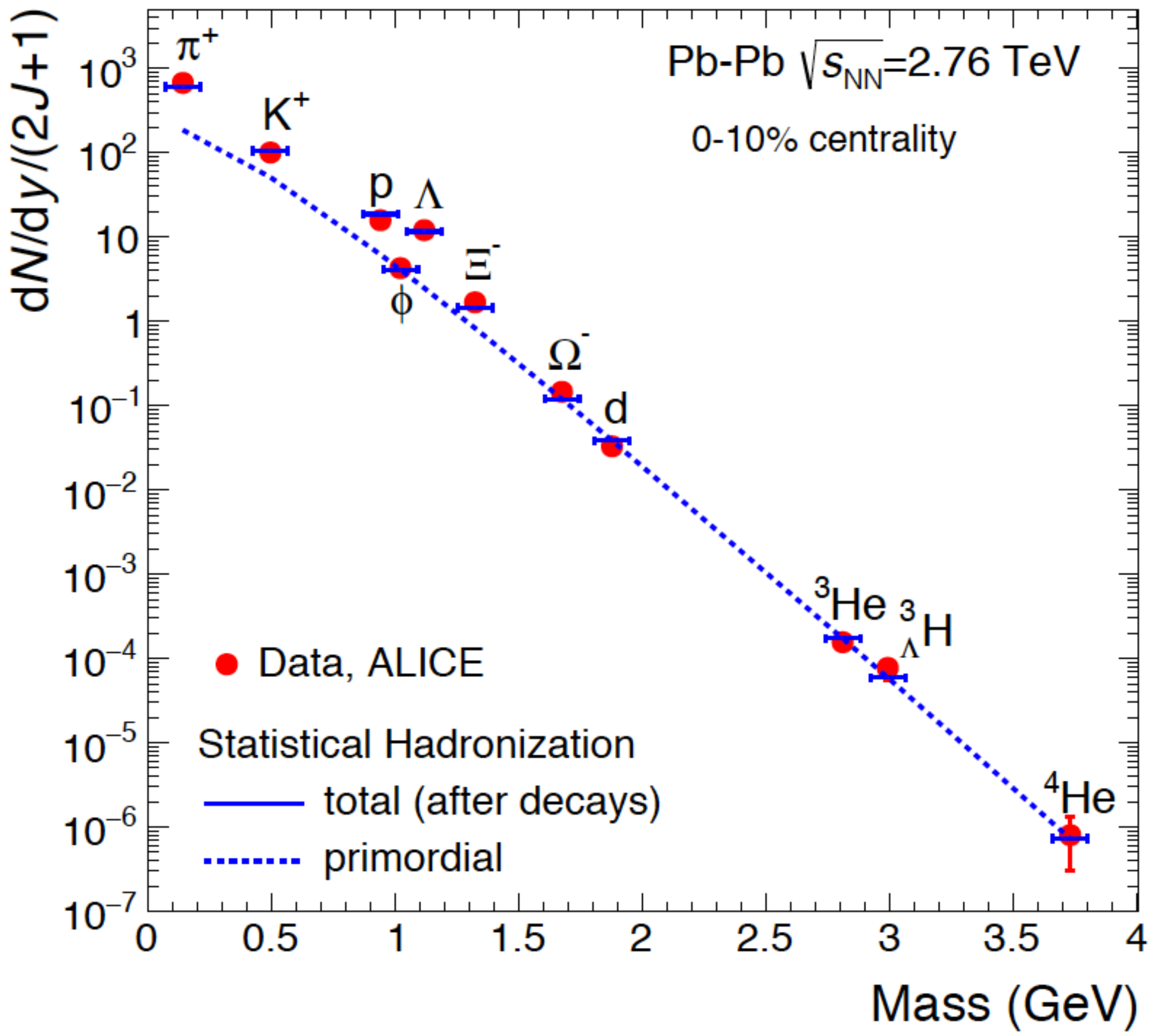


The statistical-thermal model as a production scenario

→ Production yields of light flavour hadrons from a chemically equilibrated fireball can be calculated by statistical-thermal models (roughly $dN/dy \sim \exp\{-m/T_{ch}\}$, in detail derived from partition function)

→ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 7 orders of magnitude with a **common** chemical freeze-out temperature of $T_{ch} \approx 156$ MeV.

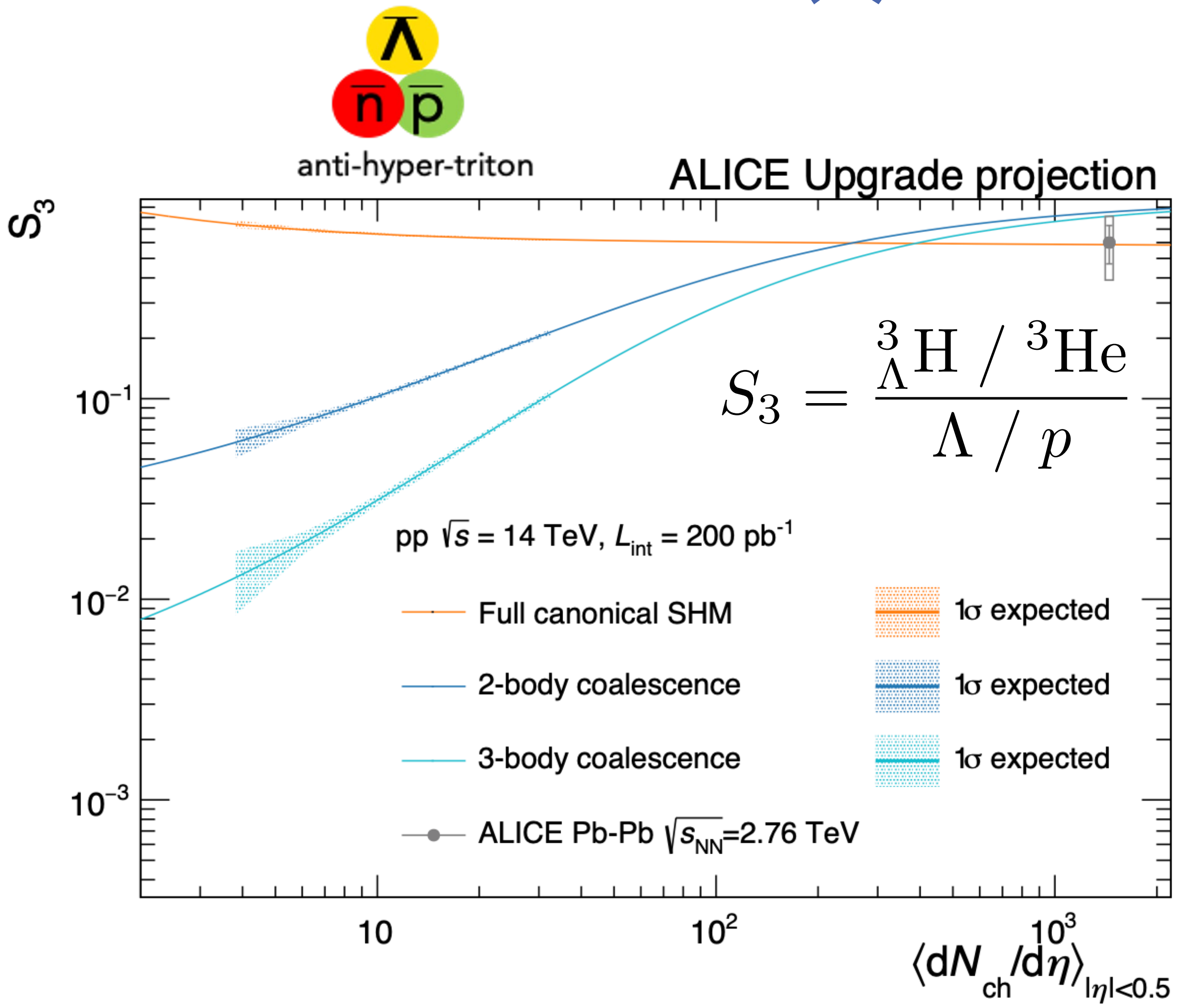
→ Light (anti-)nuclei are also well described despite their low binding energy ($E_{b,d}$ = 2.2 MeV << T_{ch}).



[A. Andronic *et al.*, *Nature* 561 (2018) 7723, 321-330]

Alternative production scenarios for antinuclei (1)

- It is often argued that statistical-thermal production for such weakly bound states is coincidental.
- Coalescence approaches or continuous generation and destruction via hadronic interactions are proposed as alternatives.
- This is an interesting physics topic, but not the subject of my talk today.
- What is relevant for charm nuclei here: in central heavy-ion collisions, the statistical-thermal model is at least a reliable baseline for the expected yields.



[Public note on ALICE pp program]

Alternative production scenarios for antinuclei (2)

- It is often argued that statistical-thermal production for such weakly bound states is coincidental.
- Coalescence approaches or continuous generation and destruction via hadronic interactions are proposed as alternatives.
- This is an interesting physics topic, but not the subject of my talk today.
- What is relevant for charm nuclei here: in central heavy-ion collisions, the statistical-thermal model is at least a reliable baseline for the expected yields.

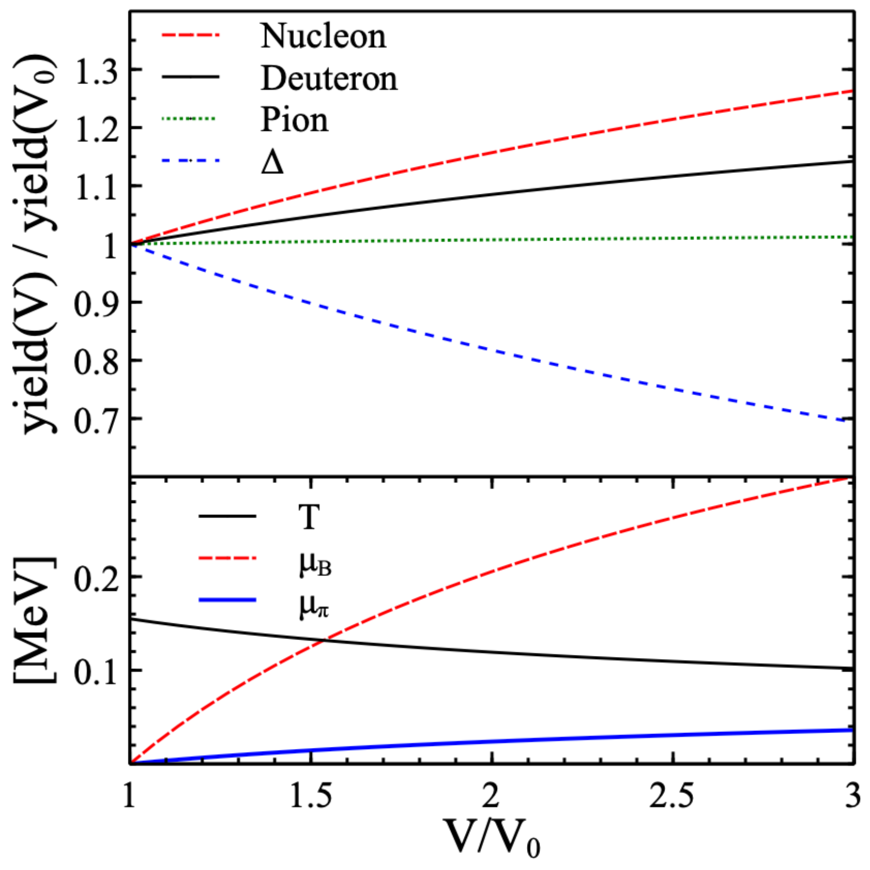


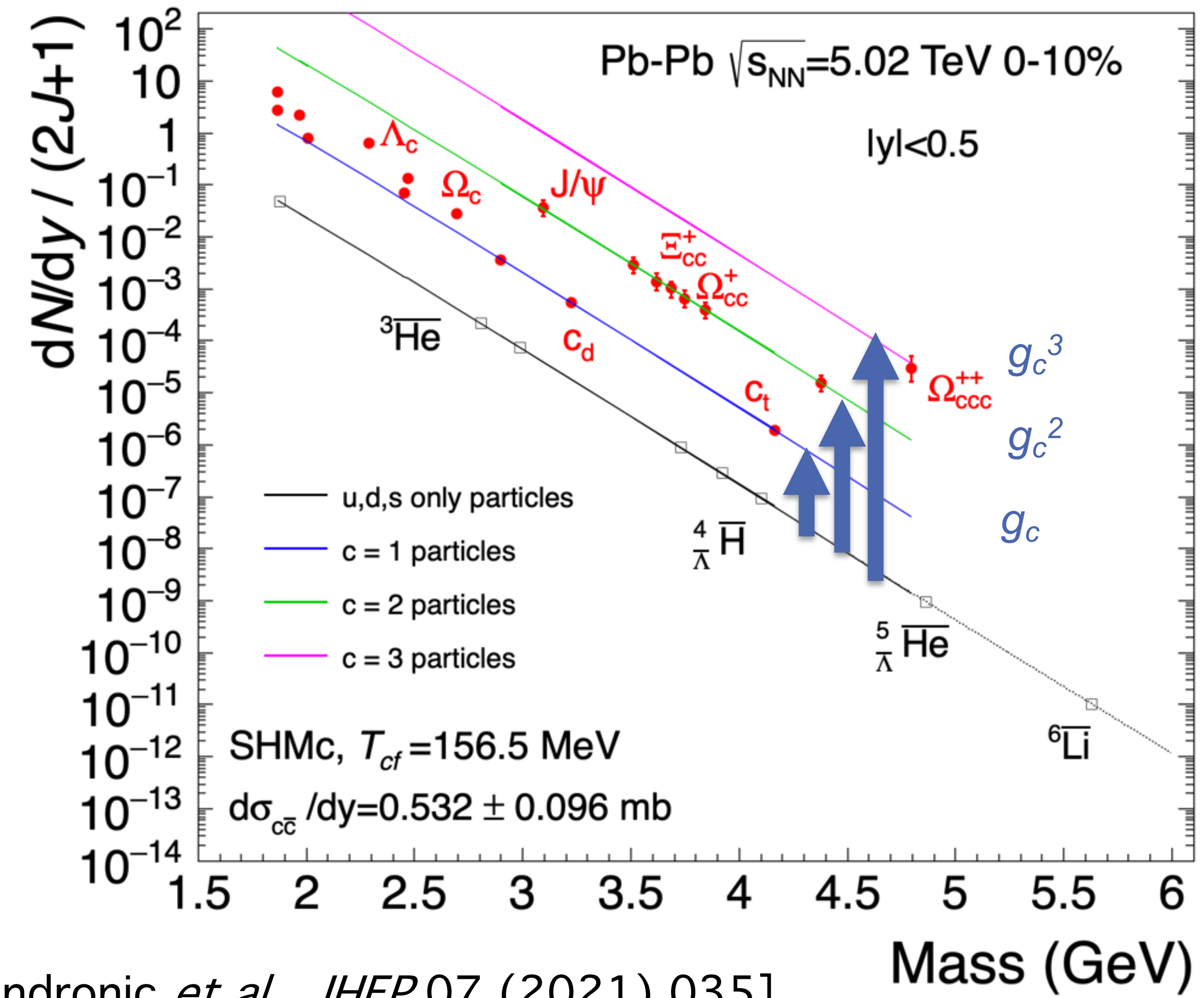
FIG. 8: Evolution of yields (upper panel) and thermodynamic variables (lower panel) in our toy model without annihilations for $T_0 = 155$ MeV. The deuteron yield grows, which is similar to our simulation within the fourth scenario in Fig. 7.

[Phys. Rev. C 99, 044907 (2019)]

Thermal production of charm particles

- Charm particle production rates are expected to be enhanced by the factor of the charm fugacity $g_c \approx 30$ (including charm nuclei).
- This makes multi-charm observable at LHC energies despite small branching ratios.
- Excellent synergy between charm and anti-nuclei physics: anti- and hyper-nuclei provide the baseline to measure g_c with multi-charm hadrons!

Predictions of statistical-thermal hadronization model



[A. Andronic *et al.*, *JHEP* 07 (2021) 035]

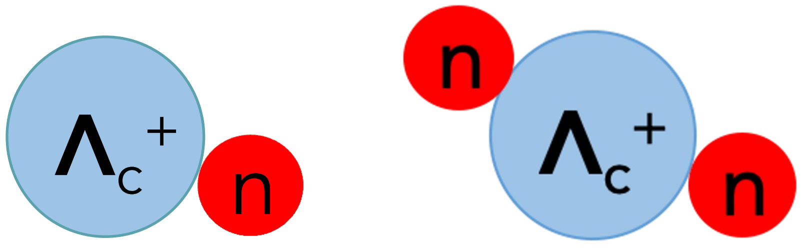
c-deuteron and c-triton

- The lightest possible bound states of a charm baryon and a nucleon without Coulomb repulsion are bound states of Λ_c^+ and a neutron: c-deuteron and c-triton.

- Their possible existence is widely and controversially discussed in the literature since the 1970s with the c-triton being more likely to exist than the c-deuteron, see e.g.:

  [Phys. Rev. Lett. 39, 1506]
  [Eur.Phys.J.A 54 (2018) 11, 199]

- Their possible (non-)existence sheds light on the charm-nucleon potential.



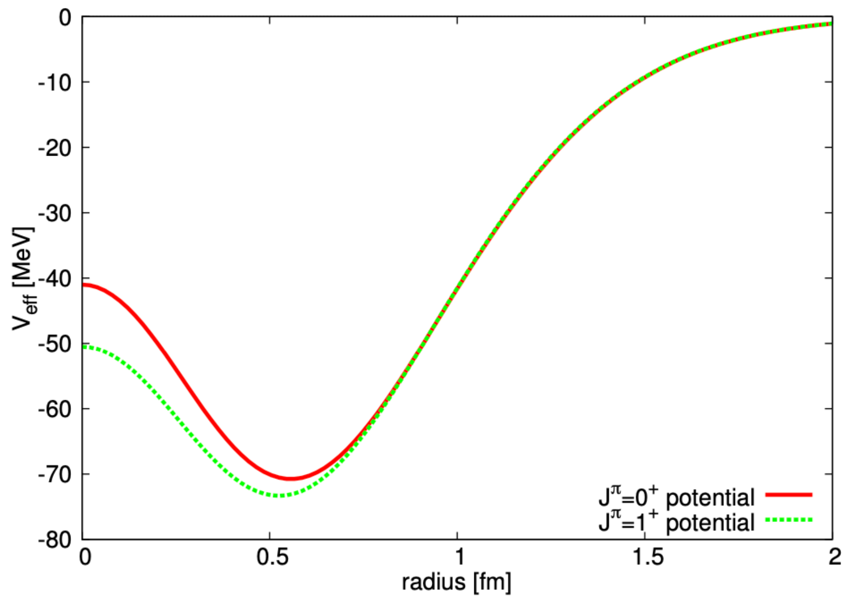


Fig. 9 $\Lambda_c N$ effective potentials for $J^\pi = 0^+$ and 1^+.

[*PTEP* 2016 (2016) 2, 023D02]

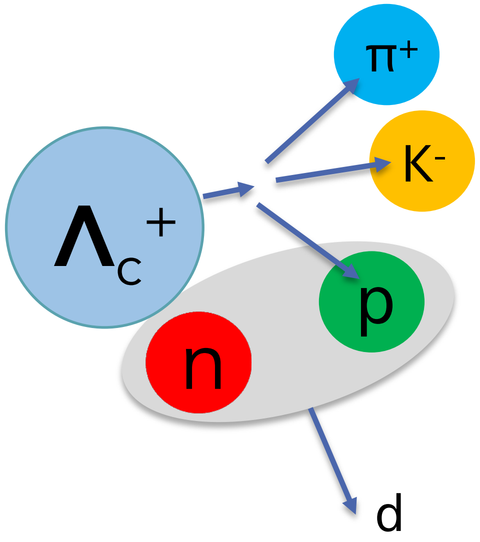
Decay channels and branching ratios

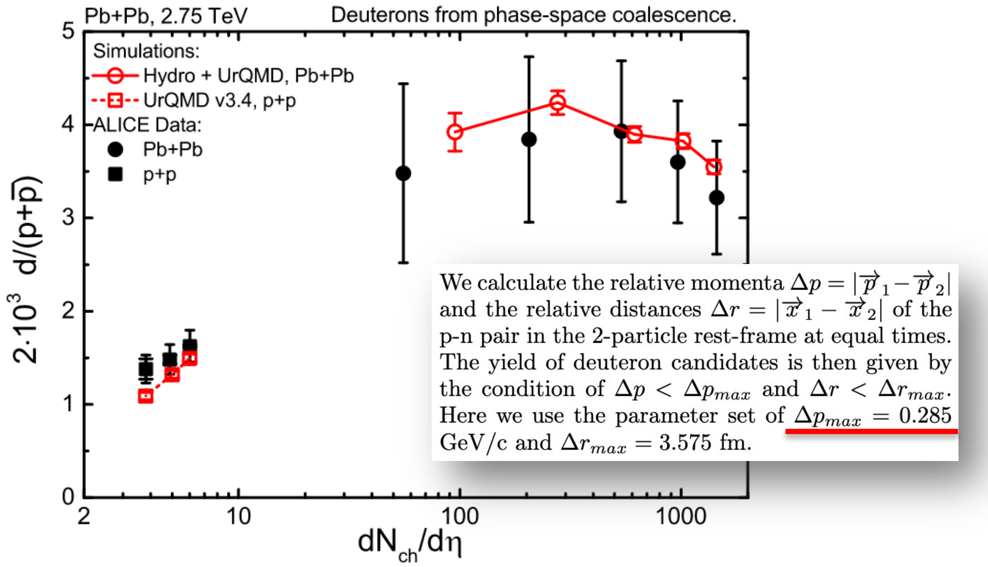
- Most promising decay channels:
  - $c_d \rightarrow d + K^- + \pi^+$
  - $c_t \rightarrow t + K^- + \pi^+$

- The relevant decay of the bound $\Lambda_c^+ \rightarrow p + K^- + \pi^+$ has a branching ratio of 6.28±0.32%.

- Probability of the decay proton to bind with the bound neutron can be estimated by requiring $p \lesssim 200$ MeV in the rest frame of the Λ_c^+ and is found to be ≈ 3-10%.

- This momentum scale for binding of protons and neutrons to deuterons is itself constrained by the deuteron production measurements at LHC energies ;-)

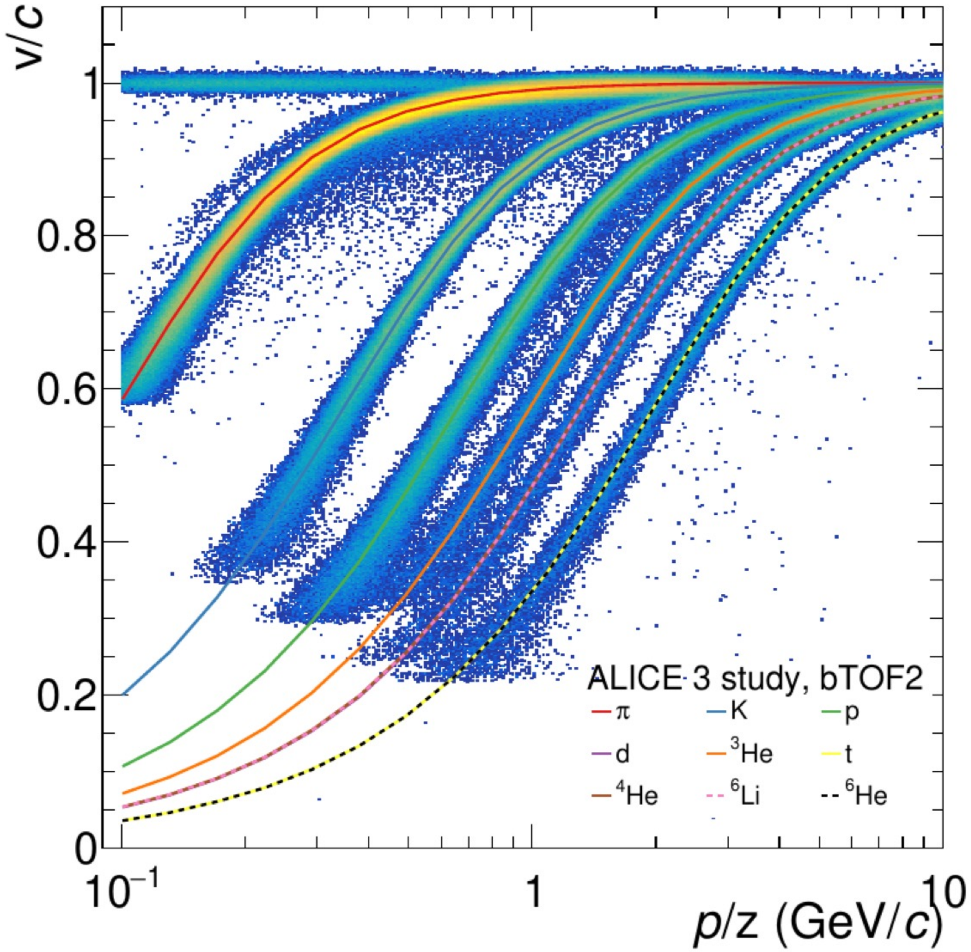


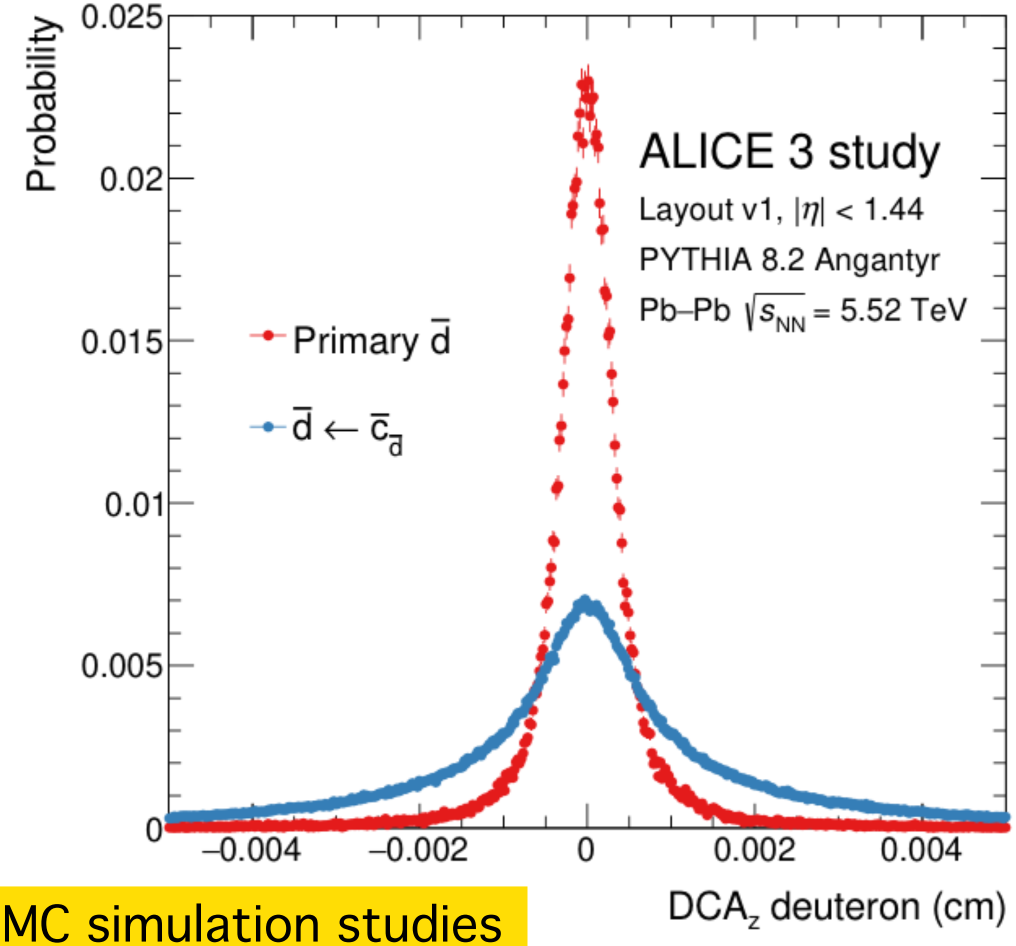


[Phys. Rev. C 99, 014901 (2019)]

Experimental challenges: PID and vertexing

- Rare production of anti-nuclei requires excellent particle identification
- Main background source: primary deuterons that are combined with random pions and kaons → excellent dca-resolution.

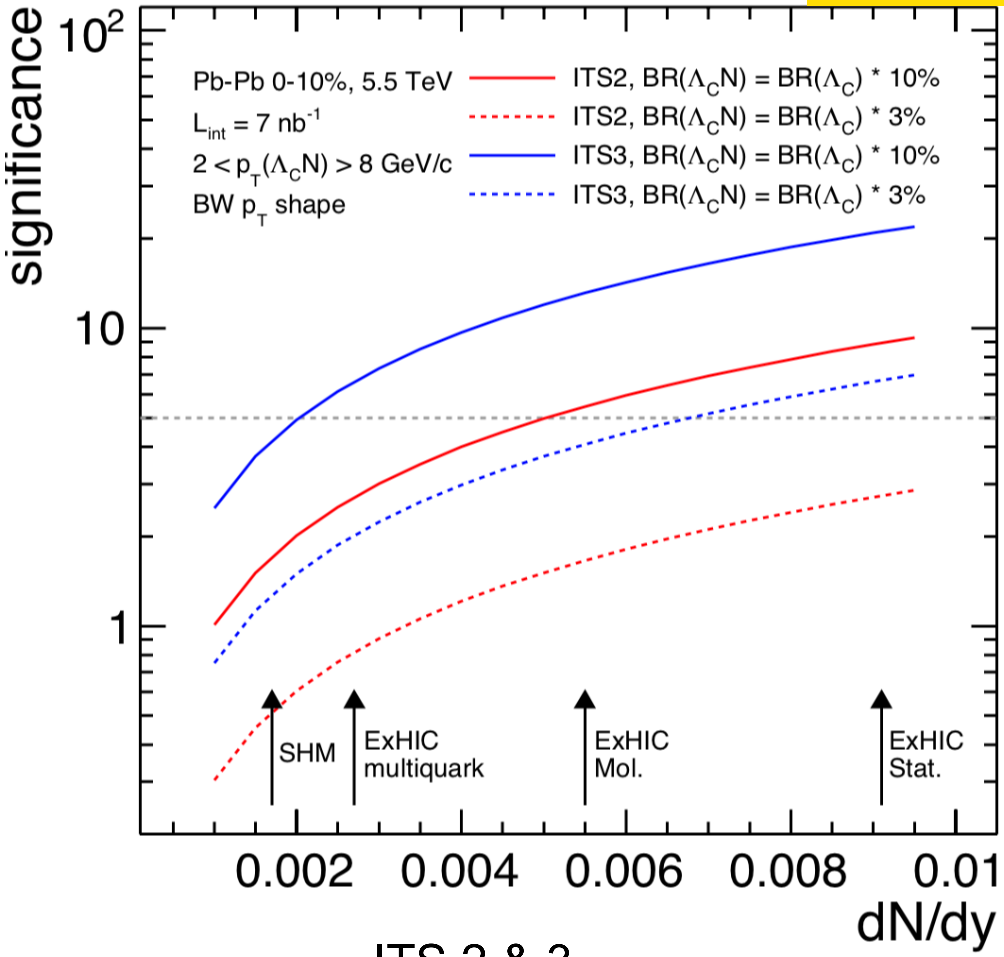




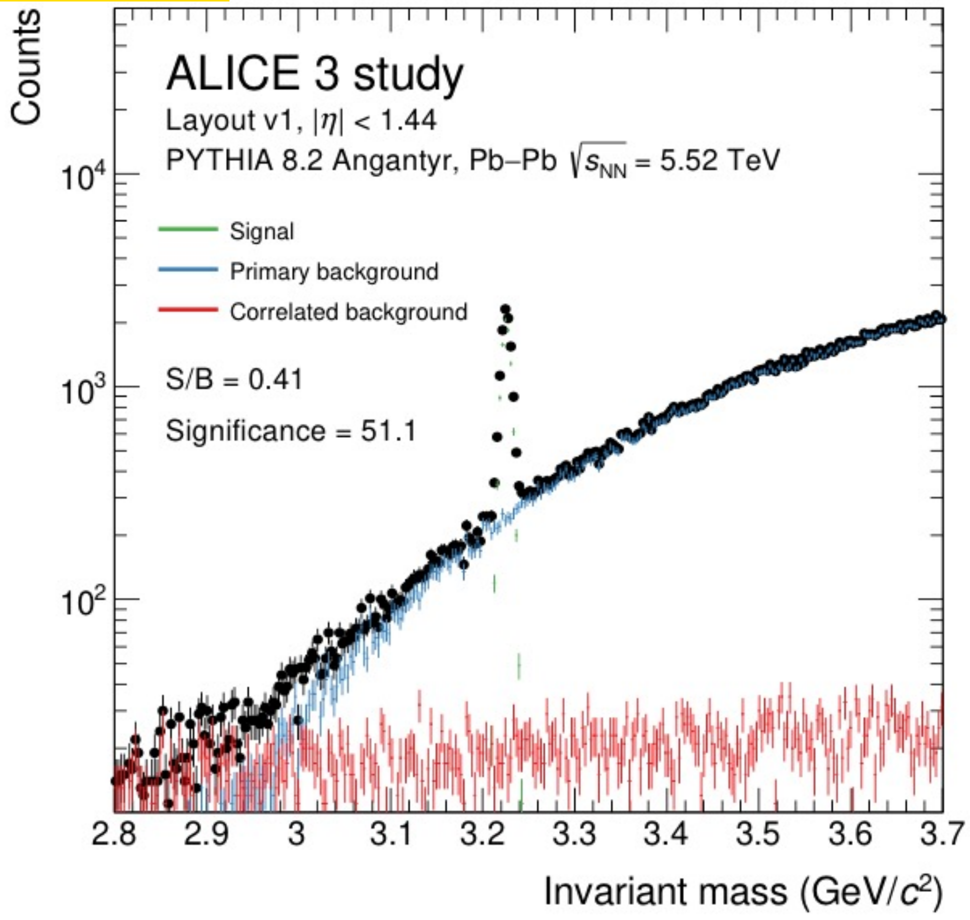
MC simulation studies

c-deuteron: physics performance simulation

MC simulation studies



ITS 2 & 3

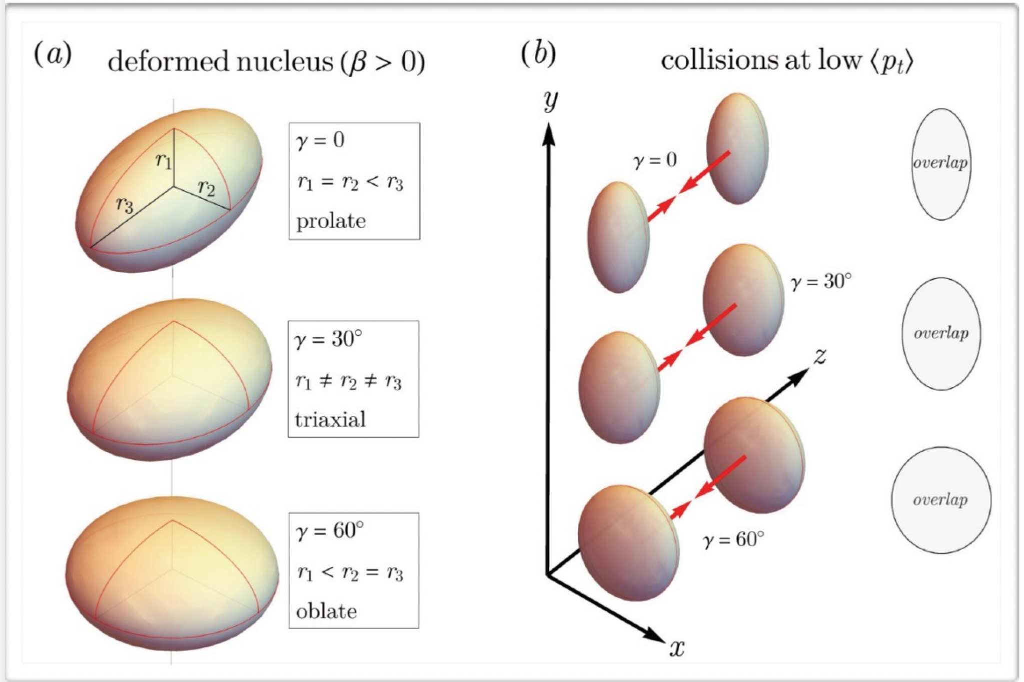


ALICE3 (SHM)

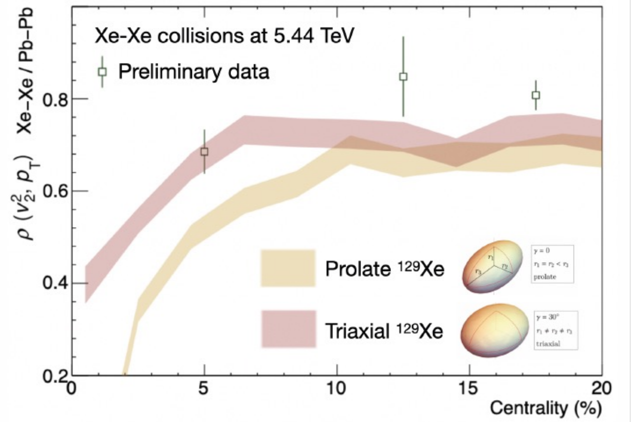
The ITS3 upgrade will allow ALICE to start to become sensitive to c-deuteron production (if it exists); a definitive answer will be provided by ALICE 3.

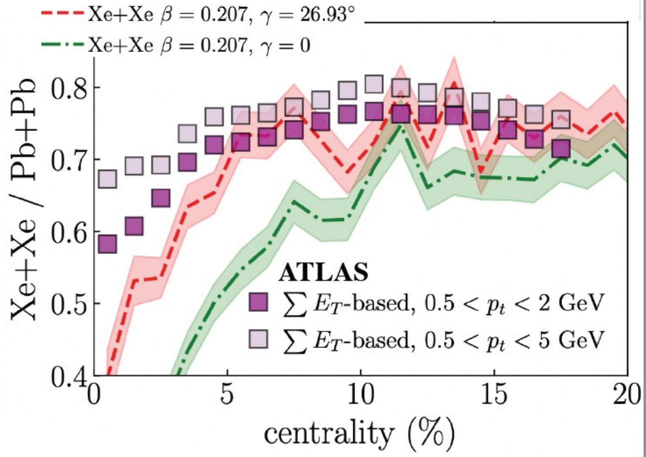
Excursus: nuclear structure

B. Bally etc, arXiv:2108.09578



ALICE, arXiv: 2111.06106





- Better agreement between LHC data and calculations with γ = 26.93°
  - Indication of triaxial structure of ^{129}Xe at high energy collisions at the LHC
  - New connection of high-energy heavy-ion physics to low-energy nuclear (structure) physics

→ See the interesting workshop in Saclay last autumn: *Deciphering nuclear phenomena across energy scales*

Summary & Outlook

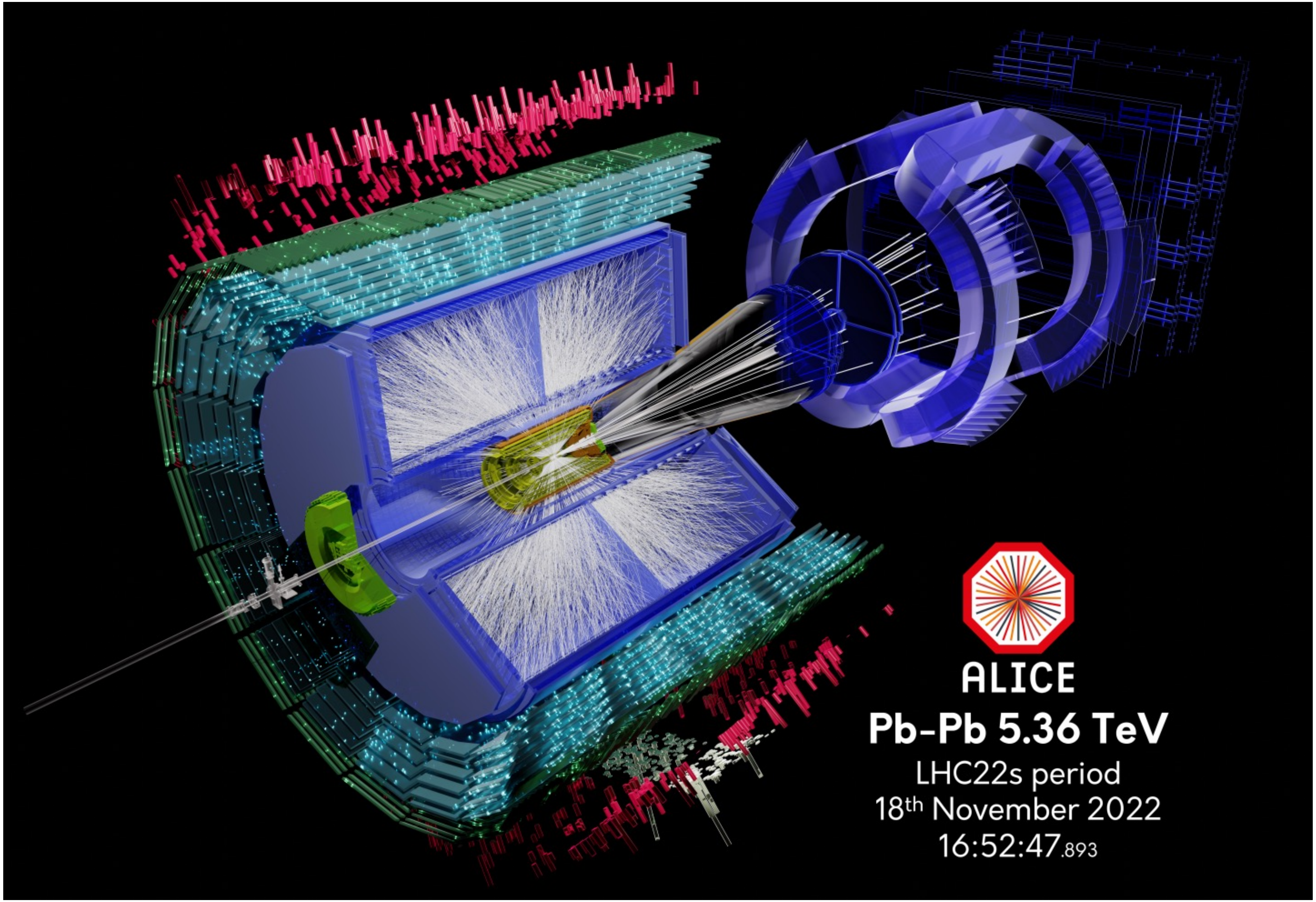
Summary

- ALICE was originally designed to study the creation and properties of the quark-gluon-plasma – a deconfined state of matter that is created in ultra-relativistic heavy-ion collisions and that also existed in the early universe shortly after the big bang.

- Recently, the unique particle identification and tracking capabilities of ALICE have also been utilized to provide crucial input for astrophysical challenges: the search for anti-nuclei in space and the equation-of-state of neutron stars.

- These two a priori very different topics show intriguing connections.

- The future for the topic is bright: with the new ALICE 2 detector taking data in LHC Run 3 and the planned ALICE 3 detector in the 2030s!


ALICE
Pb-Pb 5.36 TeV
LHC22s period
18th November 2022
16:52:47.893

Thank you!