(Hyper)nuclei measurements with ALICE

JENAA Workshop, 20/08/24

Francesco Mazzaschi

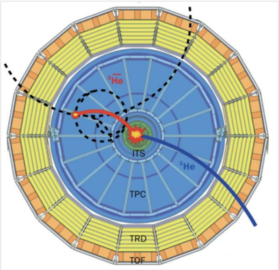
ALICE and Astrophysics

- Recent papers published by ALICE recently have close connections with relevant problems for astrophysics
  - Hypernuclei to get a glimpse into the neutron stars
  - Antinuclei to understand their production and propagation in the galaxy

ANTIMATTER | NEWS

ALICE looks through the Milky Way

1 March 2023



Annihilation Schematic showing a $^3\overline{\text{He}}$ annihilating in the gas of the ALICE time projection chamber (red) and a ^{3}He that does not undergo an inelastic reaction and reaches the time-of-flight detector (blue), with dashed curves representing charged (anti)particles produced in the $^3\overline{\text{He}}$ annihilation. Source: *Nat. Phys.* **19** 61

Antinuclei can travel vast distances through the Milky Way without being absorbed, concludes a novel study by the ALICE collaboration. The results, published in December, indicate that the search for $^3\overline{\text{He}}$ in space is a highly promising way to probe dark matter.

First observed in 1965 in the form of the antideuteron at CERN's Proton Synchrotron and Brookhaven's Alternating Gradient Synchrotron, antinuclei are exceedingly rare. Since they annihilate on contact with regular matter, no natural sources exist on Earth. However, light antinuclei have been produced and studied at accelerator facilities, including recent precision measurements of the mass difference between deuterons and antideuterons and between ^{3}He and $^3\overline{\text{He}}$ by ALICE, and between the hypertriton and antihypertriton by the STAR collaboration at RHIC.

[CERN Courier #1]

[CERN Courier #2]

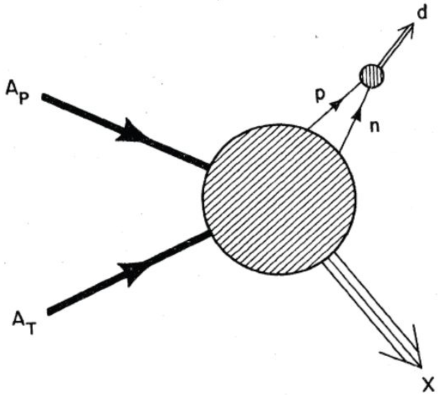
STRONG INTERACTIONS | NEWS

Hypertriton characterised with unprecedented precision

7 November 2022

A report from the ALICE experiment.

(Hyper)Nucleosynthesis at collider



Coalescence

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

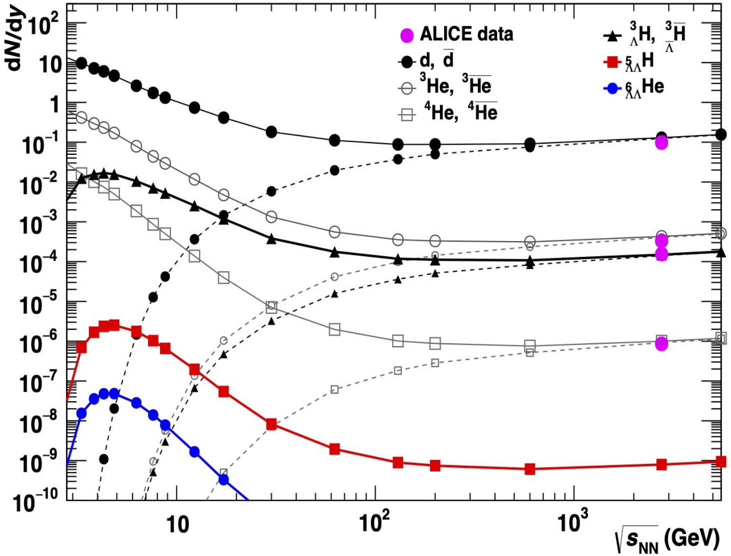
Baryons close in phase space can form a nucleus
- Interplay between the configuration of the phase space of the nucleons and the wave function of the nucleus

Thermal Models (SHMs)

Hadrons emitted from the interaction region in statistical equilibrium when the system reaches a limiting temperature T_{eq}

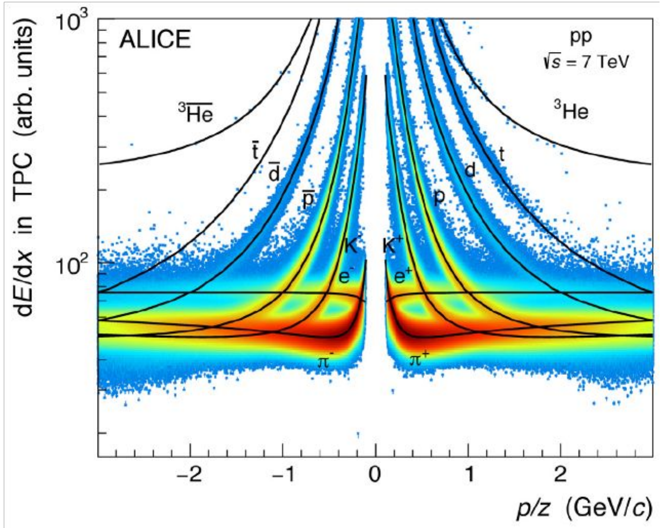
- Abundance of a species
  - ➢ $\propto \mathrm{Exp}(-M/T_{eq})$
- No dependency on the nuclear size

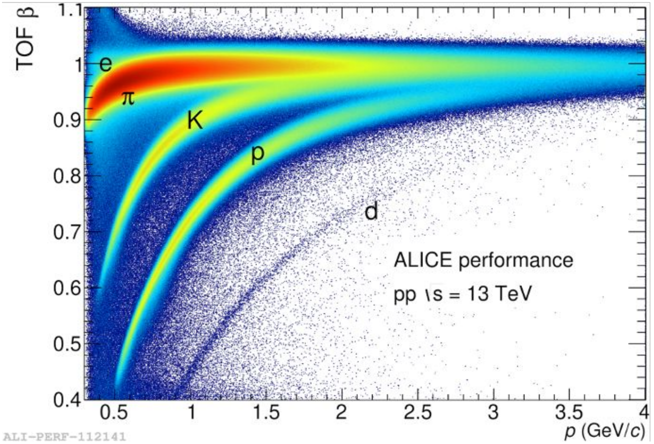
B. Dönigus et al.,Nucl.Phys.A 987 (2019)



F. Mazzaschi

Nuclei identification in ALICE

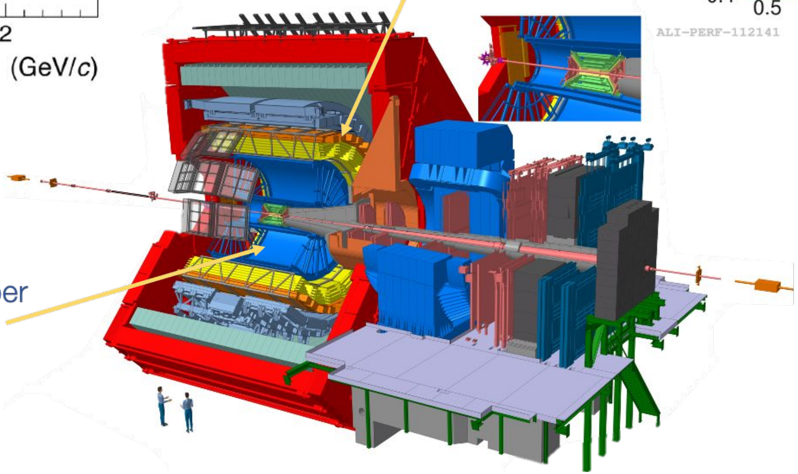




Time Of Flight

PID via β

σ_{PID} ~ 70 ps



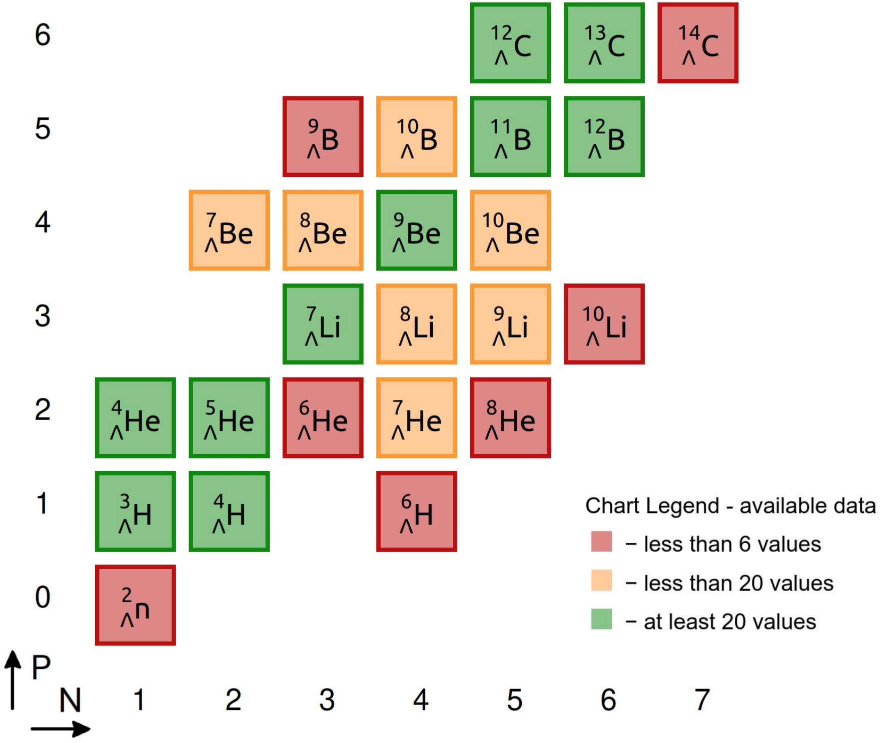
Time Projection Chamber

tracking, PID via dE/dx

$\sigma_{dE/dx}$ ~ 6%

Hypernuclei

- Hypernuclei: bound states of strange baryons (hyperons) and ordinary nuclei
  - ➢ Extend the nuclear chart to a third dimension, the strangeness one
  - ➢ Poorly known bound states
  - ➢ Unique probes for studying the interaction of hyperons with the ordinary matter



Hypernuclear database

Hypernuclei

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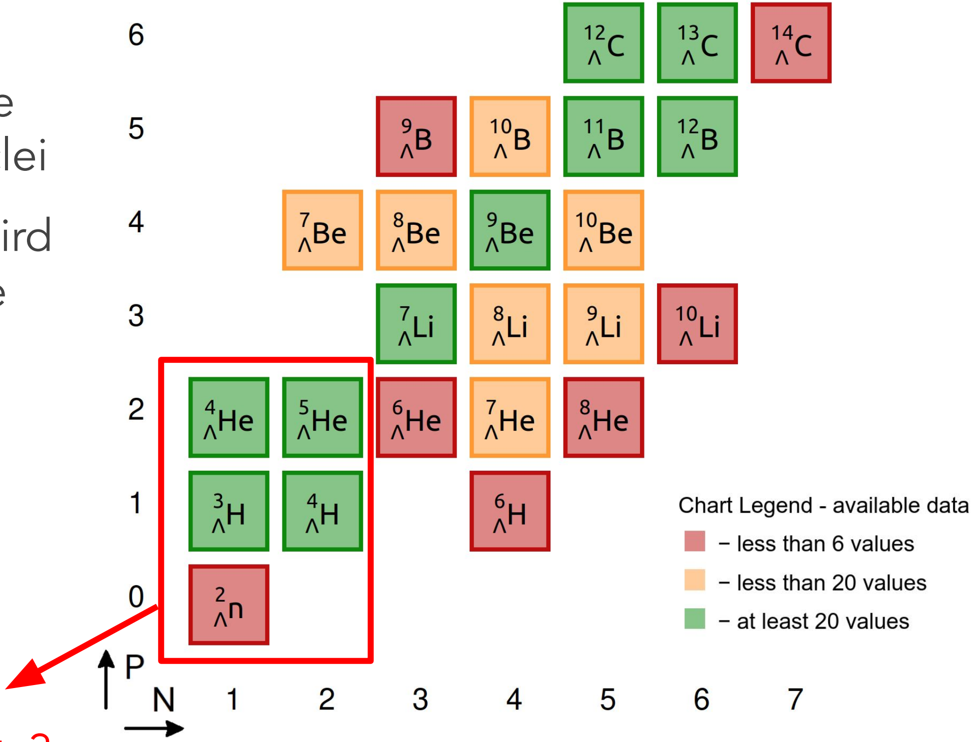
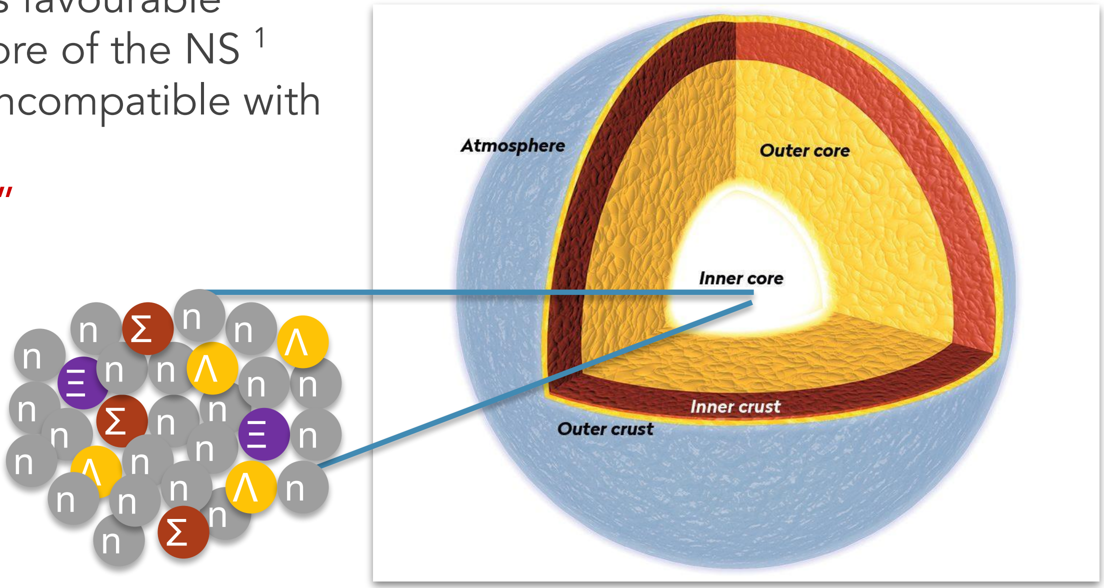


ALICE Run 2 + 3

Hypernuclear database

Probing the core of the neutron stars

- Neutron stars (NSs) equation of state (EoS)
  - Production of hyperons favourable inside the innermost core of the NS [1]
  - Softening of the EoS, incompatible with measured heavy NS
    - "Hyperon puzzle"

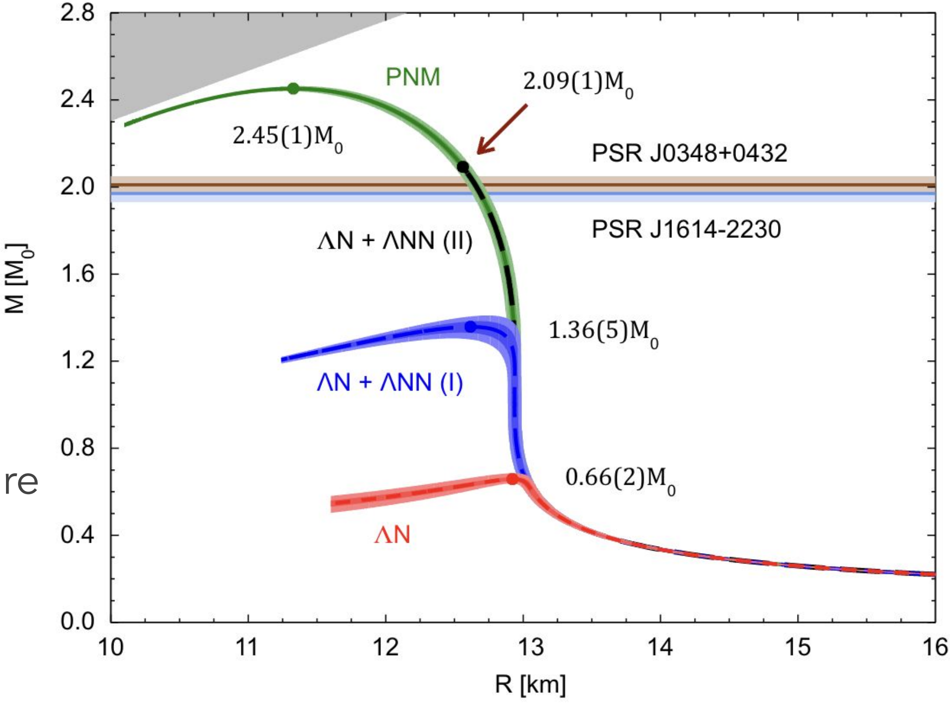


[1] D. Logoteta et al., Eur.Phys.J.A 55 (2019) [2] D. Lonardoni et al., Phys. Rev. Lett. 114 (2019)

Probing the core of the neutron stars

- Neutron stars (NSs) equation of state (EoS)
  - ➢ Introduction of Λ-N-N repulsion might solve the hyperon puzzle
  - ➢ Models need additional experimental constraints!
- Study Λ-N and Λ-N-N forces with ALICE
  - ➢ p–Λ and p–p–Λ femtoscopy
  - ➢ Binding energies of light hypernuclei are used to benchmark/tune the Λ–N interaction potential models [1, 2]

D. Lonardoni et al., Phys. Rev. Lett. 114 (2015)



[1] *Le et at al.*, EPJA 60 1 (2024)
[2] *Garrido et at al.*, arXiv:2408.01750 (2024)

$^{3}_{\Lambda}$H structure: lifetime and B_{Λ}

- More than 50 years after the first measurement, B_{Λ} was poorly known

Implications of an increased Λ-separation energy of the hypertriton

Hoai Le [a], Johann Haidenbauer [a], Ulf-G. Meißner [b a c], Andreas Nogga [a]

Consequences of increased hypertriton binding for *s*-shell Λ-hypernuclear systems

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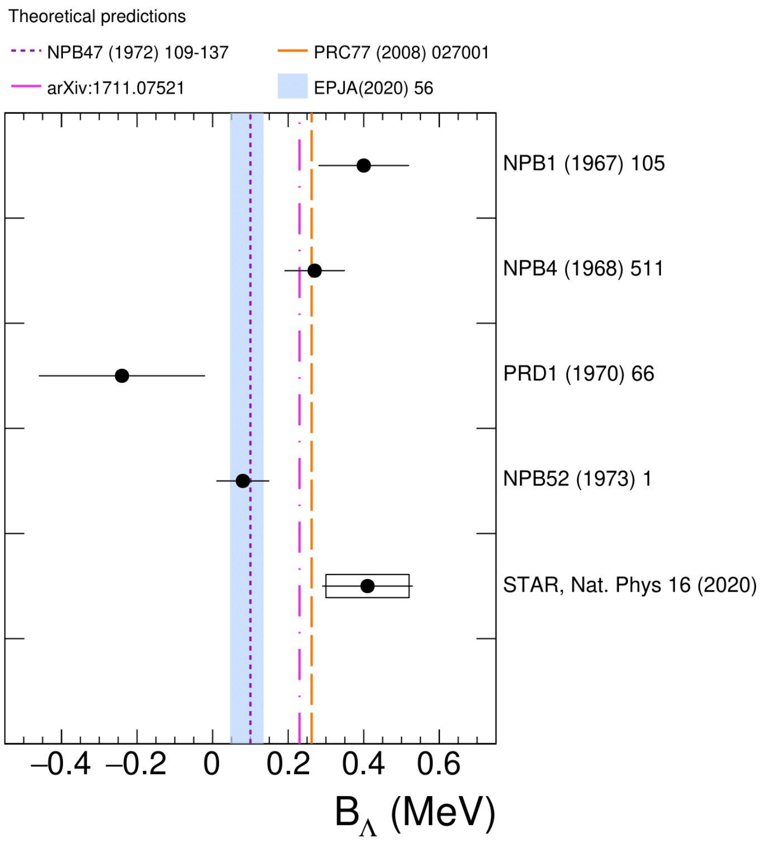
Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel and Nuclear Physics Institute of the Czech Academy of Sciences, 25068 Řež, Czech Republic

B. Bazak,† N. Barnea,‡ and A. Gal§
Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

J. Mareš‖
Nuclear Physics Institute of the Czech Academy of Sciences, 25068 Řež, Czech Republic

- Lifetime:
  - ➢ A low B_{Λ} should imply a lifetime close to the free Λ hyperon one (262 ps)
  - ➢ more measurements, but all with uncertainties larger than 10%

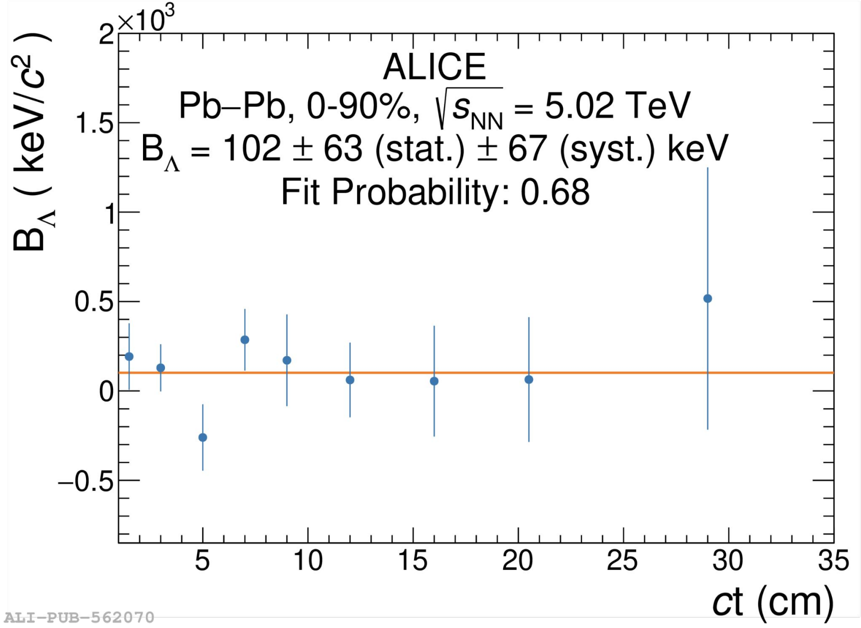


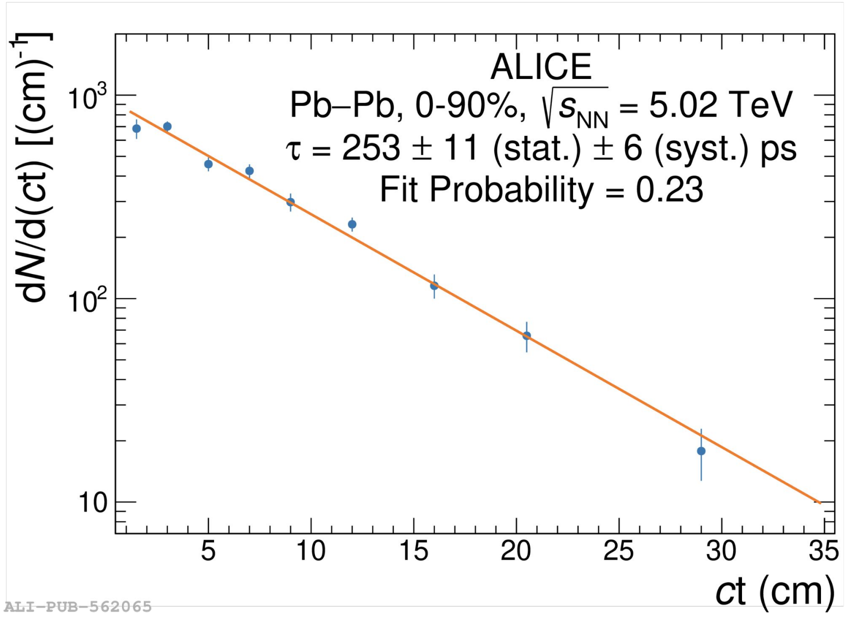
Schäfer et al., Phys. Rev. C 105 (2022) 015202
Le et al., Phys.Lett.B 801 (2020) 135189

Properties of $^{3}_{\Lambda}H$ uncovered

- $^{3}_{\Lambda}H$ lifetime compatible within 1σ with free Λ lifetime
- Low B_{Λ} , in agreement with early emulsion experiments

📕 Phys. Rev. Lett. 131, 102302 (2023)

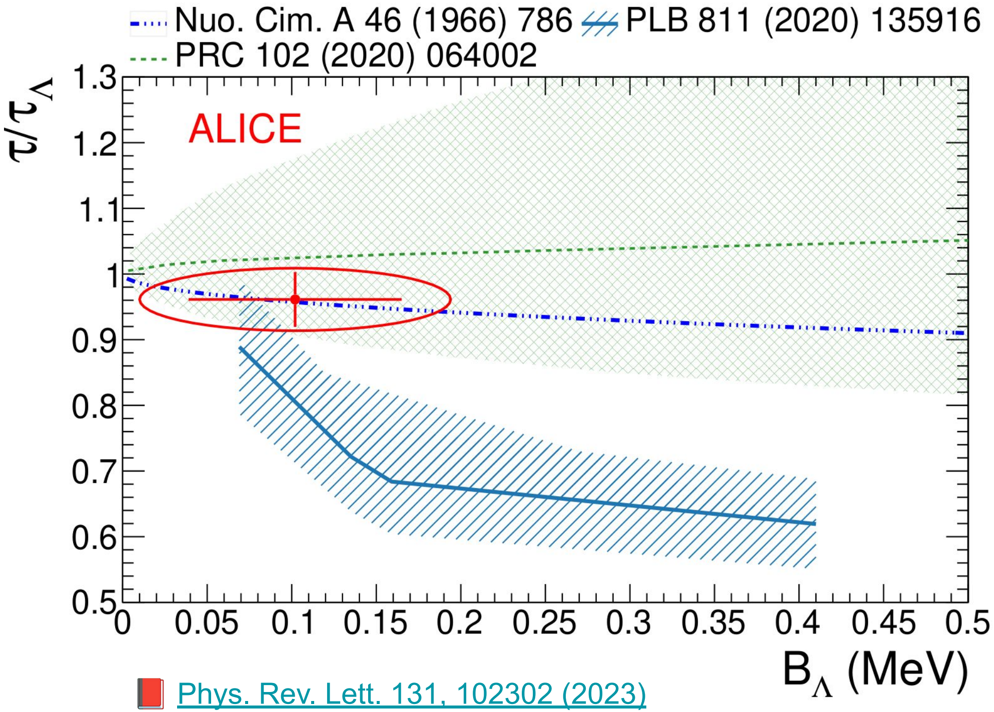




Most precise measurements to date of τ and B_{Λ} of the $^{3}_{\Lambda}H$

Final results

- Most precise measurements to date of τ and B_Λ of the $^{3}_{\Lambda}H$
  - ➢ $\tau = 253 \pm 11$ (stat.) ± 6 (syst.) ps
  - ➢ $B_\Lambda = 102 \pm 63$ (stat.) ± 67 (syst.) keV



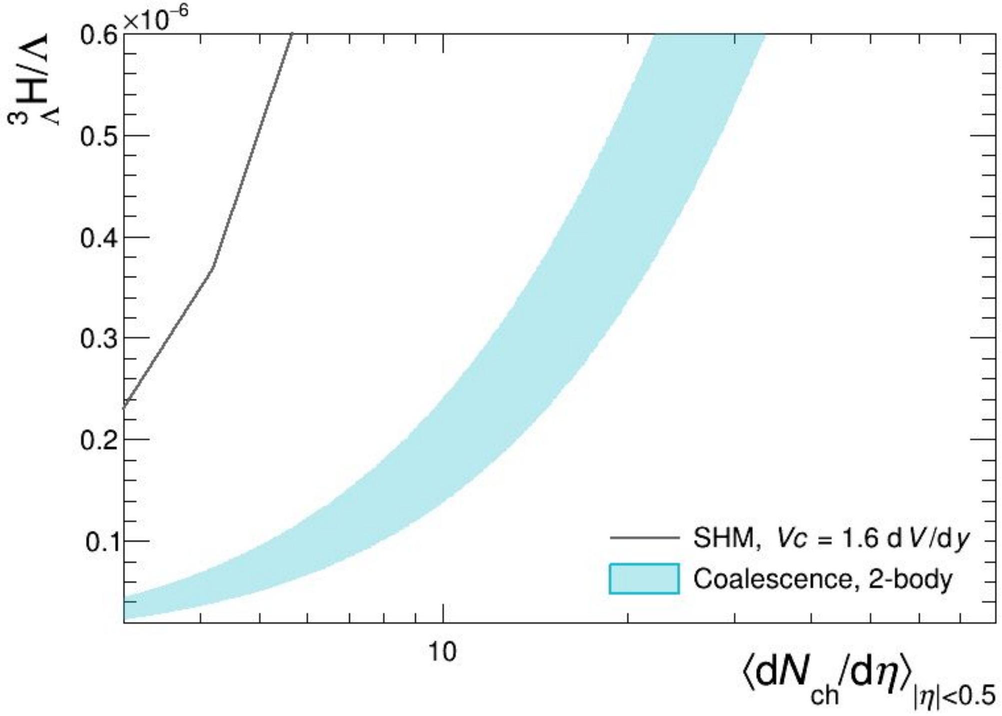
📕 [Phys. Rev. Lett. 131, 102302 (2023)]

- Weakly-bound nature of the $^{3}_{\Lambda}H$ finally confirmed
  - ➢ $^{3}_{\Lambda}H$ could be approximated as a shallow d-Λ state with a wide d-Λ radius of ~ 10 fm

- How does this reflect on its production?

$^{3}_{\Lambda}H$ synthesis in pp collisions

- Weakly bound state
  - $^{3}_{\Lambda}H / \Lambda \rightarrow$ large separation between SHM [1] and coalescence [2] predictions at low charged-particle multiplicity density due to the extended $^{3}_{\Lambda}H$ wave function
- $^{3}_{\Lambda}H$ production in pp and p–Pb collisons: a key to understand the nuclear production mechanism at the LHC

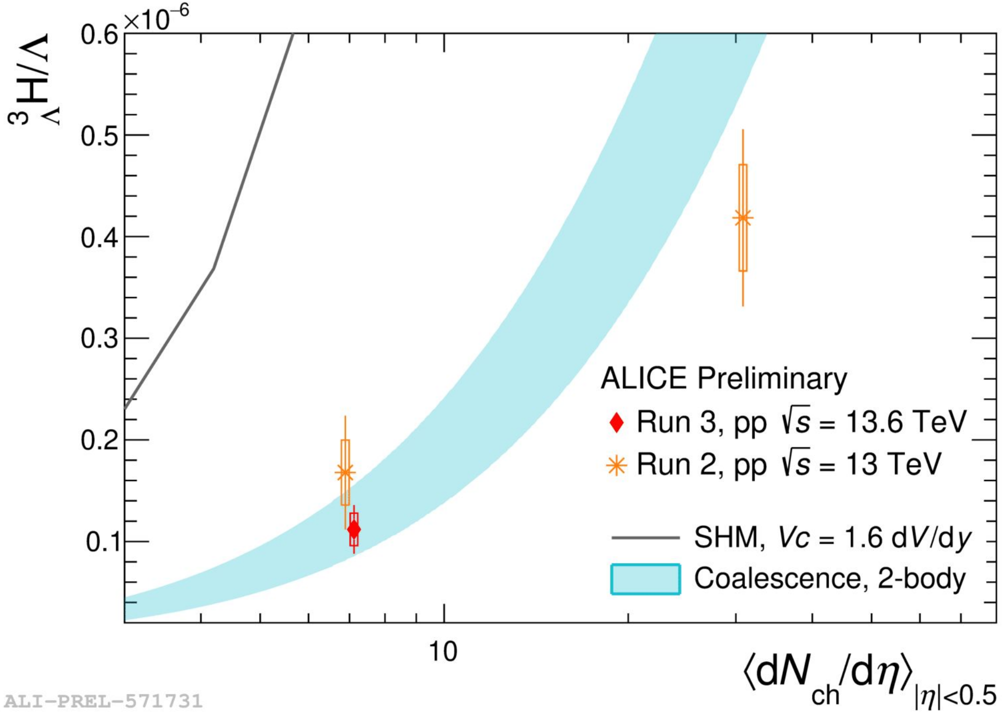


[1] *Vovchenko, et al.*, Phys. Lett., B 785, 171-174, (2018)
[2] *Sun. et al.*, Phys. Lett. B 792, 132–137, (2019)
[3] Phys. Lett. B 754, 360–372, (2016)

$^{3}_{\Lambda}H$ synthesis in pp collisions

- First measurements of $^{3}_{\Lambda}H/\Lambda$ in pp Run 2
- Run 3, 2022 pp data taking: precision increased by a factor ~ 3
  - ➢ good agreement with coalescence
  - ➢ SHM description fails

- Coalescence quantitatively describes the $^{3}_{\Lambda}H$ suppression in small systems
  - ➢ the nuclear size matters at low charged-particle multiplicity
  - ➢ open point: can we measure it ?



[1] *Vovchenko, et al.*, Phys. Lett., B 785, 171-174, (2018)
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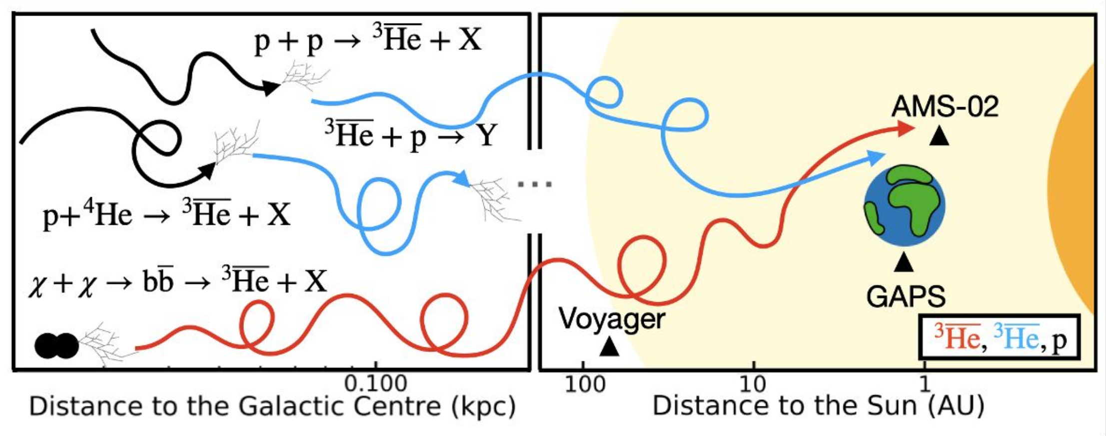
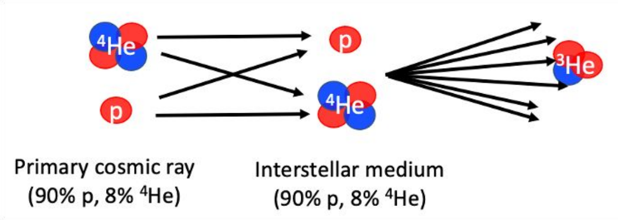
Antinuclei from galaxy to the LHC

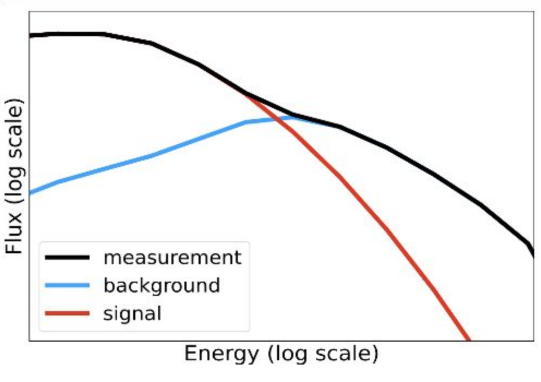


Antinuclei production:

- pp, pA and (few) AA reactions between primary cosmic rays and the interstellar medium



- High Signal/Noise ratio (~$10^2 - 10^4$) at low E_{kin} expected by models
- To correctly interpret any future measurement, we need precise knowledge of
  1. antinuclei production
  2. annihilation



Antinuclei production

Antinuclei from cosmic rays are produced interactions of cosmic rays with interstellar medium (p, ^{4}He) with $|y| < 1.5$ and $\sqrt{s}$ of ~ 10^{1} GeV [1, 2]

1 📚 K. Blum, arxiv:2306.13165

2 📚 Serksnyte et al., Phys. Rev. D 105 (2022) 8, 083021

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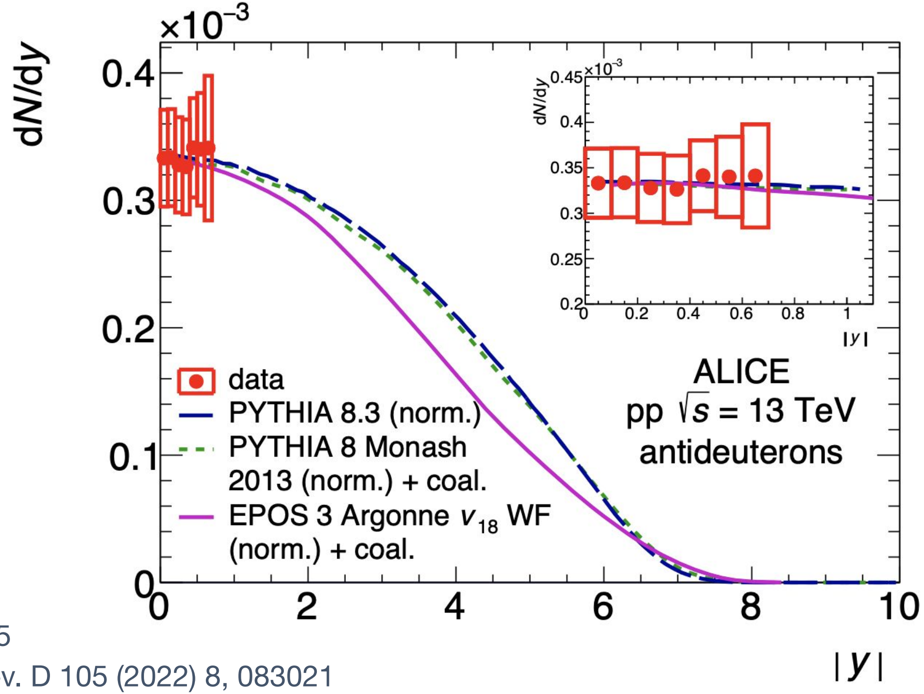

arXiv:2407.10527

[1] K. Blum, arxiv:2306.13165
[2] Serksnyte et al., Phys. Rev. D 105 (2022) 8, 083021

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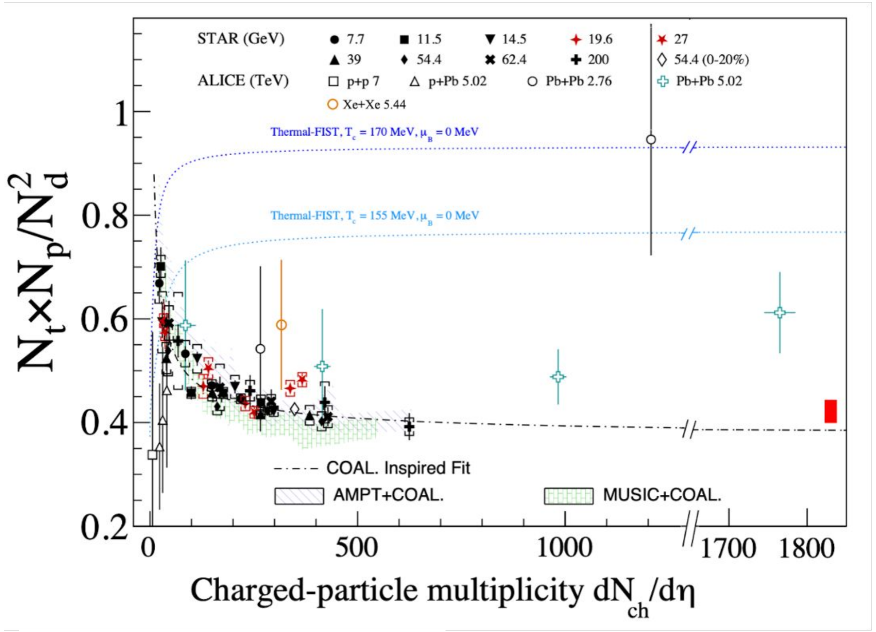

figure adapted from: STAR Coll. Phys. Rev. Lett. **130**, 202301 (2024)

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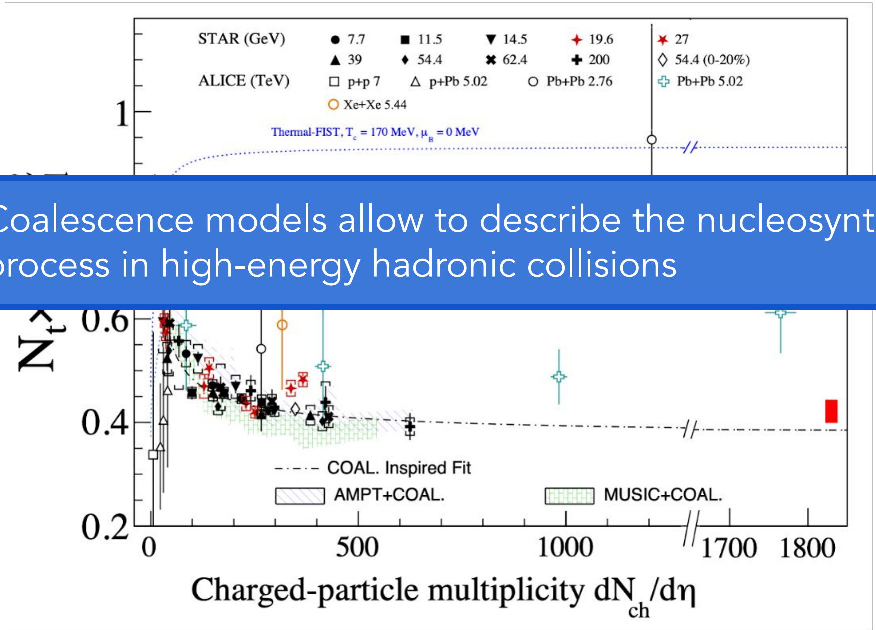

Coalescence models allow to describe the nucleosynthesis process in high-energy hadronic collisions

📚 figure adapted from: STAR Coll. Phys. Rev. Lett. **130**, 202301 (2024)

Antinuclei annihilation

ALICE measured the **inelastic cross section** for **antinuclei** using the LHC as antimatter factory and the ALICE detector as a target

- anti d, t, He^3

antid: 📚 Phys.Rev.Lett. (2020) 125, 162001
anti^{3}He: 📚 Nature Phys. (2023) 19, 61–71
anti^{3}H: 📚 Phys. Lett. B (2024) 848, 138337

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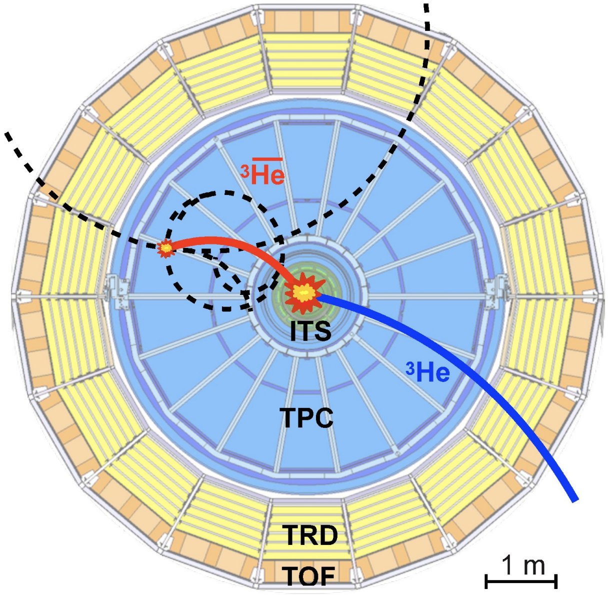
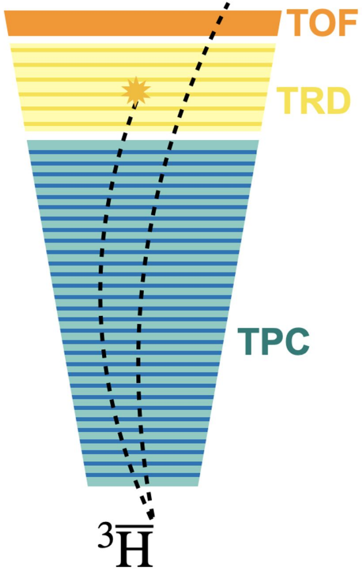
- anti d, t, He^3
- Two methods: antinuclei to nuclei or TOF to TPC ratios

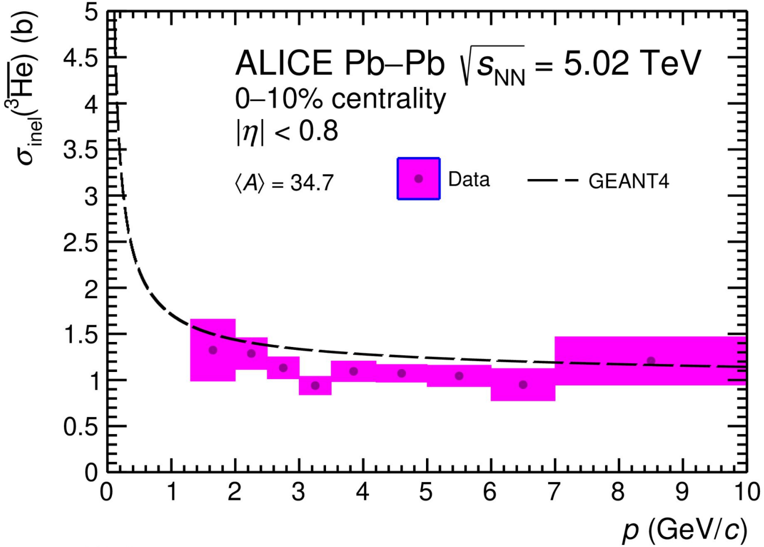
antid: 📚 Phys.Rev.Lett. (2020) 125, 162001
anti^{3}He: 📚 Nature Phys. (2023) 19, 61–71
anti^{3}H: 📚 Phys. Lett. B (2024) 848, 138337



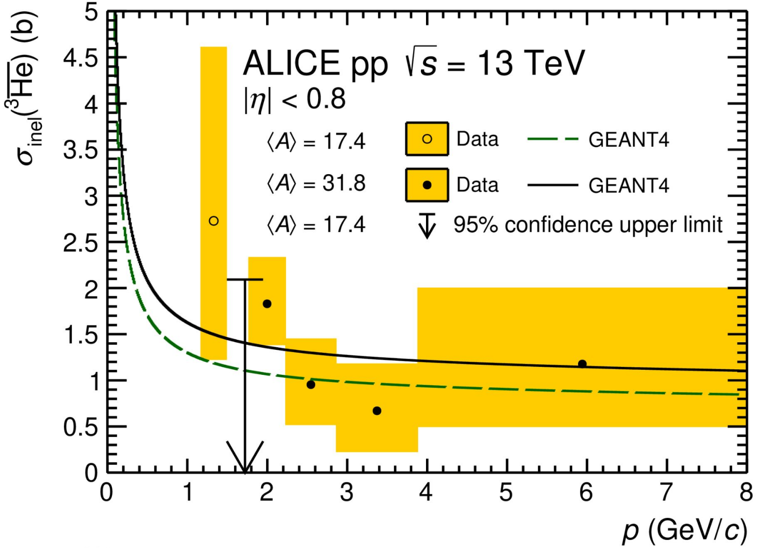


Antinuclei annihilation: anti-^{3}He

- First inelastic cross section measurement for the anti-^{3}He
  - 2σ agreement with GEANT4 σ_{inel} parameterization



ALI-PUB-532048

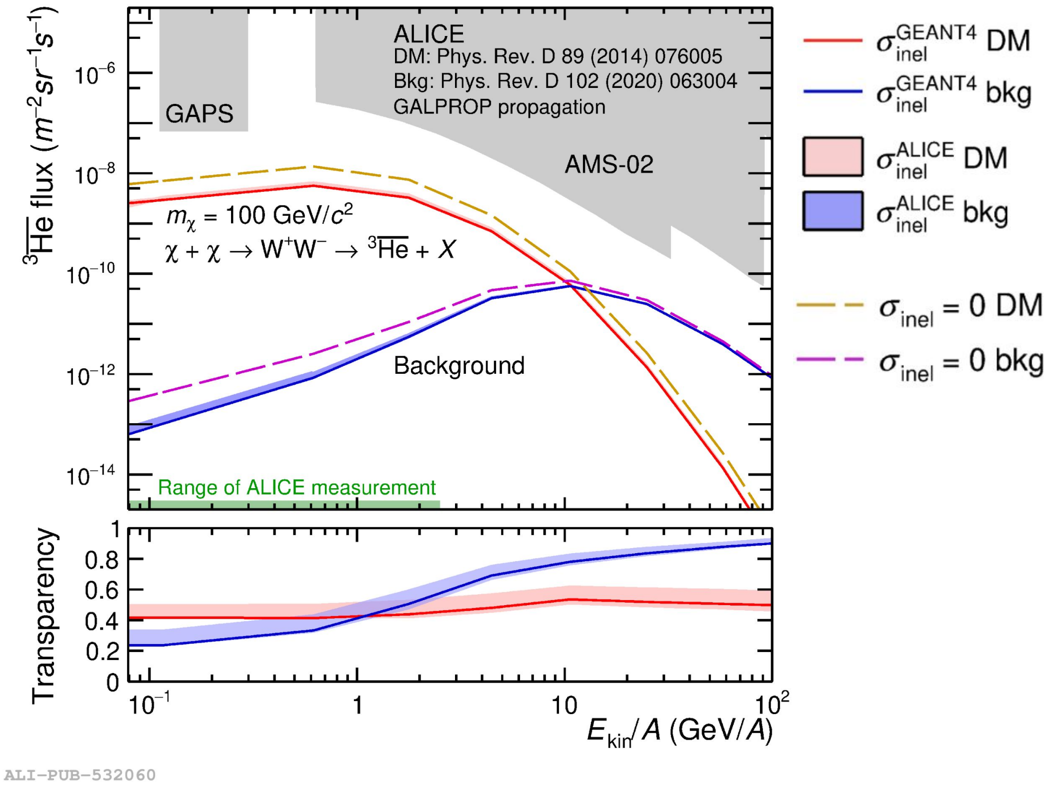


ALI-PUB-532044

Nature Phys. (2023) 19, 61–71

Antinuclei annihilation: anti-^{3}He

- GALPROP used to propagate antinuclei in the interstellar medium
- **Our Galaxy is rather constantly transparent to ^{3}He passage**
- Uncertainties on Transparency only due to absorption measurements (10-20%) computed for the first time
  - Subleading contribution wrt cosmic ray and DM modelling



Transparency = (flux with annihilation)/(flux without annihilation)

Nature Phys. (2023) 19, 61–71

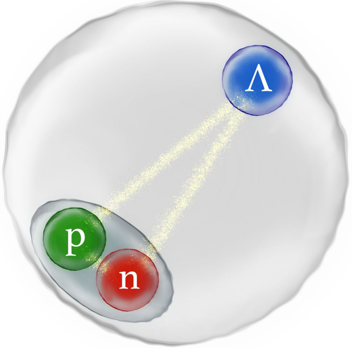
Summary and outlook

- Significant contributions provided by ALICE in different fields relevant for astrophysics
  - Neutron stars
  - CR and DM fluxes
- Effort ongoing in Run 3 to improve precision and provide tighter constraints
  - A<5 hypernuclei
  - Σ-hypernuclei
  - Production and annihilation cross-sections down to low momenta

Backup

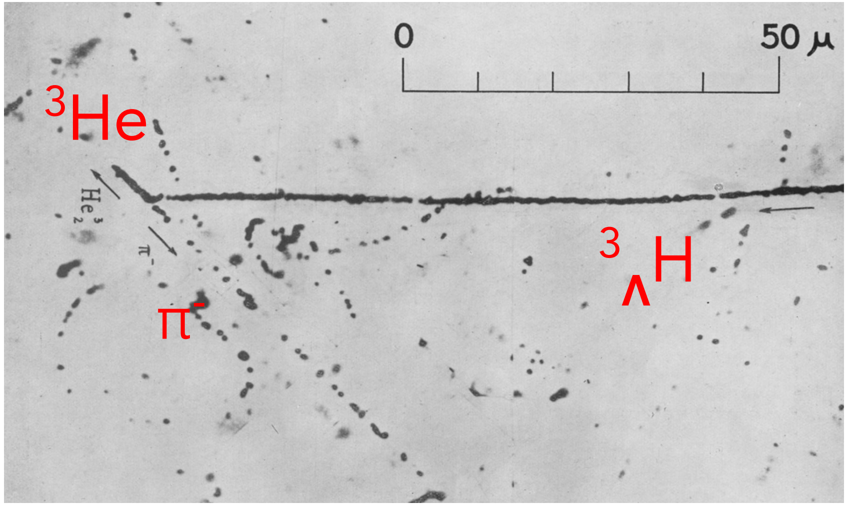
The simplest (?) hypernucleus: $^{3}_{\Lambda}H$

- Lightest known hypernucleus
  - Bound state of a neutron, a proton and a Λ
  - Discovered in early 50s by M.Danysz and J.Pniewski
    - Balloon-flown experiments [1, 2]



Mass: ~ 2.991 GeV/c^2
Spin: 1/2
Lifetime: ~ 250 ps

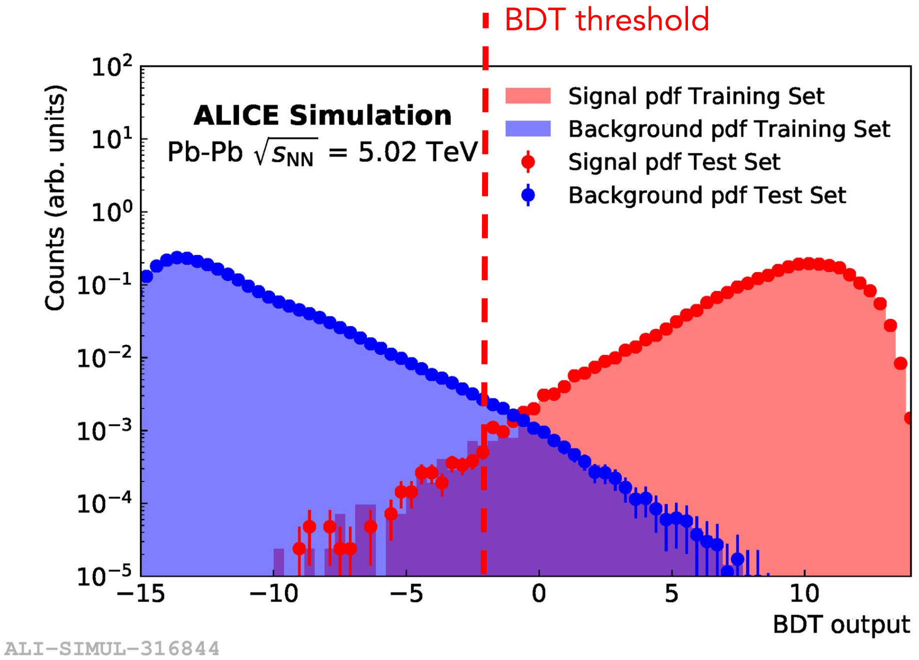
Mesonic charged decay channels:
$^{3}He + \pi$ (B.R. ≅ 0.25)
$d + p + \pi$ (B.R. ≅ 0.40)

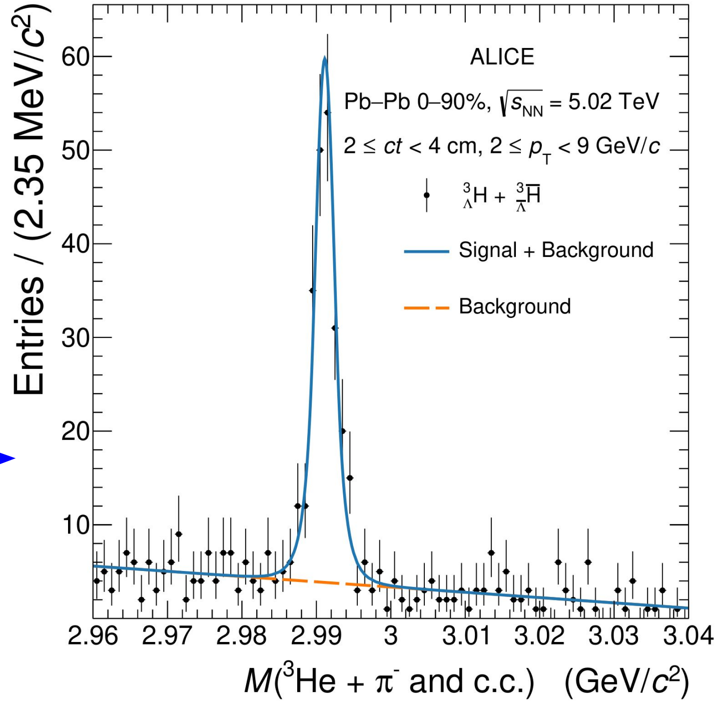


[1] M. Danysz et al., Philos. Mag. 44, (1953)
[2] Bonetti et al., Il Nuovo Cimento 11.2, (1954)

${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ selection

- ${}^{3}_{\Lambda}H$ candidates selected with Boosted Decision Trees
- Signal extracted analysing the invariant mass spectrum

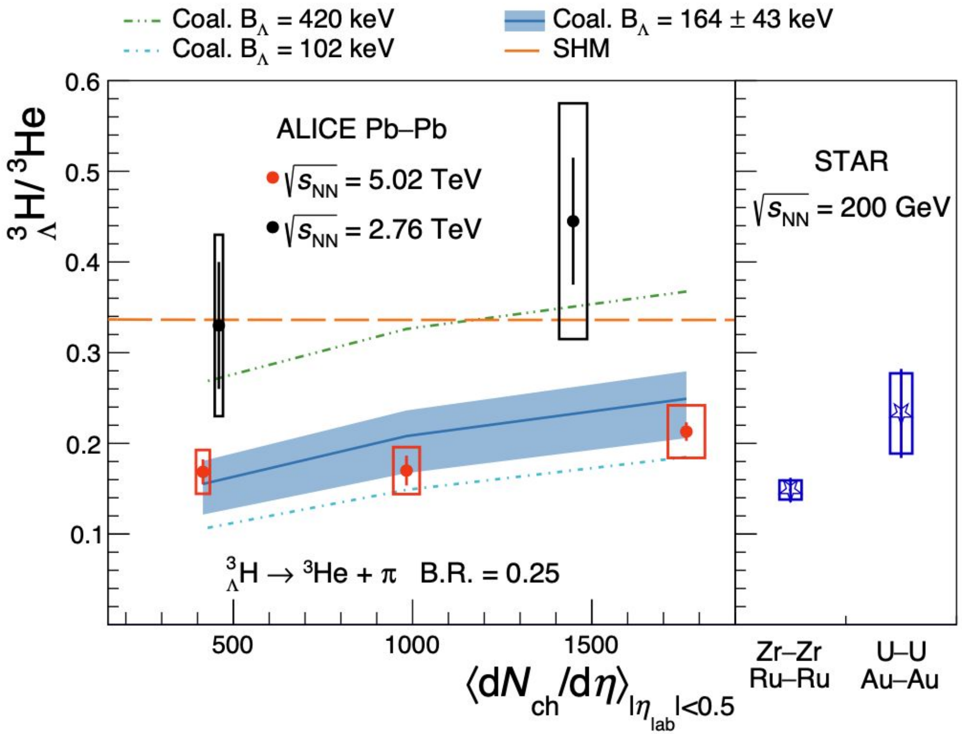




[Phys. Rev. Lett. 131, 102302 (2023)]

$^{3}_{\Lambda}H$ in Pb–Pb at 5.02 TeV

- Less model separation than small systems, but much more precise measurements vs multiplicity
  - ➢ Coalescence afterburner (MUSIC+UrQMD+COAL) w/ measured B_{Λ} describes the data

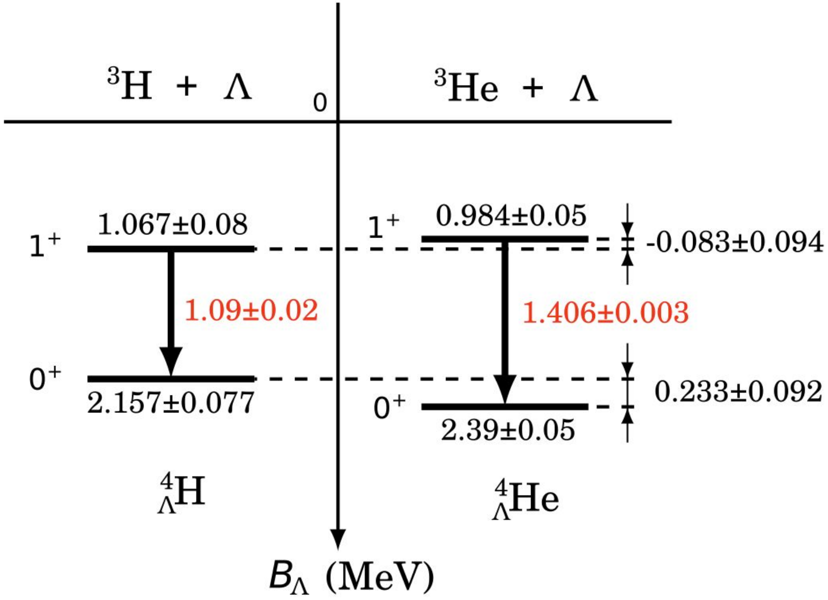


Coalescence model: Dai-Neng Liu et al., Phys.Lett.B 855 (2024) 138855 https://arxiv.org/abs/2404.02701

ALICE paper: https://arxiv.org/abs/2405.19839

$^4_\Lambda$H and $^4_\Lambda$He in Pb–Pb collisions

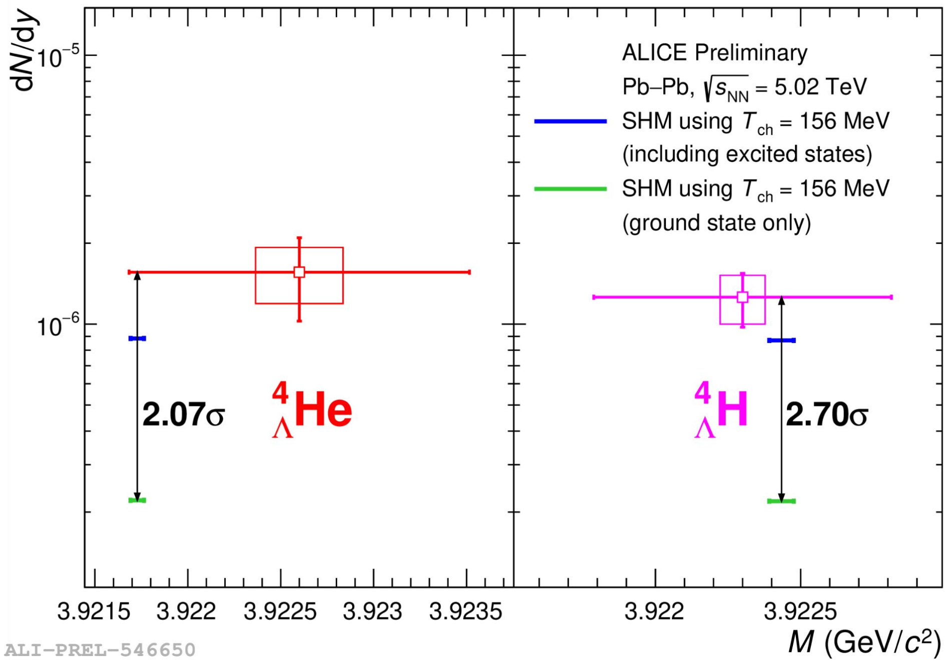
- $^4_\Lambda$H and $^4_\Lambda$He are expected to be compact states
  - ➢ SHM should give a good estimation of the yield
- And the SHM correctly describes the yield only when including the higher spin states



M. Schäfer et al., Phys.Rev.C 106, L031001 (2022)

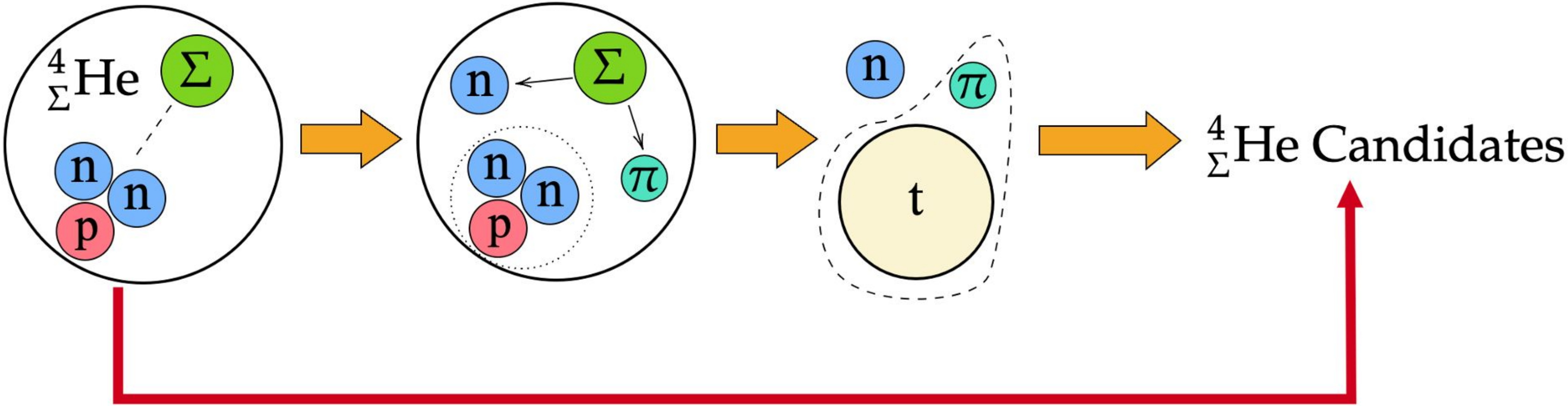
$^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He in Pb–Pb collisions

- Significant deviation from SHM with ground state only
  - ➢ Nuclear properties inferred again starting from the production mechanism
  - ➢ Missing coalescence calculations, limited precision



Outlook: Σ-hypernuclei

- Lattice QCD calculation shows that ΣN is similar to ΛN in $^1S_0$ but has a stronger repulsive core in $^3S_1$[1]
- Only non-Λ hypernucleus found so far[2,3]. Neutral decay, how do we measure it in ALICE?



[1] T. Inoue et al. Nucl. Phys. A881, 28 (2012)
[2] H. Outa et al., Prog. Theor. Phys. Supp. 117 (1994), 177-199
[3] Nagae, T et al., Phys. Rev. Lett. 80 (1998), 1605

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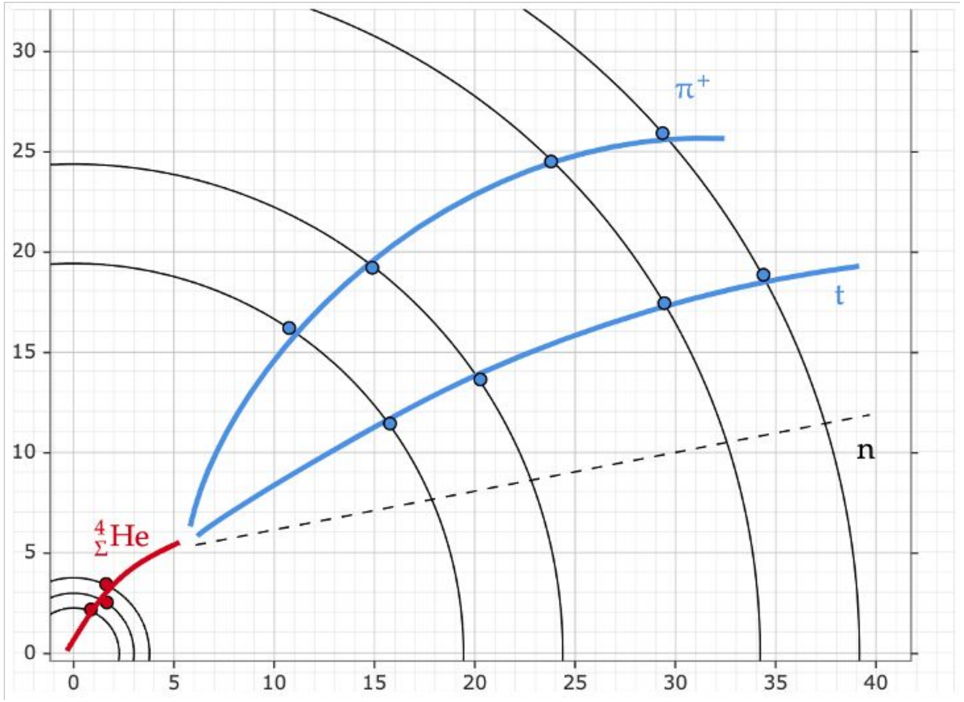
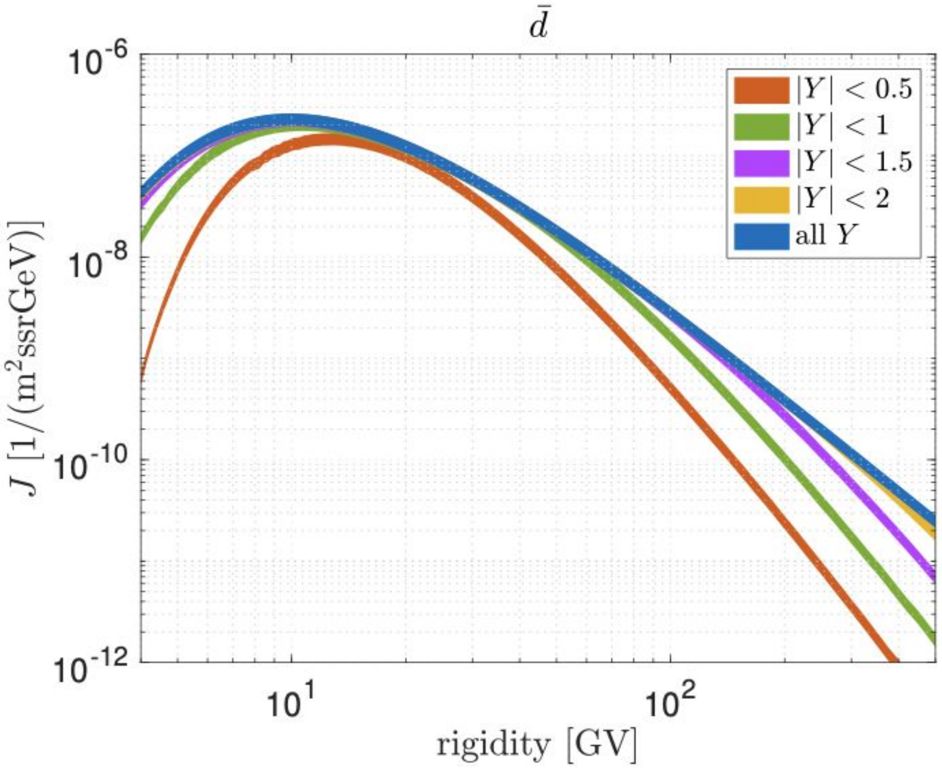
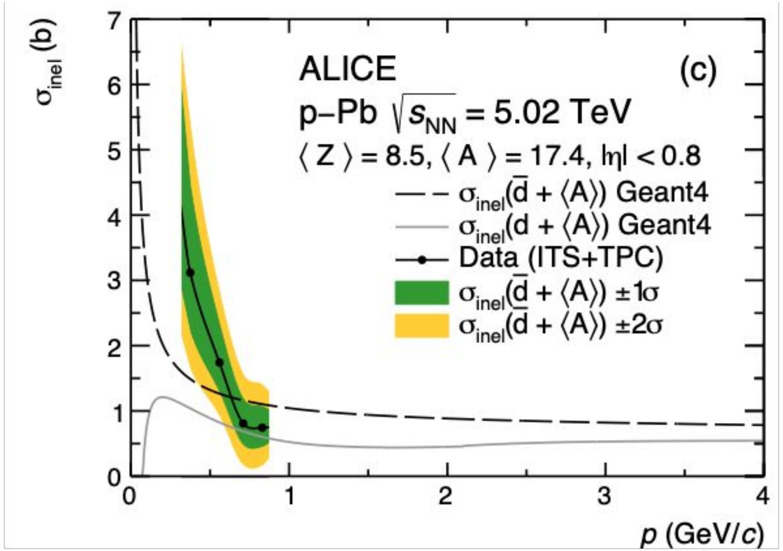


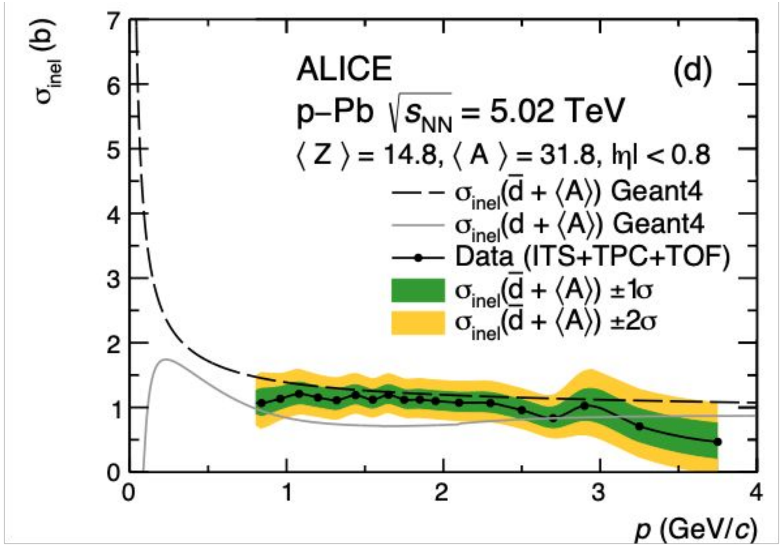
Antideuterons from interstellar medium



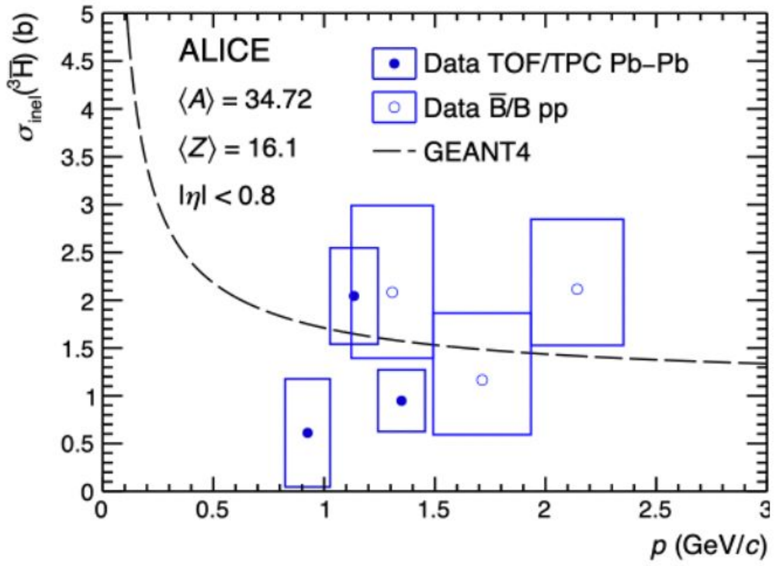
[1] 📚 K. Blum, arxiv:2306.13165

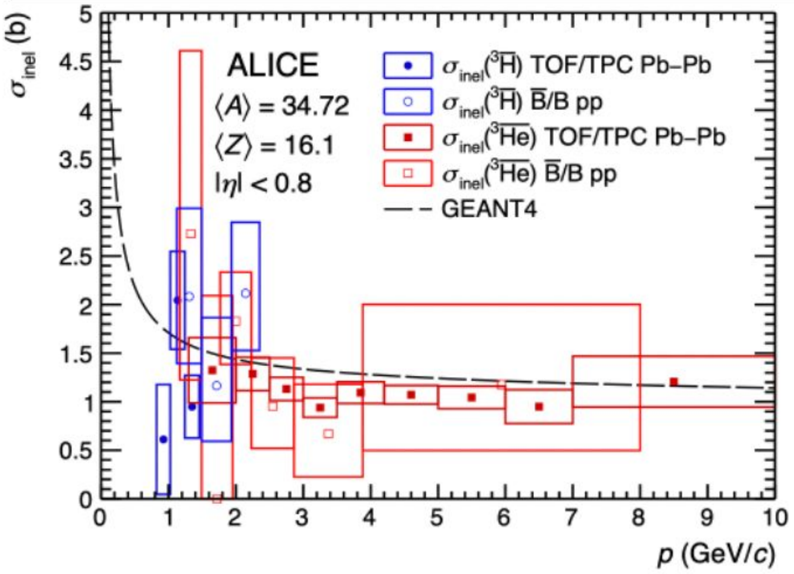
Antideuteron absorption





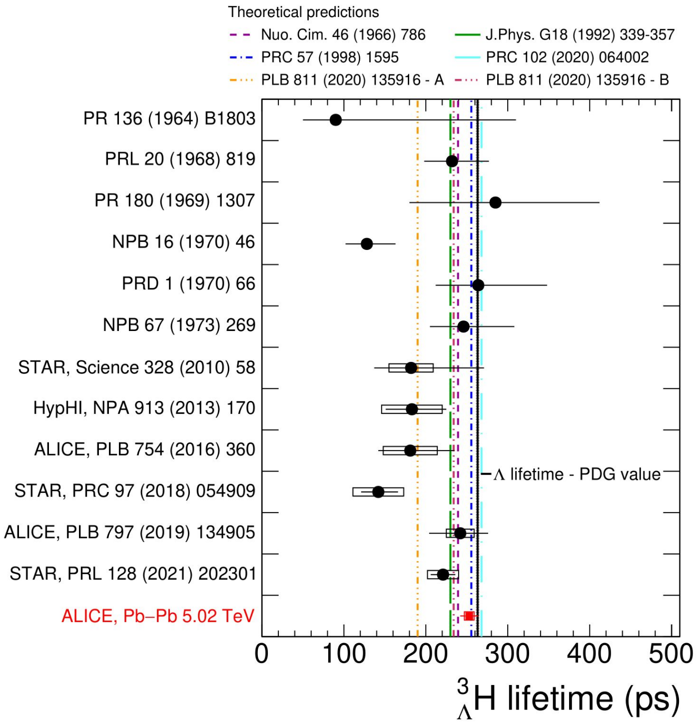
Antitriton absorption

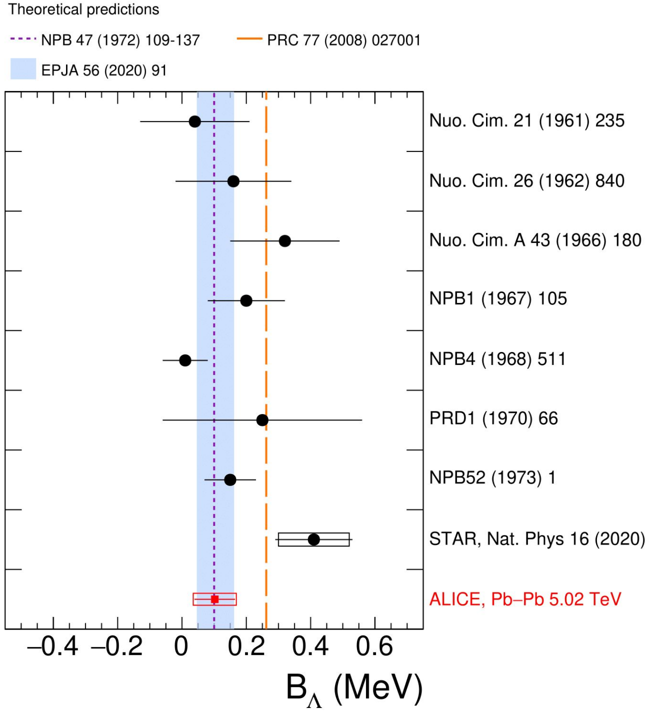




Final results

- Most precise measurements to date of τ and B_Λ of the ${}^{3}_{\Lambda}H$
  - Weakly-bound nature of the ${}^{3}_{\Lambda}H$ finally confirmed
  - ${}^{3}_{\Lambda}H$ could be approximated as a shallow d-Λ state with a wide d-Λ radius of ~ 10 fm





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