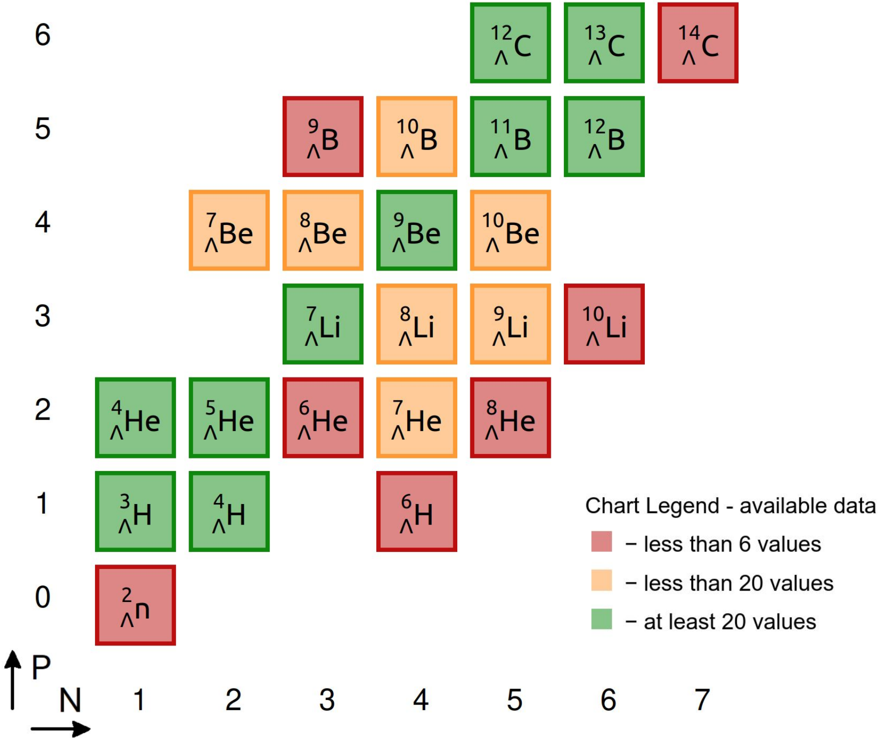
Probing the structure of light hypernuclei at the LHC

Francesco Mazzaschi

SPICE Workshop, 14/05/24

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



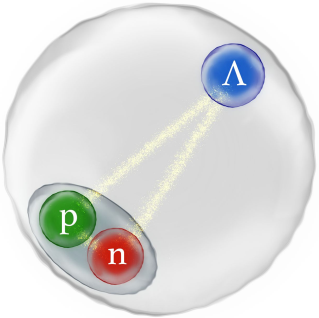
Hypernuclear database

Hypertriton structure: B_Λ

- Λ - separation energy $B_\Lambda = m(d) + m(\Lambda) - m(^3_\Lambda H)$
  - Reflects the extension of the $^3_\Lambda H$ wave function
- Emulsion experiments[1] : $^3_\Lambda H$ is a loosely bound nucleus
  - $B_\Lambda = 130 \pm 50$ keV

From the observation of 82 examples of $^3_\Lambda H$, the binding energy of this hypernucleus is found to be 0.15 ± 0.08 MeV. An accurate determination of the binding energy of the $^3_\Lambda H$ hypernucleus is of great importance to estimate the strength of the ΛN interaction in the singlet state. Combining the result obtained in this experiment with the data compiled by Bohm et al. [2], reanalysed using the methods and selection criteria defined in the present work, the best estimate for the binding energy of $^3_\Lambda H$ is found to be $B_\Lambda = 0.13 \pm 0.05$ MeV.

Hypernucleus	Decay mode	No of events	$B_\Lambda \pm \Delta B_\Lambda$ (MeV)
$^3_\Lambda H$	$\pi^- + {}^1H + {}^2H$	24	0.23 ± 0.11
	$\pi^- + {}^3He$	58	0.06 ± 0.11
	total	82	0.15 ± 0.08



Recent pionless Effective Field Theory (EFT) calculations [2] show large separation (~11 fm) between the Λ and the "deuteron core" for B_Λ = 130 keV

[1] M.Juric et al., Nucl. Phys. B, 52, 1-30, (1973)

[2] F. Hildenbrand et al., Phys. Rev. , 100 (2019)

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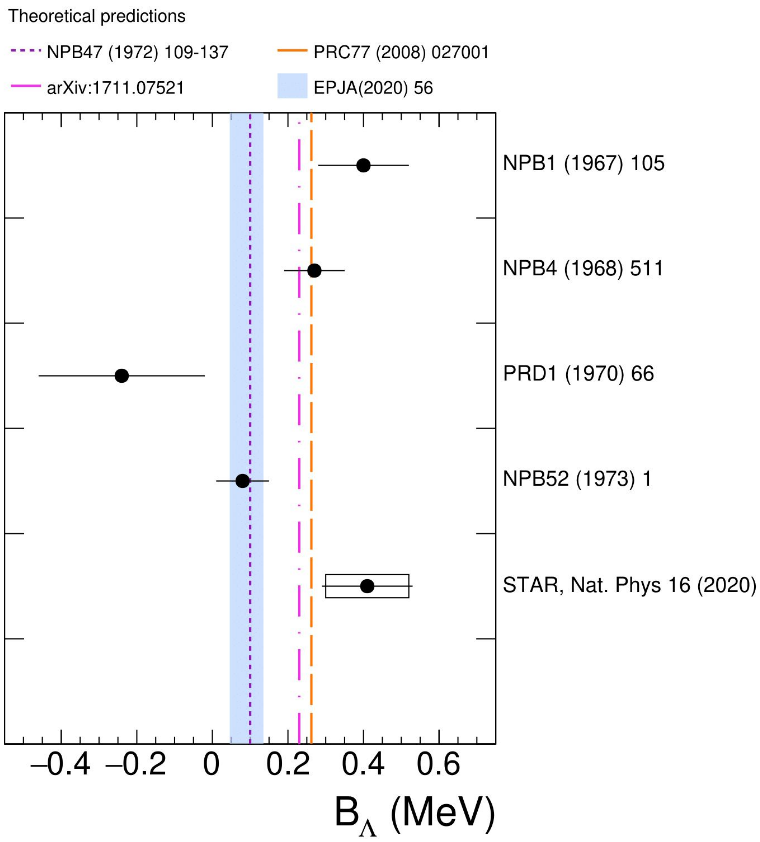
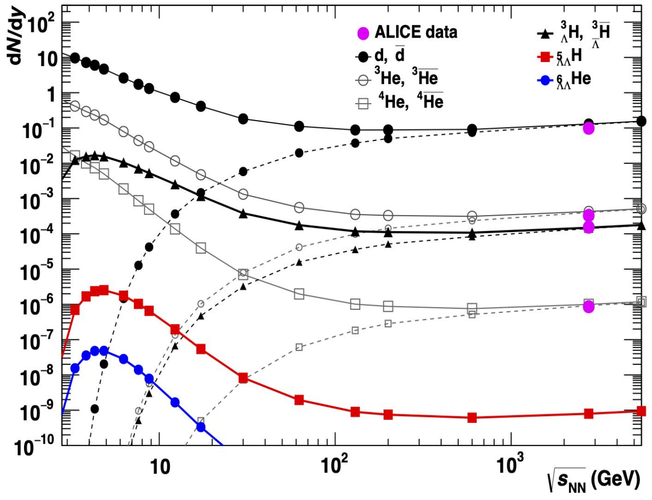
- Lifetime:
  - ➢ A low B_Λ should imply a lifetime close to the free Λ hyperon one (262 ps)
  - ➢ more measurements, but all with uncertainties larger than 10%



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

(Hyper)Nucleosynthesis at collider: how?

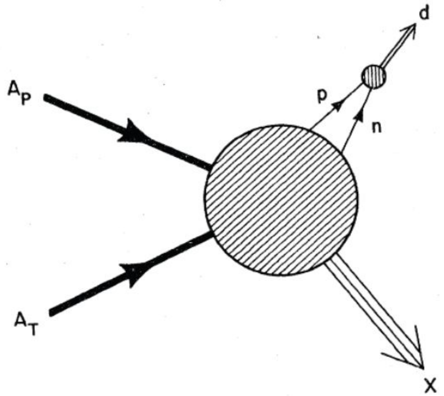
📕 B. Dönigus et al.,Nucl.Phys.A 987 (2019)



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
  - $\propto Exp(-m/T_{eq})$



Coalescence

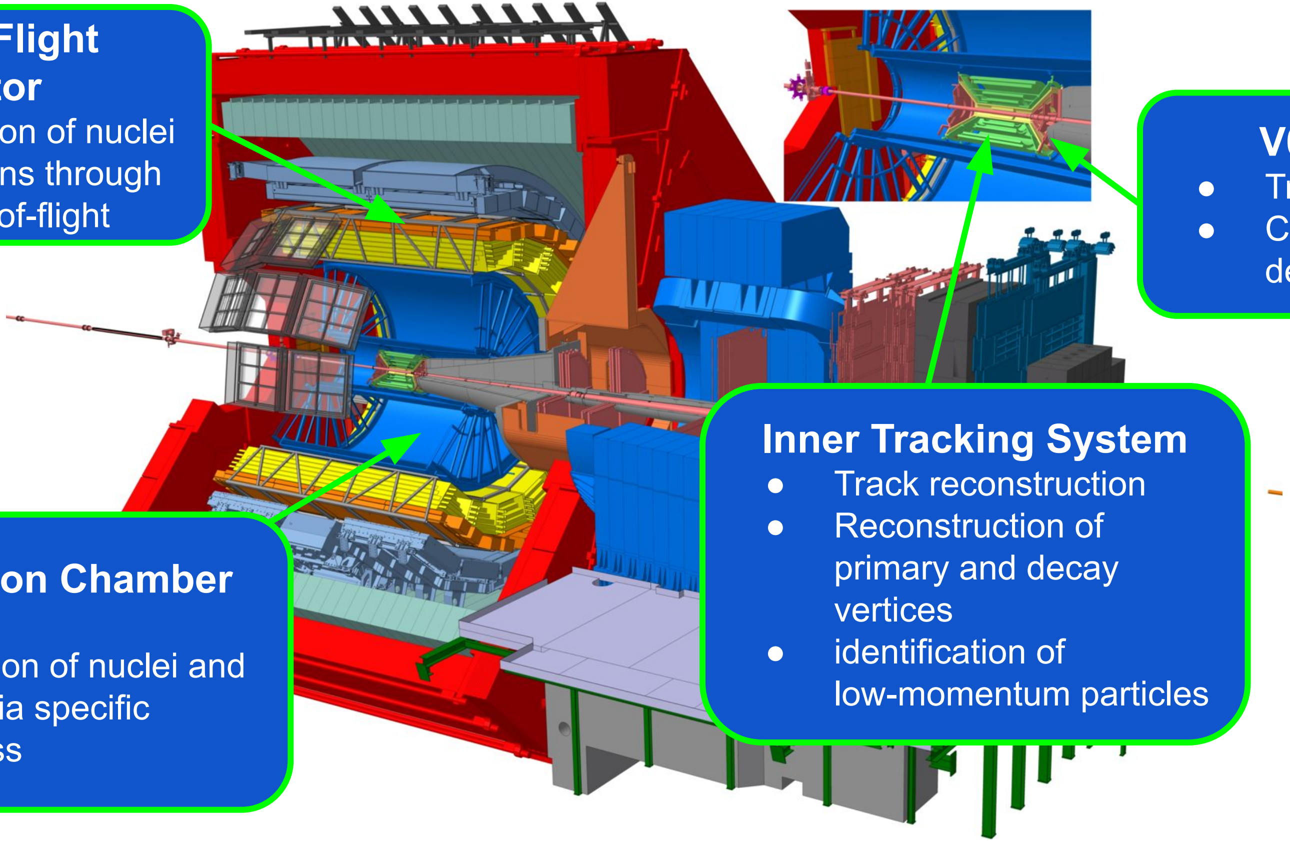
Baryons close in phase space can form a nucleus

- Interplay between the configuration of the phase space of the nucleons and the wave function of the nucleus

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

$^{3}_{\Lambda}H$ measurements at the LHC

The ALICE Run 2 detector



Time-Of-Flight detector
- Identification of nuclei and hadrons through their time-of-flight

V0 detectors
- Trigger
- Centrality/multiplicity determination

Inner Tracking System
- Track reconstruction
- Reconstruction of primary and decay vertices
- identification of low-momentum particles

Time Projection Chamber
- Tracking
- Identification of nuclei and hadrons via specific energy loss

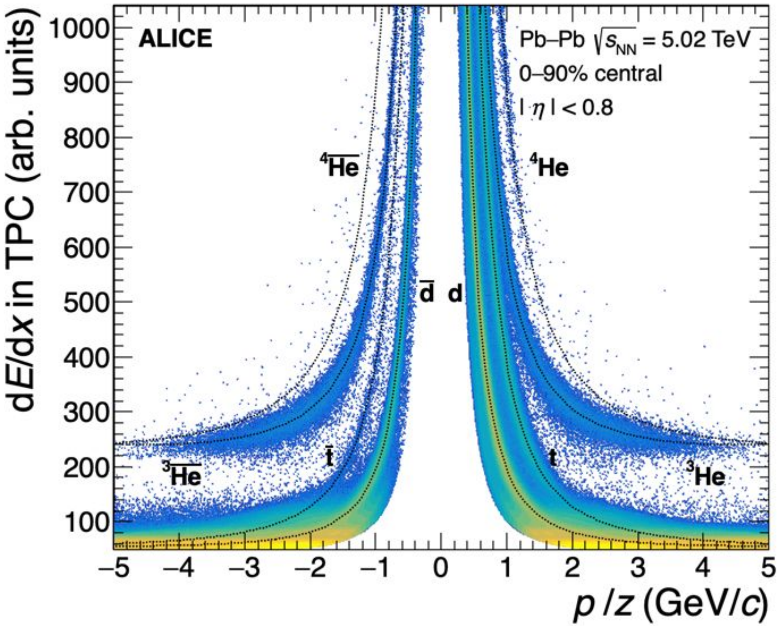
LHC Run 3: ITS and TPC upgrades

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

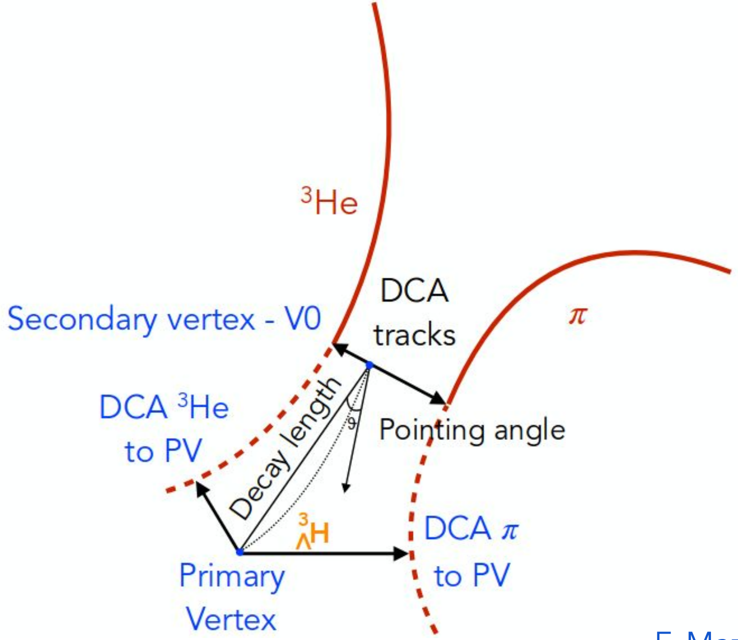
- Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE during 2018

^{3}He and π^{-} identified through their specific energy loss in the TPC

Secondary vertex reconstruction: loose pre-selections applied to the decay topology



Phys. Rev. C 107 (2023) 064904



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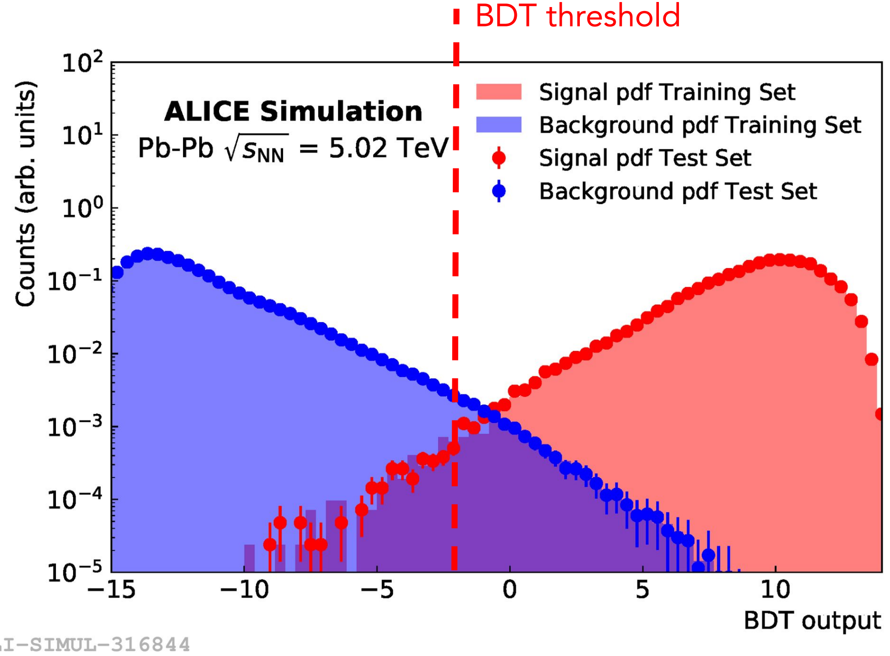
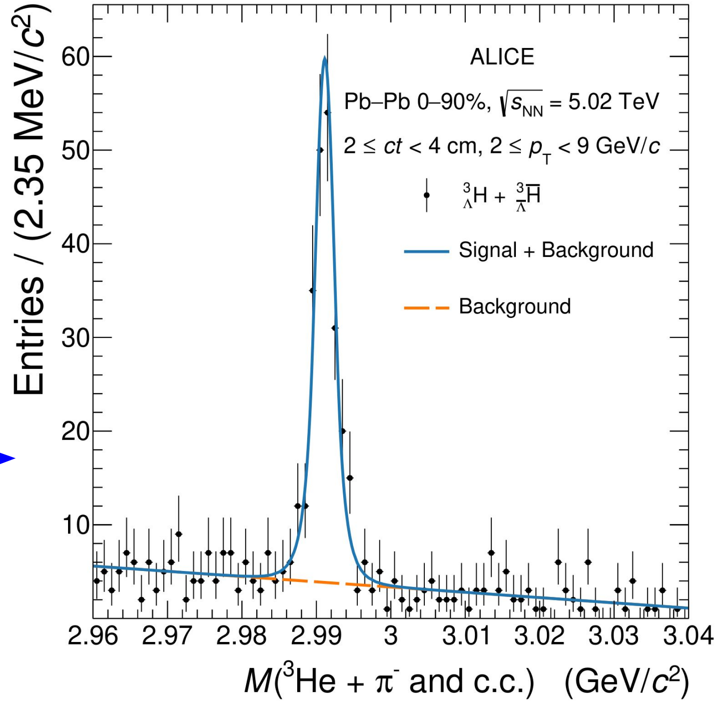
$^{3}_{\Lambda}$H selection with machine learning

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



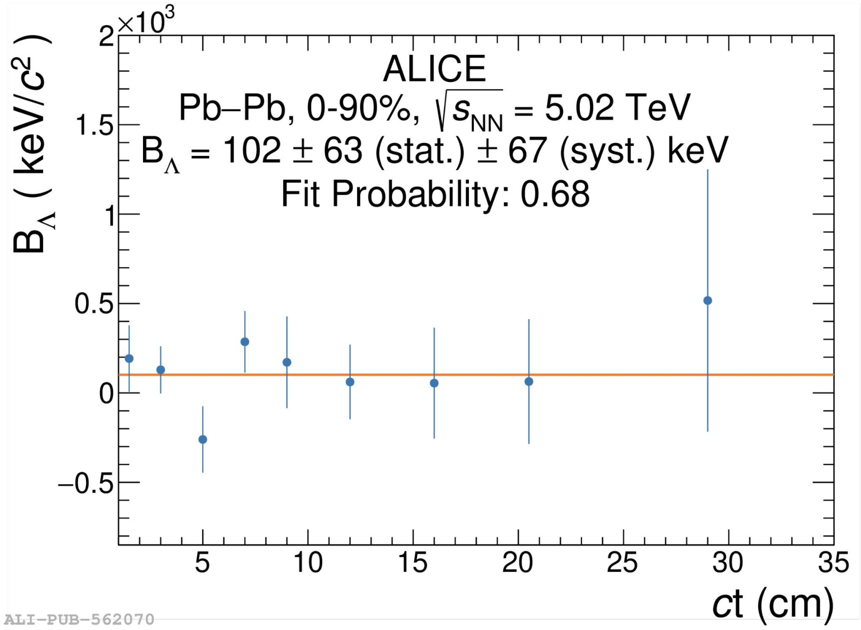


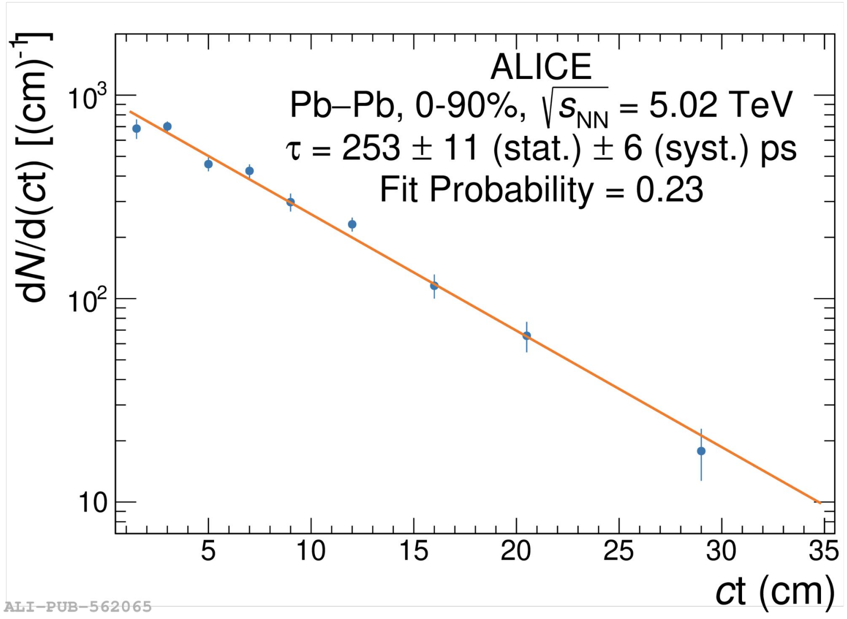
Phys. Rev. Lett. 131, 102302 (2023)

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)

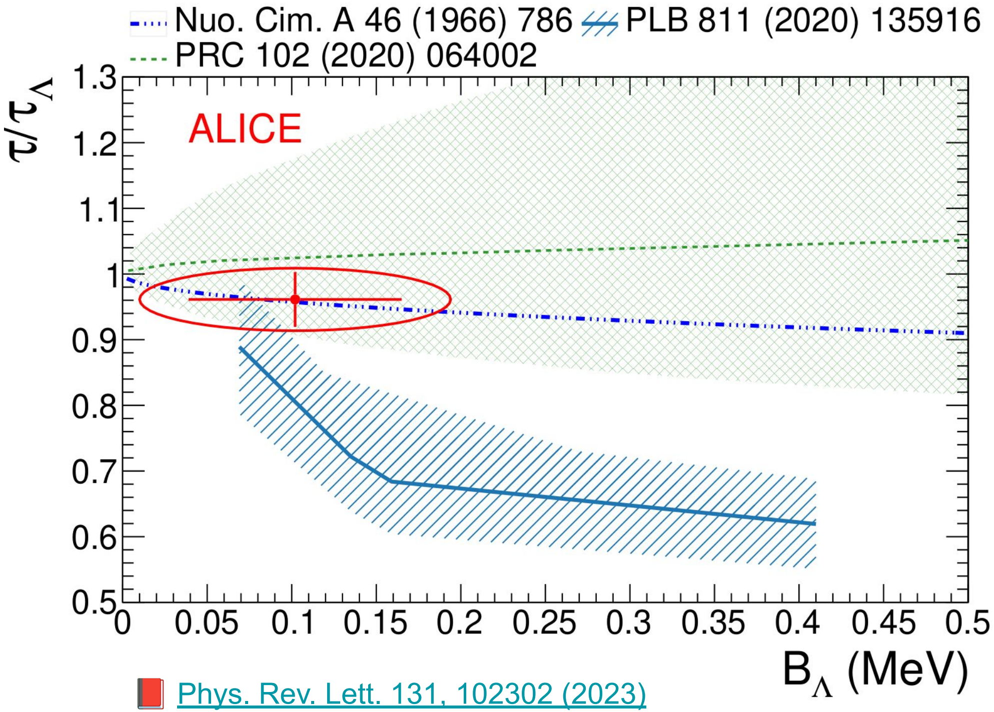




Most precise measurements to date of τ and B_{Λ} of the $^{3}_{\Lambda}H$

Final results

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



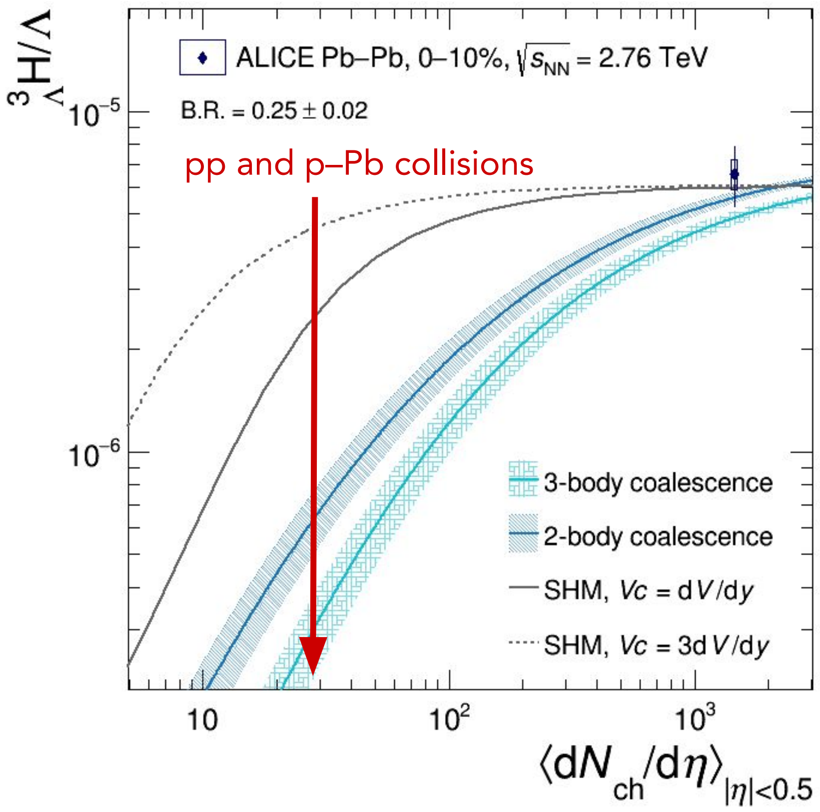
📕 [Phys. Rev. Lett. 131, 102302 (2023)]

- 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 at the LHC

- Weakly bound state
  - ➢ $^{3}_{\Lambda}H / \Lambda \rightarrow$ large separation between SHM [1] and coalescence [2] predictions at low charged-particle multiplicity density → coalescence is sensitive to the interplay between the size of the collision system and the spatial extension of the nucleus wave function

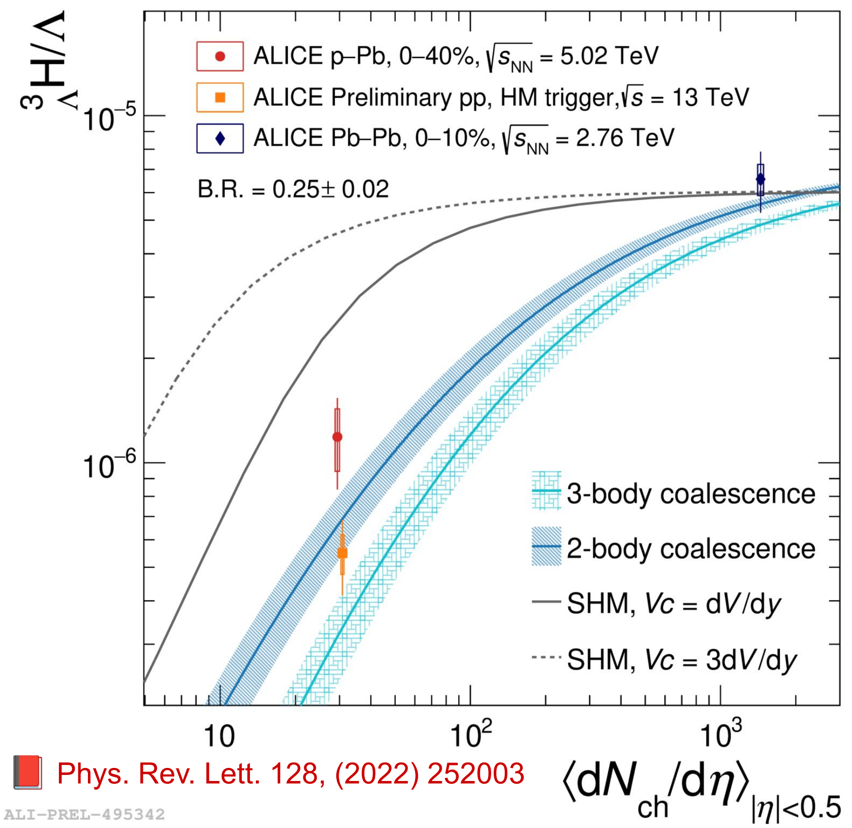
- $^{3}_{\Lambda}H$ production in pp and p–Pb collisons: a key to understand the nuclear production mechanism at the LHC



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)

Production yields

- First measurement of ${}^{3}_{\Lambda}$H/Λ in pp and p–Pb collisions
  - ➢ good agreement with 2-body coalescence
  - ➢ tension with SHM at low charged-particle multiplicity density
    - V_C = 3 dV/dy excluded: deviation > 6σ
    - First significant constraint to SHM possible configurations
- Coalescence quantitatively describes the ${}^{3}_{\Lambda}$H suppression in small systems
  - ➢ the nuclear size matters at low charged-particle multiplicity (and we will measure it!)



Phys. Rev. Lett. 128, (2022) 252003

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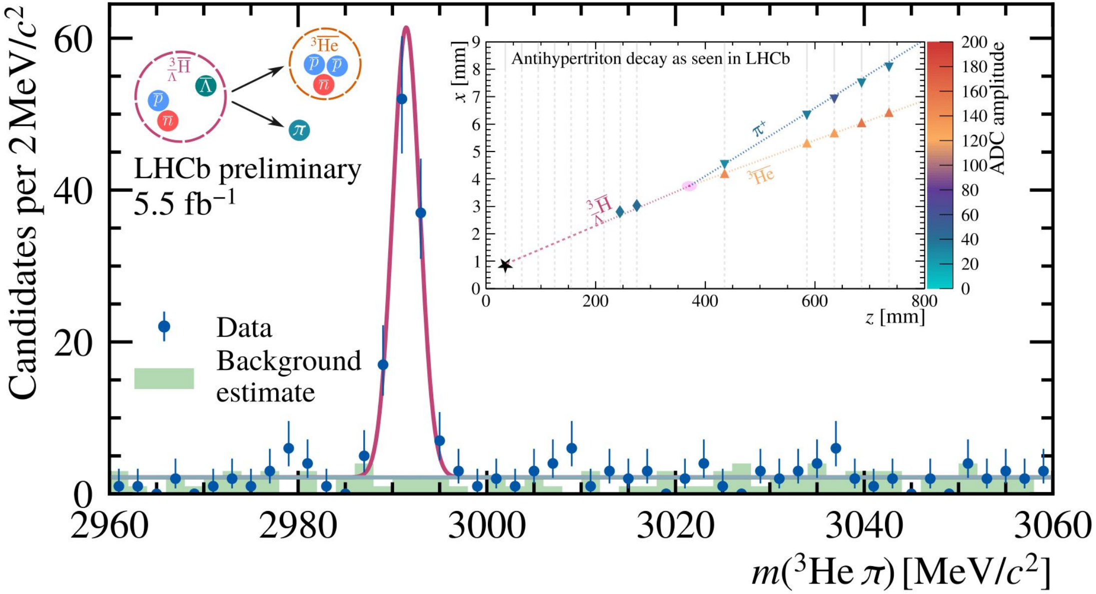
First hypertritons seen by LHCb!

- LHCb observed the (anti-)hypertriton on Run 2 pp data: link
  - ~ 100 anti-$^{3}_{\Lambda}$H analysing 5.5 fb^{-1}
  - Innovative method for tagging ^{3}He nuclei
  - Allows for complementary measurements with ALICE in the forward region



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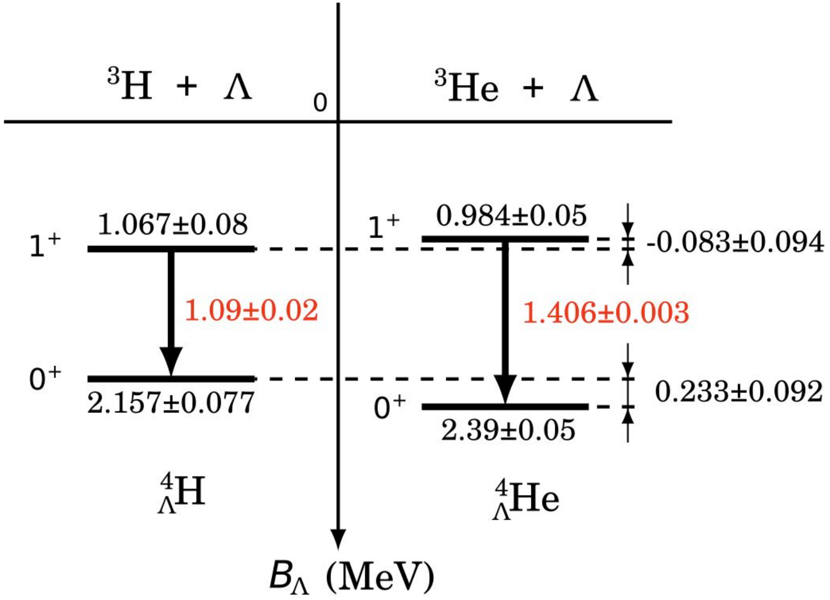
A=4 Hypernuclei at the LHC

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

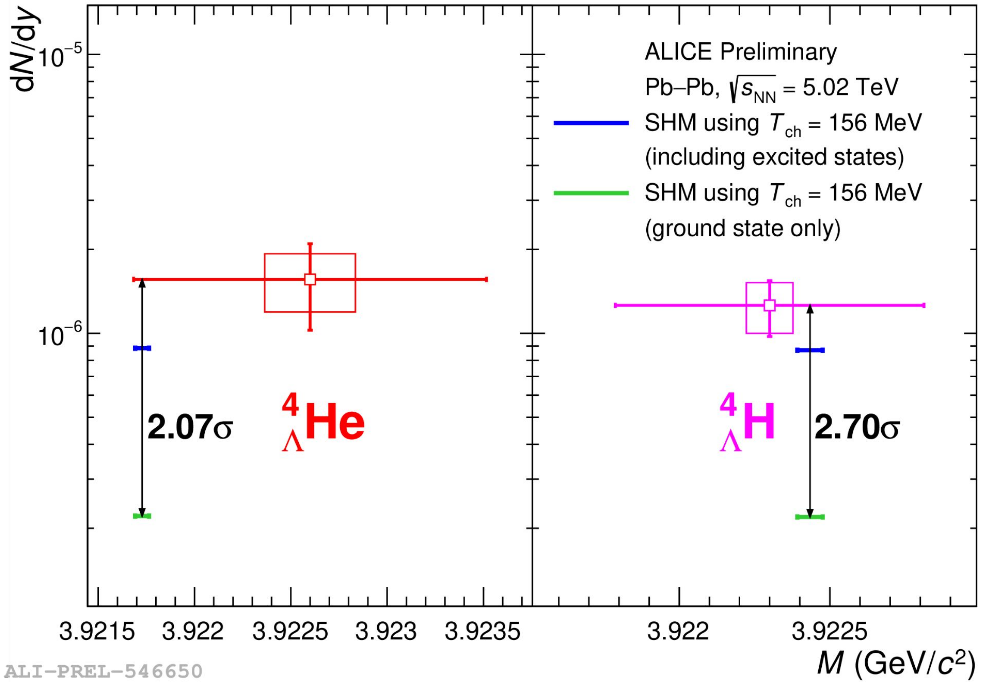
- $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He are expected to be compact states
  - ➢ SHM should give a good estimation of the yield
- And the SHM correctly describes the yield only when including the higher spin states



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

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

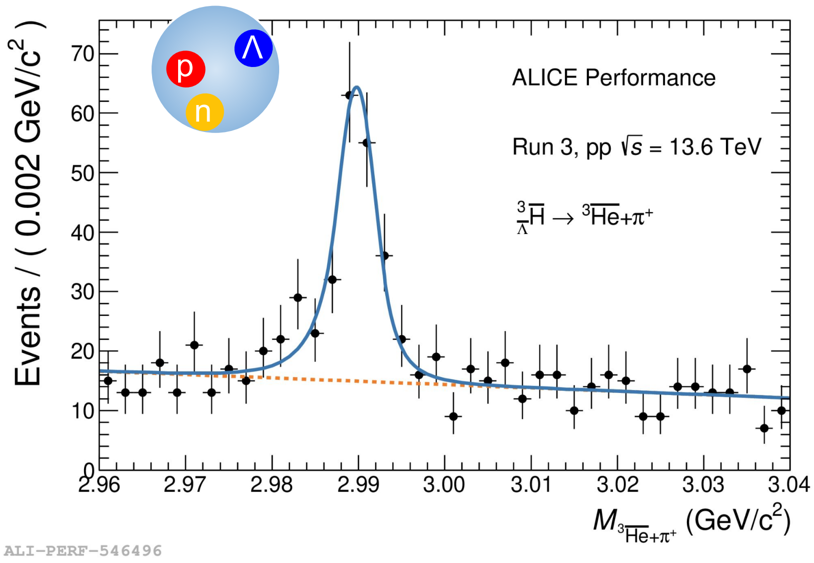
- Significant deviation from SHM with ground state only
  - ➢ Nuclear properties inferred again from the production mechanism

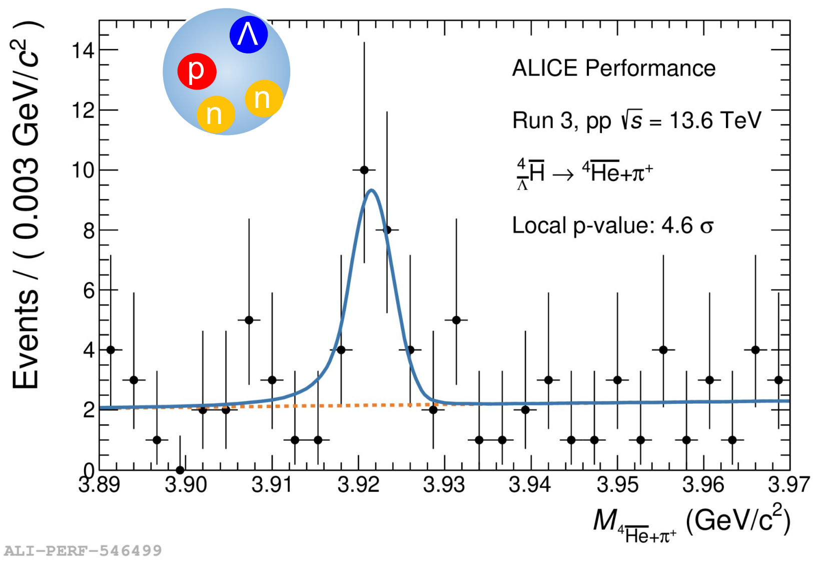


Hypernuclei in the Run 3 era

ALICE in Run 3: going to A > 3

- LHC Run 3: continuous readout + ITS and TPC upgrades
  - ➢ O(10^3) and O(10^2) larger with respect to minimum bias pp and Pb–Pb samples
  - ➢ Dedicated trigger on ^{3}He and ^{4}He
  - ➢ Precision measurements of $^3_\Lambda$H in small colliding systems
- Extend ALICE hypernuclear program to A > 3 hypernuclei in all collision systems



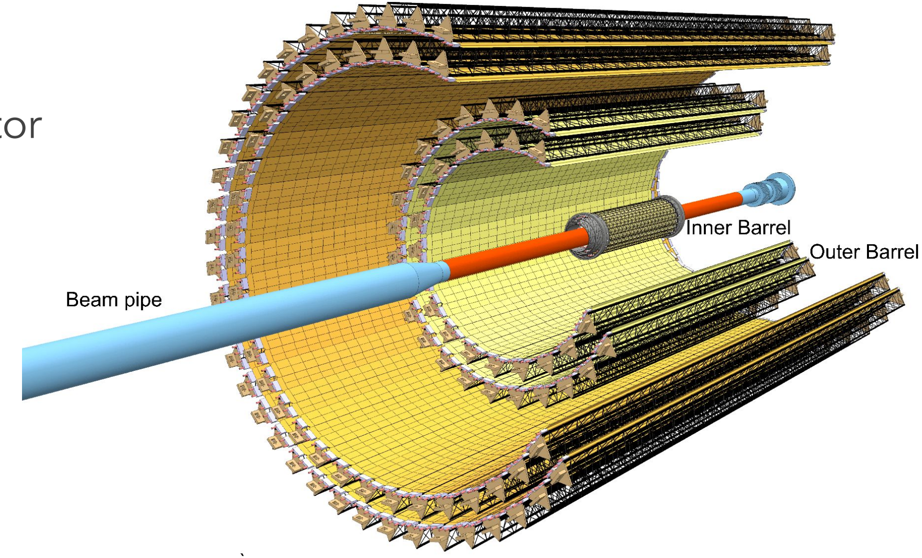


The upgraded Inner Tracking System

- ITS2: 7 layers based on Monolithic Active Pixel Sensors (MAPS)

- 24120 chips, 12.5 Gpixel
  - Largest MAPS-based detector in High-Energy Physics

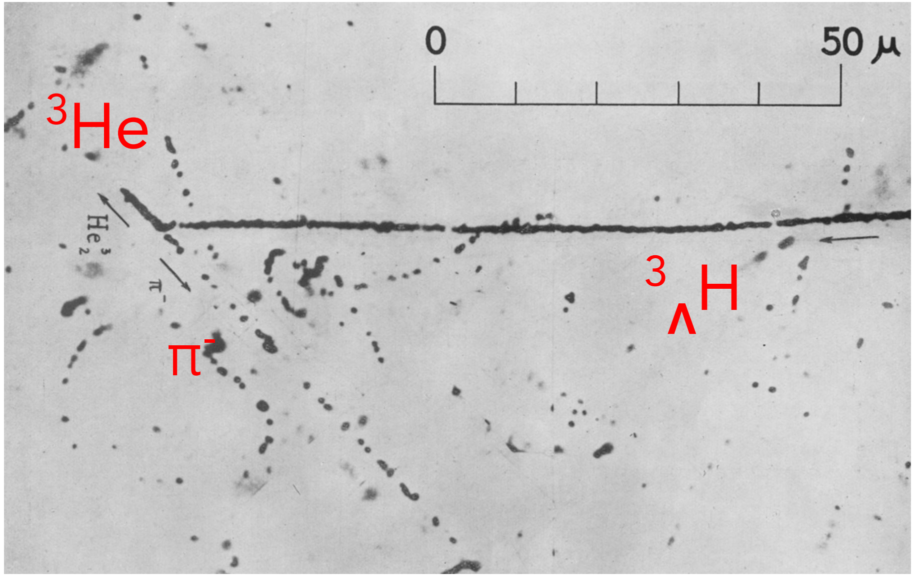
- 3 Inner Barrel layers (IB)
  - radii from 2.2 to 3.8 cm
- 4 Outer Barrel layers (OB)
  - radii from 19 to 39 cm



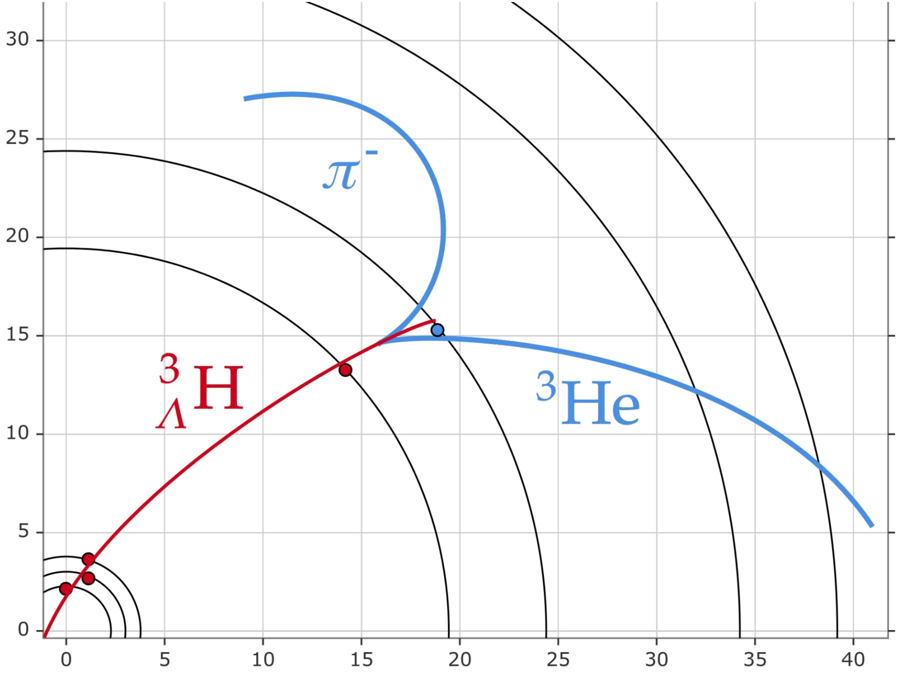
Reduced material budget and higher spatial resolution: $(r\varphi, z)$ = 5x5 μm^2

Back to the origin

- Hypernuclei are directly tracked with the ITS2 !
  - Possibility to reconstruct the full decay chain → silicon MHz bubble chamber



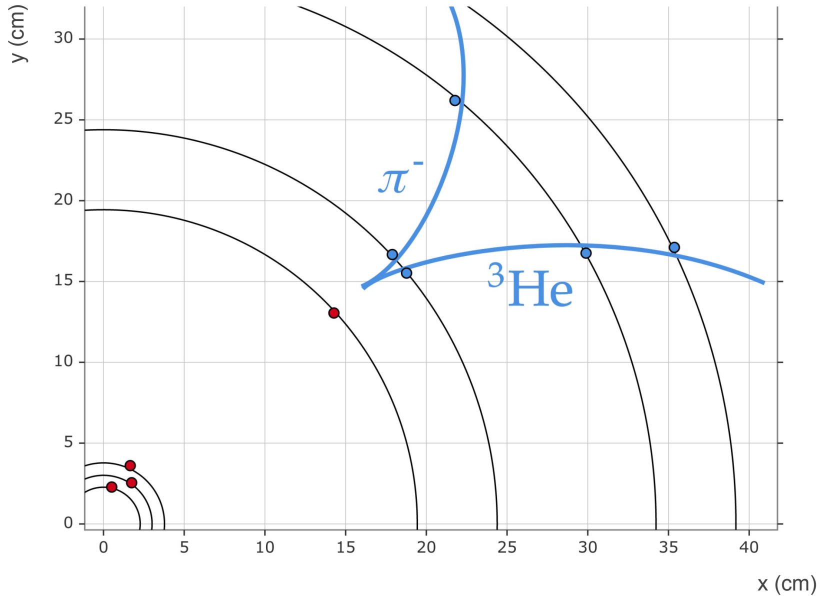
Bonetti et al., Il Nuovo Cimento 11.2, (1954)

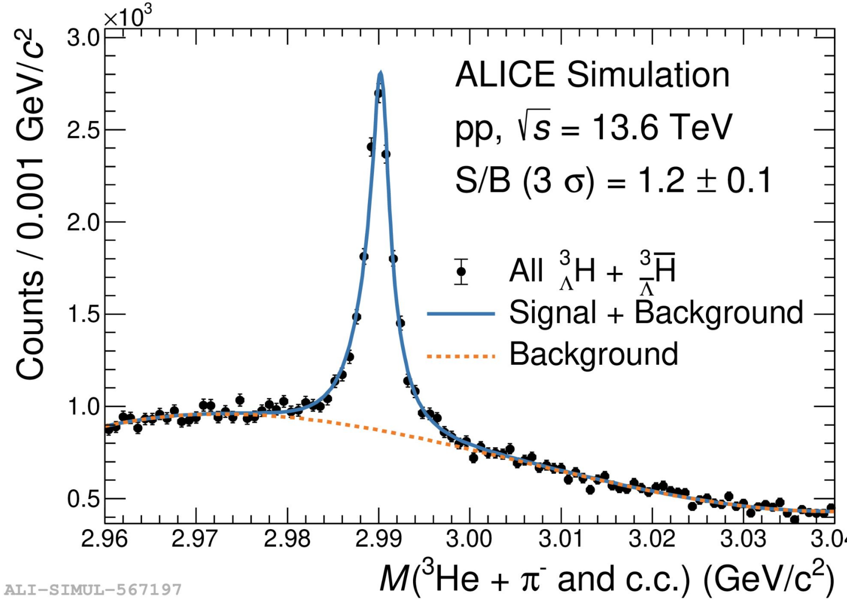


The strangeness tracking algorithm

1. Matches the ${}^{3}_{\Lambda}H$ ITS track with the decay daughter tracks
2. Final kinematic fit of the decay topology (WIP)

Before strangeness tracking





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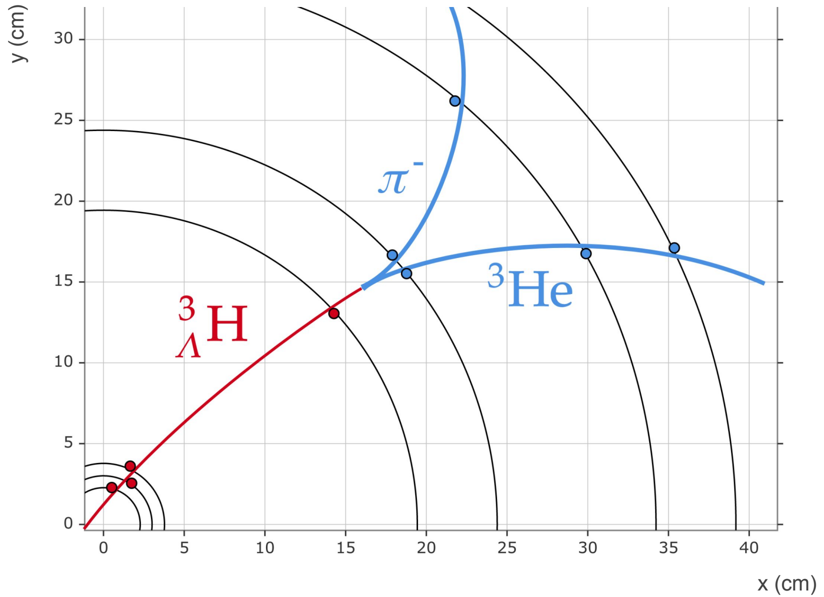
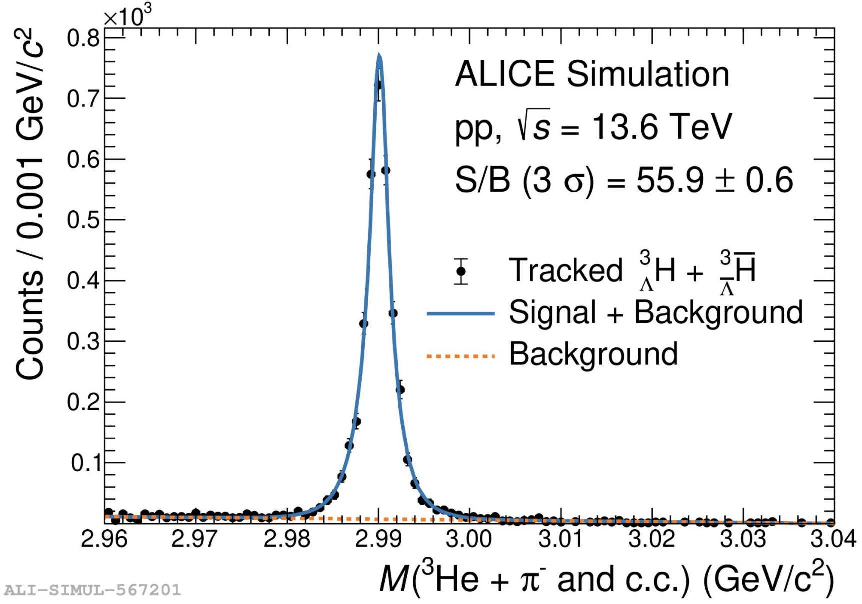




Outstanding background suppression!

Conclusions

Conclusions

- ${}^{3}_{\Lambda}H$ in large systems:
  - Precise measurements of lifetime and B_{Λ} in Pb–Pb collisions
    - Weakly bound nature of ${}^{3}_{\Lambda}H$ confirmed

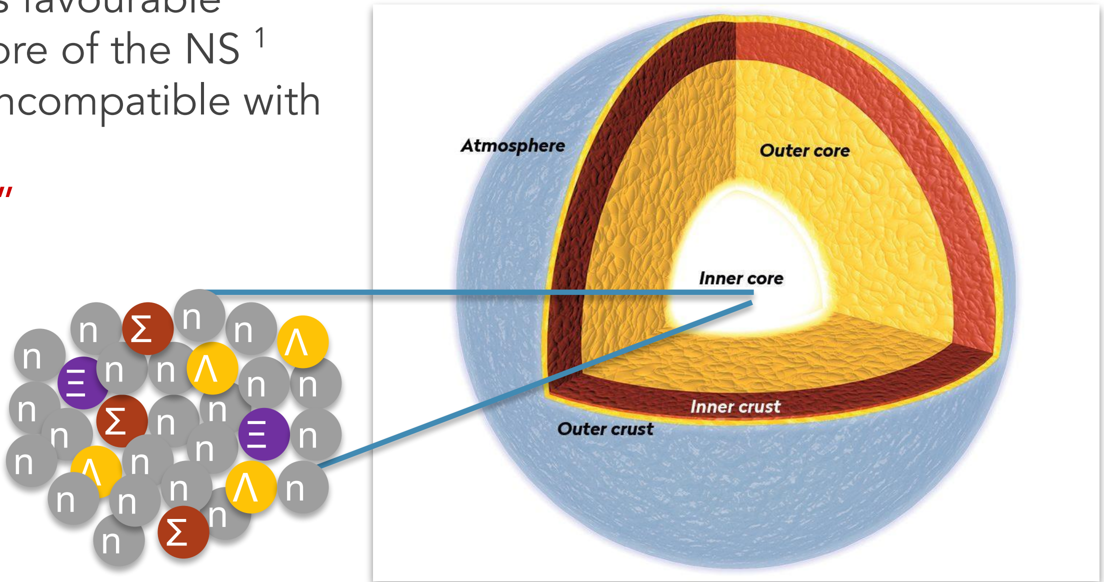
- First measurement of the ${}^{3}_{\Lambda}H$ production in p–Pb collisions:
  - ${}^{3}_{\Lambda}H$ / Λ favours coalescence expectation
  - Nuclear size matters at low-charged particle multiplicity

- Run 3:
  - Large sample + strangeness tracking → new era for light-hypernuclei with $A < 5$

Backup

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"

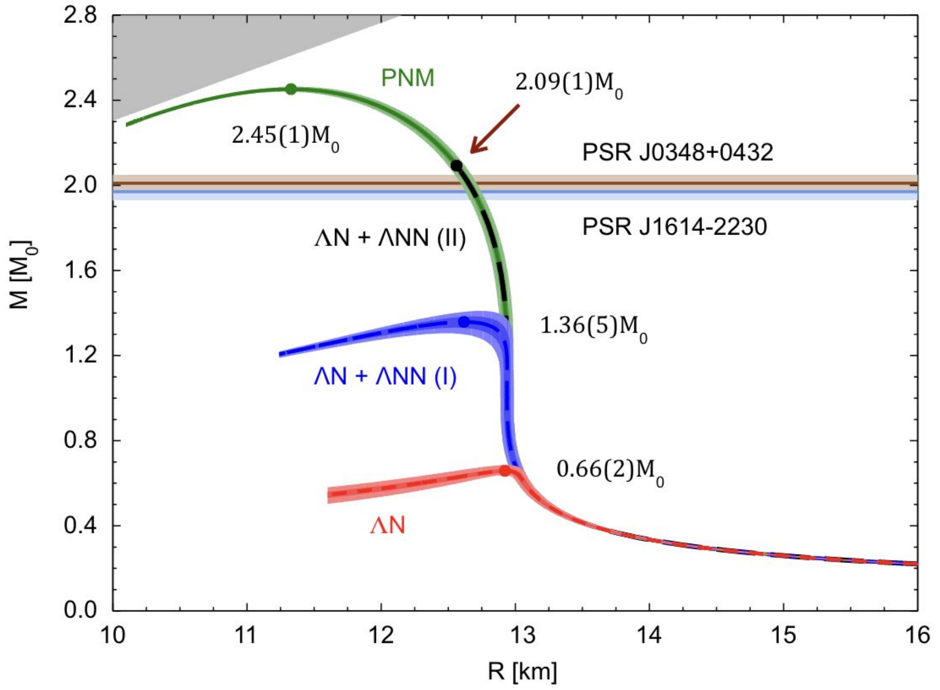


[1] D. Logoteta et al., Eur.Phys.J.A 55 (2019) [2] D. Lonardoni et al., Phys. Rev. Lett. 114 (2019)

Probing the core of the neutron stars

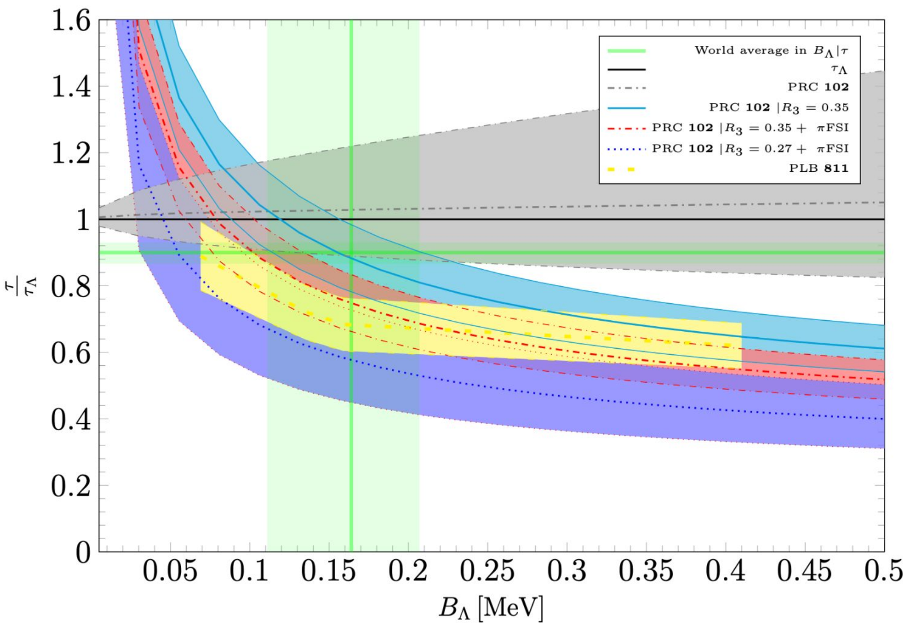
- Neutron stars (NSs) equation of state (EoS)
  - Introduction of Λ-N-N repulsion might solve the hyperon puzzle
  - Models need additional experimental constraints!

- $^{3}_{\Lambda}H$: most direct probe on earth to study the Λ-N and Λ-N-N forces
  - Binding energy of the $^{3}_{\Lambda}H$ employed to model the ΛN interaction potential



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

The R3 dependency

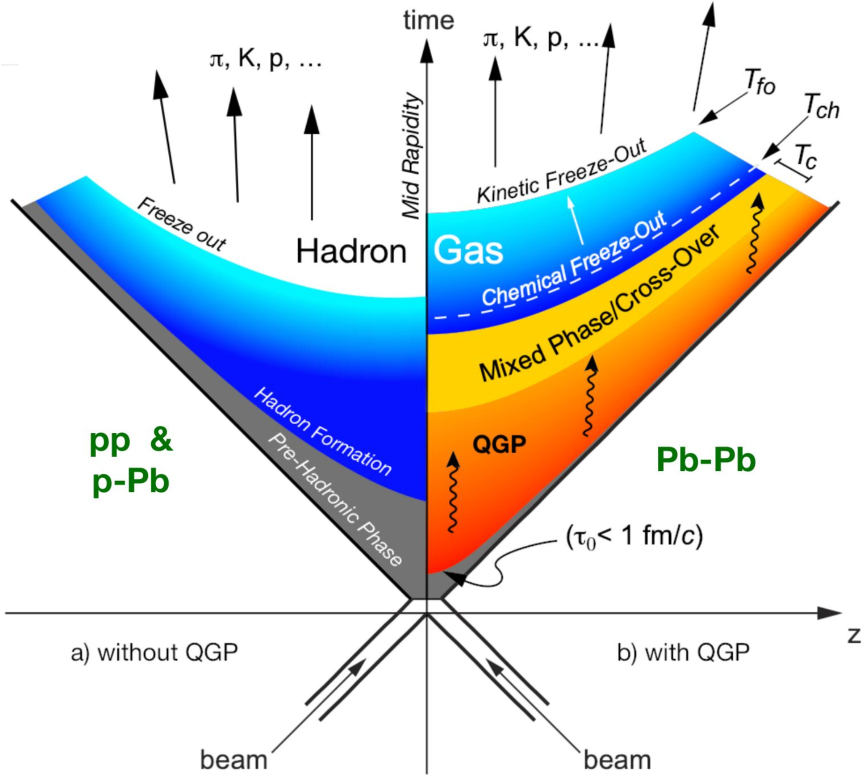


arXiv:2309.12822

Figure 3. Lifetime of the hypertriton τ relative to the free Λ lifetime τ_Λ. The grey band represents the result obtained in Ref. [16]. In addition, we show the results using a fixed branching ratio R_3 to calculate the total width with and without pionic final state interactions, similar to the approach in Ref. [15], which is given in yellow for reference. The green areas give the world average for the hypertriton lifetime as well as the Λ separation energy according to Ref. [10]. In order to keep the plot readable we show EFT uncertainty bands only for the results of Ref. [16].

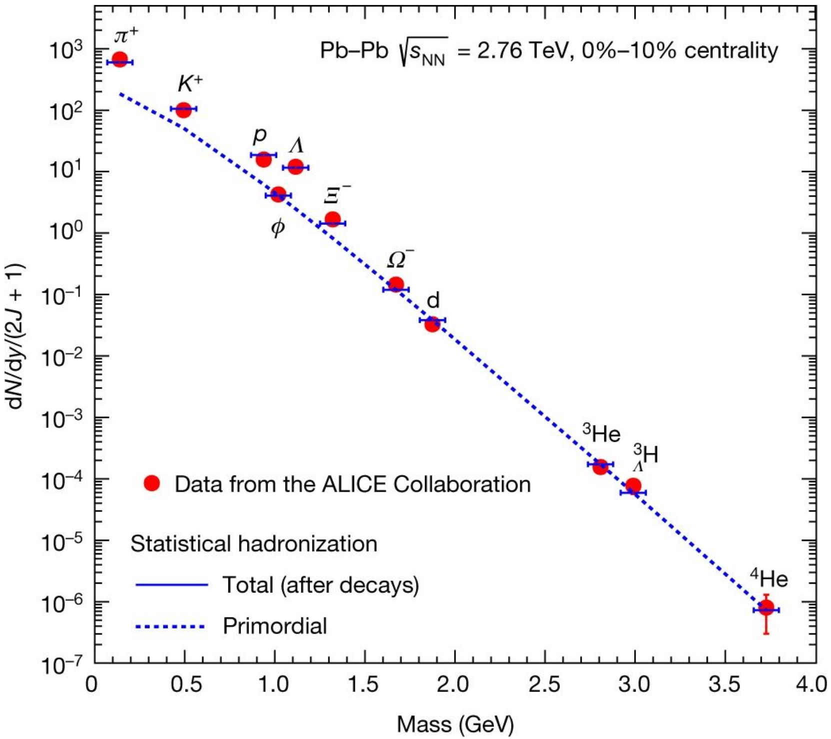
(Hyper)nuclei at the LHC

- (Hyper)nuclei at the LHC observed in all the collision systems
  - pp, p–Pb, Pb–Pb
  - Pb–Pb: complex dynamics and Quark Gluon Plasma (QGP) formation
- Nuclei and hypernuclei produced in the latest stages of the collision evolution
  - Chemical and kinetic freeze outs
- $B_{\Lambda} \cong 100$ keV , $T_{ch} \cong 100$ MeV
  - which is the formation mechanism of these objects at the LHC energies ?



The Statistical Hadronisation Model (SHM)

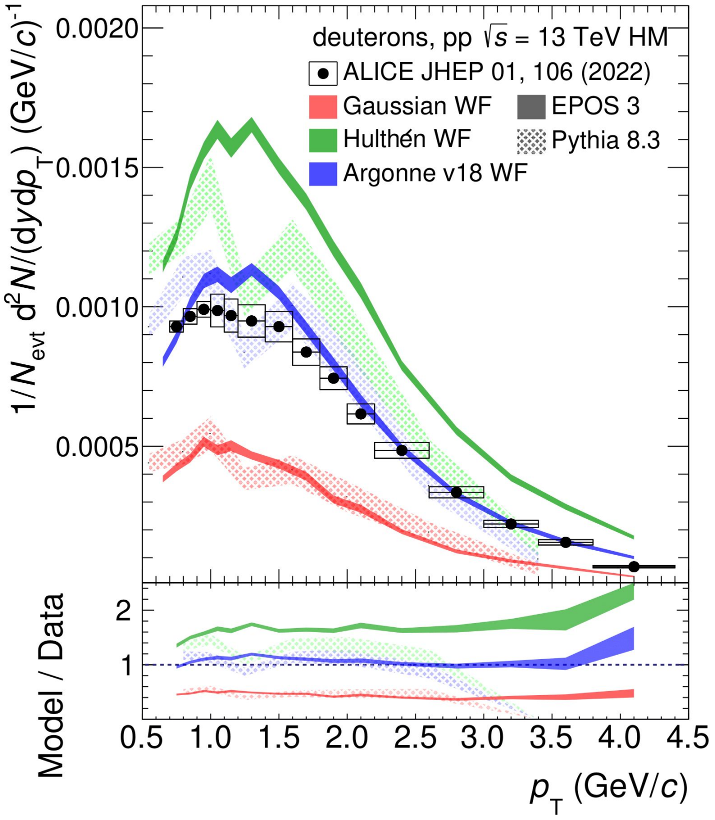
- Hadrons emitted from the interaction region in statistical equilibrium when the system reaches the chemical freeze-out temperature
- Abundance of a species
  - $\propto \mathrm{Exp}(-m/T_{chem})$
- Mainly used for Pb–Pb, it can be used in smaller systems (pp and p–Pb) by using the canonical ensemble



[1] A. Andronic et al., Nature 561, (2018) 3210
[2] *Vovchenko et al.*, Phys. Lett. B 785, (2018) 171

Coalescence Models

- Original idea:
  - Nucleons close in phase space at the freeze-out can form a nucleus via coalescence
- Today: Wigner function formalism[1, 2]
  - Overlap between nucleus wave-function and nucleon phase-space distribution
  - Dynamic description, but yield predictions only relative to the nucleon ones

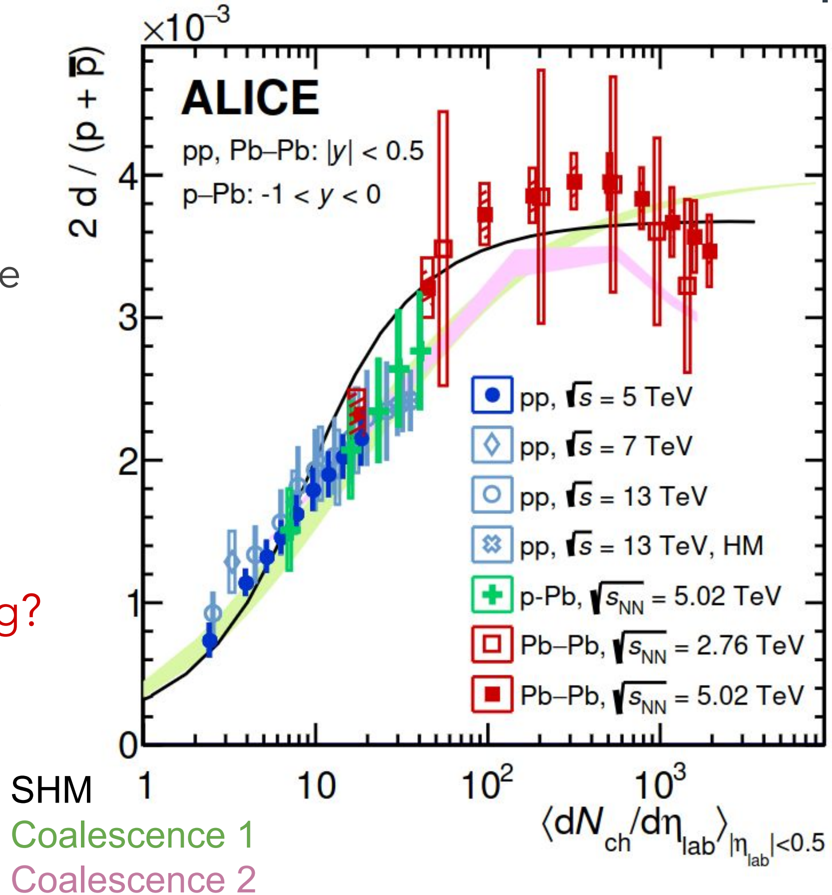


[1] Sun et al., Phys. Lett. B 792, (2019) 132
[2] Horst et al. , arXiv:2302.12696

Coalescence vs SHM

- Production vs charged particle multiplicity
  - Dependence on the system size
- d/p ratio successfully described by both SHM and Coalescence from pp to Pb–Pb collisions

How can we improve our understanding?

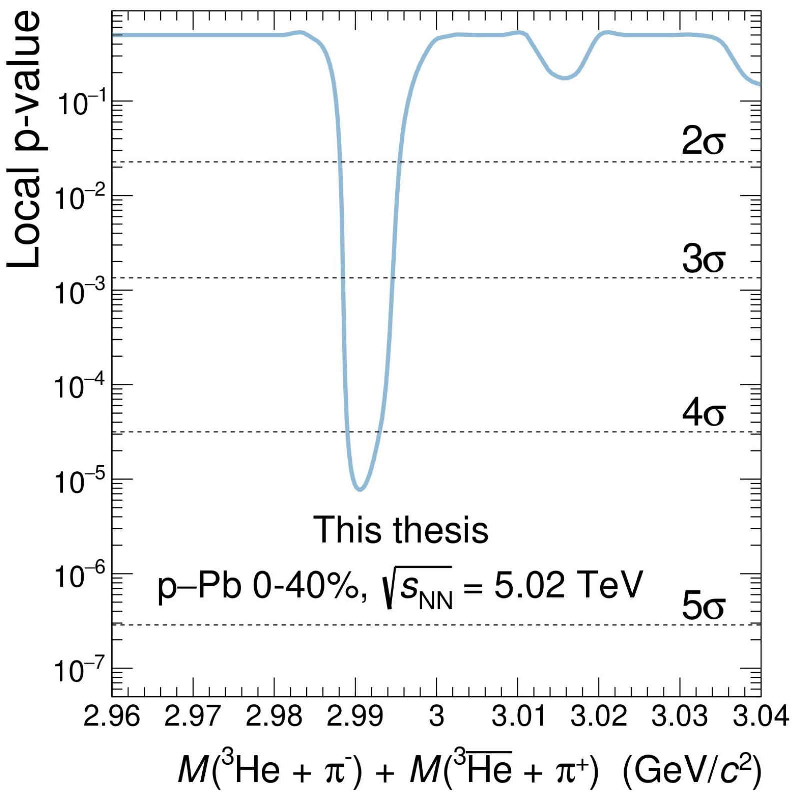


arXiv:2211.14015

Significance

- Significance estimated with local p-value
  - Probability for a background fluctuation to be at least as large as the observed maximum excess
  - Asymptotic formulae for likelihood-based tests [1]
  - Significance of 4.4σ

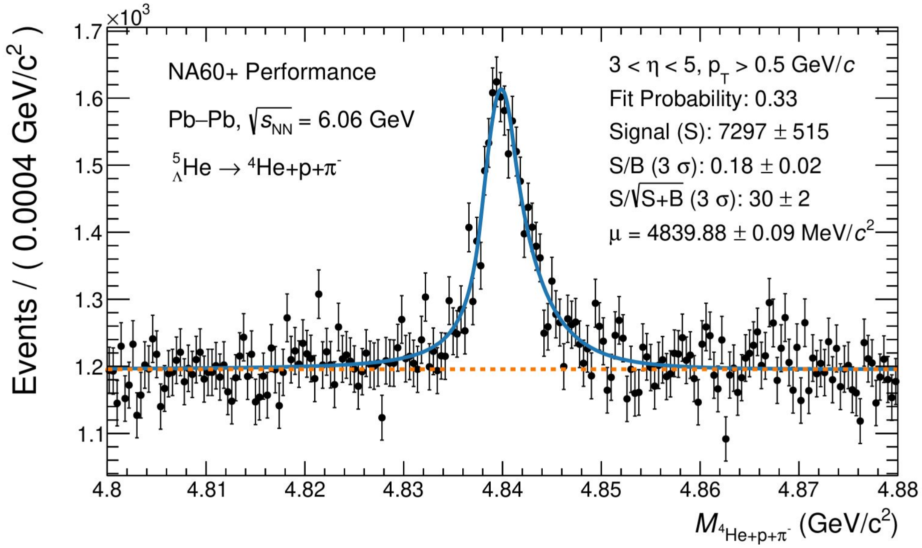
Phys. Rev. Lett. 128, (2022) 252003

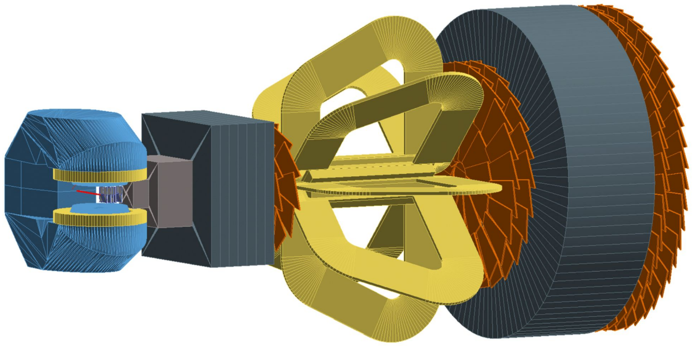


[1] Cowan et al. Eur. Phys. J. C 71 (2011)

NA60+

- Performance study for the NA60+ experiment: ${}^{5}_{\Lambda}He$





EFTs

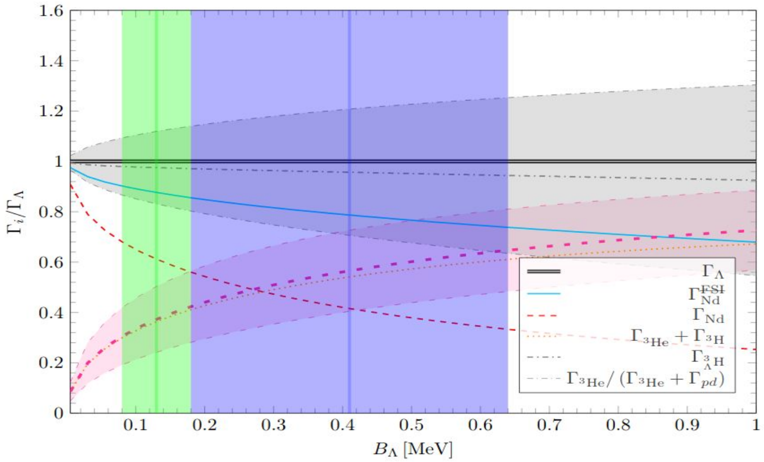
- Chiral EFT

Λ_{UV} (MeV)	B_Λ (keV)	$\Gamma_{^3_\Lambda H \to ^3He + \pi^-}$ (GHz)	$\tau(^3_\Lambda H)$ (ps)
800	69	0.975	234 ± 27
900	135	1.197	190 ± 22
1000	159	1.265	180 ± 21
–	410	1.403	163 ± 18

Strong B_Λ dependence

📕 Pérez-Obiol A., *Physics Letters B*, vol. 811 (2020)

- Pionless EFT

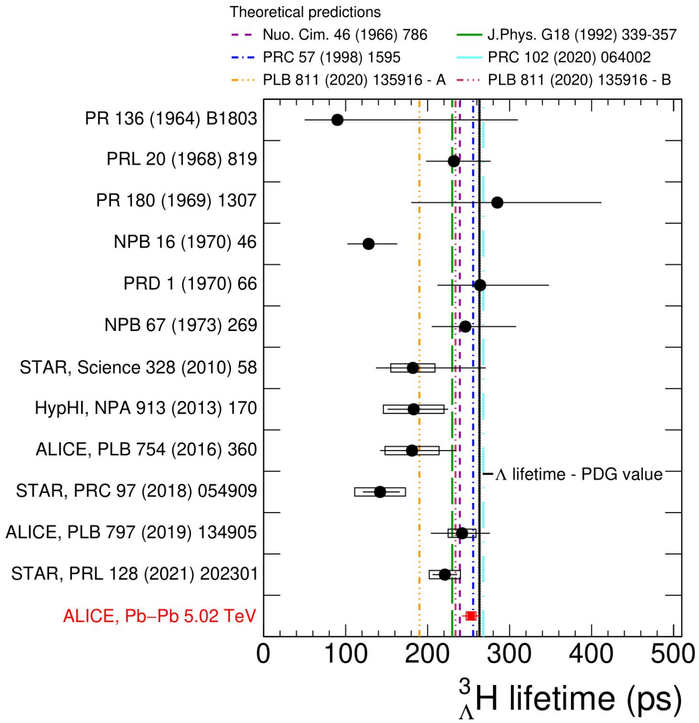


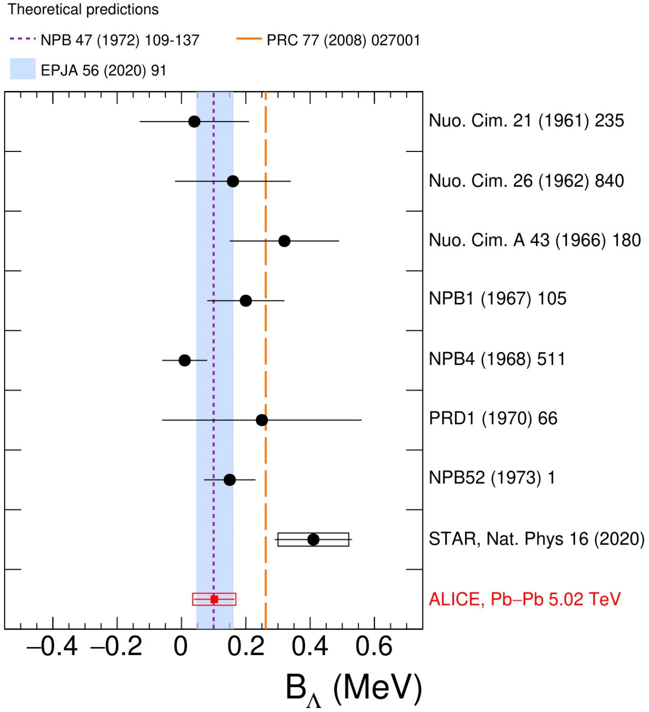
Mild B_Λ dependence

📕 Hildenbrand F. et al., *Physical Review C*, vol. 102, no. 6 (2020)

Final results

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

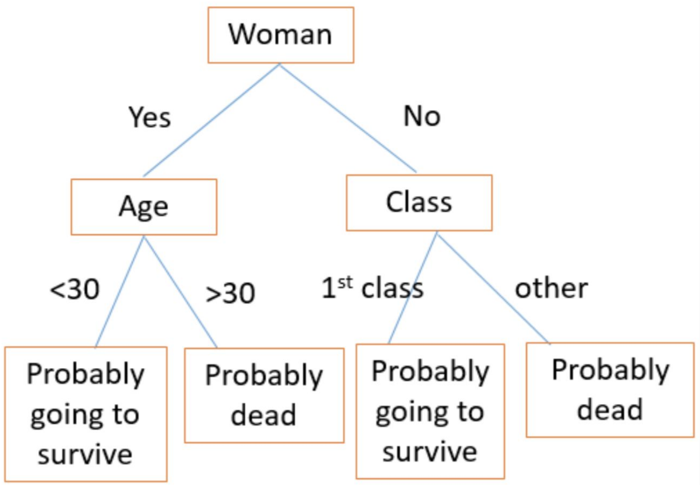




Compatible with all the theoretical predictions assuming $^3_\Lambda H$ as weakly bound

Boosted Decision Trees

- Simple (apparently) supervised learning model well suited for classification and regression problems
- Building block → Decision Tree (DT)
  - A sequence of simple tests on the variables of the hypertriton candidate
  - Combining all the tests one gets an output as a function of the variables of the single candidate
- Training a DT:
  - each test is built to maximise the separation between the signal and the background classes



DT applied to the Titanic dataset: was the passenger survived?

Boosted Decision Trees

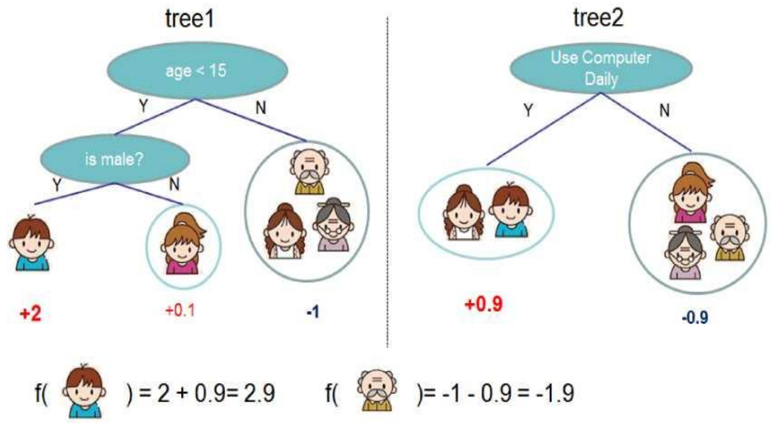
- DT: poor performances on independent samples → overfitting

Boosting

- Many simple (shallow) trees built sequentially
- Each tree is built to compensate the errors of the previous one

Ensemble model

- predictions are made combining the output of all the trees
- Very resilient to overfitting



Do they like computer games?
Score based approach to evaluate it

${}^{3}_{\Lambda}H$ signal in pp and p–Pb collisions

- Data samples:
  - pp collisions at $\sqrt{s}$ = 13 TeV and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected during Run 2
- ${}^{3}_{\Lambda}H$ selection in pp: trigger on high multiplicity events using V0 detectors + topological selections on triggered events
- ${}^{3}_{\Lambda}H$ selection in p–Pb: 40% most central collisions + BDT Classifier
- Significance > 4σ both in pp and p–Pb

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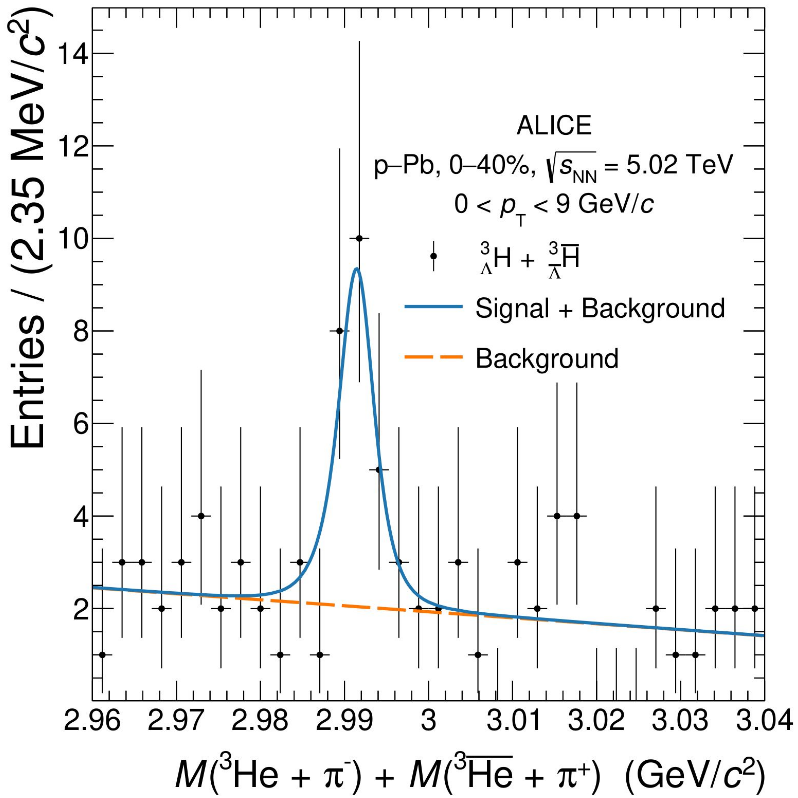

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