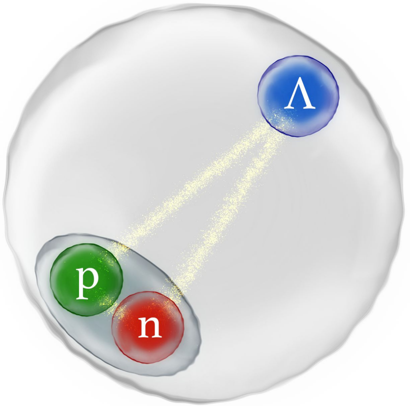
Probing the (anti)hypertriton properties with ALICE at the LHC

Francesco Mazzaschi

CERN-LHC Seminar, 12/12/23

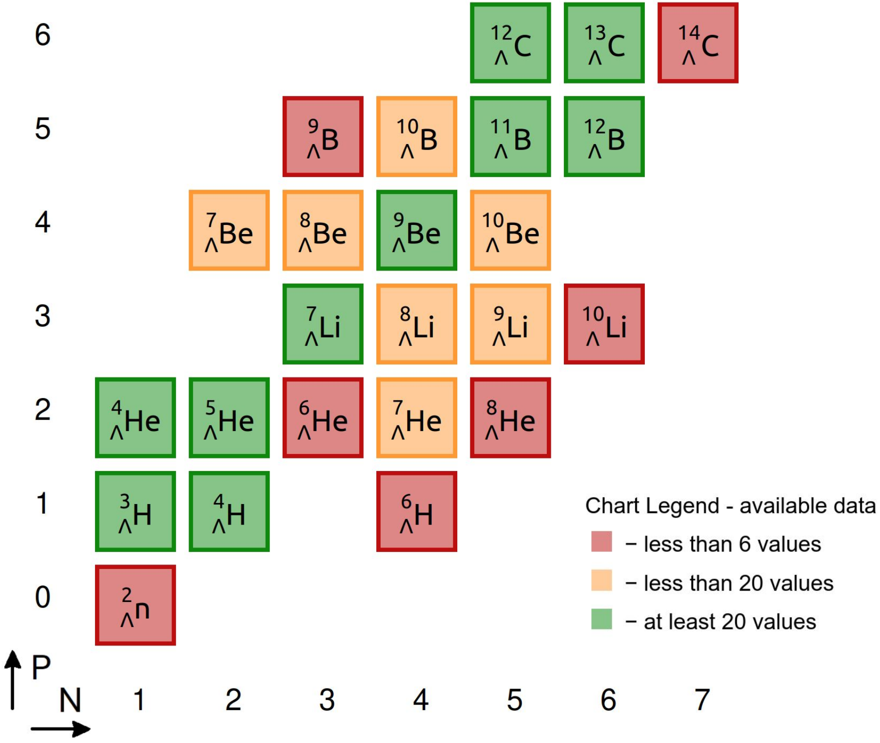


INFN ALICE UNIVERSITÀ DI TORINO

Hypernuclei

ALICE

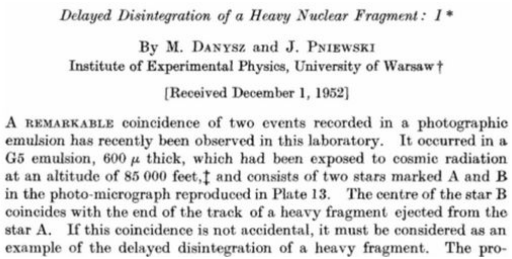
- Hypernuclei: bound states of strange baryons (hyperons) and ordinary nuclei
  - ➢ Extend the nuclear chart to a third dimension, the strangeness one
  - ➢ Poorly known bound states
  - ➢ Unique probes for studying the interaction of hyperons with the ordinary matter
    - Relevant for the physics of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



Hypernuclear database

Hypertriton ($^{3}_{\Lambda}$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]


Delayed Disintegration of a Heavy Nuclear Fragment: I *

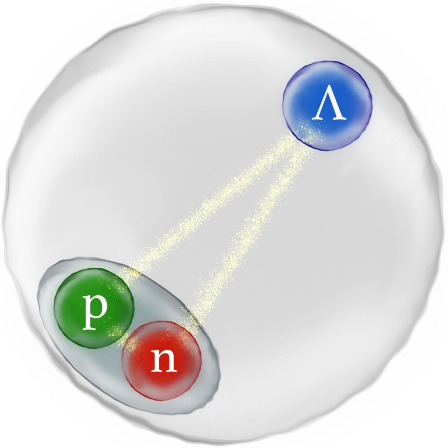
By M. Danysz and J. Pniewski
Institute of Experimental Physics, University of Warsaw †

[Received December 1, 1952]

A remarkable coincidence of two events recorded in a photographic emulsion has recently been observed in this laboratory. It occurred in a G5 emulsion, 600 μ thick, which had been exposed to cosmic radiation at an altitude of 85 000 feet,‡ and consists of two stars marked A and B in the photo-micrograph reproduced in Plate 13. The centre of the star B coincides with the end of the track of a heavy fragment ejected from the star A. If this coincidence is not accidental, it must be considered as an example of the delayed disintegration of a heavy fragment. The pro-

Mass: ~ 2.991 GeV/c^2
Spin: ½ (?)
Lifetime: ~ 250 ps ($c\tau$ ~ 7.7 cm)

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



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

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_Λ = 130 ± 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_Λ = 0.13 ± 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

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

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

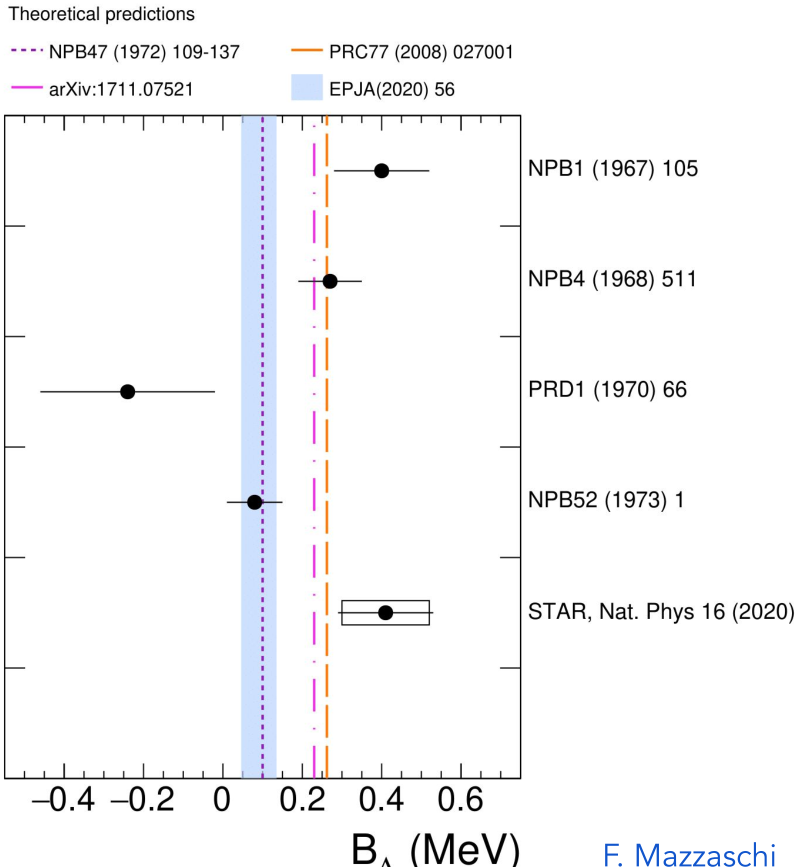
Hypertriton structure: B_Λ

- Recent measurement from the STAR Coll.[1]
  - ➢ B_Λ = 0.41 ± 0.12 (stat.) ± 0.11 (syst.) MeV

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]

- More than 50 years after the first measurement, B_Λ has still large uncertainties
  - ➢ Precision measurements needed!

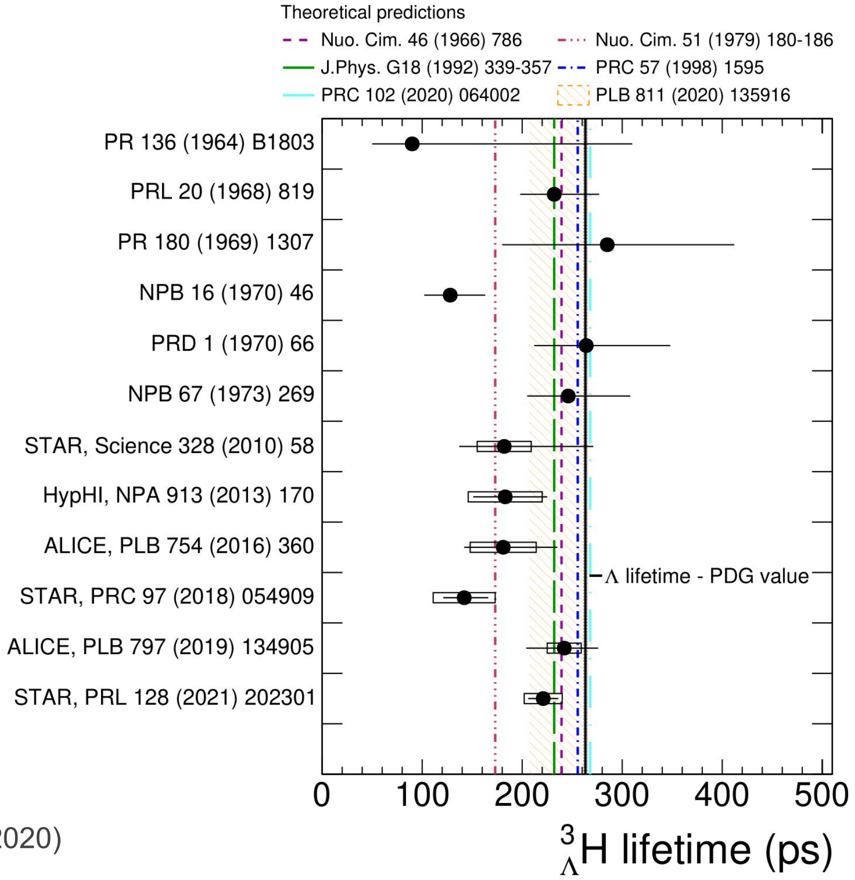


1 STAR, Nature Physics 16 (2020), 409–412
2 Le et al., Phys.Lett.B 801 (2020) 135189

Hypertriton structure: lifetime

- Lifetime of the $^{3}_{\Lambda}H$
  - ➢ A low B_{Λ} should imply a lifetime close to the free Λ hyperon one
  - ➢ Many measurements performed, all with uncertainties > 10%
    - ■ <τ> = 219 ± 13 ps

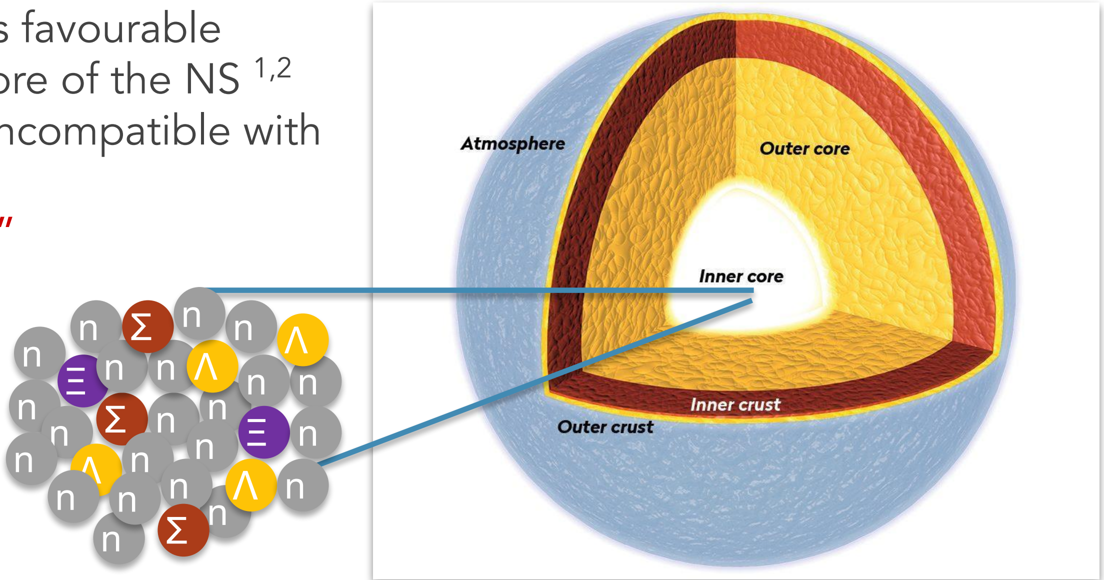
- Large theoretical uncertainties
  - ➢ connection between τ and B_{Λ} not well constrained even in state-of-the-art EFT models[1, 2]



[1] Hildenbrand F. et al., *Physical Review C*, vol. 102, no. 6 (2020)
[2] Pérez-Obiol A., *Physics Letters B*, vol. 811 (2020)

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 [1,2]
  - ➢ Softening of the EoS, incompatible with measured heavy NS
    - "Hyperon puzzle"

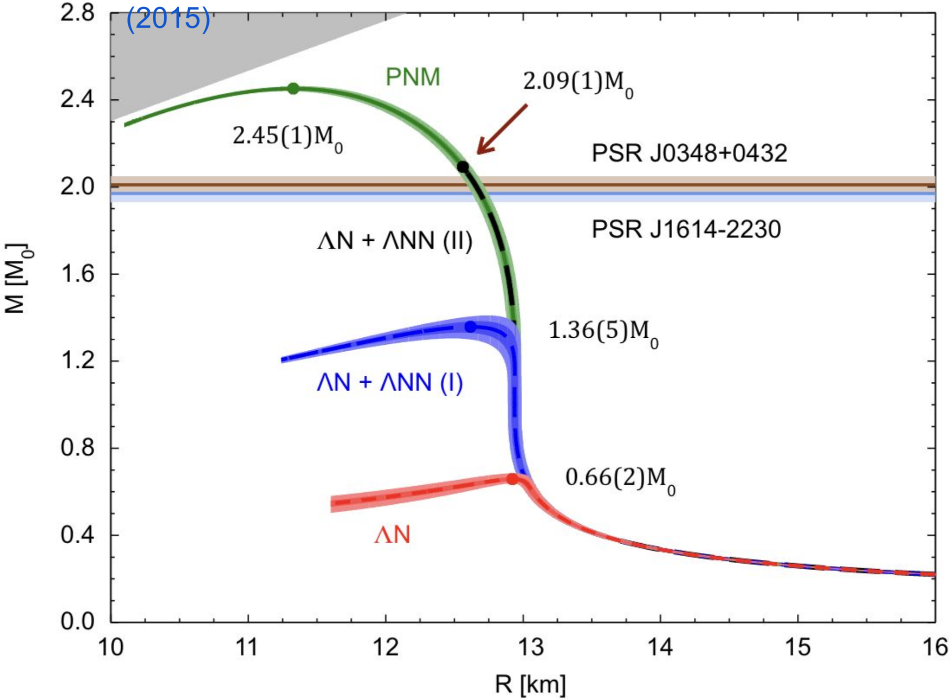


[1] D. Logoteta et al., Eur.Phys.J.A 55 (2019)   [2] D. Lonardoni et al., Phys. Rev. Lett. 114 (2019)

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
  - ➢ ${}^{3}_{\Lambda}$H is the most direct probe
    - B_Λ of the ${}^{3}_{\Lambda}$H employed to model the Λ–N interaction potential

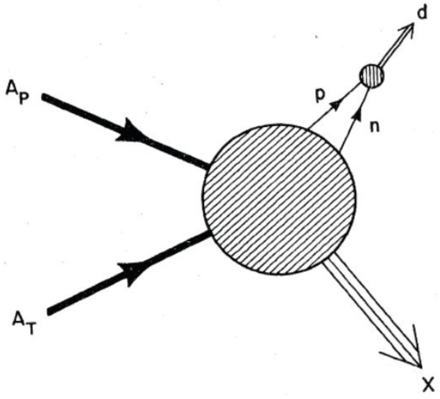
D. Lonardoni *et al.*, Phys. Rev. Lett. 114 (2015)



ALICE: precision measurements of ${}^{3}_{\Lambda}$H lifetime and B_Λ in heavy-ion collisions

(Hyper)Nucleosynthesis at collider: how?

(Hyper)Nucleosynthesis at collider: how?



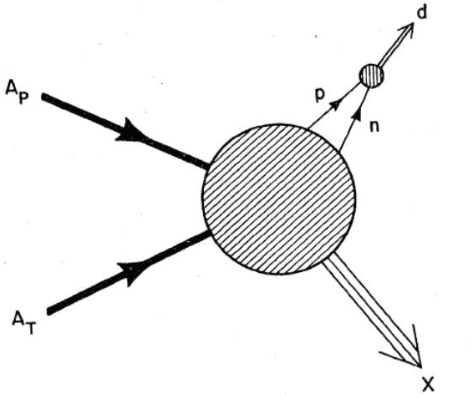
Coalescence

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

(Hyper)Nucleosynthesis at collider: how?



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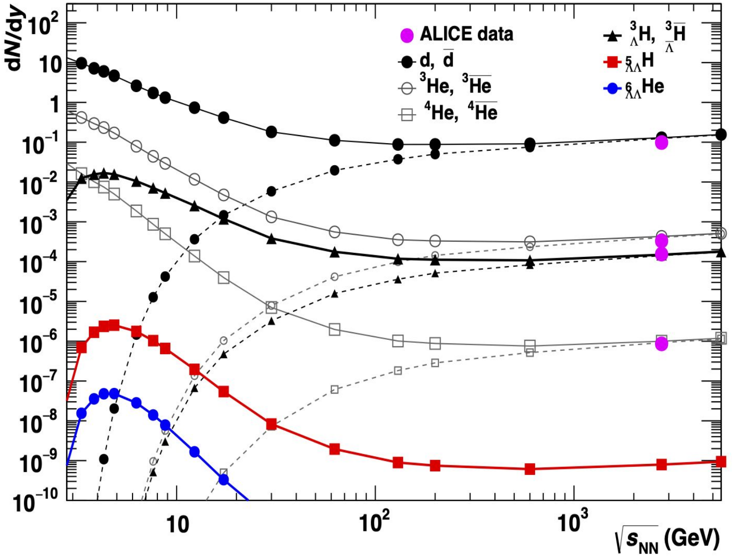
- Interplay between the configuration of the phase space of the nucleons and the wave function of the nucleus

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

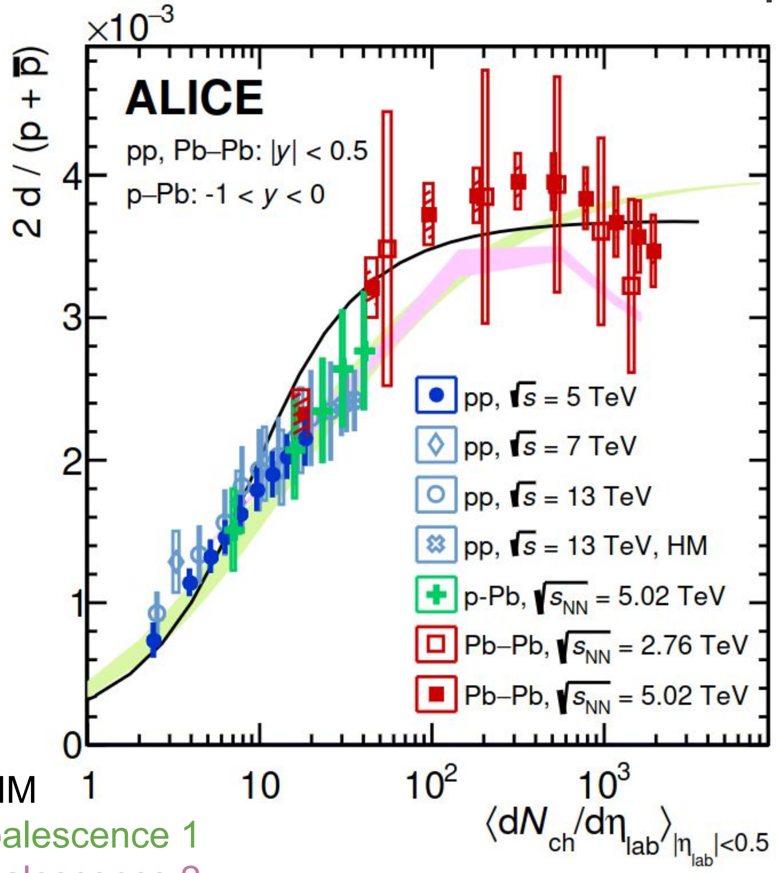
B. Dönigus et al.,Nucl.Phys.A 987 (2019)



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

Can we use hypernuclei to improve our understanding?



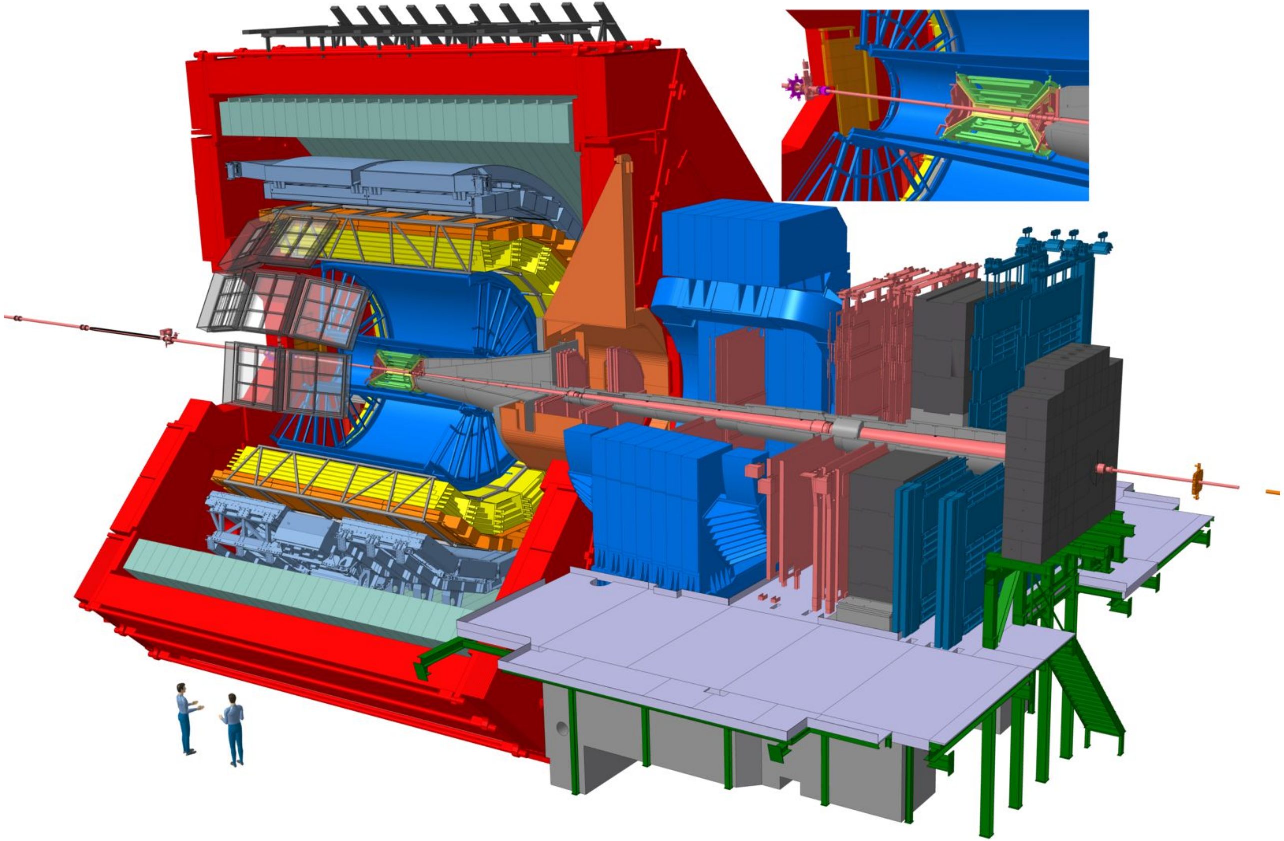
SHM
Coalescence 1
Coalescence 2

Phys. Rev. C 107 (2023) 064904

Hypertriton measurements at the LHC

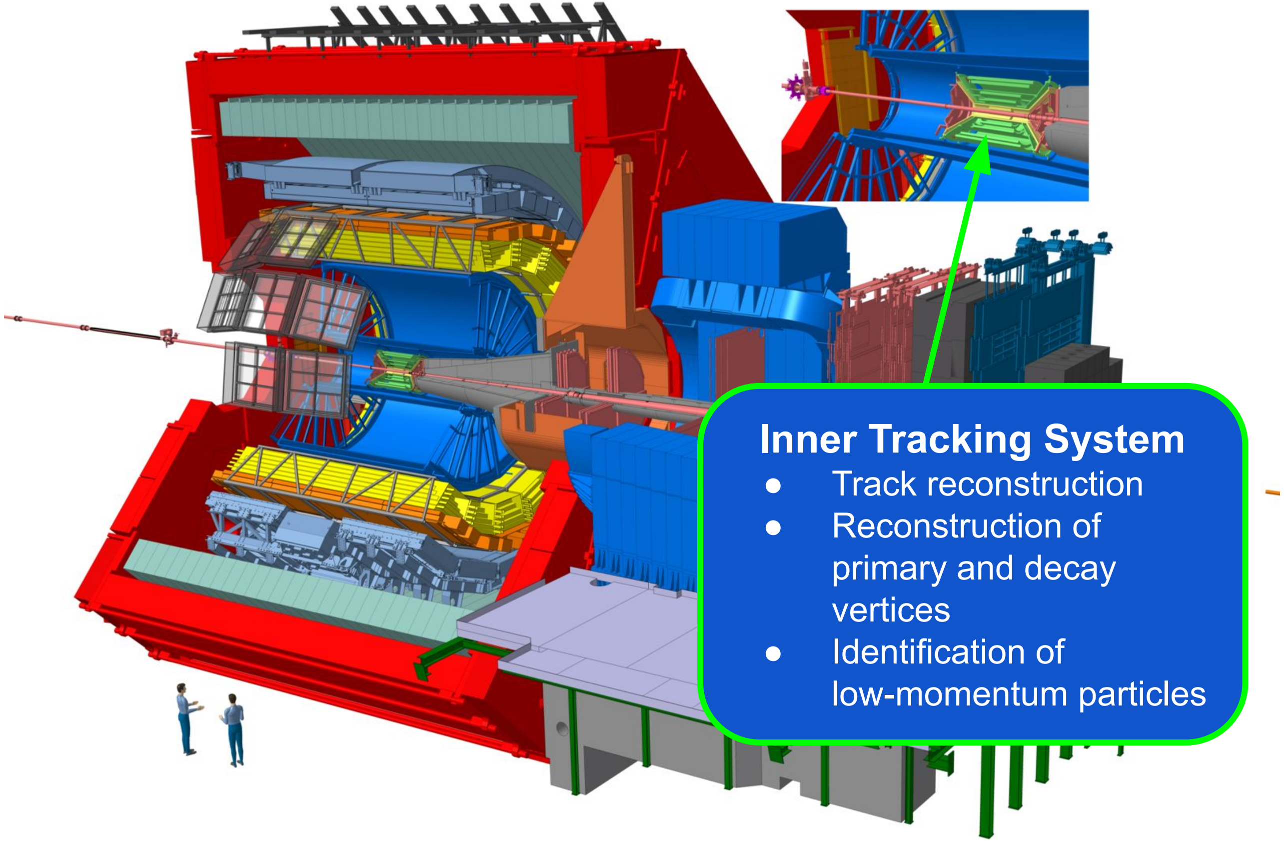
- Phys. Rev. Lett. 131, 102302 (2023)
- Phys. Rev. Lett. 128, 252003 (2022)

The ALICE Run 2 detector



LHC Run 3: ITS and TPC upgrades

The ALICE Run 2 detector



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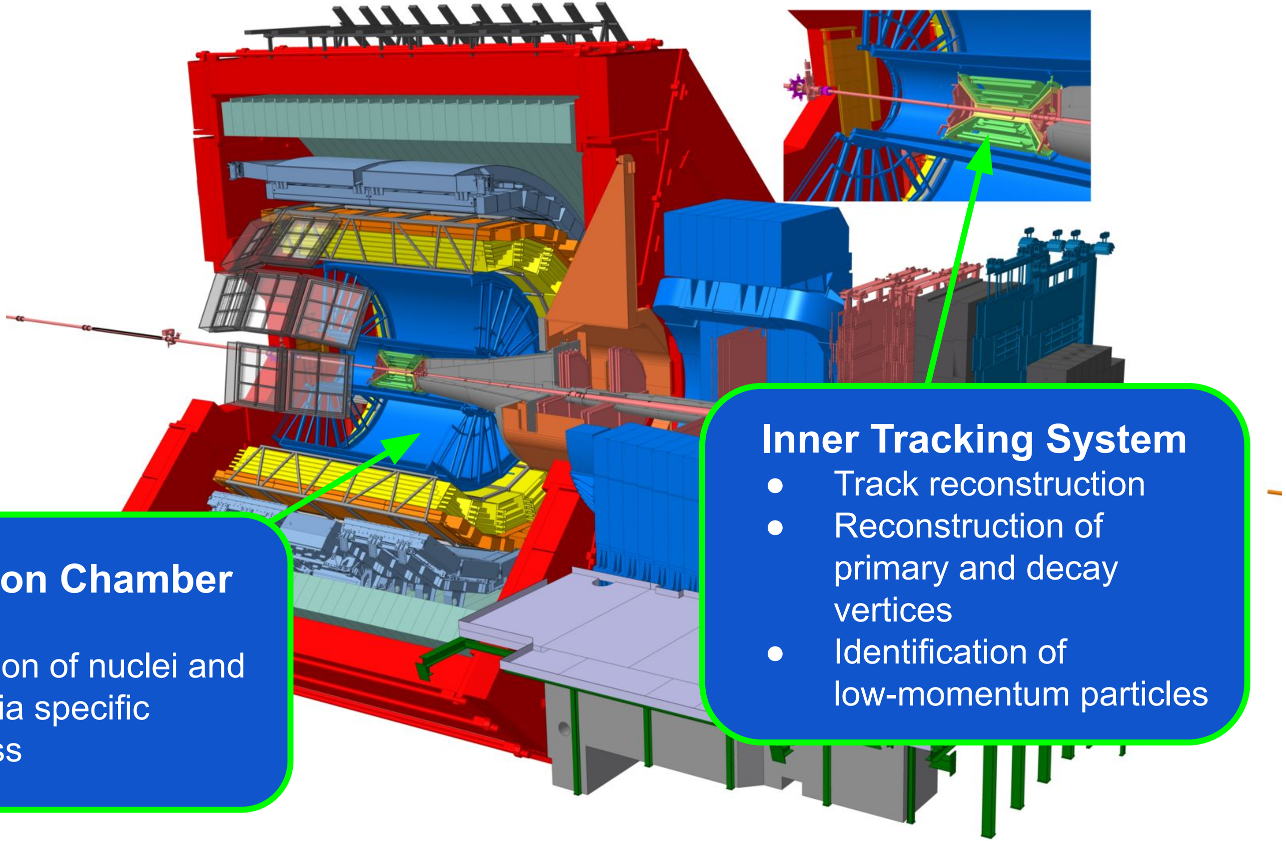


Time Projection Chamber

- Tracking
- Identification of nuclei and hadrons via specific energy loss

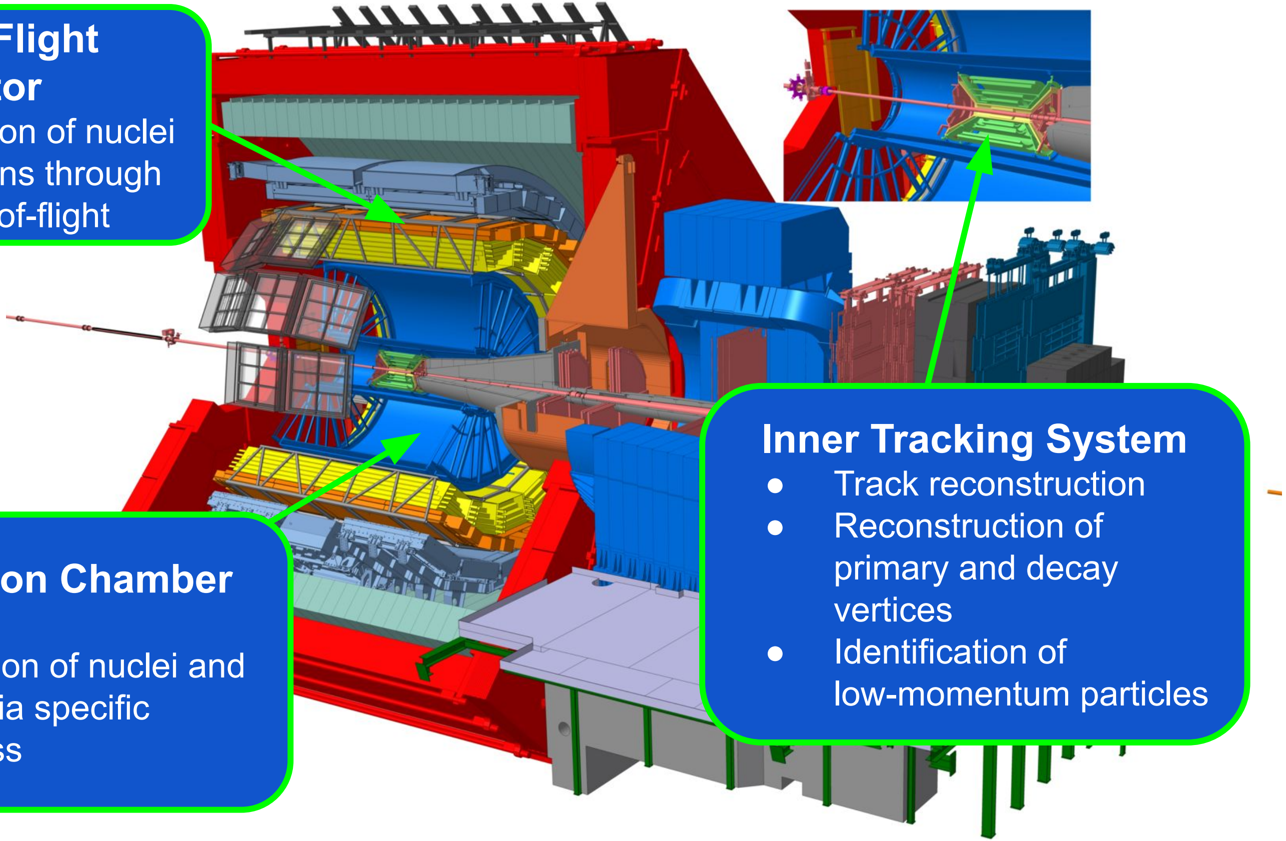
Inner Tracking System

- Track reconstruction
- Reconstruction of primary and decay vertices
- Identification of low-momentum particles

LHC Run 3: ITS and TPC upgrades

The ALICE Run 2 detector

ALICE



Time-Of-Flight detector

- Identification of nuclei and hadrons through their time-of-flight

Time Projection Chamber

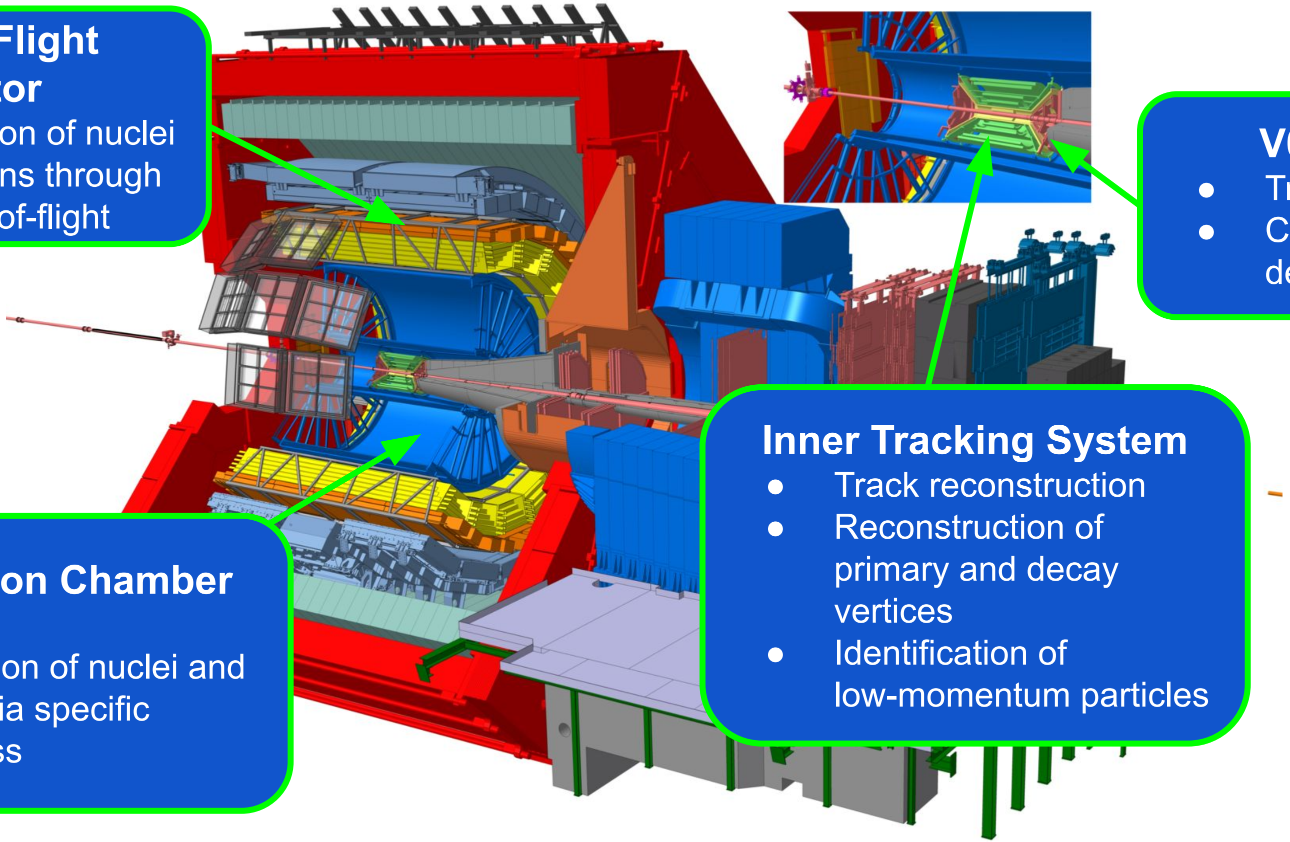
- Tracking
- Identification of nuclei and hadrons via specific energy loss

Inner Tracking System

- Track reconstruction
- Reconstruction of primary and decay vertices
- Identification of low-momentum particles

LHC Run 3: ITS and TPC upgrades

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

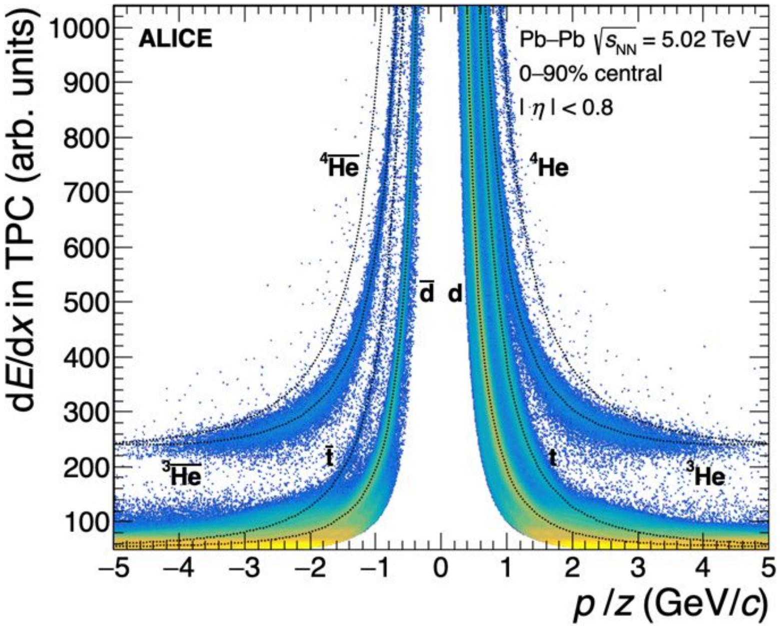
$^{3}_{\Lambda}H$ reconstruction

- Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE during 2018
  - ➢ $^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$

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



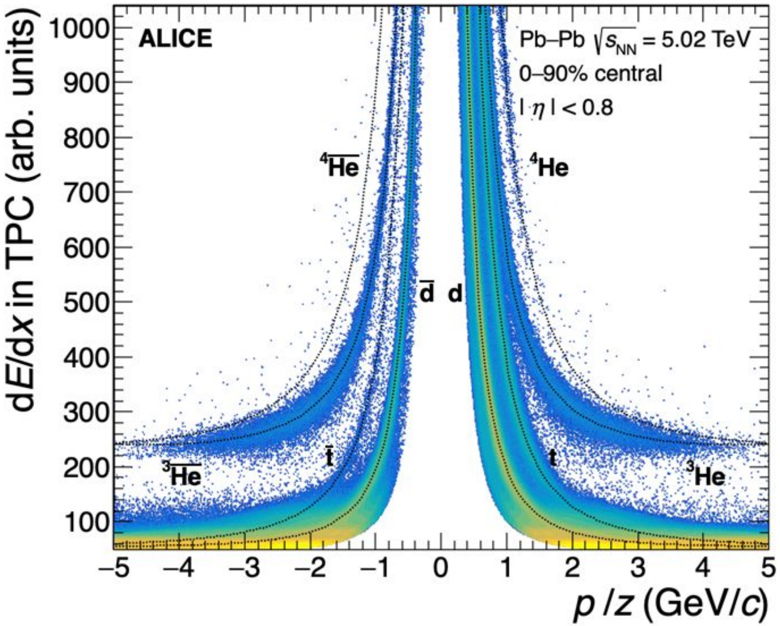
Phys. Rev. C 107 (2023) 064904

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



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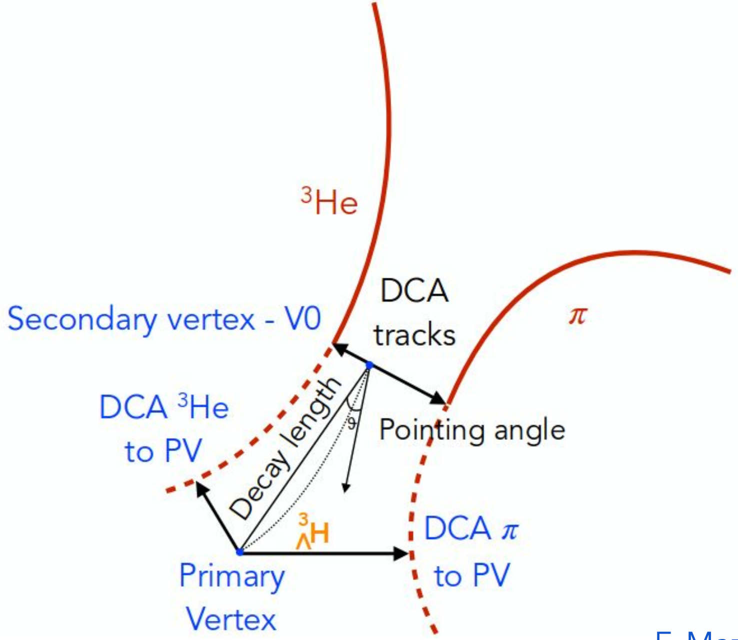

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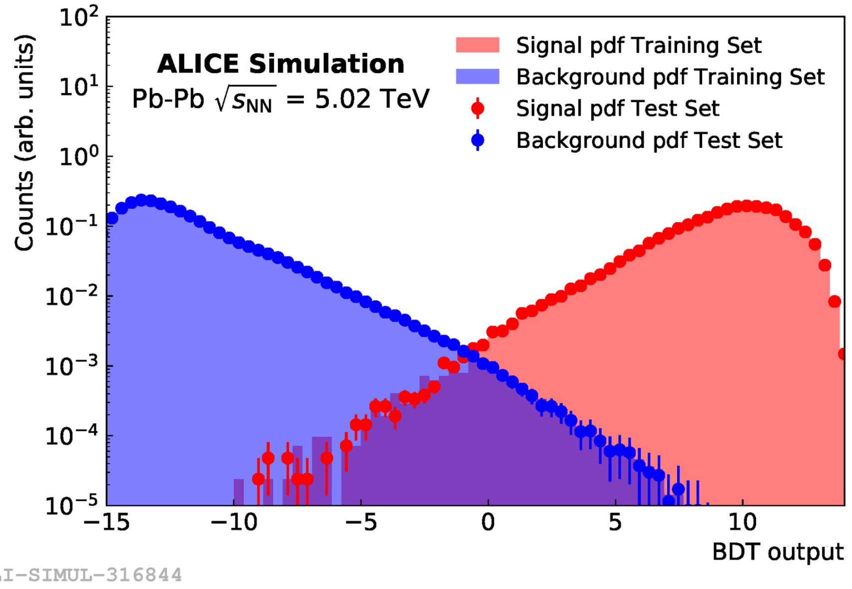
${}^{3}_{\Lambda}H$ selection: machine learning approach

ALICE

Boosted Decision Trees Classifier (BDT) trained on a dedicated sample

XGBoost

- BDT output
  - Score related to the probability of the candidate to be signal or background
  - Nine proper decay length intervals (1 to 35 cm)

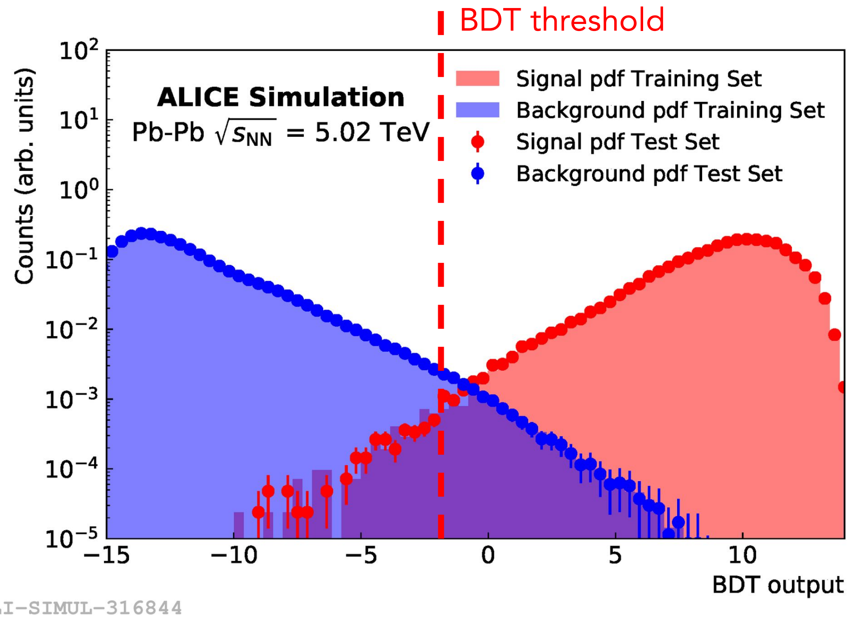


${}^{3}_{\Lambda}H$ selection: machine learning approach

Boosted Decision Trees Classifier (BDT) trained on a dedicated sample

XGBoost

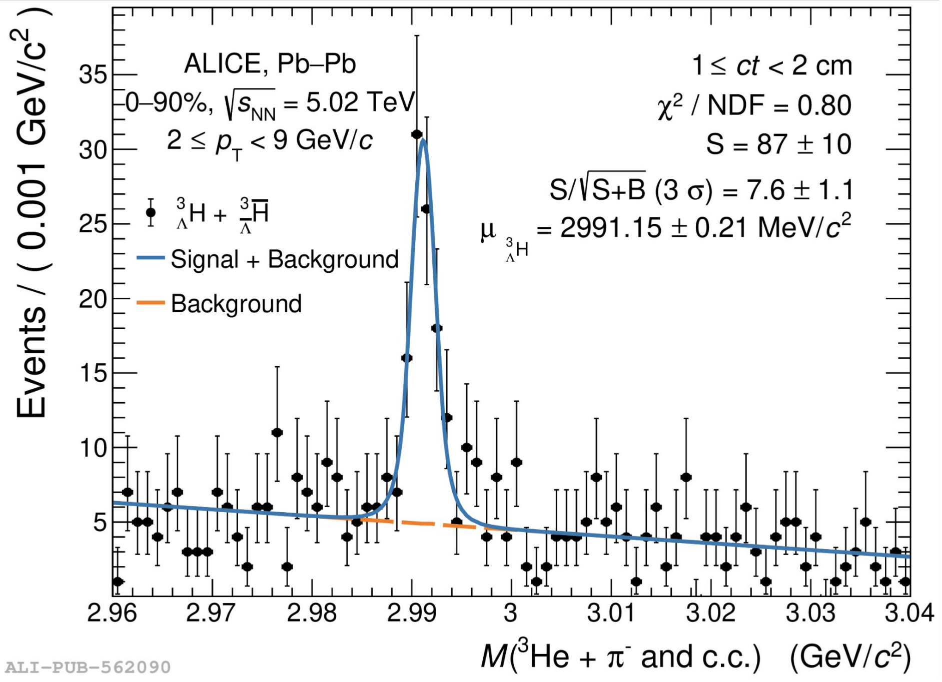
- BDT output
  - Score related to the probability of the candidate to be signal or background
  - Nine proper decay length intervals (1 to 35 cm)
- Selection applied on the BDT score
  - maximisation of the expected significance (assuming thermal production)



Signal extraction

- Signal extracted with an unbinned likelihood fit to the invariant mass spectrum of the selected candidates
  - ➢ Kernel Density Estimation (KDE) function tuned on the MC to model the signal shape
  - ➢ 1st order polynomial for the background component
- High significance from 1 to 35 cm
- Integral of the signal function (N^{raw}) for the lifetime, mass peak position (μ) for the B_Λ

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



Lifetime measurement

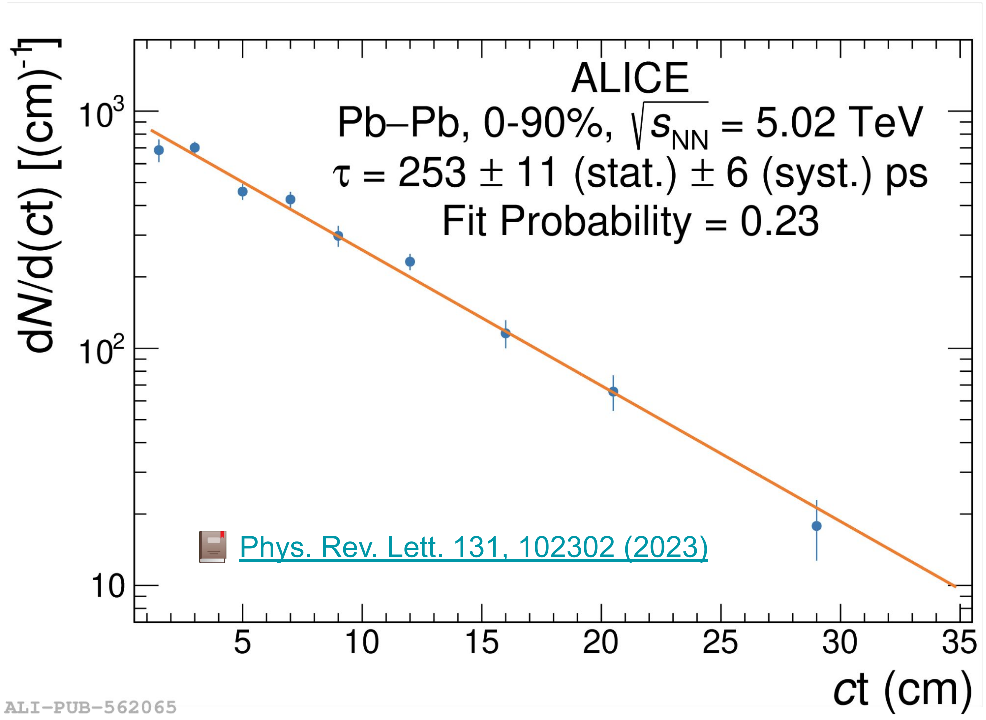
- Corrected *ct* spectrum: $$\frac{\mathrm{d}N}{\mathrm{d}(ct)} = \frac{1}{\Delta ct}\frac{1}{\epsilon_{\mathrm{pres}}}\frac{1}{\epsilon_{\mathrm{BDT}}}\frac{1}{(1-f_{\mathrm{abs}})} \times N^{\mathrm{raw}}(ct)$$

- ε_{pres} : topology reconstruction and pre-selection efficiencies
- ε_{BDT} : BDT selection efficiency
- f_{abs} : fraction of $^{3}_{\Lambda}H$ that are absorbed in the ALICE detector material
  - ➢ simulated with GEANT4, cross-section from
    - 📕 M.V. Evlanov, Nucl. Phys. A 632 (1998)

Lifetime measurement

- Corrected *ct* spectrum: $$\frac{dN}{d(ct)} = \frac{1}{\Delta ct}\frac{1}{\epsilon_{\mathrm{pres}}}\frac{1}{\epsilon_{\mathrm{BDT}}}\frac{1}{(1-f_{\mathrm{abs}})} \times N^{\mathrm{raw}}(ct)$$

- Fitted with an exponential function
- Lifetime value from the fit
  - ➢ Statistical uncertainty ~ 4%
  - ➢ Value compatible within 1σ with free Λ lifetime



Towards the B_Λ measurement

$B_\Lambda = M(d) + M(\Lambda) - M(^3_\Lambda H)$

- $M(^3_\Lambda H)$: extracted from the mean value μ of the signal pdf in each *ct* interval
- $M(^3_\Lambda H) = \mu - \delta^{MC} - \delta^{data}$

Towards the B_Λ measurement

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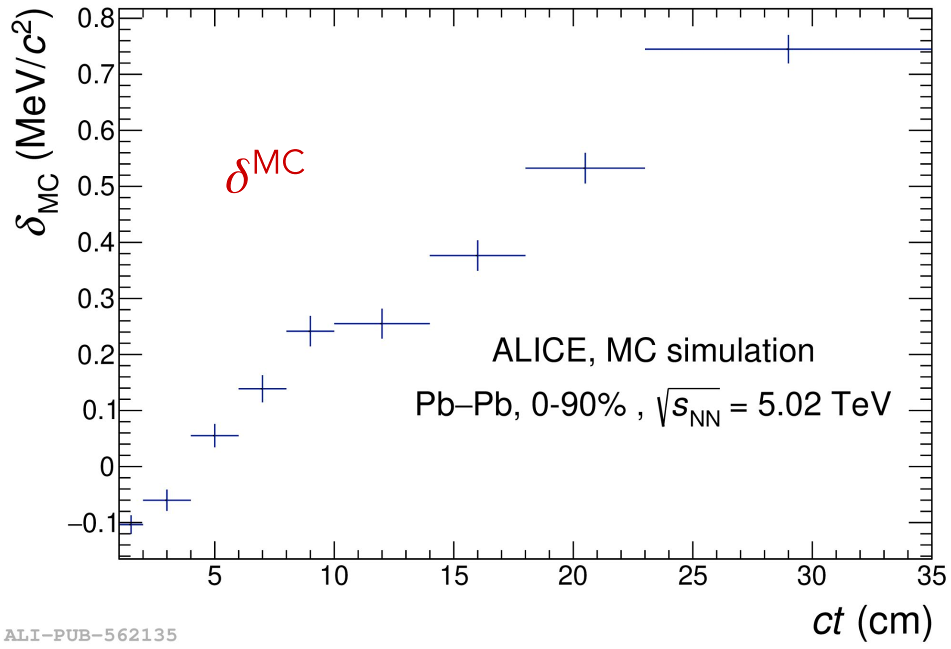


- Reconstruction shift observed in the MC due to missing energy loss corrections applied to the $^3_\Lambda H$ daughter tracks
- *ct* dependent, from -0.1 to 0.8 MeV/c^2

Towards the B_Λ measurement

$B_\Lambda = M(d) + M(\Lambda) - M({}^3_\Lambda H)$

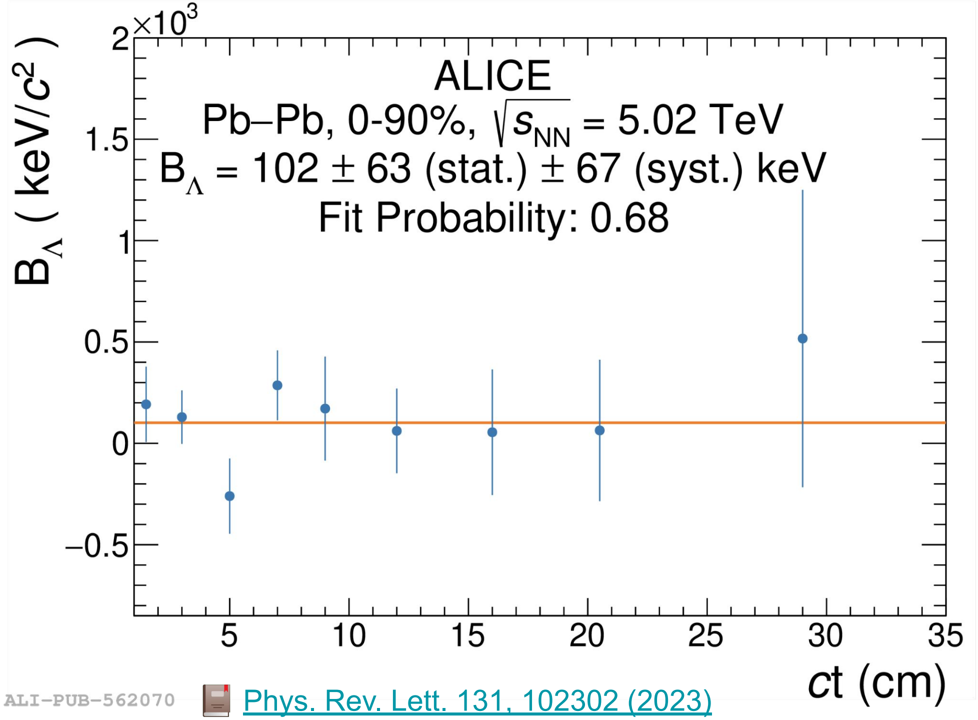
- $M({}^3_\Lambda H)$: extracted from the mean value μ of the signal pdf in each *ct* interval
- $M({}^3_\Lambda H) = \mu - \delta^{MC} - \delta^{data}$

δ^{data}

- Data driven correction due to
  - ➢ Residual misalignment
  - ➢ B-field uncertainty
- Shift wrt the PDG value of the Λ mass
  - ➢ Same analysis procedure
  - ➢ ~ 60 keV / c^2

B_Λ measurement

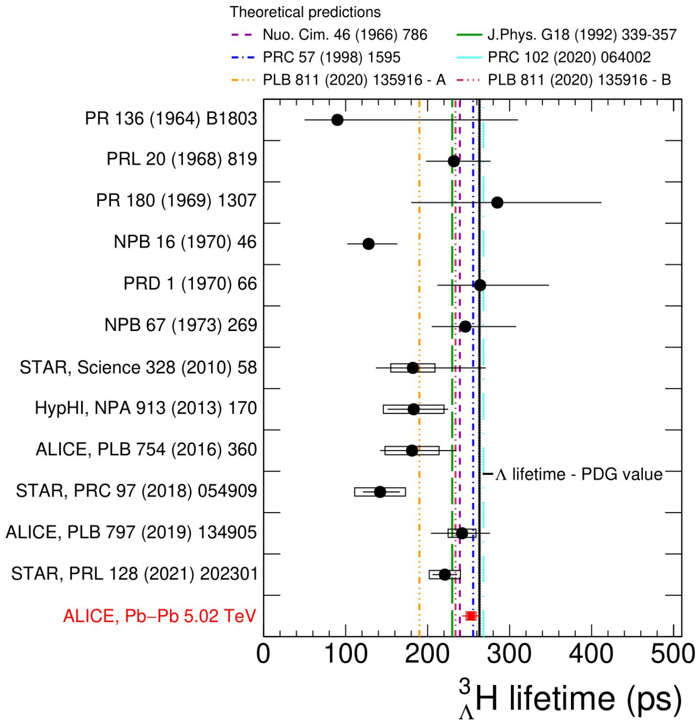
- Weighted average / pol0 fit of the different *ct* interval values
- Extremely precise mass measurement
  - ➢ o(100 keV) precision at the LHC
- Low B_Λ , in agreement with early emulsion experiments

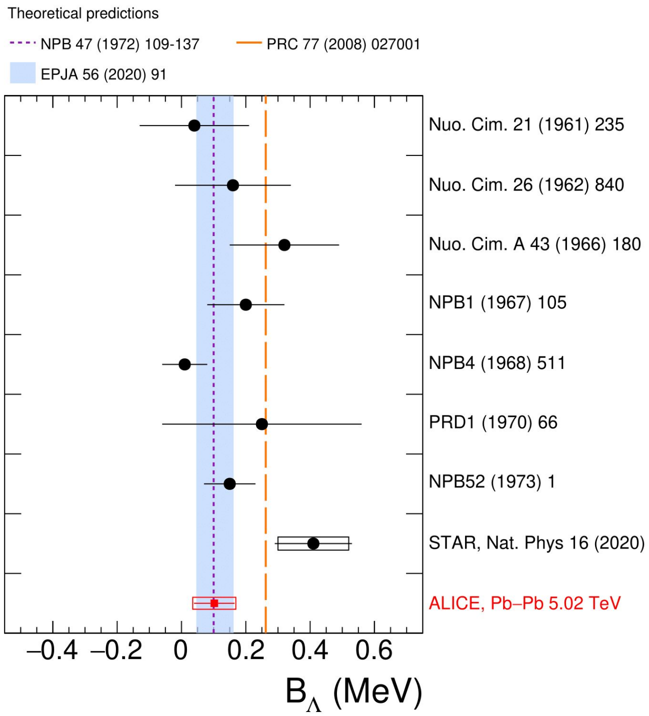


Phys. Rev. Lett. 131, 102302 (2023)

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

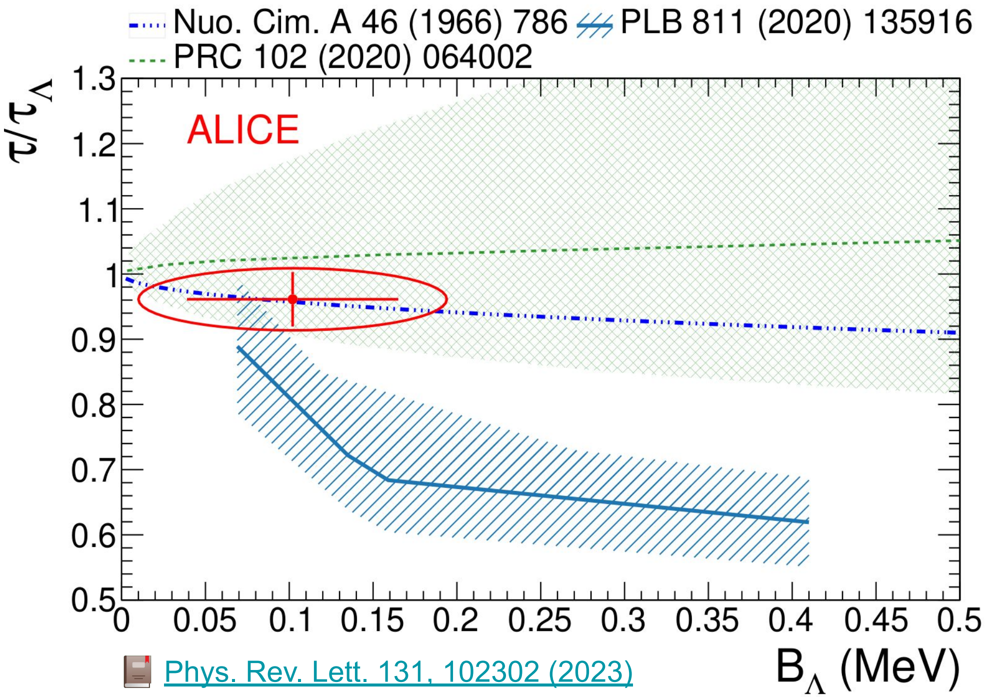




Compatible with all the theoretical predictions assuming ${}^{3}_{\Lambda}H$ as weakly bound

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

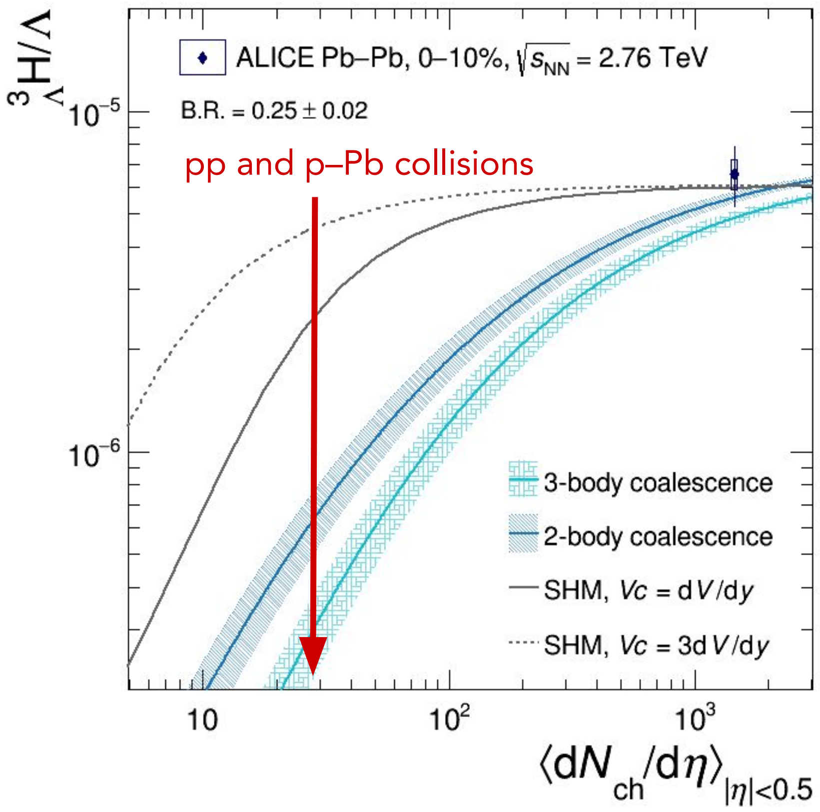


Phys. Rev. Lett. 131, 102302 (2023)

- 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 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 $\rightarrow$ coalescence is sensitive to the interplay between the size of the collision system and the spatial extension of the nucleus wave function



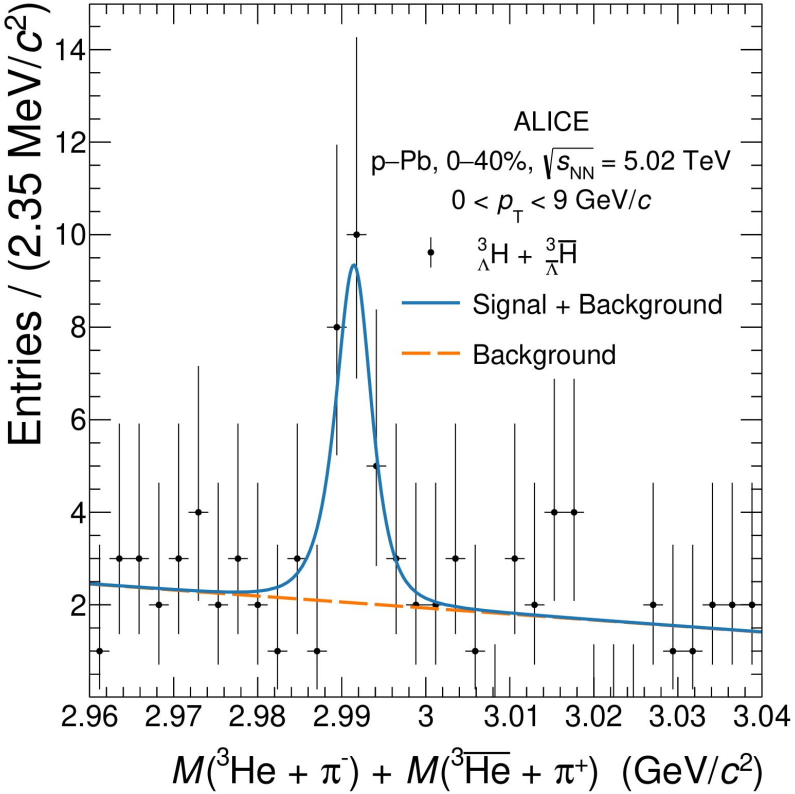
- $^{3}_{\Lambda}H$ production in pp and p–Pb collisons: a key to understand the nuclear production mechanism at the LHC

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)

${}^{3}_{\Lambda}$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

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



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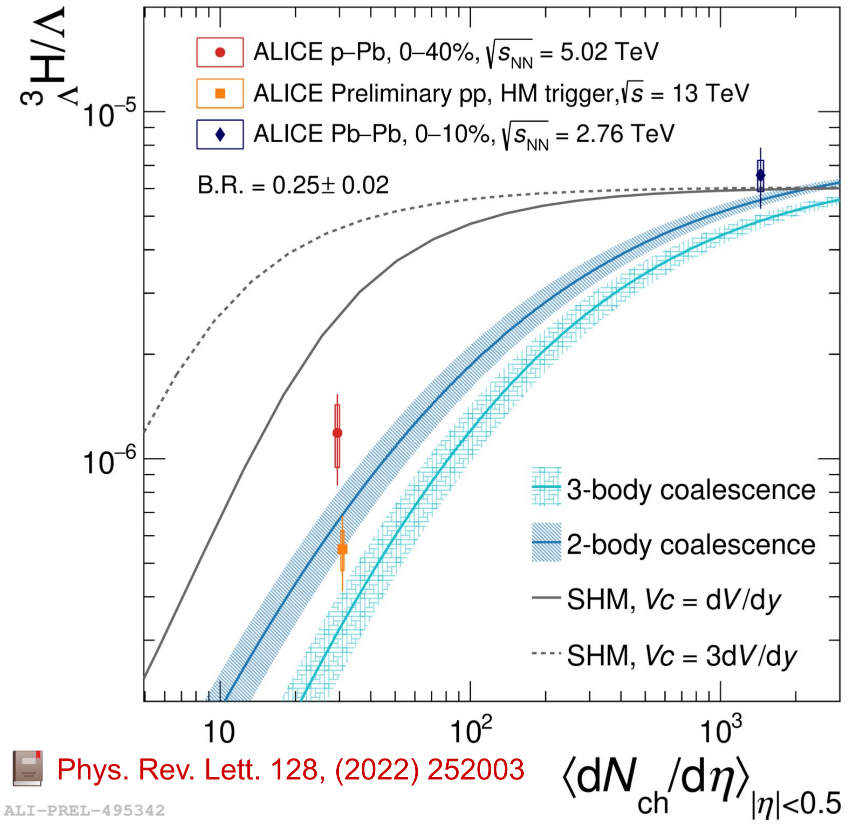
Production yields

- First measurement of $^{3}_{\Lambda}H/\Lambda$ 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 can measure it!)



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

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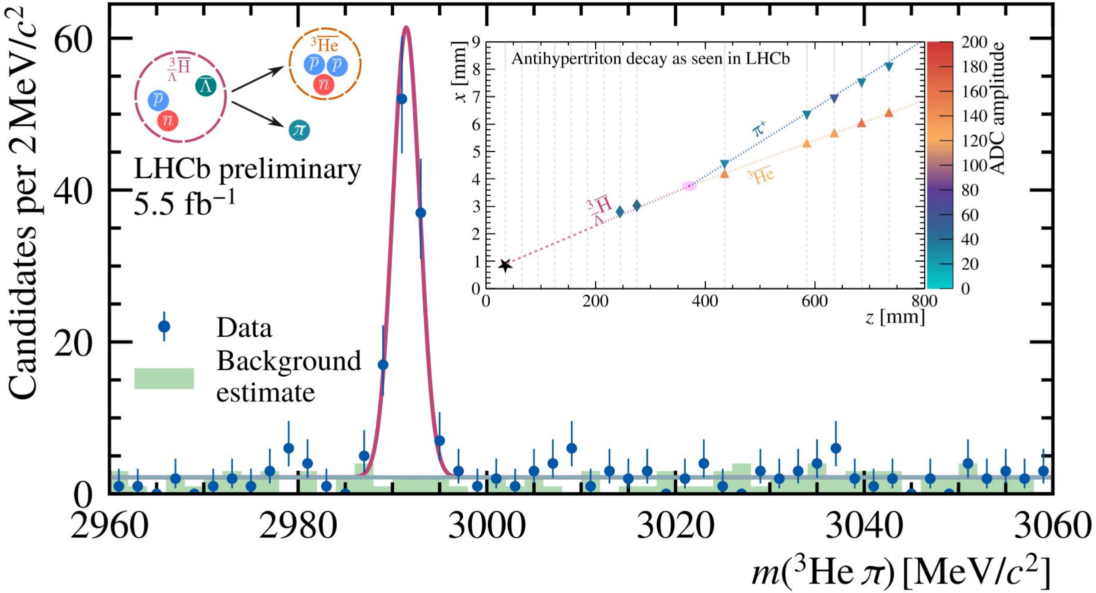
First hypertritons seen by LHCb!

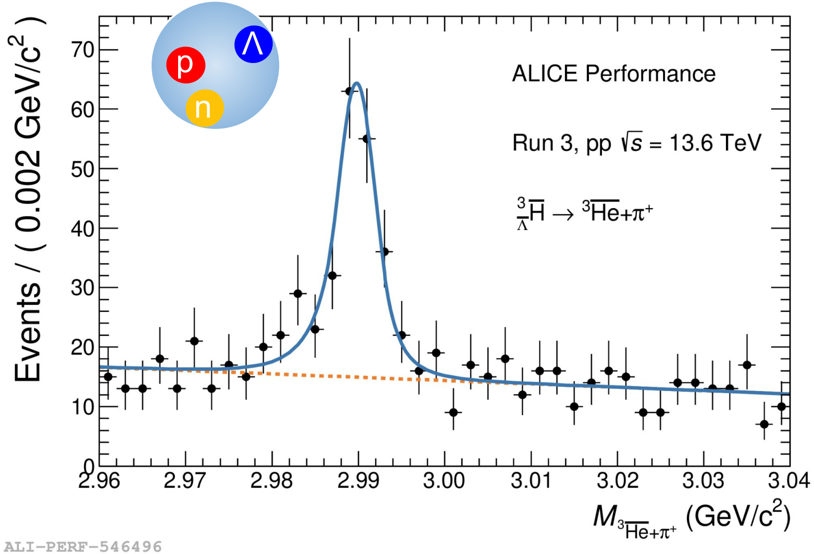
- LHCb observed the (anti-)hypertriton on Run 2 pp data: [link]
  - ~ 100 anti-$^{3}_{\Lambda}$H analysing 5.5 fb^{-1}
  - Innovative method for tagging ^{3}He nuclei
  - Allows for complementary measurements with ALICE in the forward region



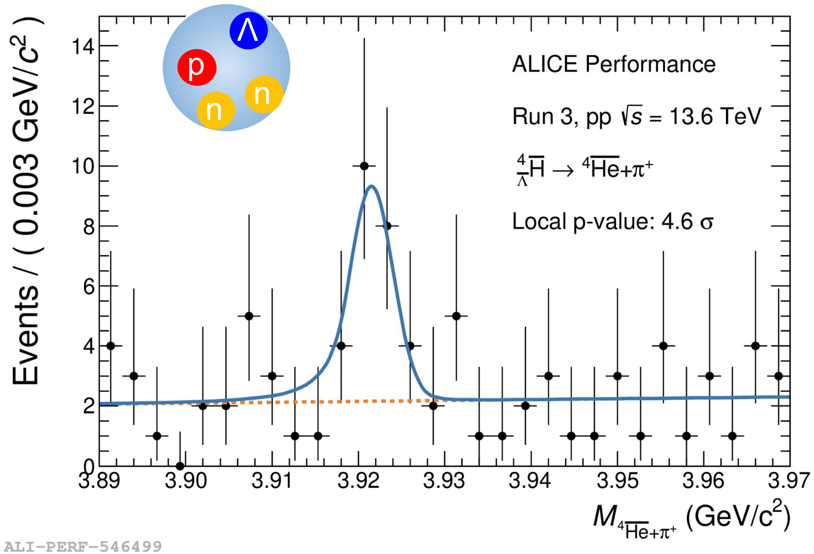
Hypernuclei in the Run 3 era

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



ALI-PERF-546496

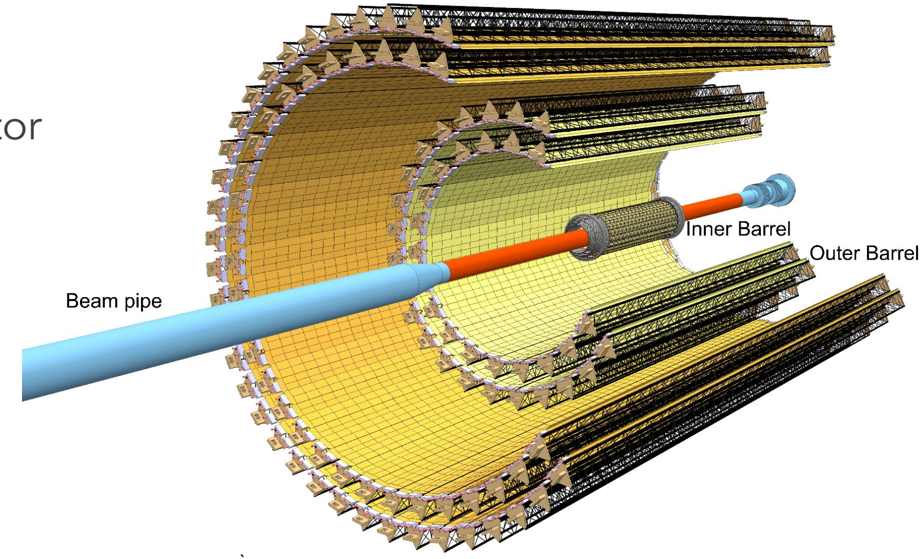


ALI-PERF-546499

The upgraded Inner Tracking System

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

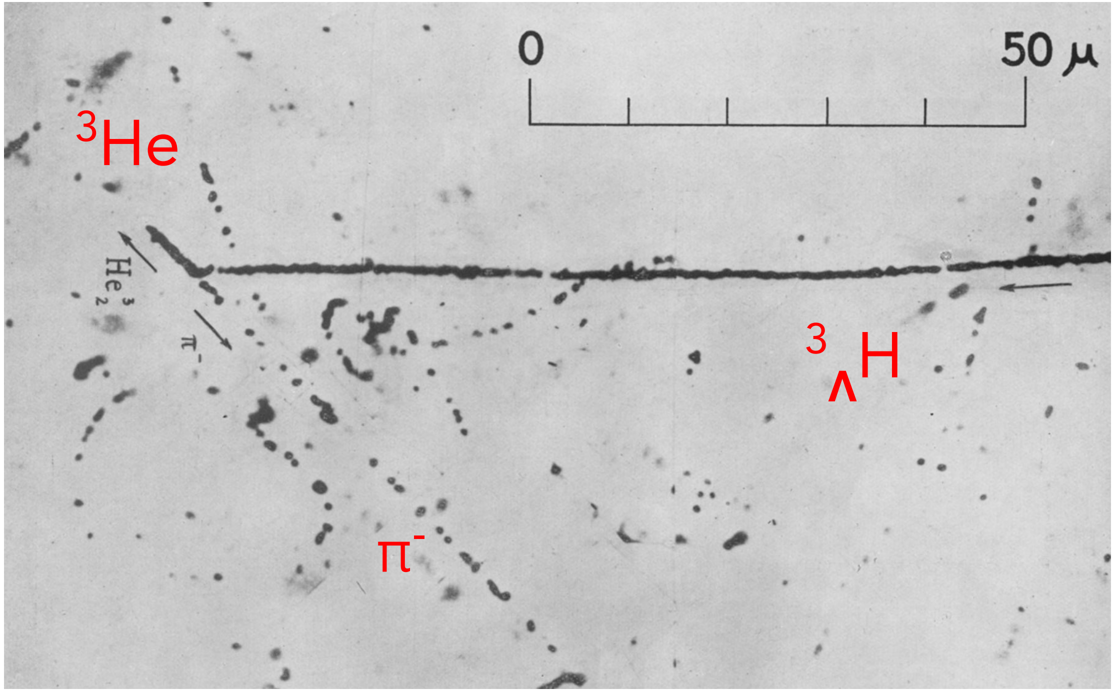
- 24120 chips, 12.5 Gpixel
  - Largest MAPS-based detector in High-Energy Physics
- 3 Inner Barrel layers (IB)
  - radii from 2.2 to 3.8 cm
- 4 Outer Barrel layers (OB)
  - radii from 19 to 39 cm



Reduced material budget and higher spatial resolution: $(r\varphi, z) = 5\text{x}5\ \mu m^2$

Back to the origin: direct tracking of hypernuclei

- Hypernuclei ($c\tau$ ~ 7cm) can be 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)

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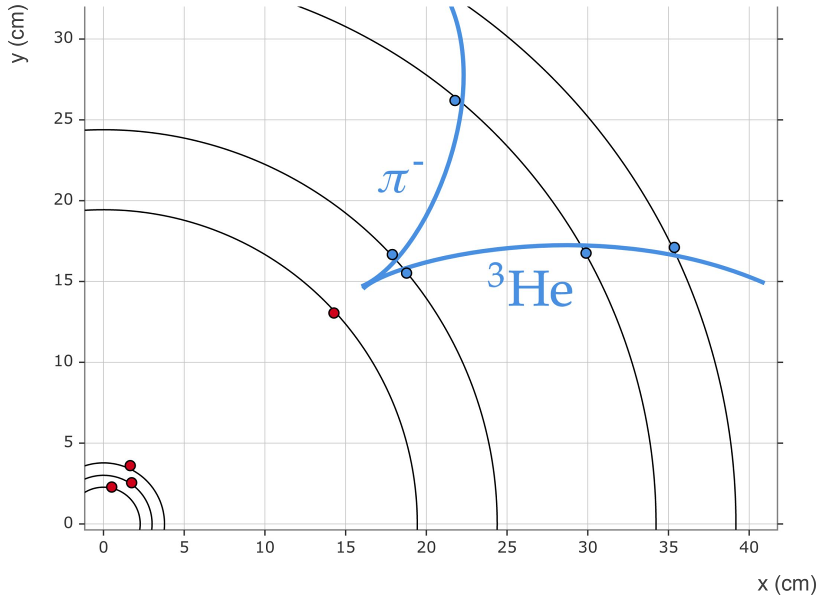
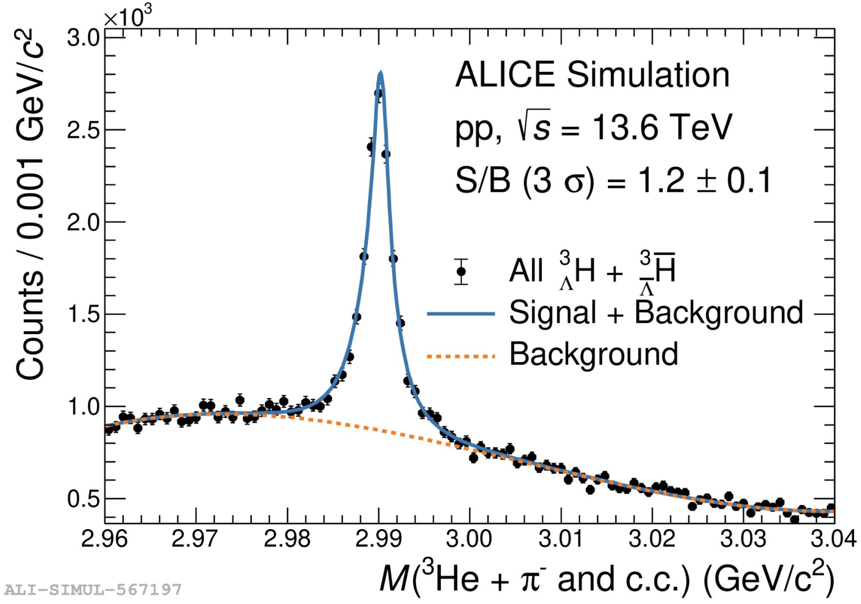
Before strangeness tracking





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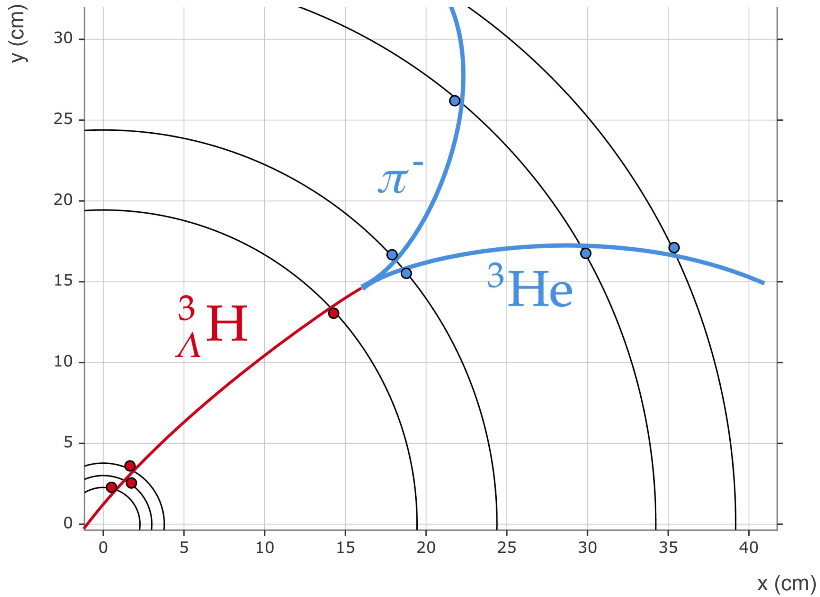
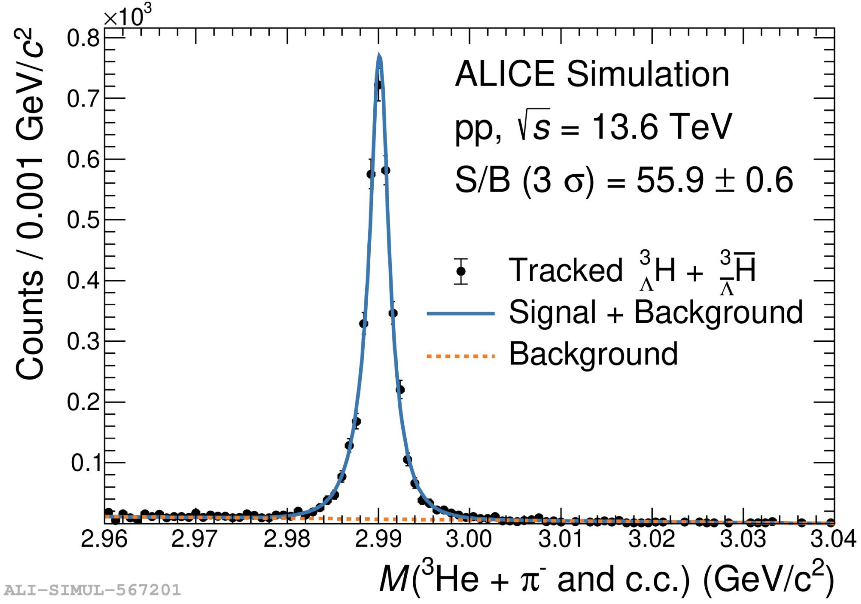




Outstanding background suppression!

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

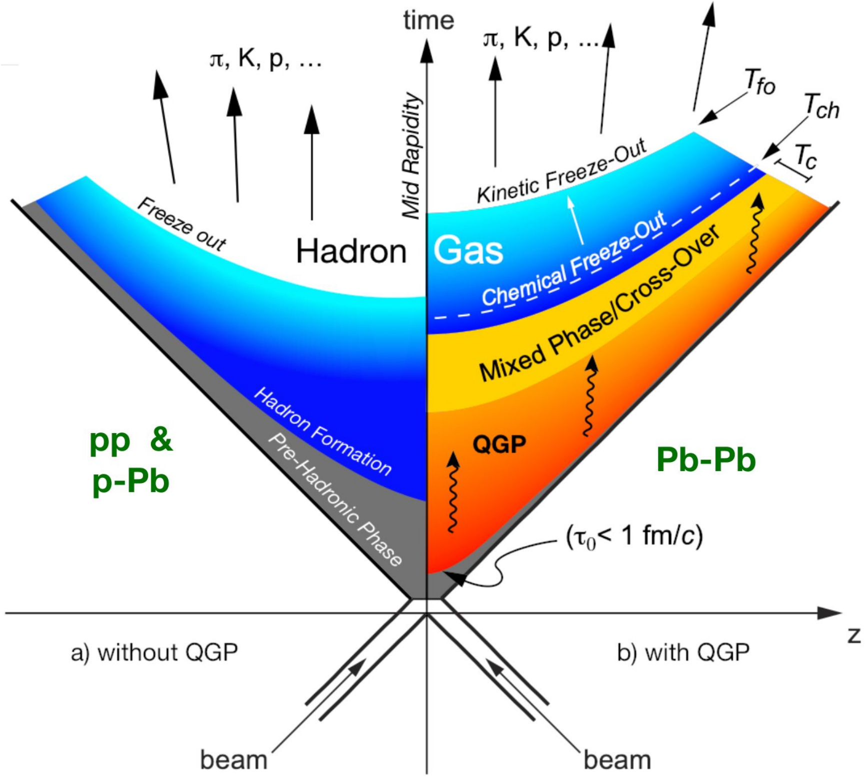
- First measurement of the ${}^{3}_{\Lambda}H$ production in p–Pb collisions:
  - ➢ ${}^{3}_{\Lambda}H$ / Λ favours coalescence expectation
  - ➢ Nuclear size matters at low-charged particle multiplicity

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

Additional material

(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_Λ ≅100 keV , T_{ch} ≅ 100 MeV
  - which is the formation mechanism of these objects at the LHC energies ?

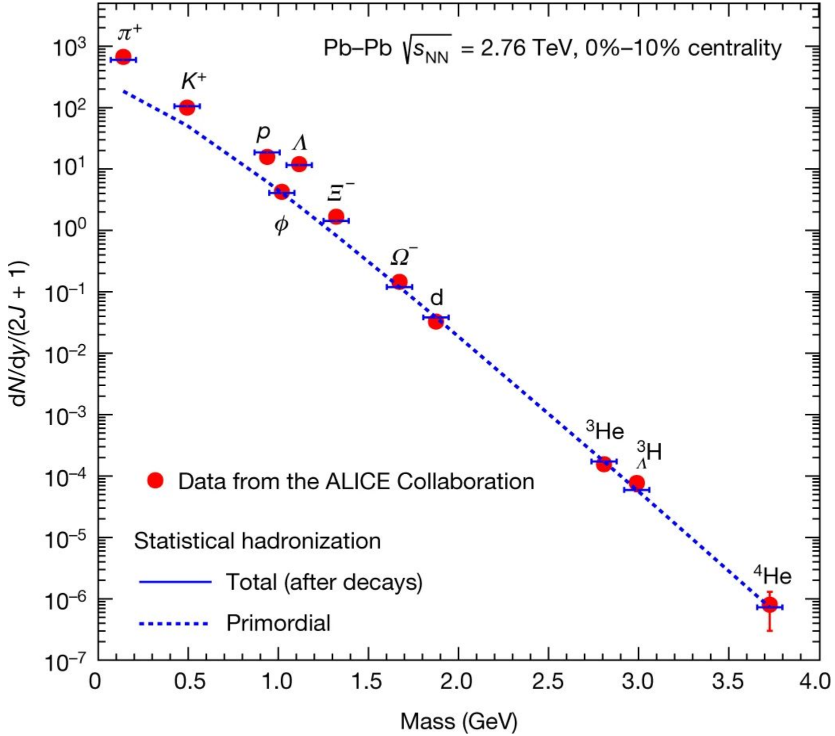


The Statistical Hadronisation Model (SHM)

- Hadrons emitted from the interaction region in statistical equilibrium when the system reaches the chemical freeze-out temperature

- Abundance of a species
    - $\propto \mathrm{Exp}(-m/T_{chem})$

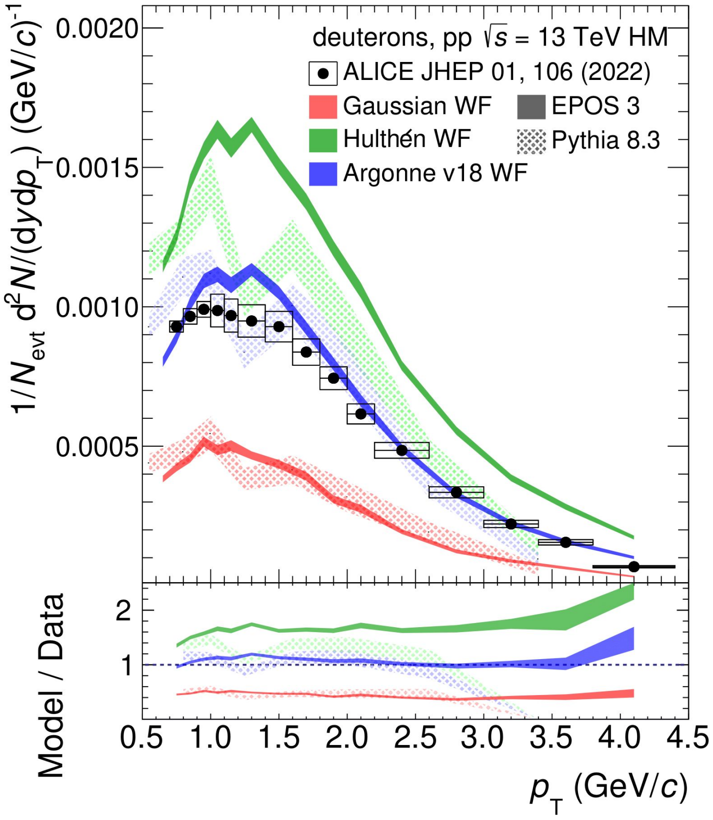
- Mainly used for Pb–Pb, it can be used in smaller systems (pp and p–Pb) by using the canonical ensemble



[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



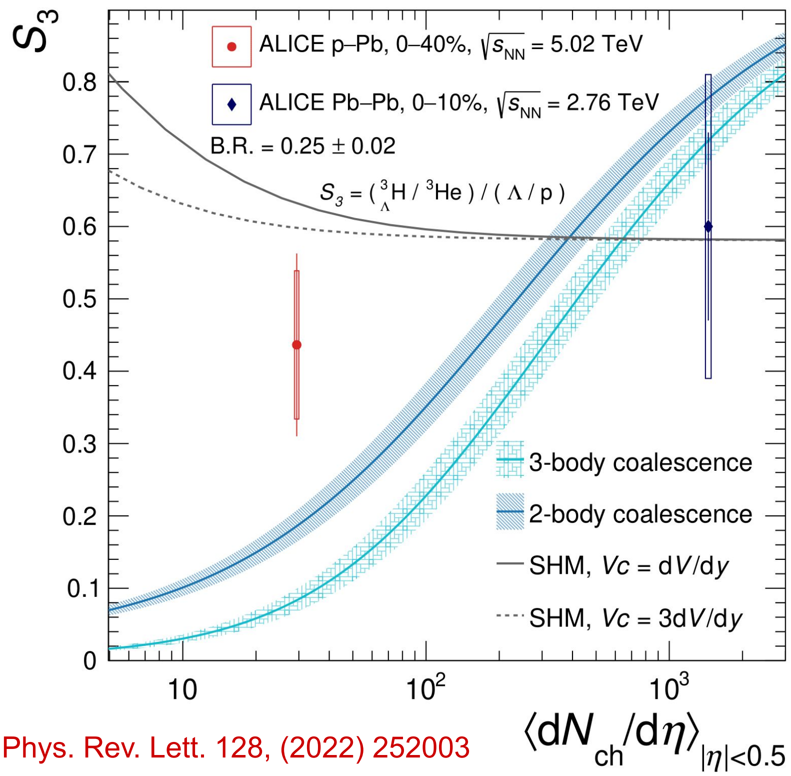
[1] Sun et al., Phys. Lett. B 792, (2019) 132
[2] Horst et al. , arXiv:2302.12696

Results

- S_3 : strangeness population factor

$$({}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He})/(\Lambda/\mathrm{p})$$

- S_3 in small systems:
  - same conclusions as for ${}^{3}_{\Lambda}\mathrm{H}$ / Λ but with a lower sensitivity
  - More measurements to come will explore the multiplicity dependence of the S_3



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

EFTs

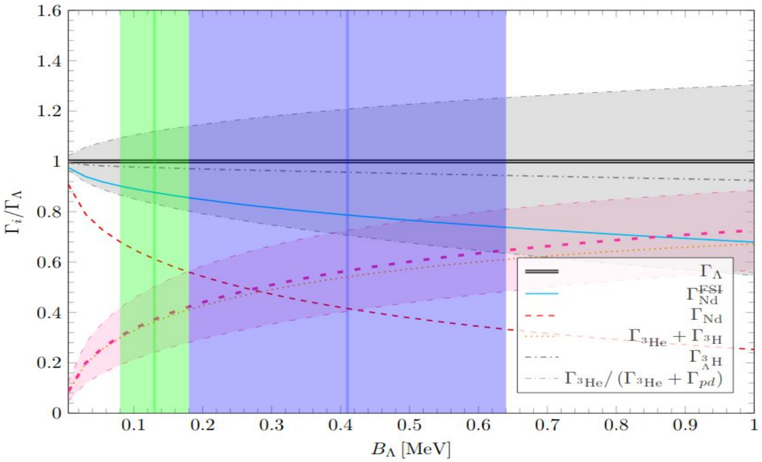
- Chiral EFT

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

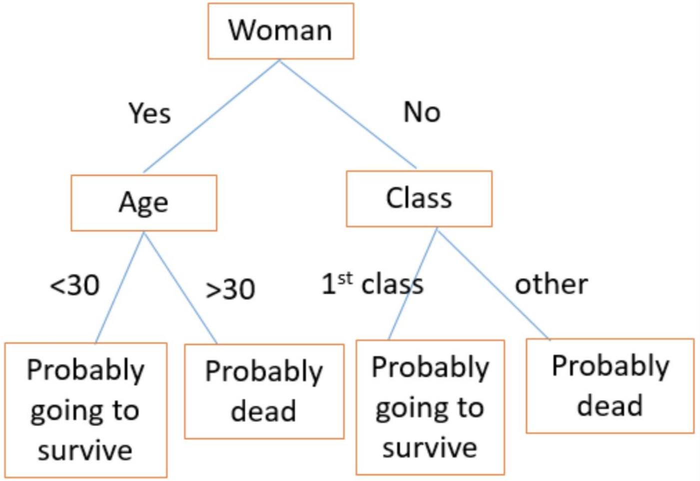


Mild B_Λ dependence

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

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

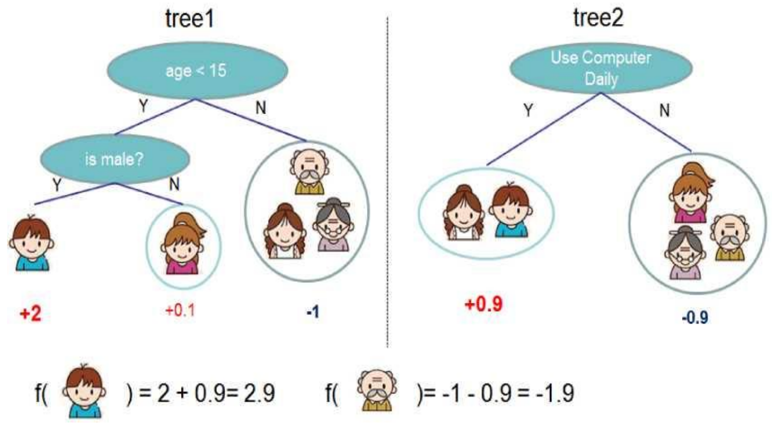
- DT: poor performances on independent samples → overfitting

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

Systematics

- Production yield: $$\frac{dN}{dy} = \frac{1}{\epsilon_{\rm pres}} \frac{1}{\epsilon_{\rm BDT}} \frac{1}{\rm N_{ev}} \frac{1}{\rm B.R.} \frac{1}{(1-f_{\rm abs})} \times N^{\rm raw}$$
- Multi-trial for systematic uncertainty due to signal selection and extraction
  - BDT selection: BDT efficiency variations of ± 5%
  - Signal extraction: signal and background fit function variations
- Absorption correction: cross section variations up to ± 50%
- Branching ratio (B.R.): never measured experimentally, data driven uncertainty based on the measurement of a derived quantity (R_3)
- Input p_T distribution: using different shapes that describe the ^{3}He spectrum

Systematic contribution	Value (%)
Signal selection and extraction	15 %
Choice of the $p_{\rm T}$ shape	7 %
Absorption in the detector	2 %
Branching ratio value	9 %
Total	19 %

Systematic uncertainties

- Common: multi trial approach to evaluate uncertainty on
  - BDT selection: BDT efficiency variations of ± 10%
  - Signal extraction: signal and background fit function variations
- Lifetime
  - Absorption cross section: cross section variations up to ± 50%
- B_Λ
  - Data driven shift δ^{data}: evaluated on the Λ mass repeating the analysis splitted for matter and antimatter, B^+ and B^- fields

τ

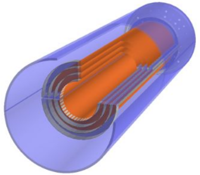
Systematic contribution	Value (ps)
Signal selection and extraction	5.2
Absorption in the detector	3
BDT hyperparameters	/
Input p_T shape	/
Linear selection vs ML	/
Total	6.0

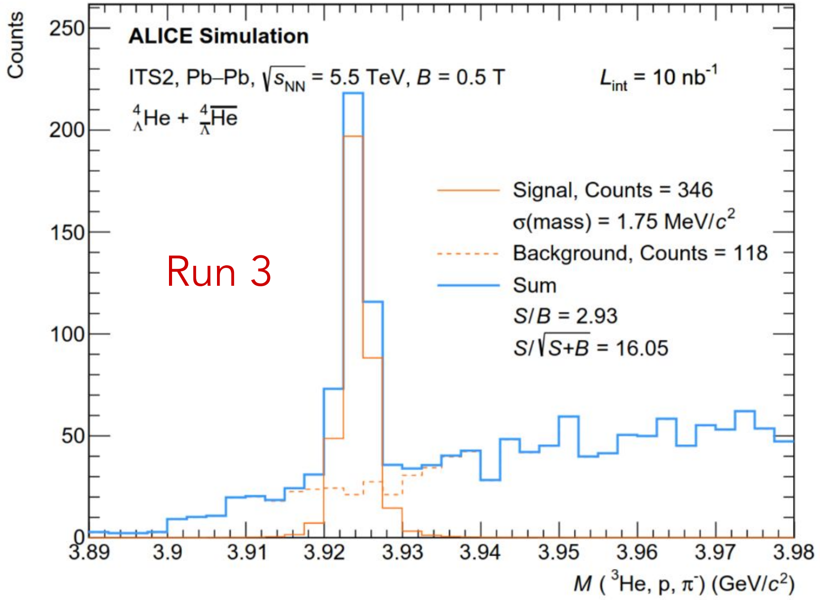
B_Λ

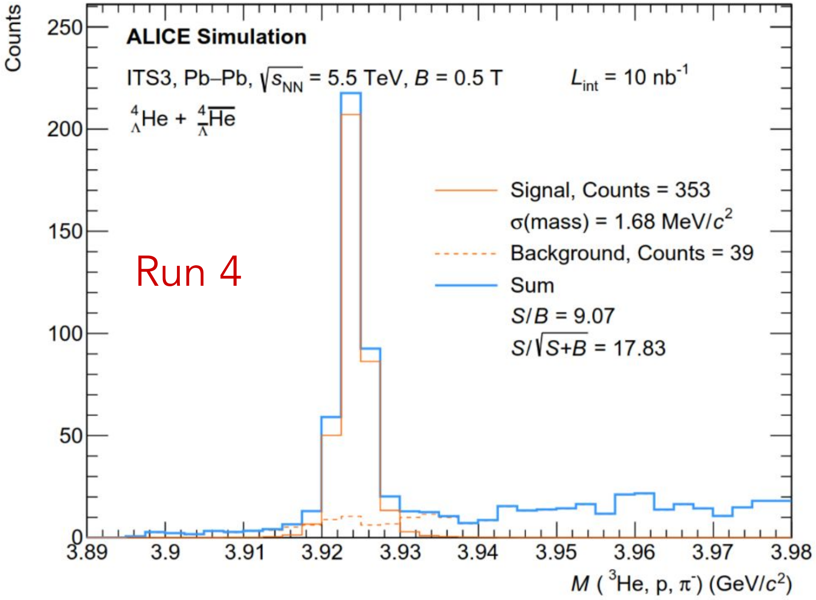
Systematic contribution	Value (keV)
Signal selection and extraction	28
Data-MC mismatch	61
BDT hyperparameters	/
Input p_T shape	/
Linear selection vs ML	/
Total	67

Beyond Run 3

- ITS3 will be installed during LS3
  - ➢ Truly cylindrical silicon pixel layers
  - ➢ Reduced material budget, closer to the IP (1.8 cm)







https://cds.cern.ch/record/2868015?ln=en

Improved impact parameter resolution → S/B improves by a factor 3

Final results

ALICE

ALICE pins down hypermatter properties

The collaboration's latest study of a "strange", unstable nucleus known as the hypertriton offers new insight into the particle interactions that may take place at the hearts of neutron stars

20 SEPTEMBER, 2022 | By ALICE collaboration

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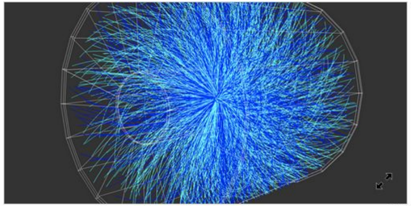
SYNOPSIS

How Tightly Bound Are Hypertritons?

September 5, 2023 • *Physics* 16, s129

Researchers have pinned down the binding energy and lifetime of the so-called hypertriton, a particle that could help explain the structure of neutron stars.



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Physics (PRL)

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SEPTEMBER 29, 2023 FEATURE Editors' notes

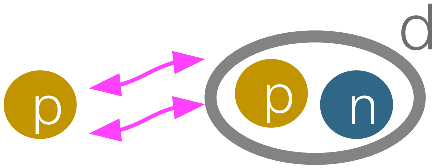
A new highly precise measurement of the hypertriton lifetime

by Ingrid Fadelli , Phys.org

PHYS.org

Beyond the synthesis: nuclear interactions

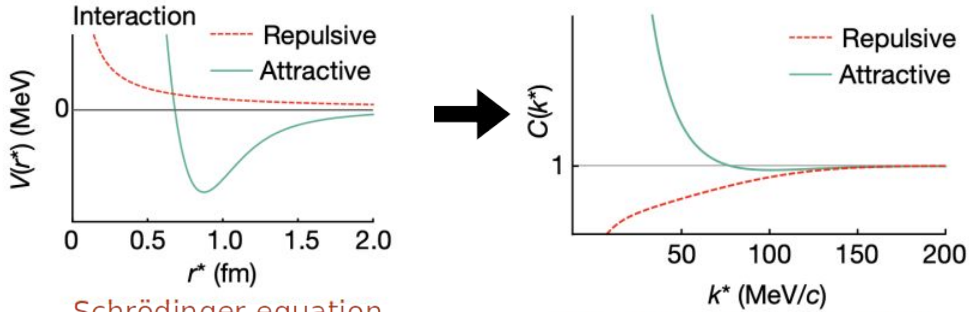
- Femtoscopic measurement of the proton - deuteron interaction in pp collisions
  - Access to the strong interaction and short-range dynamics between hadrons (~ 1-2 fm)



$$k^* = \frac{|\vec{p}_i^* - \vec{p}_j^*|}{2}$$

[1] Koonin, Physics Letters B 70 (1977) 43-47

- Two particle correlation function [1]: $C(k^*) = N\frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(r^*)|\psi(k^*,r^*)|^2 d^3r^*$
  - emitting source (anchored to p-p correlation in ALICE data) [2]
  - two-particle wave function



Schrödinger equation
Two-particle wave function

Correlation function C(k*)

[2] PLB 811 (2020) 135849
Nature 588 (2020) 232-238