Investigating the hyperon-nucleon strong interaction with a precision measurement of the hypertriton lifetime in ALICE

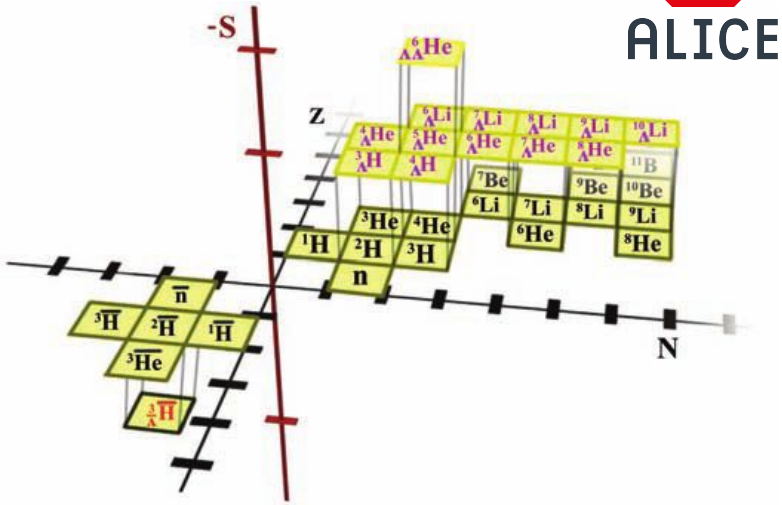
Francesco Mazzaschi [1, 2]
on behalf of the ALICE Collaboration

ICHEP 2020, Prague, 31/07/2020

Università degli Studi di Torino [1], INFN Torino [2]

Hypertriton

- Lightest known hypernucleus:
  - bound state of a neutron, a proton and a Λ
  - mass: 2.99116 ± 0.00005 GeV/c^2 [1]
- Unique probe for understanding the strong interactions beyond the u and d quark sector:
  - Λ hyperons can "explore" the nuclear structure without being affected by the Pauli principle

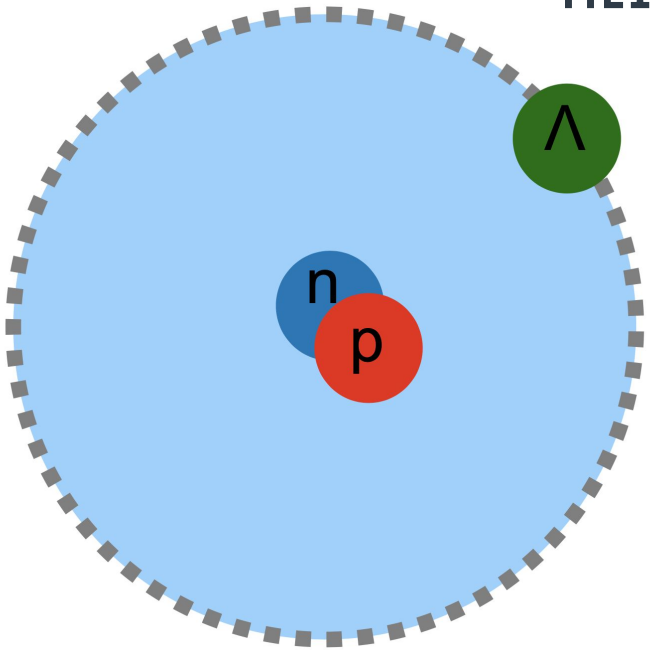


- Hypertriton in ALICE reconstructed via its mesonic charged decay channels
  - $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi$ B.R. = 0.25
  - $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi$ B.R. = 0.40

[1] D.H. Davis., Nucl. Phys. A 754 (2005) 3-13

Hypertriton as a d-Λ bound state

- Hyperons could be produced in the inner core of neutron stars [1]
  - hypertriton is a powerful tool to study the Λ-nucleus interaction
- The measured Λ separation energy E_Λ is only 130 ± 50 keV [2]:
  - hypertriton could be approximated as a bound state of a deuteron and a Λ
- Recent calculations [3] based on pionless 3-body Effective Field Theory (EFT) show a large separation between the Λ and the "deuteron core"
  - $r = 10.79^{+3.04}_{-1.52}\,\mathrm{fm}$

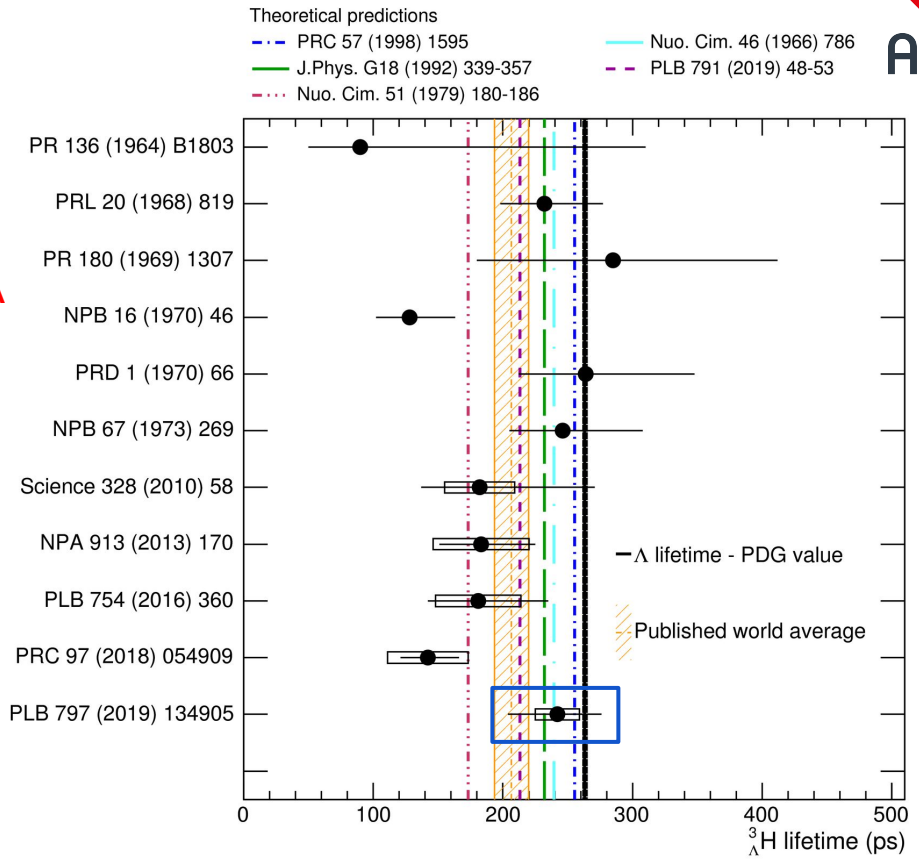


[1] L. Tolos et al., Progress in Particle and Nuclear Physics, 112 (2020)
[2] M. Jurič et al., Nucl. Phys. B, 52 (1973), p. 1
[3] F. Hildenbrand et al., Phys. Rev. , 100 (2019)

The lifetime puzzle

- Low Λ separation energy
  - expected lifetime of the hypertriton close to the free Λ hyperon one (263.2±2.0 ps) [1]

- Recent measurements [2] lower than predictions: latest ALICE published result [3] compatible within 1σ with most of the theoretical models

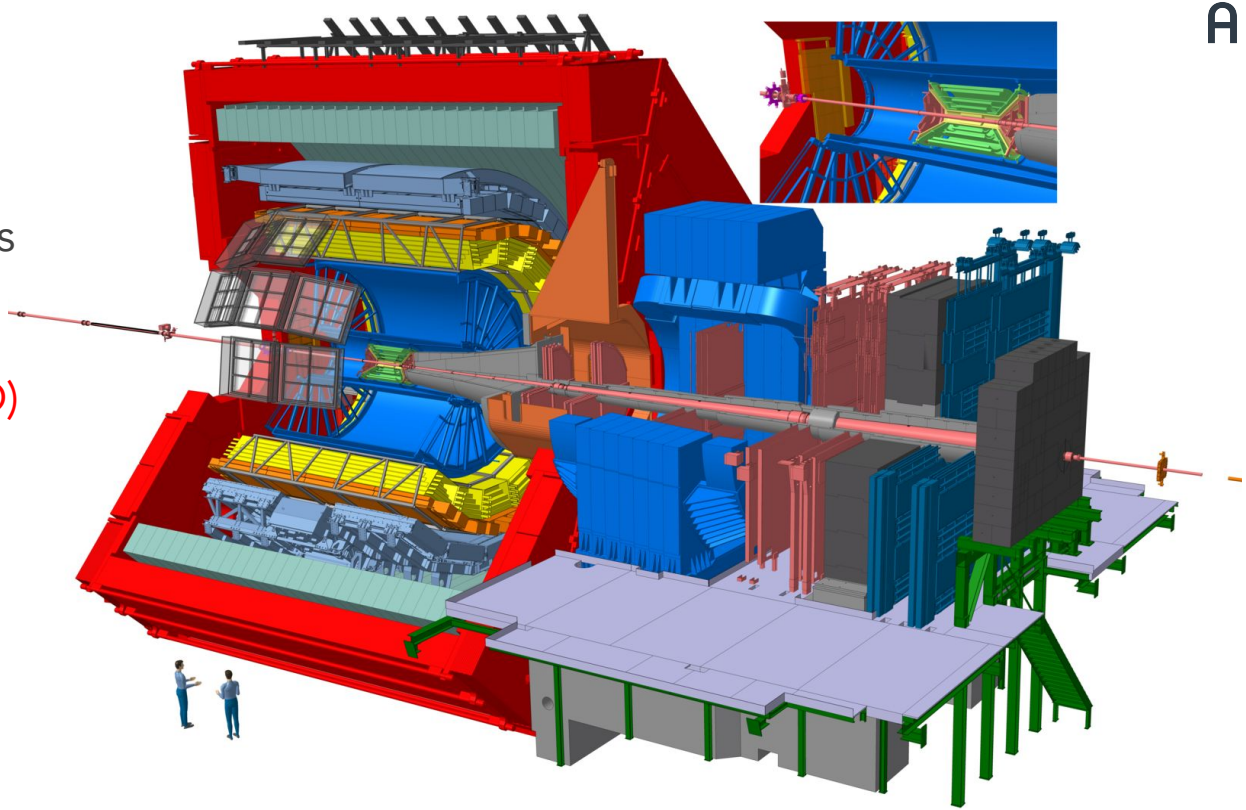


[1] Kamada et al., Physical Rev.C 57.4, p. 1595 (1998)
[2] STAR Collaboration Phys. Rev. C 97, 5, 054909 (2018)
[3] ALICE Collaboration Phys. Lett. B 797, 134905 (2019)

A new precise lifetime measurement is crucial to finally shed light on the hypertriton internal structure

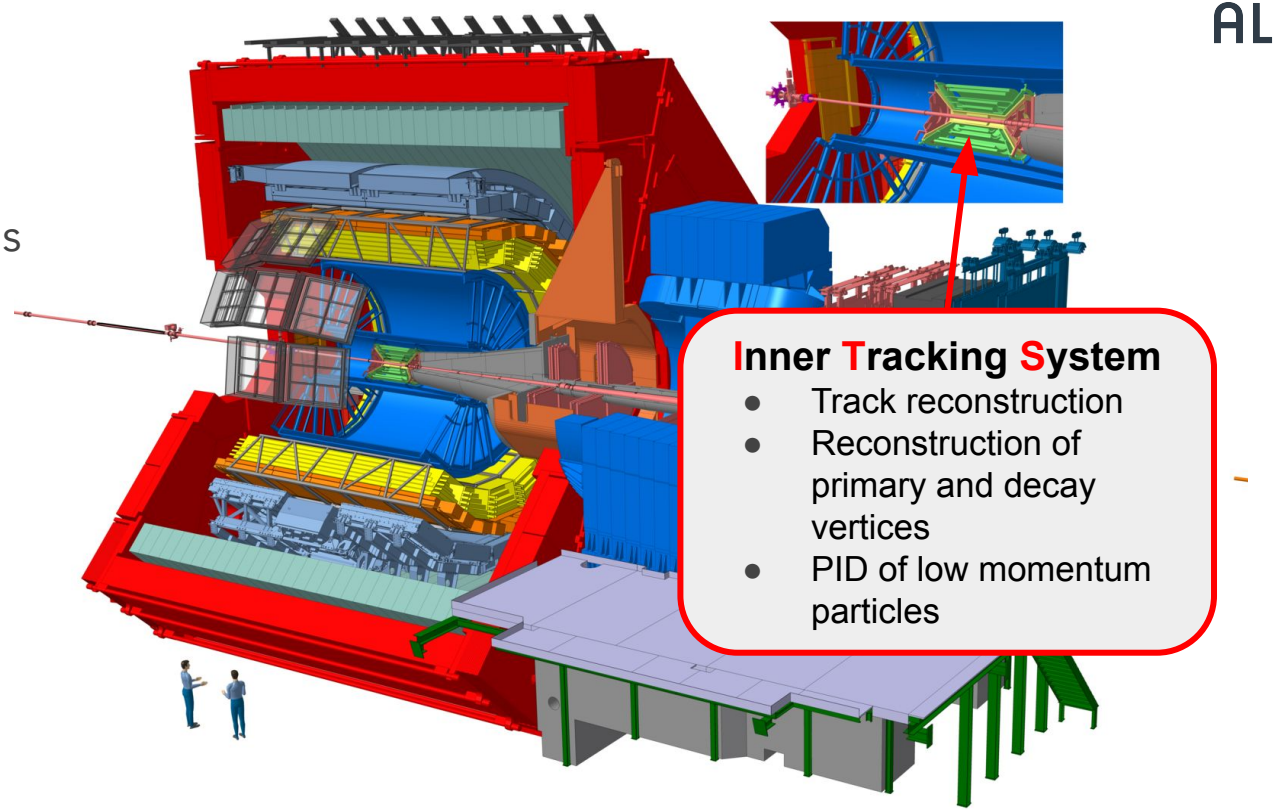
The ALICE detector

- We can identify the hypertriton daughter particles exploiting the excellent particle identification (PID) of the ALICE apparatus



The ALICE detector

- We can identify the hypertriton daughter particles exploiting the excellent PID of the ALICE apparatus

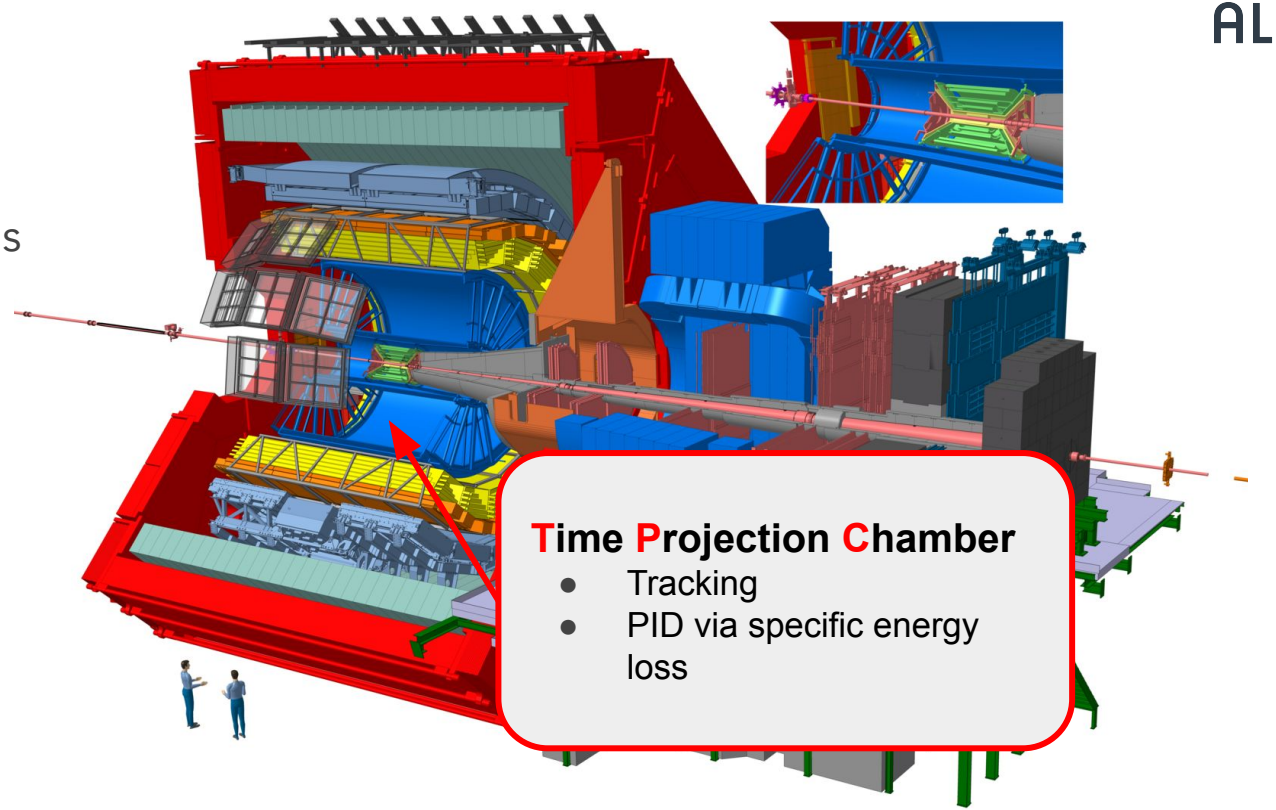


Inner Tracking System

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

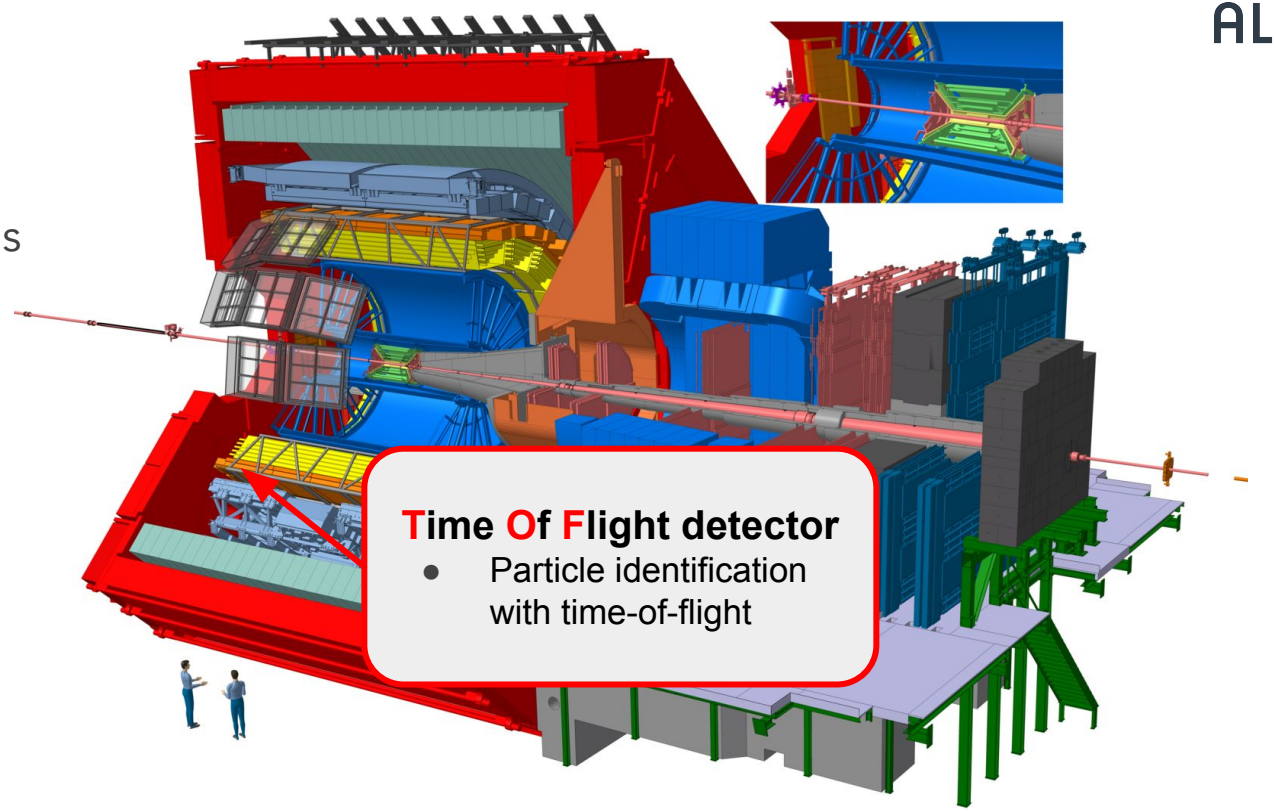
The ALICE detector

- We can identify the hypertriton daughter particles exploiting the excellent PID of the ALICE apparatus



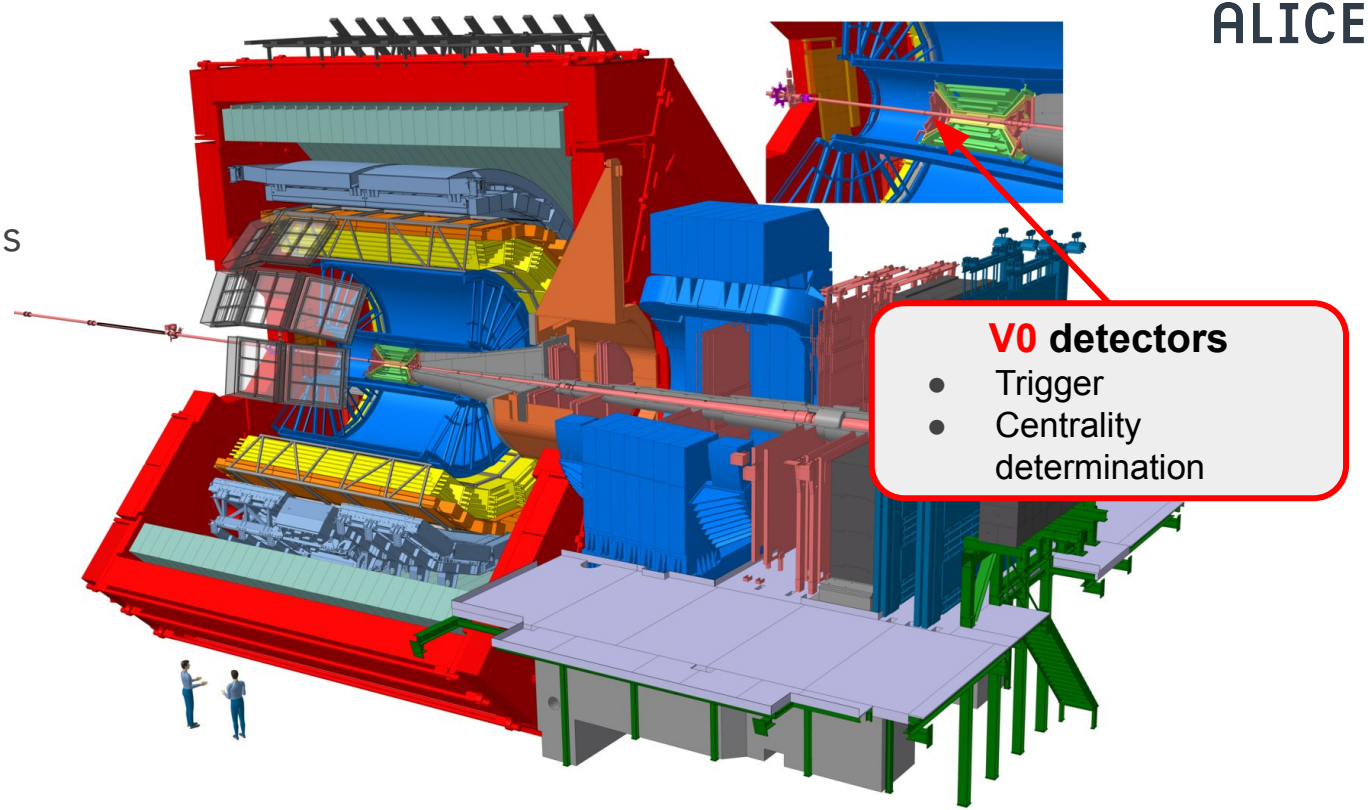
The ALICE detector

- We can identify the hypertriton daughter particles exploiting the excellent PID of the ALICE apparatus



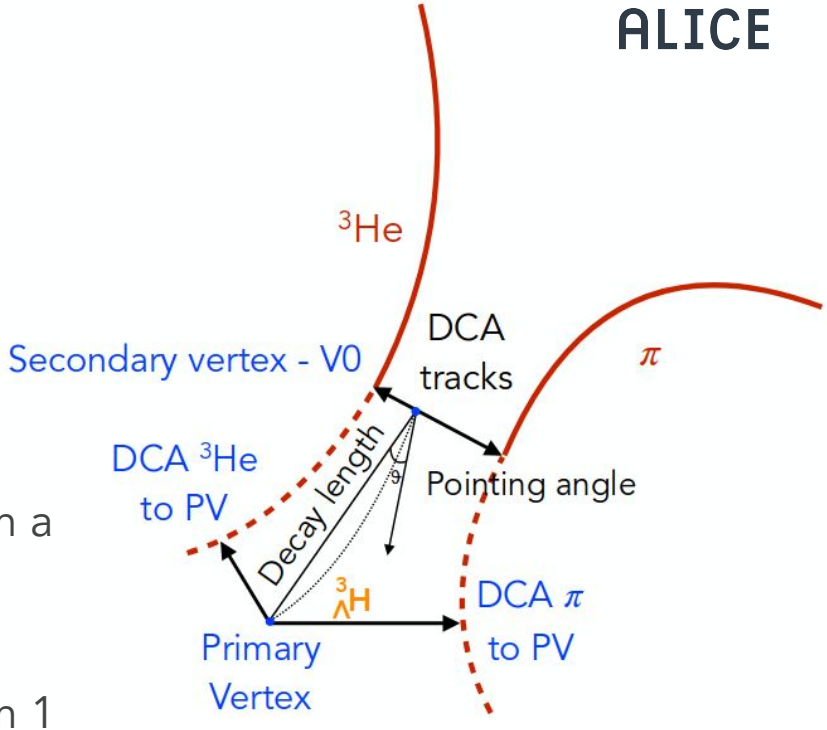
The ALICE detector

- We can identify the hypertriton daughter particles exploiting the excellent PID of the ALICE apparatus



Hypertriton in the two-body decay channel

- Analysed data sample:
  - Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE in 2018
- Hypertriton candidate: ^{3}He + π^- pairs (and related charge conjugates)
- Secondary vertex reconstruction
  - matching of ^{3}He + π^- tracks coming from a common vertex
- Candidates divided in 9 different ct bins from 1 to 35 cm

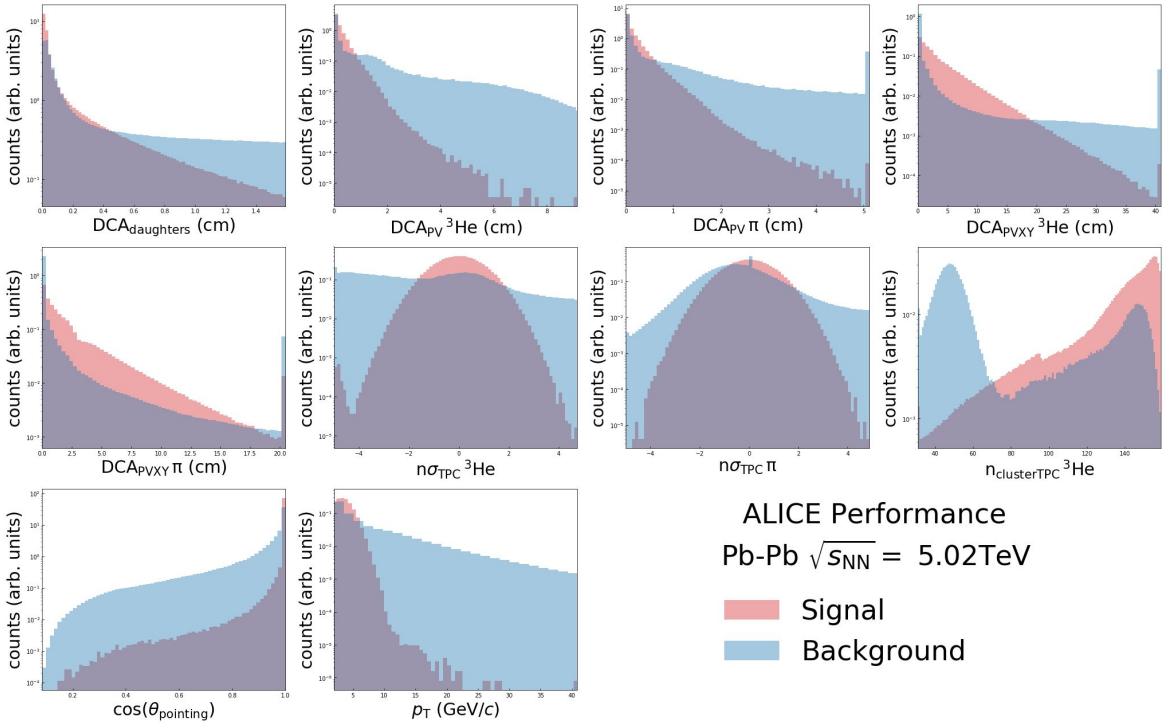


Hypertriton selection: machine learning approach

- Boosted Decision Trees Classifier (BDT) to discriminate between signal and background candidates

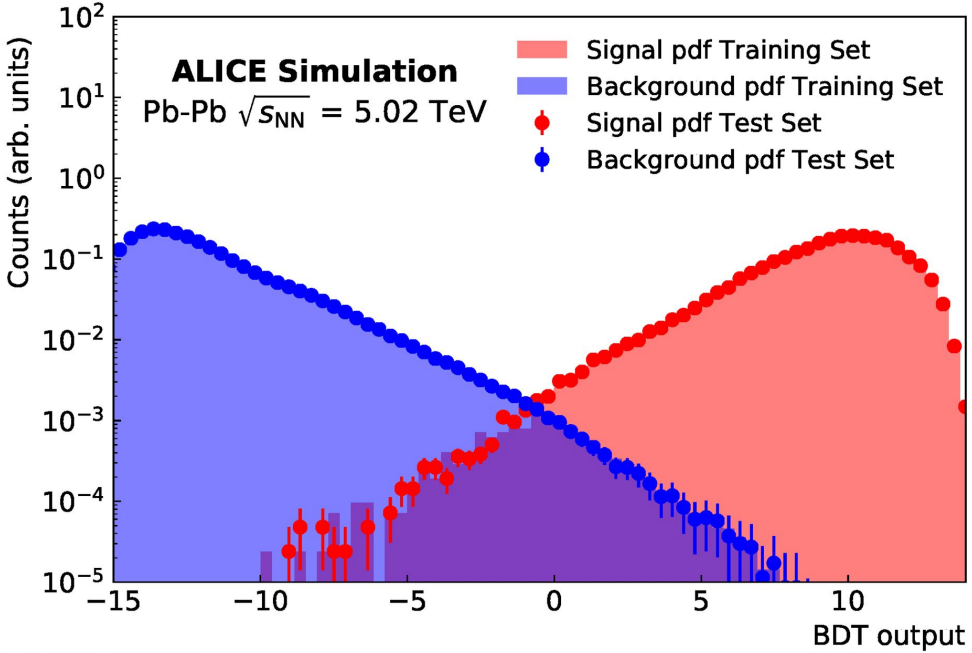
- BDT training and testing on a dedicated sample containing labeled signal and background candidates

  - Signal candidates taken from Monte Carlo
  - Background candidates taken from like-sign (^{3}He + π^+ pairs)



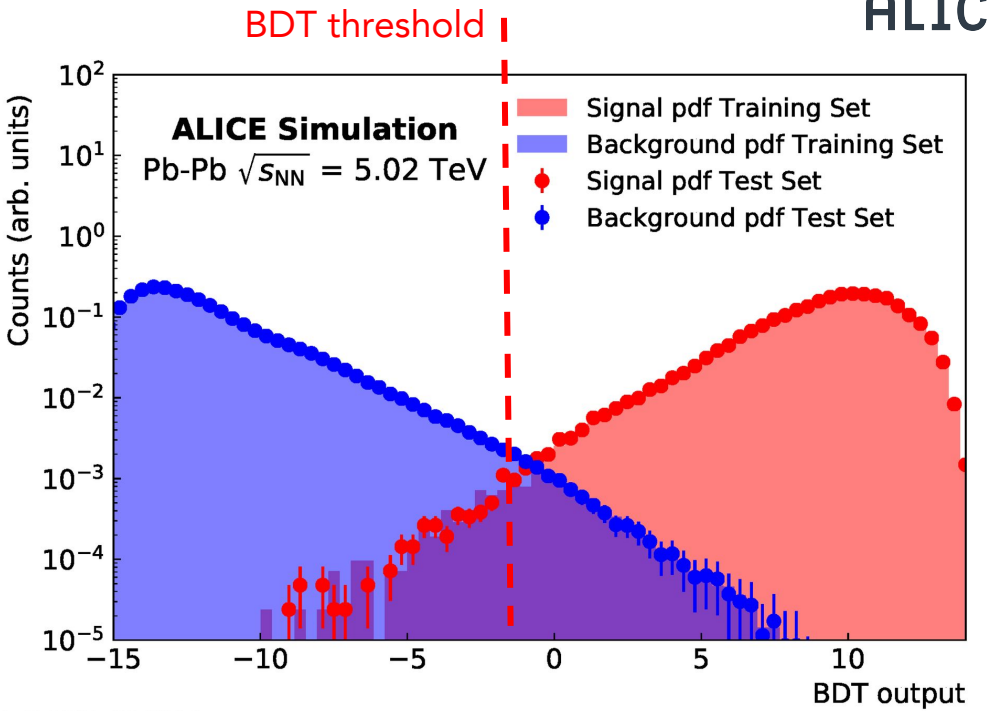
Hypertriton selection: BDT output

- BDT output (independent trainings for each *ct* bin) :
  - Score related to the probability of the candidate to be signal or background
- High discrimination power and no overfitting



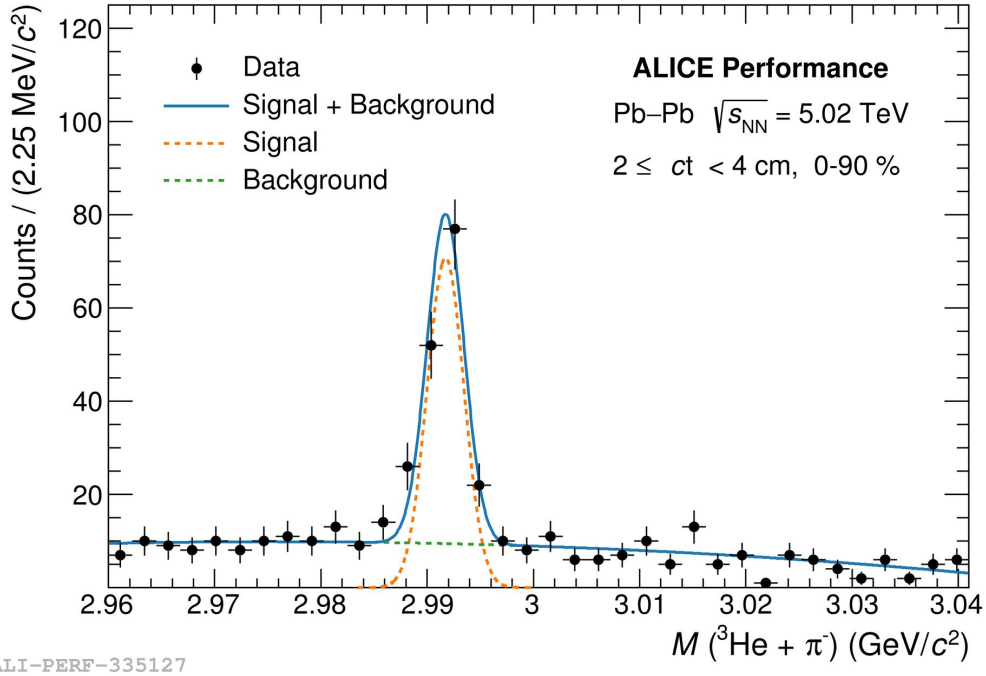
Hypertriton selection: BDT output

- The BDT model reduces the dimensionality of the selection problem
  - selection on the BDT score only
- How to choose it?
  - maximisation of the expected significance (assuming thermal production)

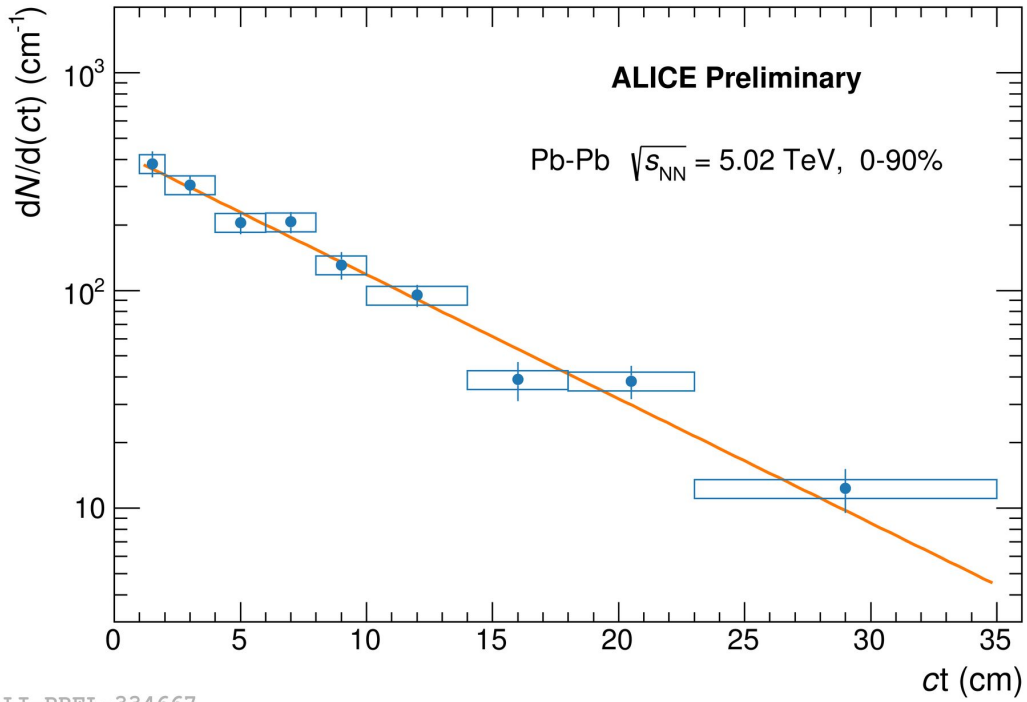


Signal extraction

- Signal extracted with a fit to the invariant mass spectrum of the selected candidates
  - Background fitted with a polynomial
  - Signal fitted with a Gaussian
- Signal extracted in 9 *ct* bins from 1 to 35 cm



Lifetime

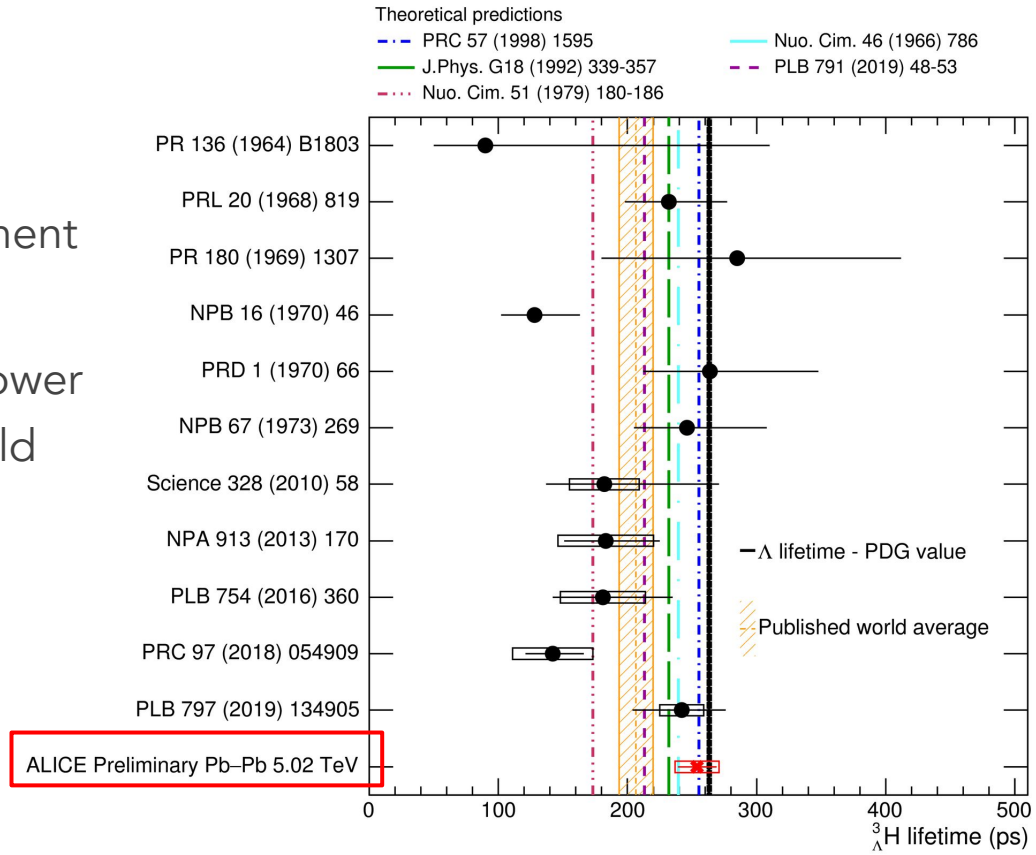


ALI-PREL-334667

- Corrected *ct* spectrum fitted with exponential function
- Lifetime value from the fit
  - 254 ± 15 (stat.) ± 17 (syst.) ps
- Statistical uncertainty ~ 6%
- Systematic uncertainty (boxes) ~ 6.7%

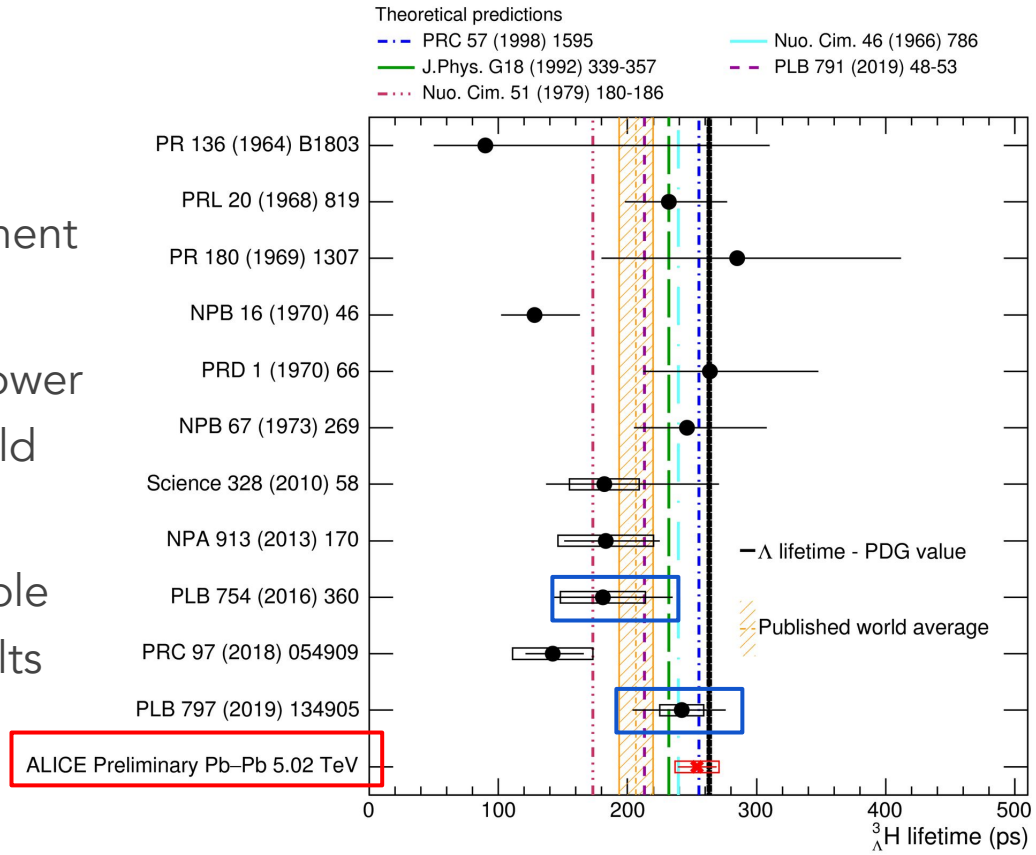
Lifetime - discussion

- Most precise measurement in the world
- Statistical uncertainty lower than the published world average uncertainty



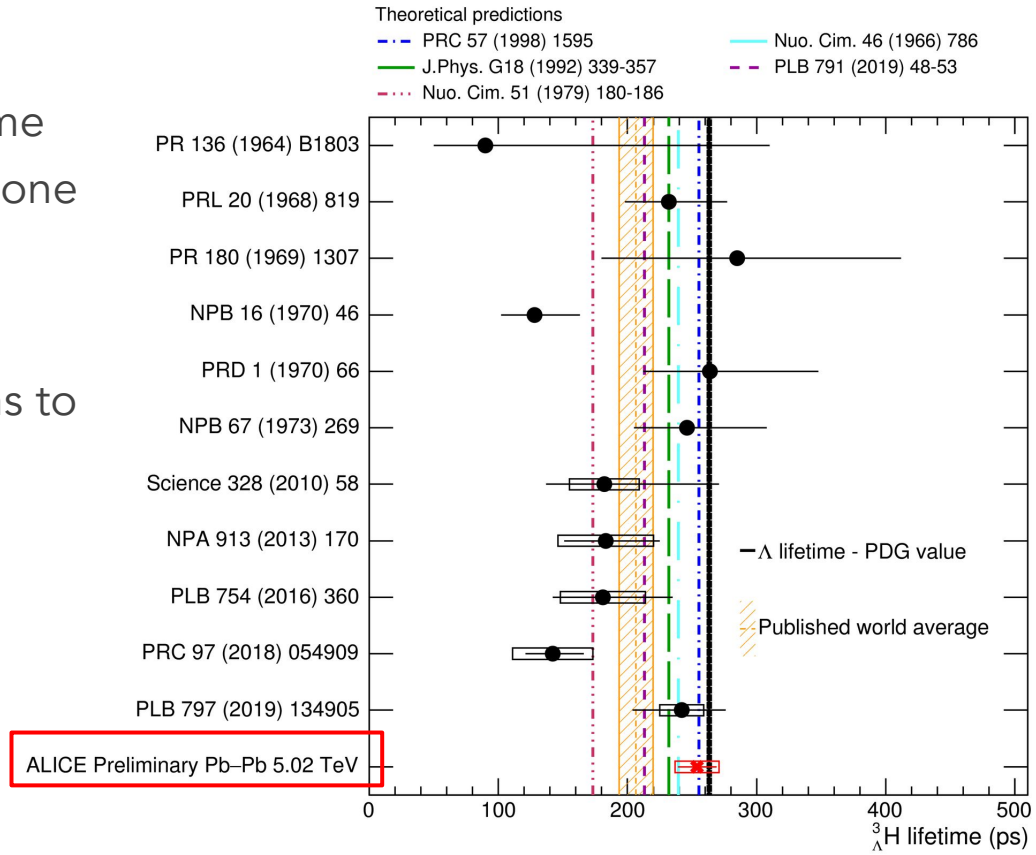
Lifetime - discussion

- Most precise measurement in the world
- Statistical uncertainty lower than the published world average uncertainty
- Measurement compatible with former ALICE results



Lifetime - discussion

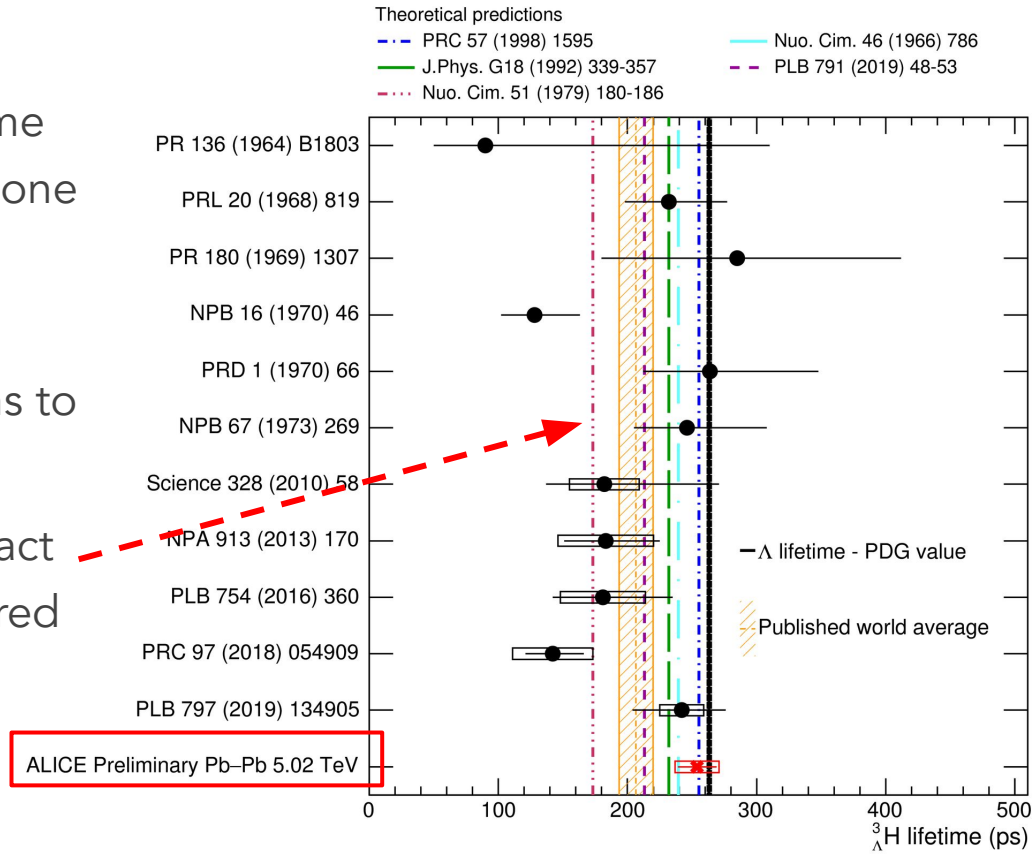
- Models predicting lifetime to be near to the free Λ one are favoured
  - hypertriton weakly bound nature seems to be confirmed



[1] H. M. M. Mansour et al., Nuo.Cim. 51, p. 180-186 (1979)

Lifetime - discussion

- Models predicting lifetime to be near to the free Λ one are favoured
  - hypertriton weakly bound nature seems to be confirmed
- Models assuming compact hypertriton are disfavoured (3.6σ far from [1])



[1] H. M. M. Mansour et al., Nuo.Cim. 51, p. 180-186 (1979)

Summary

- ALICE has performed a new measurement of the hypertriton lifetime in the 2-body decay channel in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV using a machine learning approach for the signal selection
  - higher precision with respect to all the previous measurements
  - lifetime value confirms that hypertriton is a weakly bound state of a deuteron and a Λ

Thanks for your attention!

Backup

Short lifetime: possible explanations

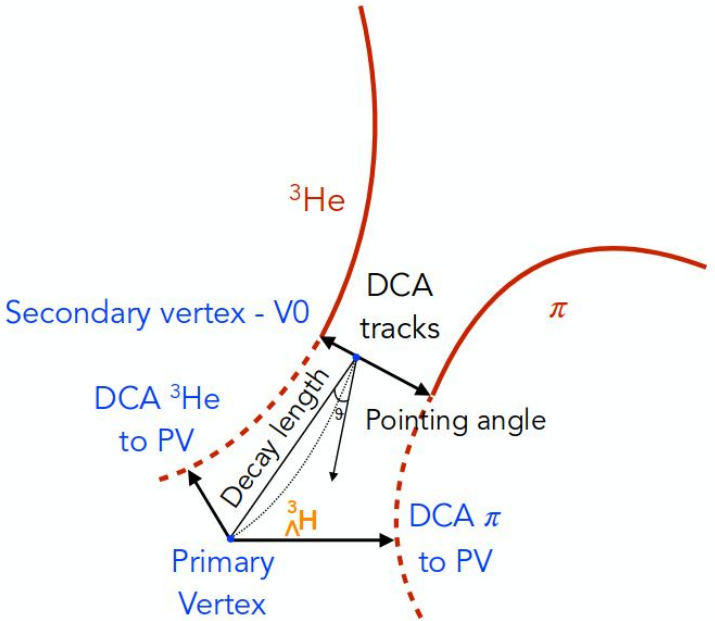
- The free Λ lifetime value is a consequence of a striking fine-tuned cancellation between two pole terms:
  - hypertriton decay breaks this effect and consequently the transition amplitude is enhanced → shorter lifetime [1]
- The real E_Λ is larger than the measured one
  - STAR latest measurement [2] :
    - $E_\Lambda = 0.41 \mp 0.12\ (\text{stat.}) \mp 0.11\ (\text{syst.})$
  - emulsion experiments + EFT are not in agreement with this hypothesis [3]

[1] J.M. Richard et al., arXiv:1604.04208
[2] STAR Collaboration, Nature Physics 16 (2020), 409–412
[3] H.-W. Hammer, "Hypertriton Structure", "Origin of nuclear clusters in hadronic collisions" Workshop(https://indico.cern.ch/event/893621/timetable/)

Why Machine Learning ?

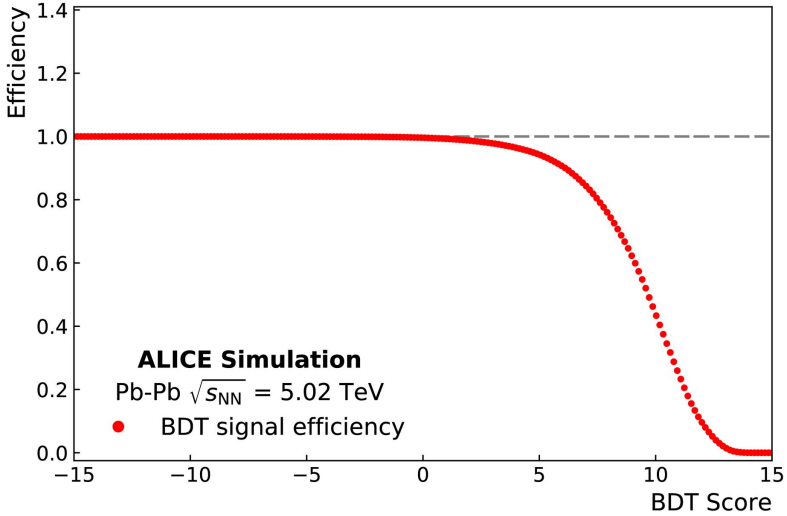
- Huge combinatorial background in heavy-ion collisions
  - pions are the most abundant species produced in the collisions (~ 1700 per event in central collisions)
  - thousands of hypertriton candidates for each ^{3}He identified

- Previous analyses were based on manual selections on topological and track observable
  - new selection approach employing a machine learning algorithm

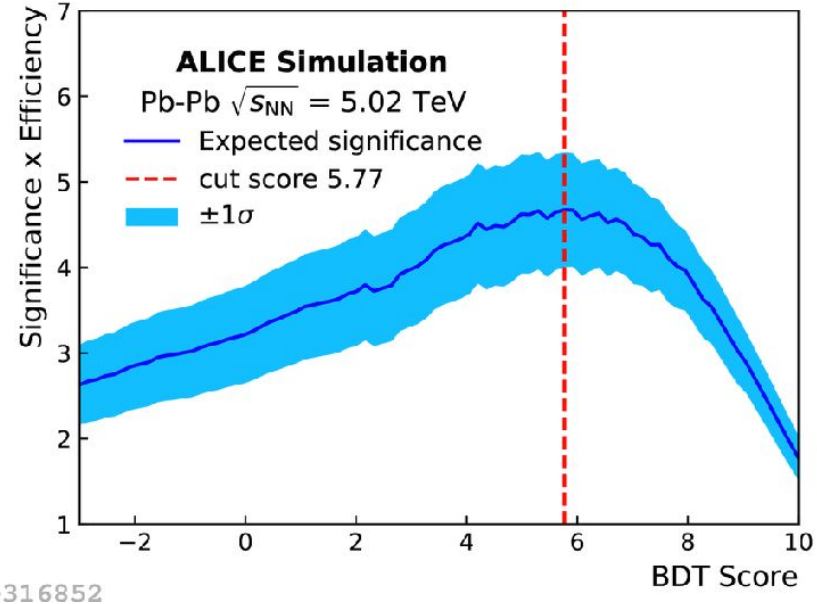


Hypertriton selection: choice of the BDT threshold

- Choice of the BDT threshold: BDT cut that maximizes the product between the expected significance (estimated from the previous measurements) and the BDT efficiency



ALI-SIMUL-316848



ALI-SIMUL-316852

Lifetime - systematic uncertainties

- ML selection and signal extraction
  - evaluated following a multi-trial approach
    - simultaneous variation of BDT thresholds and background fit functions for each *ct* bin
    - systematic uncertainty evaluated re-computing the lifetime for 10^5 different combinations of BDT thresholds and fits
- Other contributions
  - absorption in the ALICE detector
  - material budget

Contribution	Value
Signal selection and extraction	4.3%
Absorption	5%
Material budget	0.6%
Total	6.7%

Perspectives: hypertriton in the 3-body channel

- Hypertriton in the 3-body channel
  - lifetime measurement(combined with the 2-body one) could definitely solve the lifetime “puzzle”
  - could provide a first estimate of the 2-3 body relative Branching Ratio

- 3-body decay
  - Enormous combinatorial background
  - more complexity but also more variables for feeding the BDT!