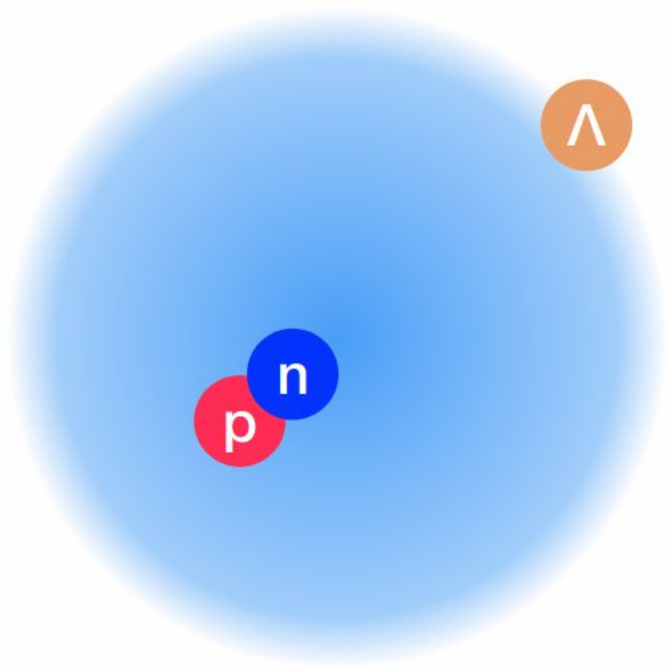
Hypertriton production in large and small systems

Francesco Mazzaschi [1, 2]
on behalf of the ALICE Collaboration
HADRON 2021, Mexico City, 30/07/2021

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

Hypertriton ($^{3}_{\Lambda}H$)

- Lightest known hypernucleus
  - bound state of a neutron, a proton and a Λ
  - the measured Λ separation energy B_{Λ} is only 130 ± 50 keV [1]:
    - hypertriton could be approximated as a bound state of a deuteron and a Λ
- Unique probe for understanding the Λ-nucleus interaction, with strong implications for astro-nuclear physics
  - hyperons are expected to be produced in the inner core of neutron stars [2]

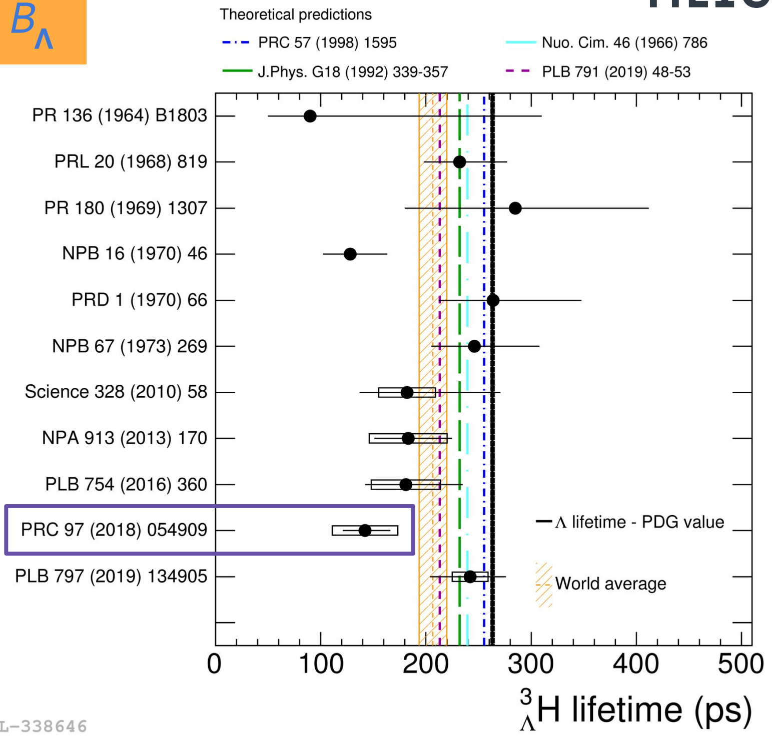


[1] D.H. Davis., Nucl. Phys. A 754 (2005) 3-13
[2] L. Tolos et al., Progress in Particle and Nuclear Physics, 112 (2020)

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

$^{3}_{\Lambda}$H in large systems (Pb-Pb collisions): lifetime and B_{Λ}

- $^{3}_{\Lambda}$H expected to be a weakly bound state with a radius of ~ 10 fm [1]
  - small B_{Λ} implies a lifetime close to the free Λ hyperon one
- recent results from STAR suggest that $^{3}_{\Lambda}$H could be more compact than expected [2, 3]
  - precise measurements are required to shed light on the $^{3}_{\Lambda}$H structure



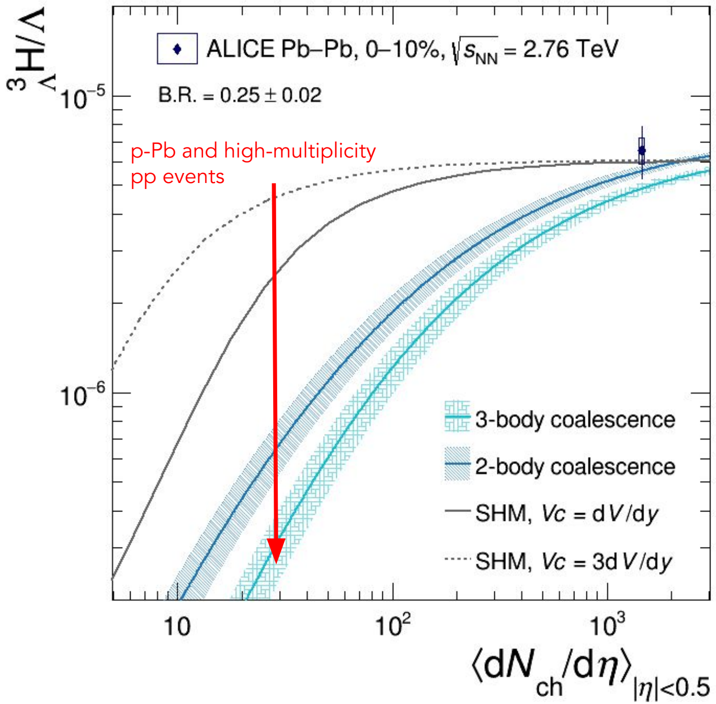
[1]Hildenbrand, F., & Hammer, H.W. (2019). Phys. Rev. C, 100(3), 034002
[2] STAR Collaboration Phys. Rev. C 97, 5, 054909 (2018)
[3] STAR Collaboration, Nature Physics 16 (2020), 409–412

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

$^{3}_{\Lambda}H$ production in small systems (pp and p-Pb collisions)

- loosely bound nature of $^{3}_{\Lambda}H$ has strong implications for its production mechanism
  - thermal (SHM) [1] and coalescence[2] predictions well separated at low charged-particle multiplicity density
- Studying $^{3}_{\Lambda}H$ production in pp and p-Pb is a key to understand the nuclear production mechanism in the hot and dense matter

ALICE Collaboration (2016). *Phys. Lett. B, 754, 360–372.*



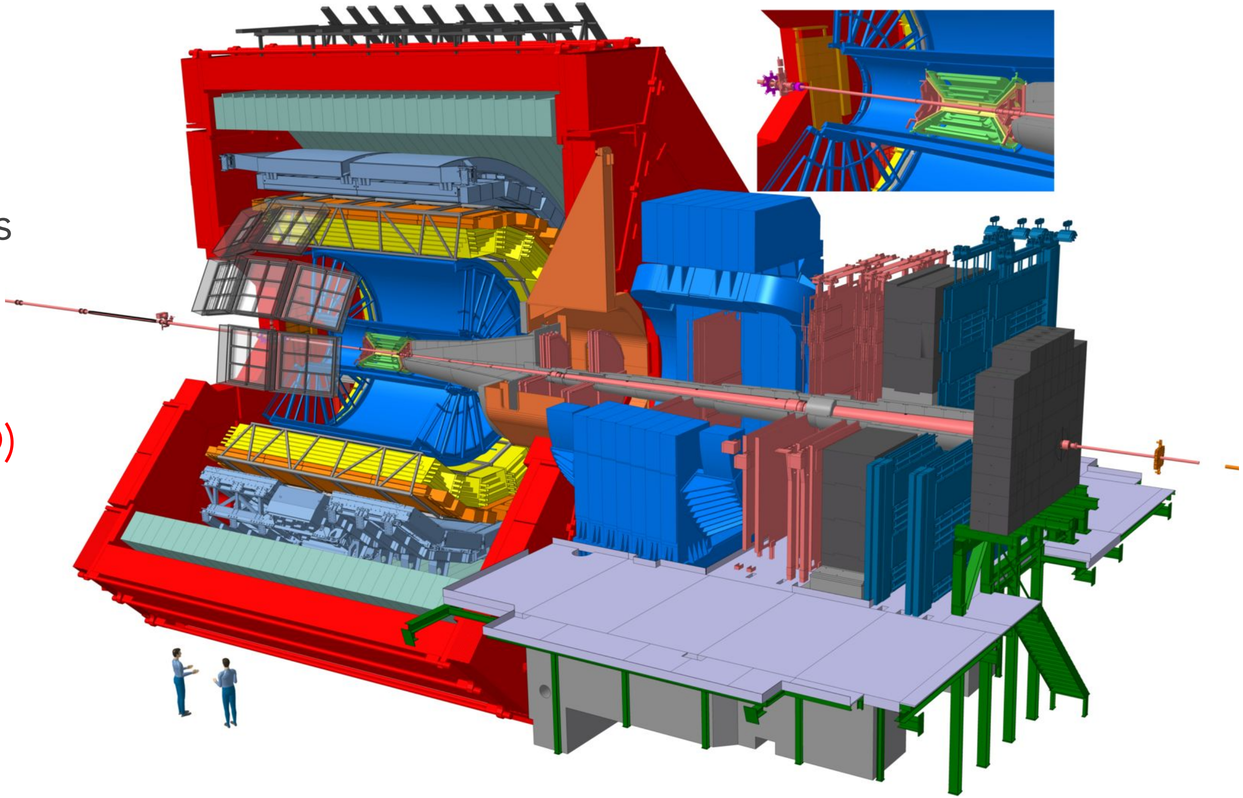
[1]Vovchenko, V., Dönigus, B., & Stoecker, H. (2018). *Phys. Lett., B785, 171-174.*
[2]Sun, K.J., Ko, C., & Dönigus, B. (2019). *Phys. Lett. B, 792, 132–137.*

Hypertriton in large systems

Precision measurements of lifetime and B_{Λ} in Pb-Pb collisions

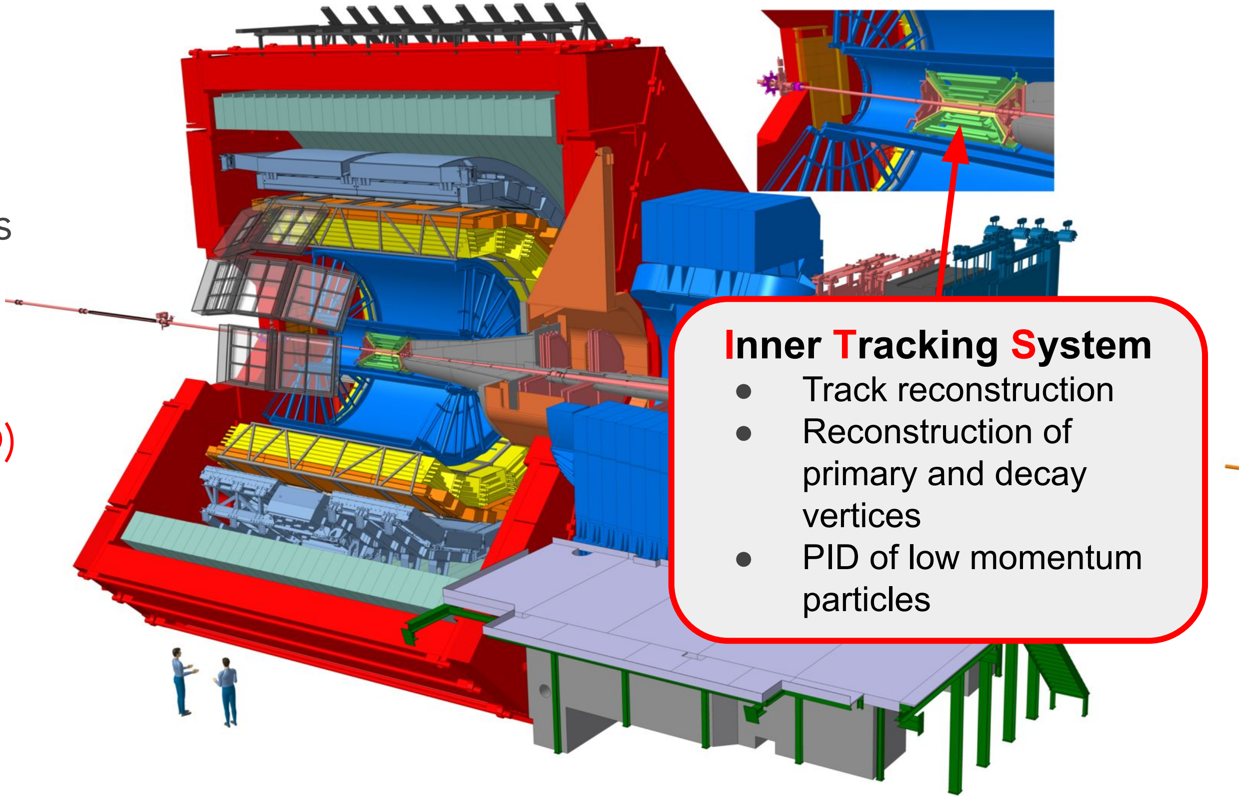
The ALICE detector

- We can identify the hypertriton daughter particles (^{3}He and π^{-}) exploiting the excellent particle identification (PID) of the ALICE apparatus



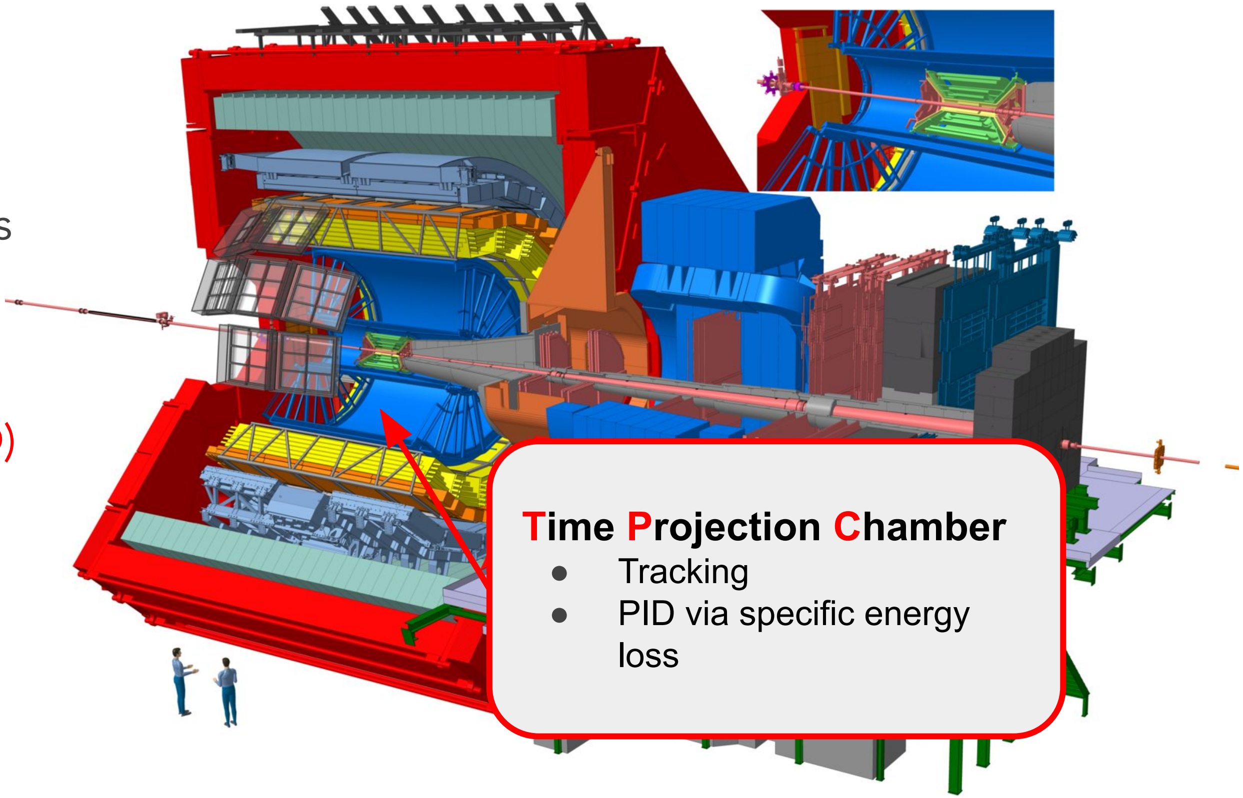
The ALICE detector

- We can identify the hypertriton daughter particles (^{3}He and π^{-}) exploiting the excellent particle identification (PID) of the ALICE apparatus



The ALICE detector

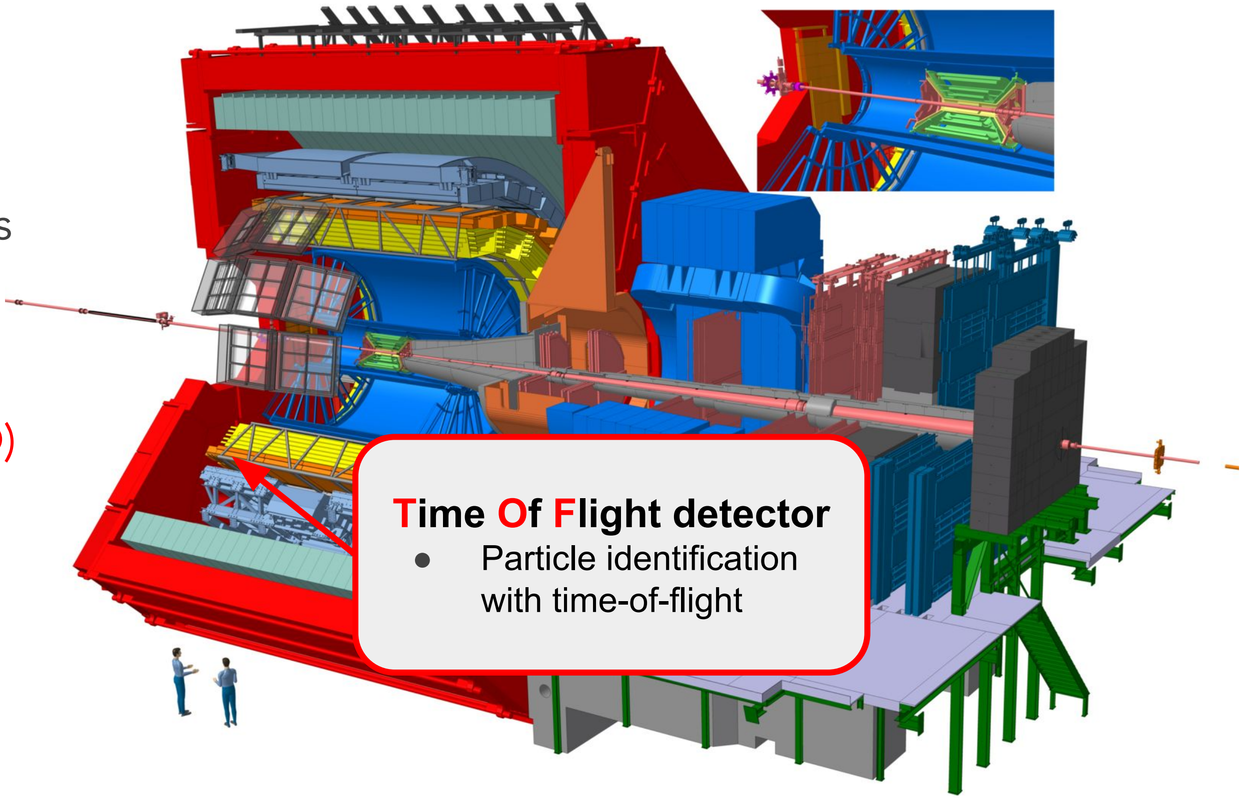
- We can identify the hypertriton daughter particles (^{3}He and π^-) exploiting the excellent particle identification (PID) of the ALICE apparatus



Time Projection Chamber
- Tracking
- PID via specific energy loss

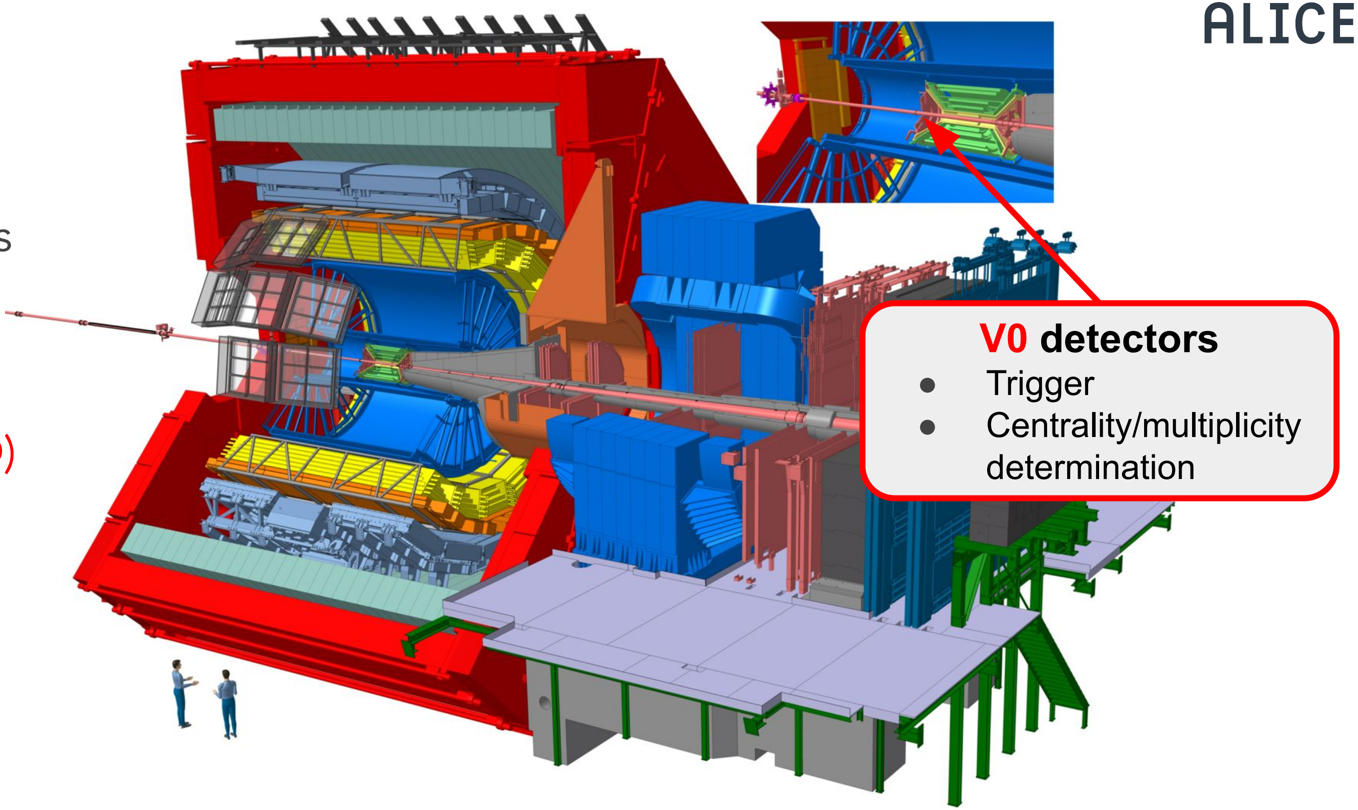
The ALICE detector

- We can identify the hypertriton daughter particles (^{3}He and π^{-}) exploiting the excellent particle identification (PID) of the ALICE apparatus



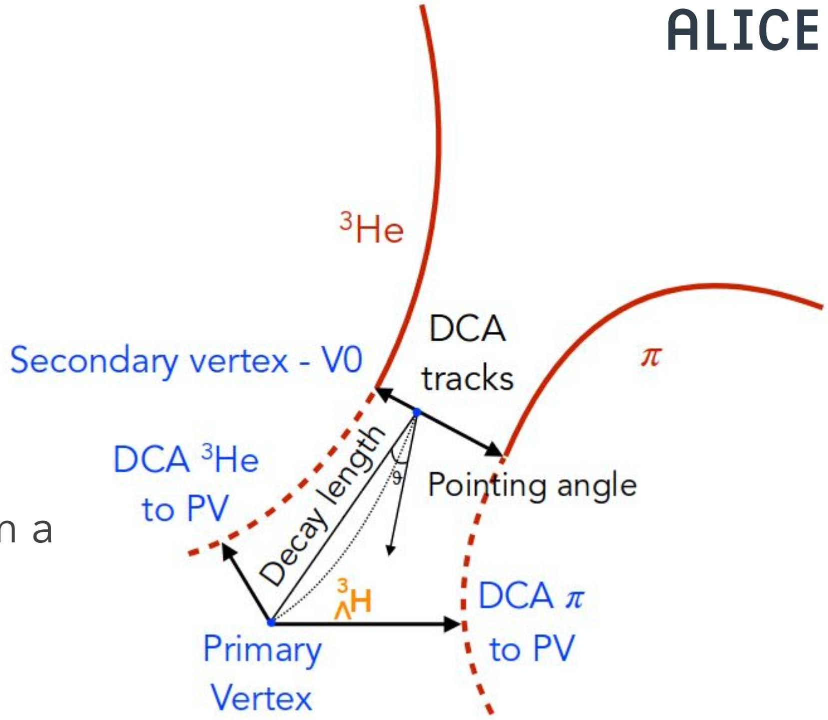
The ALICE detector

- We can identify the hypertriton daughter particles (^{3}He and π^{-}) exploiting the excellent particle identification (PID) of the ALICE apparatus



${}^{3}_{\Lambda}H$ in large systems

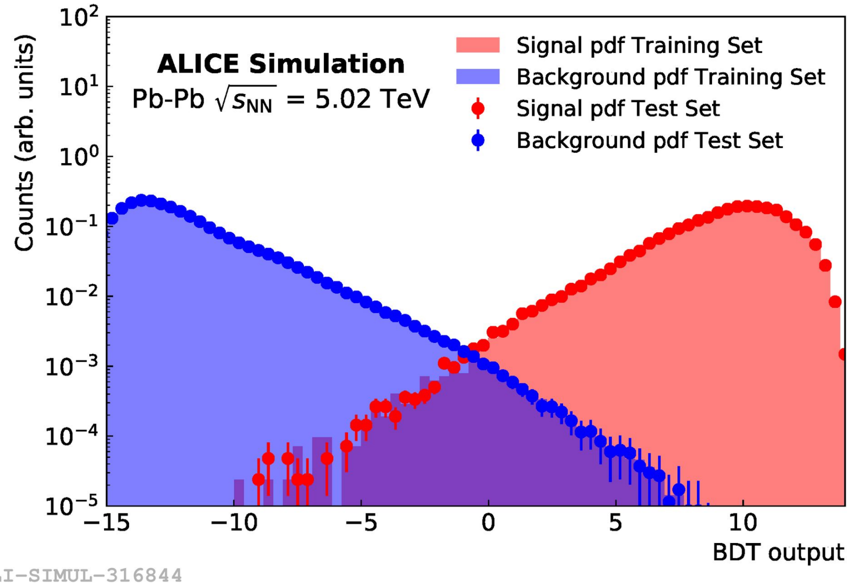
- Analysed data sample:
  - Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE in 2018
- ${}^{3}_{\Lambda}H$ candidate: ${}^{3}He + \pi^{-}$ pairs (and related charge conjugates)
- Secondary vertex reconstruction
  - matching of ${}^{3}He + \pi^{-}$ tracks coming from a common vertex
- Huge combinatorial background



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

Boosted Decision Trees Classifier (BDT) trained on dedicated sample to discriminate between signal and background candidates

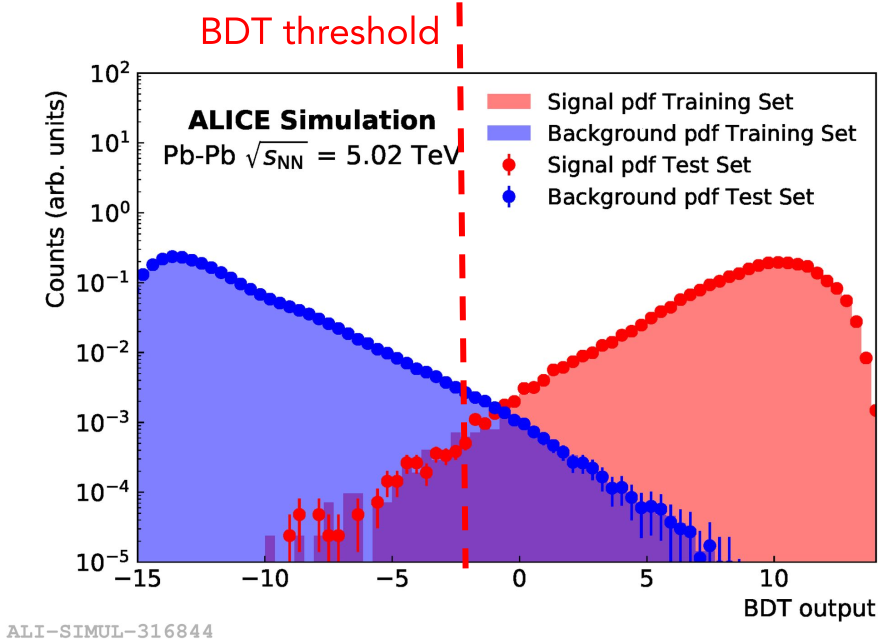
- BDT output (independent trainings for each bin) :
  - Score related to the probability of the candidate to be signal or background



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

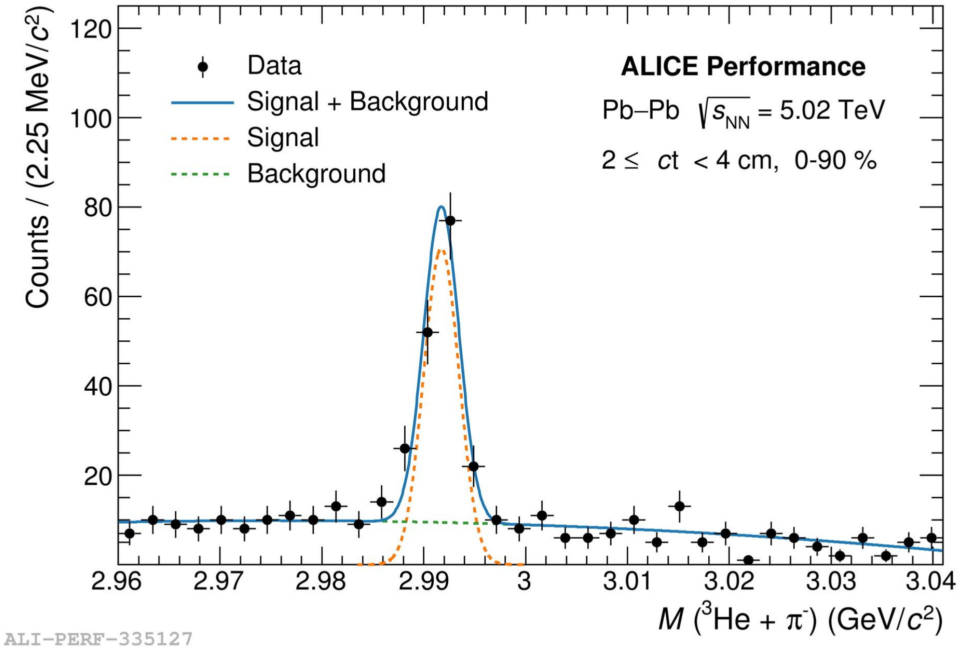
Boosted Decision Trees Classifier (BDT) trained on dedicated sample to discriminate between signal and background candidates

- Selection applied on the BDT score
  - maximisation of the expected significance (assuming thermal production)



Signal extraction

- Signal extracted with a fit to the invariant mass spectrum of the selected candidates
- high significance over a wide range
    - 9 *ct* bins from 1 to 35 cm

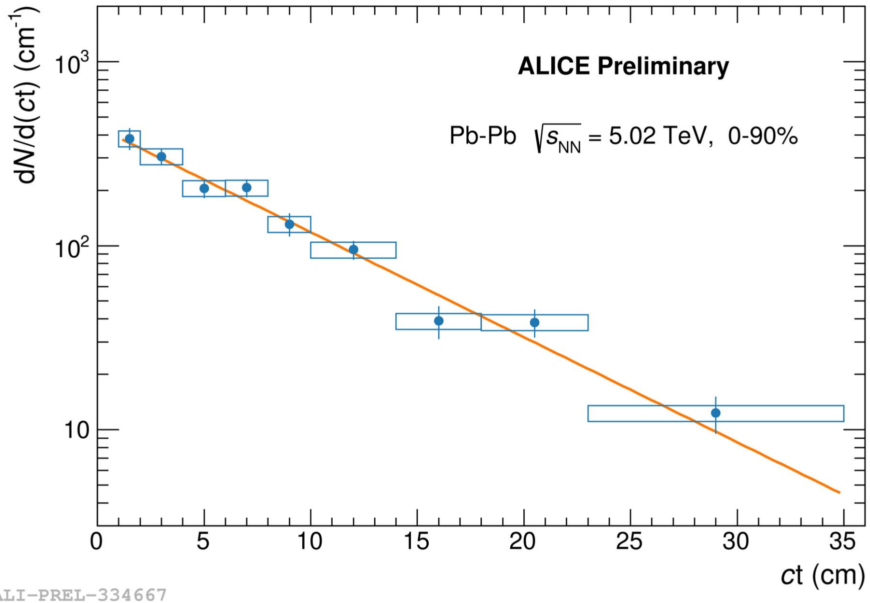


${}^{3}_{\Lambda}H$ Lifetime

- Corrected *ct* spectrum fitted with exponential function
- Lifetime value from the fit

254 ± 15 (stat.) ± 17 (syst.) ps

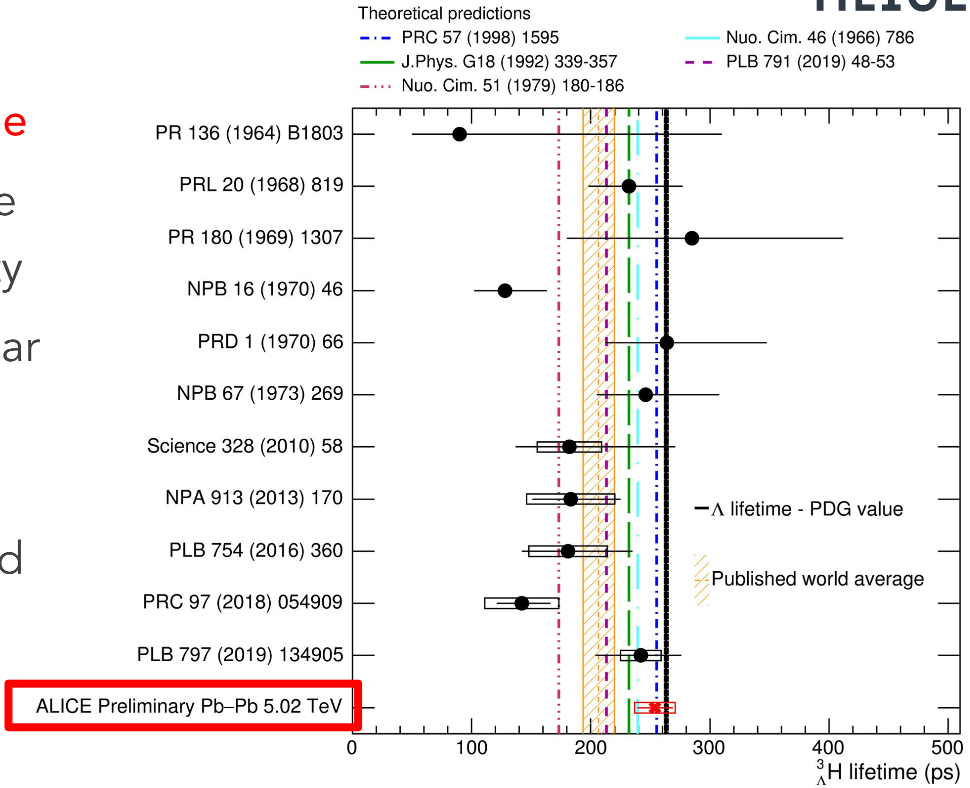
- Statistical uncertainty ~ 6%
- Systematic uncertainty (boxes) ~ 7%



ALI-PREL-334667

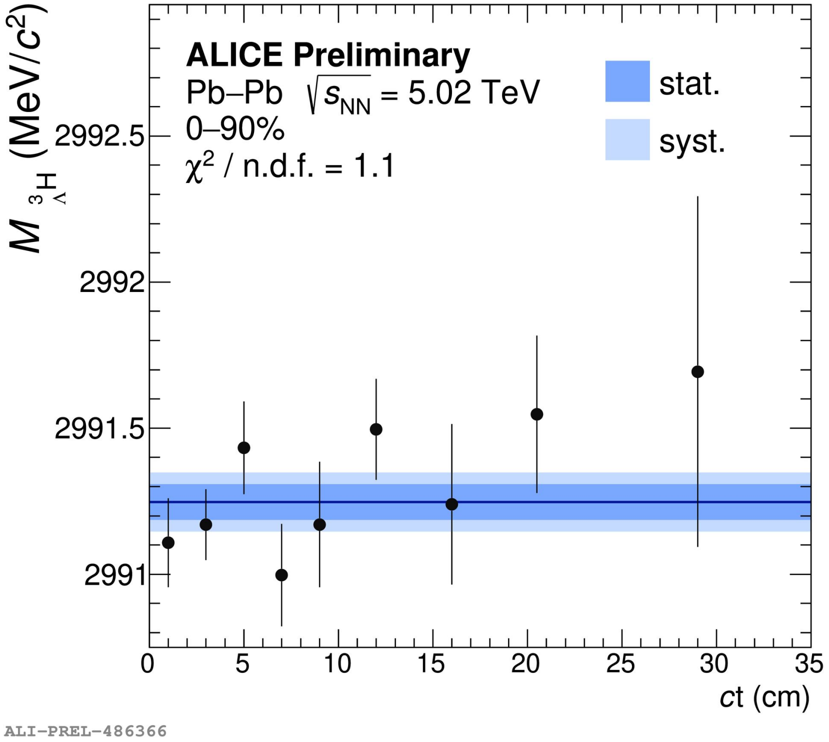
$^{3}_{\Lambda}$H Lifetime

- Most precise measurement available
- Statistical uncertainty lower than the published world average uncertainty
- Models predicting lifetime to be near to the free Λ one are favoured
  - strong hint that hypertriton is weakly bound, but we still need B_Λ to finally solve the puzzle



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

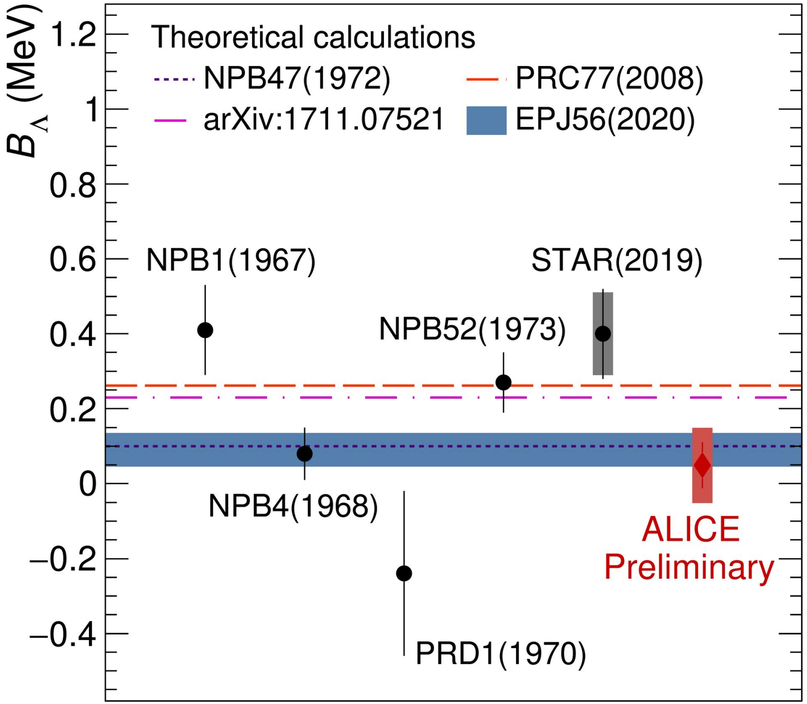
- Same signal extraction and *ct* bins used for the lifetime: precise mass measurement needed to obtain B_{Λ}
- Extremely precise measurement
  - 0.0016% stat.
  - 0.003 syst.
- Systematic uncertainty of ~100 keV



B_Λ

- From the mass measurement to B_Λ
  - $B_\Lambda = M_\Lambda + M_\mathrm{d} - M_{^3_\Lambda\mathrm{H}}$
- Weakly bound nature of $^3_\Lambda$H is confirmed by the latest ALICE measurement
  - B_Λ consistent with zero
  - consistent with SU(3) chiral effective field theory and Dalitz predictions

NEW



ALI-PREL-486370

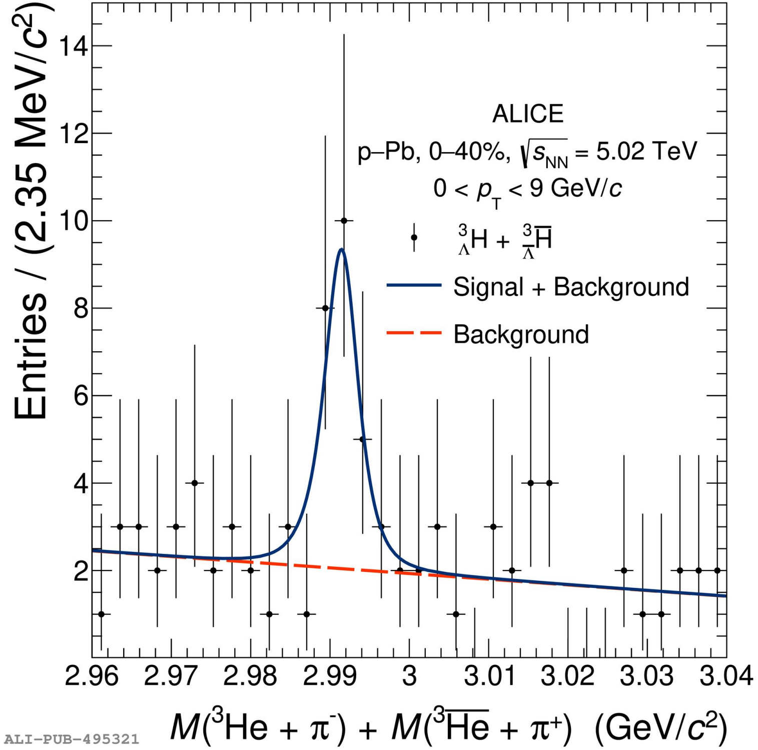
Hypertriton in small systems

First measurements of $^{3}_{\Lambda}H$ production in pp and p-Pb collisions

$^{3}_{\Lambda}H$ selection in p-Pb collisions

- Analysed data sample:
  - p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE in 2016 and 2013
- $^{3}_{\Lambda}H$ candidate: $^{3}He + \pi^{-}$ pairs (and related charge conjugates)
- Signal selection using a BDT Classifier
  - fundamental contribution of ML to extract the signal with good significance: 4.6**σ**

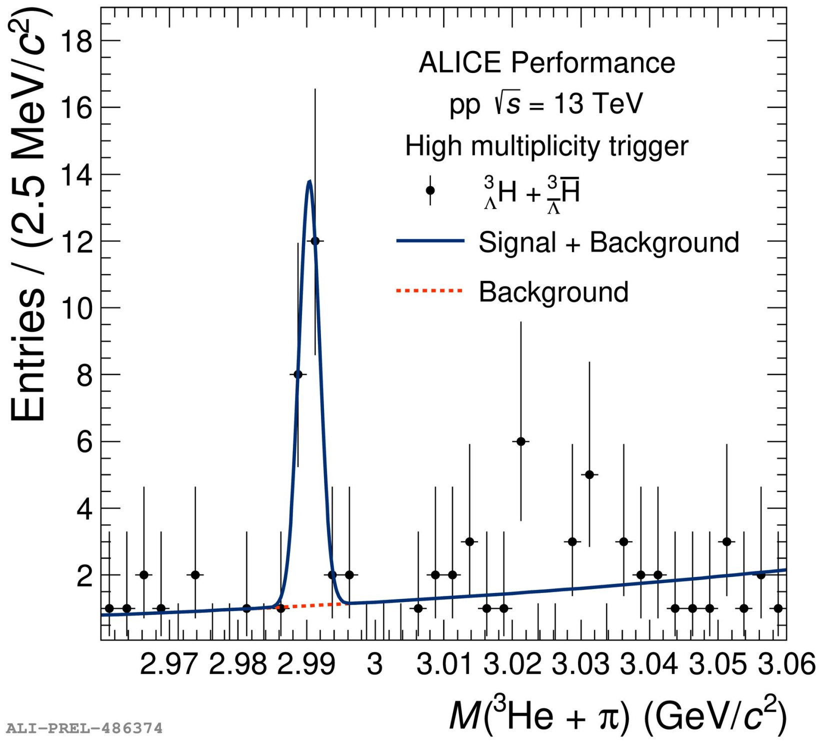
NEW https://arxiv.org/abs/2107.10627



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

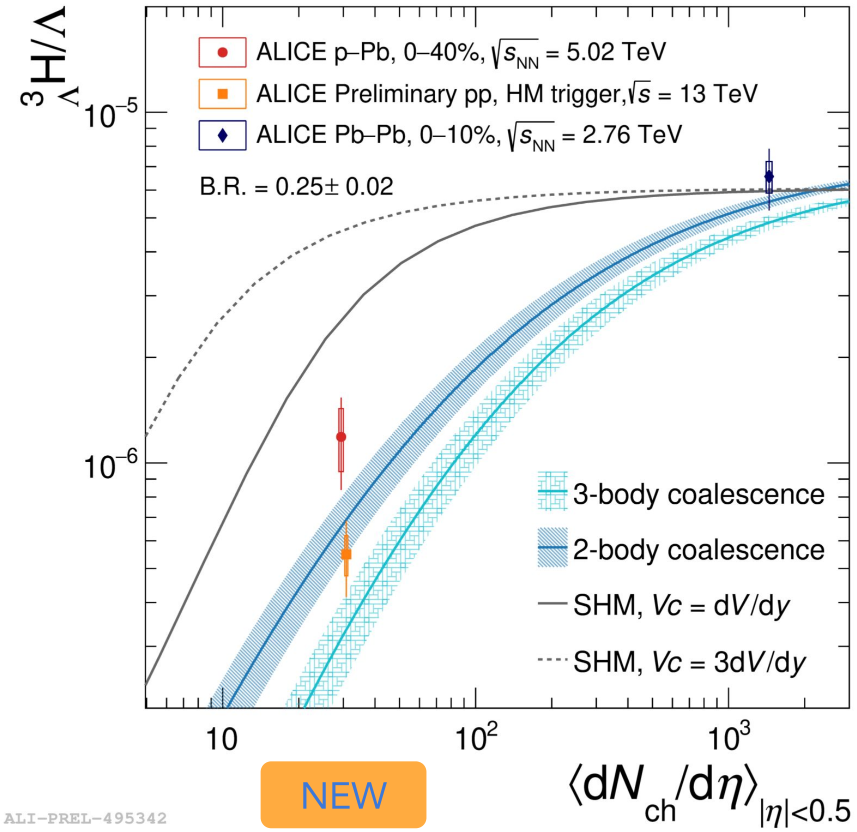
- Analysed data sample:
  - pp collisions at $\sqrt{s}$ = 13 TeV collected by ALICE during Run 2
- ${}^{3}_{\Lambda}H$ candidate: ${}^{3}He + \pi^{-}$ pairs
(and related charge conjugates)
- Trigger on high multiplicity events using V0 detectors
- Selection using topological cuts on triggered events

NEW



ALI-PREL-486374

$^{3}_{\Lambda}H$ / Λ in pp and p--Pb collisions

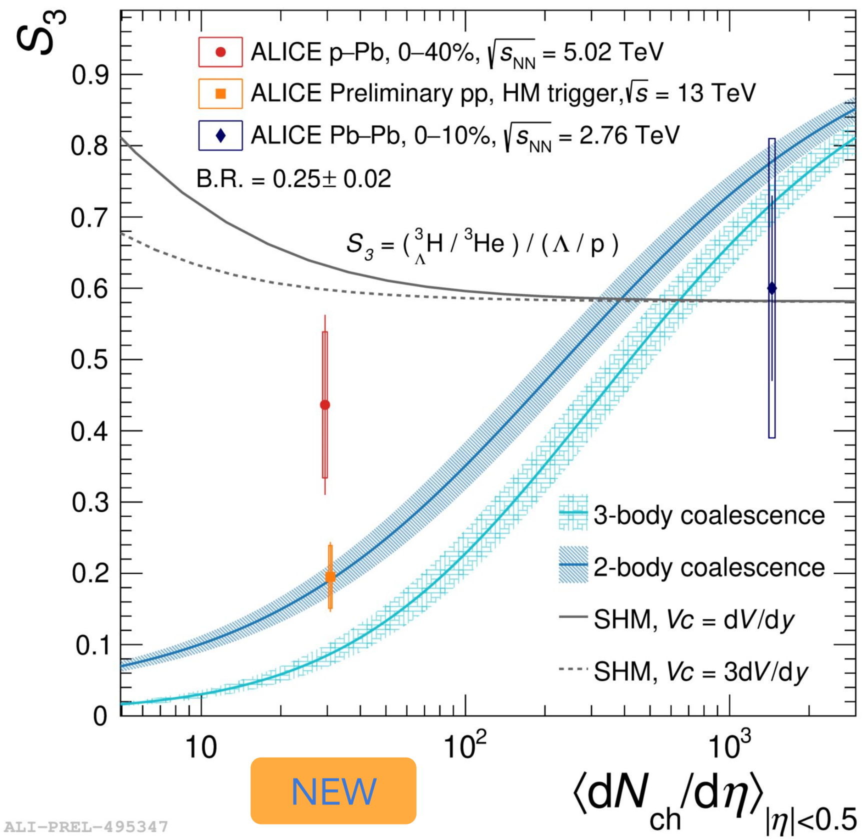


- $^{3}_{\Lambda}H$ / Λ in small systems:
  - large separation between production models
  - measurements in good agreement with 2-body coalescence [2]
  - tension with SHM [1] at low charged-particle multiplicity density
    - configuration with V_C = 3dV/dy is excluded at level of more than 6σ

https://arxiv.org/abs/2107.10627

[1]Vovchenko, V., Dönigus, B., & Stoecker, H. (2018). *Phys. Lett., B785, 171-174.*
[2]Sun, K.J., Ko, C., & Dönigus, B. (2019). *Phys. Lett. B, 792, 132–137.*

S_3 in pp and p--Pb collisions



- S_3 : strangeness population factor

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

- S_3 in small systems:
  - same conclusions as for ${}^{3}_{\Lambda}H$ / Λ but with less sensitivity
  - Run 3 will be crucial to finally distinguish between SHM [1] and coalescence [2] !

https://arxiv.org/abs/2107.10627

[1]Vovchenko, V., Dönigus, B., & Stoecker, H. (2018). *Phys. Lett., B785, 171-174.*
[2]Sun, K.J., Ko, C., & Dönigus, B. (2019). *Phys. Lett. B, 792, 132–137.*

Summary and perspectives

- ${}^{3}_{\Lambda}H$ in large systems:
  - most precise measurements of lifetime and B_{Λ} in Pb-Pb collisions
    - weakly bound nature of ${}^{3}_{\Lambda}H$ confirmed
  - 3-body decay analysis on-going, it will allow us to infer the spin of the particle

- ${}^{3}_{\Lambda}H$ in small systems:
  - first measurement of ${}^{3}_{\Lambda}H$ production in pp and p-Pb collisions
  - concrete possibility to distinguish with high significance between the two nucleosynthesis mechanisms
    - during Run 3 we will be able to do that!

Thanks for your attention!