Hypertriton lifetime and binding energy measurement with ALICE

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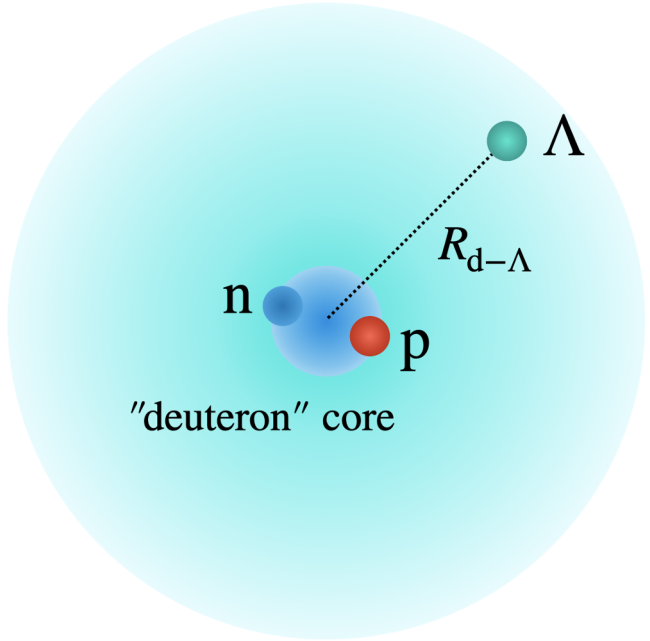
The hypertriton ($^3_\Lambda$H) in a nutshell

- Lightest known hypernucleus
  - bound state of a neutron, a proton and a Λ
  - discovered in early 50s by M. Danysz and J. Pniewski [1]

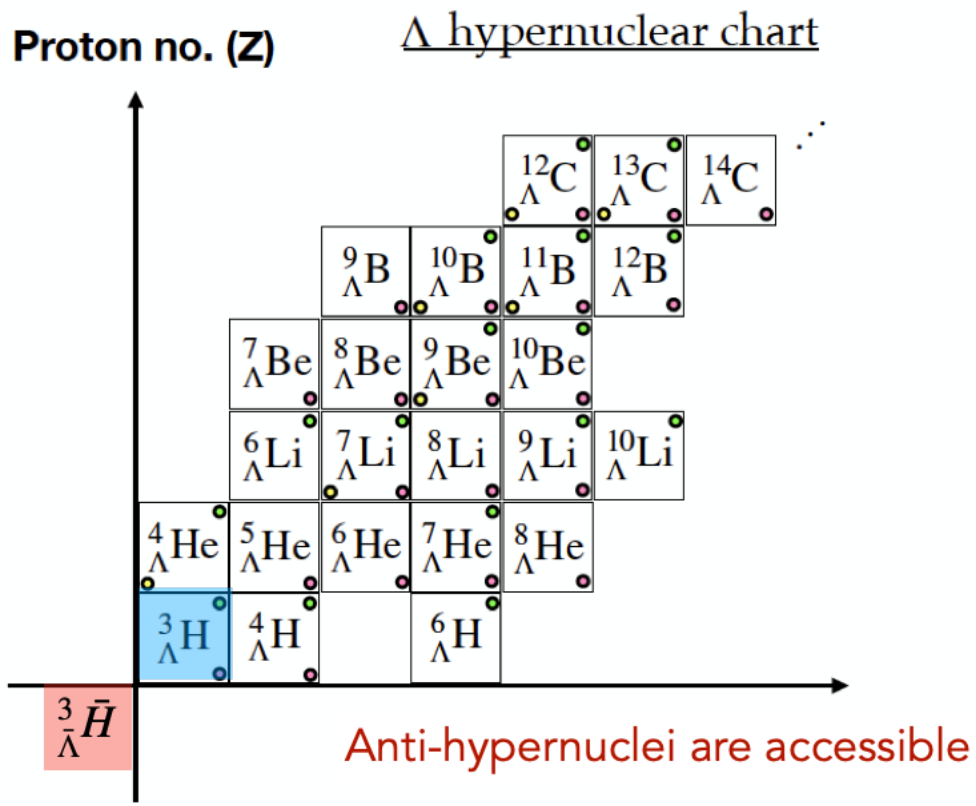
- $^3_\Lambda$H approximated as a bound state of a deuteron and a Λ with an expected radius[2] of ~ 10 fm
  - two-body halo nucleus

- $^3_\Lambda$H lifetime and B_Λ reflect its structure
  - most of the theoretical models assume $B_\Lambda \approx 130$ keV and predict lifetime close to the free **Λ** one
  - latest models based on EFT[3,4] give lifetime predictions as a function of B_Λ



1 M. Danysz, J. Pniewski, Philos. Mag. 44, 348, (1953)
2 Hildenbrand F. et al., Phys. Rev. C, 100(3), 034002 (2019)
3 Hildenbrand F. et al., *Physical Review C*, vol. 102, no. 6 (2020)
4 Pérez-Obiol A., *Physics Letters B*, vol. 811 (2020)

The hypertriton at the LHC

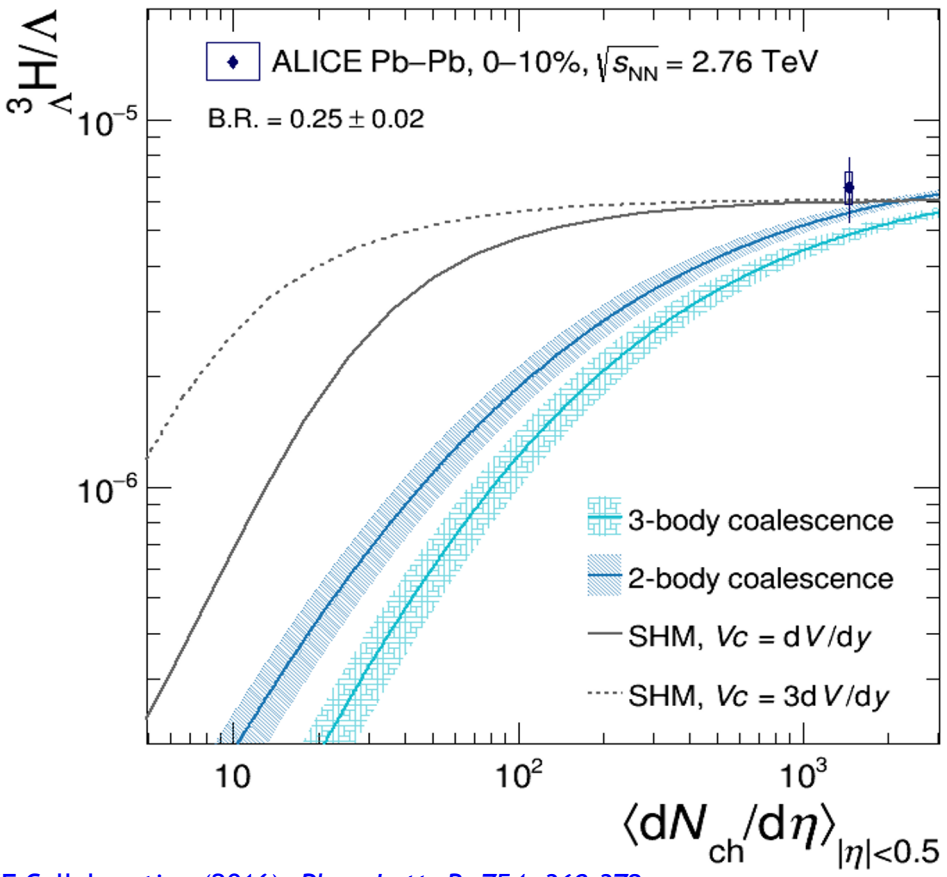


- Unique probe for understanding the **Λ**-nucleus interaction
  - strong implications for astro-nuclear physics
  - hyperons expected to be produced in the inner core of neutron stars [1]

- Strangeness in high-density nuclear matter
  - hadronic phase of a heavy-ion collision
  - two classes of models for comparison: thermal (SHM)[2] and coalescence[3] predictions

[1] Tolos L. et al., Progress in Particle and Nuclear Physics, 112 (2020)
[2] Vovchenko, et al., *Phys. Lett., B785, 171-174,* (2018)
[3] Sun. et al., *Phys. Lett. B, 792, 132-137,* (2019)

The hypertriton in ALICE



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

- **Recent results in heavy-ion collisions** suggest that $^3_\Lambda$H could be more compact than expected [1, 2]
  - precise measurements required to shed light on the $^3_\Lambda$H structure
- loosely bound nature of $^3_\Lambda$H has strong implications for its production mechanism
  - SHM and coalescence predictions well separated at low charged-particle multiplicity density

[1] STAR, Phys. Rev. C 97, 5, 054909 (2018)
[2] STAR, Nature Physics 16, 409-412 (2020)

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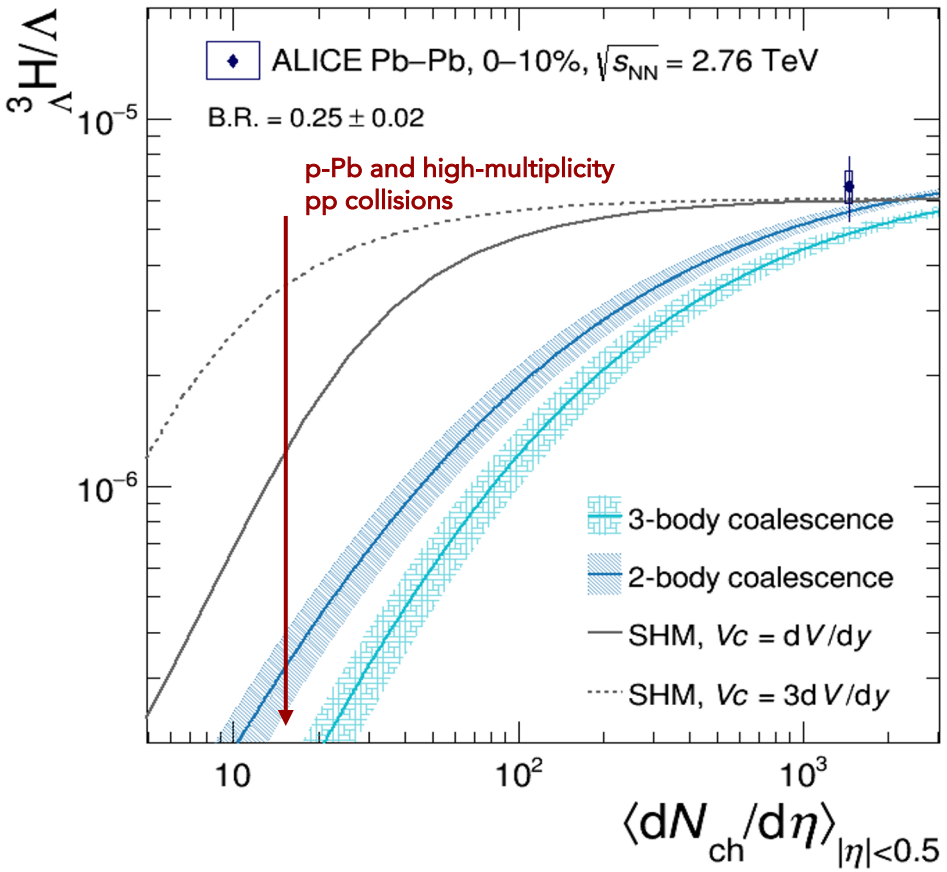

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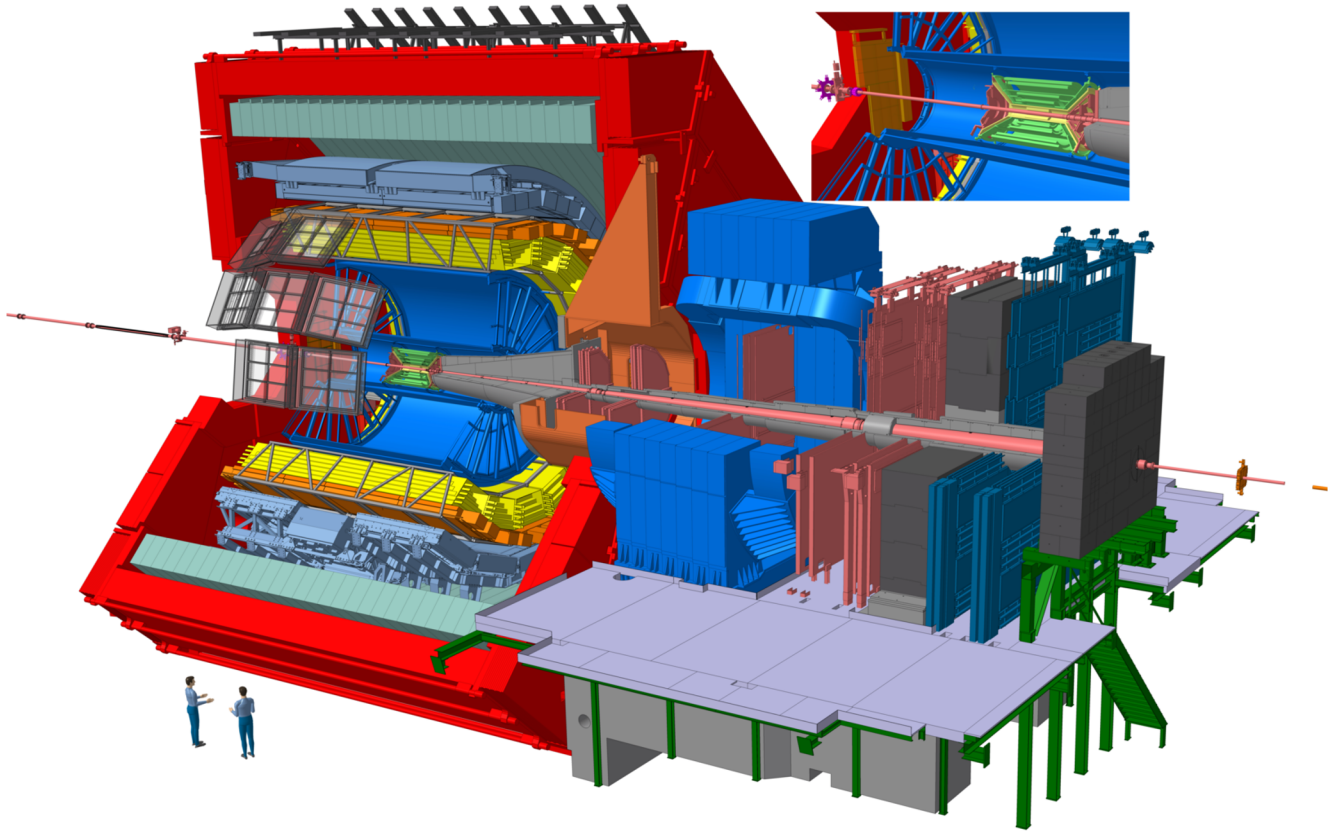
- loosely bound nature of $^3_\Lambda$H has strong implications for its production mechanism
  - SHM and coalescence predictions well separated at low charged-particle multiplicity density
- $^3_\Lambda$H production in pp and p-Pb is a key measurement to understand the nuclear production mechanism in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

[1] STAR, Phys. Rev. C 97, 5, 054909 (2018)
[2] STAR, Nature Physics 16, 409-412 (2020)

The ALICE experiment



$^{3}_{\Lambda}$H candidate: ^{3}He + π^- pairs
(and related charge conjugated states)

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

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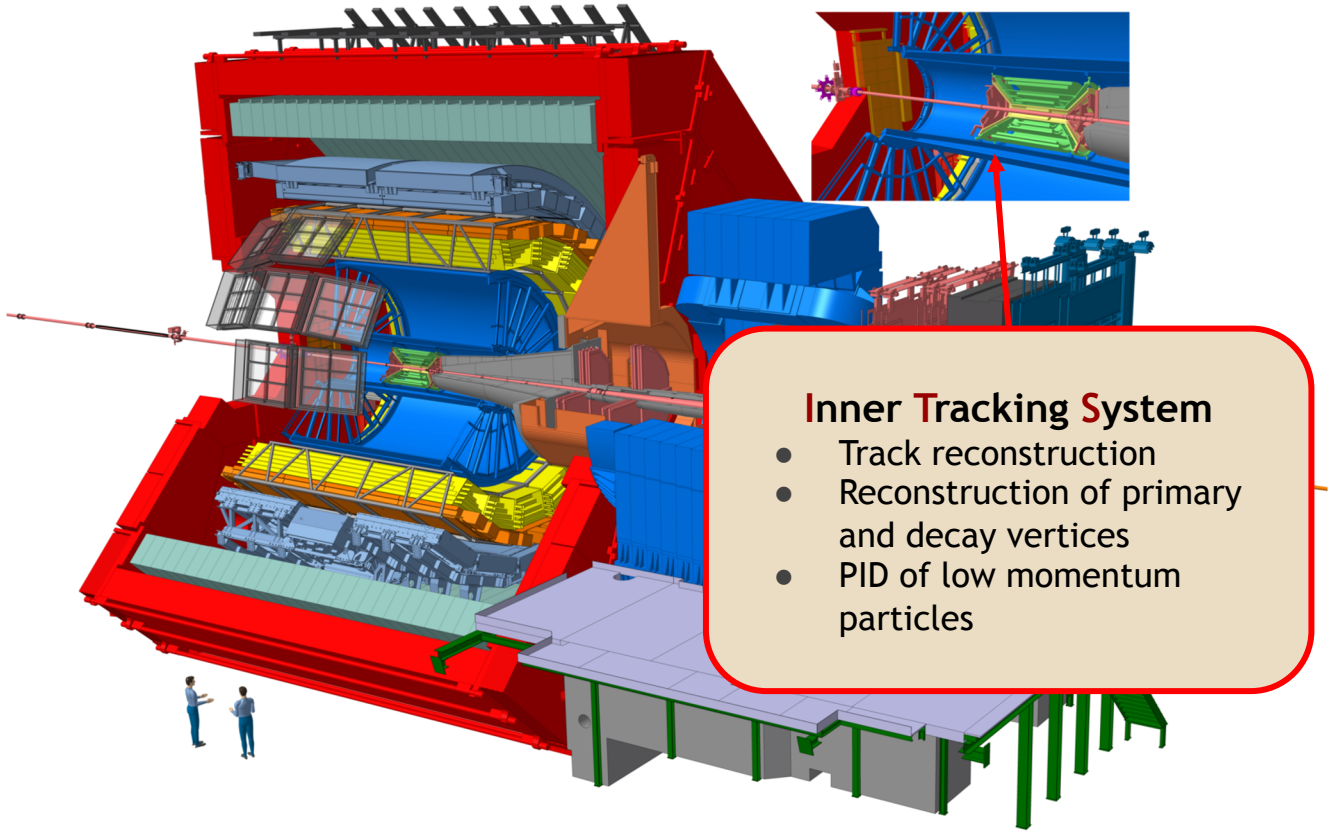

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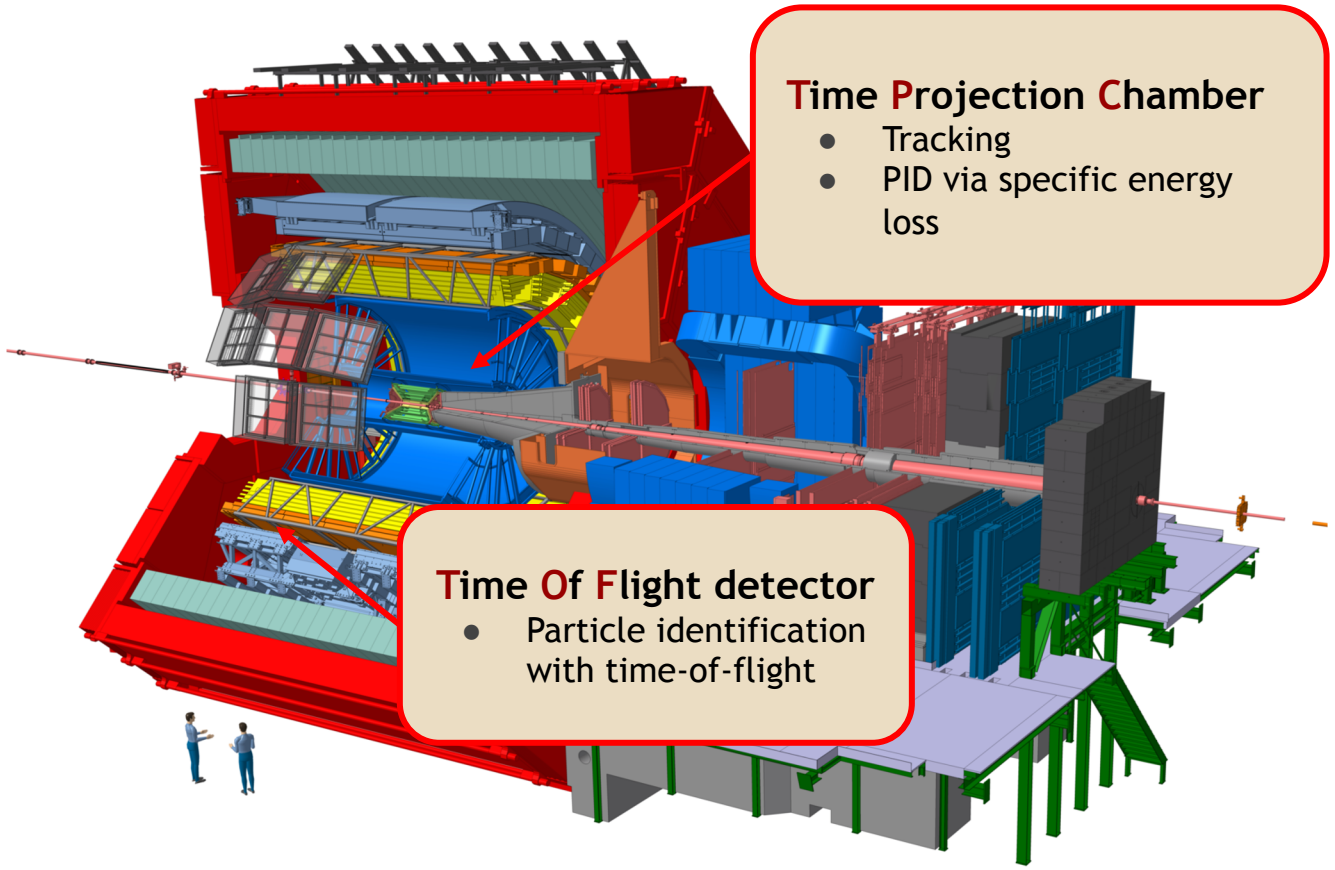

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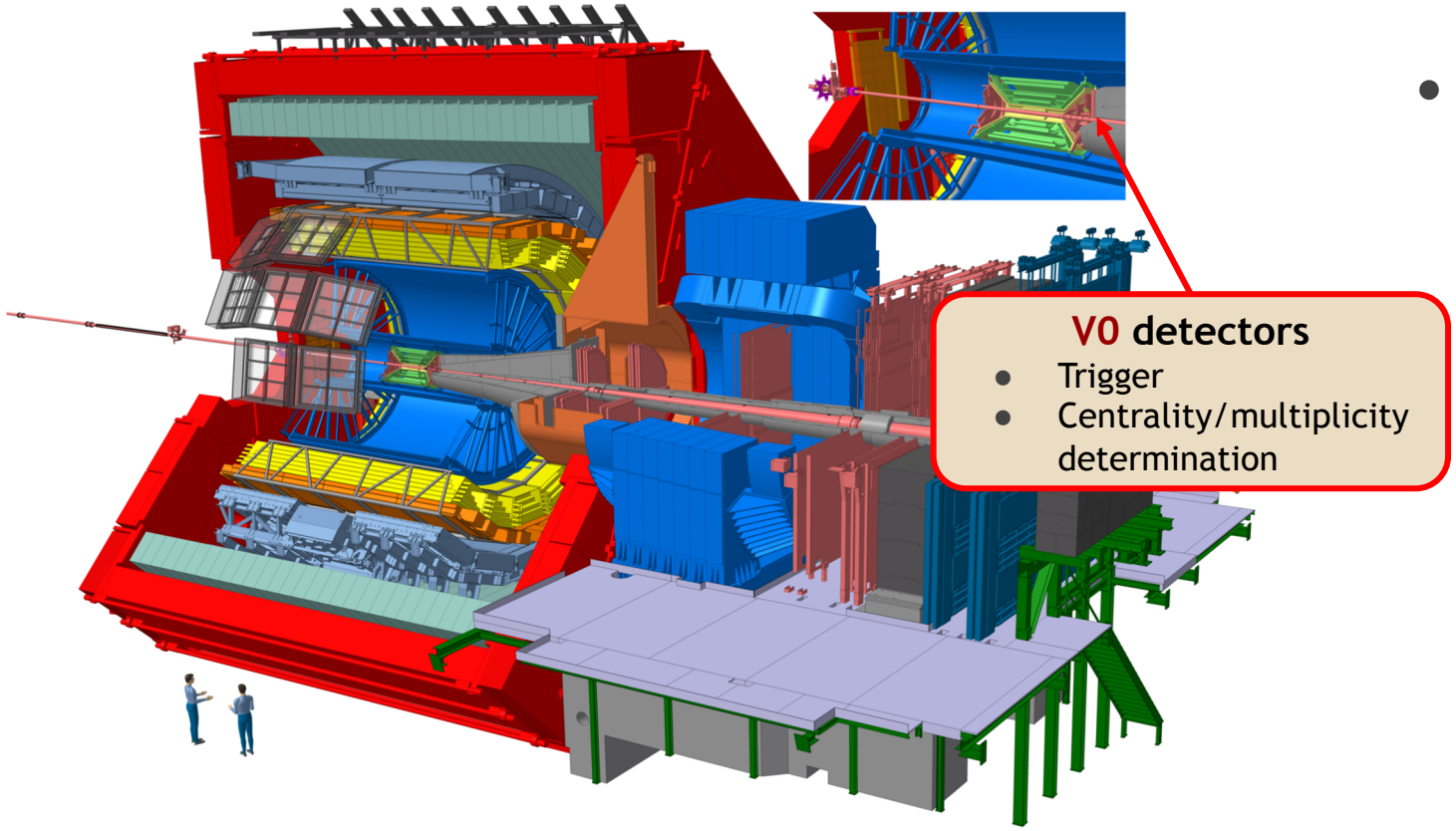

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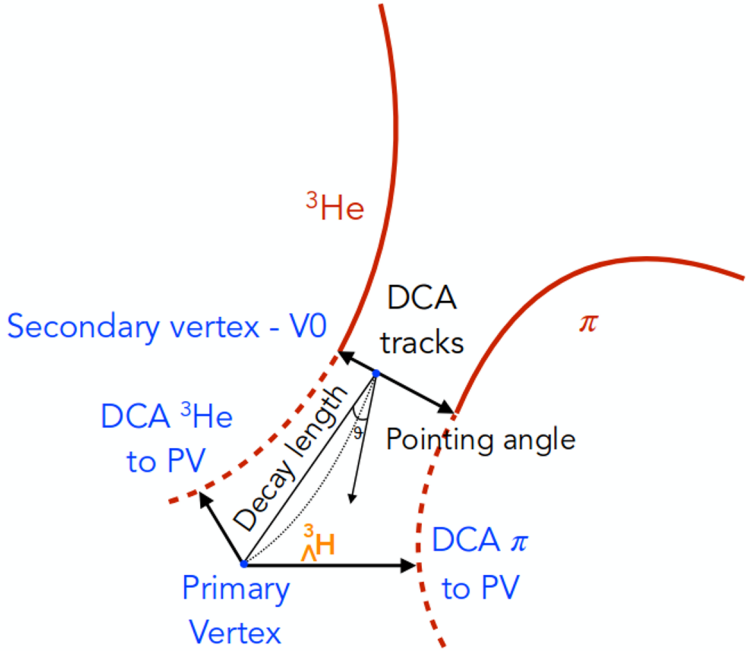
The hypertriton in large systems

- ${}^{3}_{\Lambda}\mathrm{H}$ candidate: **^{3}He + π^- pairs**
  (and related charge conjugated states)
- Secondary vertex reconstruction
  - matching of ^{3}He + π^- tracks coming from a **common vertex**
- Huge combinatorial background
  - **machine Learning technique adopted to enhance the signal significance**



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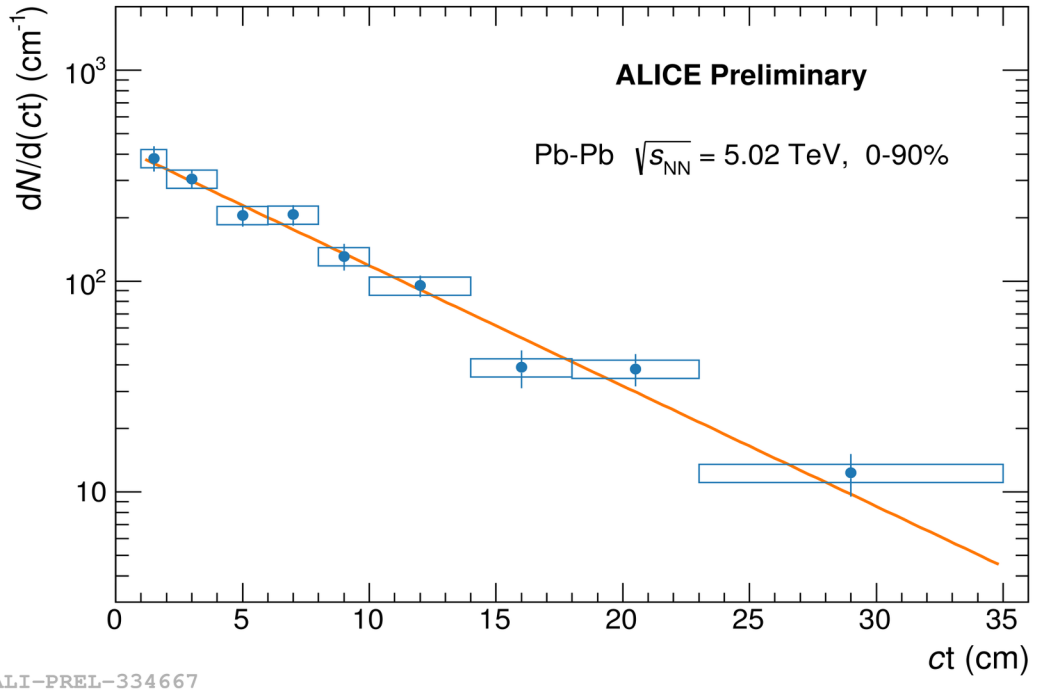
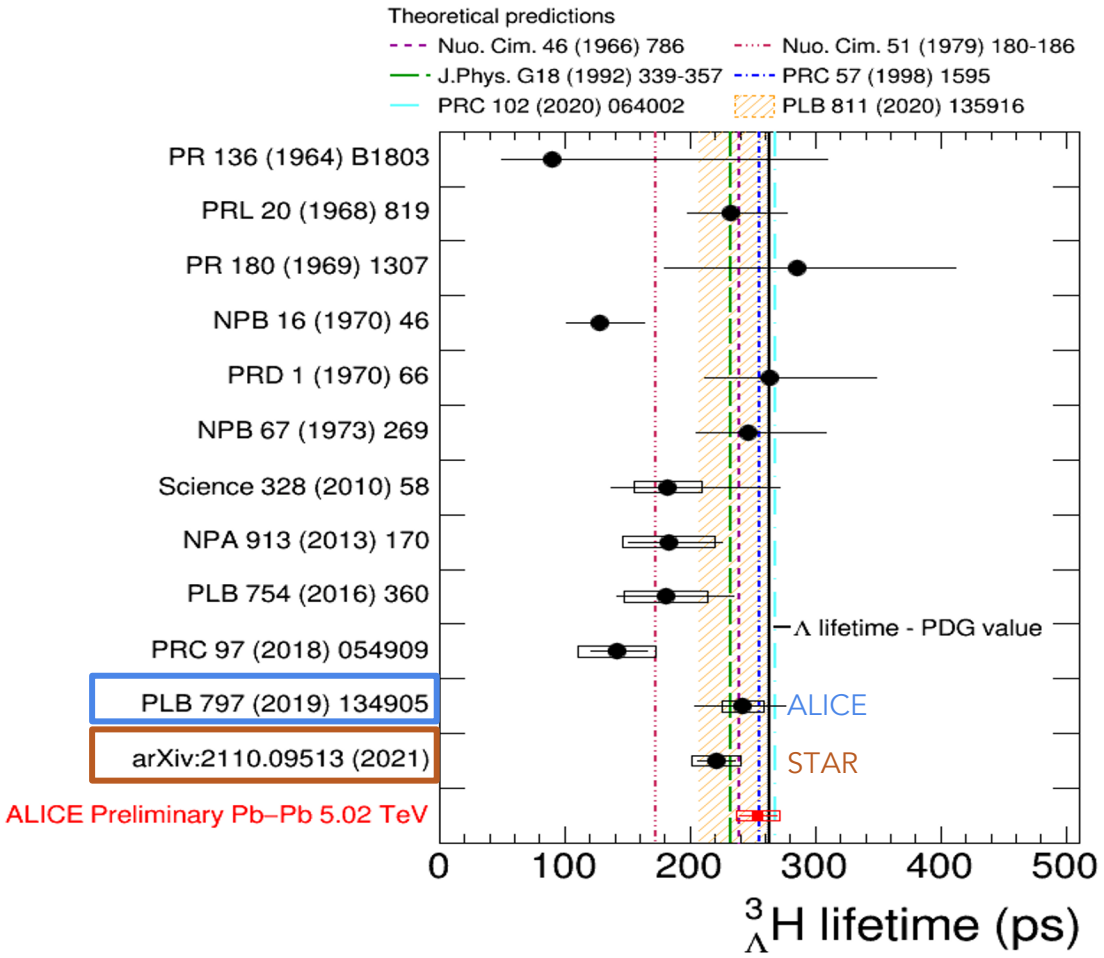
- Lifetime value from the fit
  - Statistical uncertainty ~ 6%
  - Systematic uncertainty ~ 7%

Corrected *ct* spectrum fitted with an exponential function



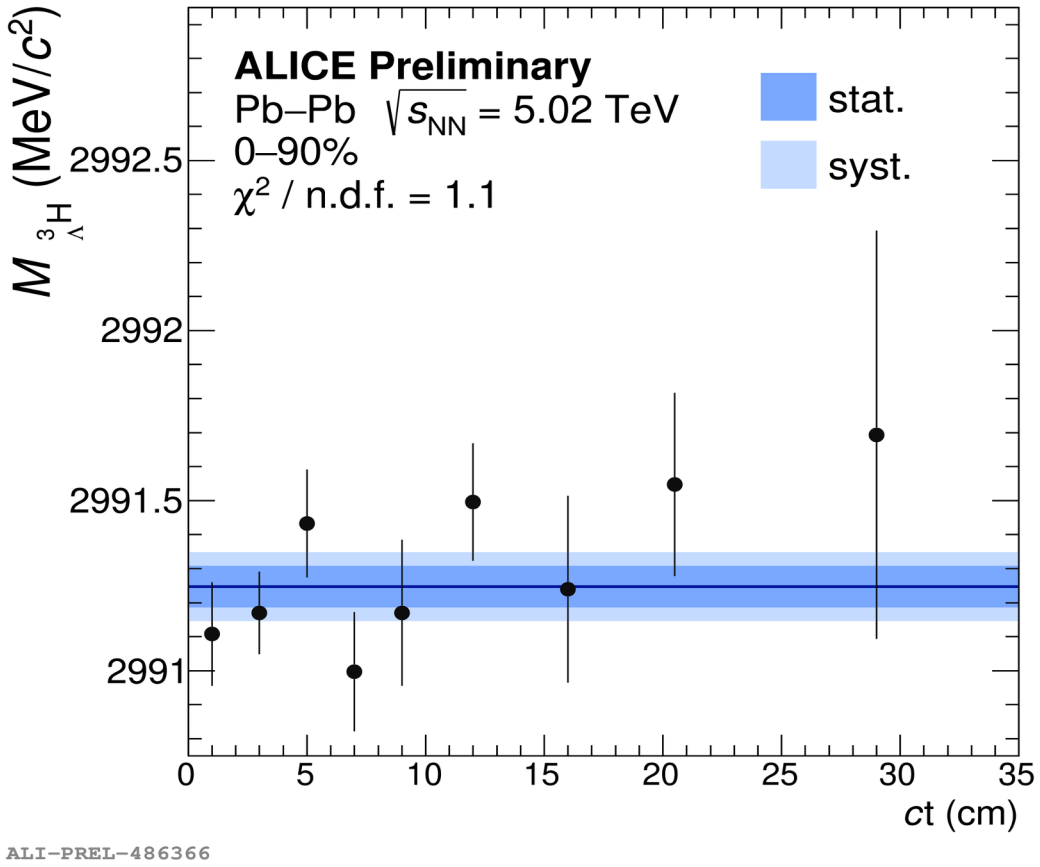
The hypertriton lifetime



Most precise measurement of the lifetime ever done so far

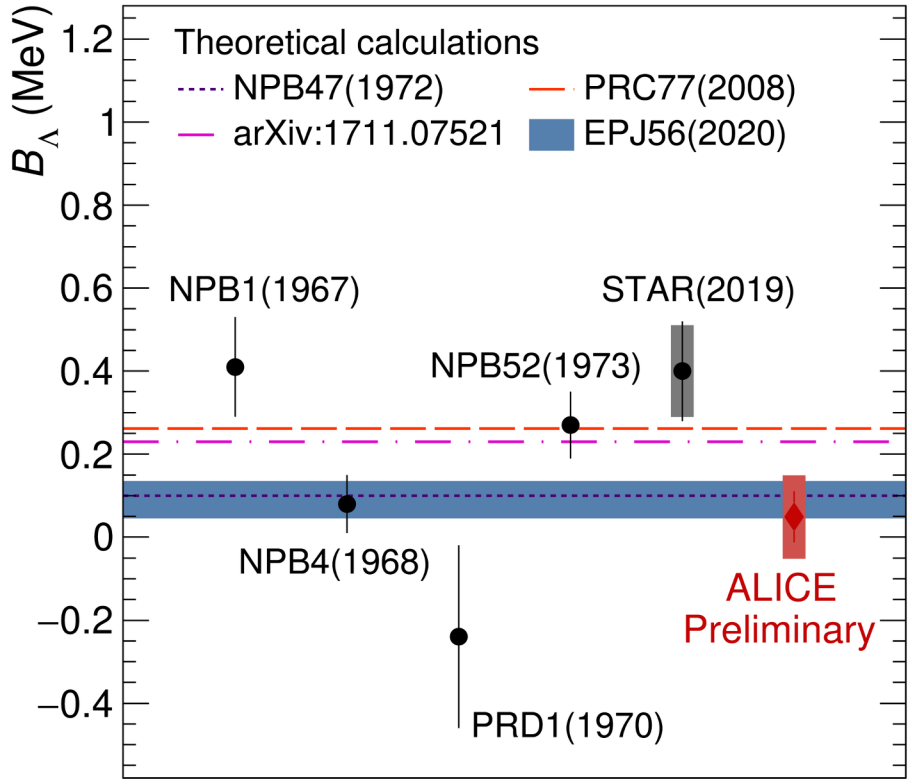
- Compatible with latest STAR measurement
- Theoretical approaches which predict a lifetime close to the free Λ one are favoured
  - **strong hint that hypertriton is weakly bound**
  - B_Λ is still needed to solve the puzzle

The hypertriton mass



- Same signal extraction technique and ct bins used for the lifetime
- precise mass measurement needed to obtain B_Λ
- **Extremely precise measurement**
  - 0.0016% stat.
- Systematic uncertainty of ~100 keV

The hypertriton B_Λ



ALI-PREL-486370

- B_Λ is derived from the mass measurement

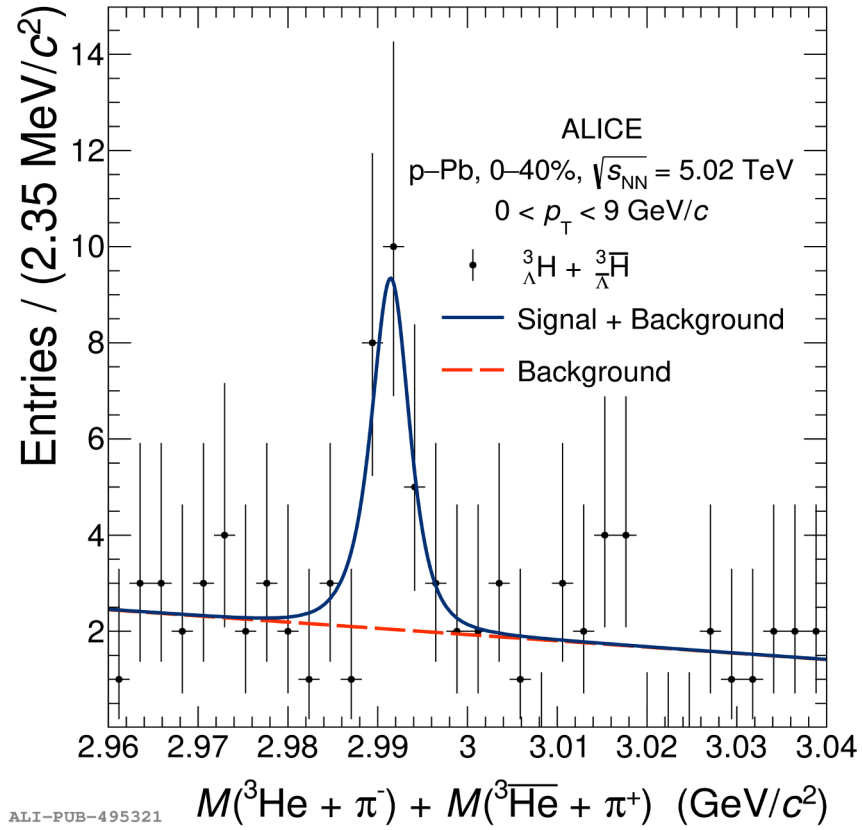
$$B_\Lambda = M_\Lambda + M_\mathrm{d} - M_{^3_\Lambda\mathrm{H}}$$

- Weakly bound nature of $^3_\Lambda$H is confirmed by the latest ALICE measurement
  - B_Λ compatible with zero
  - in agreement within 1σ with Dalitz and χEFT based predictions
  - fully consistent with the lifetime measurement according to recent theoretical calculations[1,2]

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

The hypertriton in small systems

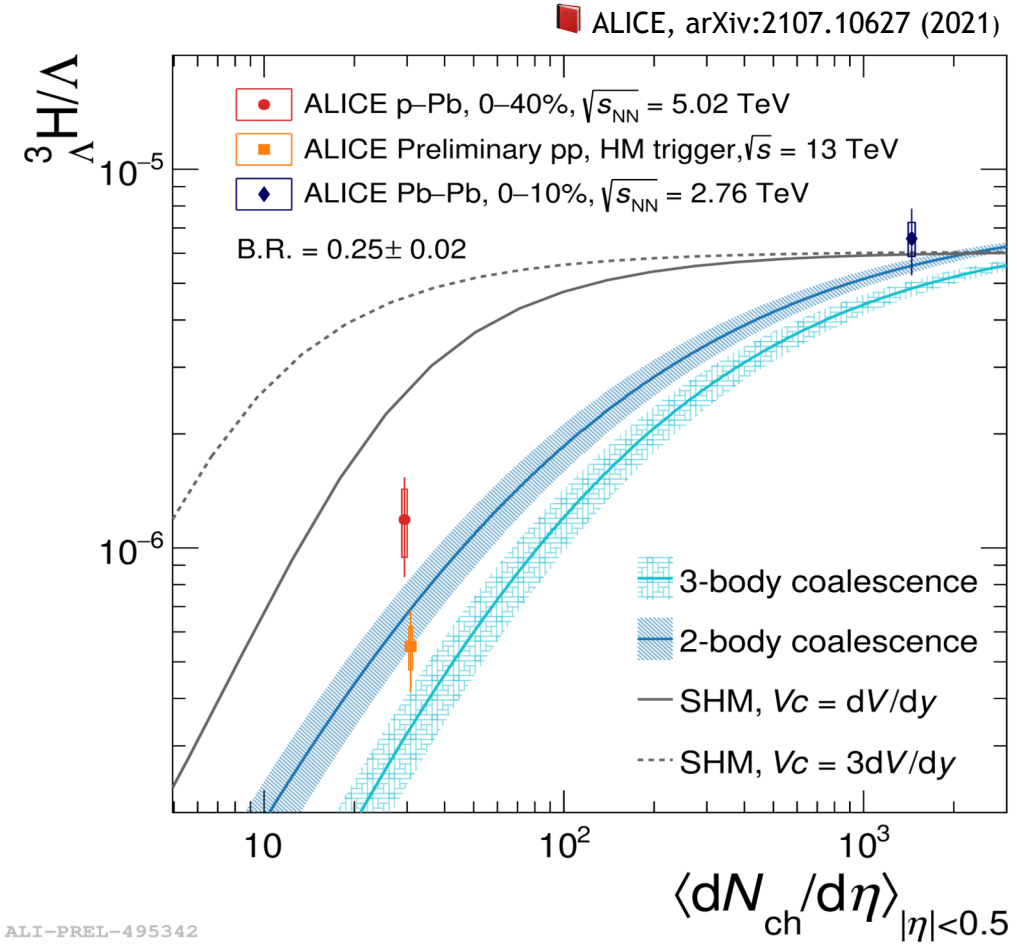
- pp collisions at $\sqrt{s}$ = 13 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected during the LHC Run 2
- **trigger on high multiplicity events +** topological cuts on triggered events to select the $^{3}_{\Lambda}$H
- Machine learning techniques used for the signal extraction in p-Pb
- Significance > 4**σ both in pp and p-Pb collisions**



ALICE, arXiv:2107.10627 (2021)

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

- large separation between production models
- **measurements in good agreement with 2-body coalescence [2]**
- SHM [1] does not catch the results for small collision systems:
  - configuration with $V_C = 3\mathrm{d}V/\mathrm{d}y$ is excluded at level of more than 6σ



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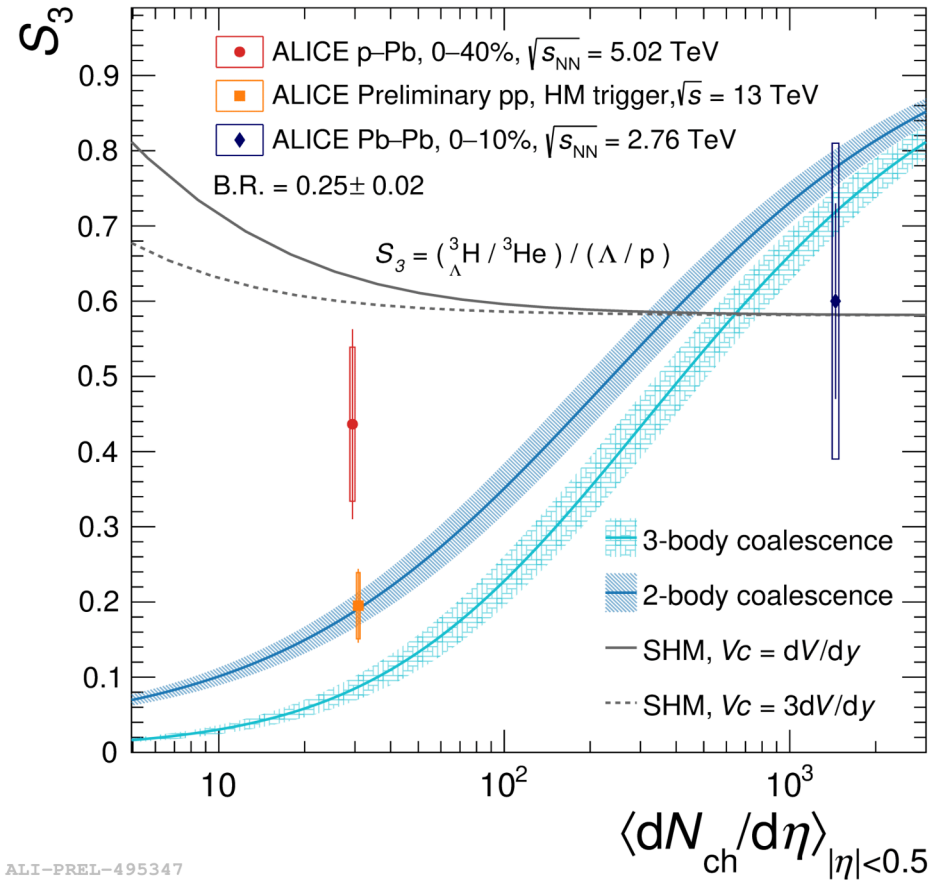
S_3 in pp and p-Pb collisions

S_3 : strangeness population factor

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

- S_3 in small systems:
  - agreement with the measurement of the ${}^3_\Lambda$H / Λ ratio but with a lower sensitivity



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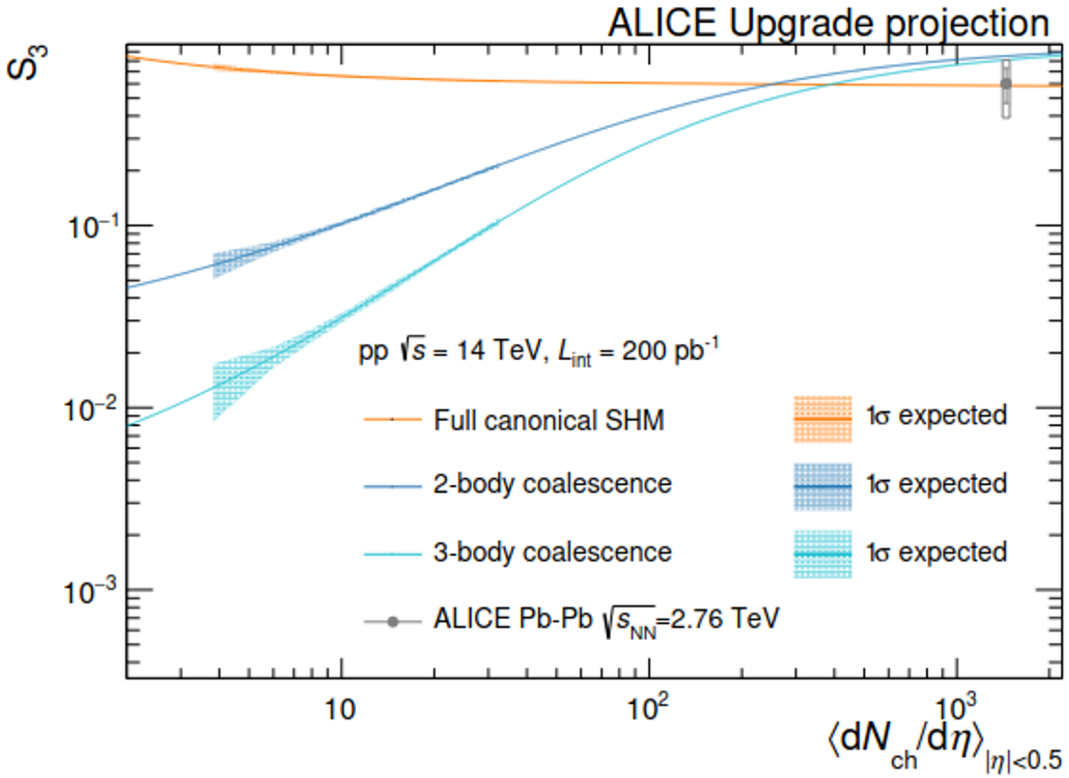
- S_3 in small systems:
  - agreement with the measurement of the $^3_\Lambda$H / Λ ratio but with a lower sensitivity
  - Run 3 data will be crucial to understand the production mechanism of hypernuclei and explore the multiplicity dependence of S_3



Summary and perspectives

- In the last decade all the hypertriton measurements come from heavy ion collisions
  - precise measurements of lifetime and B_Λ in Pb-Pb collisions confirm the weakly bound nature of ${}^3_\Lambda\mathrm{H}$
  - first measurement of ${}^3_\Lambda\mathrm{H}$ production in pp and p-Pb collisions thanks to the ML approach
  - Measurement in small colliding systems are interesting to distinguish with high significance between the two nucleosynthesis mechanisms
  - More statistics will be crucial to deepen our knowledge in this field

Stay tuned for the ongoing LHC Run 3!