Production and properties of hypernuclei with ALICE

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for the ALICE Collaboration

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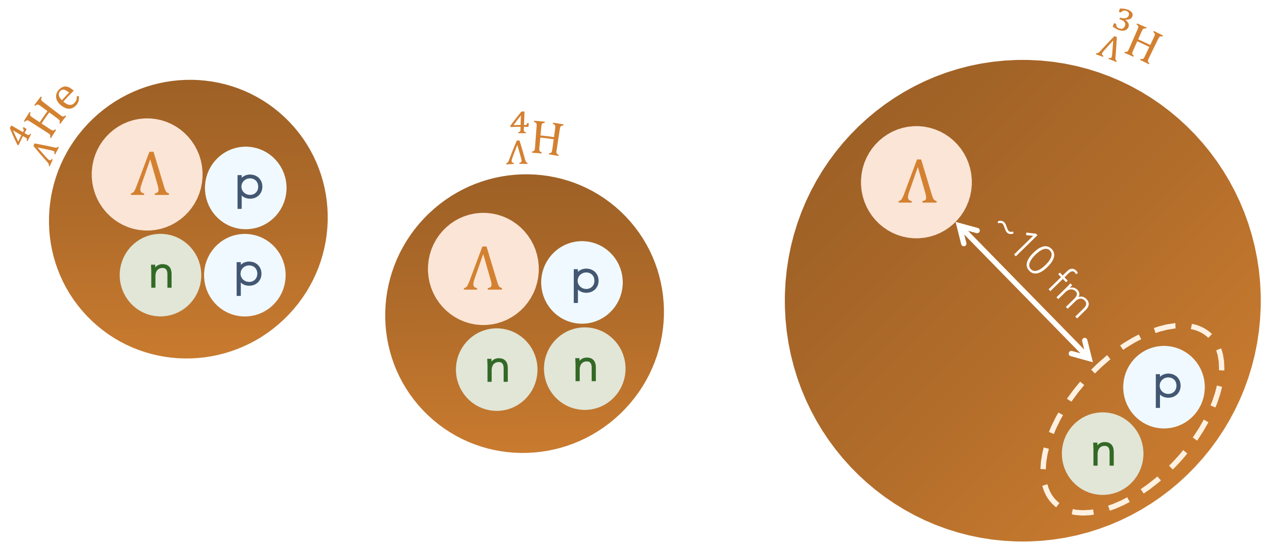
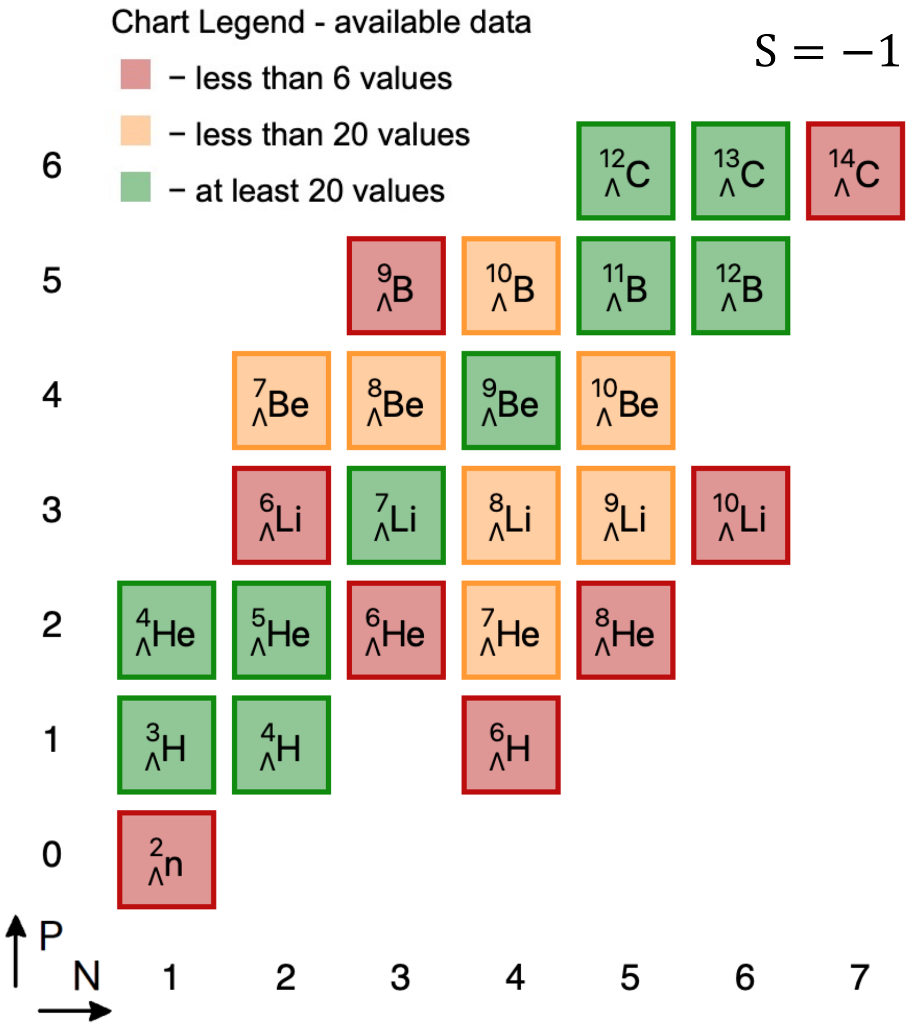
Hypernuclei

- Poorly known bound states of **nuclei** and **strange baryons (hyperons)**





Mainz hypernuclear database

[1] D. Logoteta et al., Eur. Phys. J. A 55, 207 (2019)
[2] D. Lonardoni et al., Phys. Rev. Lett. 114, 092301 (2019)

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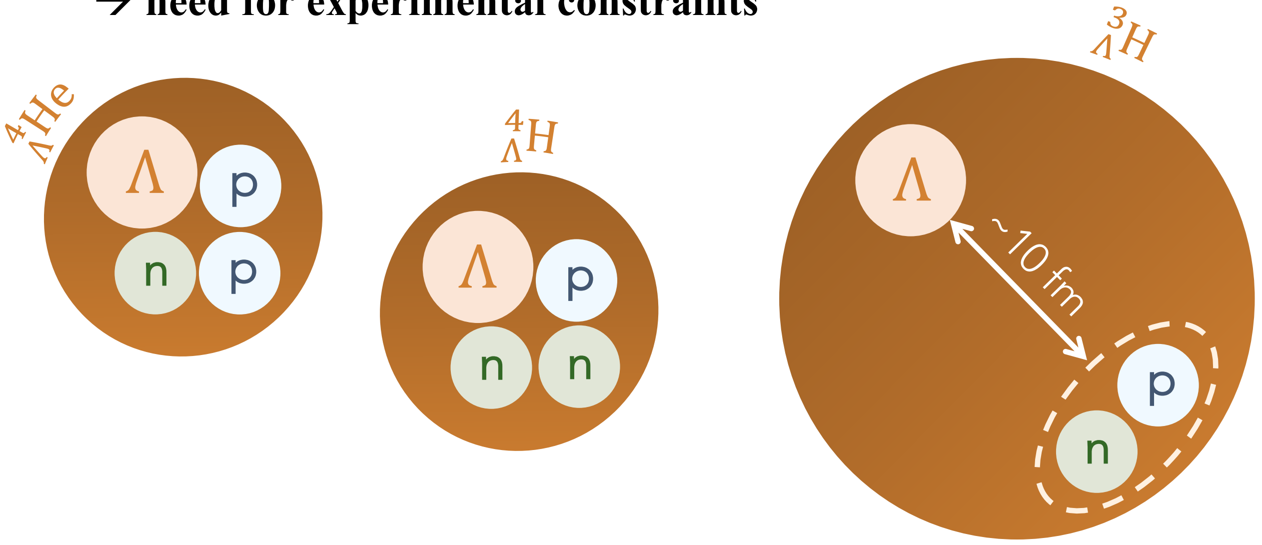
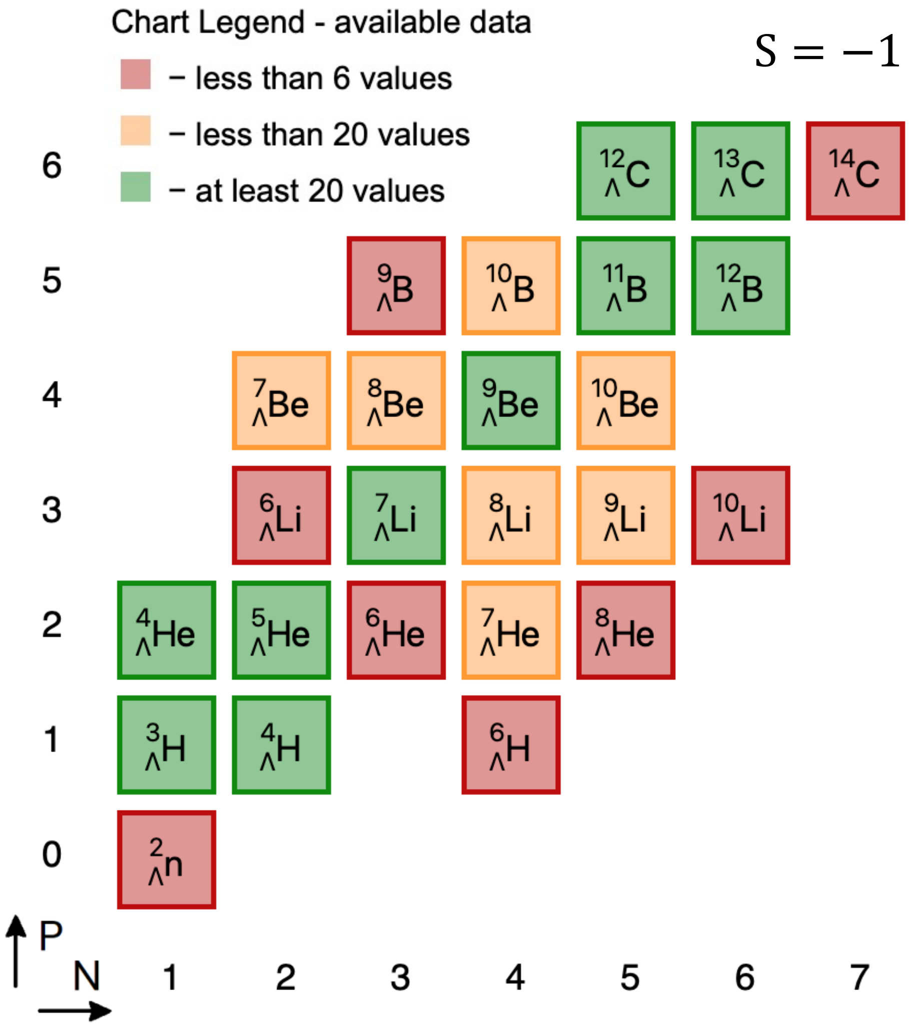
- Unique direct probes for studying the **interaction of hyperons with ordinary matter (Λ-N, Λ-N-N)**
- **Relevant for the physics of neutron stars (NS)**
  - Production of hyperons favourable inside the innermost core of NS[1][2]
  - Resulting softening of the equation-of-state (EoS) incompatible with measured heavy NS masses
  - Models introducing Λ-N-N repulsion[2] describe observed NS masses
    → **need for experimental constraints**





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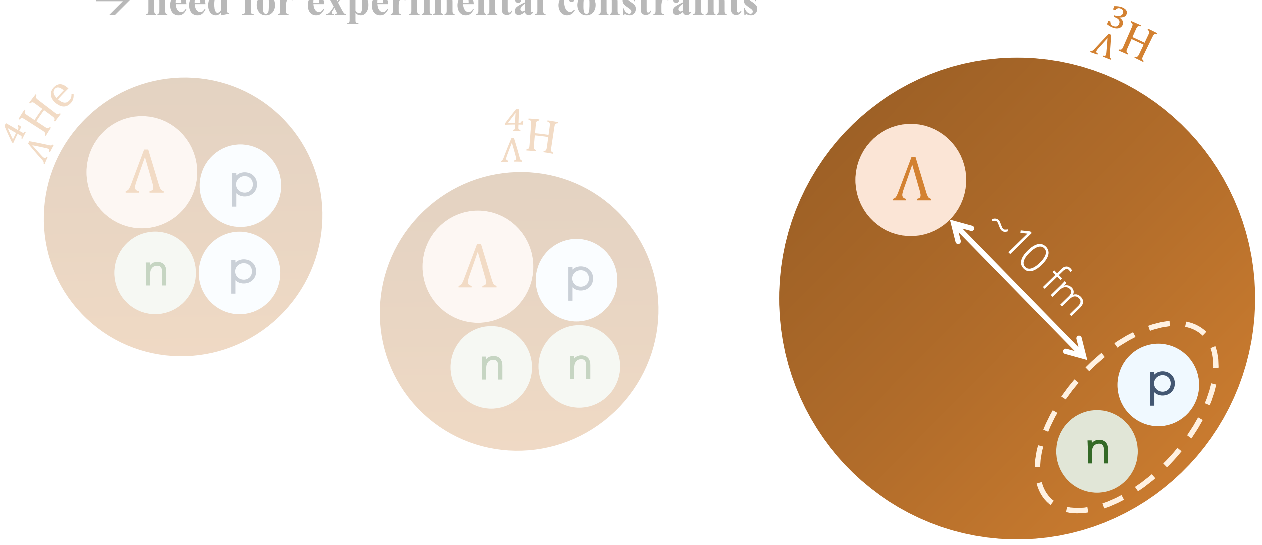
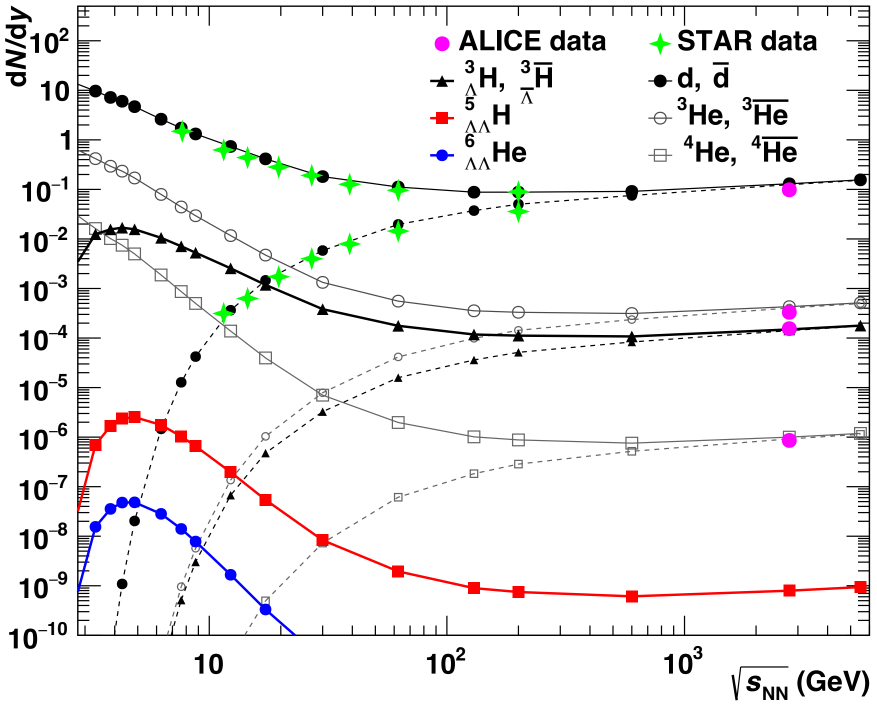


The Hypertriton ($^{3}_{\Lambda}$H)

- Lightest known hypernucleus
  $m \sim 2.991\ \mathrm{GeV}/c^2$
  $c\tau \sim 7.1\mathrm{cm}$
  $B_\Lambda = 102 \pm 63(\mathrm{stat}) \pm 67(\mathrm{syst})\mathrm{keV}$ [3]
- **Mesonic charged decay channels:**
  $^{3}_{\Lambda}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \pi^-$ (BR ≅ 0.25[4])
  $^{3}_{\Lambda}\mathrm{H} \longrightarrow \mathrm{d} + \mathrm{p} + \pi^-$ (BR ≅ 0.40[4])

[1] D. Logoteta et al., Eur. Phys. J. A 55, 207 (2019)
[2] D. Lonardoni et al., Phys. Rev. Lett. 114, 092301 (2019)
[3] ALICE, Phys. Rev. Lett. 131, 102302 (2023)
[4] H. Kamada et al., Phys. Rev. C 57, 1595 (1998)

(Hyper)nucleosynthesis at the LHC



Thermal models (SHM)[5]

- Hadrons/nuclei emitted from interaction region in **statistical equilibrium at T_{ch}**
- Predict **abundances of particle species** ($\mathrm{d}N/\mathrm{d}y \propto \mathrm{e}^{-m/T_{\text{ch}}}$)
- Yield of (hyper)nuclei in central Pb-Pb collisions described by same fit as hadrons
  → Same thermal production temperature $T_{\text{ch}} = 155$ MeV (at LHC)
- **No dependence on (hyper)nuclei structure**

[5] B. Dönigus, Eur. Phys. J. A 56, 280 (2020)

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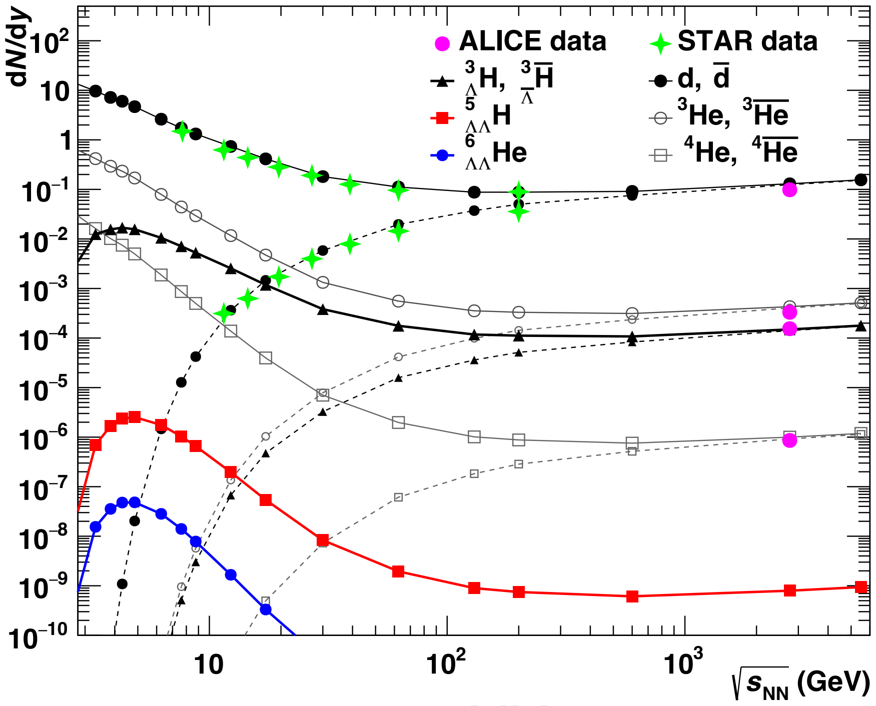

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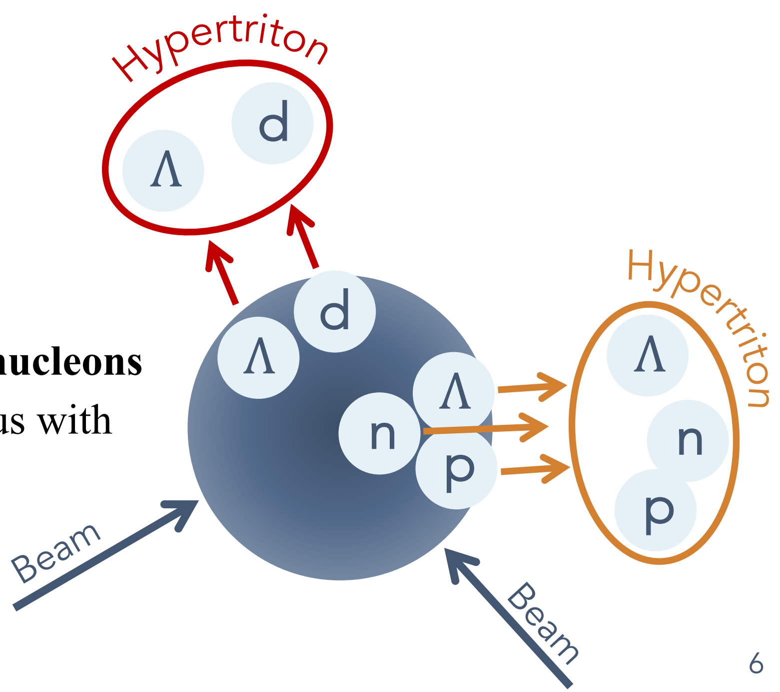
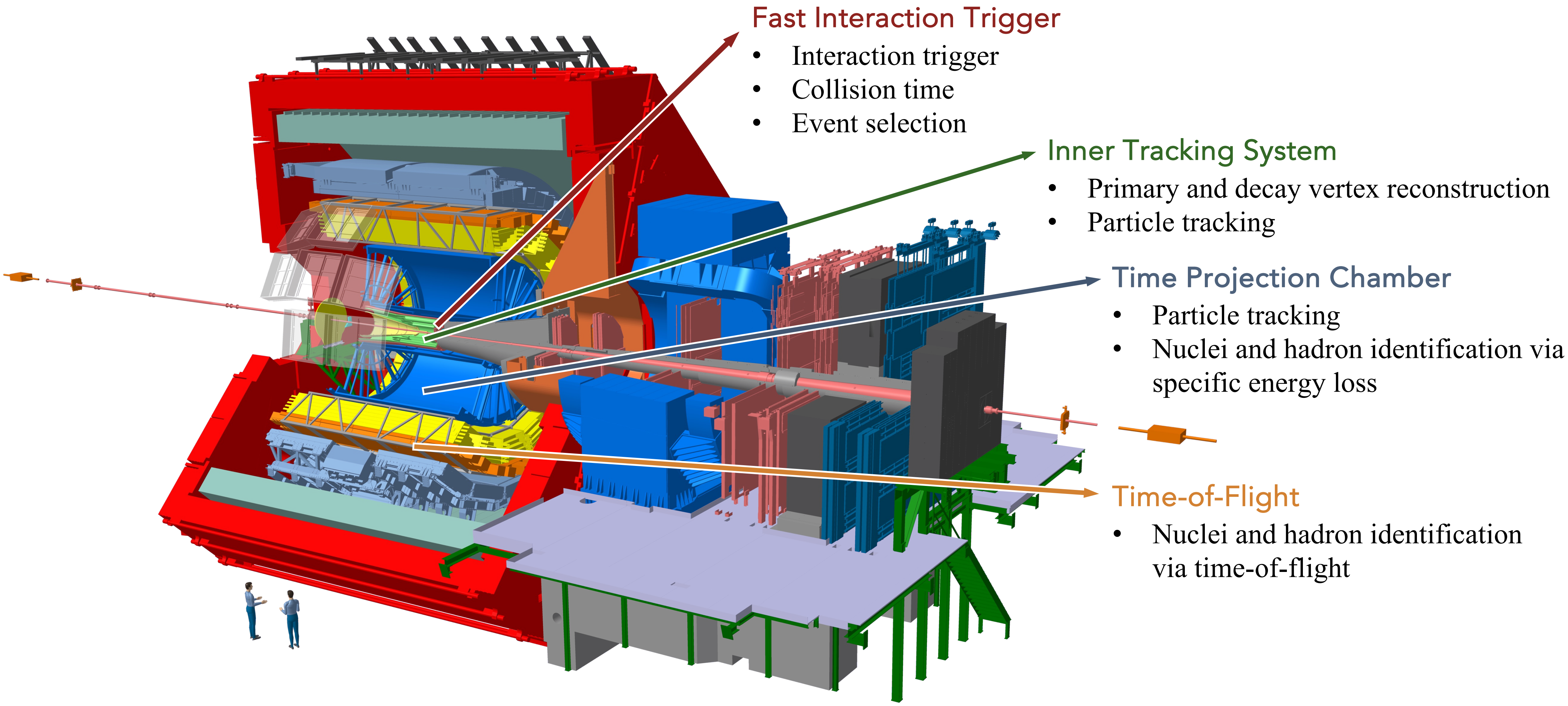


Coalescence models[6][7]

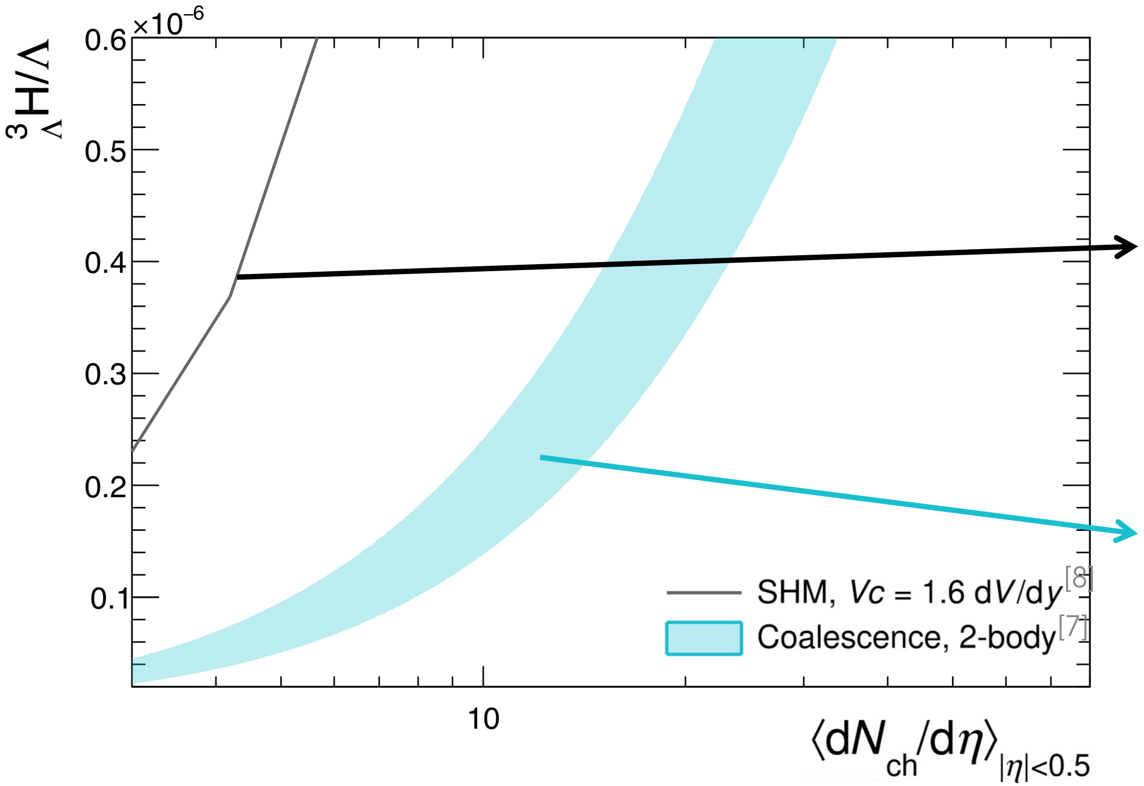
- Nucleons close in phase-space at kinetic freeze-out can form a nucleus
- Production probability depends on **overlap of nuclear wave functions and phase space of nucleons**
- **For A = 3 nuclei:** overlap of three nucleons **(3-body coalescence)** or overlap of A = 2 nucleus with nucleon **(2-body coalescence)**
- **Powerful description of formation process** → exploit different wave functions

[5] B. Dönigus, Eur. Phys. J. A 56, 280 (2020)
[6] Butler et. al., Phys. Rev. 129, 836 (1963)
[7] Sun et. al., Phys. Lett. B 792, 132 (2019)

The ALICE detector in Run 3



Hypertriton in small collision systems



- Yield ratio $^{3}_{\Lambda}\mathrm{H}/\Lambda$
  → **Large separation between SHM and coalescence models at low charged-particle multiplicity**

Thermal model[8]

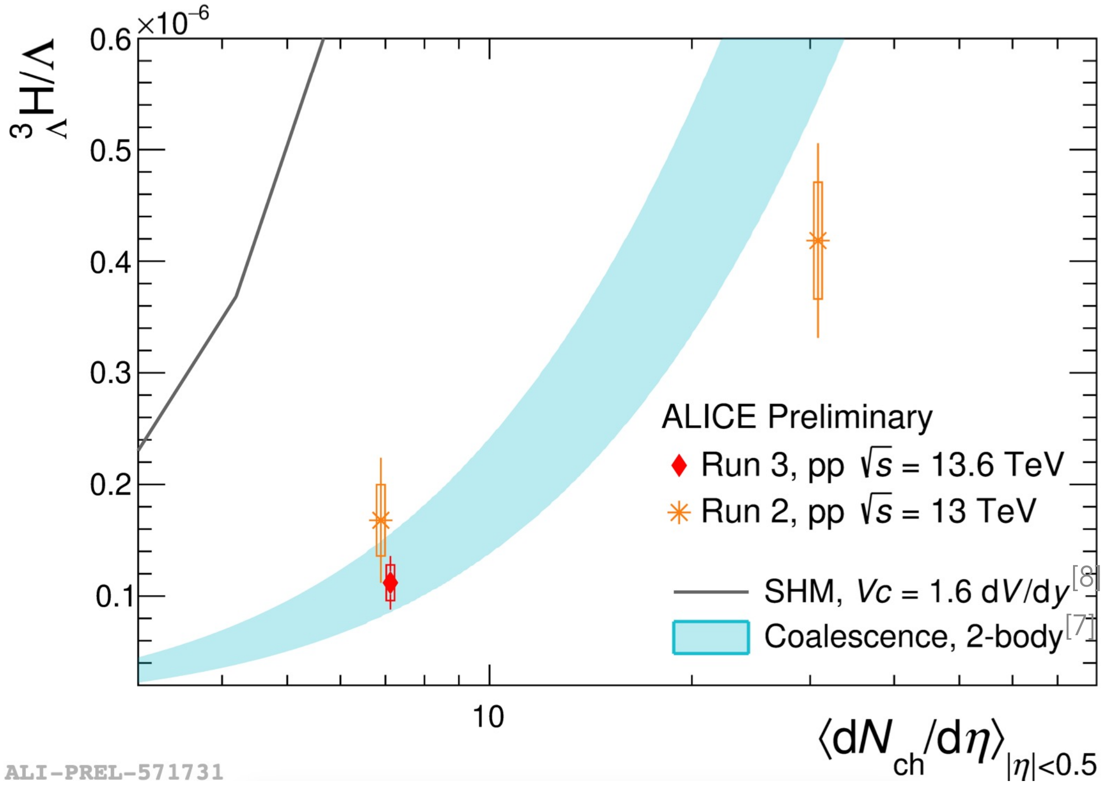
- Independent of object size
  → production suppression due to **canonical conservation of quantum numbers** in small systems

Coalescence model[7]

- Sensitive to interplay between collision system size and spatial expansion of the nucleus wave function
  → production suppression in small systems due to **small emission source size and wide $^{3}_{\Lambda}$H wave-function**

[7] Sun et. al., Phys. Lett. B 792, 132 (2019)
[8] Vovchenko, et al., Phys. Lett. B 785, 171, (2018)

Hypertriton in small collision systems



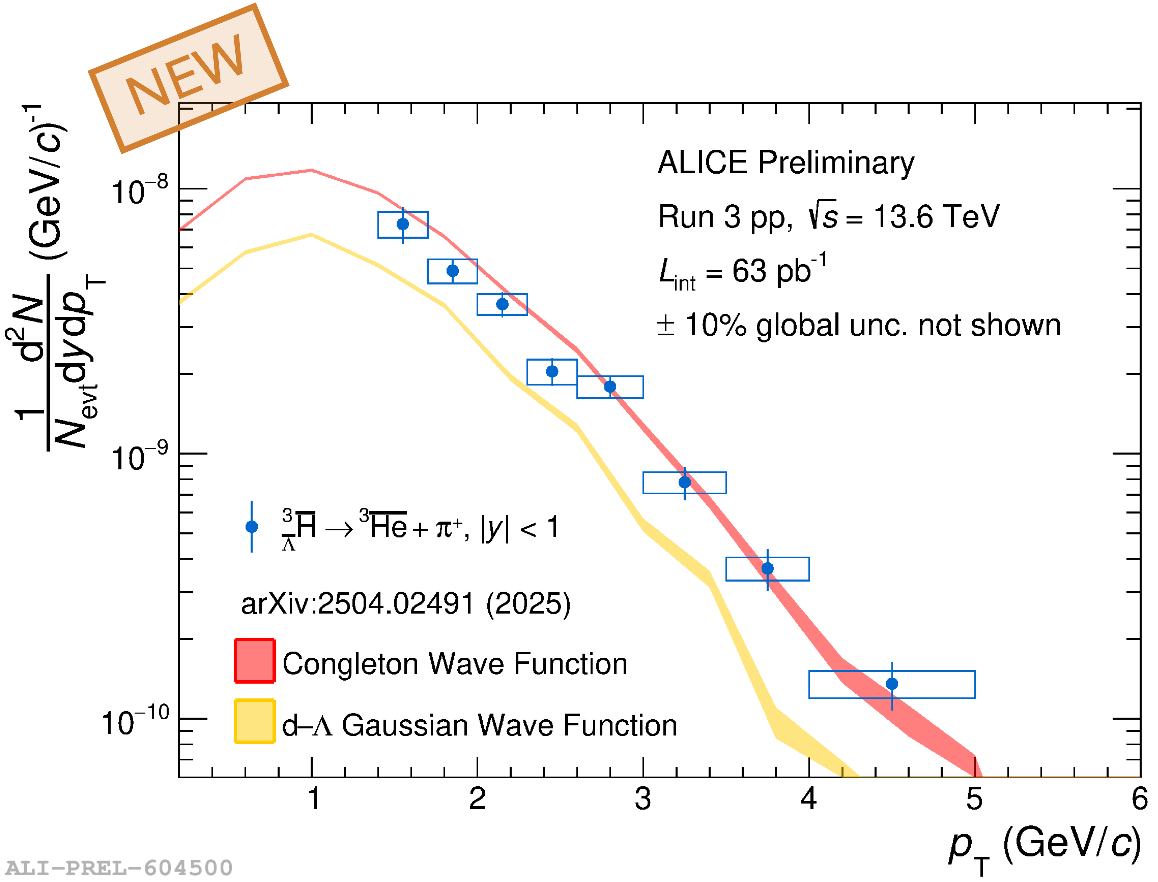
- Yield ratio $^{3}_{\Lambda}\mathrm{H}/\Lambda$
  → **Large separation between SHM and coalescence models at low charged-particle multiplicity**

Precise measurement in Run 3 pp collisions

- Tension with SHM
  → strong constraint on SHM configuration
- **Coalescence describes $^{3}_{\Lambda}$H suppression in pp collisions**
  → nuclear size seems to matter at low charged-particle multiplicity

[7] Sun et. al., Phys. Lett. B 792, 132 (2019)
[8] Vovchenko, et al., Phys. Lett. B 785, 171, (2018)

Hypertriton in small collision systems



First p_T- differential measurement of $^{3}_{\Lambda}$H spectrum in pp collisions

- **Coalescence:** p_T-dependence of emission source size
  → reduction of source size at high p_T
  → suppression of $^{3}_{\Lambda}$H yield (extended wave-function)
  → measurement of p_T-differential production ratios allows to differentiate between thermal production and coalescence[9]

[9] D. Liu, at al., Phys. Lett. B 855, 138855 (2024)
[10] M. Mahlein, et al., arXiv:2504.02491

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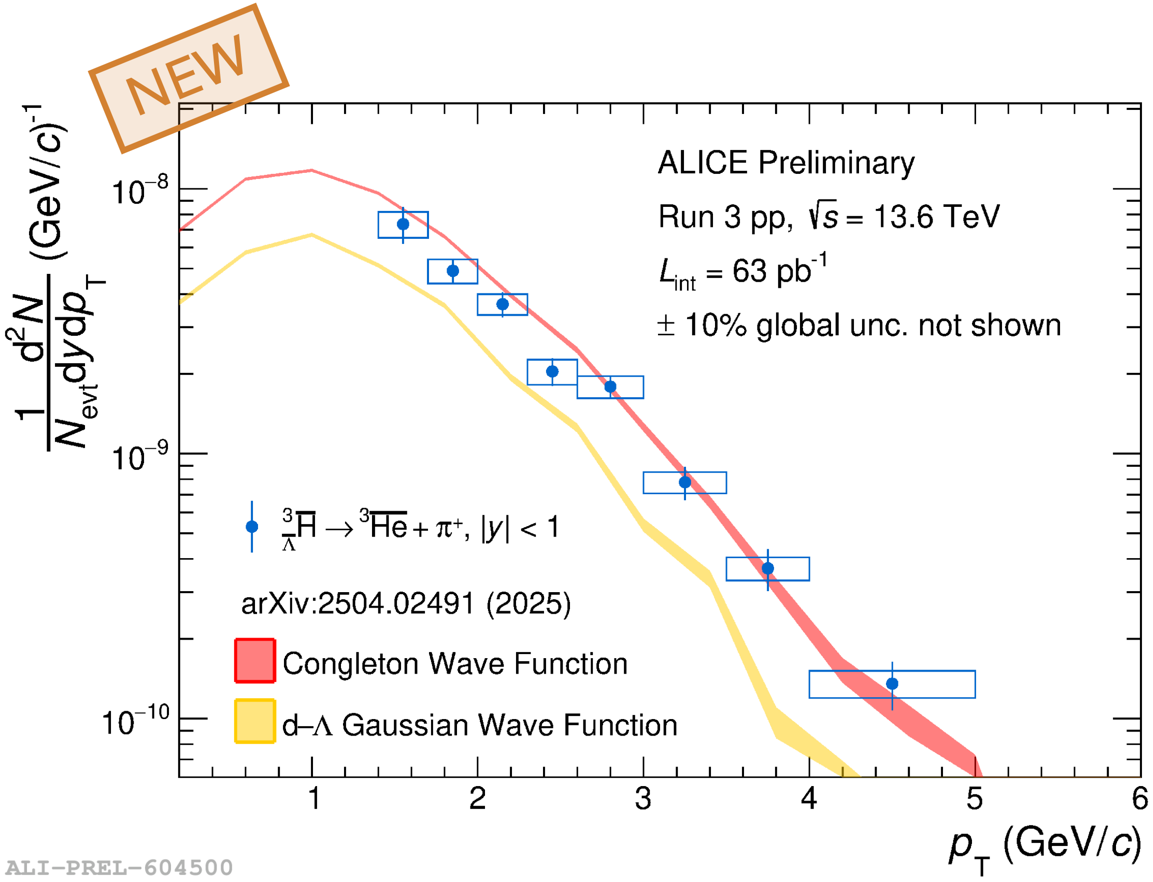

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- Measurement of anti-matter via $^{3}_{\bar{\Lambda}}\bar{H} \longrightarrow {}^{3}\overline{He} + \pi^{+}$ decay channel
- New advanced coalescence model (ToMCCA)[10]
  → coalescence afterburner employing realistic $^{3}_{\Lambda}$H wave function (**Congleton** or **Gaussian**)
  → first $^{3}_{\Lambda}$H p_T-spectrum prediction
  → **Good data description** using **Congleton wave function**
- Allows to analyse **the hypertriton wave-function**

[9] D. Liu, at al., Phys. Lett. B 855, 138855 (2024)
[10] M. Mahlein, et al., arXiv:2504.02491

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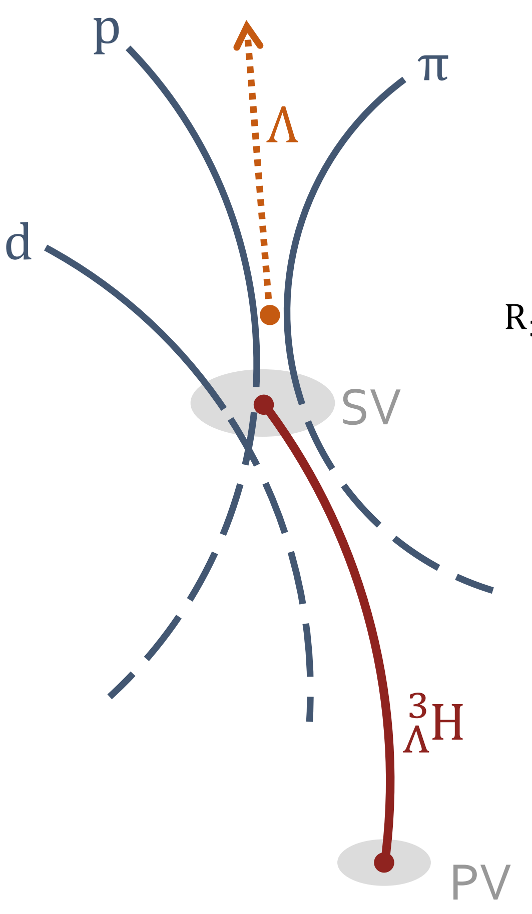
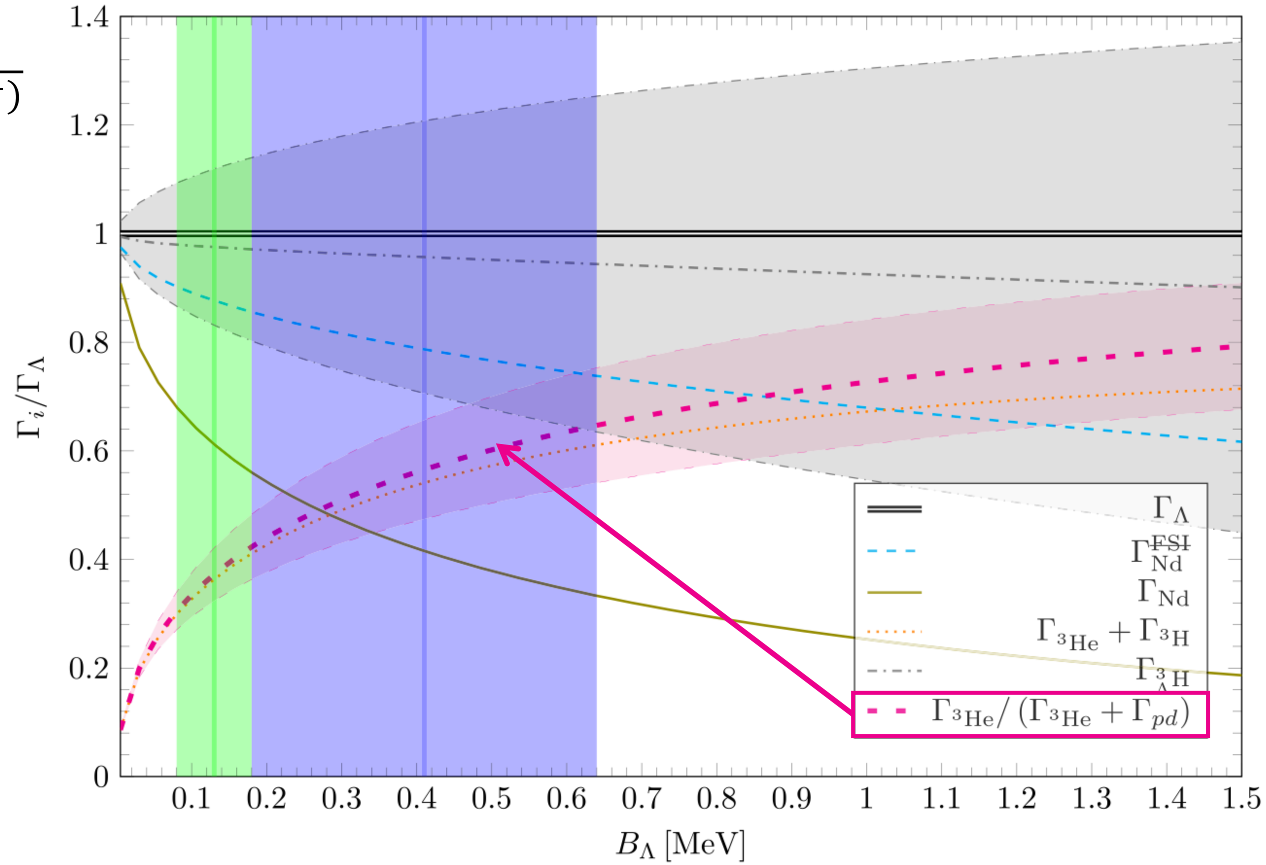


Hypertriton three-body decay measurement

- Exact measurements of all $^3_\Lambda$H decay modes and their BRs are missing
- Additional experimental constraint to $^3_\Lambda$H properties via **measurement of ratio of production rates:**

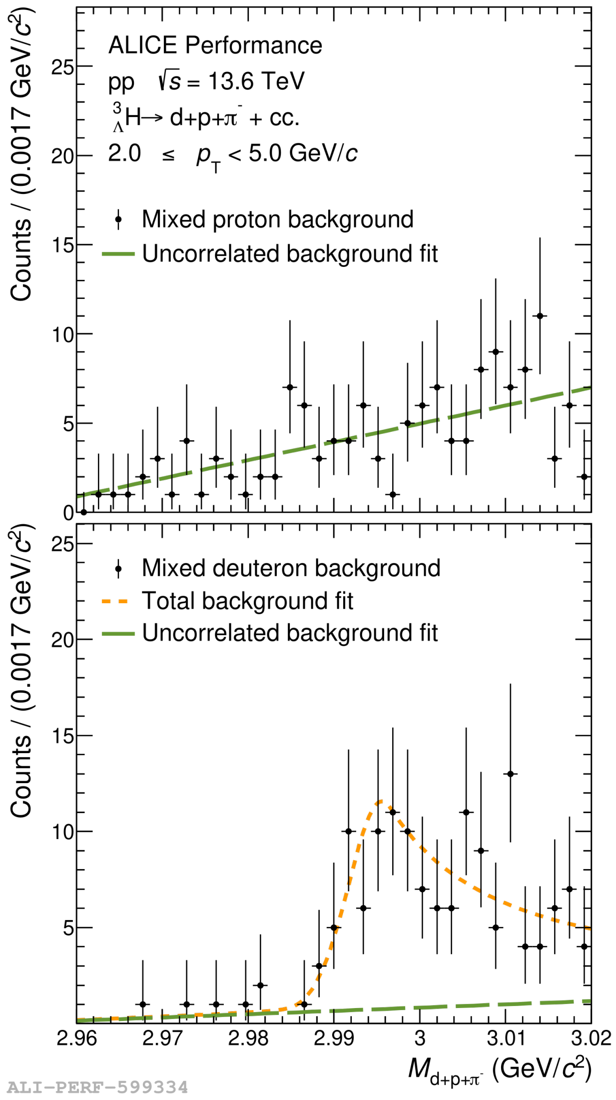
$$R_3 \approx \frac{\Gamma(^3_\Lambda H \to {}^3He\,\pi^-)}{\Gamma(^3_\Lambda H \to {}^3He\,\pi^-) + \Gamma(^3_\Lambda H \to d\,p\,\pi^-)}$$

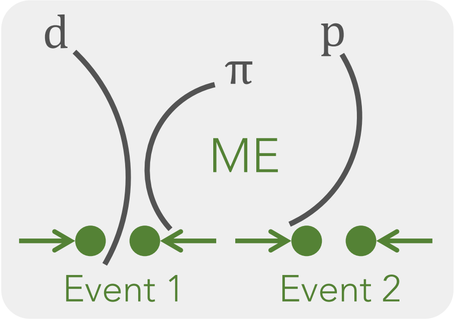
[11] F. Hildenbrand, et al., Phys. Rev. C 102, 064002 (2020)



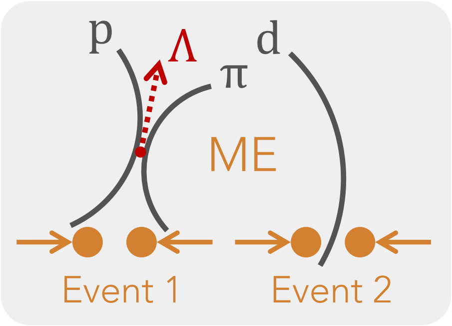
Hypertriton in small collision systems

Mixed event distributions





Fully uncorrelated background



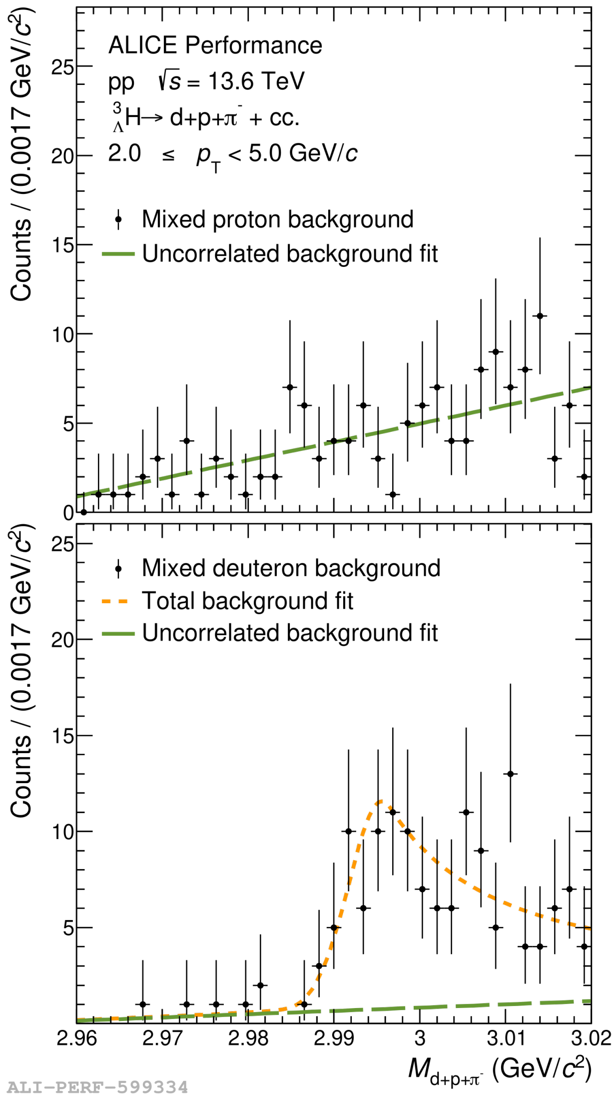
Fully uncorrelated + uncorrelated Λ-d background

Hypertriton three-body decay measurement

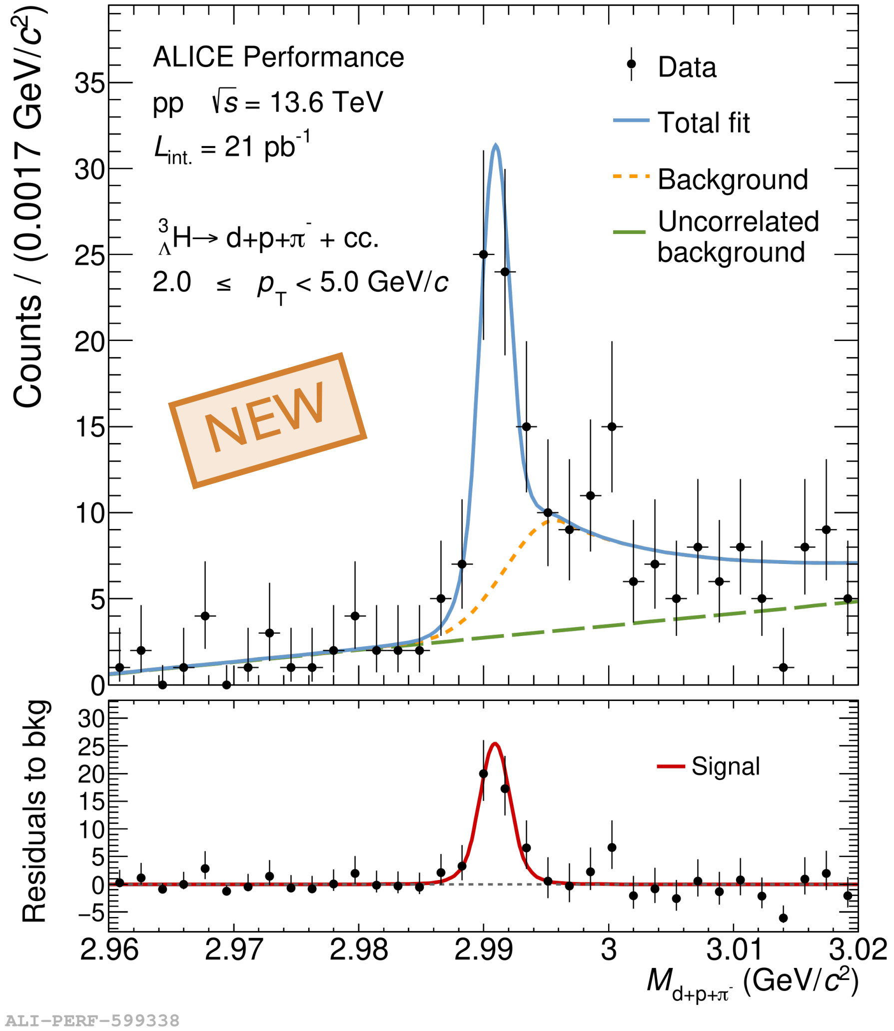
- **Background estimation with event mixing technique**
  - Invariant mass analysis of **same event (SE)** and **mixed event (ME)** triplets for background estimation

Hypertriton in small collision systems

Mixed event distributions



Same event distribution



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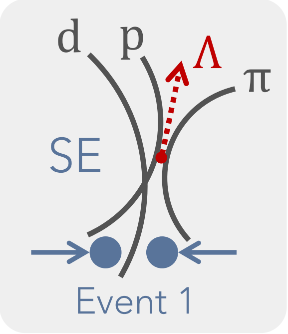

Same event distribution

Hypertriton in small collision systems

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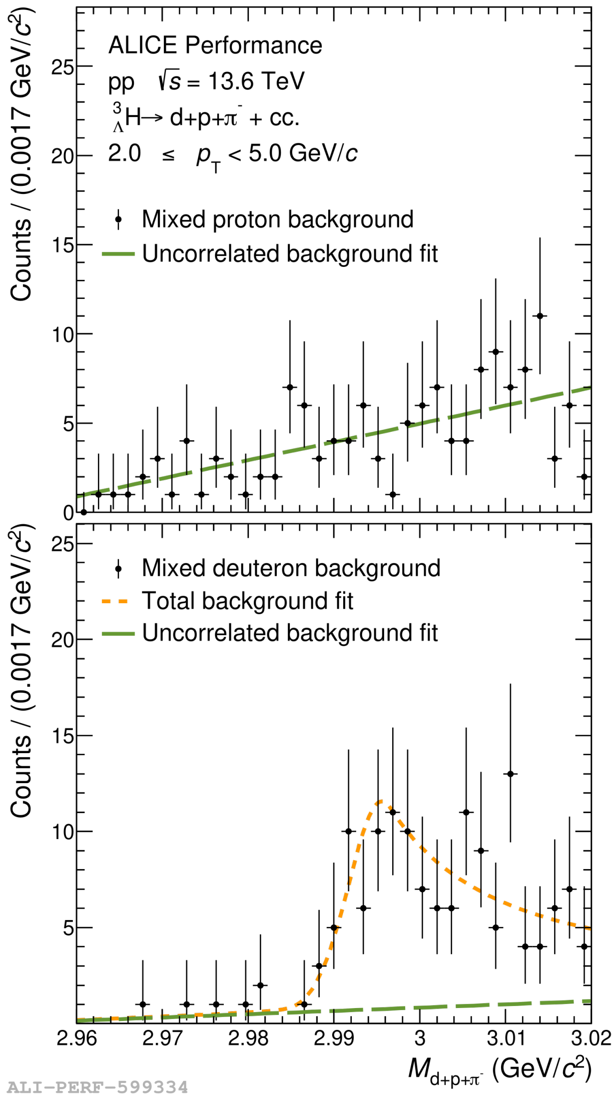

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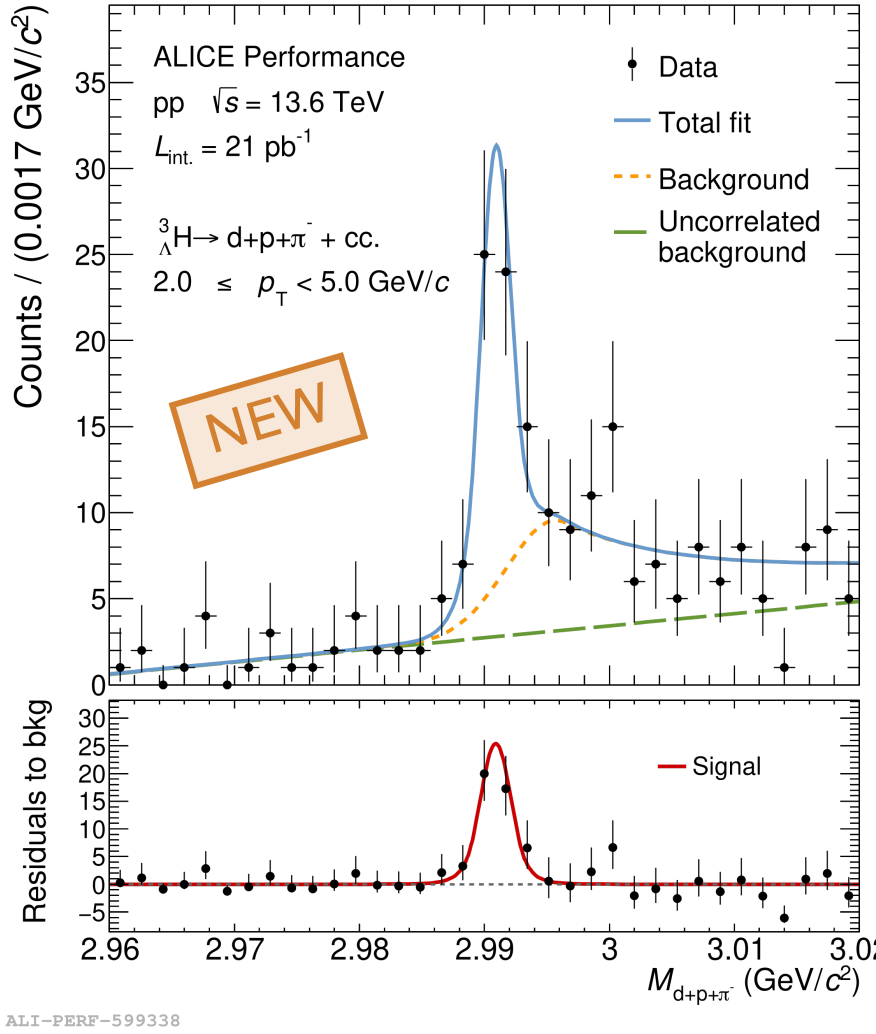

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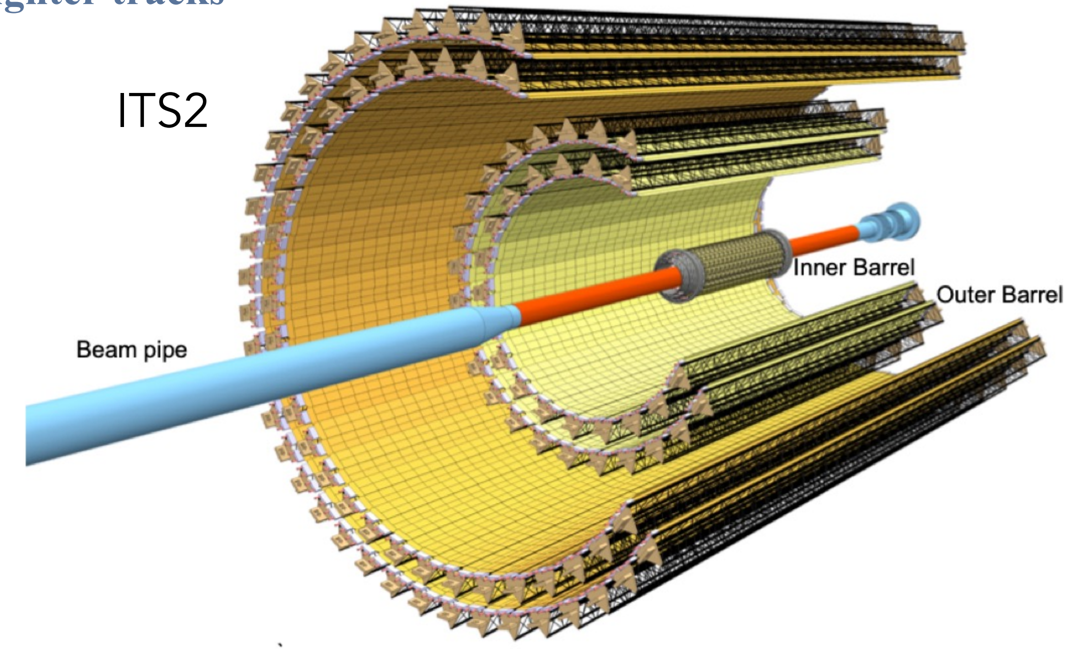
First reconstruction of $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$ in ALICE

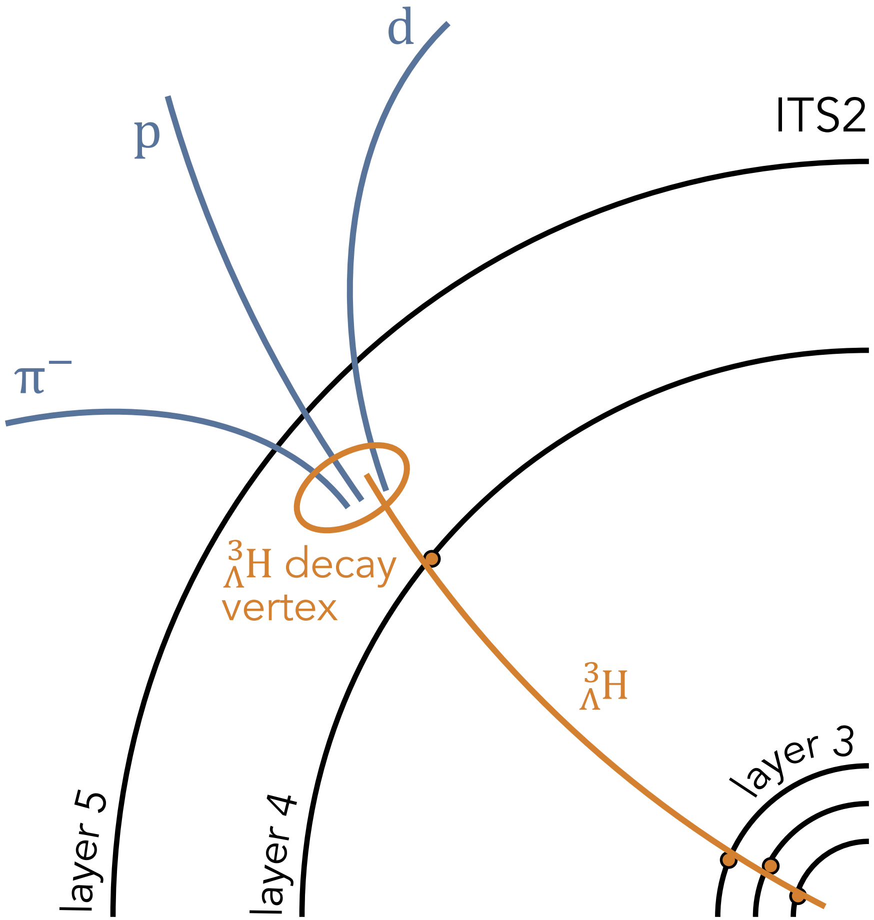
Measurement of R_3 is feasible at LHC in Run 3 pp collisions

Strangeness tracking

Strangeness tracking technique

- **New Inner Tracking System (ITS2)**
  - 7 silicon layers based on Monolithic Active Pixel Sensors (MAPS)
  - Innermost layers close to interaction point (22.4 mm)
- **Improved vertex reconstruction** via combination of
  - direct detection of **${}^{3}_{\Lambda}$H tracklet in Inner Tracking System (ITS2)**
  - vertex information of topological reconstruction from **weak decay daughter tracks**





[12] ALICE, J. Phys. G: Nucl. Part. Phys. 41, 087002 (2014)

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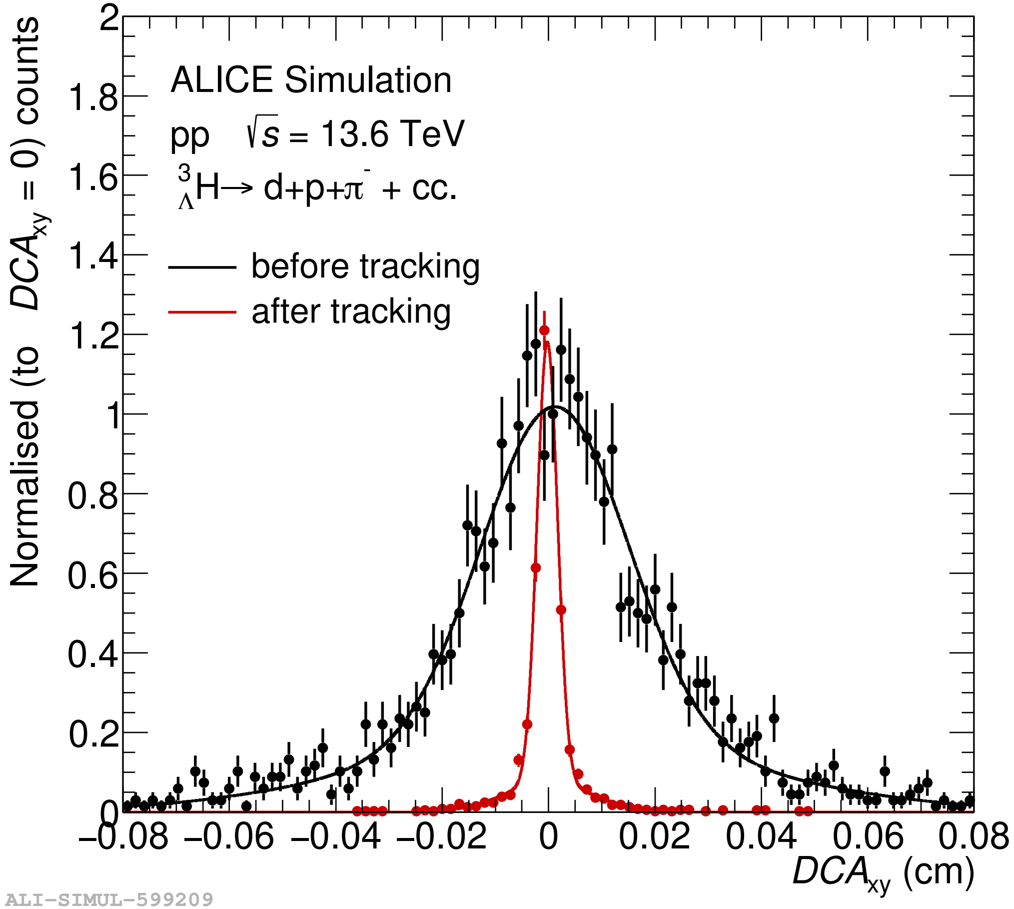
Performance

- **Improved pointing resolution** (DCA_{xy} to PV) by factor ~ 8



ALI-SIMUL-599209

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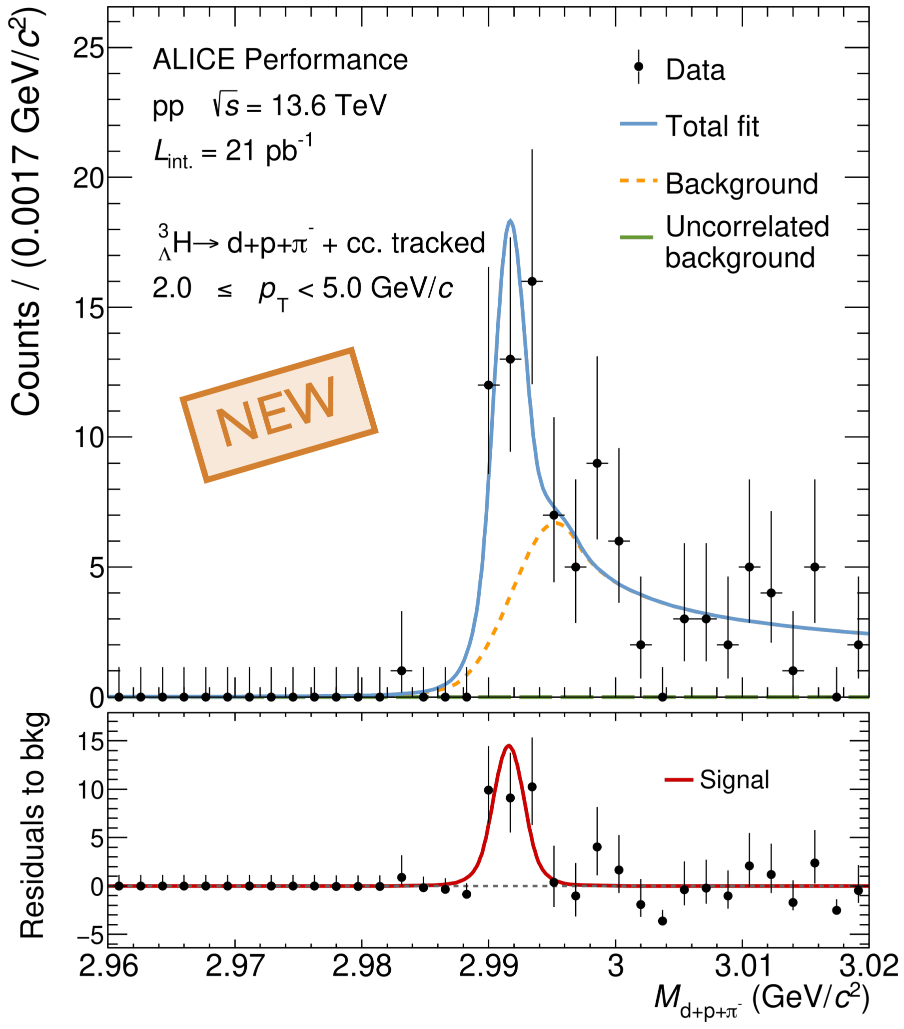
Performance

- **Improved pointing resolution** (DCA_{xy} to PV) by factor ~ 8
- Additional background from **Λ-d correlation in three-body decay channel**
  → expected to be suppressed by strangeness tracking
- **Tracked $^{3}_{\Lambda}$H visible in Run 3 pp collisions**
  → plan to apply technique in three-body analysis for additional background suppression



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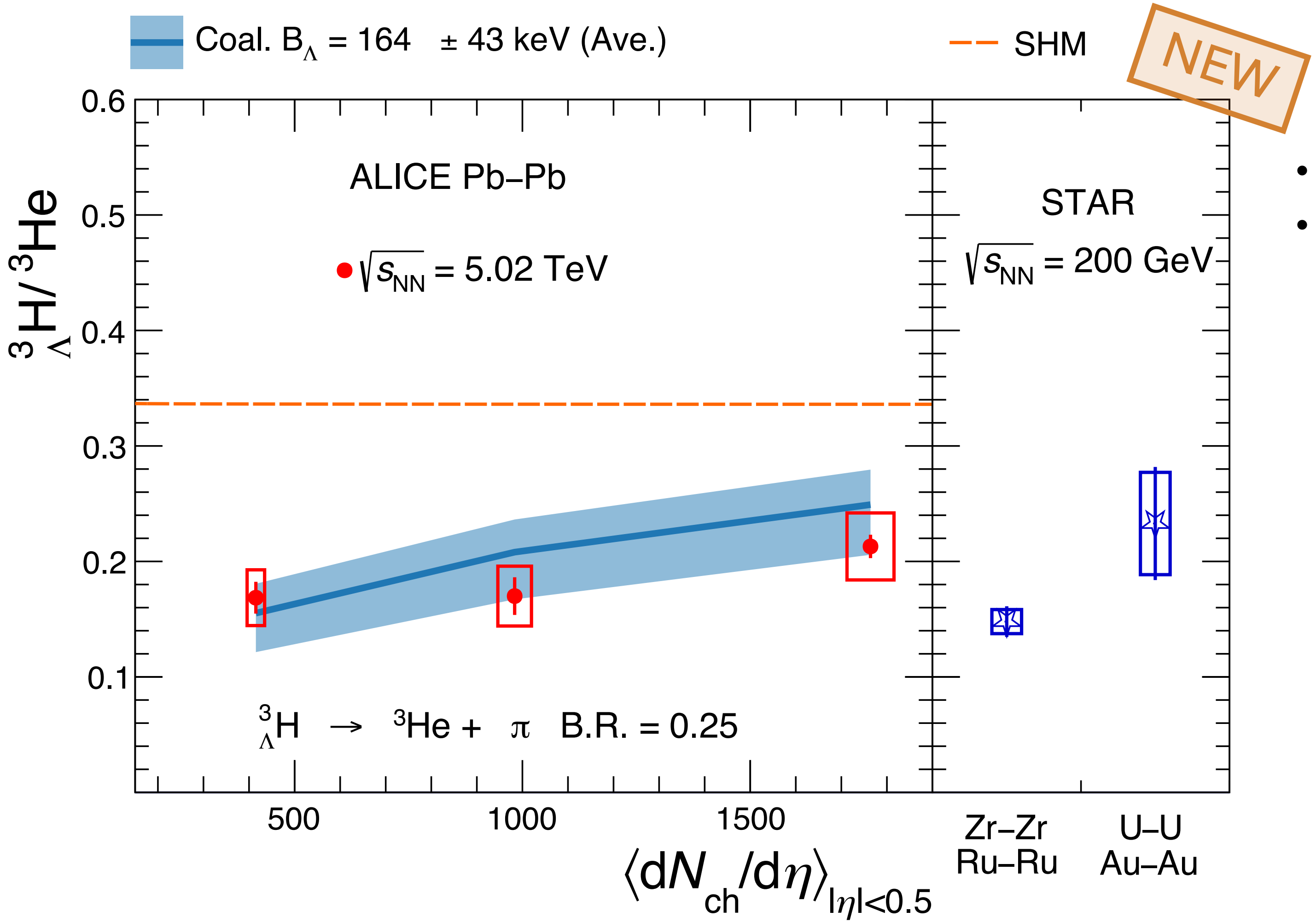
Hypertriton production in Run 2 Pb-Pb collisions



- **Multiplicity dependence of $^3_\Lambda H/{}^3He$ ratio**
- Suppression observed for smaller size of produced medium as suggested by **STAR results**[14]

[13] ALICE, Phys. Lett. B 860, 139066 (2025)
[14] STAR, Nature 632 8027, 1026 (2024)

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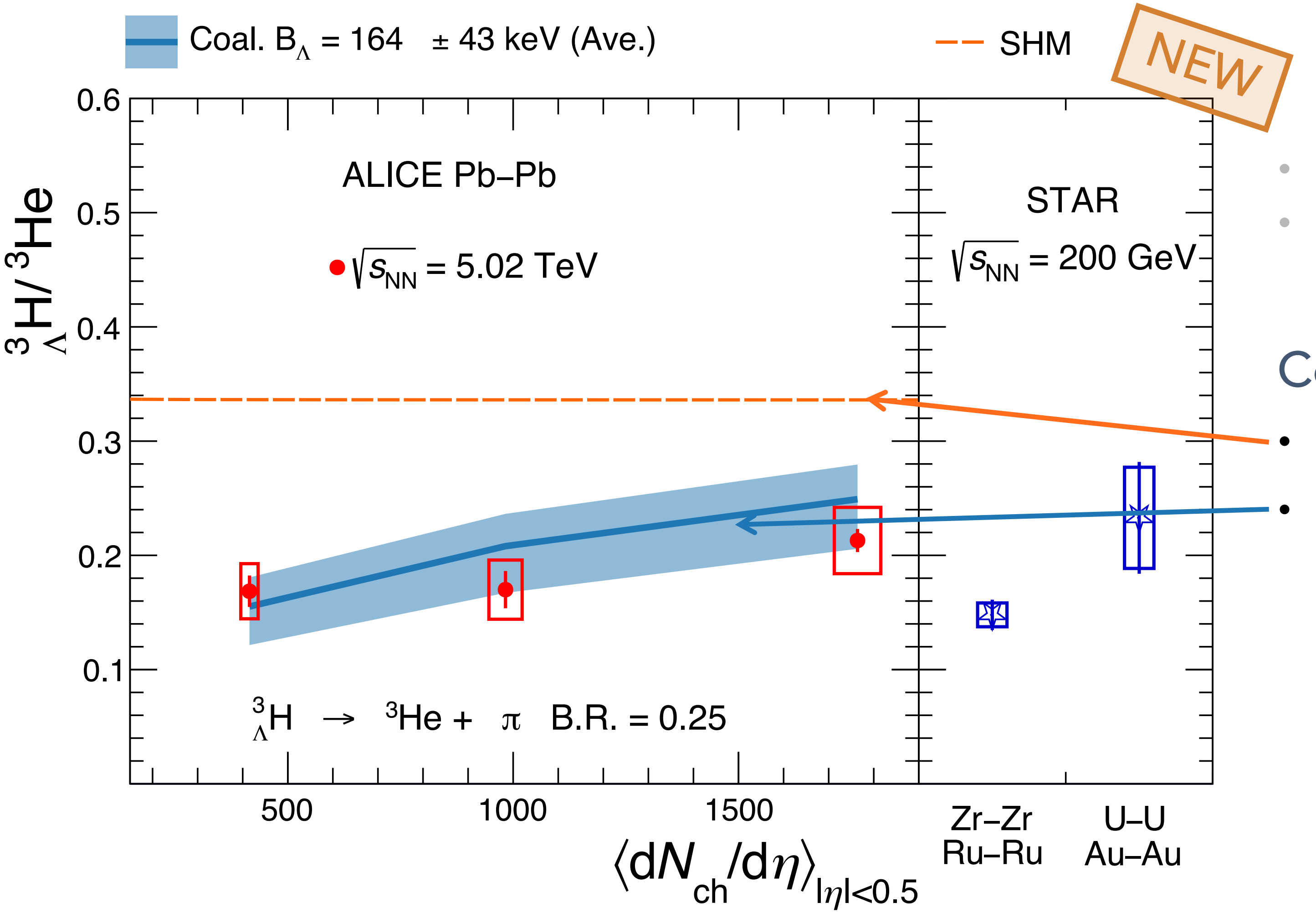

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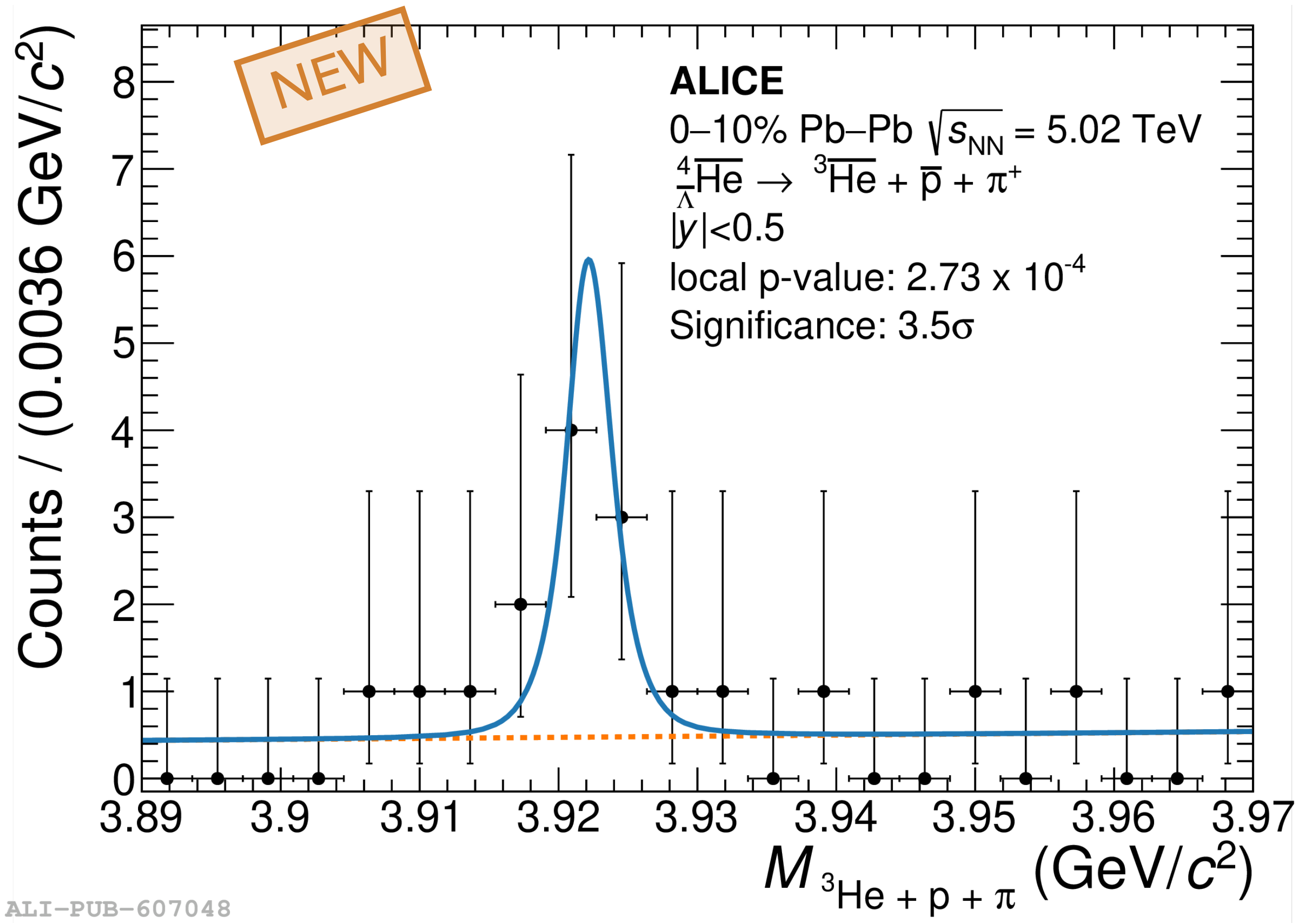
Comparison to model predictions

- **SHM prediction** constant at large multiplicities
- **Coalescence prediction** sensitive to multiplicity
  - Captures **measured $^3_\Lambda H/^3He$ ratio**

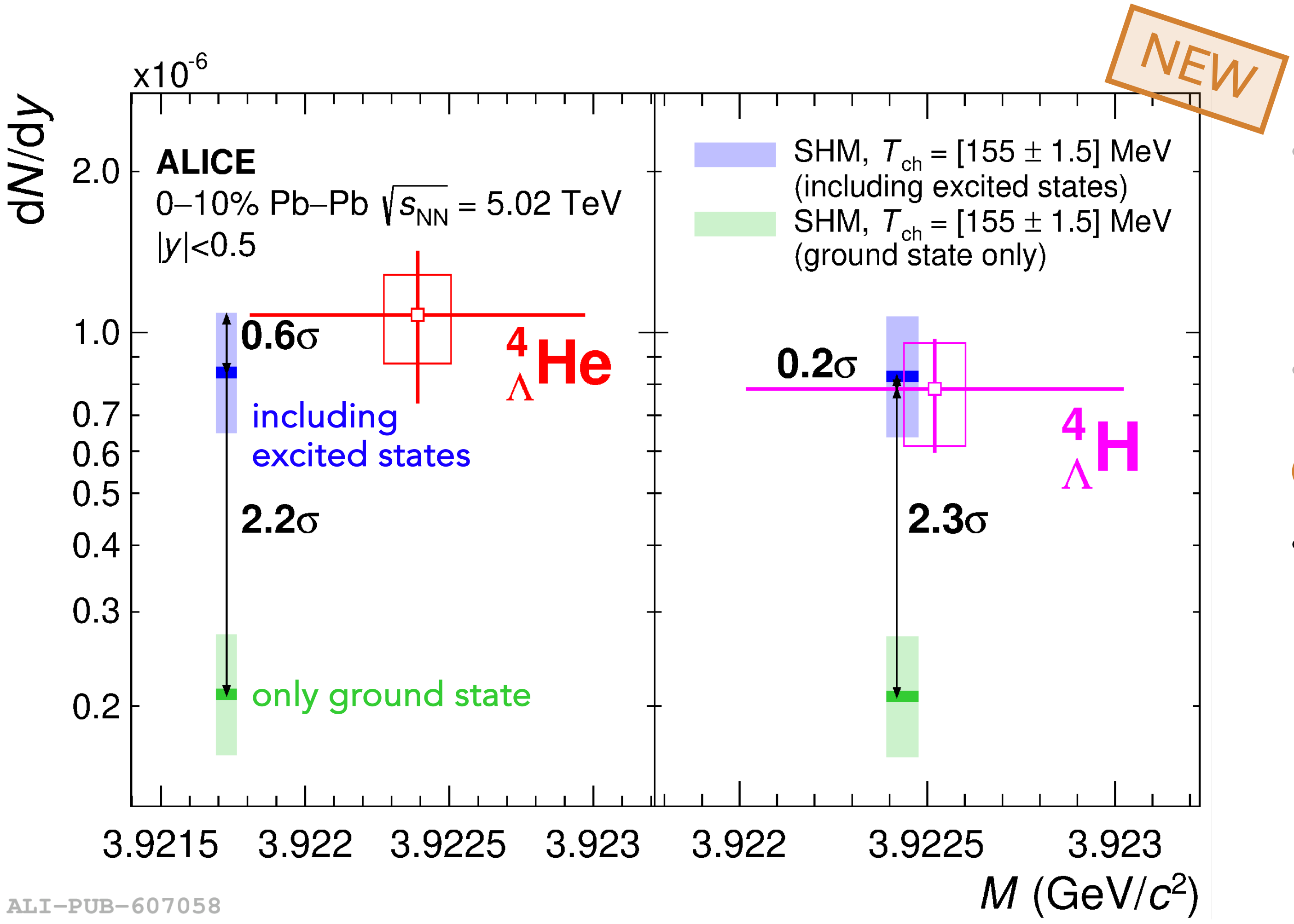
[13] ALICE, Phys. Lett. B 860, 139066 (2025)
[14] STAR, Nature 632 8027, 1026 (2024)

A = 4 hypernuclei in Run 2 Pb-Pb collisions



- First measurements of A = 4 (anti)hypernuclei yields at the LHC
  - $^{4}_{\Lambda}H \longrightarrow {}^{4}He + \pi^{-} + c.c.$
  - $^{4}_{\Lambda}He \longrightarrow {}^{3}He + p + \pi^{-} + c.c.$
- **First ever signal of $^{4}_{\bar{\Lambda}}\overline{He}$**

A = 4 hypernuclei in Run 2 Pb-Pb collisions



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  - $^{4}_{\Lambda}\mathrm{H} \longrightarrow {}^{4}\mathrm{He} + \pi^{-} + \mathrm{c.c.}$
  - $^{4}_{\Lambda}\mathrm{He} \longrightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-} + \mathrm{c.c.}$
- **First ever signal of $\overline{^{4}_{\Lambda}\mathrm{He}}$**

Comparison to SHM model predictions

- Measured yields compatible with **SHM predictions including feed-down constributions from excited states**
  - SHM yields enhanced by factor ~ 4

[15] ALICE, Phys. Rev. Lett. 134, 162301 (2025)

Summary

Hypertriton production in small collision systems

- **First p_T- differential measurement of ${}^{3}_{\Lambda}\mathrm{H}$ in pp collisions**
  - Good description by new advanced coalescence model
- **First reconstruction of ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$ in ALICE**
  - Measurement of R_3 is feasible at LHC in Run 3 pp collisions
  - Constraint for ${}^{3}_{\Lambda}\mathrm{H}$ branching ratios and properties
  - **Strangeness tracking:** New powerful tool for reconstruction of weakly decaying charged particles containing strangeness, including hypernuclei

Multiplicity dependence of ${}^{3}_{\Lambda}\mathrm{H}$ production in Pb-Pb collisions

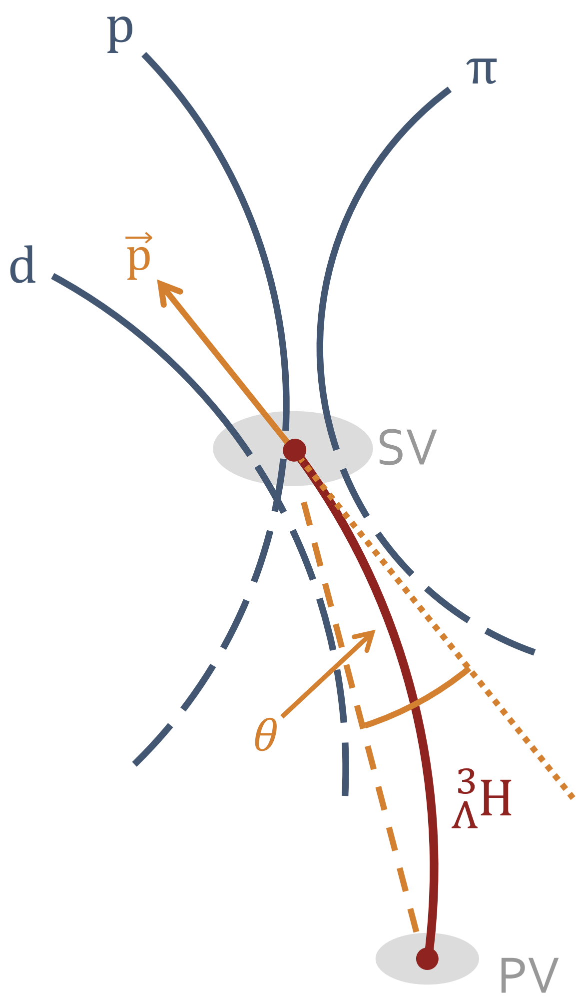
- **${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$ yield suppression at lower charged particle multiplicities** well described by coalescence model for (hyper)nuclei production

A = 4 hypernuclei production in Pb-Pb collisions

- **First measurements of A = 4 (anti)hypernuclei** yields at the LHC
  - SHM successful to describe more compact hypernuclei production
  - Provide test for dependence of the spin-degeneracy of the production models

Backup

Hypertriton in small collision systems



Hypertriton three-body decay measurement

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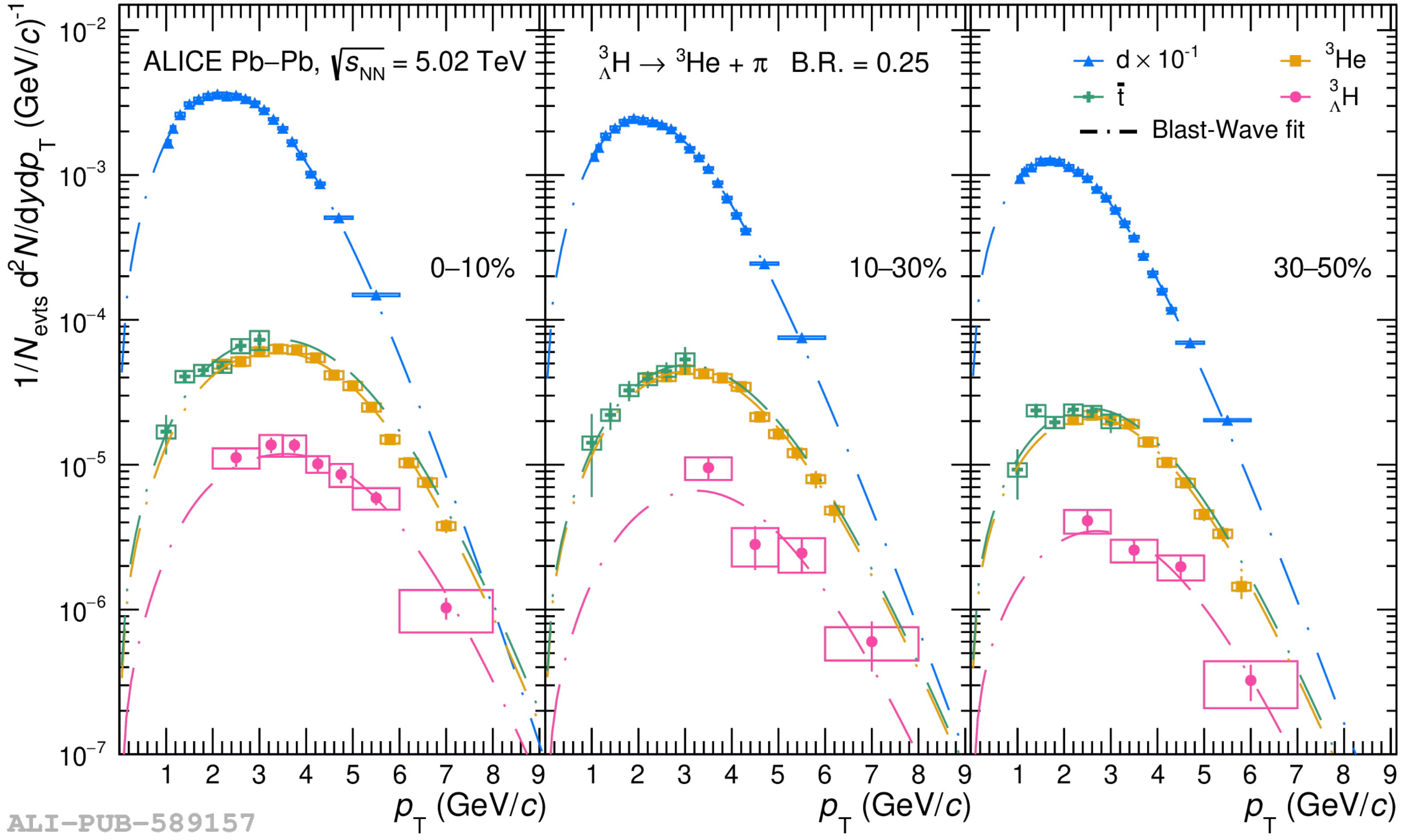
- Additional experimental constraint to $^3_\Lambda$H properties via **measurement of ratio of production rates:**

$$R_3 \approx \frac{\Gamma\left(^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-\right)}{\Gamma\left(^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-\right) + \Gamma\left(^3_\Lambda\mathrm{H} \to \mathrm{d} + \mathrm{p} + \pi^-\right)}$$

Decay reconstruction

1. **Daughter track identification** with specific energy loss and time-of-flight
2. Reconstruction of **displaced decay vertex**
3. Combinatorial background suppression via **topological selections**

Hypertriton production in Run 2 Pb-Pb collisions

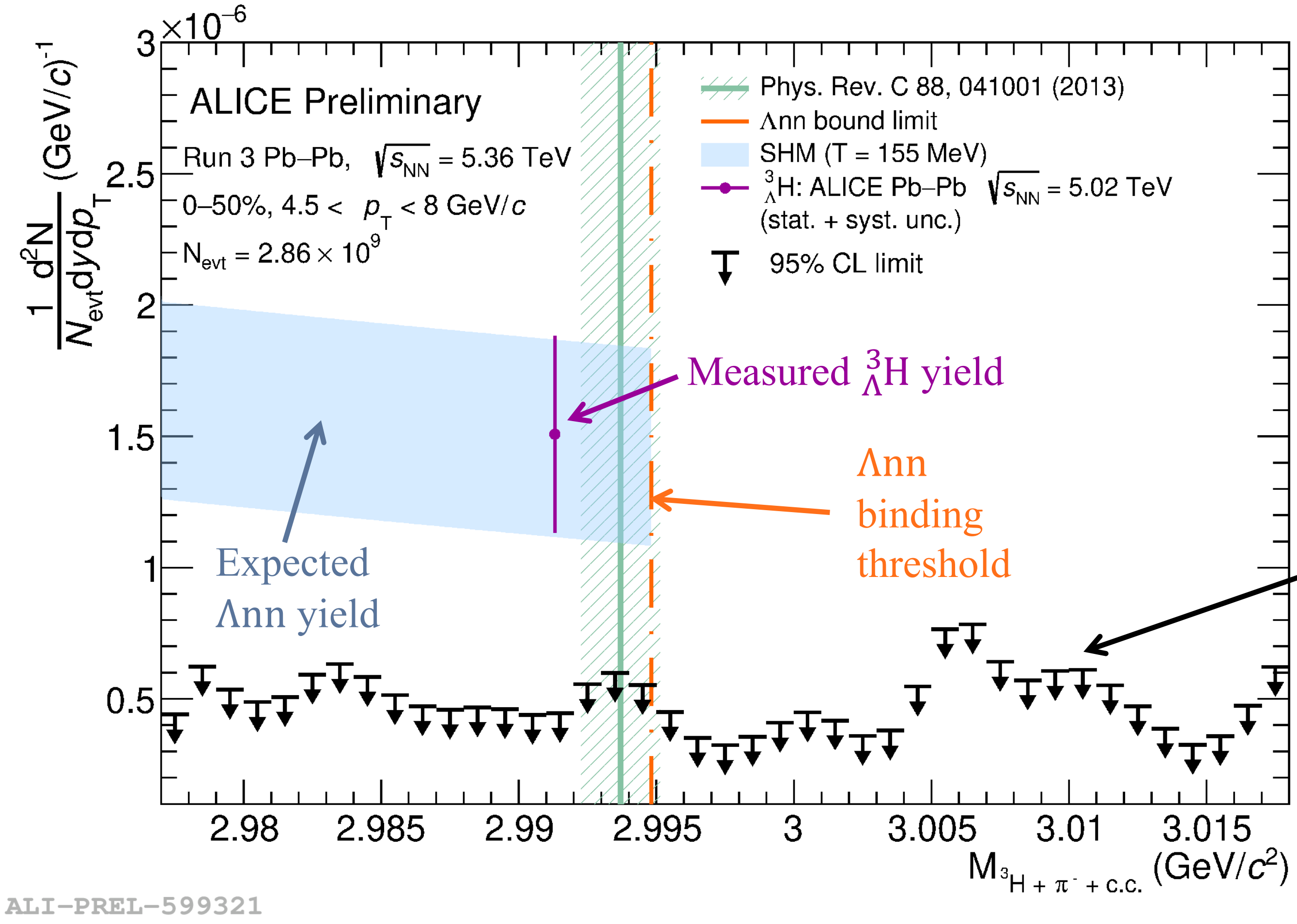


- **First measurement of p_T-differential $^3_\Lambda$H production** in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Combined Blast-Wave fit to d, t, ^{3}He, and $^3_\Lambda$H
  → **fit temperature and velocity profiles compatible** with the ones obtained from fit to ordinary light nuclei only (d, t, ^{3}He, ^{4}He)[16]

Hint for **common kinetic freeze-out surface** for hypernuclei and ordinary nuclei produced in Pb-Pb collisions

[16] ALICE, Phys. Lett. B 858, 138943 (2024)
[13] ALICE, Phys. Lett. B 860, 139066 (2025)

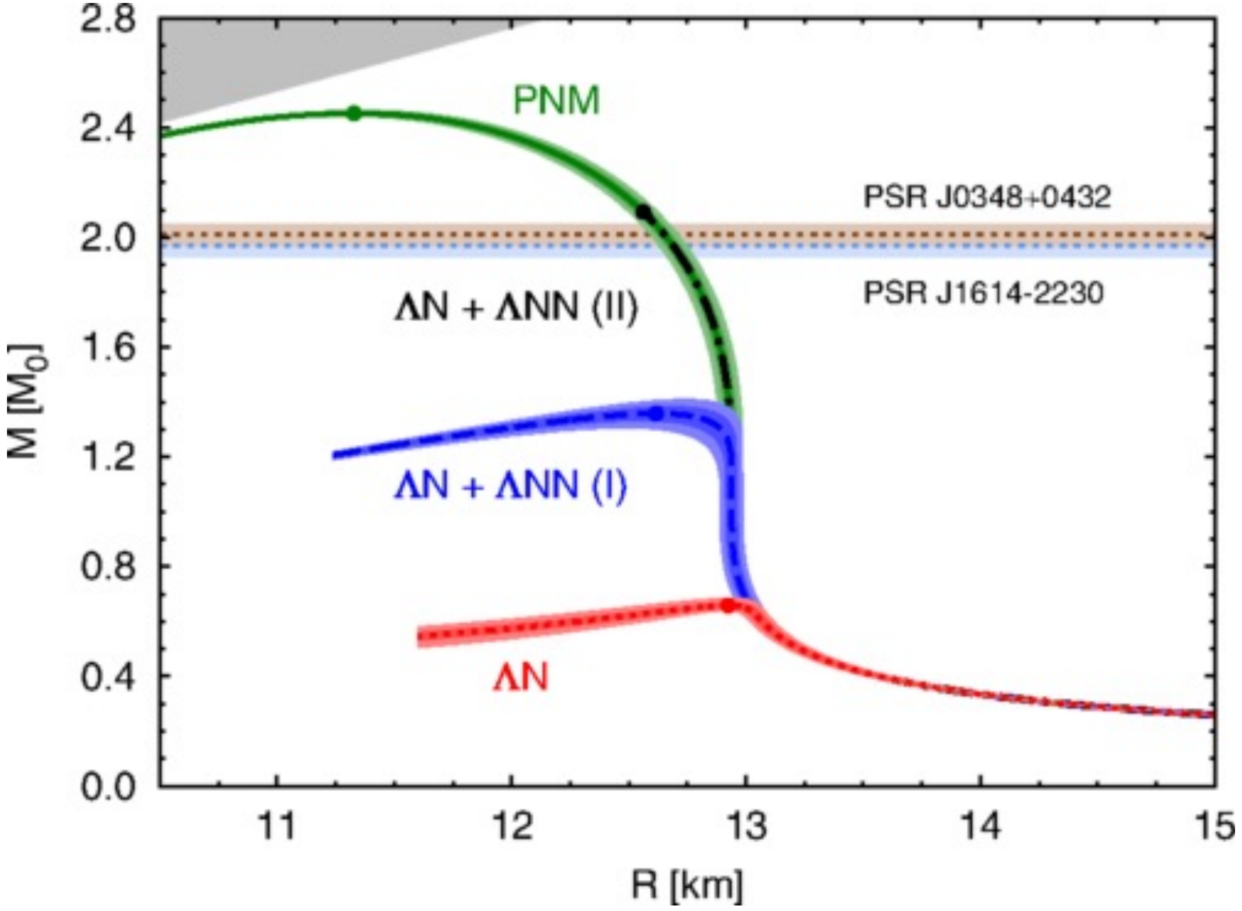
Search for exotic bound states in Run 3 Pb-Pb



- Search for Λnn bound state in Run 3 Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV
- Measurement of $\Lambda nn \to {}^3H + \pi^-$ decay
- **No significant structure** found in reconstructed invariant mass spectrum in data
- **Upper limit for expected yield is set**

Neutron stars equation of state

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



- Production of hyperons favourable inside the innermost core of NSs
- Softening of the EoS incompatible with measured heavy NSs
- Introduction of Λ-N-N repulsion could explain observed NS masses

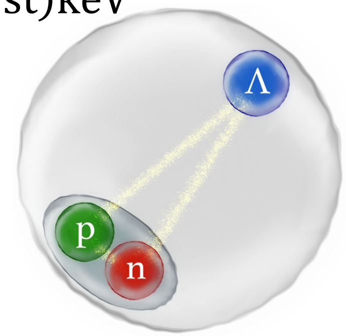
Hypertriton structure: Λ-separation energy

Λ-separation energy $B_\Lambda = m(d) + m(\Lambda) - m({}^3_\Lambda H)$

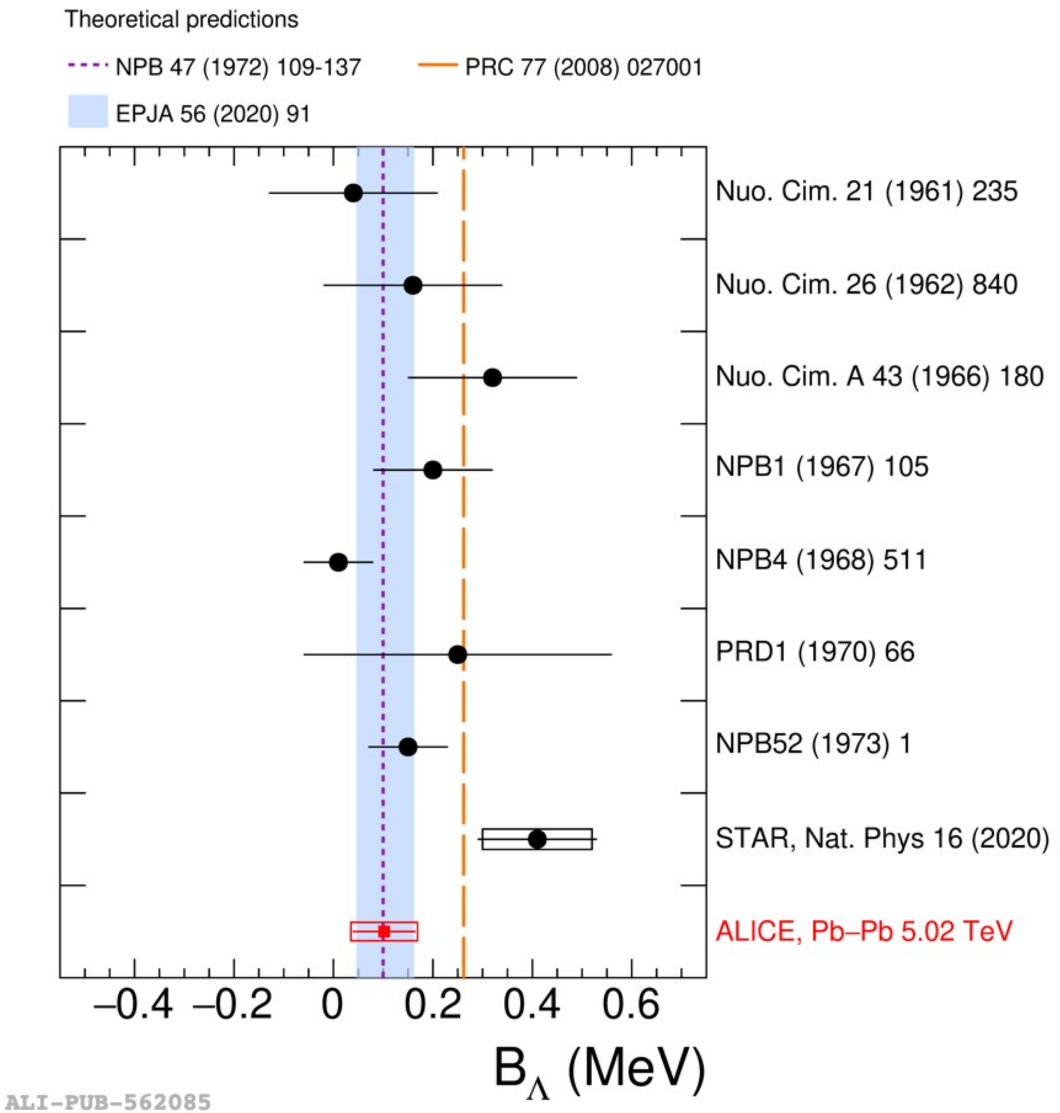
- Reflects extension of the ${}^3_\Lambda$H wave function
- Probe for Y-N interaction
  → direct measurement via correlation functions with femtoscopic method and scattering experiments (only N-N)
  → Indirect measurement via properties of bound hypernuclei
- Latest ALICE measurement (2023) [1]:

$$B_\Lambda = 102 \pm 63(\text{stat}) \pm 67(\text{syst})\text{keV}$$

→ supports loosely bound nature of ${}^3_\Lambda$H
→ compatible with results from p-Λ correlation measurements



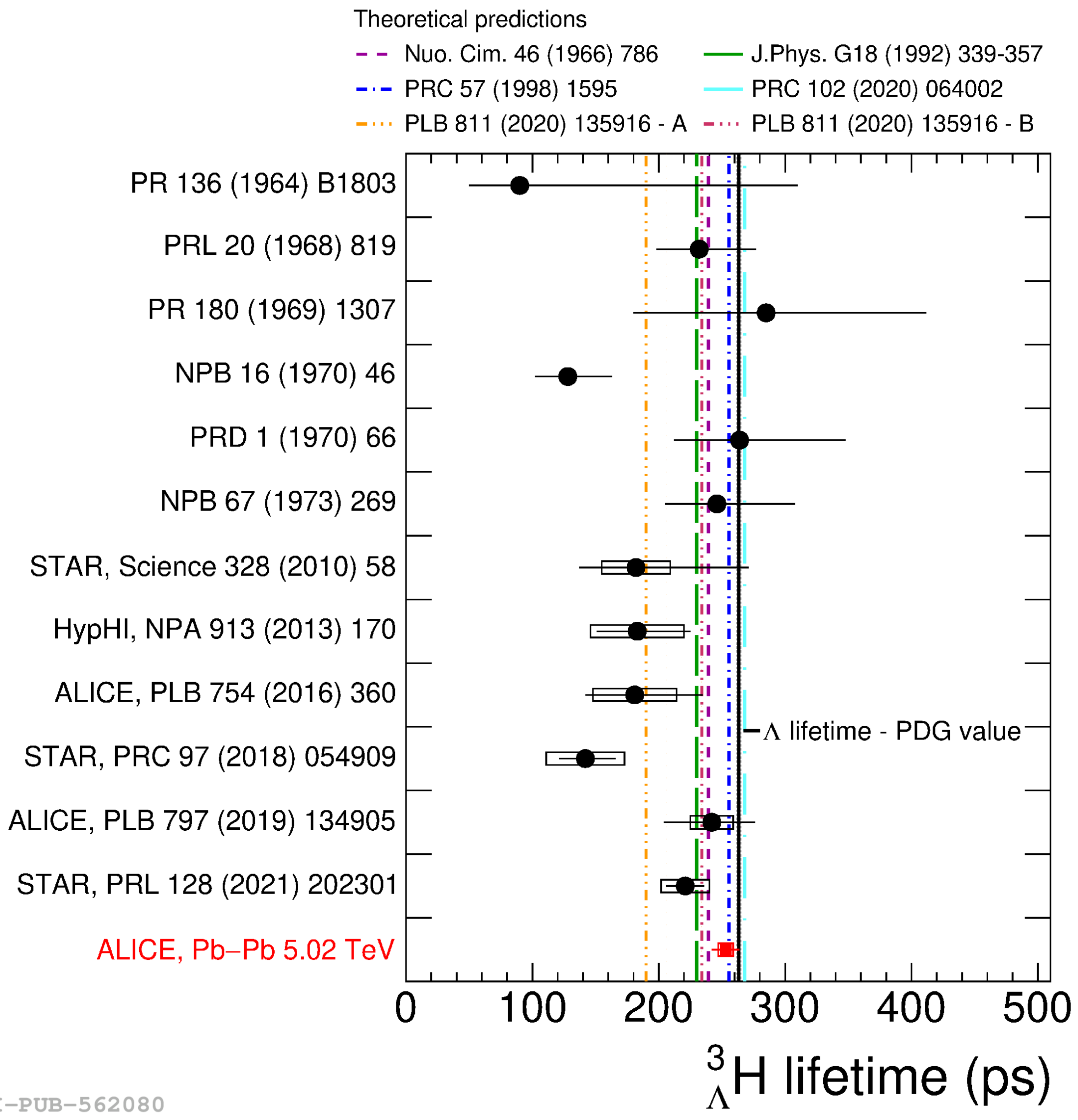
$m \sim 2.991\text{GeV}/c^2$
$c\tau \sim 7.7\text{cm}$



Hypertriton structure: Lifetime

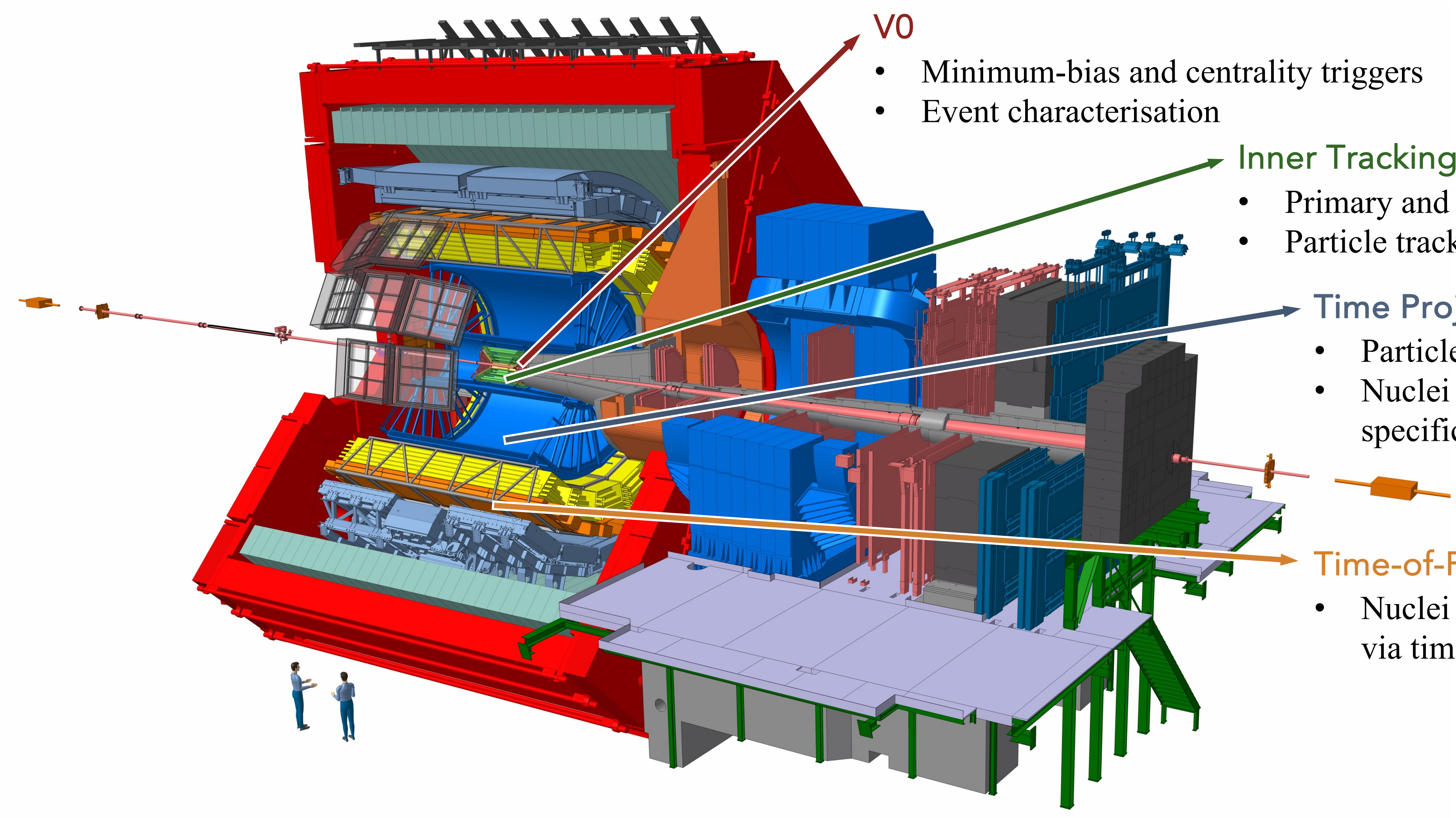
${}^{3}_{\Lambda}\mathrm{H}$ Lifetime

- Low B_{Λ} implies only small modification of Λ wave function inside hypernucleus
- Lifetime close to Λ lifetime is expected
- Indicates shallow Y-N interaction



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

The ALICE detector in Run 2



V0
- Minimum-bias and centrality triggers
- Event characterisation

Inner Tracking System
- Primary and decay vertex reconstruction
- Particle tracking

Time Projection Chamber
- Particle tracking
- Nuclei and hadron identification via specific energy loss

Time-of-Flight
- Nuclei and hadron identification via time-of-flight