Measurement of the hypertriton three-body decay with ALICE

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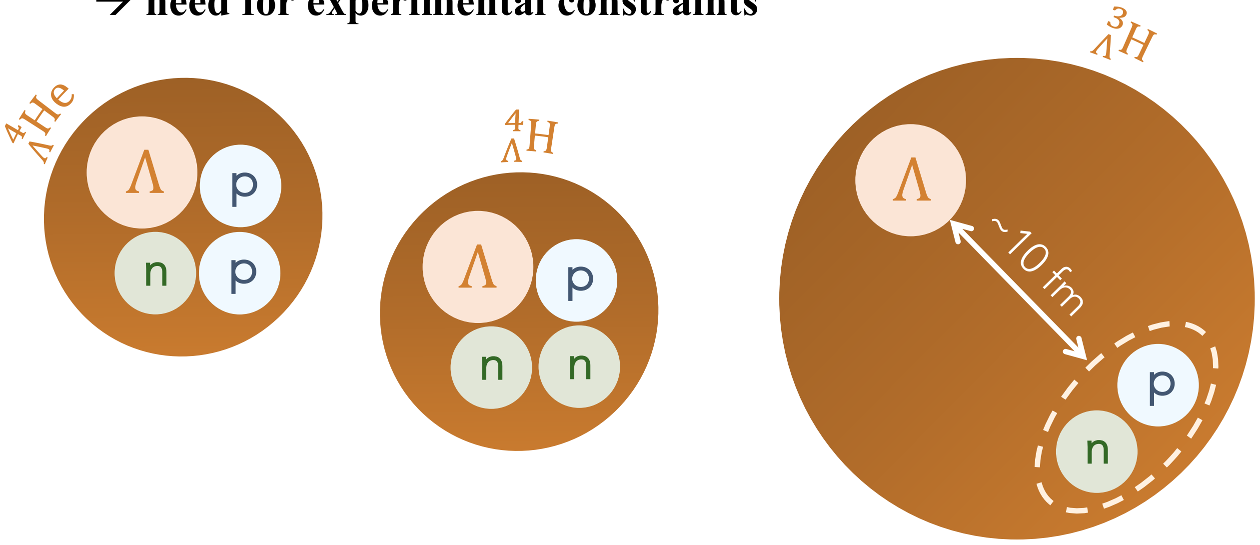
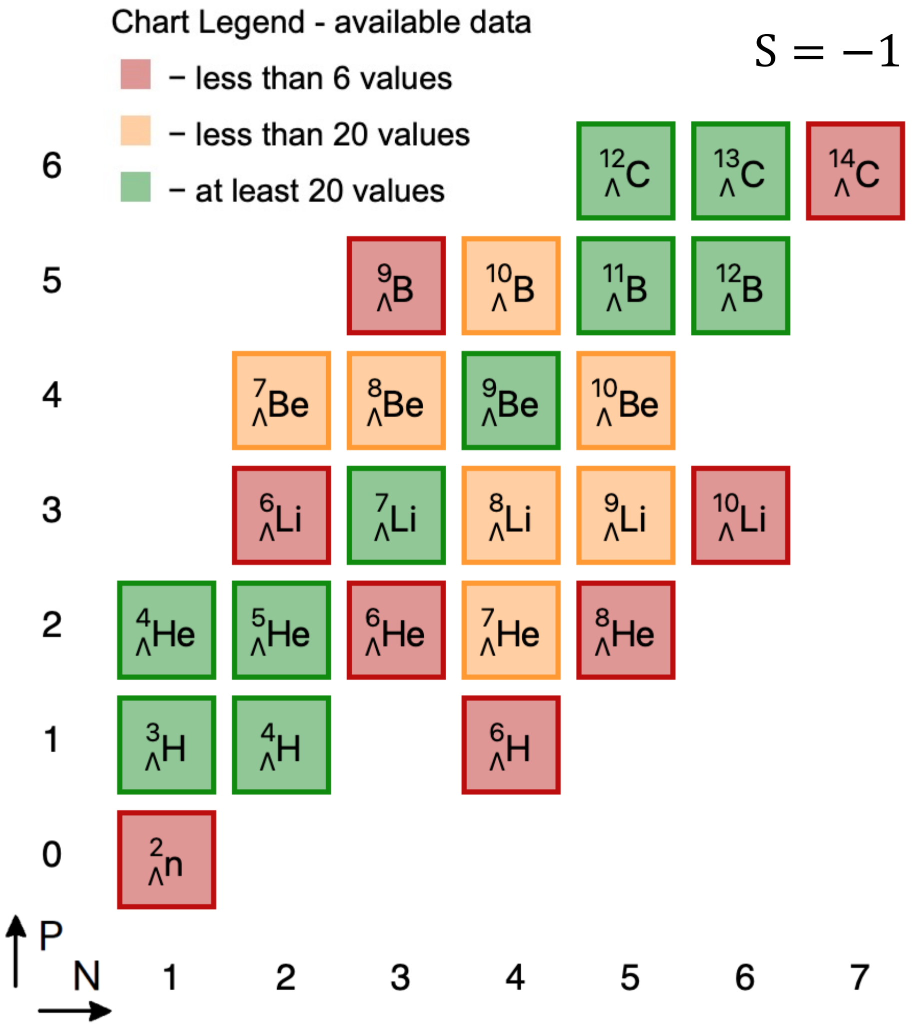
5th EMMI Workshop on Anti-Matter, Hyper-Matter and Exotica Production

Hypernuclei

- Poorly known bound states of **nuclei** and **strange baryons (hyperons)**
- 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[1][2] describe observed NS masses → **need for experimental constraints**





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)

Hypernuclei

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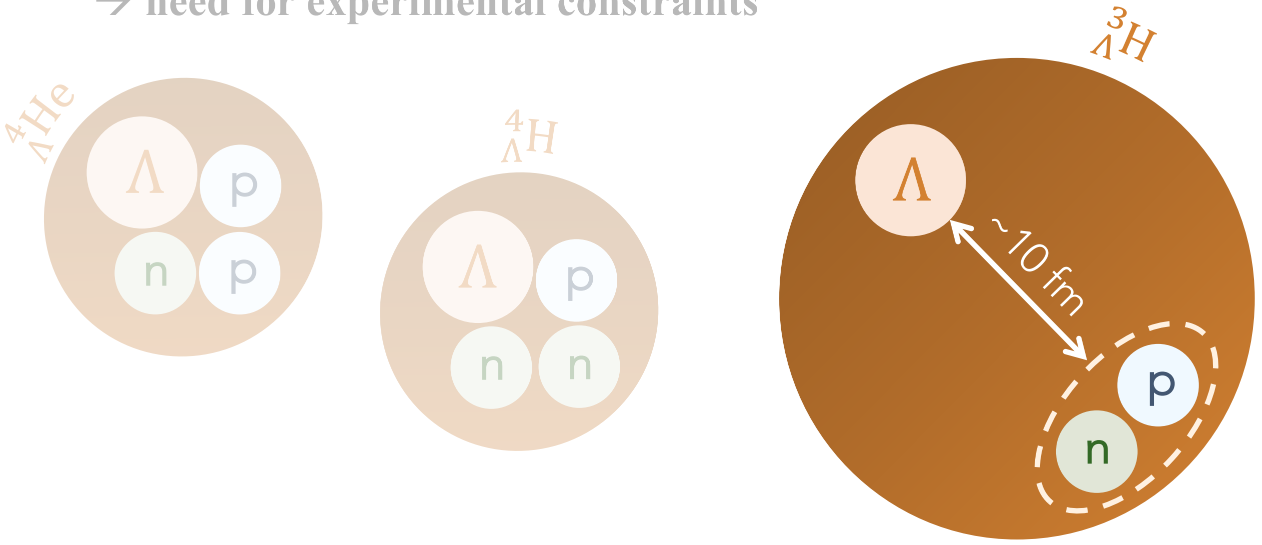
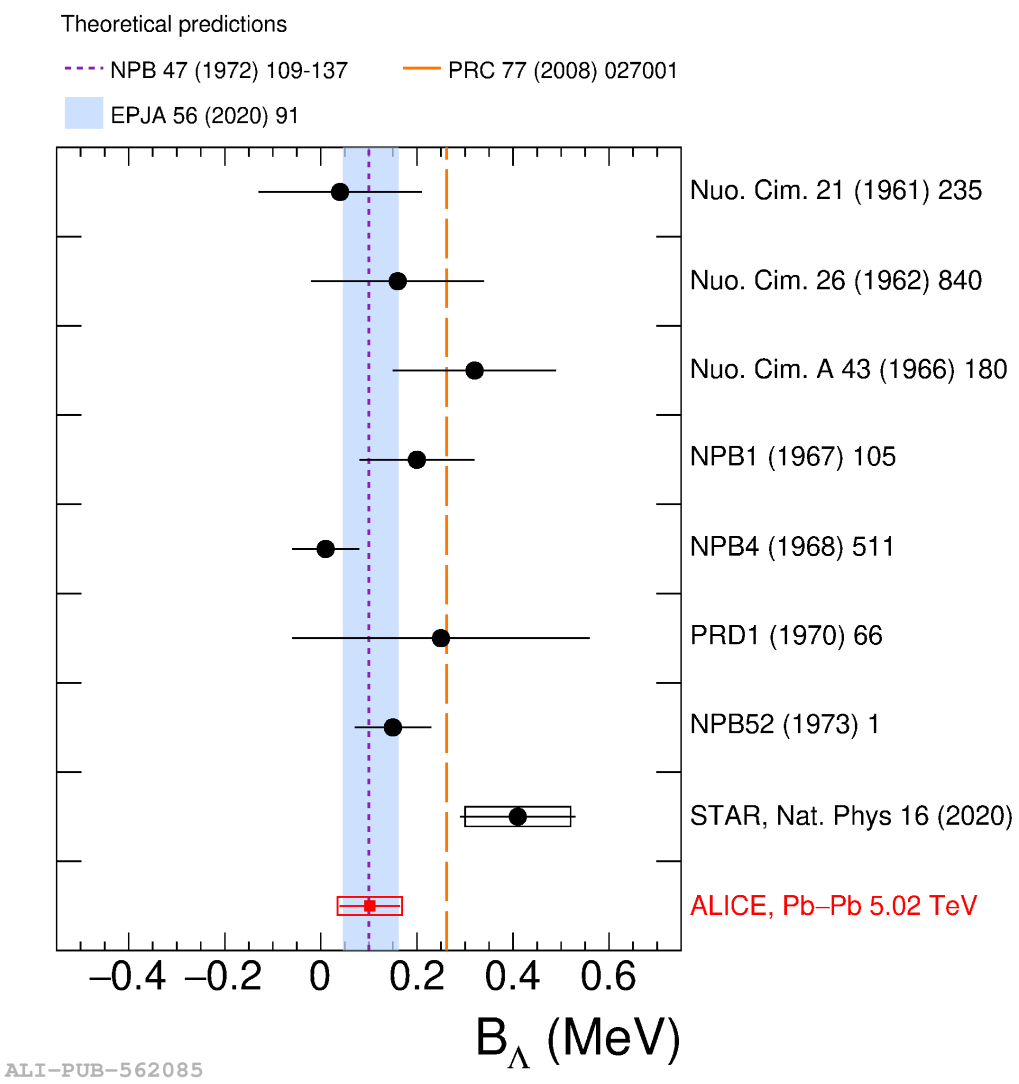


The Hypertriton ($^{3}_{\Lambda}$H)

- Lightest known hypernucleus
  $m \sim 2.991\ \mathrm{GeV}/c^2$
  $c\tau \sim 7.1\mathrm{cm}$
  $B_{\Lambda} \sim 100\ \mathrm{keV}$
- **Mesonic charged decay channels:**
  $^{3}_{\Lambda}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \pi^{-}$ (BR ≅ 0.25[3])
  $^{3}_{\Lambda}\mathrm{H} \longrightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$ (BR ≅ 0.40[3])

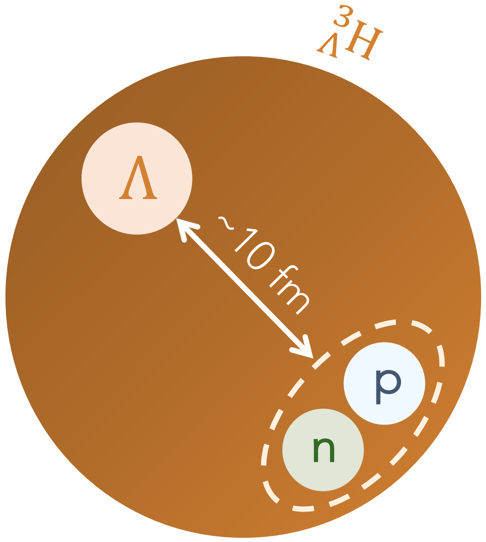
[1] D. Logoteta et al., Eur. Phys. J. A 55, 207 (2019)
[2] D. Lonardoni et al., Phys. Rev. Lett. 114, 092301 (2019)
[3] H. Kamada et al., Phys. Rev. C 57, 1595 (1998)

Hypertriton structure



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

- Reflects extension of ${}^3_\Lambda$H wave function
- First measurements in emulsion experiments[5]:
  $B_\Lambda = 130 \pm 50$ keV
  → indication for loosely bound hypernucleus
- Pionless EFT [6] : results in large separation between Λ and "deuteron core" → indication for halo-structure
- Latest ALICE measurement[4]:
  $B_\Lambda = 102 \pm 63\ (\mathrm{stat}) \pm 67 (\mathrm{syst})$ keV
  → supports loosely bound nature of ${}^3_\Lambda$H

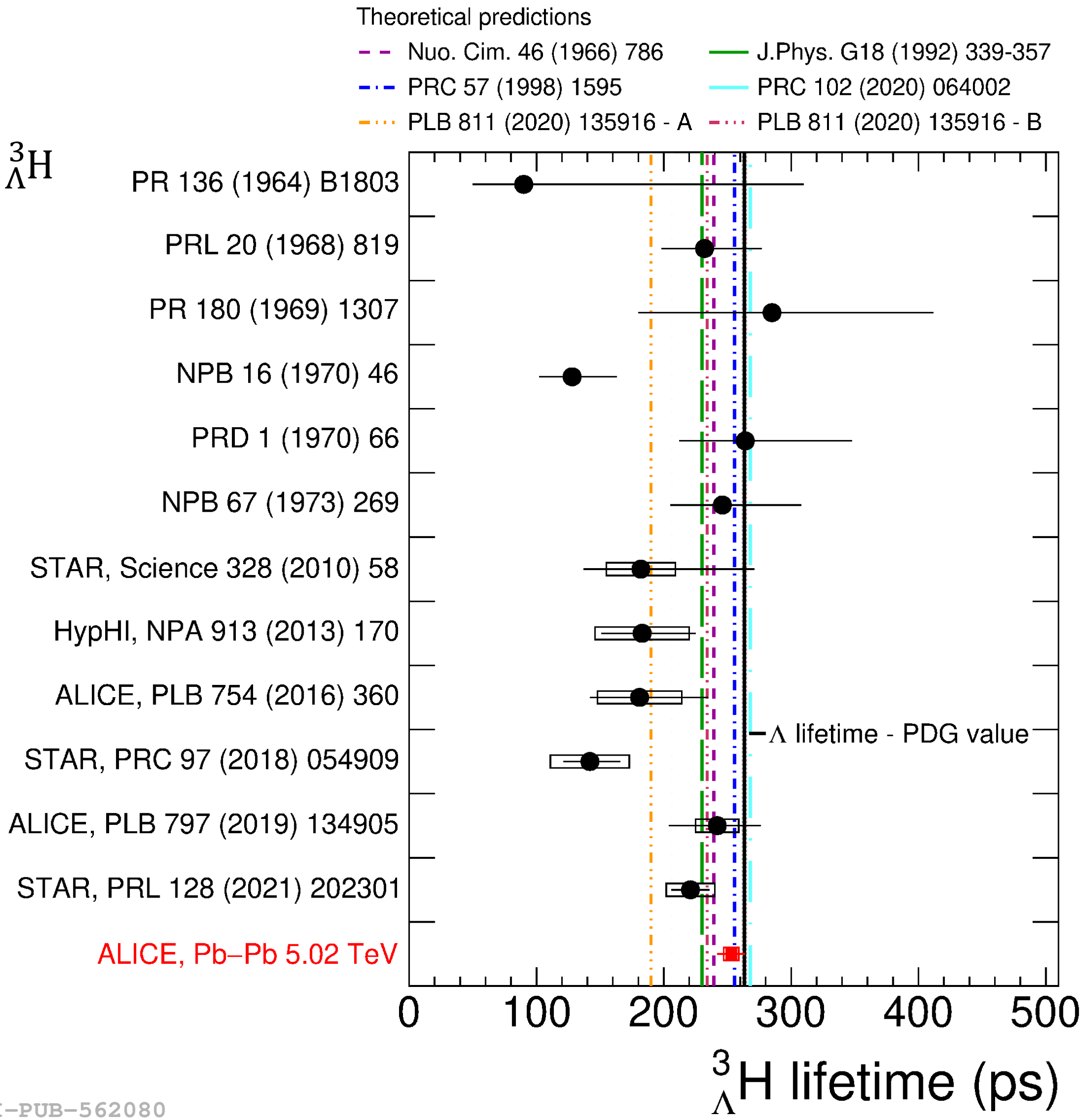


[4] ALICE, Phys. Rev. Lett. 131, 102302 (2023)
[5] *M. Juric et al.*, Nucl. Phys. B 52, 1-30, (1973)
[6] *F. Hildenbrand et al.*, Phys. Rev. C 100, 034002 (2019)

Hypertriton structure

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

- Low B_{Λ} implies only small modification of Λ wave function inside ${}^{3}_{\Lambda}$H
  → lifetime close to free Λ lifetime expected
  → indicates shallow Y-N interaction
- **Latest ALICE measurement[4]:**
  $\tau = 253 \pm 11(\mathrm{stat}) \pm 6(\mathrm{syst})$ ps
  → compatible with free Λ lifetime
- **Lifetime of ${}^{3}_{\Lambda}$H relatively insensitive to nuclear structure**
  → theoretically connection between B_{Λ} and lifetime not well constrained[7][8]



[4] ALICE, Phys. Rev. Lett. 131, 102302 (2023)
[7] *F. Hildenbrand et al.*, Phys. Rev. C 102, 064002 (2020)
[8] *A. Pe�rez-Obiol et al.*, Phys. Lett. B 811, 135916 (2020)

Hypertriton structure

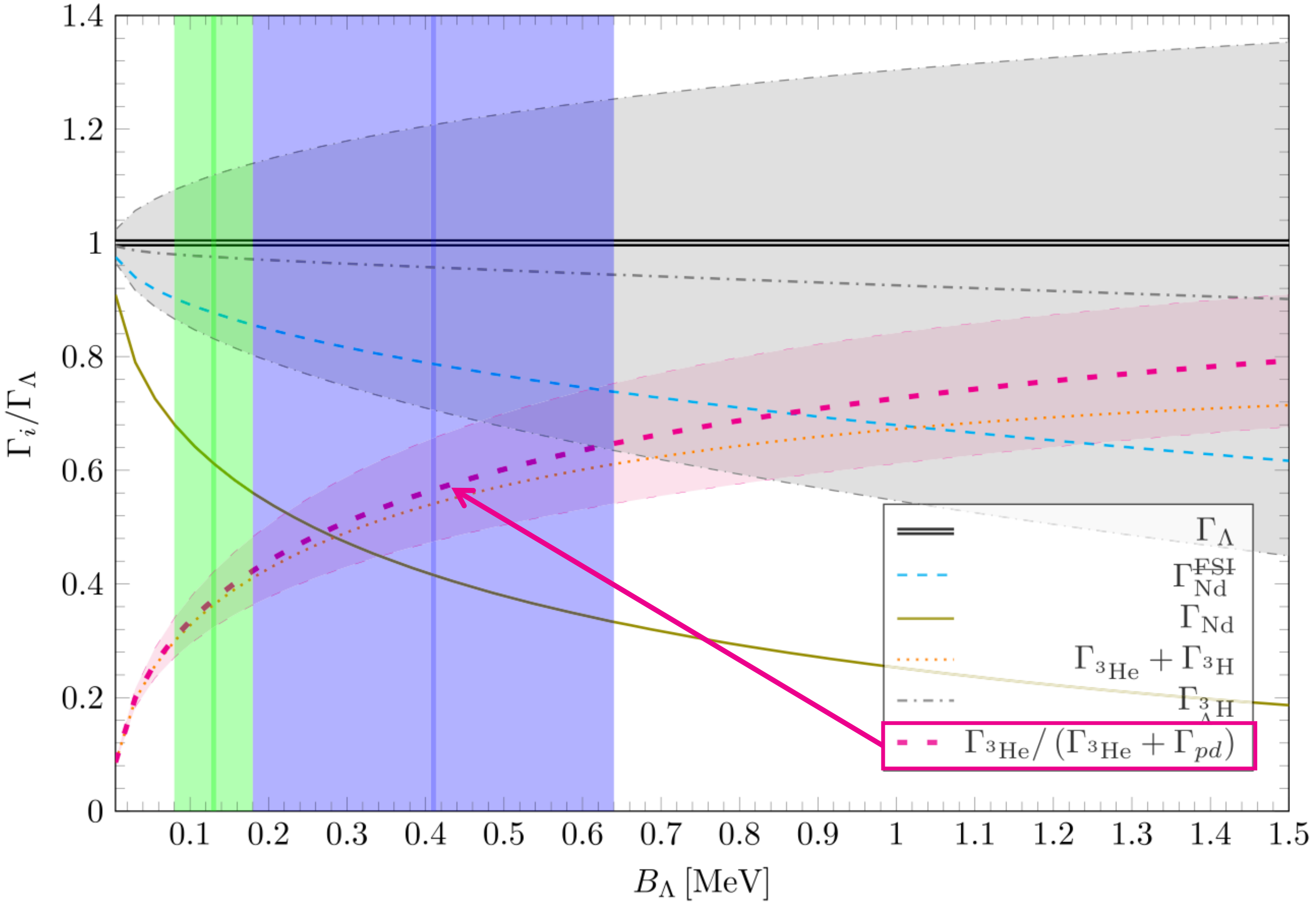
$^{3}_{\Lambda}$H relative branching ratio R_3

- Precise measurements of all $^{3}_{\Lambda}$H decay modes and their BRs are missing
- Pionless EFT[7]: partial decay width ratio is sensitive to connection of lifetime and B_Λ

$$R_3 = \frac{\Gamma\left(^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^-\right)}{\Gamma\left(^{3}_{\Lambda}\mathrm{H} \to \text{all } \pi^- \text{ meson modes}\right)}$$

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

- Additional experimental constraint to $^{3}_{\Lambda}$H binding energy and constraint for model phase-space via **measurement of R_3**
- Relative branching ratio is connected to $^{3}_{\Lambda}$H spin[9]



[7] F. Hildenbrand et al., Phys. Rev. C 102, 064002 (2020)
[9] R. H. Dalitz, Phys. Rev. 112, 605 (1958); R. H. Dalitz et al., Phys. Rev. 116, 1312 (1959)

Hypertriton structure

${}^{3}_{\Lambda}$H relative branching ratio R$_3$

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

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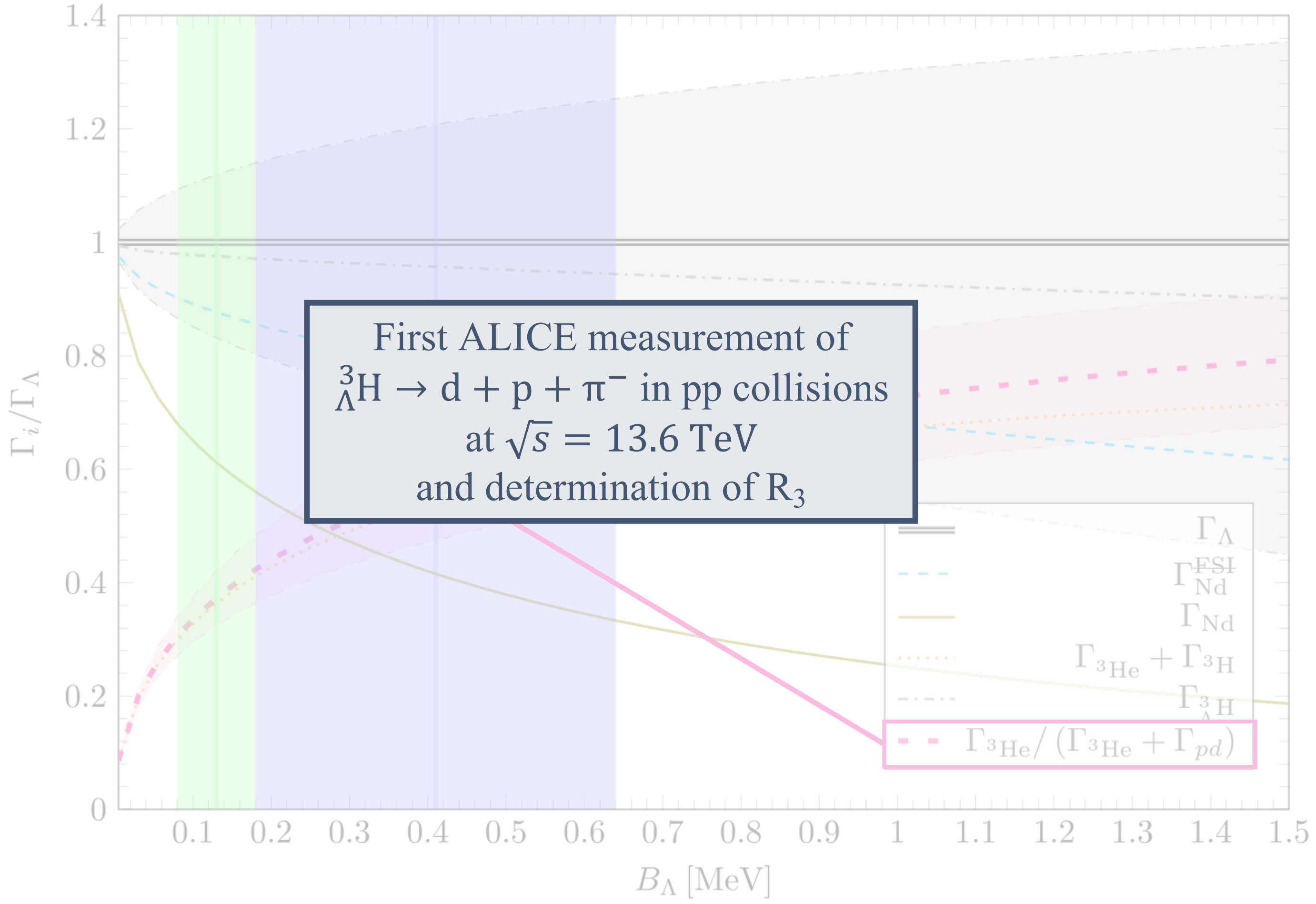

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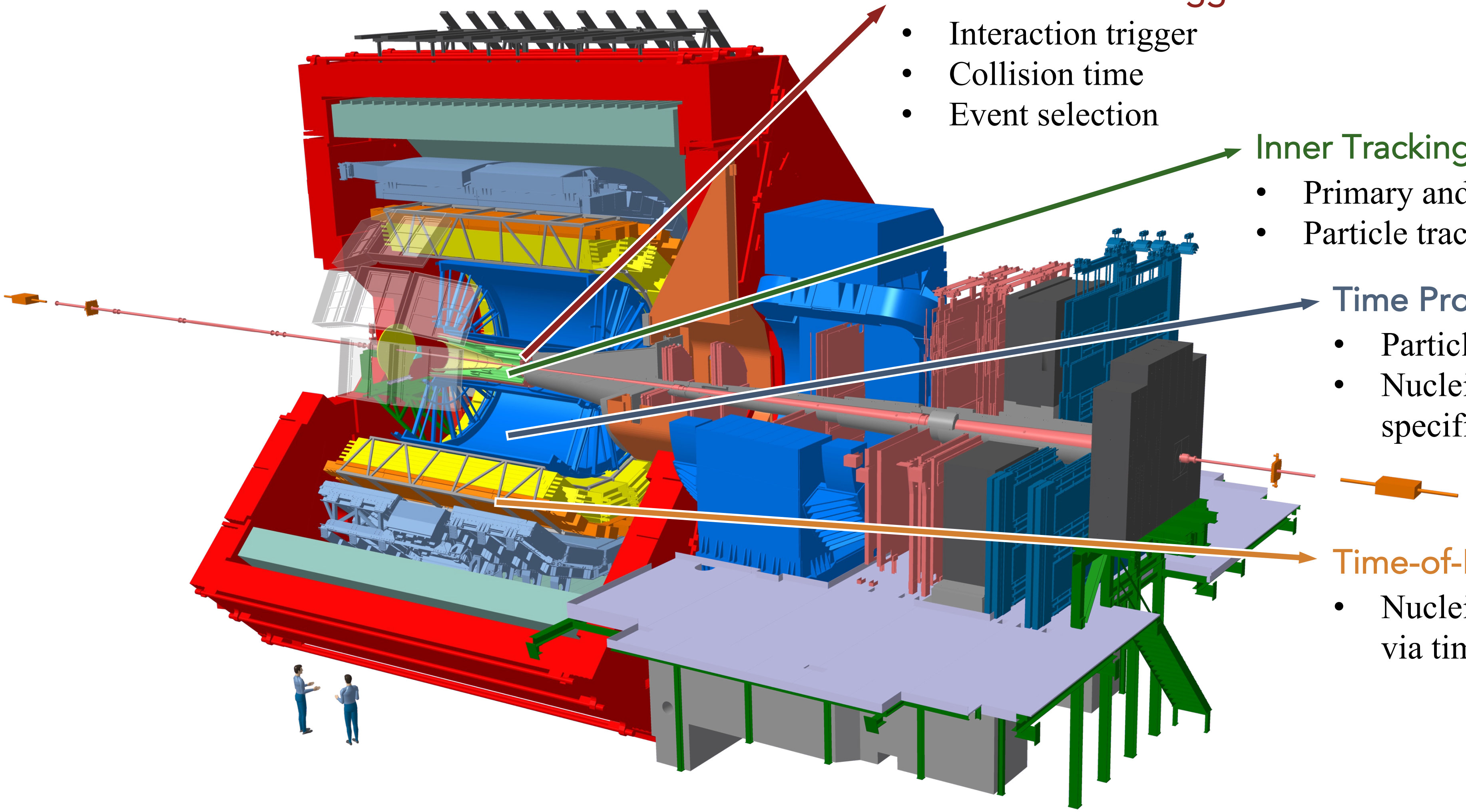
The ALICE detector in Run 3



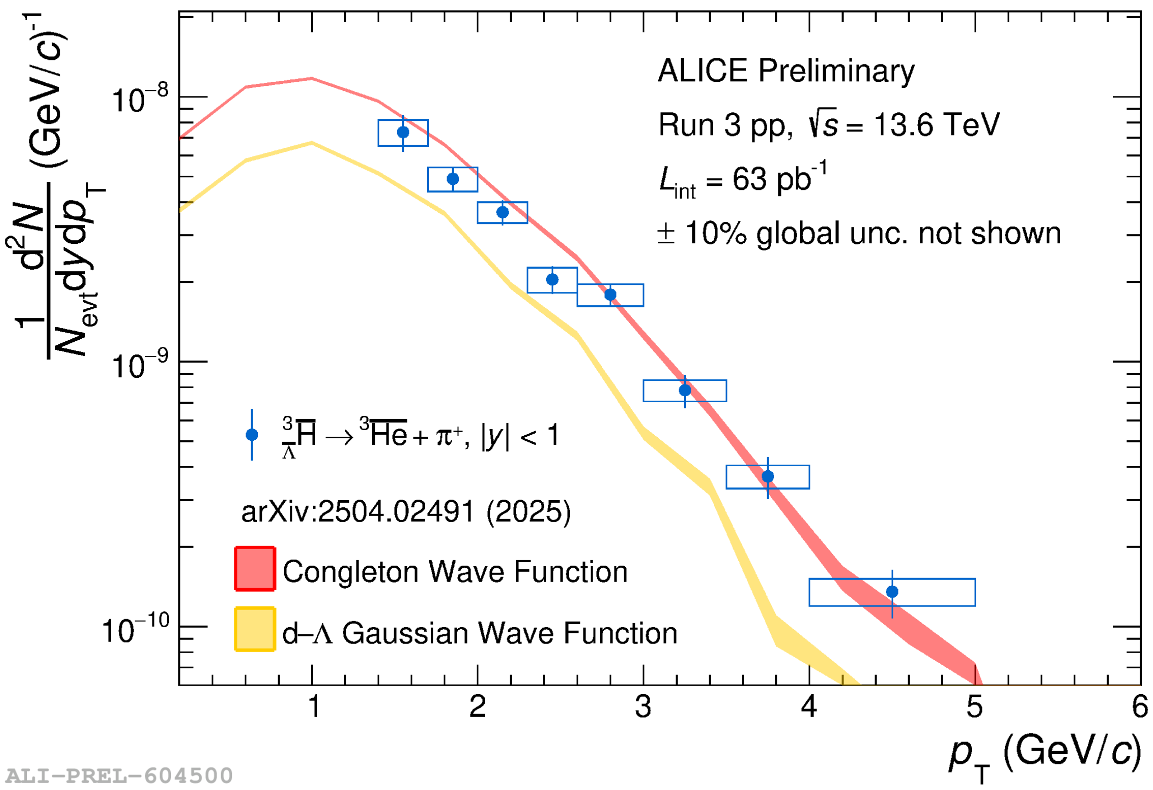
Fast Interaction Trigger
- Interaction trigger
- Collision time
- Event selection

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

Hypertriton two-body decay measurement



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

- **Coalescence:** p_T-dependence of emission source size
  → reduction of source size at high p_T
  → suppression of $^{3}_{\Lambda}\mathrm{H}$ yield (extended wave function)
  → measurement of p_T-differential production allows to differentiate between thermal production and coalescence[10]

[10] D. Liu, at al., Phys. Lett. B 855, 138855 (2024)

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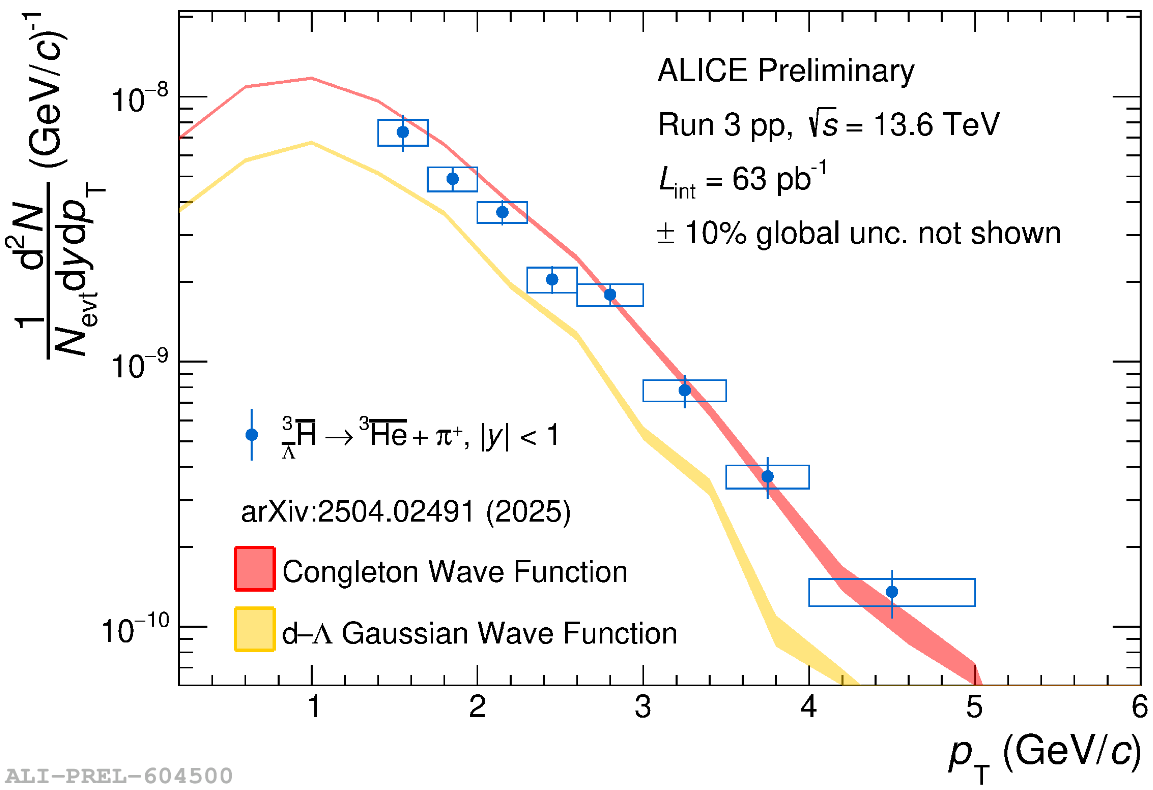

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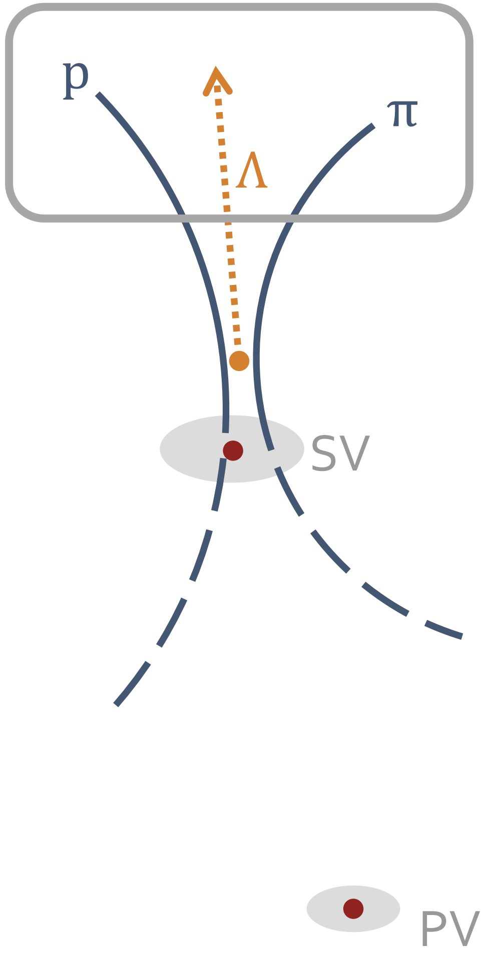
First p_T-differential measurement of ${}^{3}_{\Lambda}H$ spectrum in pp collisions

- **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 allows to differentiate between thermal production and coalescence[10]
- Measurement of anti-matter via $\overline{{}^{3}_{\Lambda}H} \longrightarrow \overline{{}^{3}He} + \pi^{+}$ decay channel
- New advanced coalescence model (ToMCCA)[11]
  → 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**[12] (assumes ${}^{3}_{\Lambda}H$ as Λ-d system)
- Allows to **analyse the ${}^{3}_{\Lambda}H$ wave function**
  → study of ${}^{3}_{\Lambda}H$ structure

[10] D. Liu, at al., Phys. Lett. B 855, 138855 (2024)
[11] M. Mahlein, et al., arXiv:2504.02491
[12] J. G. Congleton, J. Phys. G: Nucl. Part. Phys. 18, 339 (1992)

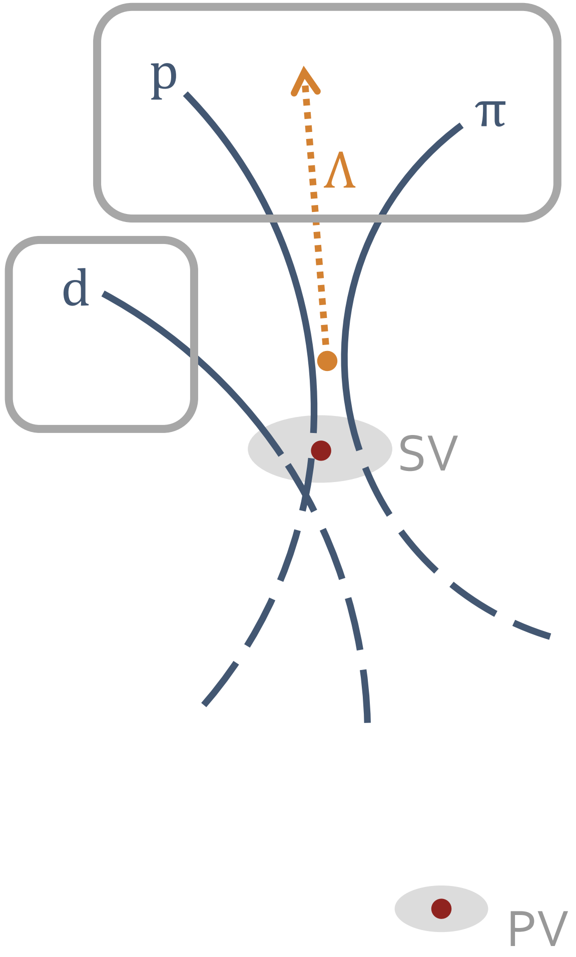
Hypertriton three-body decay measurement



1) Secondary decay vertex finding

- Displaced decay topology
- Pair combination of oppositely charged tracks for preliminary decay point finding

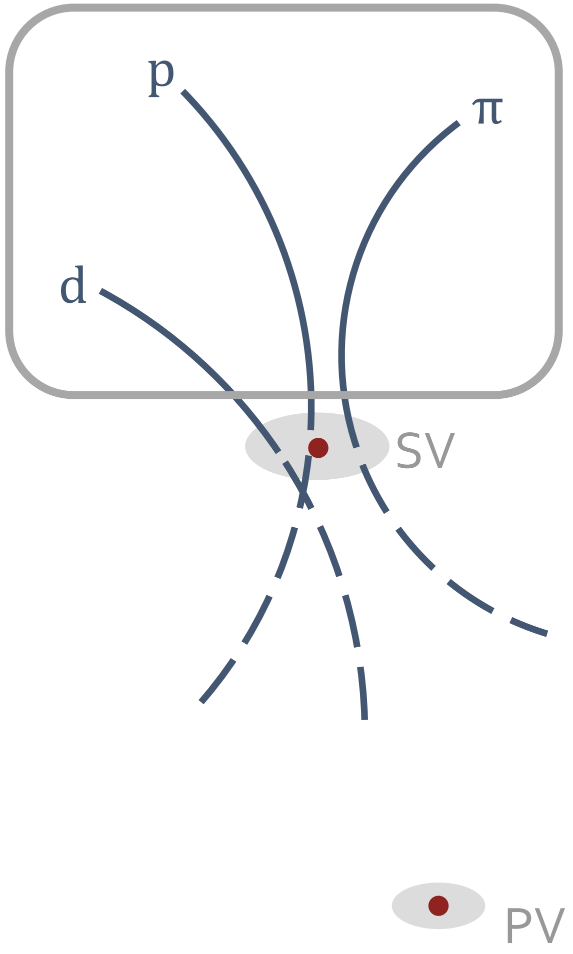
Hypertriton three-body decay measurement



1) Secondary decay vertex finding

- Displaced decay topology
- Pair combination of oppositely charged tracks for preliminary decay point finding
- Addition of third charged track to create particle candidate triplet

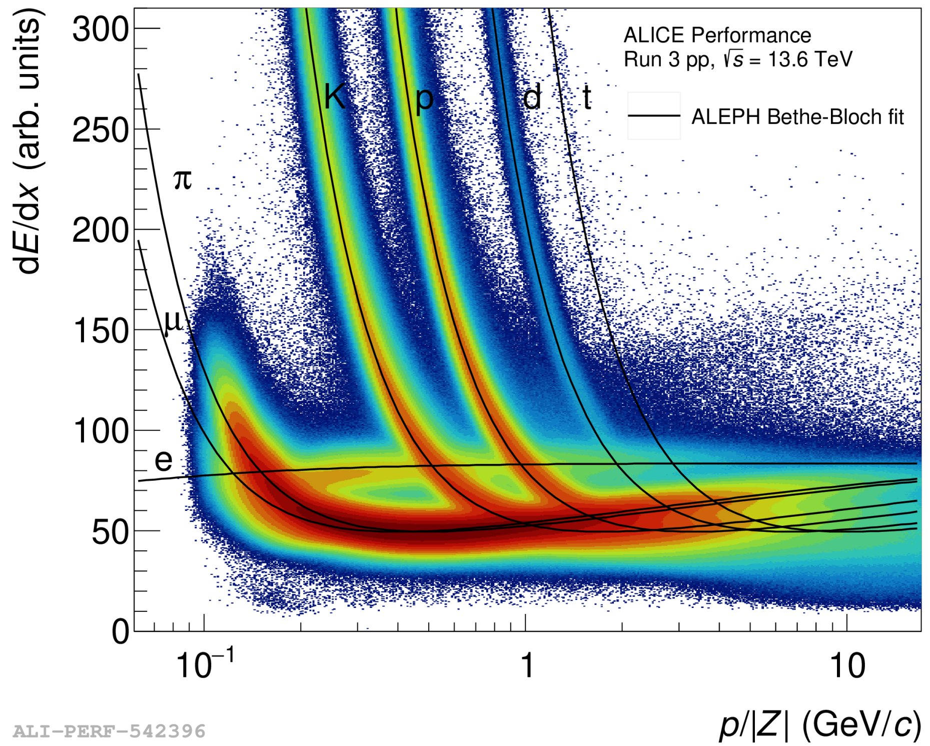
Hypertriton three-body decay measurement



1) Secondary decay vertex finding

2) ${}^{3}_{\Lambda}\mathrm{H}$ candidate reconstruction and selection

- **Data skimming:** dedicated software trigger for three-body decay candidates
- Daughter track identification with **specific energy loss and time-of-flight**



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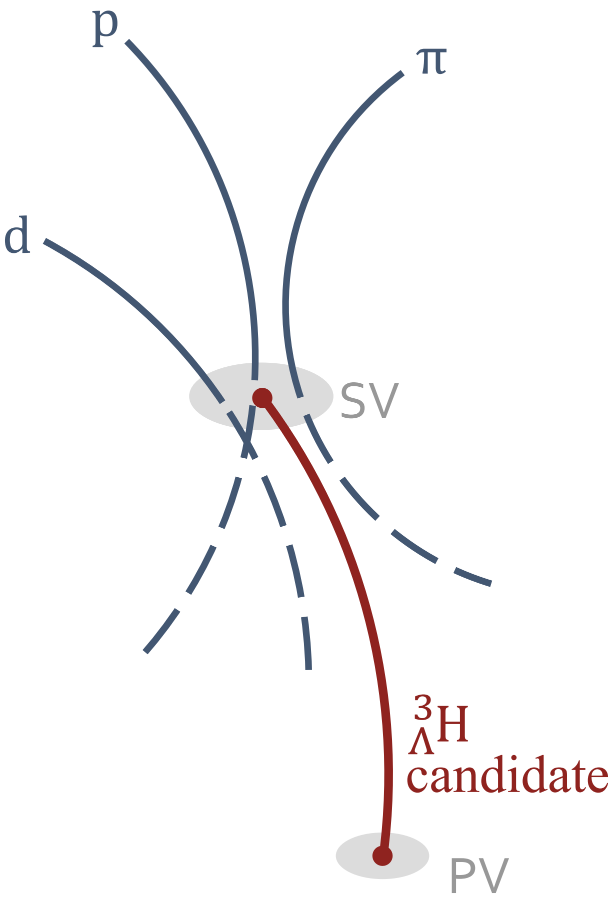
Hypertriton three-body decay measurement



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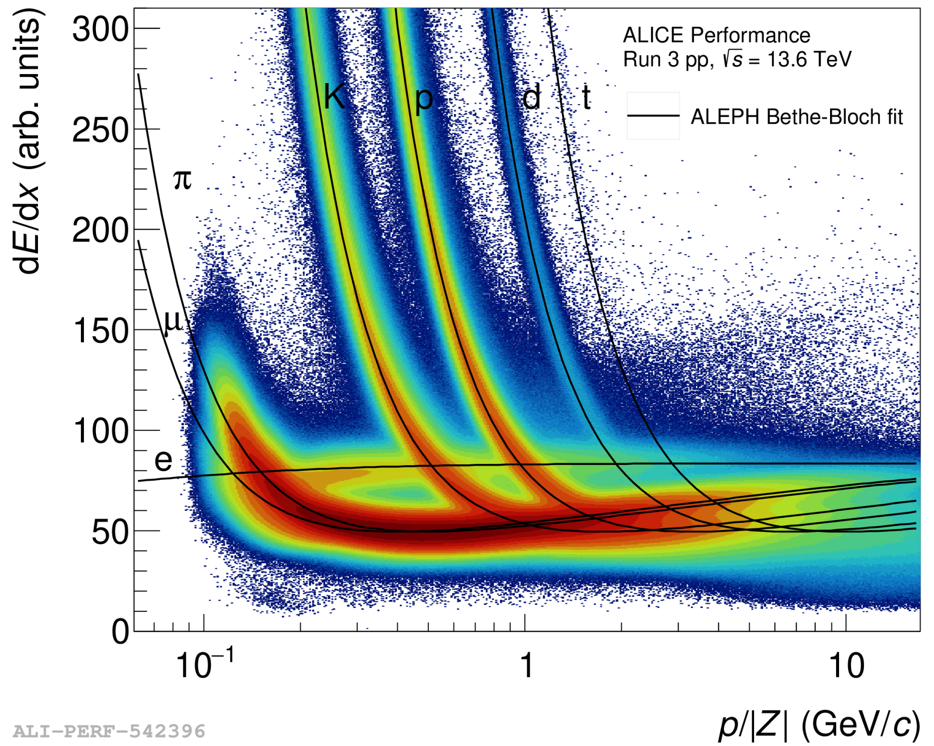
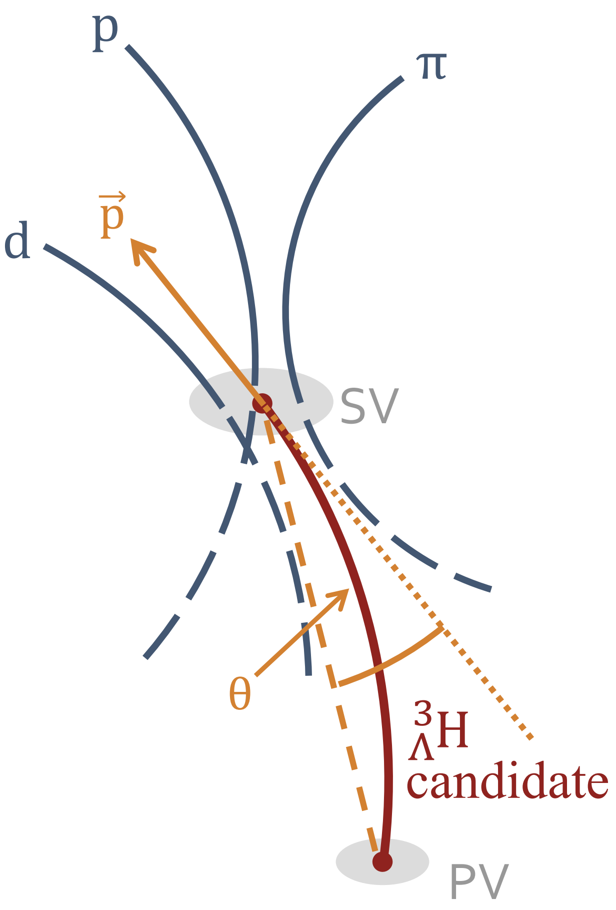
- **Data skimming:** dedicated software trigger for three-body decay candidates
- Daughter track identification with **specific energy loss and time-of-flight**
- Assume track triplet comes from common secondary vertex (SV) → vertex reconstruction with **KFParticle**[13] software package



[13] I. Kisel et al., IEEE Trans. Nucl. Sci. 60, 3703 (2013)

Hypertriton three-body decay measurement



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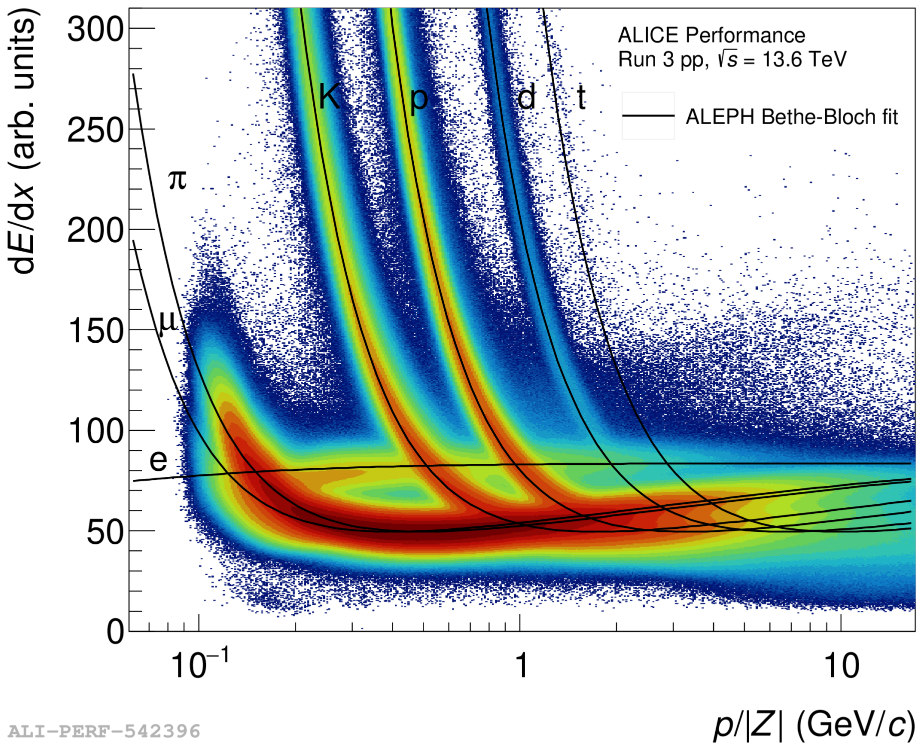
- Daughter track identification with **specific energy loss and time-of-flight**
- Assume track triplet comes from common secondary vertex (SV)
  → vertex reconstruction with **KFParticle**[13] software package
- Large combinatorial background
  → kinematic and topological selections
  → **pointing angle θ** and **distance of daughter tracks to SV**
  (semi-blind selection optimisation)



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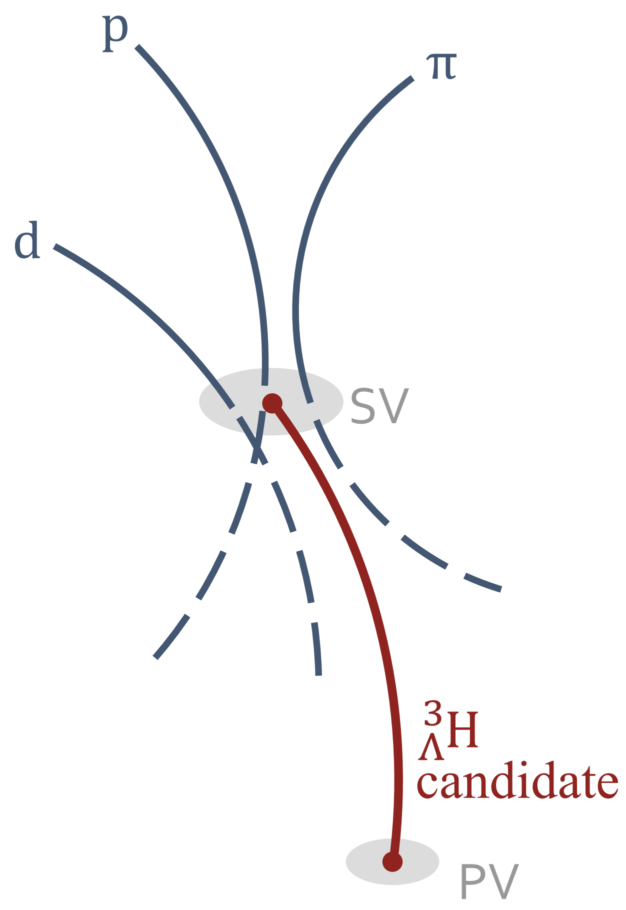
Hypertriton three-body decay measurement

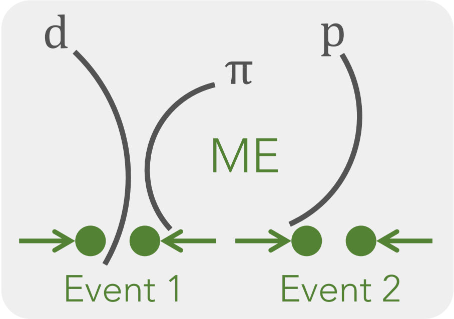


1) Secondary decay vertex finding

2) $^{3}_{\Lambda}\mathrm{H}$ candidate reconstruction and selection

3) Background modelling

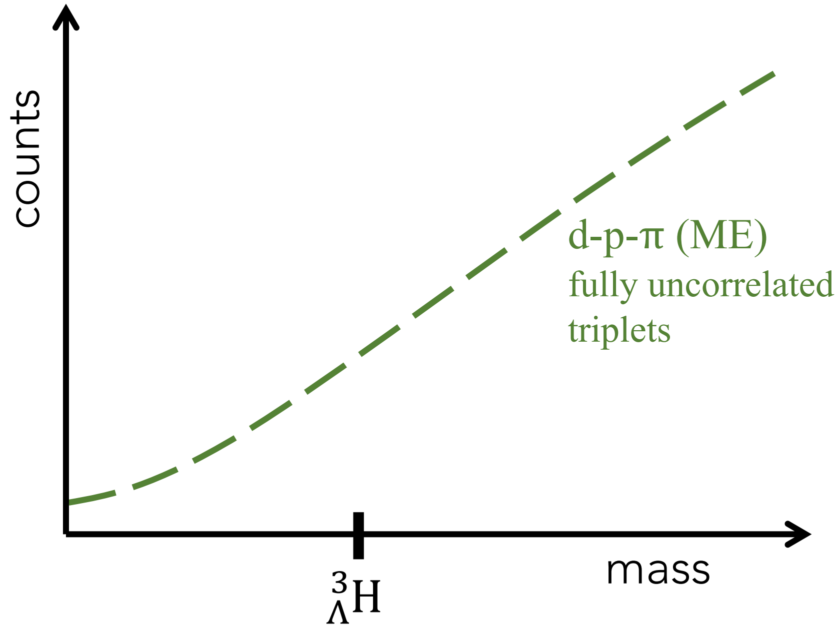
Hypertriton three-body decay measurement



Fully uncorrelated background

Background estimation

- Modelling of different background components necessary to extract signal counts
- Background estimation with **event mixing technique**
  - Invariant mass analysis of **same event (SE)** and **mixed event (ME)** triplets



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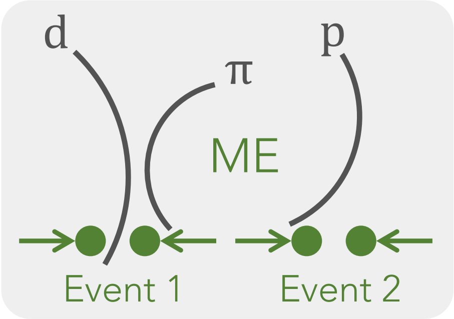

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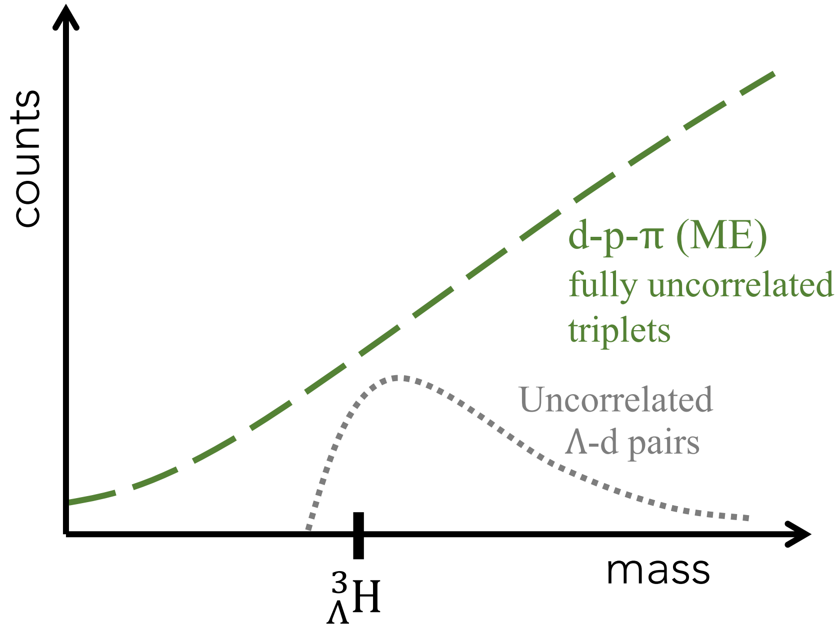

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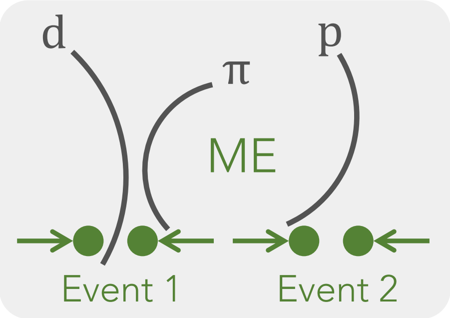

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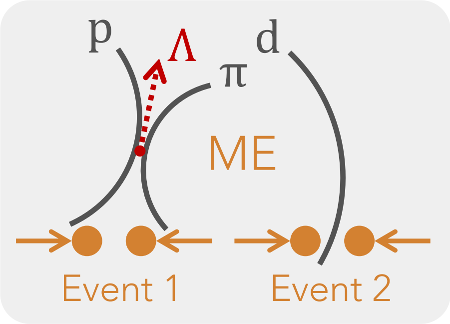

Fully uncorrelated + uncorrelated Λ-d background

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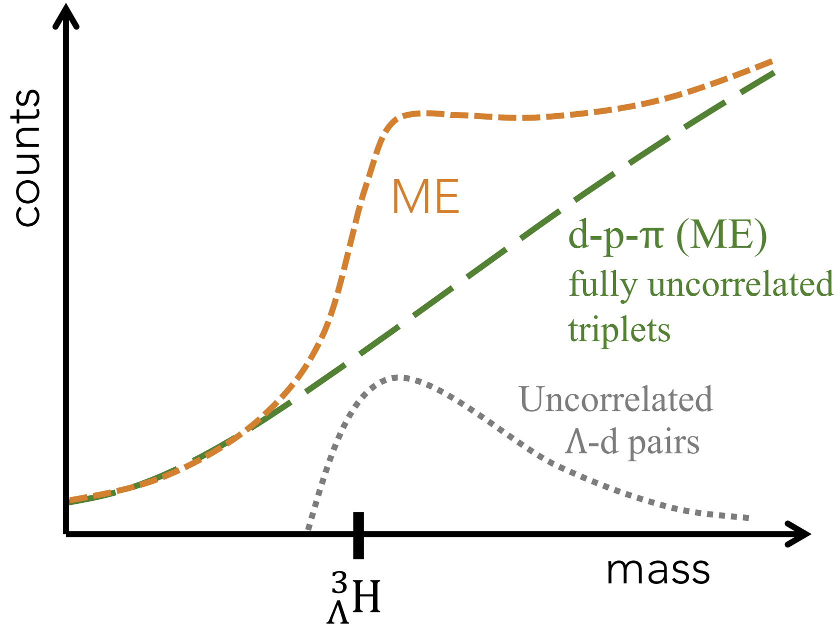
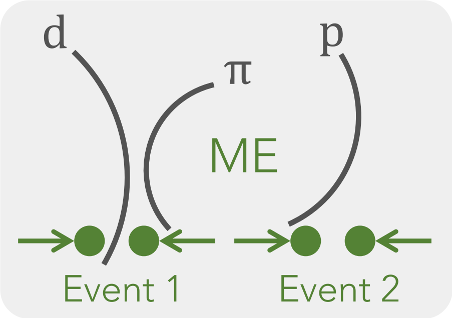


Hypertriton three-body decay measurement



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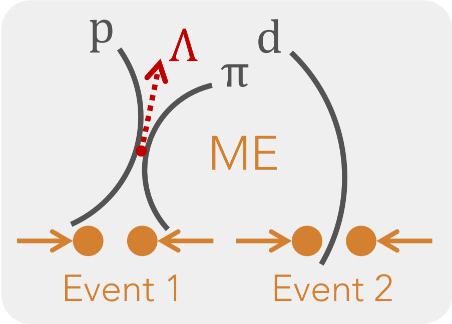

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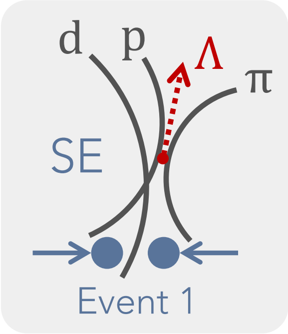

Same event distribution

Background estimation

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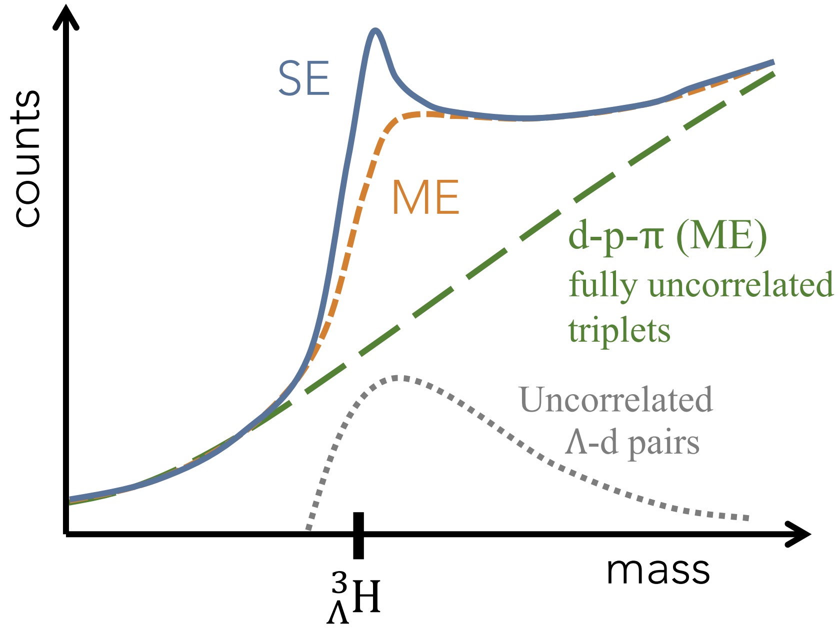
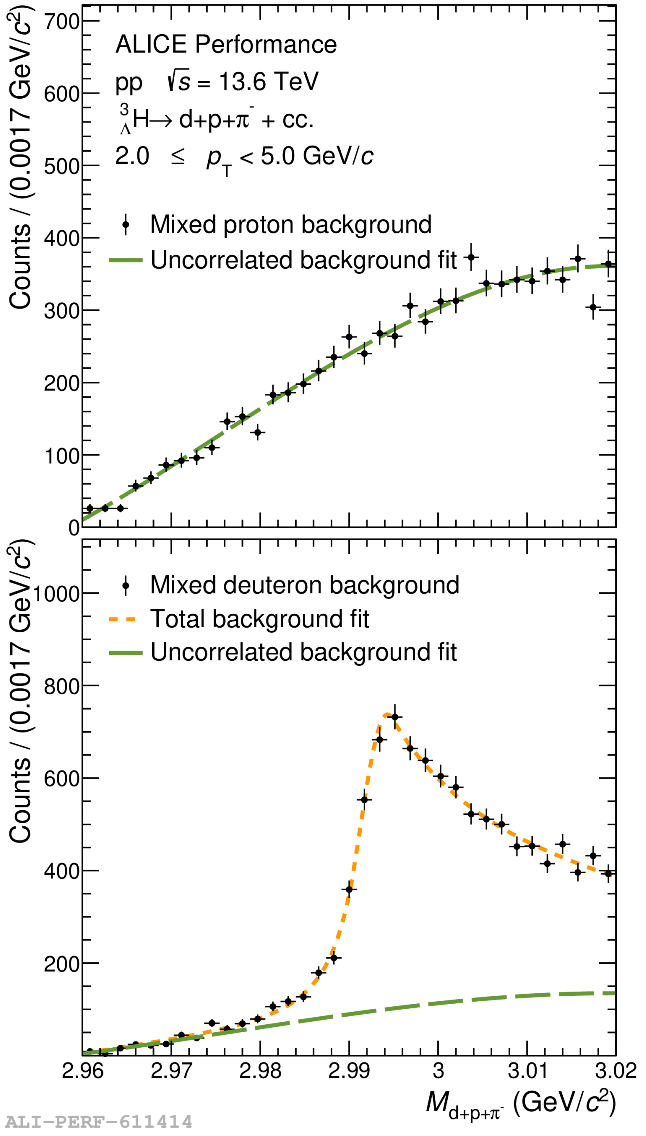
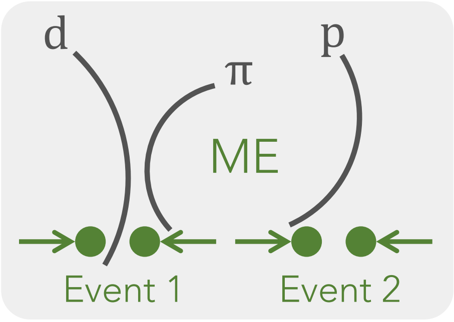
  - Invariant mass analysis of **same event (SE)** and **mixed event (ME)** triplets



Hypertriton three-body decay measurement

Mixed event distributions





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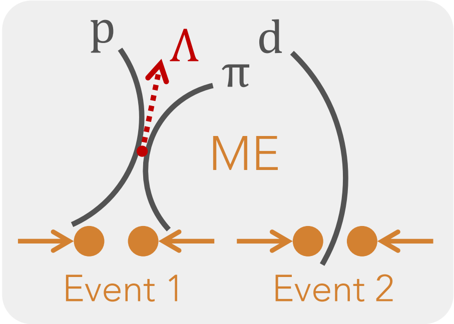
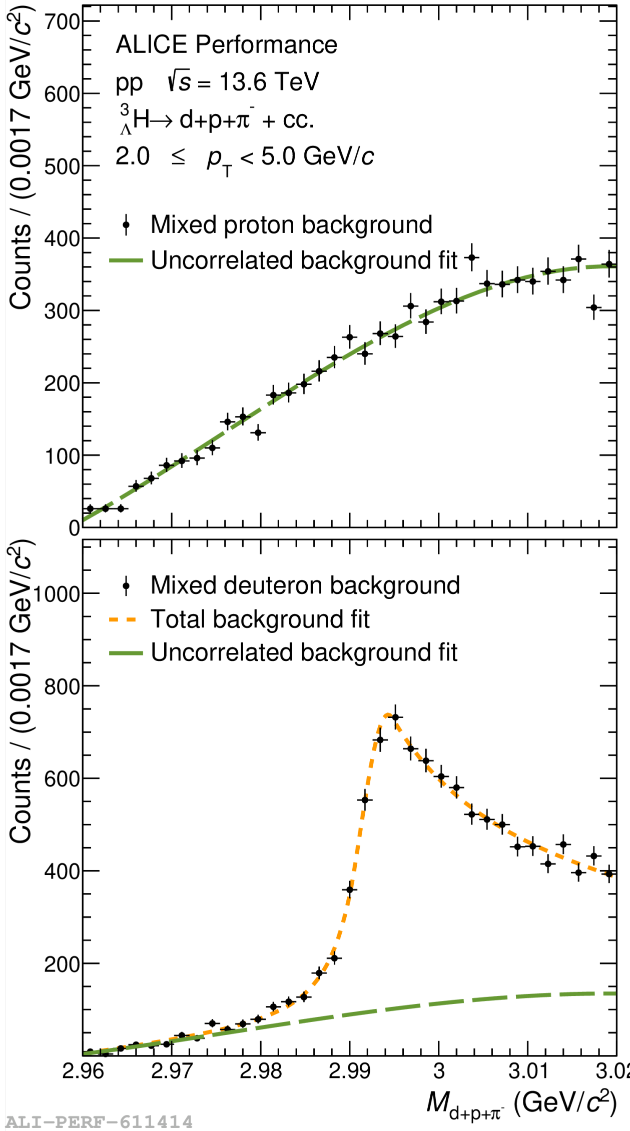


Fully uncorrelated + uncorrelated Λ-d background

Hypertriton three-body decay measurement

Mixed event distributions



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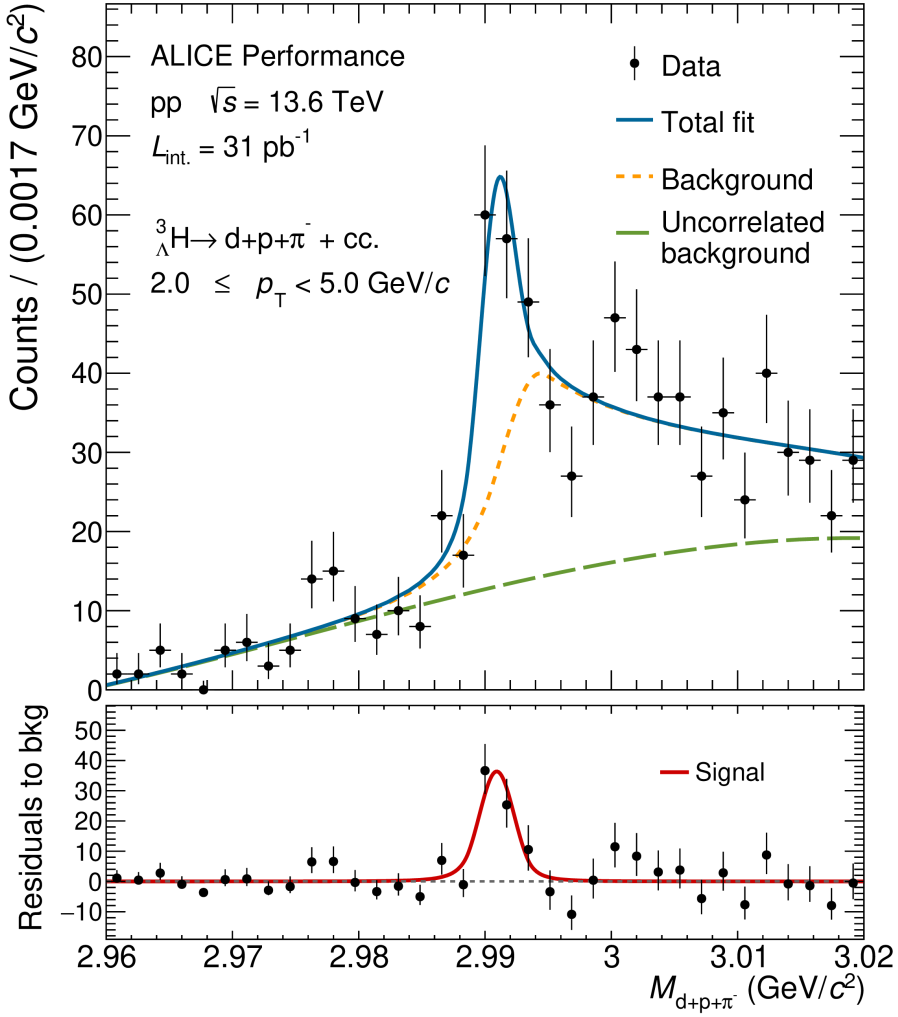
Same event distribution



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Signal extraction

- Signal yield extraction with **simultaneous background fit** to SE and ME invariant mass spectra

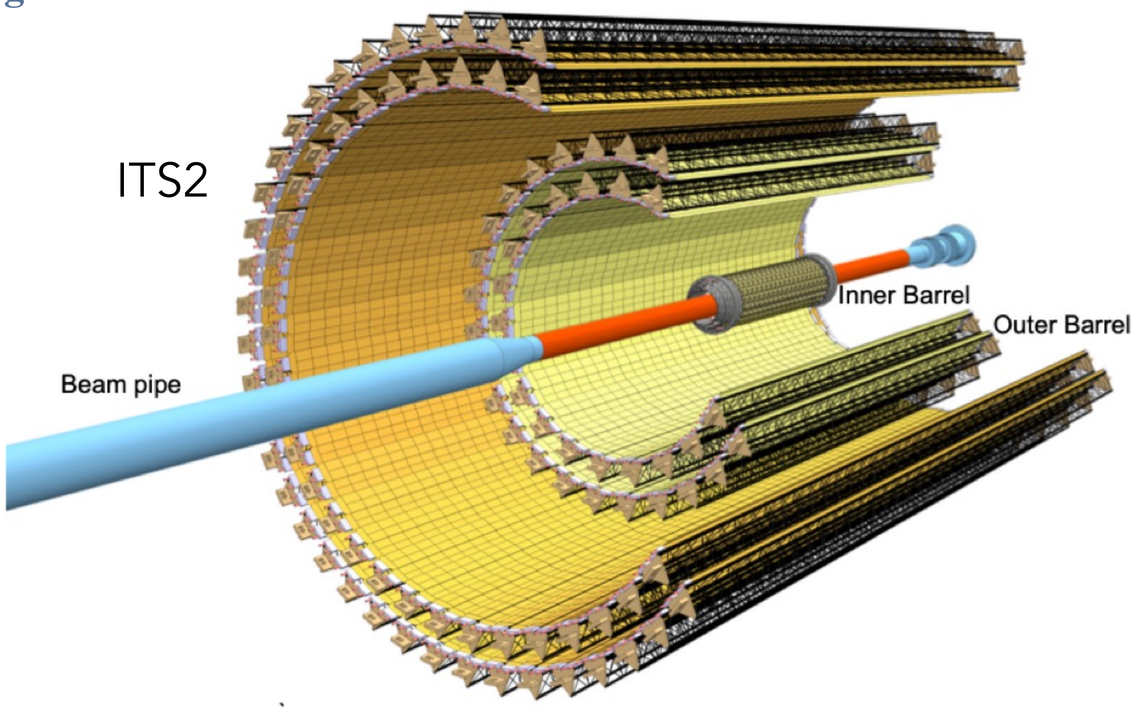
$$\overbrace{\text{signal} + \underbrace{\text{d-}\Lambda\text{ bkg.} + \text{d-p-}\pi\text{ bkg.}}_{\text{total bkg. fit}}}^{\text{total fit}}$$

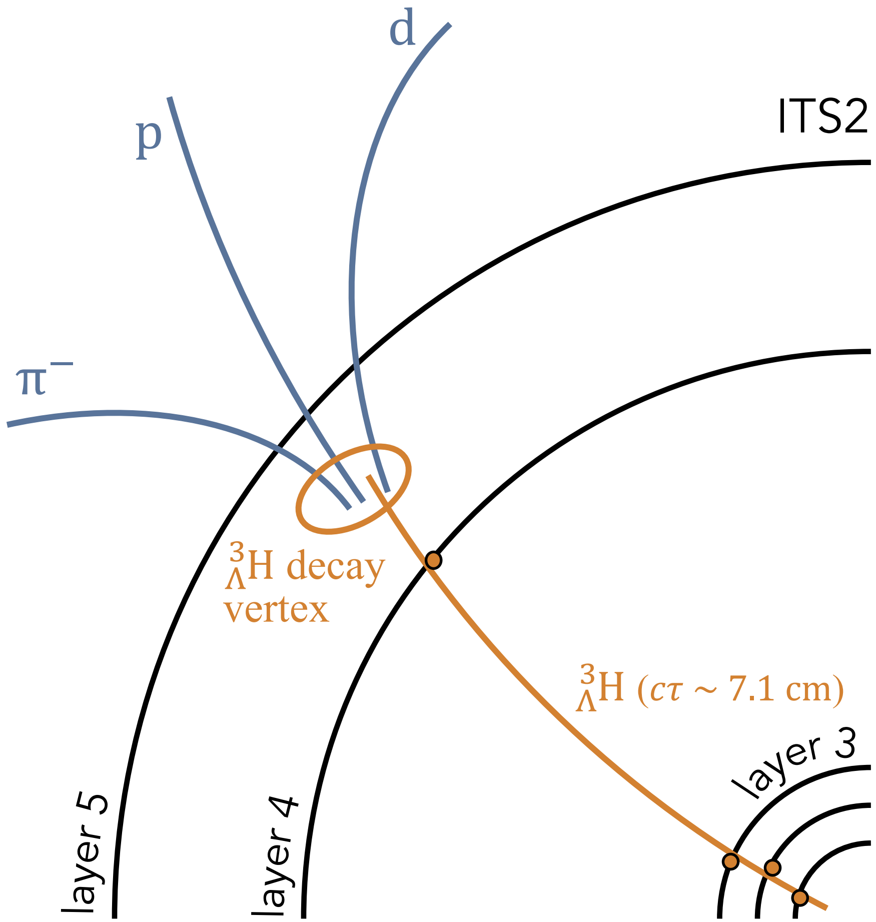
First reconstruction of
$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$ in ALICE

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

Strangeness tracking

- **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**



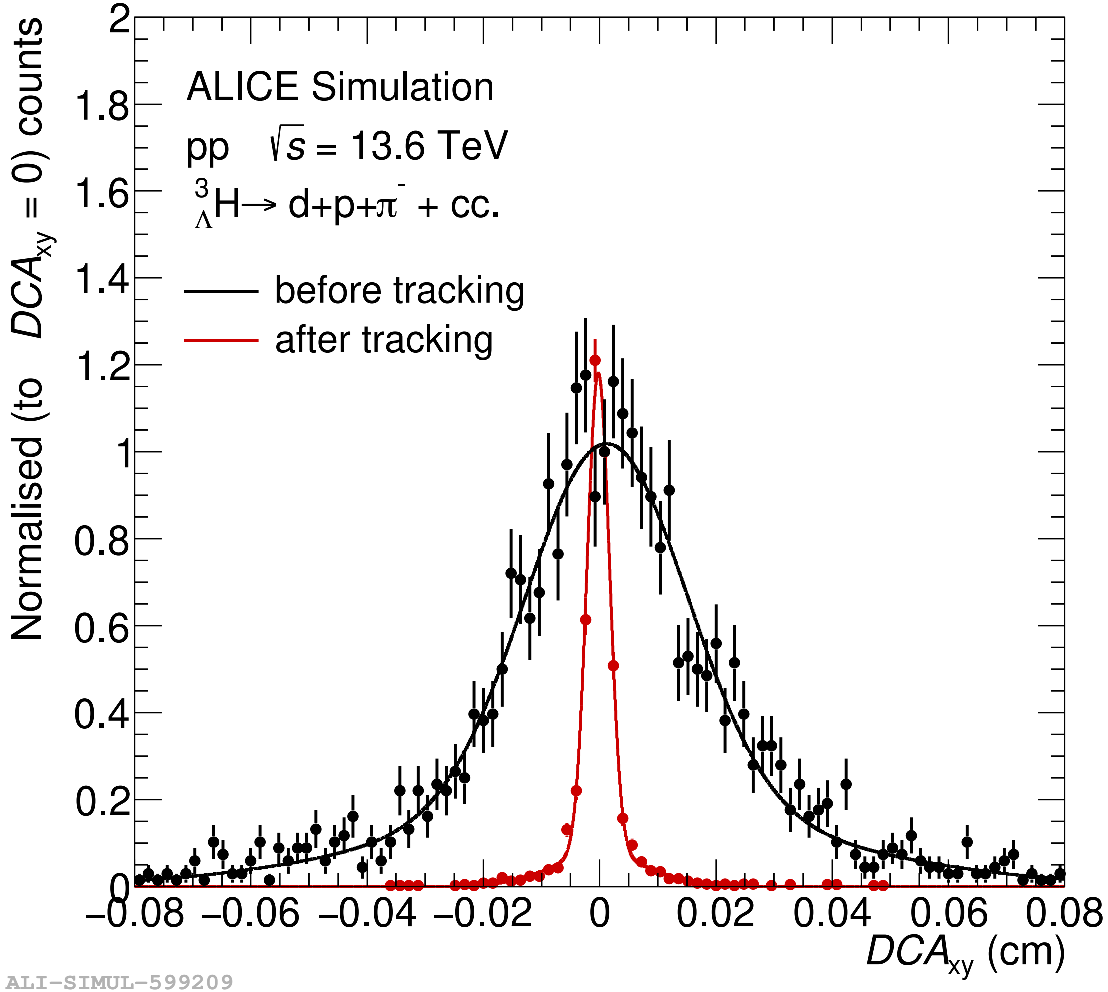


[14] ALICE, J. Phys. G: Nucl. Part. Phys. 41, 087002 (2014)

Strangeness tracking

Performance

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



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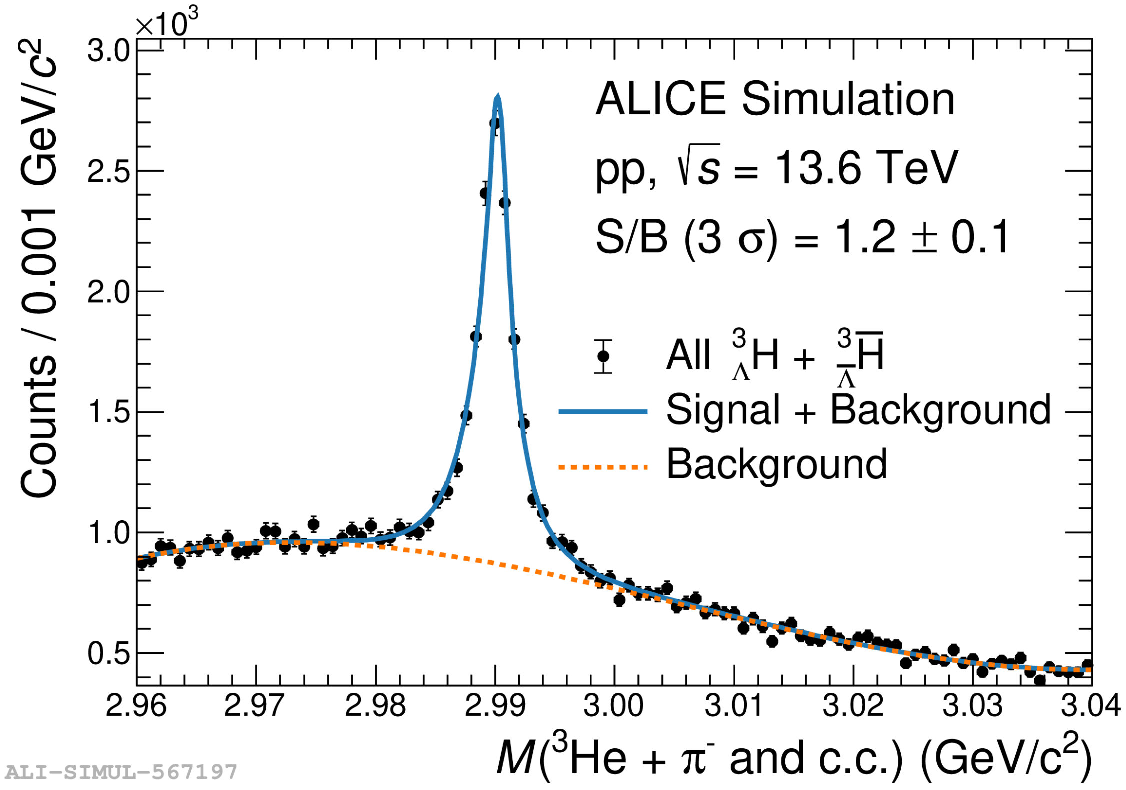
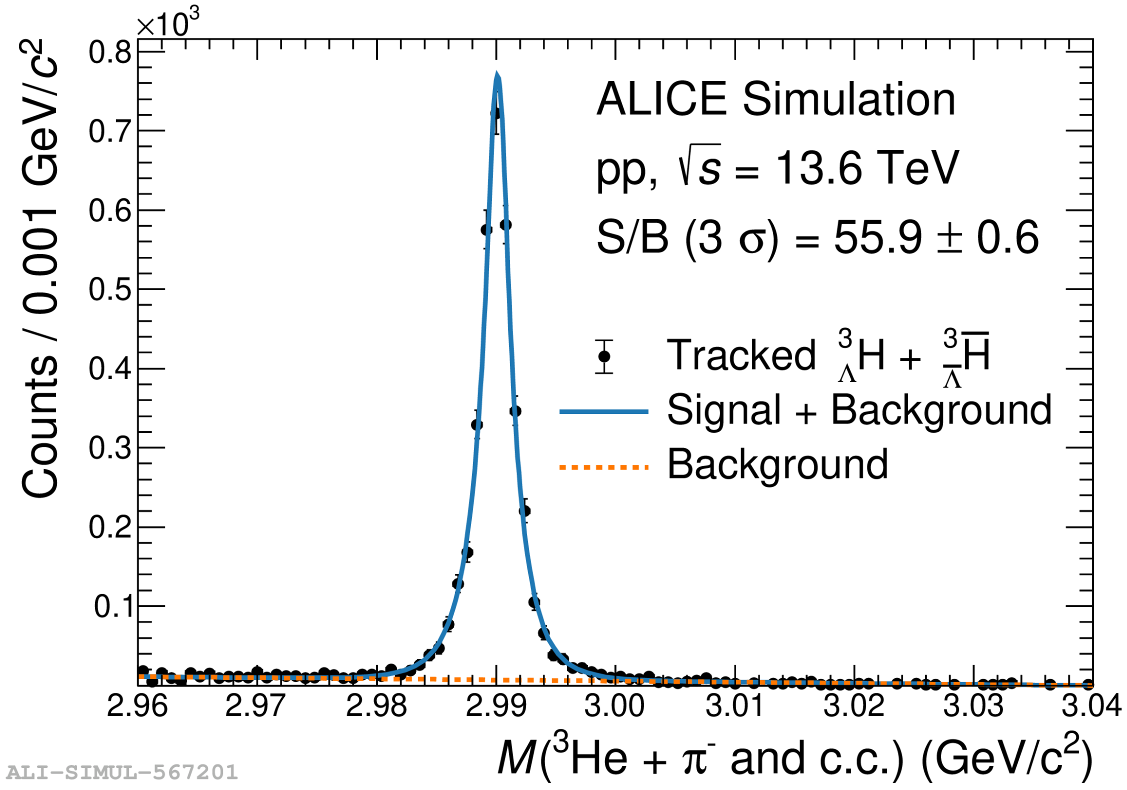
Strangeness tracking

Performance

- **Improved pointing resolution** (DCA_{xy} to PV) by factor ~ 8
- Two-body decay reconstruction:
  - **Significant background reduction** expected

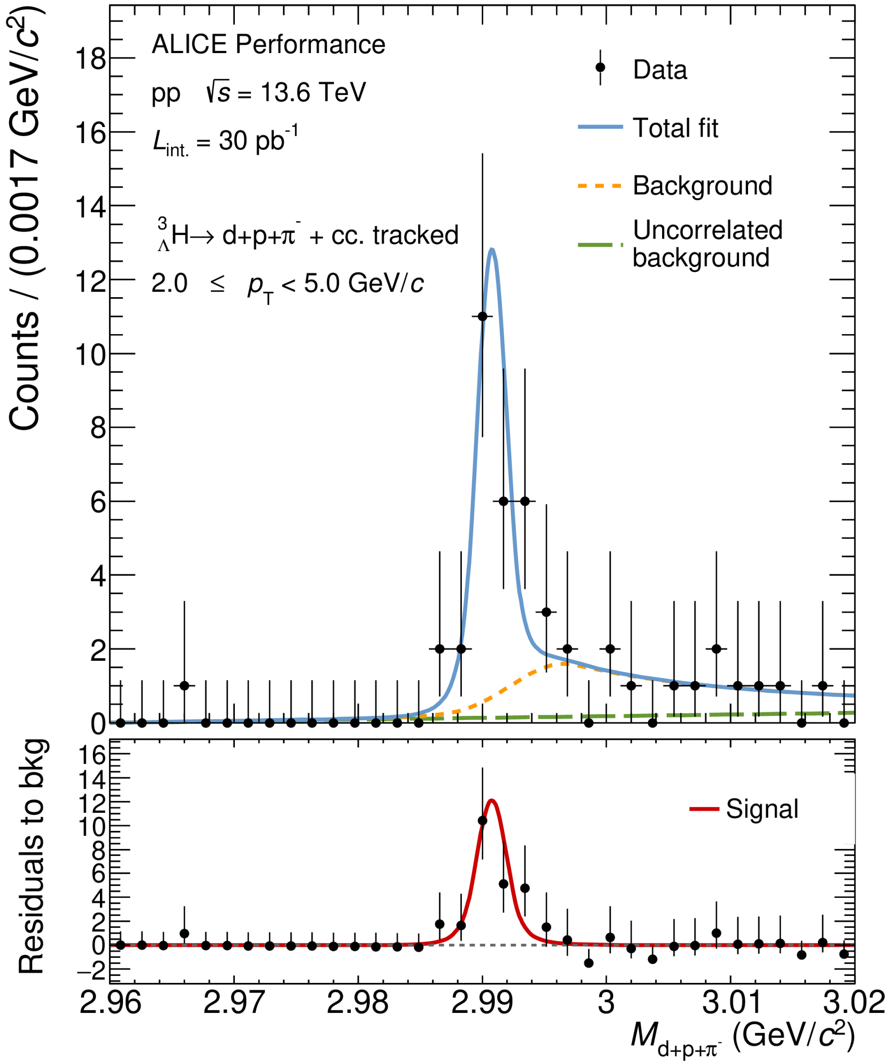




Strangeness tracking

Performance

- **Improved pointing resolution** (DCA_{xy} to PV) by factor ~ 8
- Two-body decay reconstruction:
  - **Significant background reduction** expected
- Three-body decay reconstruction:
  - High uncorrelated background with additional background from **Λ-d correlations**
    → **strong suppression** with strangeness tracking

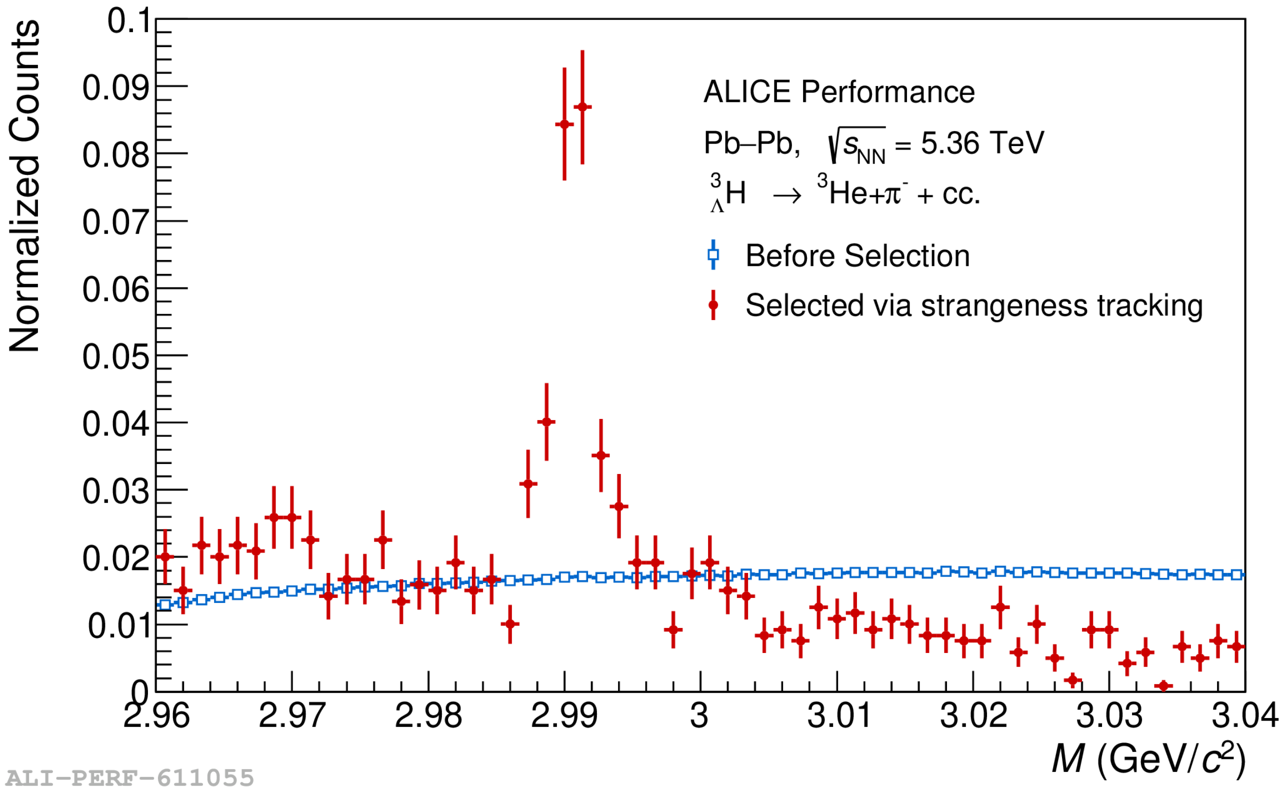


ALI-PERF-611011

Strangeness tracking

Performance

- **Improved pointing resolution** (DCA_{xy} to PV) by factor ~ 8
- Two-body decay reconstruction:
    - **Significant background reduction** expected
- Three-body decay reconstruction:
    - High uncorrelated background with additional background from **Λ-d correlations**
      → **strong suppression** with strangeness tracking
- Dominating background in Pb-Pb collisions
  → Strangeness tracking crucial for signal extraction



Conclusions

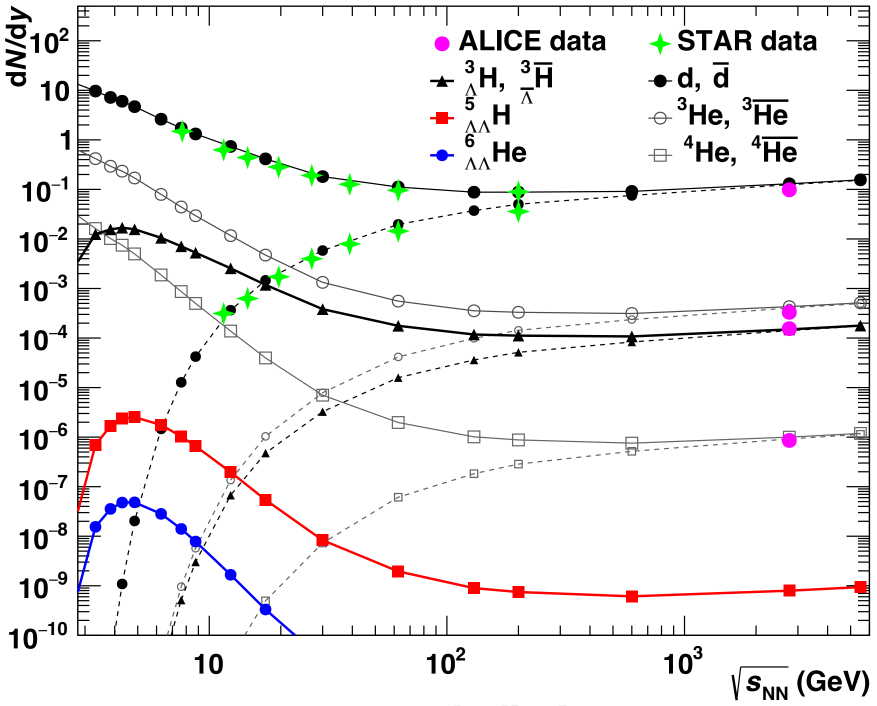
- The upgraded ALICE detector and the large collected data sample in Run 3 allows for new precision measurements to understand the structure of the hypertriton
- **First p_T-differential measurement of $^{3}_{\Lambda}$H in pp collisions**
  - Good description by new advanced coalescence model implementing a Congleton wave function
- Measurement of hypertriton relative branching ratio provides constraint on Λ-separation energy and serves as input to model calculations

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

- Dedicated asynchronous software trigger in Run 3 pp data taking
- Development of new technique for background modelling in the hypertriton candidate invariant mass spectrum
- Measurement of R_3 is feasible at LHC with full Run 3 pp statistics
- **Strangeness tracking:** New powerful tool for reconstruction of weakly decaying charged particles containing strangeness, including hypernuclei

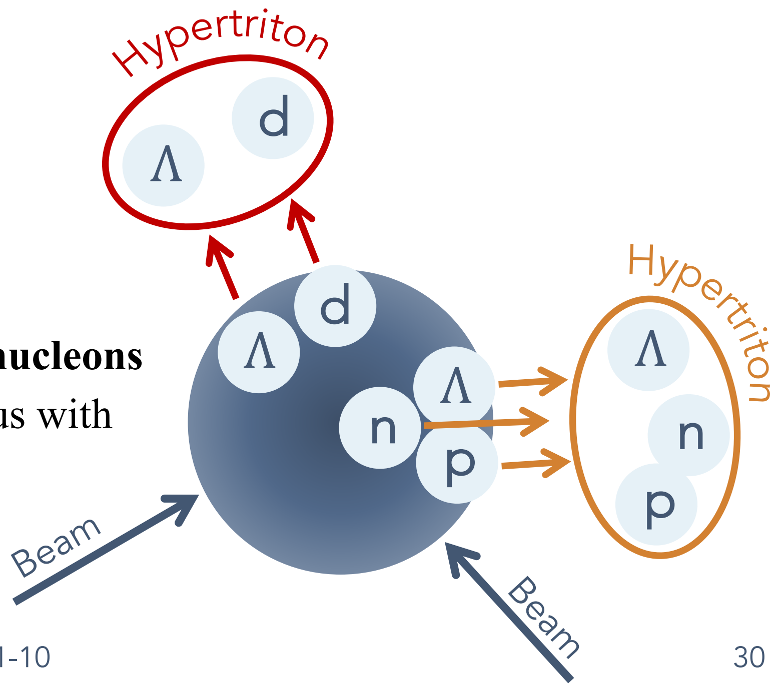
Backup

(Hyper)nucleosynthesis at the LHC



Thermal models (SHM)[15]

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

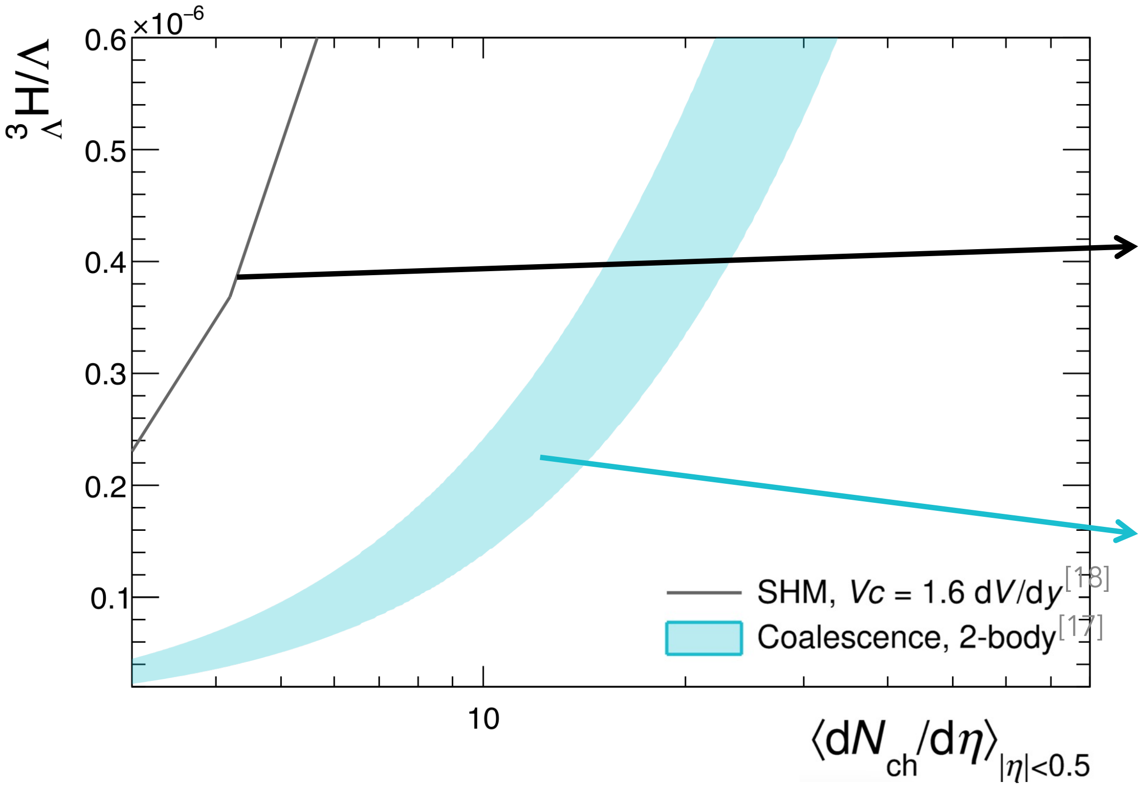


Coalescence models[16][17]

- 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

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

Hypertriton production 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[18]

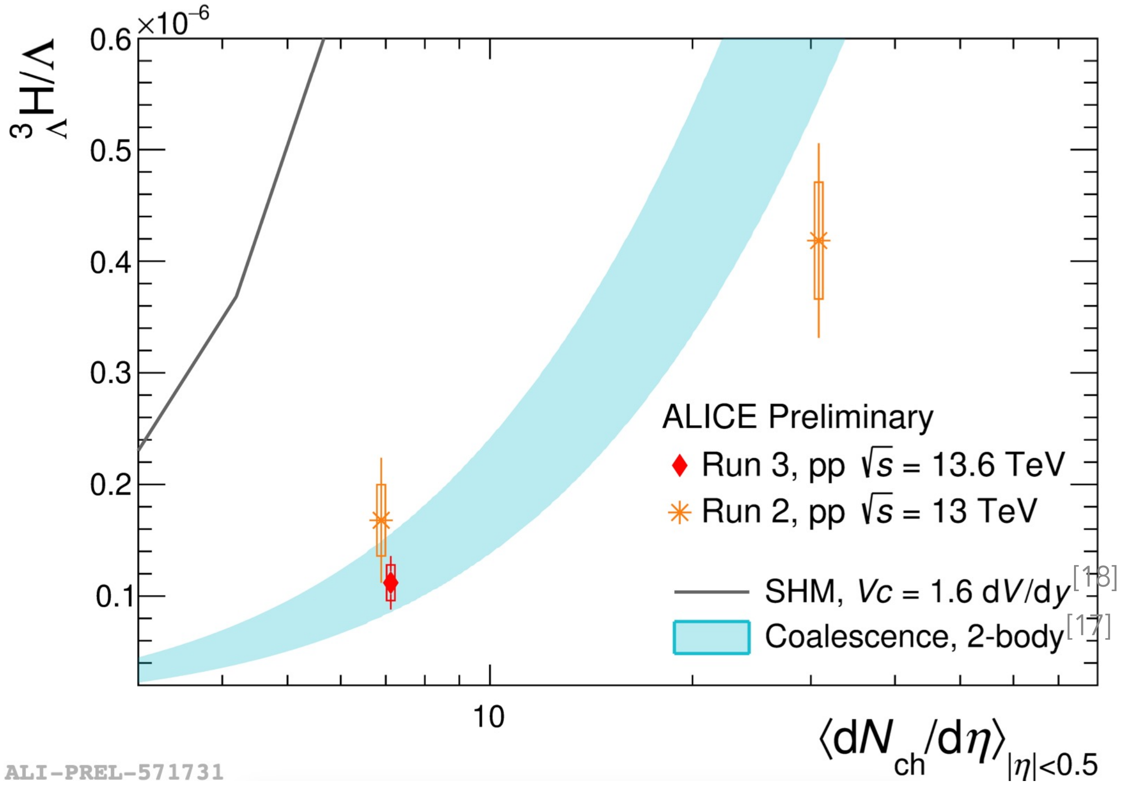
- Independent of object size
  → production suppression due to **canonical conservation of quantum numbers** in small systems

Coalescence model[17]

- 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**

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

Hypertriton production in small collision systems



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

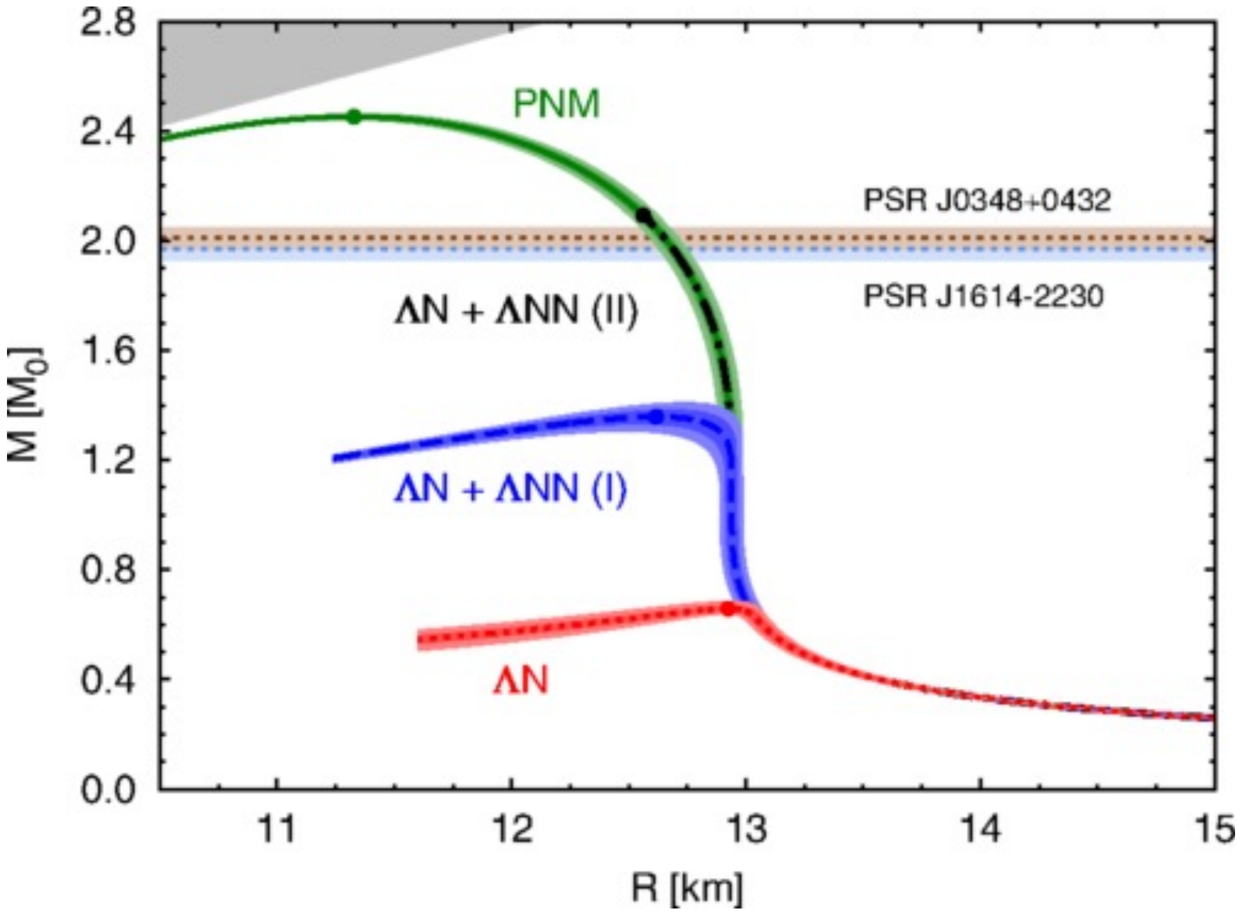
Precise measurement in Run 3 pp collisions

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

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

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