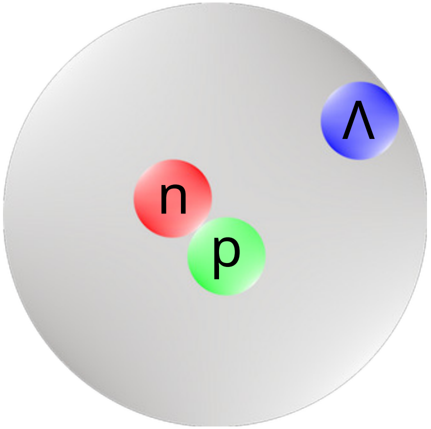
Measurement of the hypertriton properties and production at the LHC

Michael Hartung on behalf of the ALICE collaboration

September 5, 2021

Hypertriton

- Λ, p, n bound state
- Lightest known hypernucleus
- Mass ≈ 2.991 GeV/c^2
- Λ separation energy ≈ 130 keV
- Recent calculations predict a large radius for the hypertriton wave function
  [e.g. F. Hildenbrand, H.-W. Hammer, Phys. Rev. C 100 (2020), 034002]



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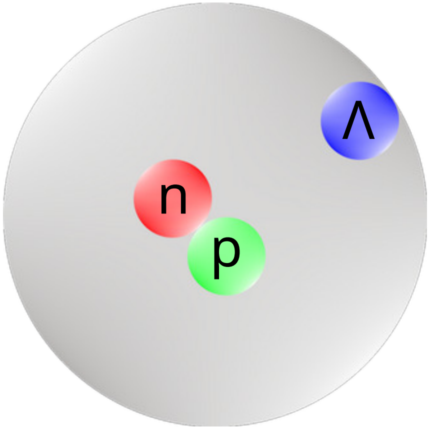
  [e.g. F. Hildenbrand, H.-W. Hammer, Phys. Rev. C 100 (2020), 034002]
- Decay modes:

$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ $\quad$ $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$

$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{0}$ $\quad$ $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^{0}$

and related charge conjugates



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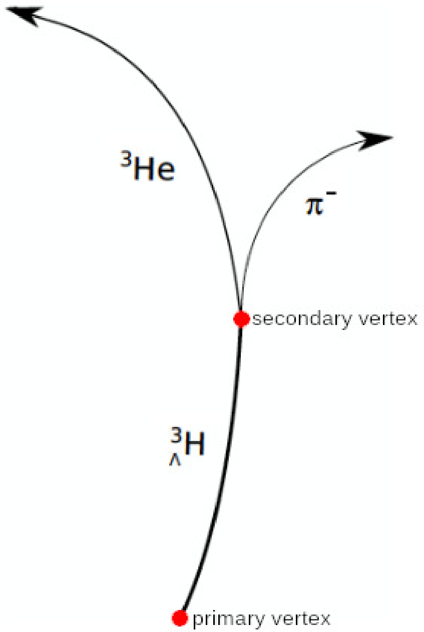
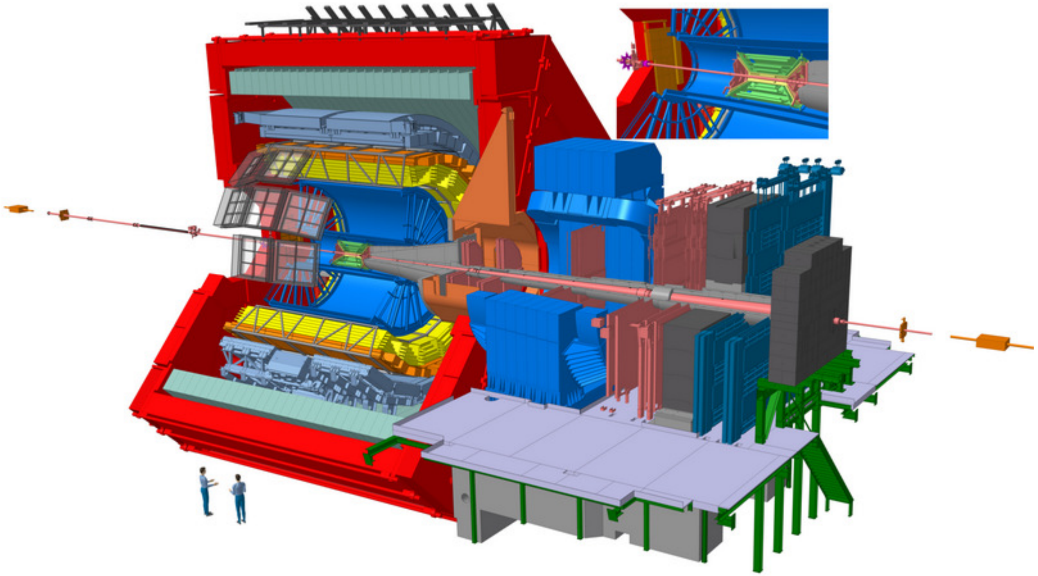


ALICE

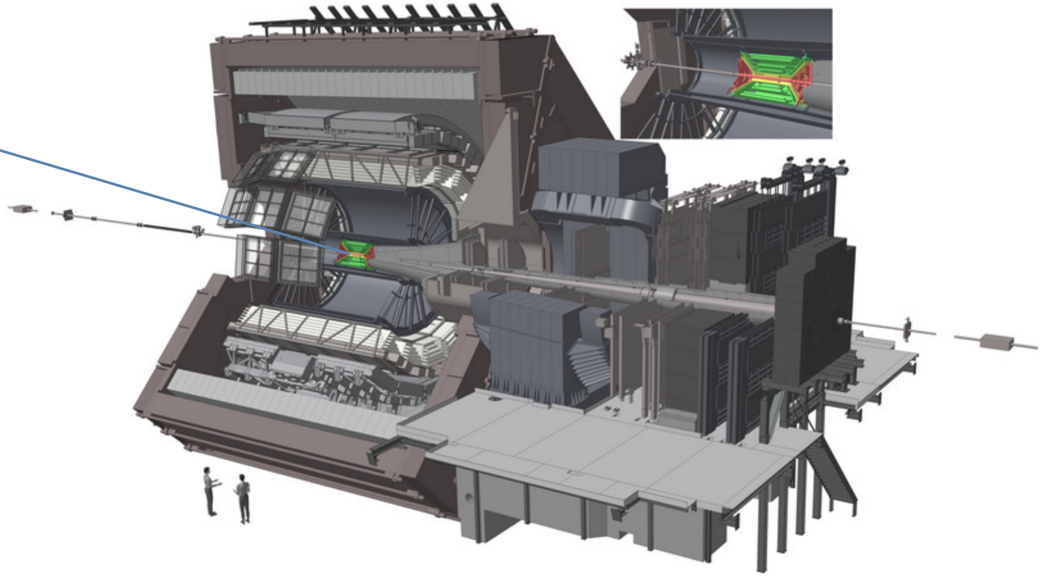
- One of the four major LHC experiments
- Designed to study the quark-gluon plasma in heavy-ion collisions
- Specialized in tracking and particle identification from low to high momenta
- Different detector technologies used



ALICE detectors

ITS (Inner Tracking System)

- Reconstruction of primary and decay vertices
- Track reconstruction
- Particle identification for low momentum particles



ALICE detectors

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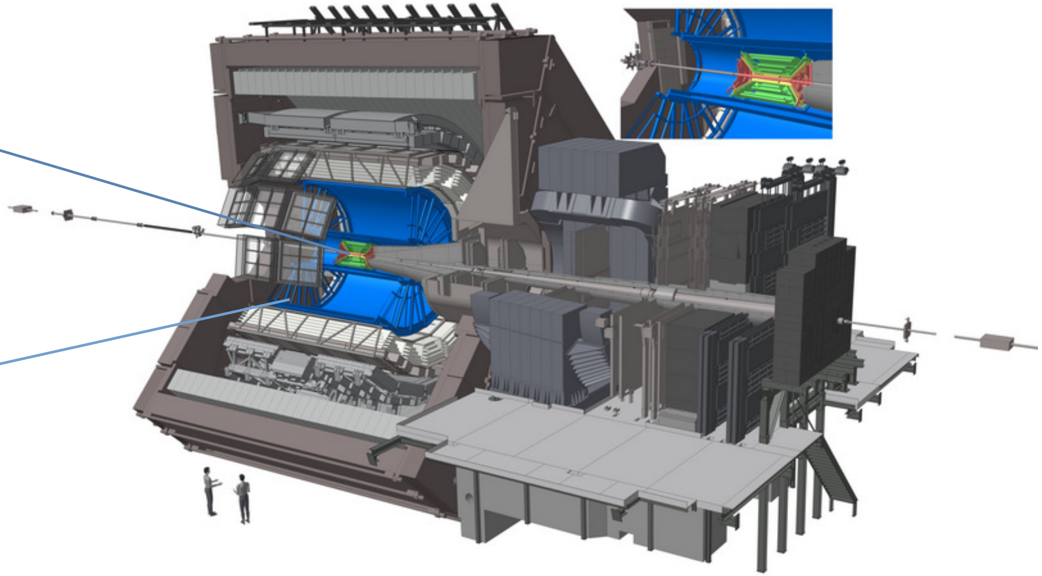
TPC (Time Projection Chamber)

- Tracking (momentum reconstruction)
- Particle identification via d*E*/dx measurement



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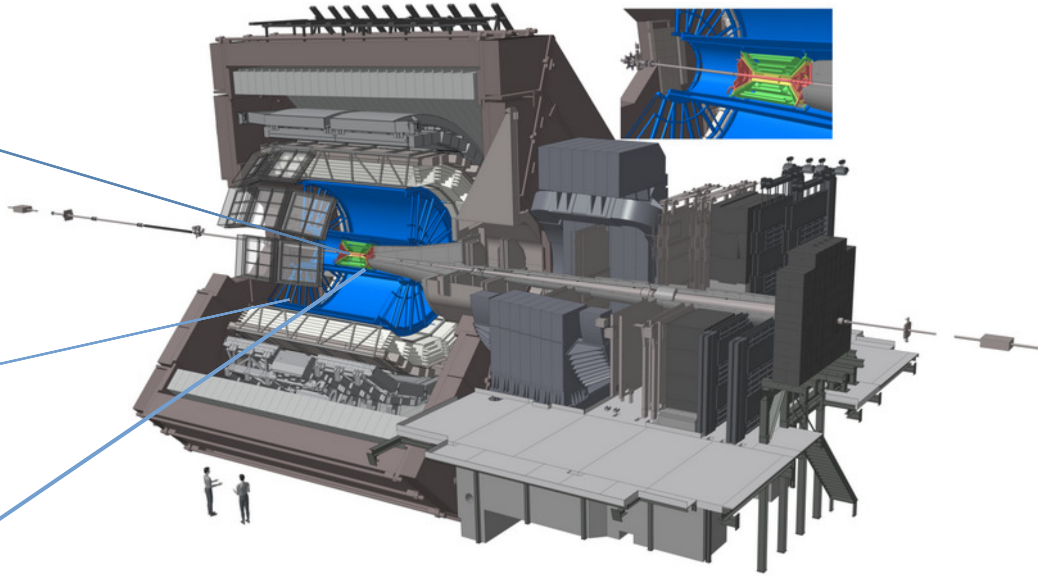
V0 detectors

- Centrality / multiplicity
- (high multiplicity) trigger



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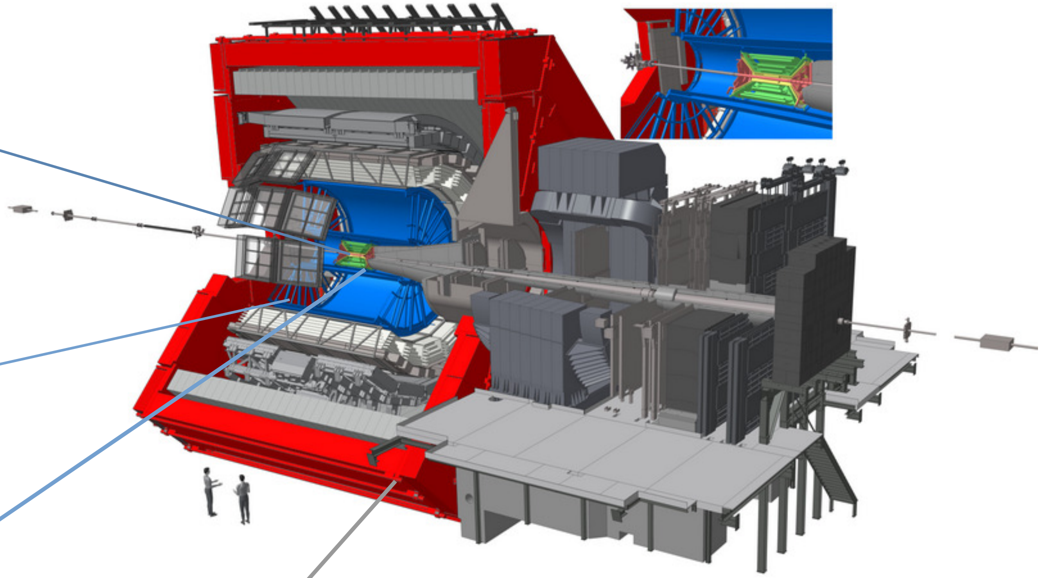
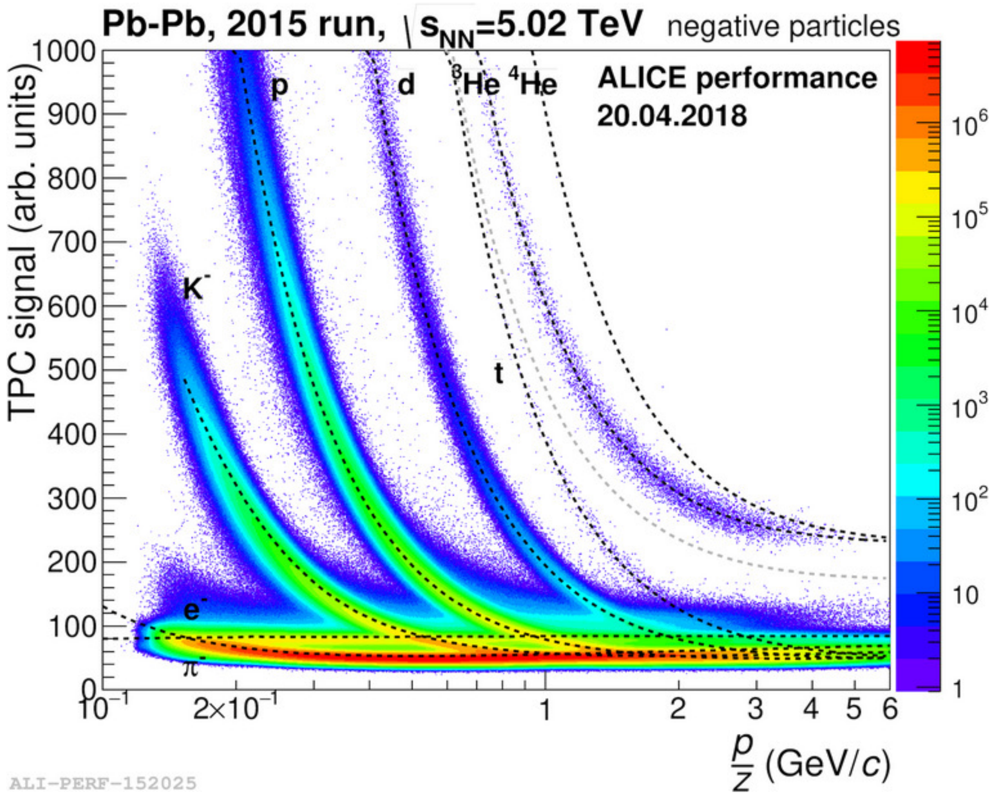


Solenoid

- Magnetic field up to 0.5 T

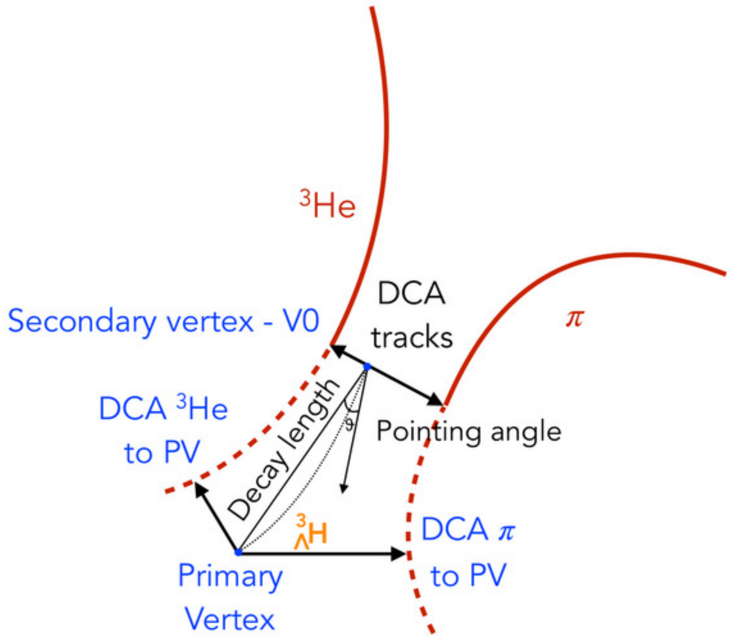
Hypertriton reconstruction

- **Find and identify the daughter particle tracks**
  - $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-} \quad (+\ \mathrm{c.\ c.})$
  - Using the TPC PID via the specific energy loss
  - Excellent separation of different particle species



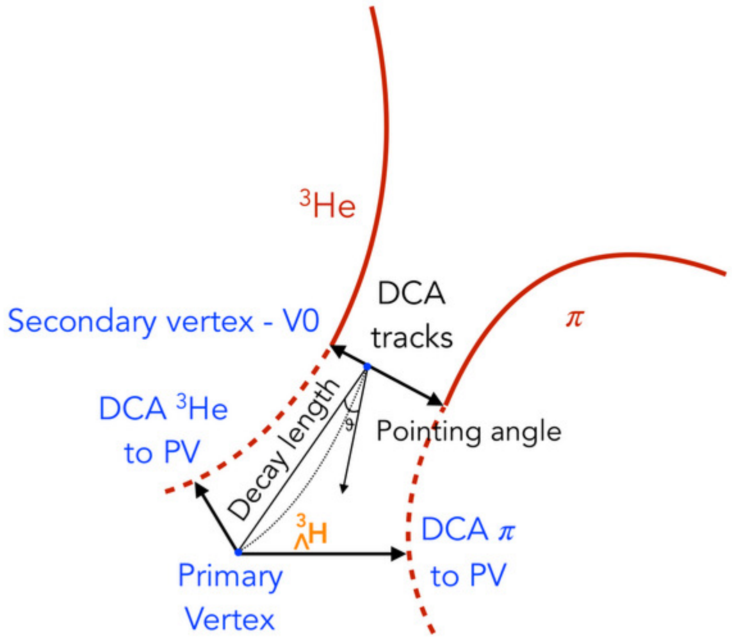
Hypertriton reconstruction

- **Find and identify the daughter particle tracks**
- **Reconstruct the decay vertex of the hypertriton**
  - The identified daughters are assumed to come from a common vertex
  - Their tracks are matched by algorithms to find the best possible decay vertex
  - Huge combinatorial background
    - Topological and kinematical cuts **or** machine learning approach



Hypertriton reconstruction

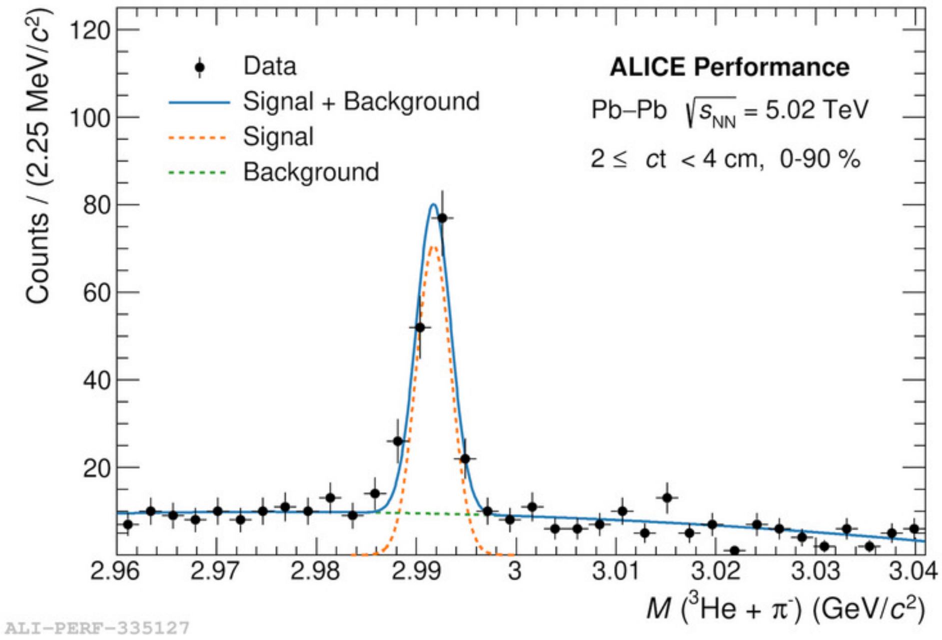
- **Find and identify the daughter particle tracks**
- **Reconstruct the decay vertex of the hypertriton**
- **Applying corrections**
  - Tracking efficiency and detector acceptance
  - Assuming a branching ratio of 25%
    [H. Kamada, J. Golak, K. Miyagawa, H. Witala and W. Gloeckle, PRC. 57 (1998), 1595 - 1603]



Lifetime and B_Λ

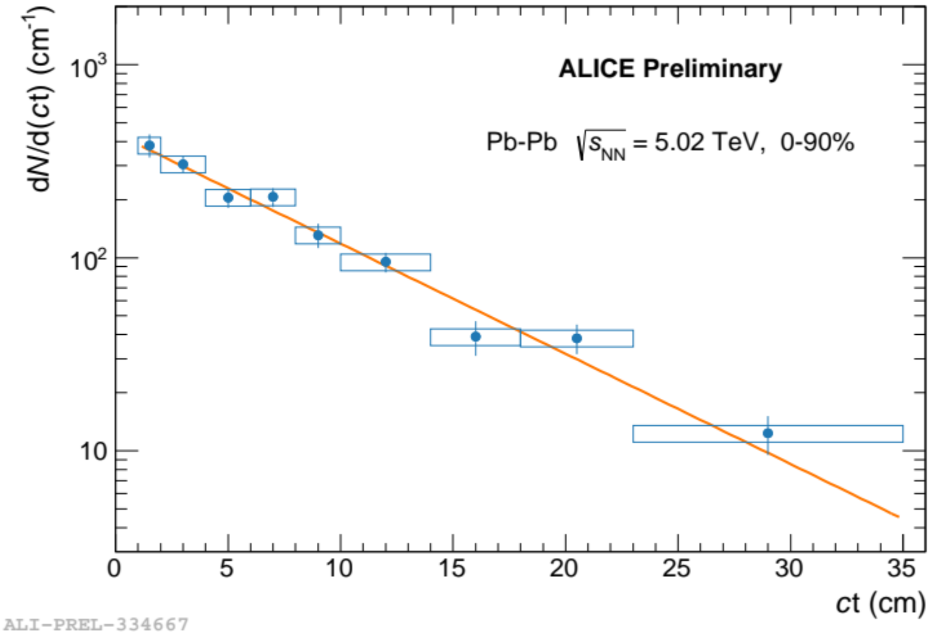
- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Signal extraction by using a machine learning approach
- Signal split into 9 *ct* bins
- Clearly visible peak with high significance

$$S/\sqrt{S/B} = 10.2 \pm 0.6$$



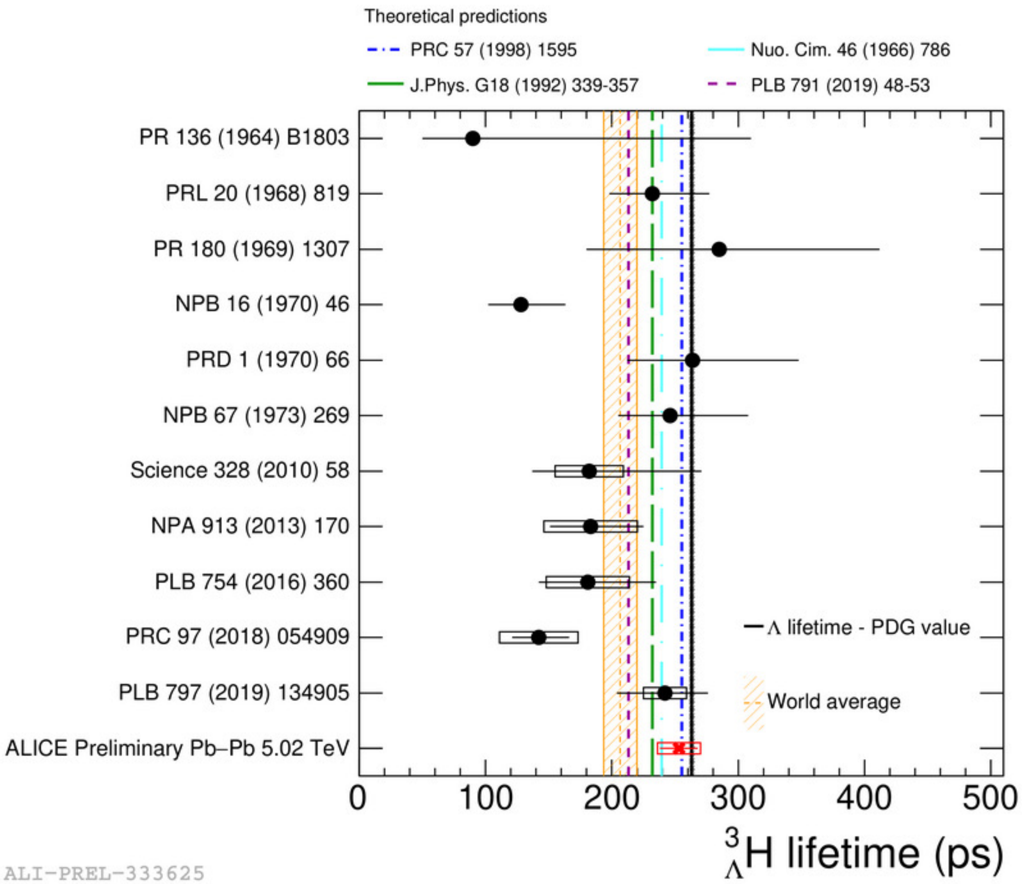
Hypertriton lifetime

- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Signal extraction by using a machine learning approach
- Signal split into 9 *ct* bins
- *ct* spectrum of (anti-)hypertriton with statistical and systematic uncertainties
- Fitted with exponential function
- Most precise hypertriton lifetime measurement so far



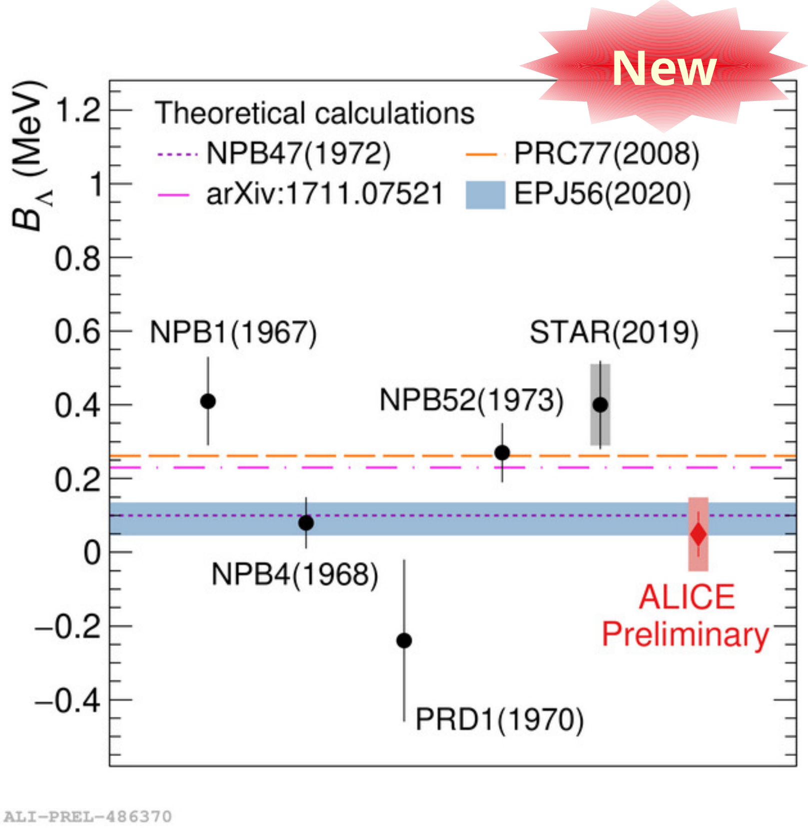
Hypertriton lifetime

- Data before 2010 coming from emulsions and bubble chambers
- Most precise data points coming from heavy-ion collisions
- Latest ALICE data points consistent with free Λ lifetime



Λ separation energy

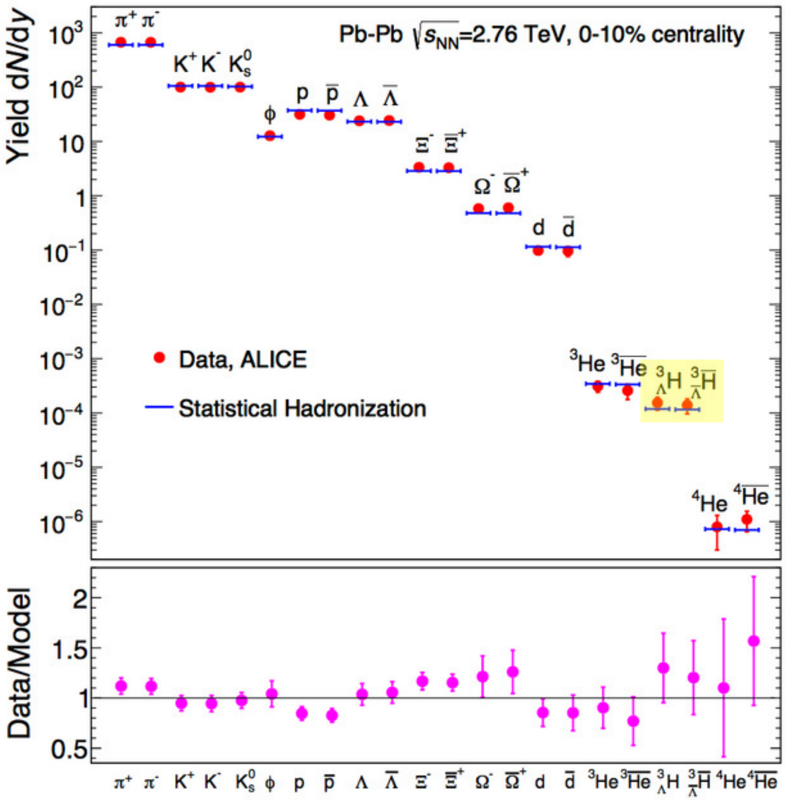
- **Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV**
- **Extremely precise measurement**
  - Supports the loosely bound nature of the hypertriton
  - Agrees with SU(3) chiral effective field theory and Dalitz prediction
  - 1.9 σ from the last measurement (STAR 2019)



NPB47: R.H. Dalitz, R.C. Herndon, Y.C. Tang, Nuclear Physics B, Volume 47, 1972, 109-137
arXiv:1711.07521: Lonardoni, D. and Pederiva, F, arXiv:1711.07521 [nucl-th]
PRC77: Y. Fujiwara, Y., Suzuki, M. Kohno and K. Miyagawa, Phys. Rev. C 77, 027001
EPJ56: B.Dönigus, Eur.Phys.J.A 56 (2020) 11, 280

Hypertriton production

- **Statistical Hadronization Model (SHM)**
  - SHM assumes hadron abundances from statistical equilibrium at the common chemical freeze-out temperature $T_{\text{ch}} = 156$ MeV
  - Heavier particles are produced with lower probability
  - In very good agreement with the ALICE Pb-Pb data
  - Particles and anti-particles are produced equally at LHC

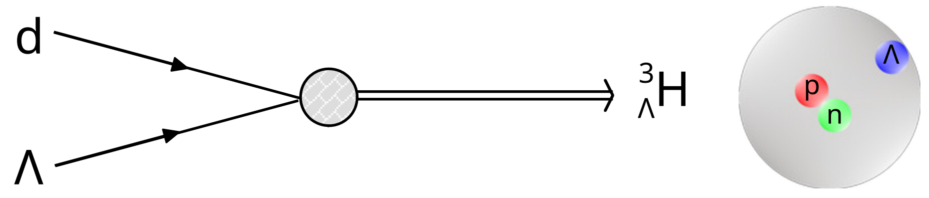


A. Andronic, P. Braun-Munzinger, K. Redlich, J.Stachel, Nature 561 (2018) 321

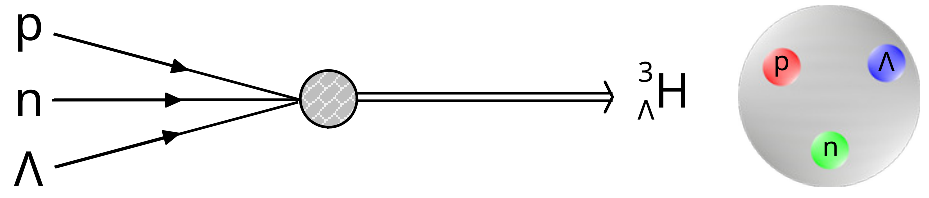
Hypertriton production

- **Statistical Hadronization Model (SHM)**
- **Coalescence Model:**
  [e.g. https://arxiv.org/abs/1812.05175]
  - Nucleons that are close in phase space at the freeze-out can form a nucleus via coalescence
  - The key concept is the overlap between the nuclear wave functions and the phase space of the nucleons
  - Production rate is connected to the size of the bound state

Two body coalescence



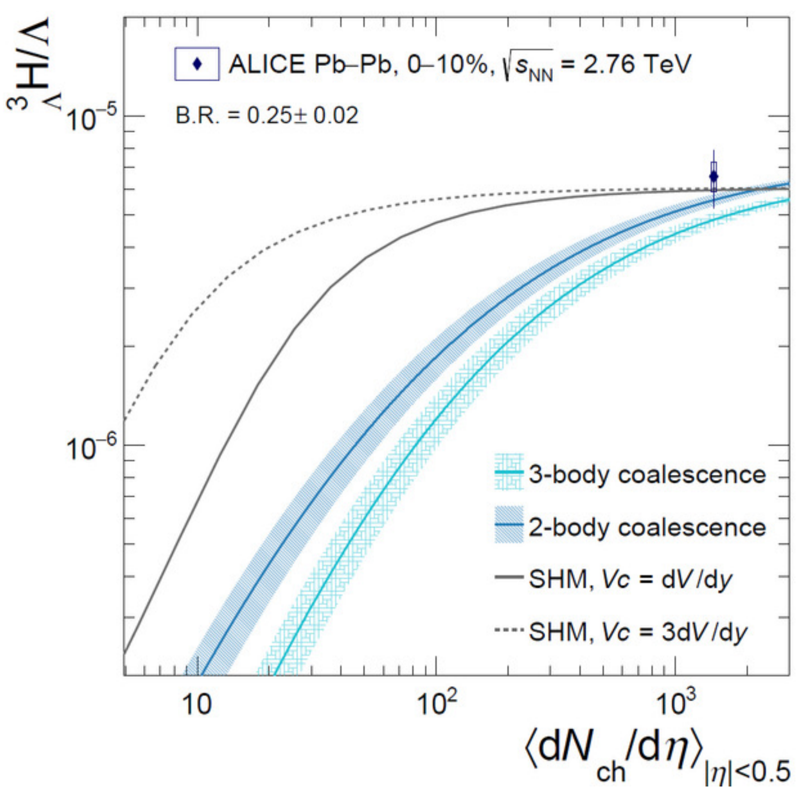
Three body coalescence



Hypertriton production

Model predictions:

- $^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratio vs multiplicity
  - Extremely sensitive to the nuclei production mechanism
  - In statistical hadronization models (SHM) the hypertriton yield does not depend on the object size
  - In a coalescence picture large suppression of the production in small systems expected



Coalescence: K.-J. Sun, C.-M. Ko and B. Dönigus, Phys. Lett. B 792 (2019)132–137

SHM: V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B 785 (2018)171–174

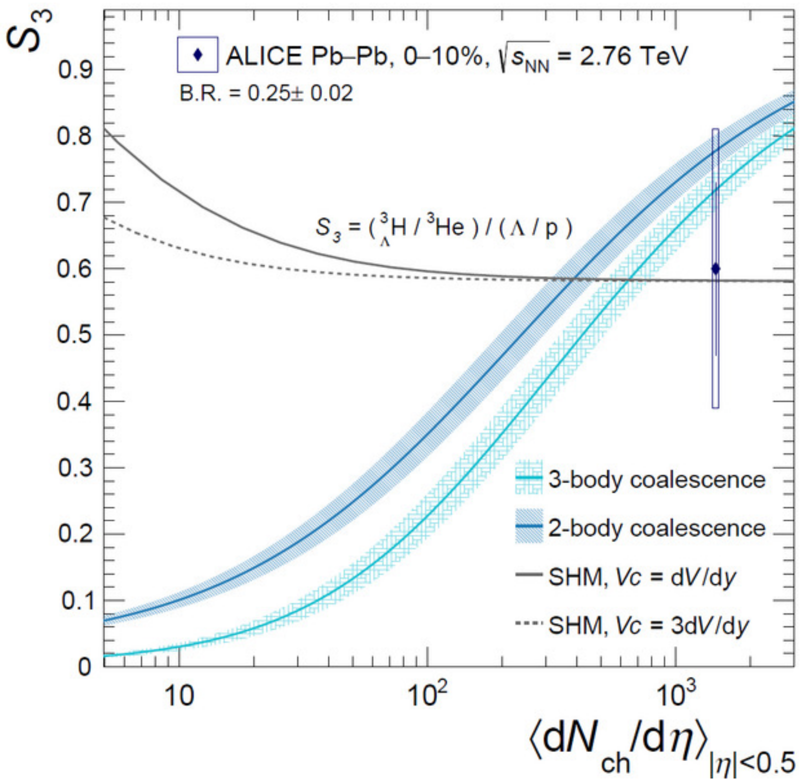
Pb-Pb: $^{3}_{\Lambda}\mathrm{H}$ und $^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}$ production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, PLB 754 (2016) 360-372

Hypertriton production

Model predictions:

- ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratio vs multiplicity
- S_3 ratio vs multiplicity

  - $$S_3 = \frac{{}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}}{\Lambda/\mathrm{p}}$$
  - Strangeness population factor for the measurement of baryon-strangeness correlations
  - Extremely sensitive to the nuclei production mechanism
  - In a coalescence picture large suppression of the production in small systems expected



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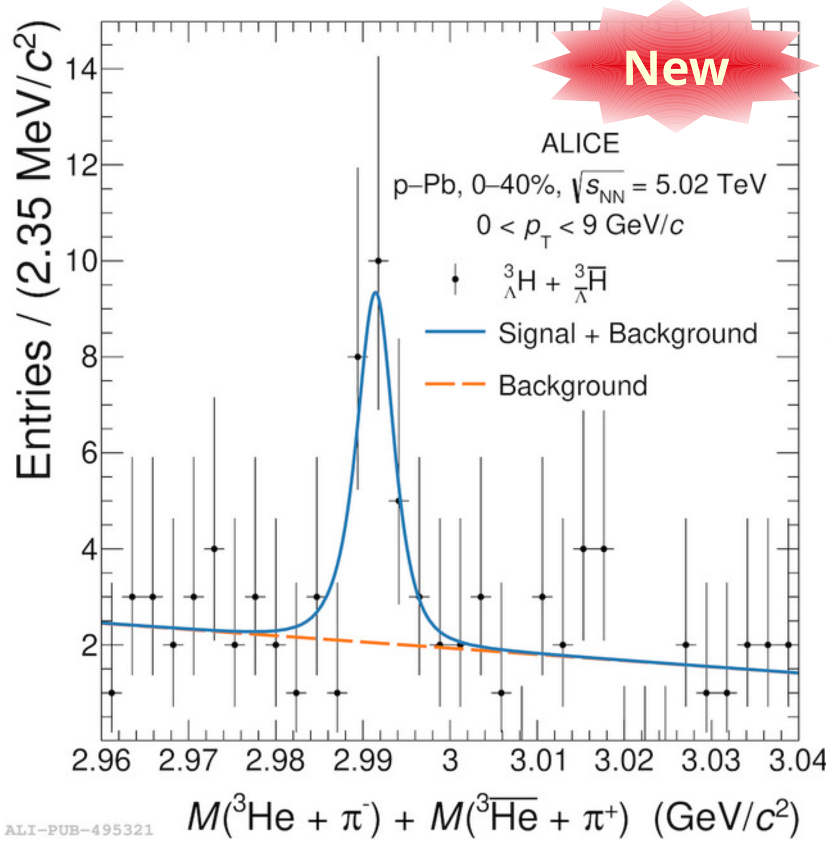
Hypertriton in p-Pb

- First hypertriton measurement in p-Pb collisions
- p-Pb data at 5.02 TeV from Run 2 are used
- Signal extraction by using a machine learning approach

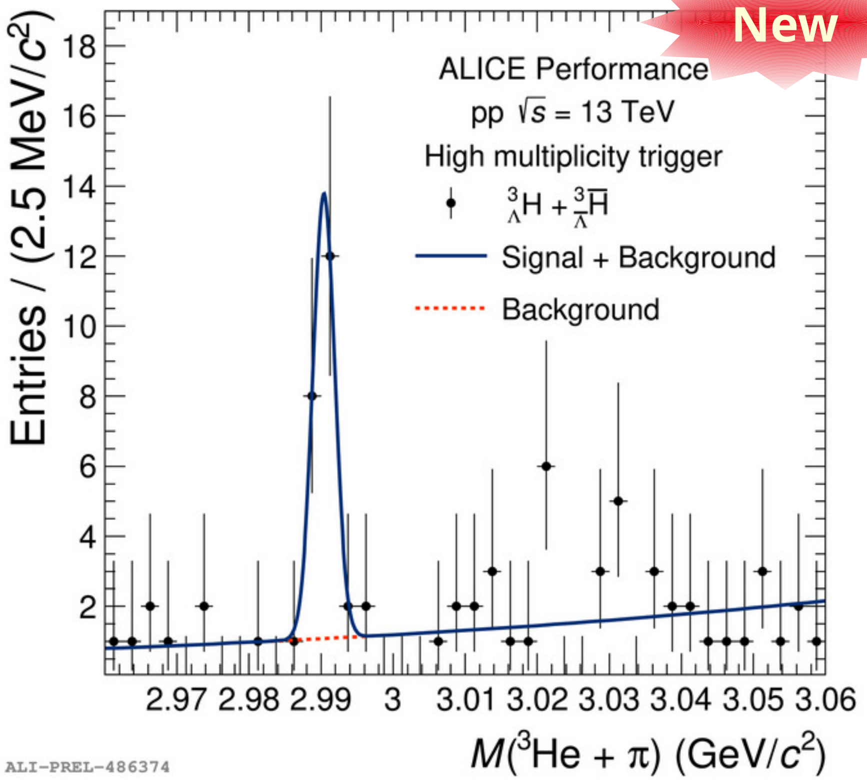


Hypertriton production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, arXiv: 2107.10627

Hypertriton in pp

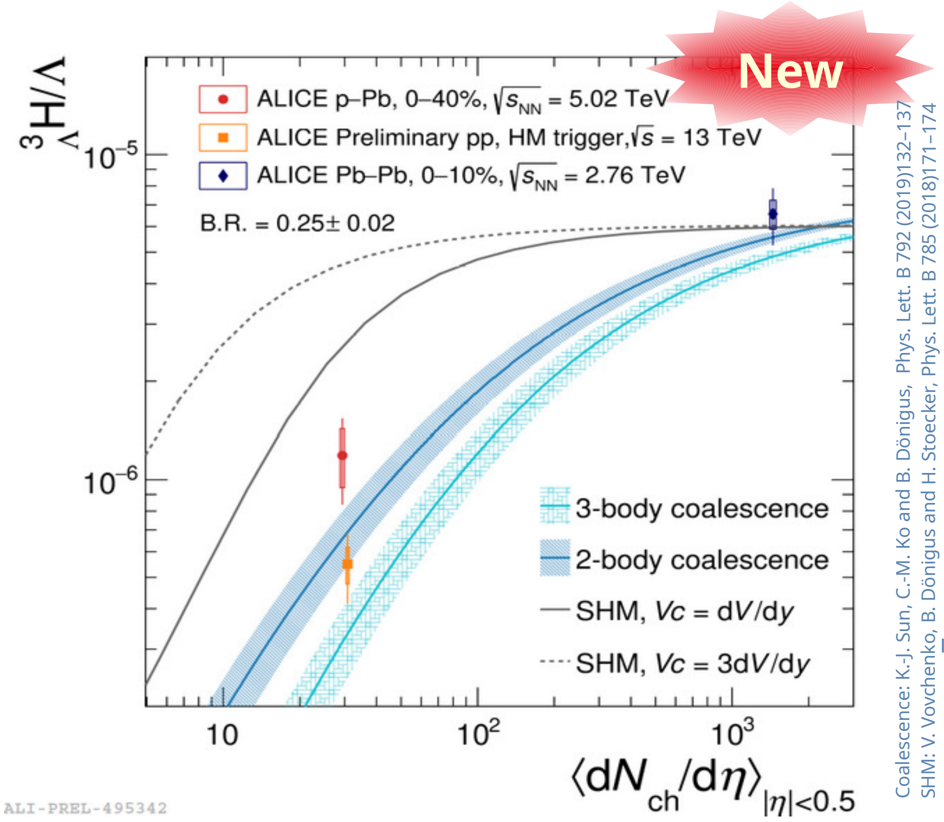
- First hypertriton measurement in pp collisions
- High multiplicity triggered pp data at 13 TeV from Run 2 are used
- Topological and kinematical cuts applied to optimize the signal-to-background ratio and improve the significance in a traditional analysis

New



${}^{3}_{\Lambda}H$ / Λ ratio

- Measurements in pp and p-Pb: Two new points at different multiplicities
- Points disfavor SHM predictions
- Points slightly favor two-body coalescence
- But do not exclude three-body coalescence



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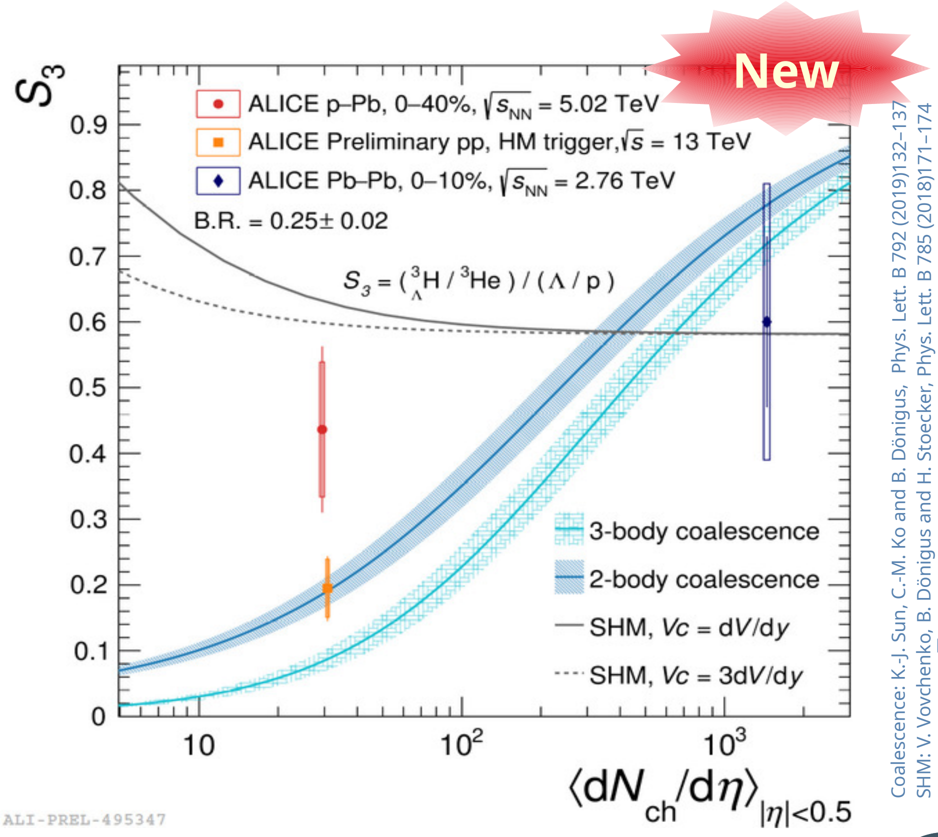
S_3 ratio

- Measurements in pp and p-Pb: Two new points at different multiplicities
- Points slightly favor two-body coalescence
- But do not exclude three-body coalescence
- Less sensitivity with respect to ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratio



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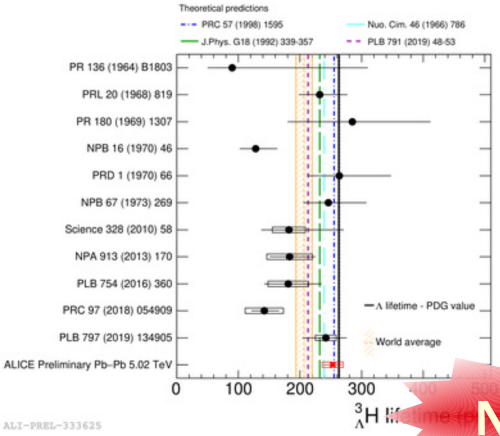
Summary & Outlook

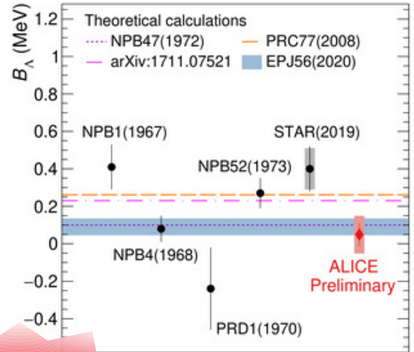
New ALICE results:

- **Lifetime and B_Λ in Pb-Pb collisions measured with extremely high precision**
  - ${}^{3}_{\Lambda}\mathrm{H}$ loosely bound nature confirmed
- **Production in pp and p-Pb collisions**
  - (2-body) coalescence favored over SHM

Run 3 at the LHC starting next year

- **Significantly more statistics for small systems**
- **Possibility of a conclusive answer to the question of the correct production model**





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