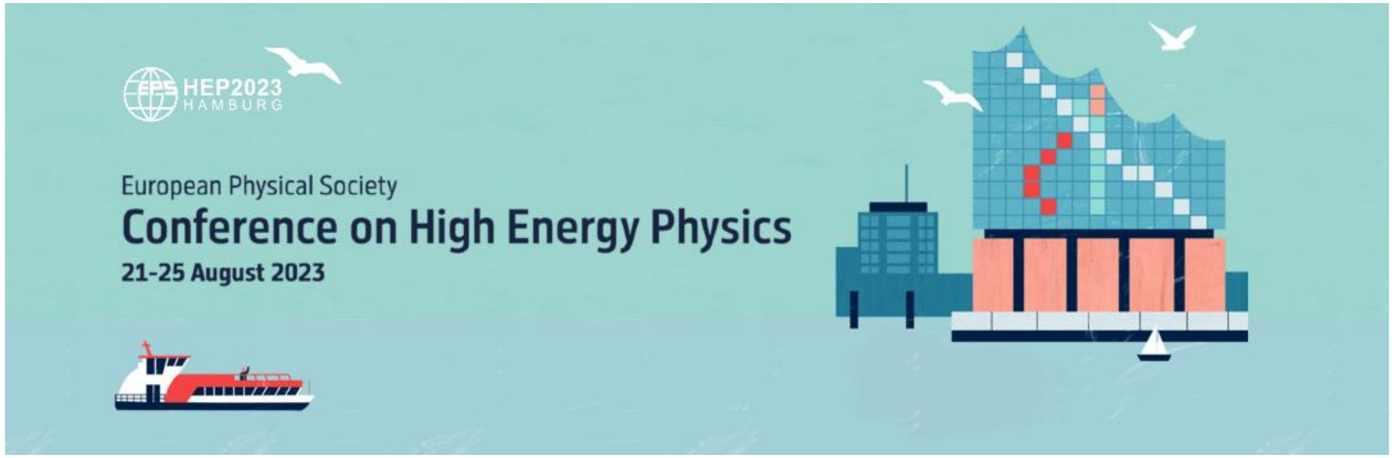
Measurements of rare (anti)hypernuclei with ALICE



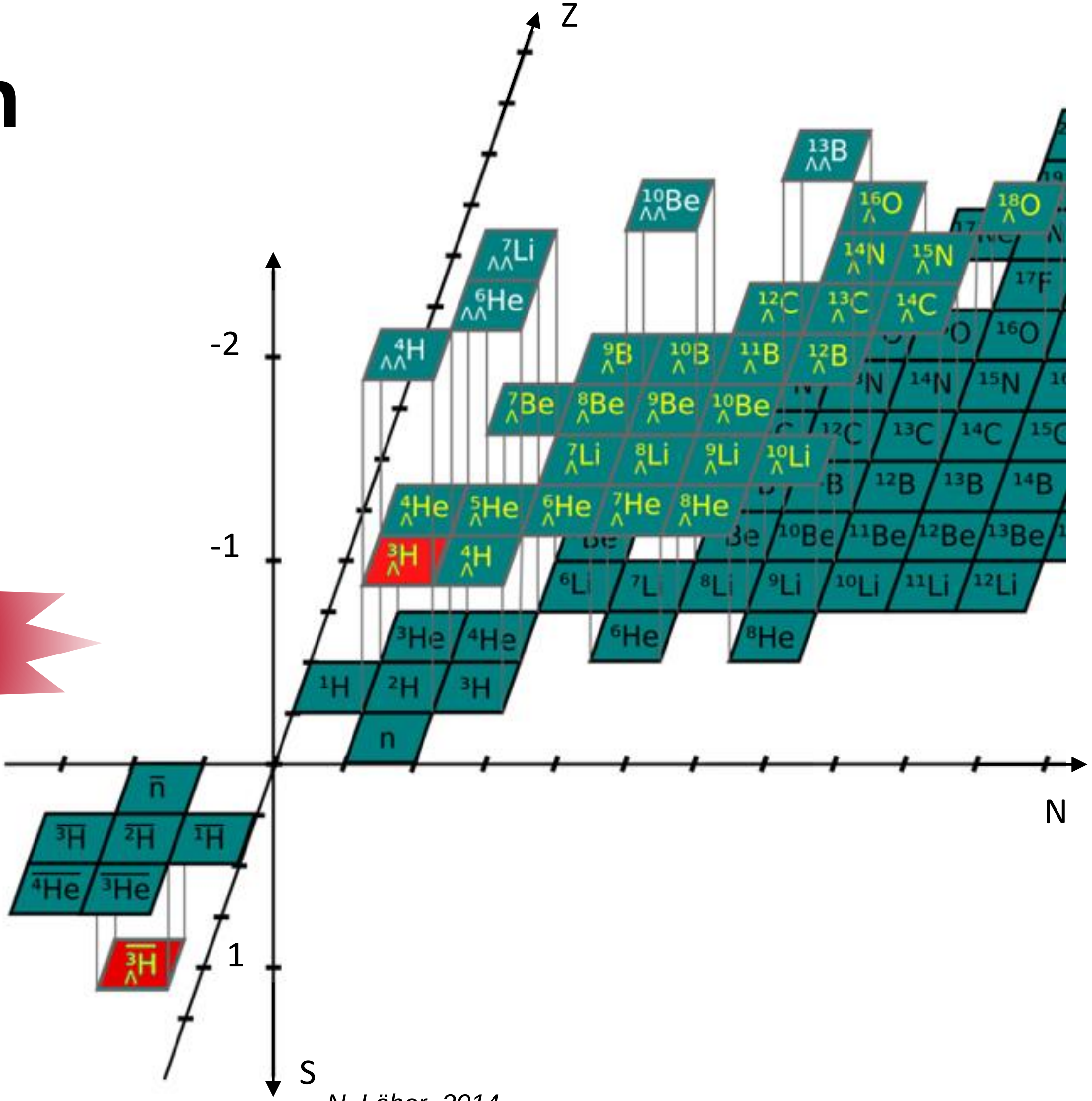
Janik Ditzel
on behalf of the ALICE Collaboration

Hypernuclei: Introduction

- Hypernuclei consist of nucleons and hyperons
- Hyperons are baryons containing at least one strange quark
- Λ hyperon
  - Composition: uds
  - Mass: 1115.6 MeV/c^2
  - Lifetime: [261.07 ± 0.37 (stat.) ± 0.72 (syst.)] ps
- Only the (anti)hypertriton has been measured by ALICE so far

NEW ALICE MEASUREMENT

Phys. Rev. D 108, 032009 (2023)



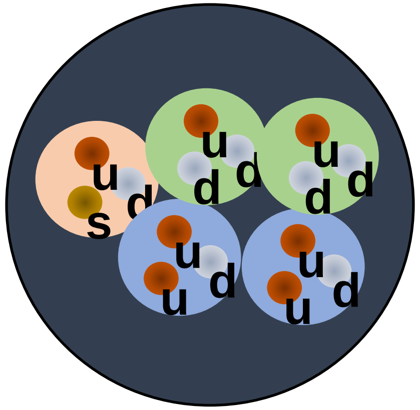
N. Löher, 2014

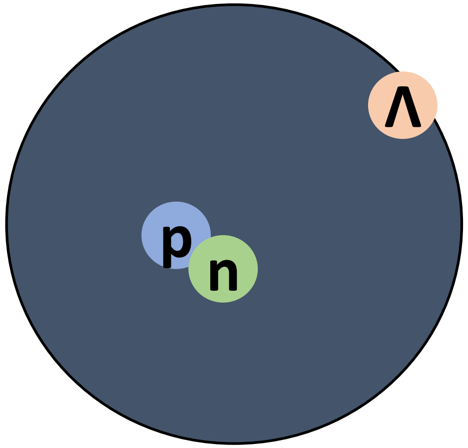
Hypernuclei: Motivation

But why hypernuclei?
What are they good for?

1) Λ hyperons in a system of nucleons allow for the formation of interesting bound states, e.g. the hyperhelium-5 or the hypertriton

A. Gal, E.V. Hungerford, D.J. Millener, Rev.Mod.Phys. 88 (2016) 3, 035004





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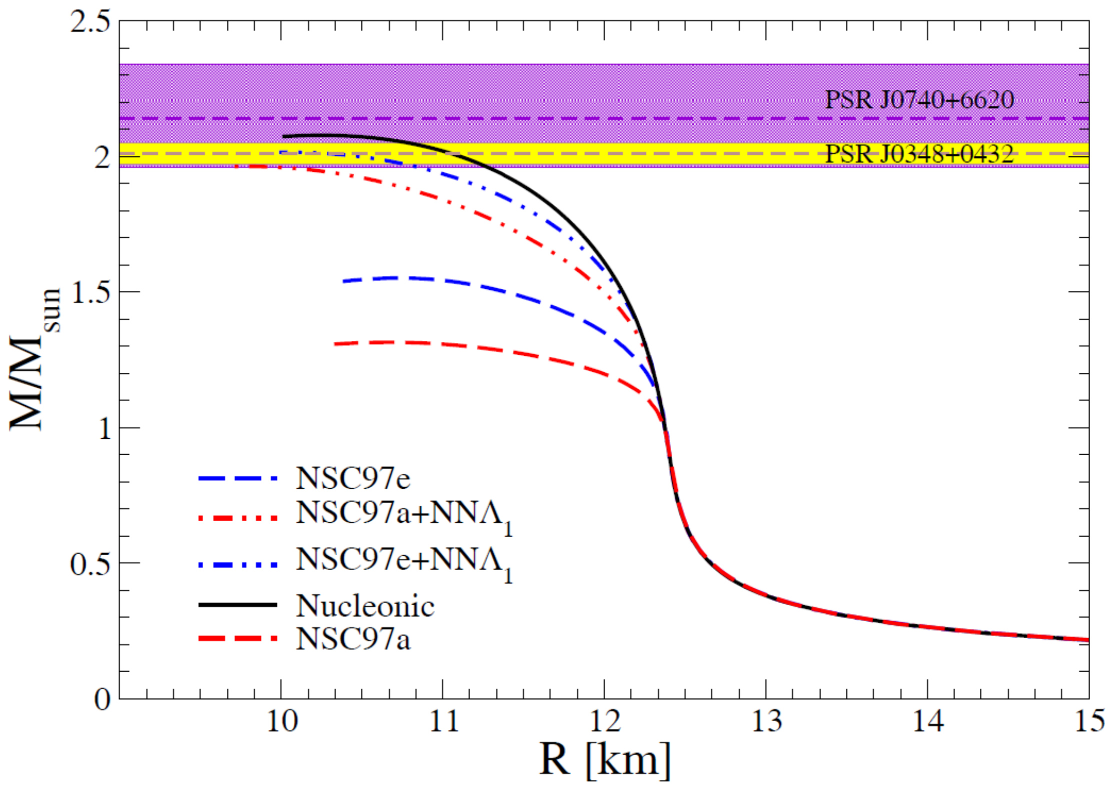
2) Hyperons in neutron stars? Very dense objects (mass > 2 solar masses while having a radius of a few km)

→ understanding of the Λ-N and Λ-Λ interaction



D. Logoteta, I. Vidana, I. Bombaci, Eur. Phys. J. A (2019) 55: 207

Hypernuclei: Motivation

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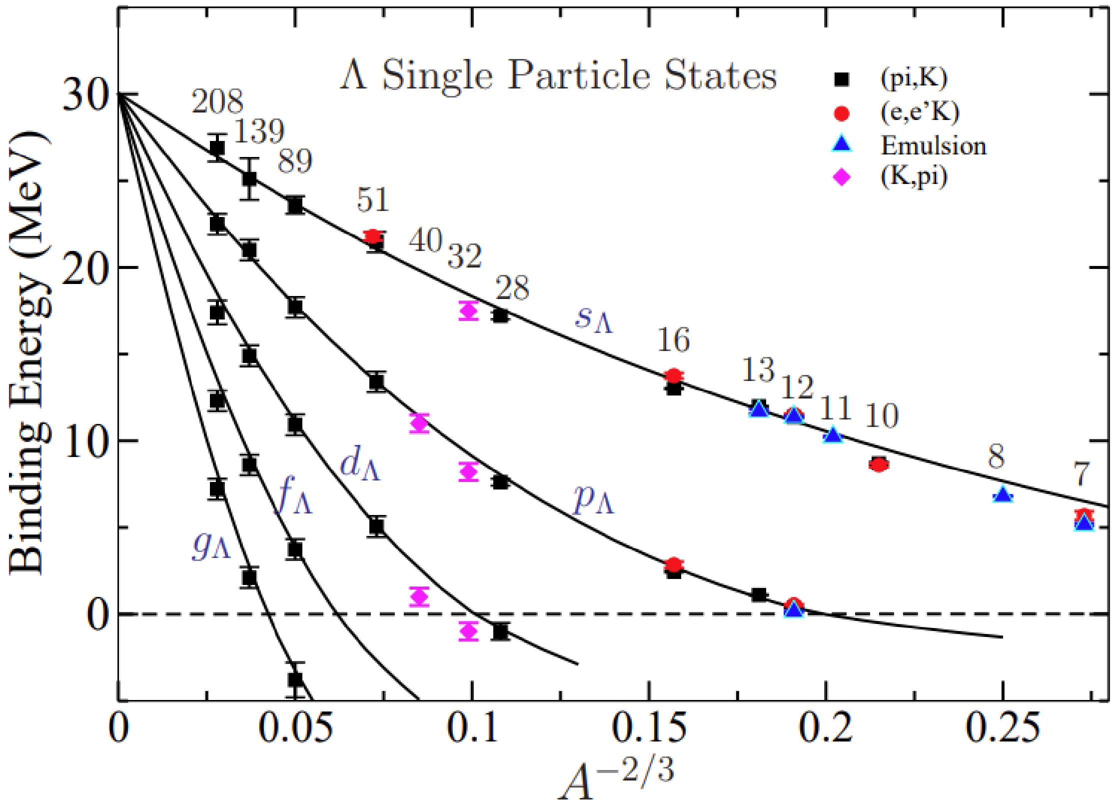
3) Testing the nuclear shell model with the Λ hyperon



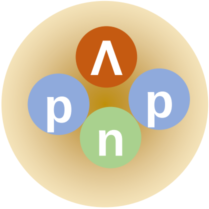
A. Gal, E.V. Hungerford, D.J. Millener, Rev.Mod.Phys. 88 (2016) 3, 035004

Hypernuclei in ALICE

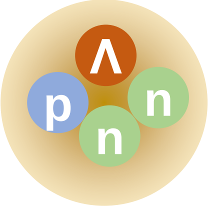
NEW ALICE MEASUREMENT

[arxiv:2209.07360 [nucl-ex]](arxiv:2209.07360)
accepted by PRL

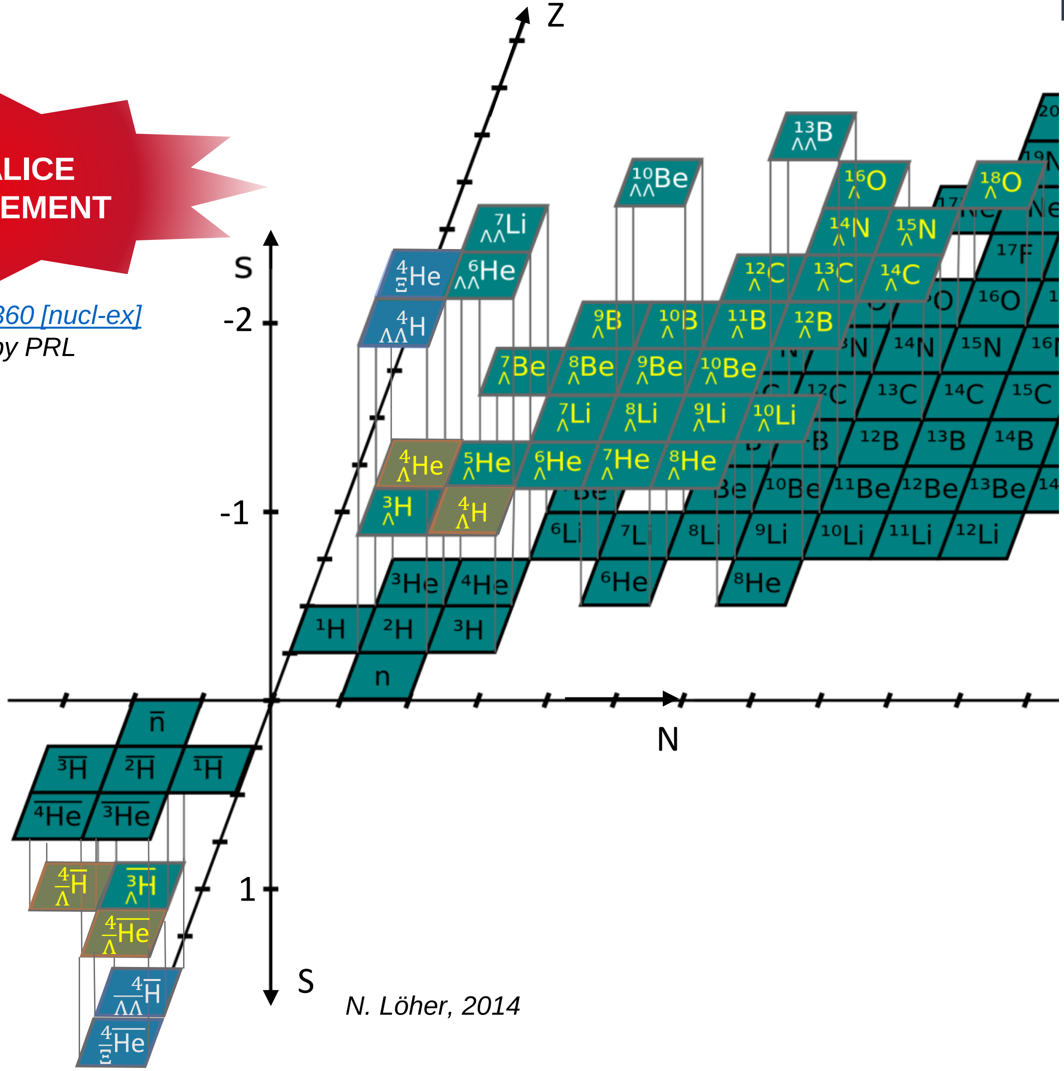
- In the last couple of years, several precise results on the (anti)hypertriton production and properties were presented
- Are we able to also study heavier hypernuclei at the LHC?



$^{4}_{\Lambda}\mathrm{He}$



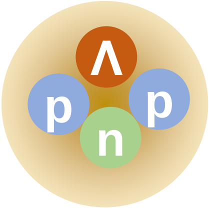
$^{4}_{\Lambda}\mathrm{H}$



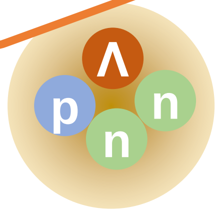
N. Löher, 2014

Hypernuclei in ALICE

- In the last couple of years, several precise results on the (anti)hypertriton producti[...] and properties were [...]
- Are we able to [...] hypernuclei at [...]

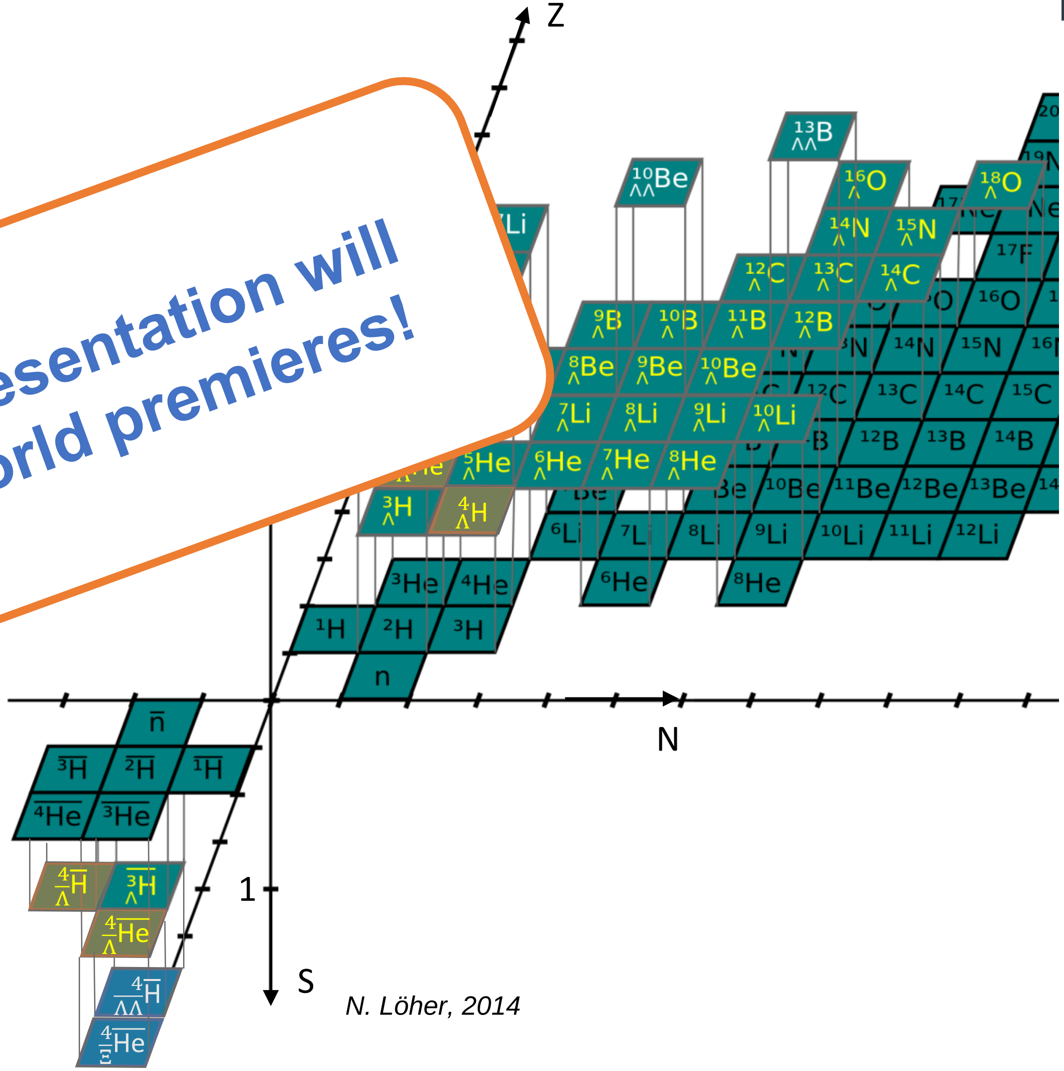


$^{4}_{\Lambda}$He



$^{4}_{\Lambda}$H

TEASER: This presentation will show several world premieres!

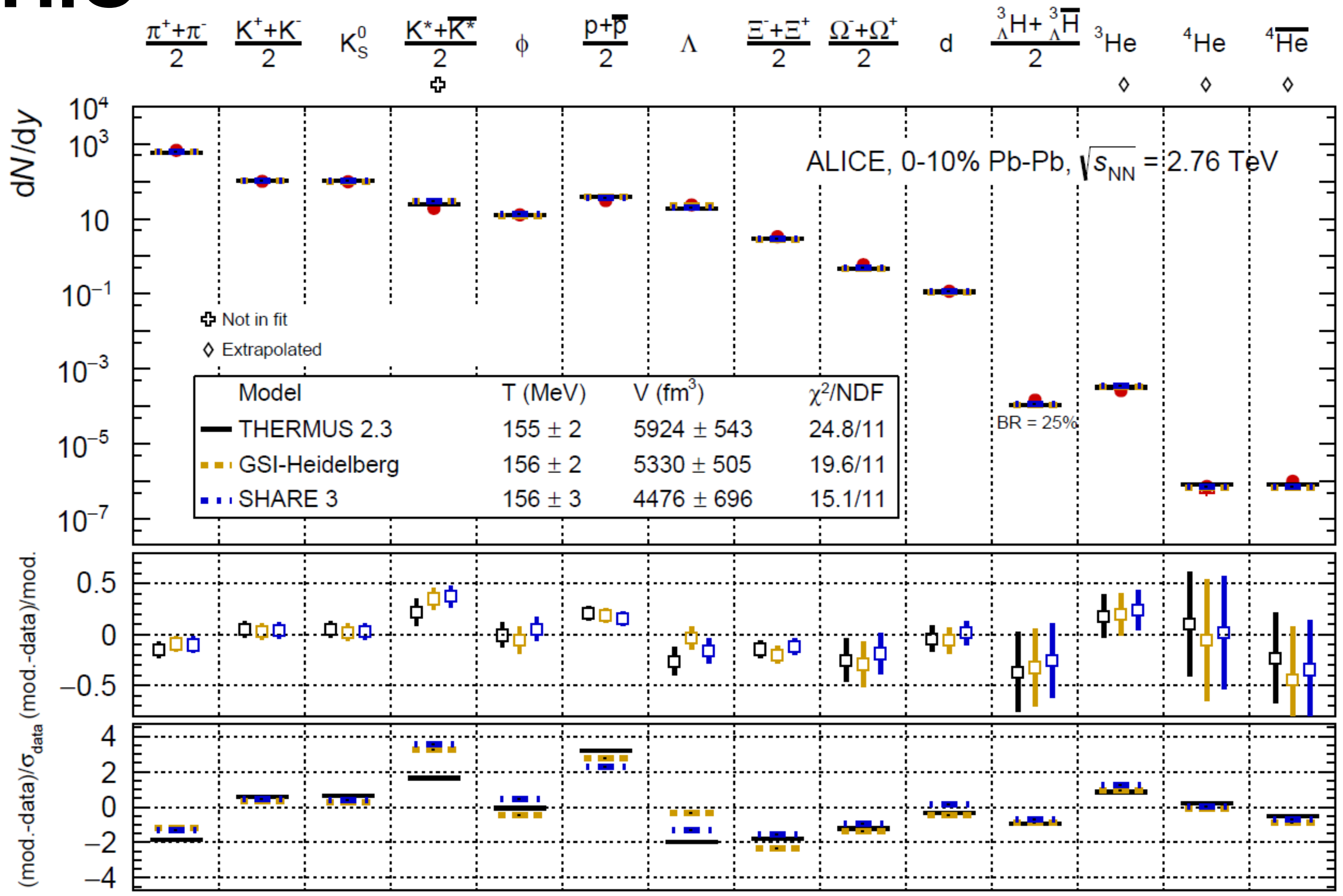


N. Löher, 2014

Particle production in HIC

- In large hadronizing systems, the integrated yield of several particle species is well described over orders of magnitude by the Statistical Hadronization Model (SHM)

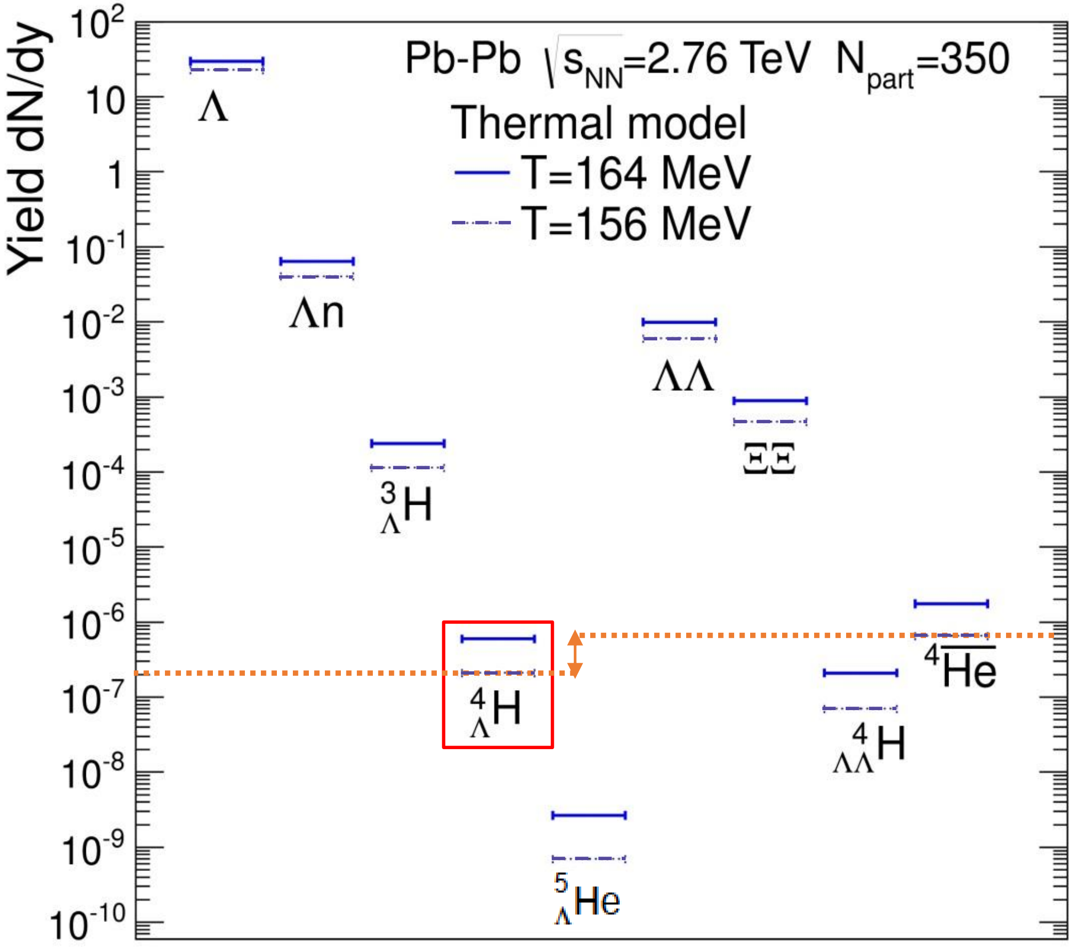
- SHM assumes hadron abundances from statistical equilibrium at the common chemical freeze-out temperature T_{ch} = 156 MeV



Nucl. Phys. A 971 (2018) 1–20, arXiv:1710.07531 [nucl-ex]

A = 4 hypernuclei in ALICE

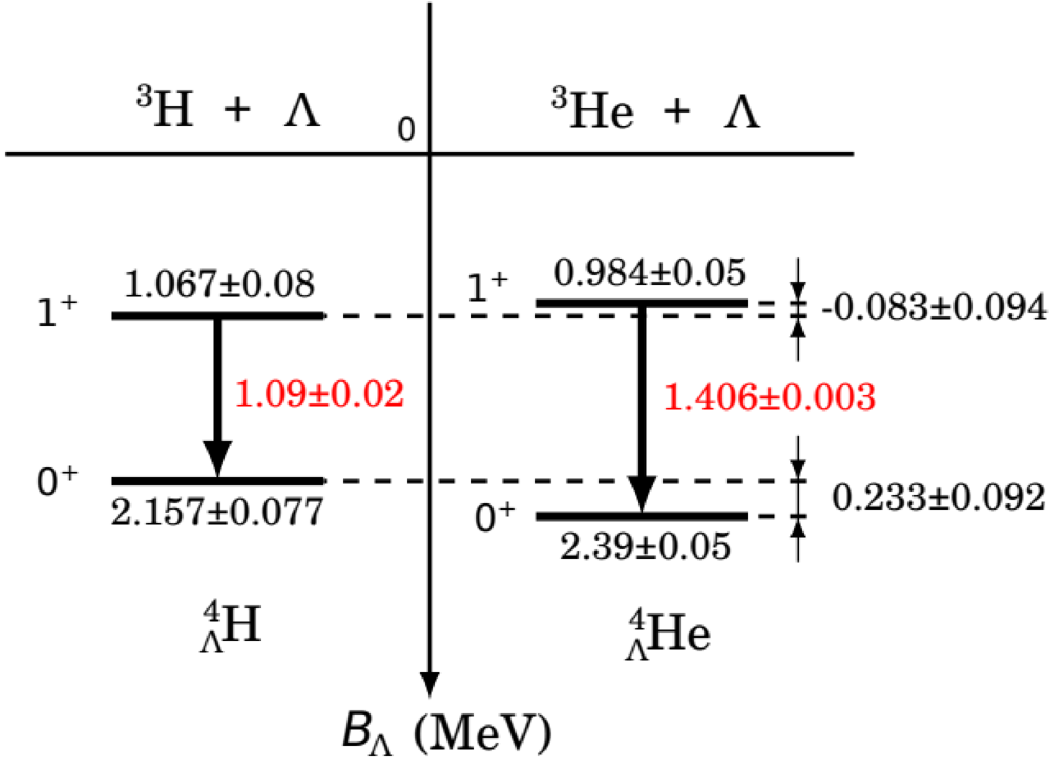
- Expectations for hypernuclei from the statistical hadronization model at T_{ch} = 156 MeV
- Penalty factor by adding one nucleon to a particle ≈ 300 in Pb-Pb collisions
- Further suppression due to strangeness content
- Comparing to only a few antialpha candidates in available Pb-Pb dataset → improbable to measure A = 4 hypernuclei



A. Andronic, private communication
model from A. Andronic et al., Phys. Lett. B 697, 203 (2011)

A = 4 hypernuclei in ALICE

- A = 4 hypernuclei are more bound and each has an excited state
  Phys. Rev. Lett. 115, 222501 (2015)
- The yields of these hypernuclei are enhanced with respect to the ground state due to the feed-down from higher mass states
- Also the yields of the SHM scale with the spin-degeneracy
- Resulting in a total enhancement of a factor 4 for both hypernuclei
  B. Dönigus, EPJ Web Conf. 276 (2023) 04002

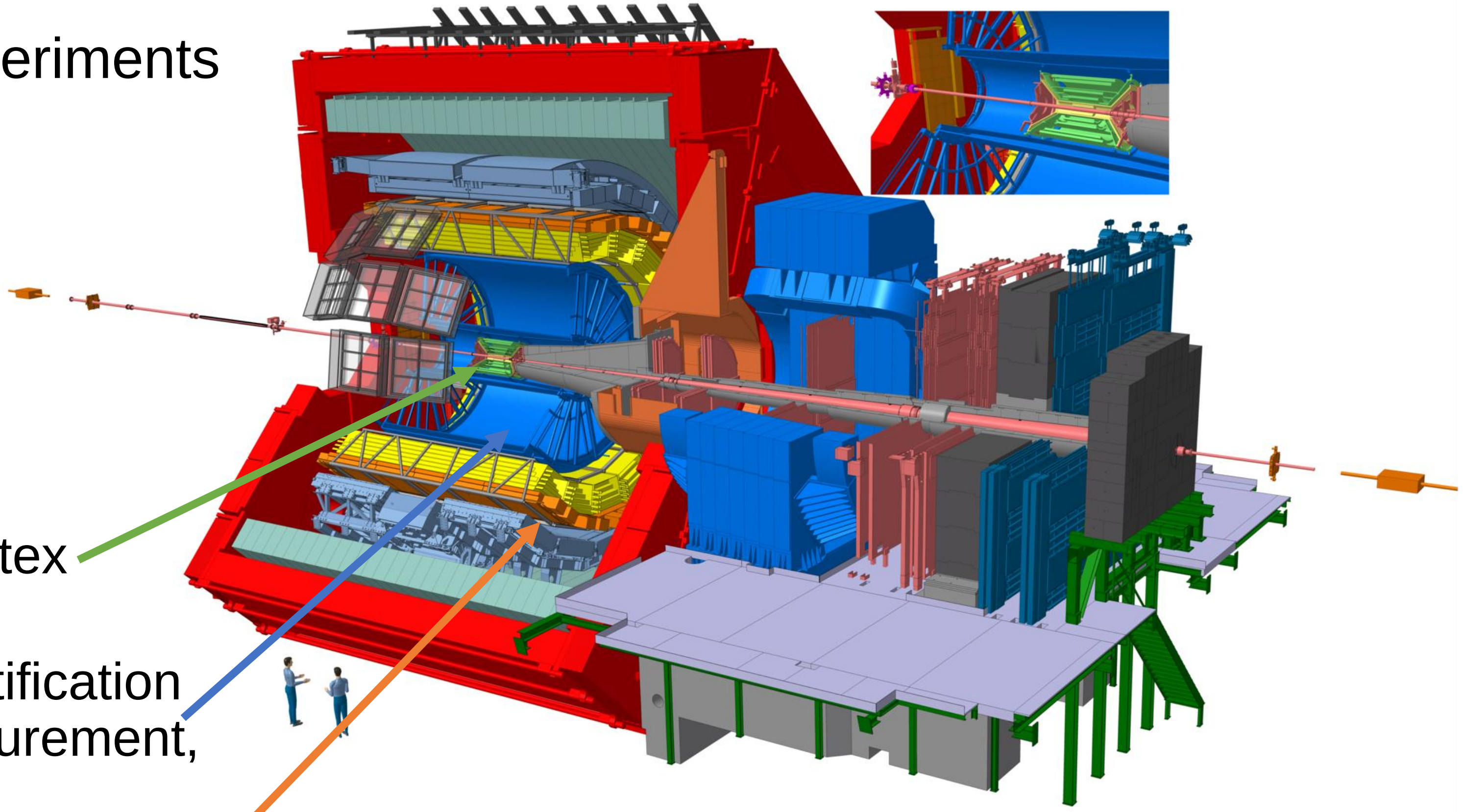


M. Schäfer, N. Barnea, A. Gal, Phys.Rev.C 106, L031001 (2022)

ALICE detector

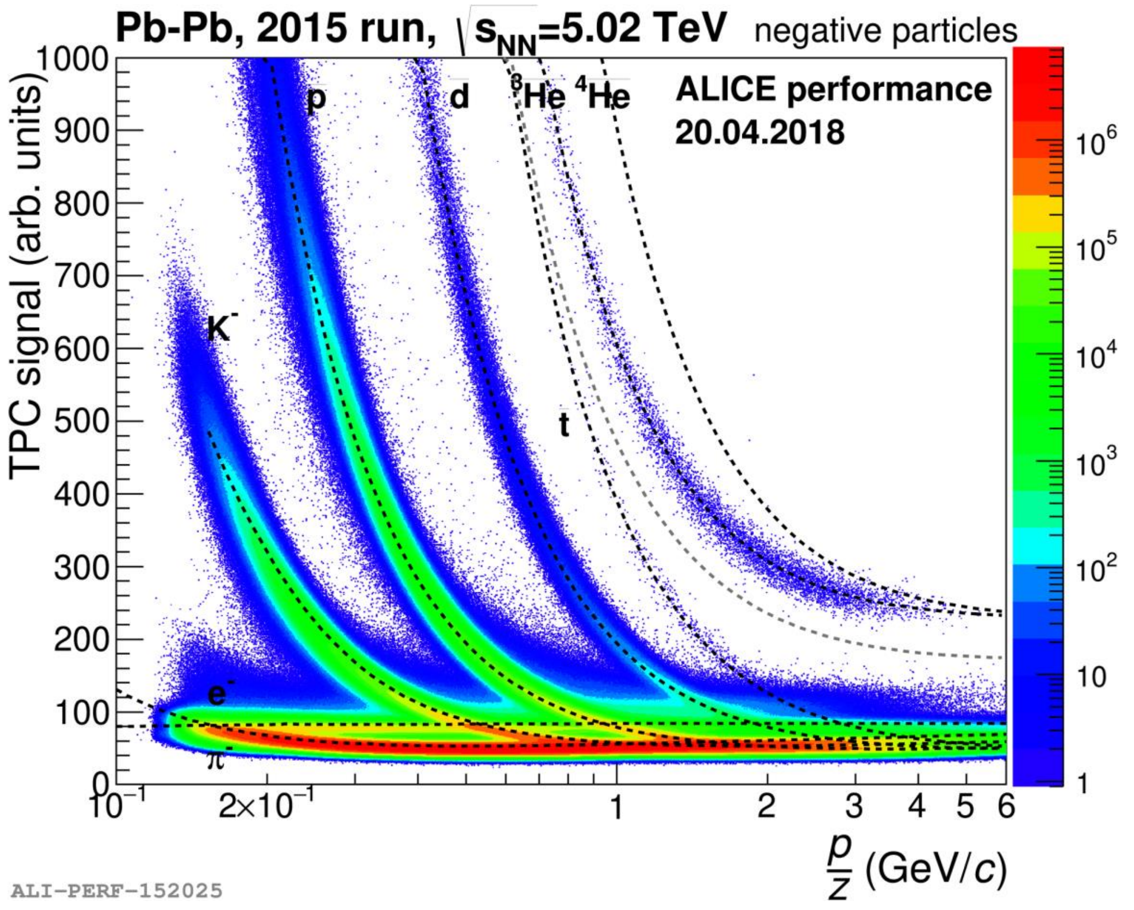
- One of the four major LHC experiments
- Specialized in tracking and particle identification from low to high momenta using different detector technologies

- Main features for this purpose:
  - ITS for primary and decay vertex reconstruction, tracking
  - TPC for charged particle identification via specific energy-loss measurement, tracking
  - TOF for time-of-flight measurement, tracking



Hypernuclei reconstruction

- **Step 1**: find and identify the daughter particle tracks
  - Using TPC PID via the specific energy loss
  - Excellent separation of different particle species

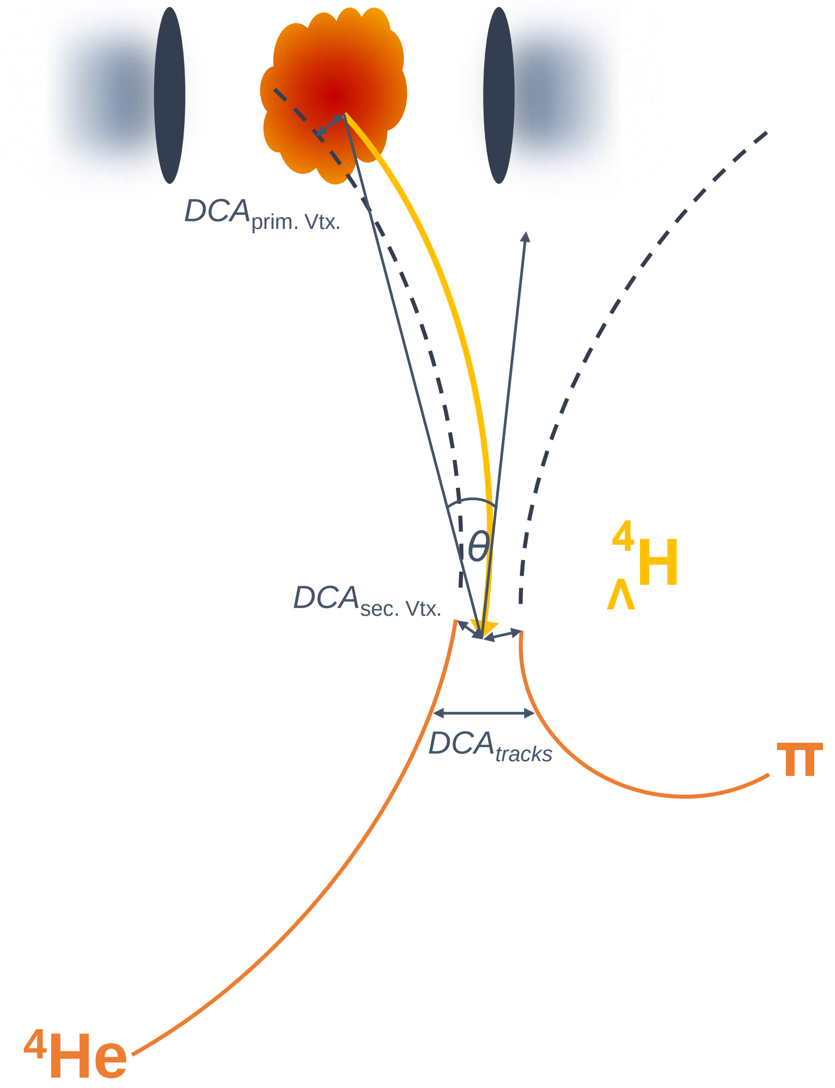


Hypernuclei reconstruction

- **Step 1**: find and identify the daughter particle tracks
- **Step 2**: reconstruct the decay vertex of the hypernucleus

  - The identified daughters are assumed to come from a common vertex
  - Their tracks are matched by algorithms to find the best possible decay vertex

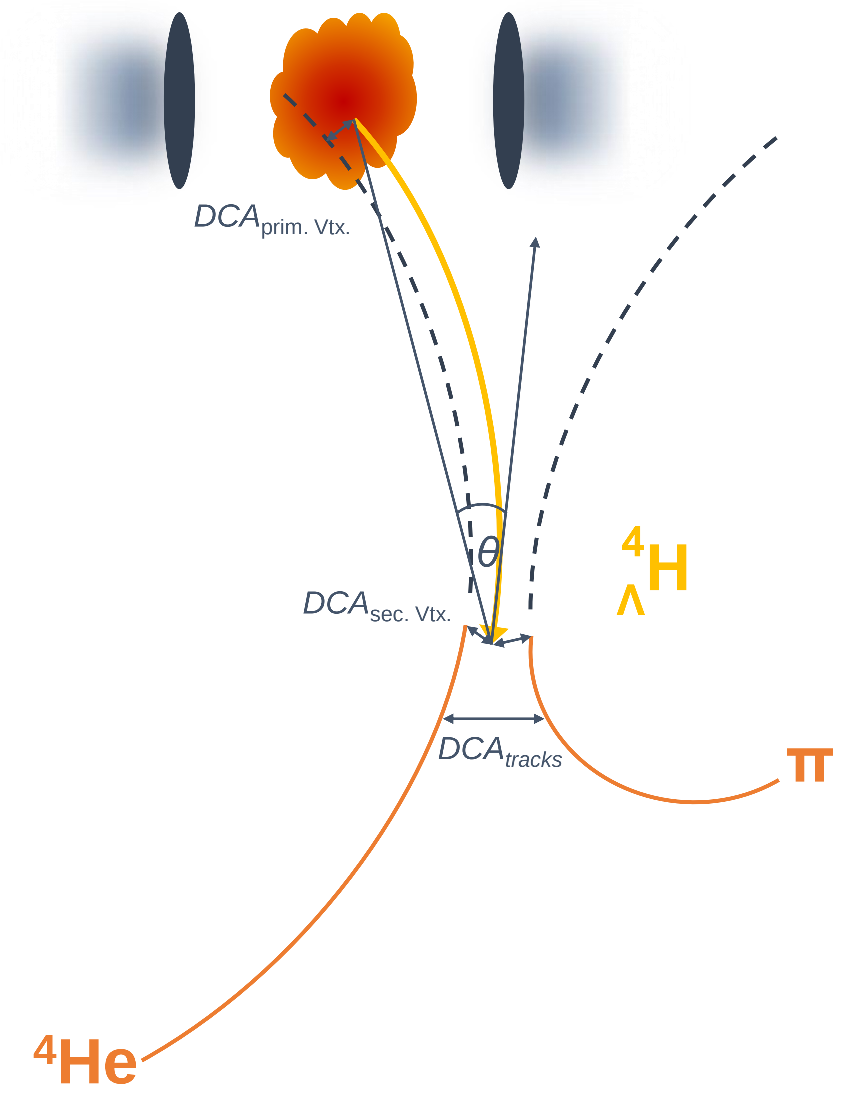
  - Problem: huge combinatorial background
  - Solution: topological and kinematical cuts



Hypernuclei reconstruction

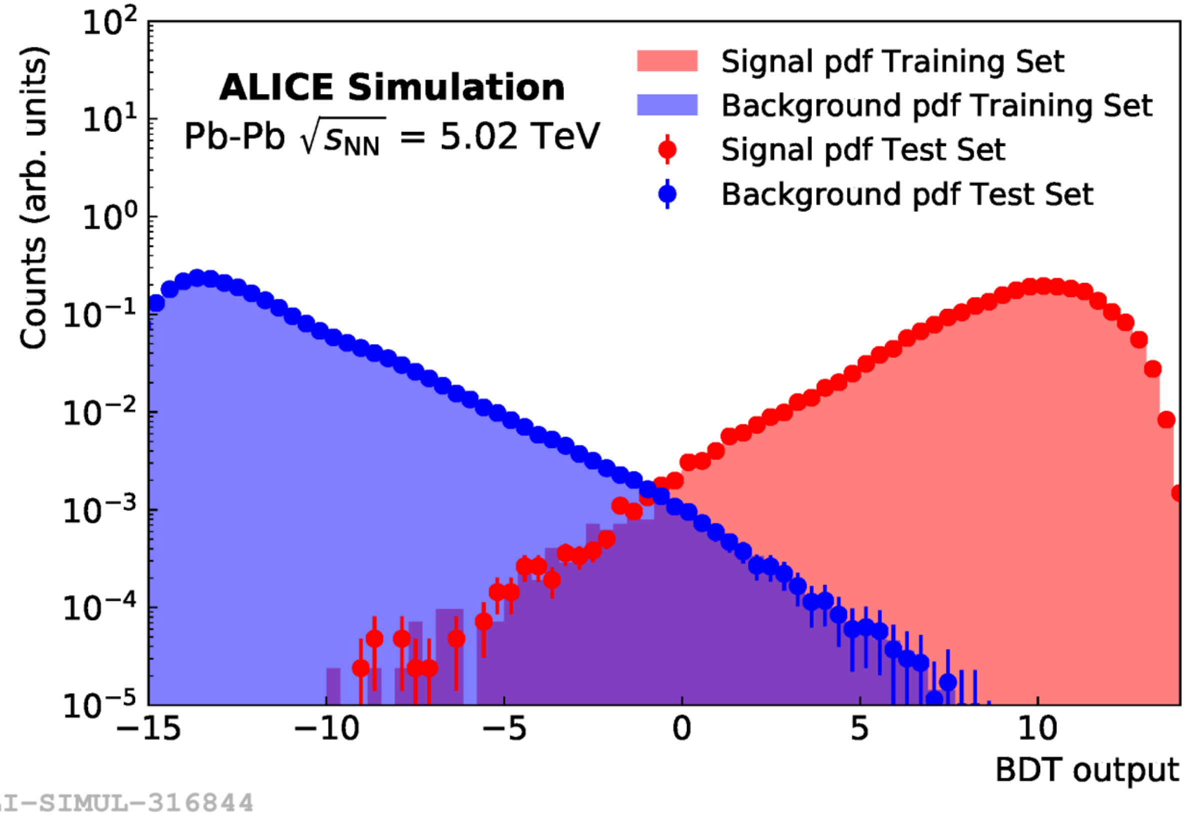
- **Step 1**: find and identify the daughter particle tracks
- **Step 2**: reconstruct the decay vertex of the hypernucleus
- **Step 3**: apply corrections

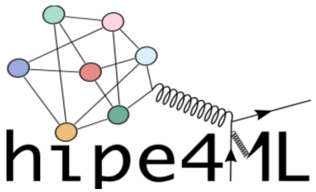
  - Tracking efficiency and detector acceptance
  - Branching ratio and absorption



Signal extraction

- Using a machine learning approach (Boosted Decision Tree) for the signal extraction
- A machine is trained and tested using a dedicated MC sample with injected hypernuclei and a background sample
- The result is a model that is applied on the data and allows a selection via the BDT output value





https://hipe4ml.github.io/

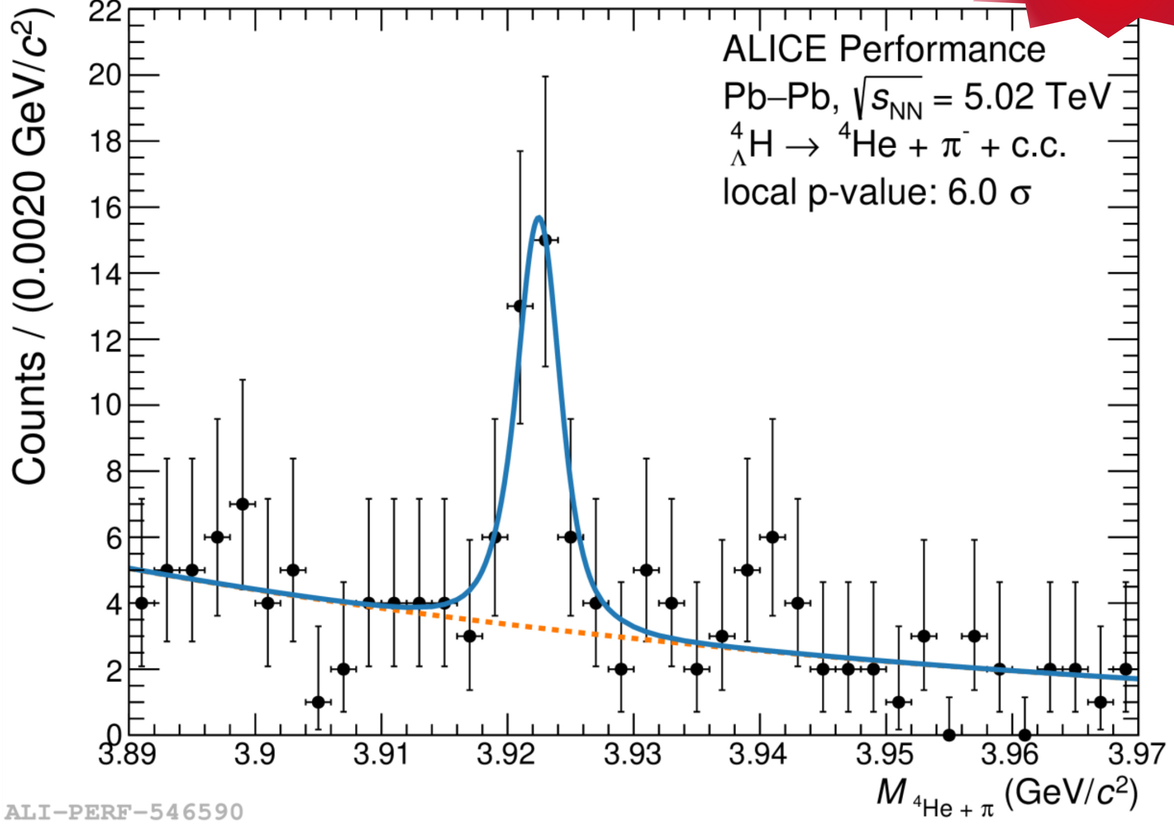
A = 4 hypernuclei in ALICE

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield
- **(Anti)hyperhydrogen-4** invariant-mass spectrum in Run 2 Pb-Pb collisions at 5.02 TeV
- Examined in the two-body decay:

$$^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-} + c.c.$$

- Reaching a local p-value of **6σ**

NEW



ALI-PERF-546590

A = 4 hypernuclei in ALICE

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield

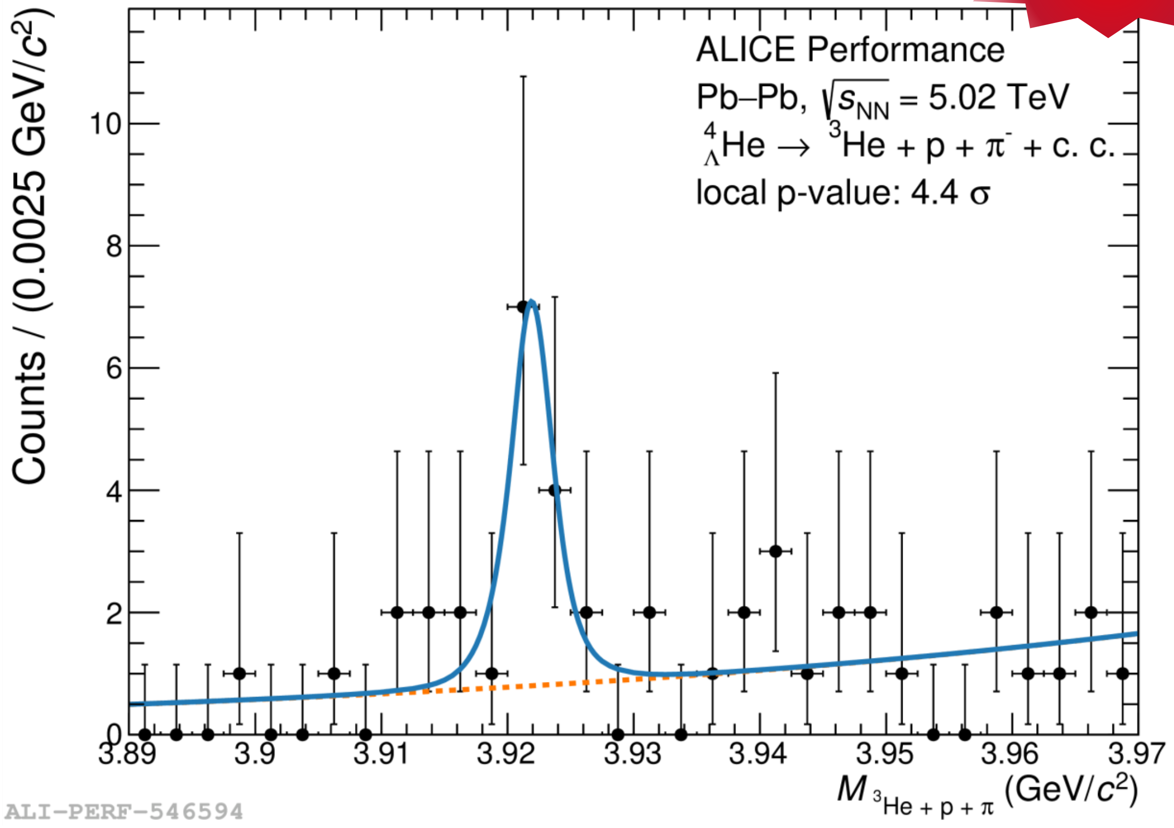
- **(Anti)hyperhelium-4** invariant-mass spectrum in Run 2 Pb-Pb collisions at 5.02 TeV

- Examined in the three-body decay:

$$^{4}_{\Lambda}\mathrm{He} \rightarrow \, ^{3}\mathrm{He} + p + \pi^{-} + \mathrm{c.c.}$$

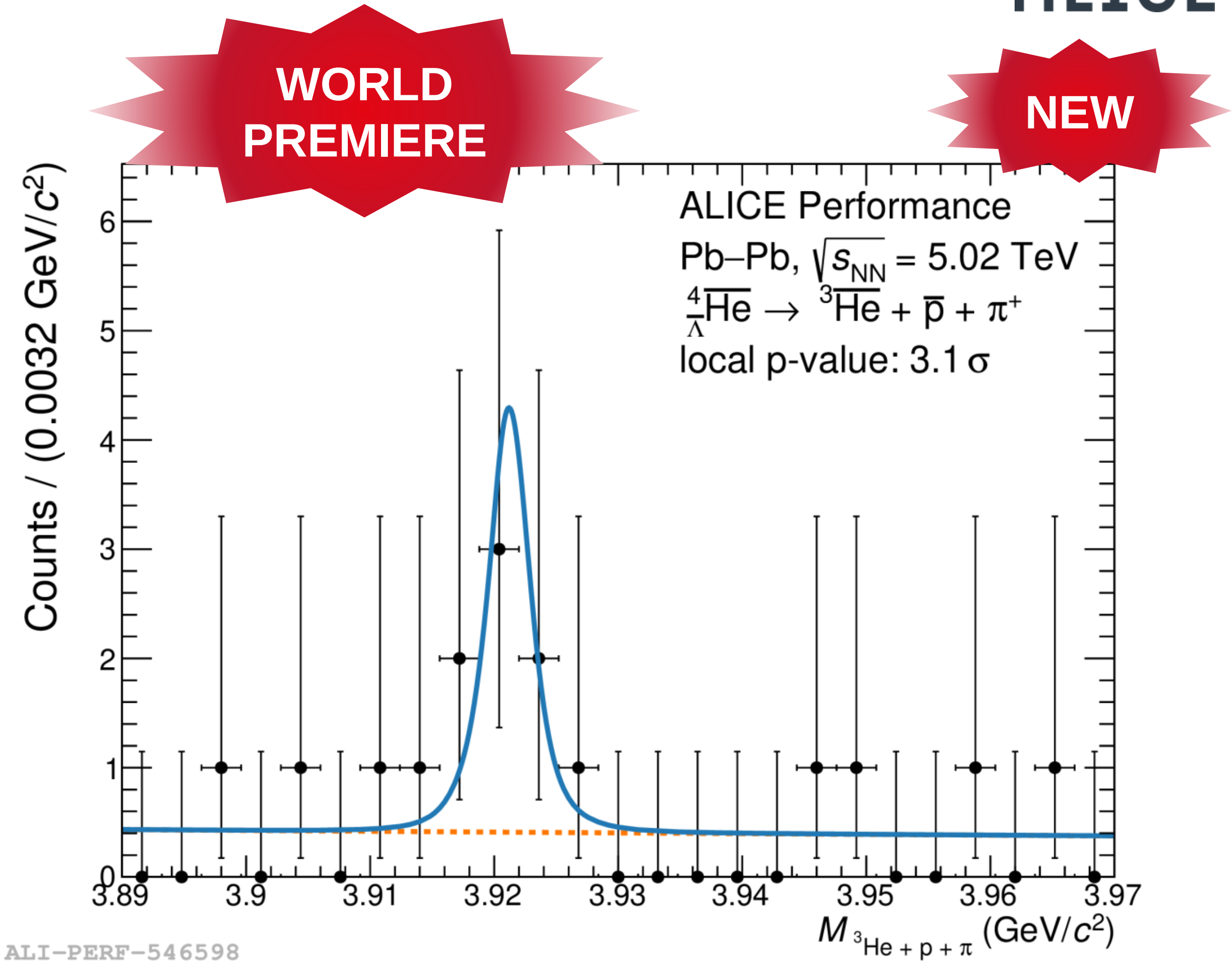
- Reaching a local p-value of **4.4σ**

NEW



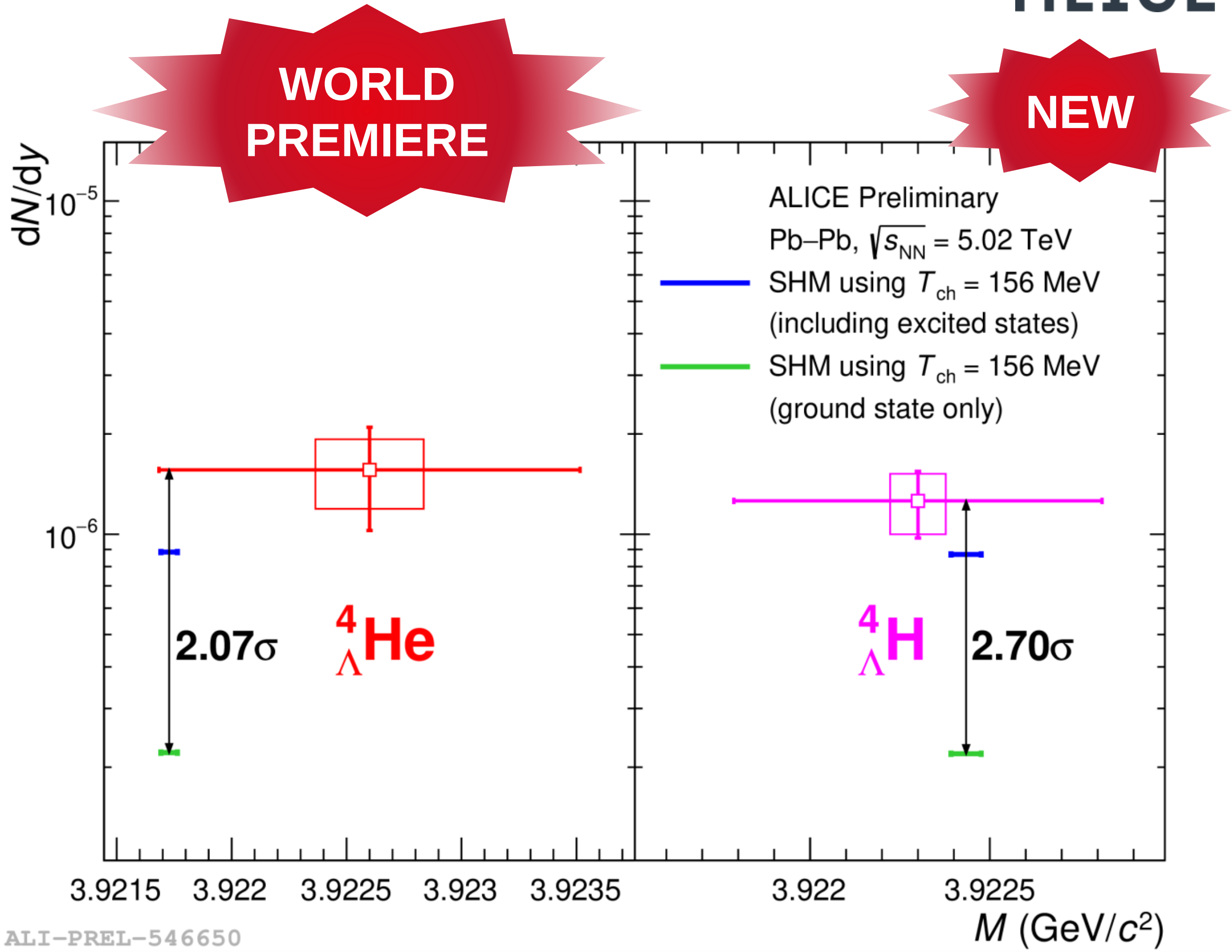
A = 4 hypernuclei in ALICE

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield
- **First observation of the antihyperhelium-4** in Run 2 Pb-Pb collisions at 5.02 TeV
- Reaching a local p-value of **3.1σ**



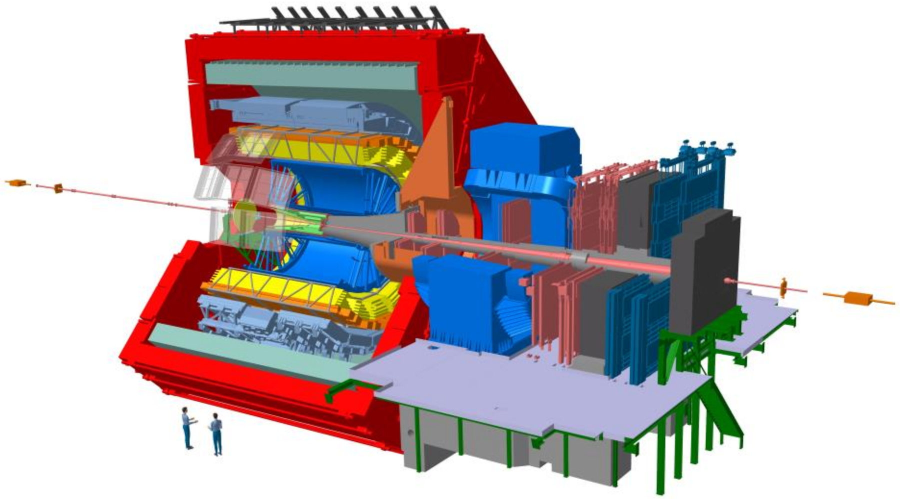
A = 4 hypernuclei in ALICE

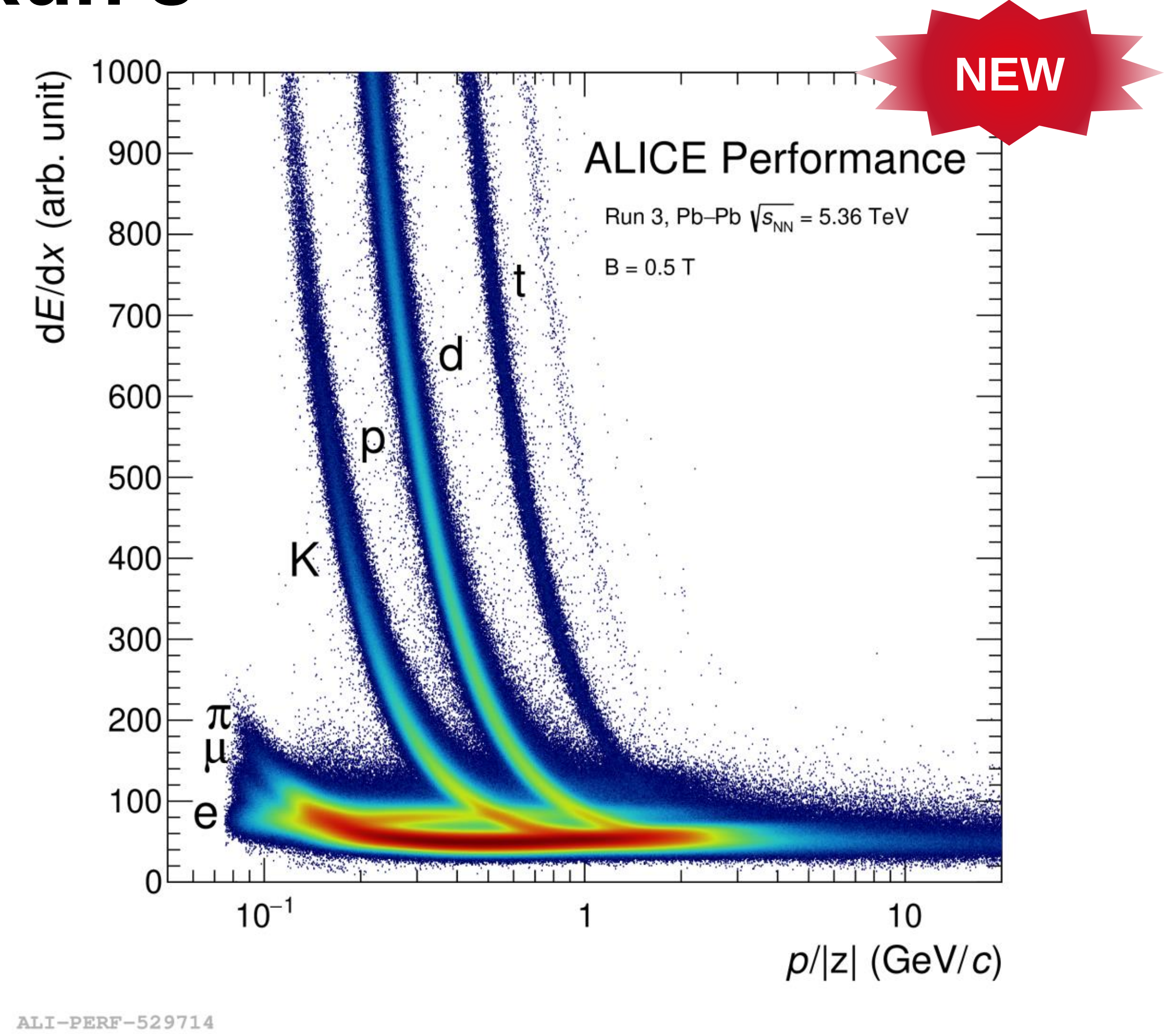
- First measurement of the (anti)hyperhelium-4 production yield
- Testing the dependence of the yields of the SHM with the spin-degeneracy
- Our yields confirm the hypothesis of excited states for both (anti)hypernuclei within 2σ
- Shedding light on the Charge-Symmetry-Breaking:
  → currently dominated by statistical uncertainties
  → with more data, a high precision measurement will be feasible (like for the Λ hyperon) Phys. Rev. D 108, 032009 (2023)



First results on the ongoing Run 3

- The ongoing Run 3 already provided ~ 540 billion events in pp at 13.6 TeV
- The performance of the upgraded detector parts allows for an excellent identification of the particle species

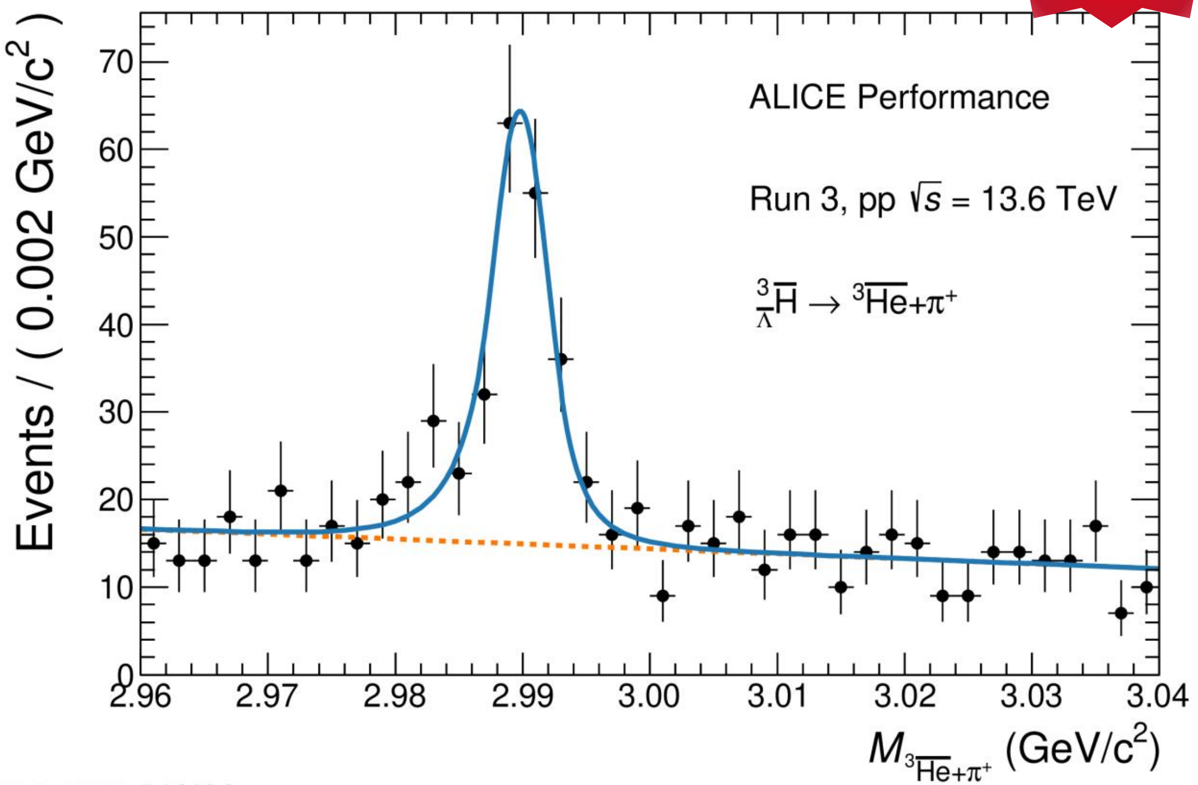




First results on the ongoing Run 3

NEW

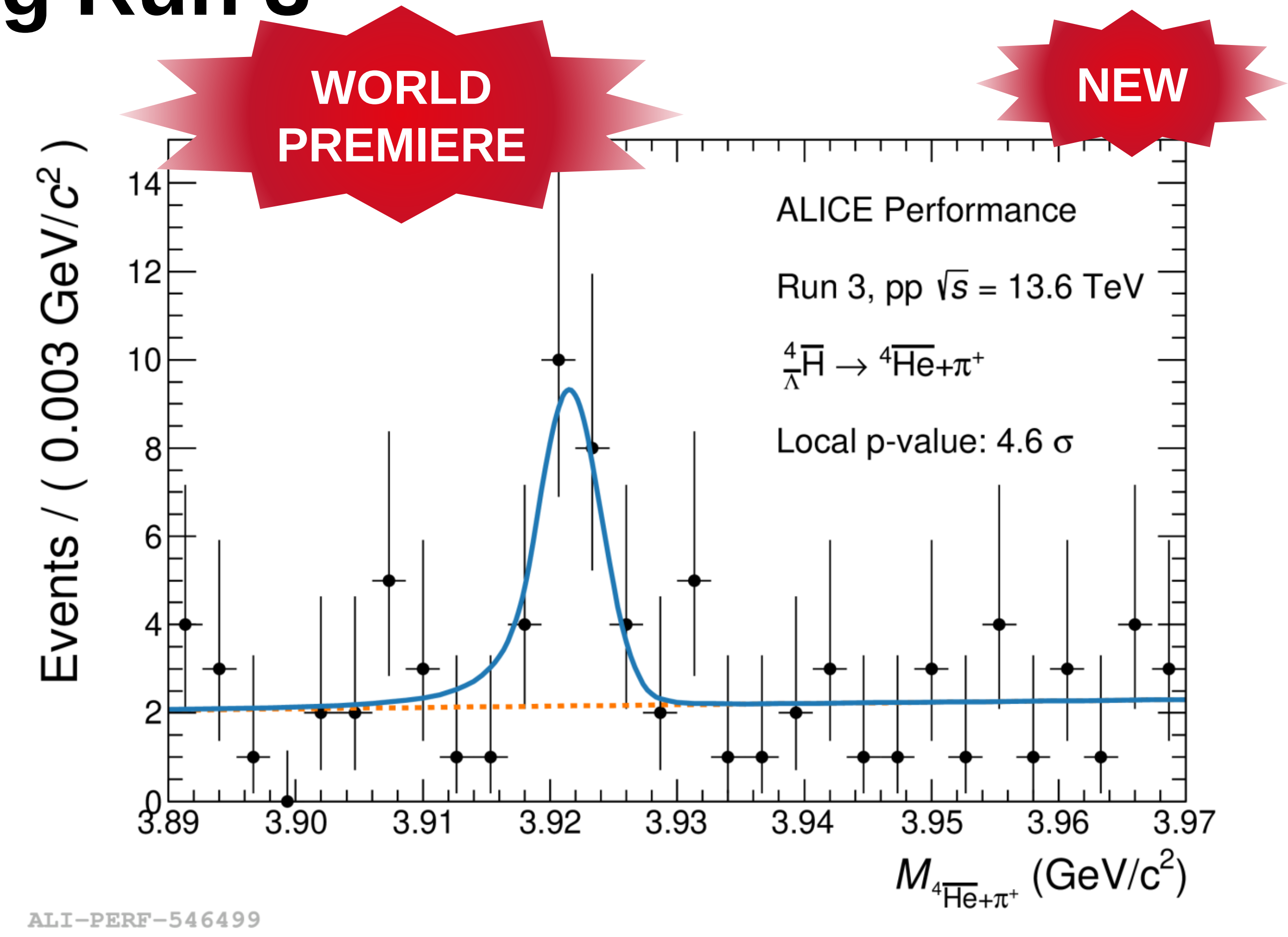
- First invariant-mass spectrum of the antihypertriton in pp collisions at 13.6 TeV
- This will allow precise studies on the lifetime and binding energy also in small systems
- Furthermore, we will be able to determine the production yield in several multiplicity classes
- This will let us come closer to an answer of the correct production model



ALI-PERF-546496

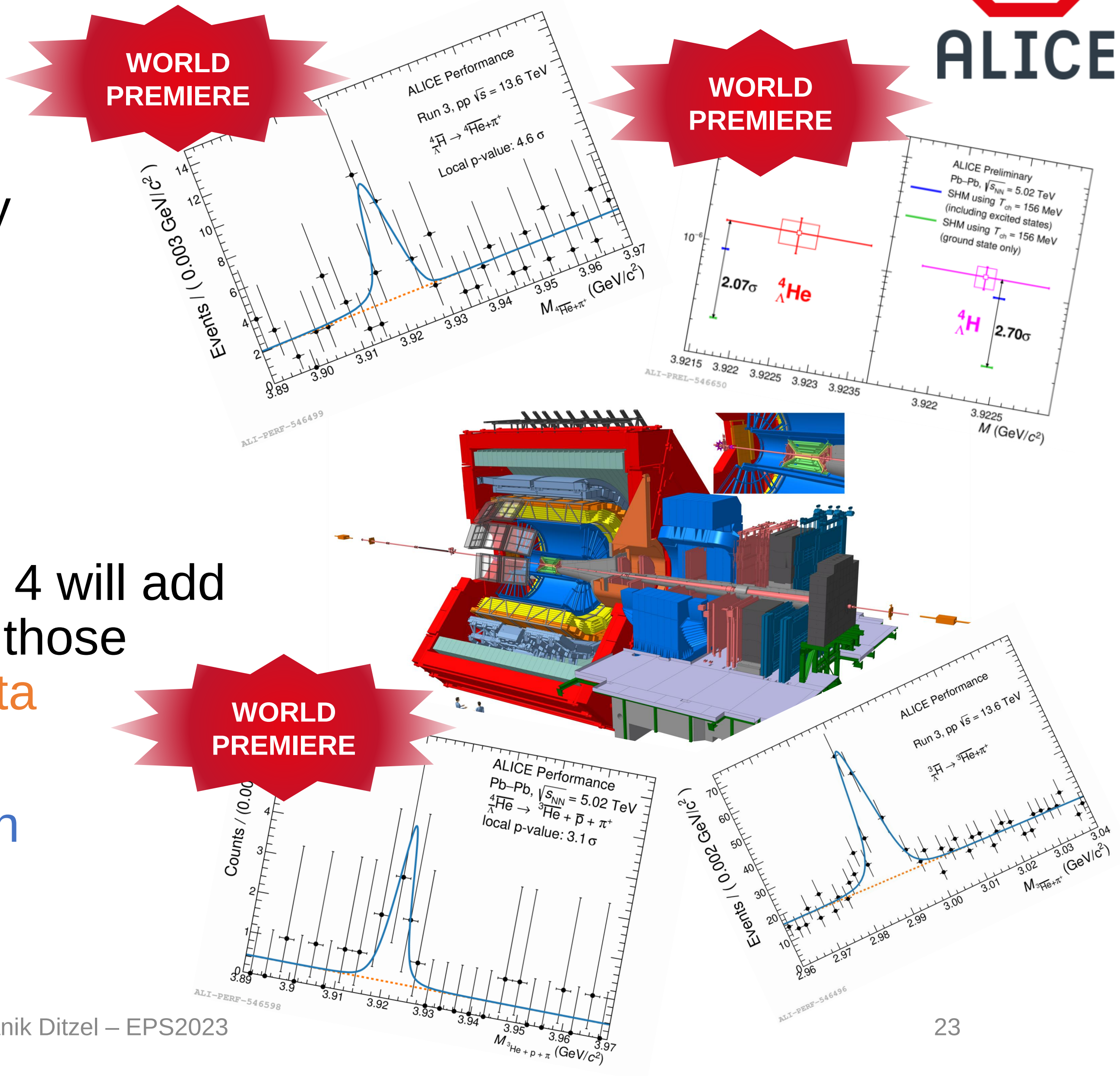
First results on the ongoing Run 3

- **First ever** invariant-mass spectrum of the **antihyperhydrogen-4 in pp collisions at 13.6 TeV**
- Reaching a local p-value of **4.6σ**
- We will be able to determine the production yield of the (anti)hyperhydrogen-4 at low multiplicities and compare to production models



Summary

- ALICE is the perfect apparatus to study the production and properties of light (anti)(hyper)nuclei
- The latest results show small uncertainties and a good agreement with the theoretical predictions
- The ongoing Run 3 and upcoming Run 4 will add large statistics for the measurement of those particles and provide high precision data
- This may also give the possibility of a more conclusive answer to the question of the correct production model

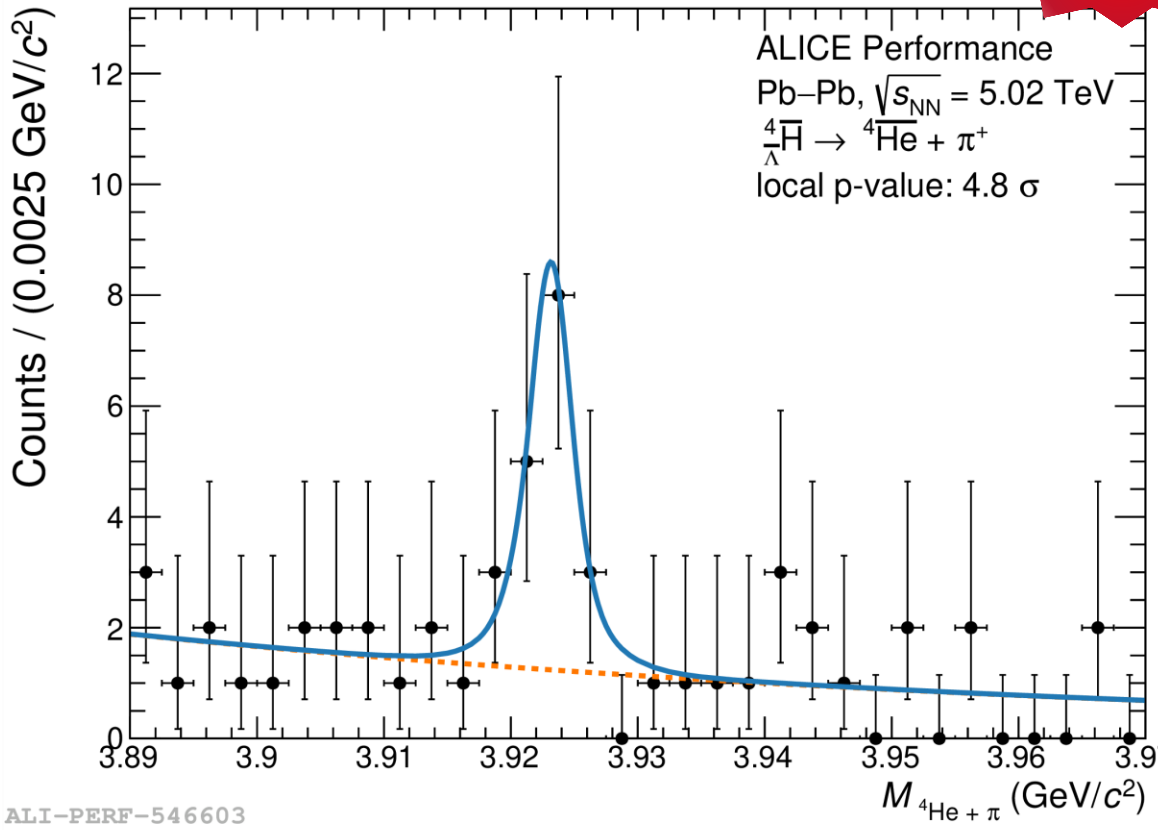


Backup

A = 4 hypernuclei in ALICE

- **For the first time**, we are able to reconstruct A = 4 hypernuclei at the LHC
- **Antihyperhydrogen-4** in Run 2 Pb-Pb collisions at 5.02 TeV
- Reaching a local p-value of **4.8σ**

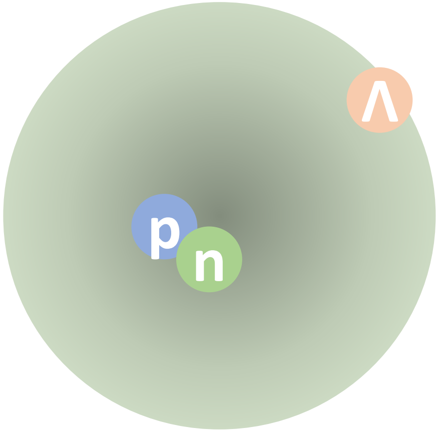
NEW



Hypertriton

- Λ, p, n bound state
- Lightest known hypernucleus and very loosely bound
- Mass ≈ 2.991 GeV/c^2
- Λ separation energy ≈ 130 keV
- Recent calculations predict a large radius for the hypertriton wave function $r_{\Lambda\text{-d}} = 10.79\,^{+3.04}_{-1.53}$ fm

F. Hildenbrand, H.-W. Hammer, Phys. Rev. C 100, 034002



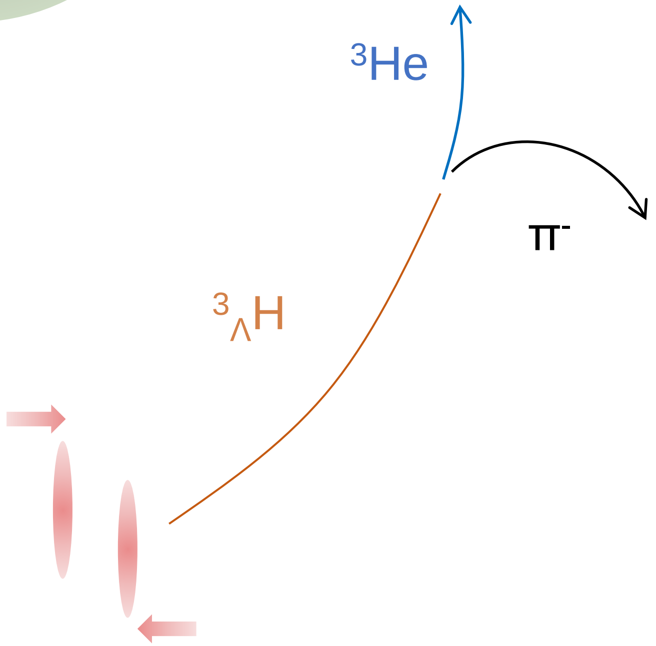
- Decay modes:

$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$

$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{0}$

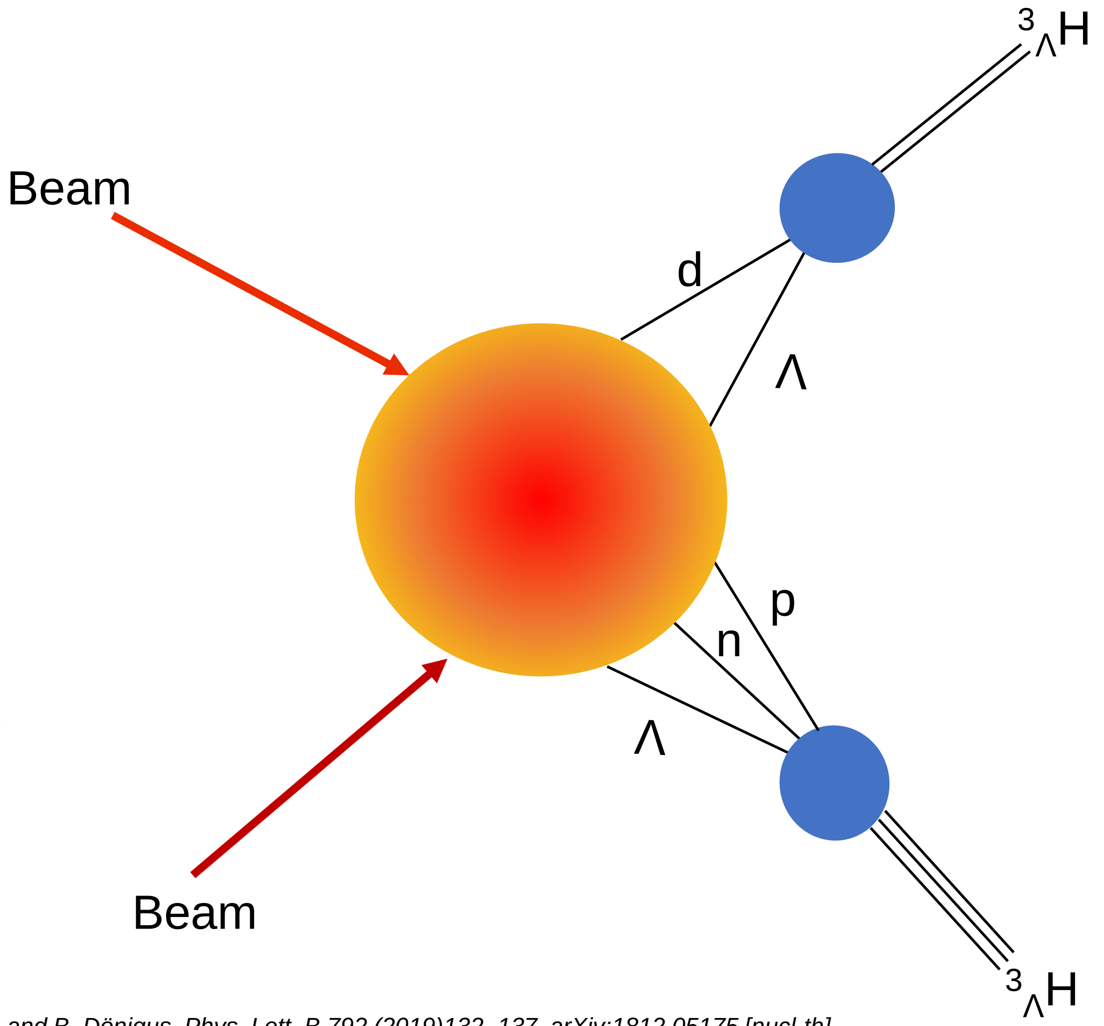
$^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$

$^{3}_{\Lambda}H \rightarrow d + p + \pi^{0}$



Hypertriton production

- Hypertriton production in heavy-ion collisions since LHC Run 1
- Coalescence Model:
  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

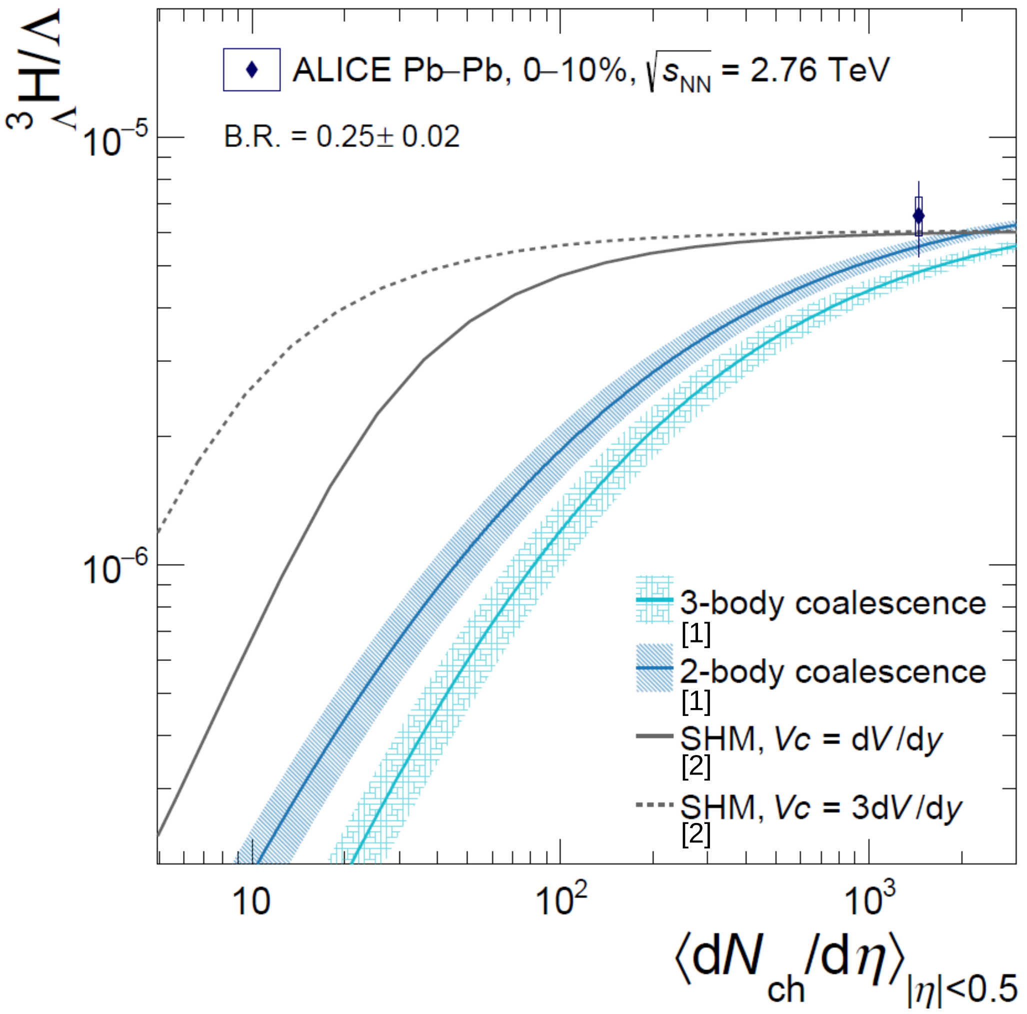


K.-J. Sun, C.-M. Ko and B. Dönigus, Phys. Lett. B 792 (2019)132–137, arXiv:1812.05175 [nucl-th]

Hypertriton in small systems

- $^{3}_{\Lambda}H$ / Λ ratio vs. multiplicity

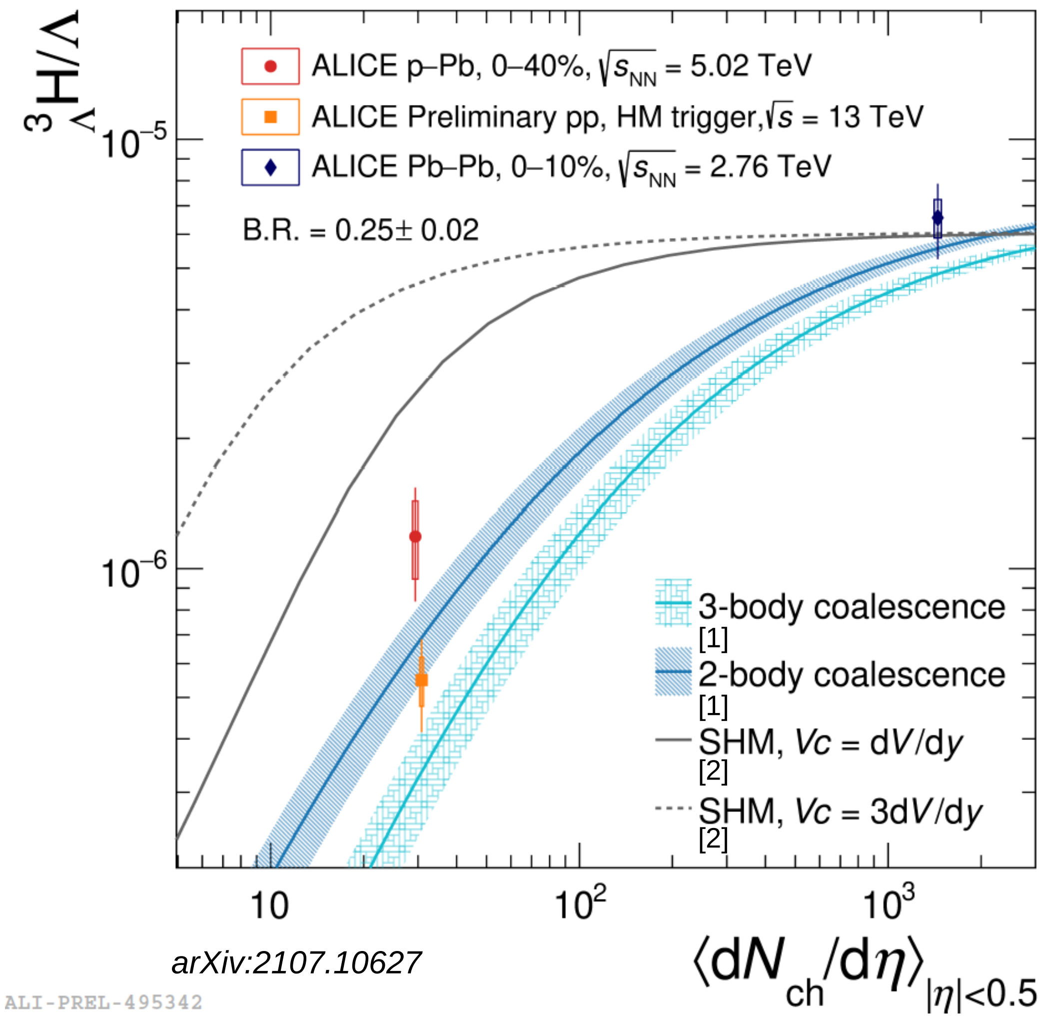
- Extremely sensitive to the nuclei production mechanism:
  - For statistical hadronization models (SHM) the object size is not relevant
  - In a coalescence picture large suppression of the production in small systems expected due to the object size



[1] K.-J. Sun, C.-M. Ko and B. Dönigus, Phys. Lett. B 792 (2019)132–137, arXiv:1812.05175 [nucl-th]
[2] V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B 785 (2018)171–174, arXiv:1808.05245 [hep-ph]

${}^{3}_{\Lambda}H$ / Λ ratio

- Measurements in pp and p-Pb:
  two new points at different multiplicities
- Points slightly favour the
  two-body coalescence
- But do not exclude
  three-body coalescence



arXiv:2107.10627

[1] K.-J. Sun, C.-M. Ko and B. Dönigus, Phys. Lett. B 792 (2019)132–137, arXiv:1812.05175 [nucl-th]
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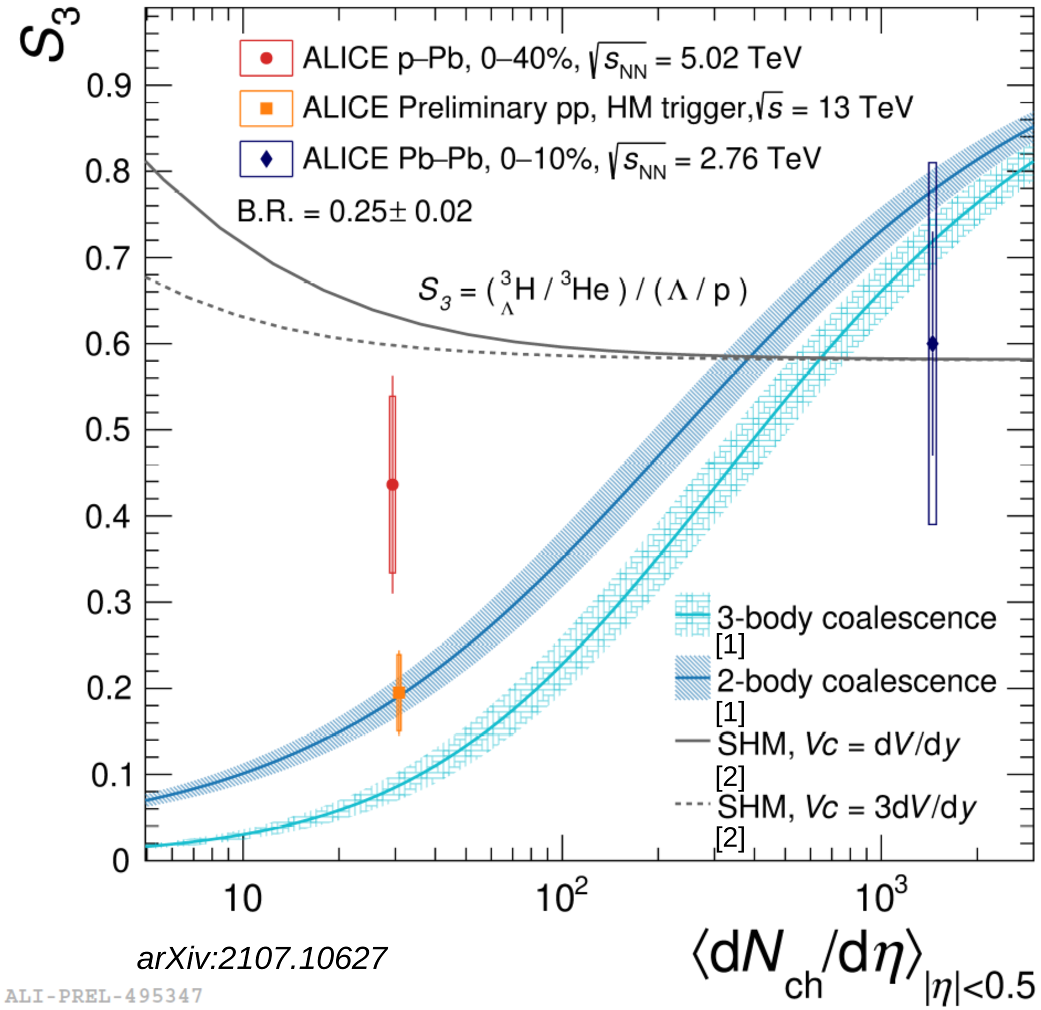
S_3

- $S_3 = ({}^3_\Lambda H\ /\ {}^3He)\ /\ (\Lambda\ /\ p)$ vs. multiplicity
- Strangeness population factor for the measurement of baryon-strangeness correlations
- Measurements in pp and p-Pb: two new points at different multiplicities
- Points slightly favour the two-body coalescence
- But do not exclude three-body coalescence



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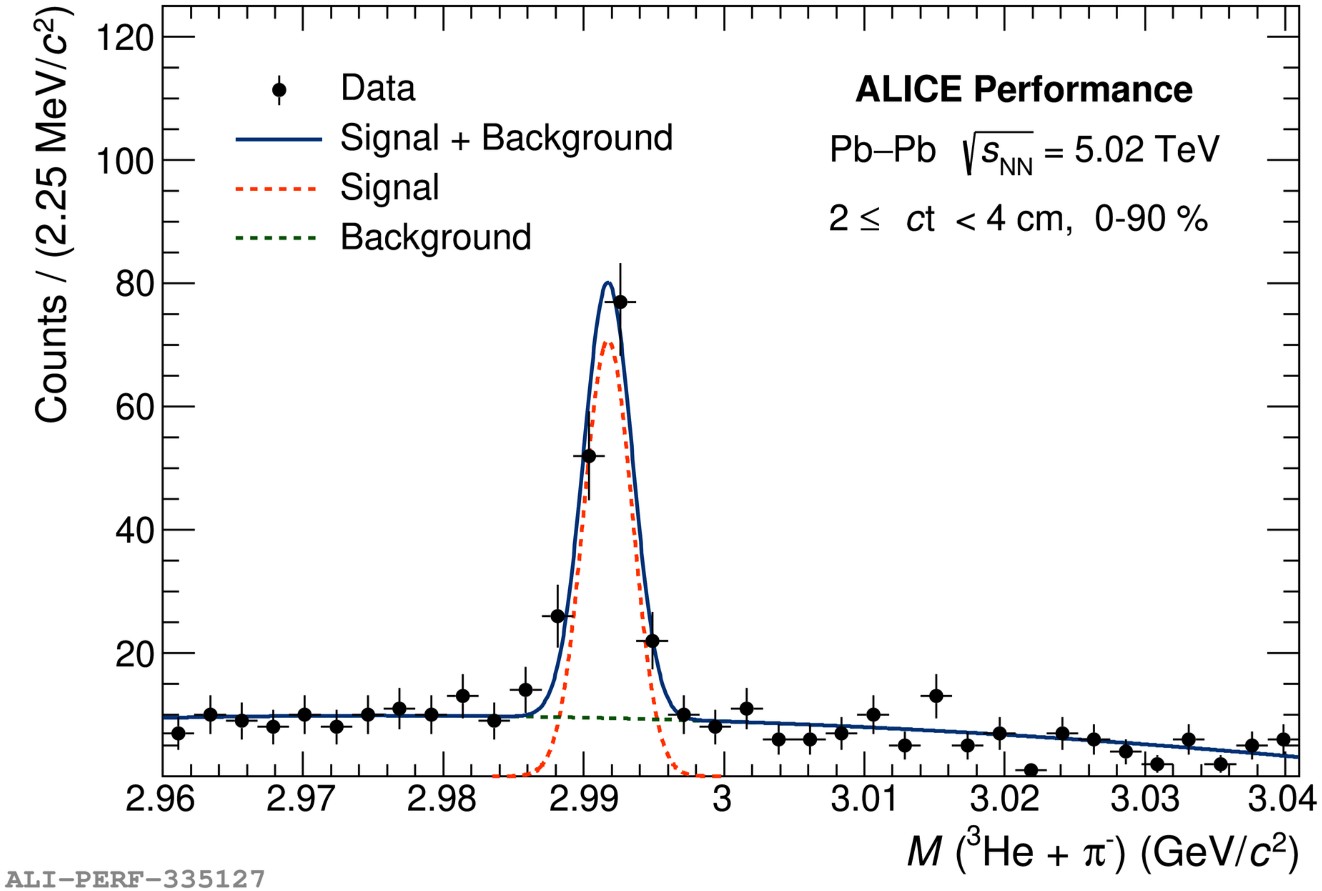
[2] V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B 785 (2018)171–174, arXiv:1808.05245 [hep-ph]

Hypertriton in Pb-Pb collisions

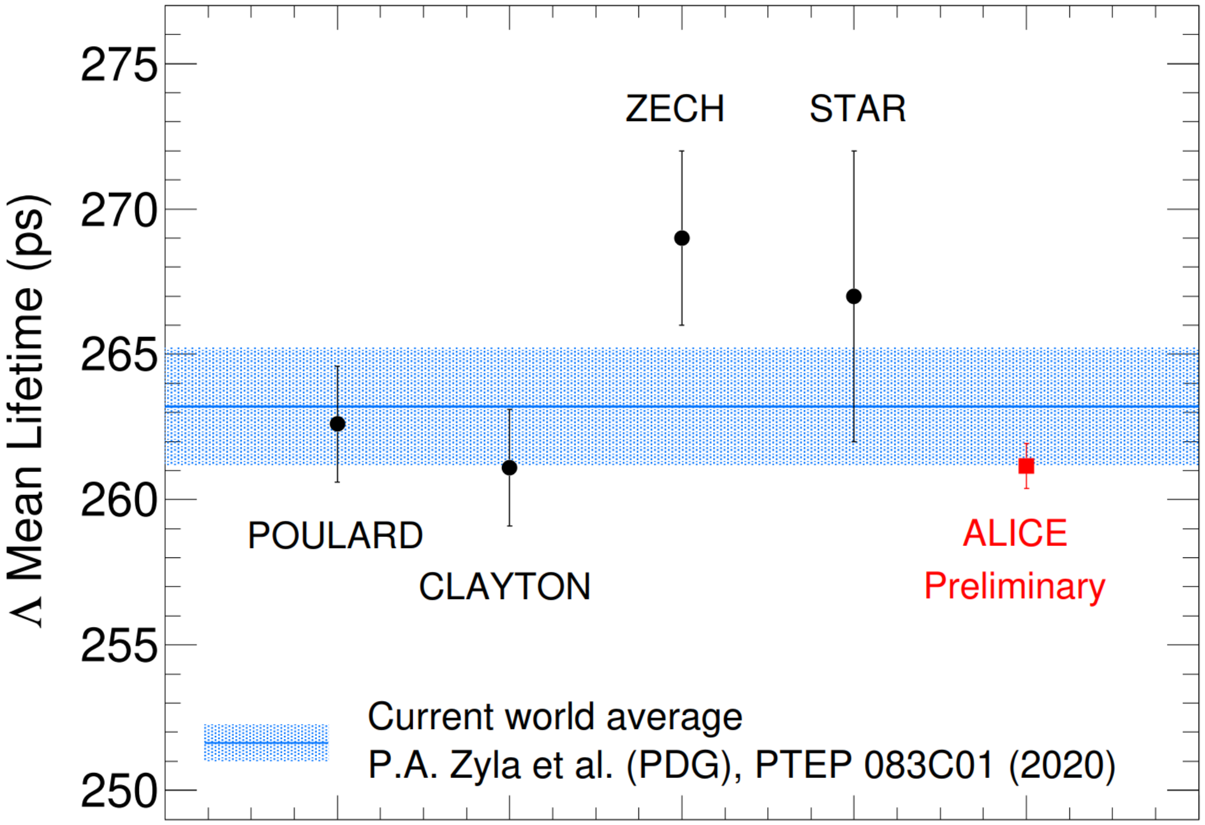
- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Signal extraction by using a machine learning approach
- Using a boosted decision tree (BDT) and hyper parameter optimisation



ALI-PERF-335127

Free Λ lifetime

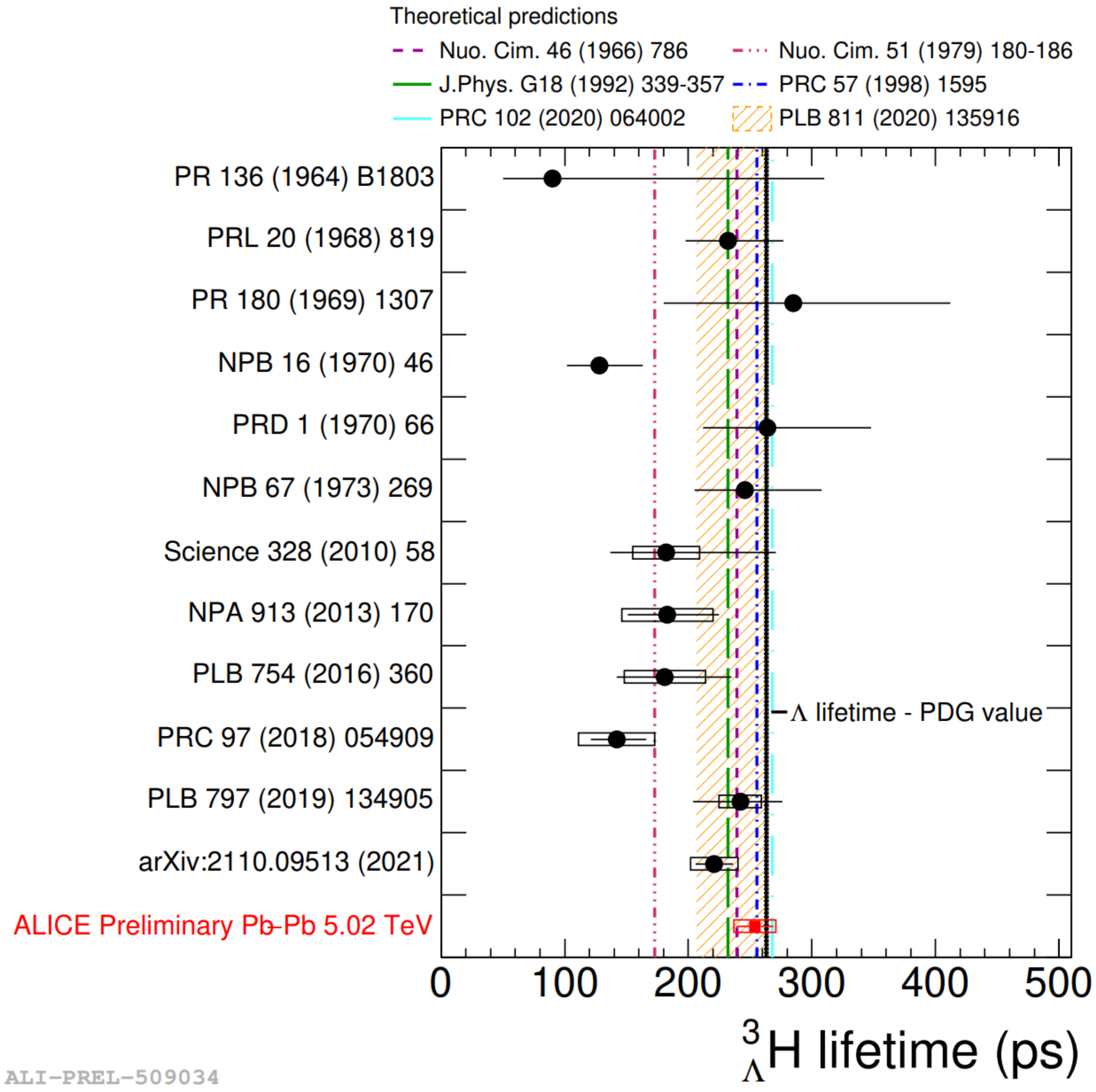
- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- New, extremely precise measurement of the free Λ lifetime as reference for the hypertriton lifetime
- This measurement is ~3 more precise than the PDG value



ALI-PREL-505548

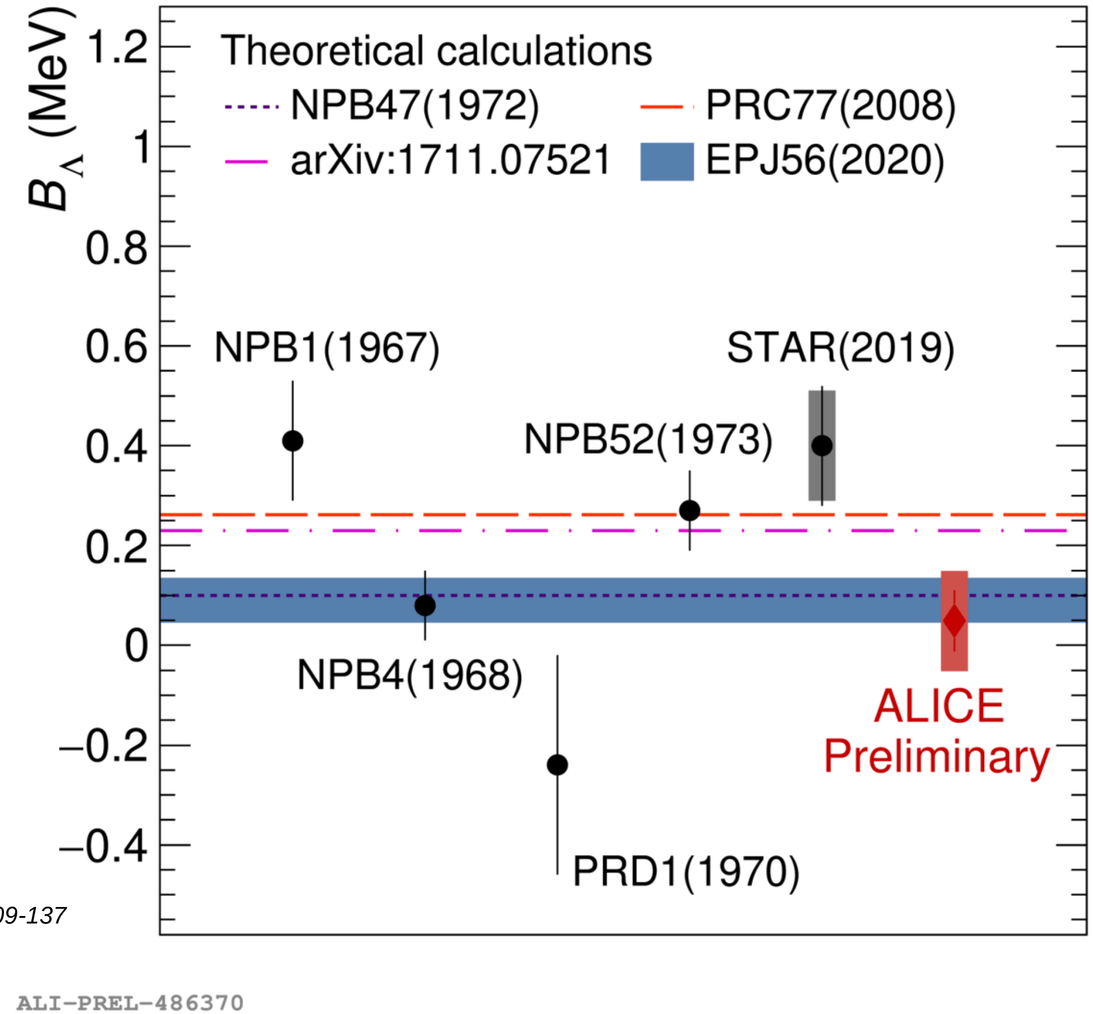
Hypertriton lifetime

- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Is compatible with the free Λ lifetime within its uncertainties
- New preliminary result will push the world average lifetime a little up



Hypertriton binding energy

- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Is compatible with the latest theoretical predictions

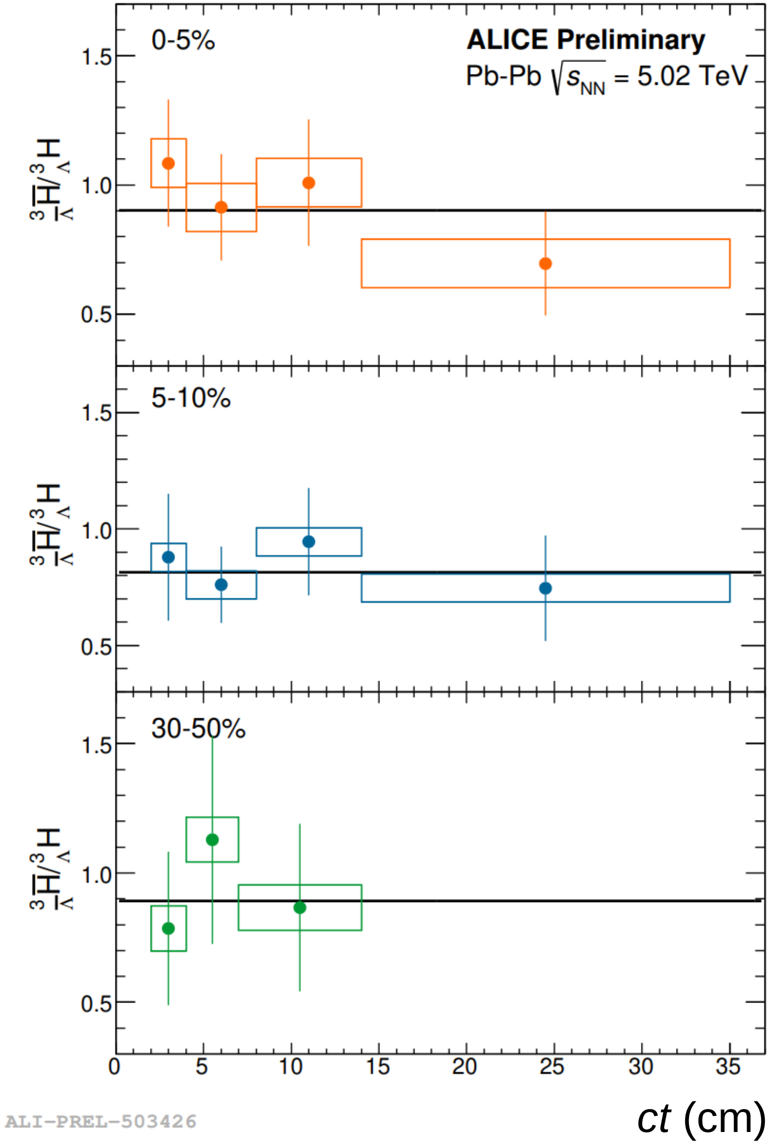


[NPB47(1972)] *R.H. Dalitz, R.C. Herndon, Y.C. Tang, Nuclear Physics B, Volume 47, Issue 1, 1972, Pages 109-137*
[arXiv:1711.07521] *Lonardoni, Diego and Pederiva, Francesco, arXiv:1711.07521 [nucl-th]*
[PRC77(2008)] *Fujiwara, Y. and Suzuki, Y. and Kohno, M. and Miyagawa, K., Phys. Rev. C 77, 027001*
[EPJ56(2020)] *F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 100, 034002*

Hypertriton production

- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Determination of the baryochemical potential including the hypertriton in different centrality bins
- Using antiparticle to particle ratios as input

$$\overline{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$



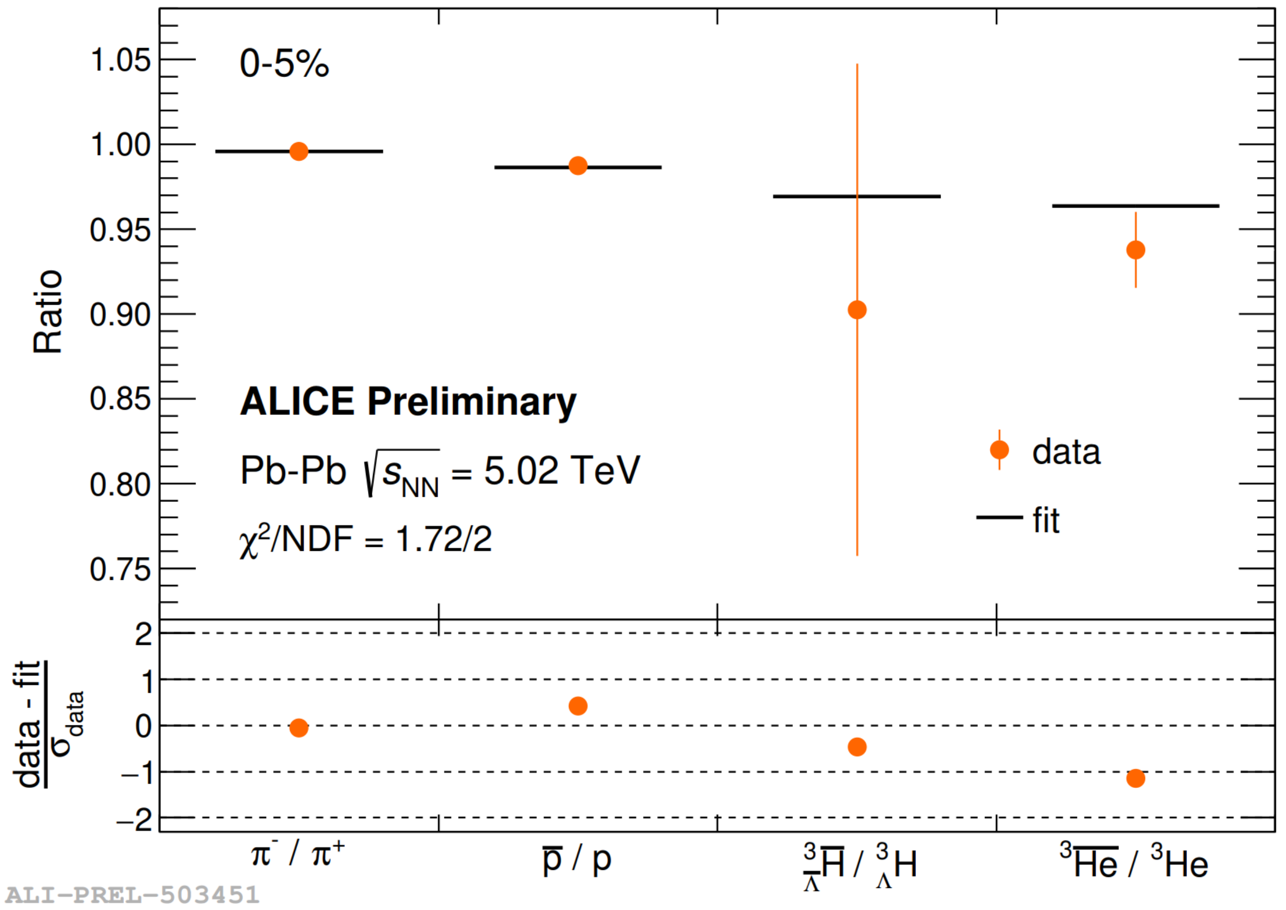
0-5%

5-10%

30-50%

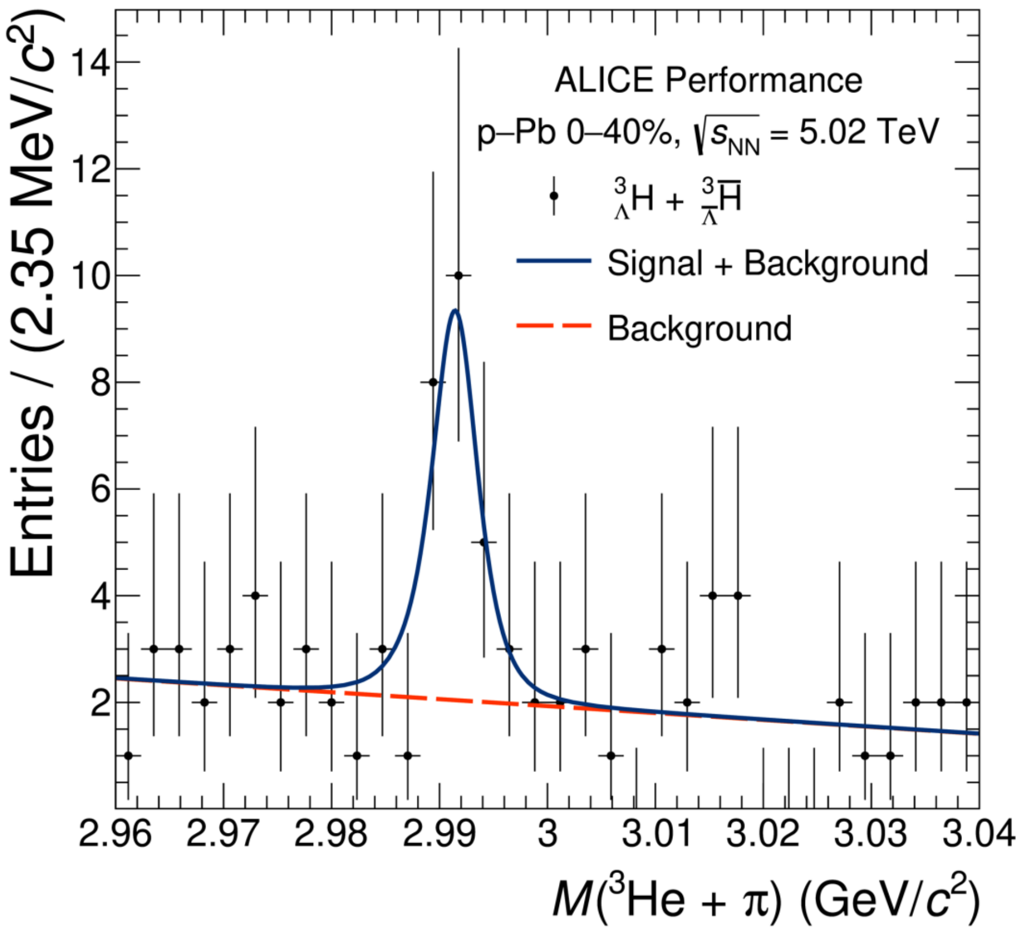
Hypertriton production

- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Fit to the data provides a value of μ_B close to zero in the most central collisions
- Antiparticle to particle ratio compared to SHM predictions at T_{ch} = 155 ± 2 MeV and using the obtained μ_B
- Very precise result even with large uncertainties for the hypertriton and a small overestimation for the ^{3}He



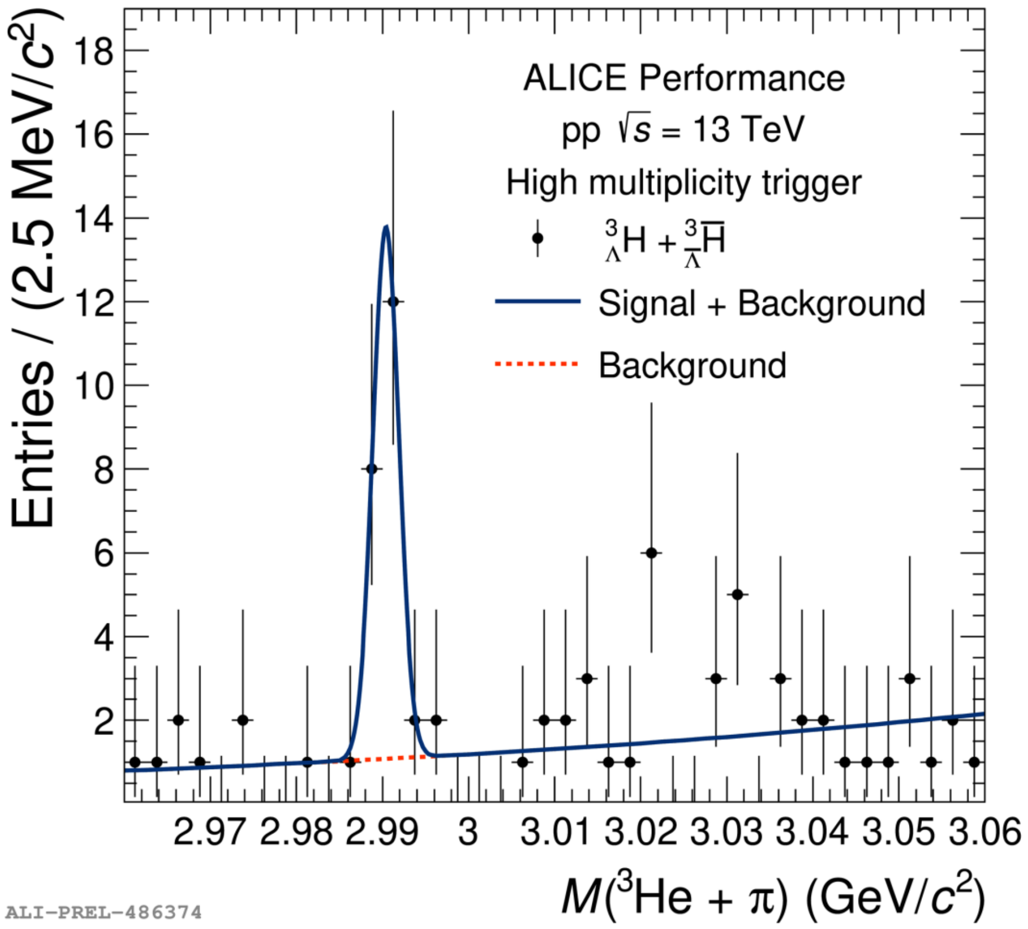
Hypertriton measurement in p-Pb

- First measurement of the hypertriton in Run 2 p-Pb collisions at 5.02 TeV
- Signal extraction by using a machine learning approach
- Using a boosted decision tree (BDT) and hyper parameter optimisation



Hypertriton measurement in pp

- First measurement of the hypertriton in Run 2 pp collisions at 13 TeV
- Topological and kinematical cuts applied to optimize the signal-to-background ratio and improve the significance in a traditional analysis



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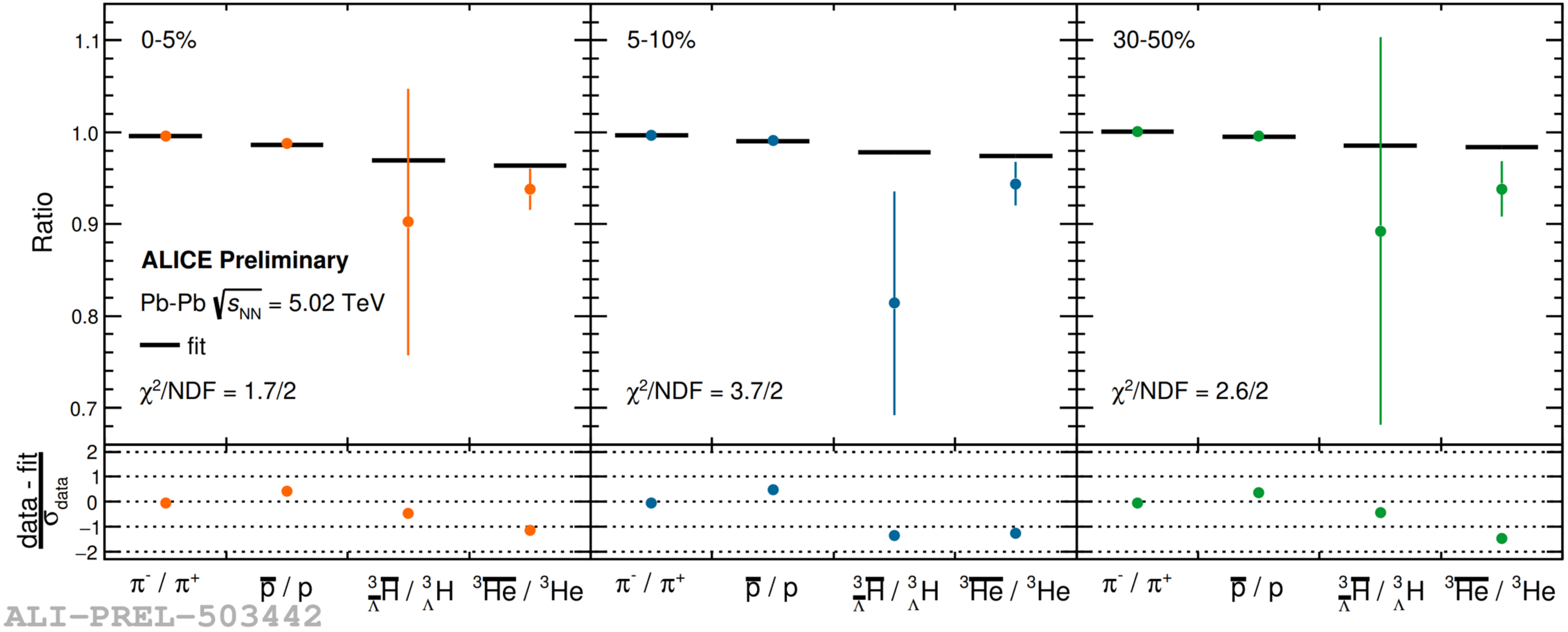
Hypertriton production

- Antiparticle to particle ratios compared to SHM predictions at T_{ch} = 155 ± 2 MeV and using the obtained μ_B for different centrality bins



Hypertriton production

- Baryochemical potential compared to SHM predictions at T_{ch} = 155 ± 2 MeV and using the obtained μ_B for different centrality bins, shown here as function of ‹N_{part}›