Investigating the system size dependence of hypernuclei production with A < 5 using the ALICE detector

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

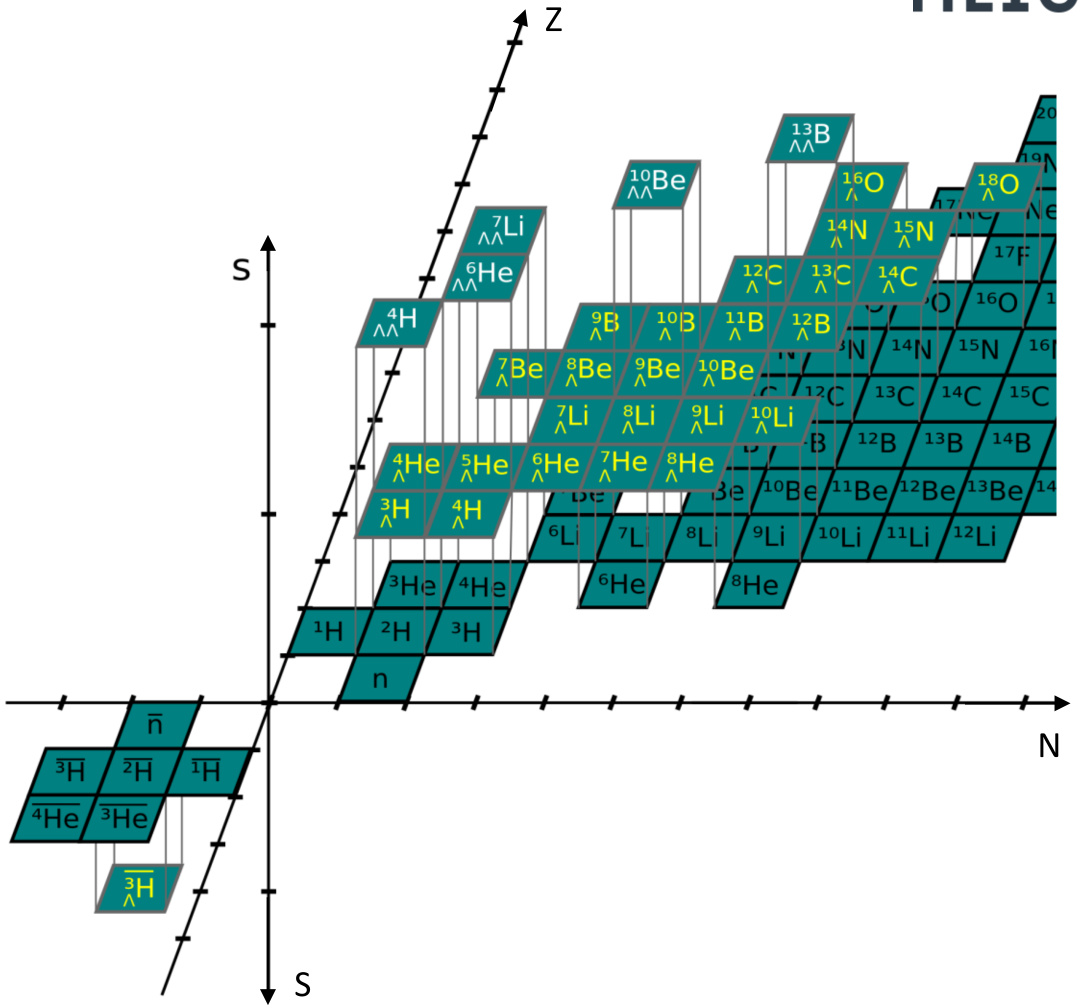
Recently measured precisely by ALICE!

Phys. Rev. D 108, 032009 (2023)

- Lightest known hypernucleus (anti)hypertriton
  - $B_\Lambda \approx 100$ keV → $r_{d\Lambda} \approx 10$ fm

Phys. Rev. Lett. 131 (2023) 102302

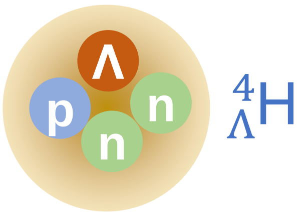
F. Hildenbrand, H.-W. Hammer, Phys. Rev. C 100, 034002

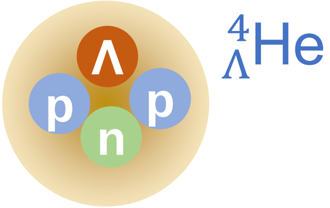


N. Löher, 2014

Hypernuclei: Introduction

- Heavier hypernuclei at the LHC

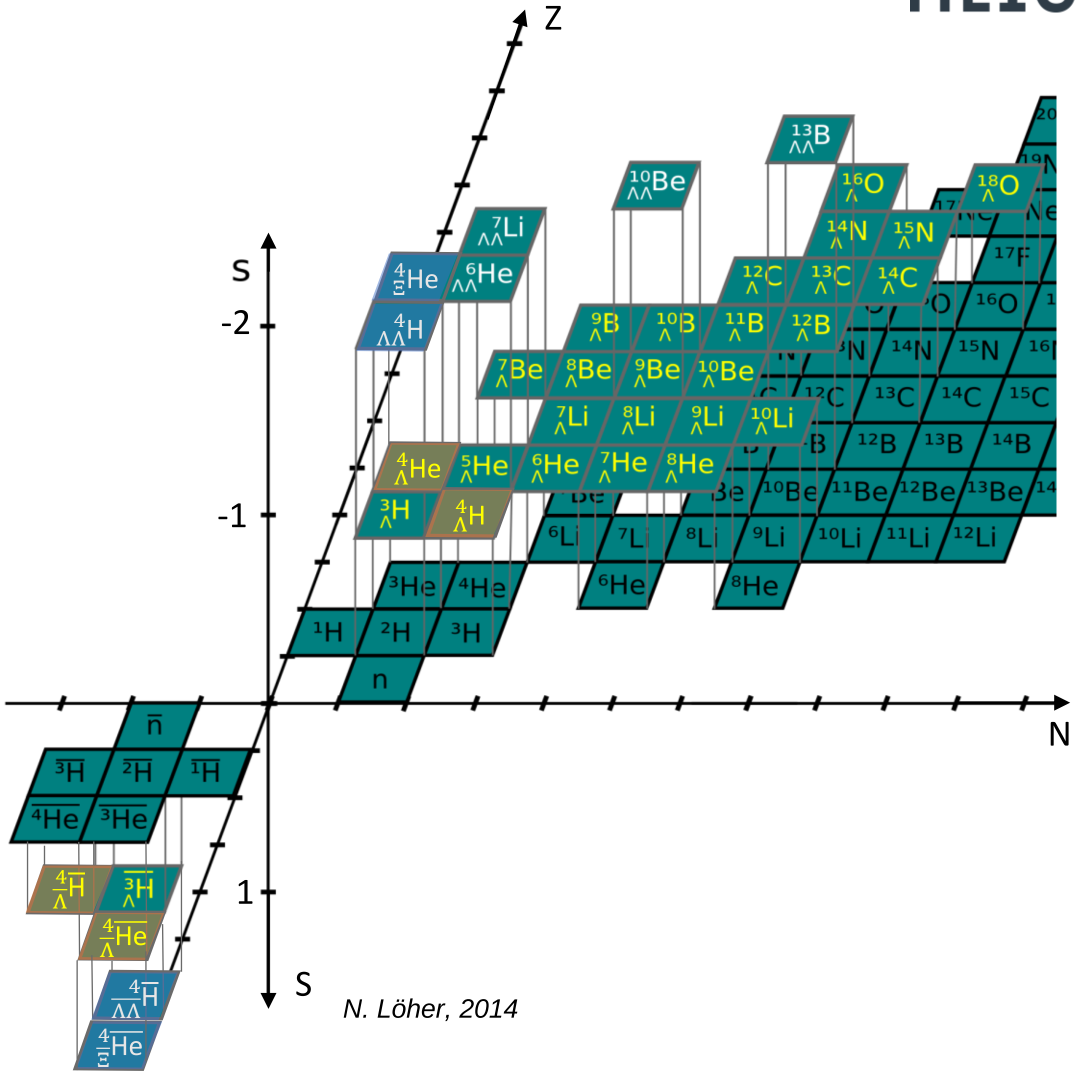




→ B_{Λ} ~ 2 MeV → $r \approx$ 2 fm
Phys. Rev. Lett. 115, 222501 (2015)

→ A = 4 hypernuclei are more bound and each has an excited state
M. Schäfer, N. Barnea, A. Gal, Phys.Rev.C 106, L031001 (2022)

→ Hypernuclei decay weakly after a few centimeters into two or more daughters



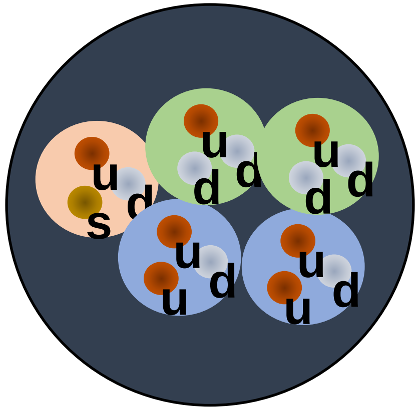
N. Löher, 2014

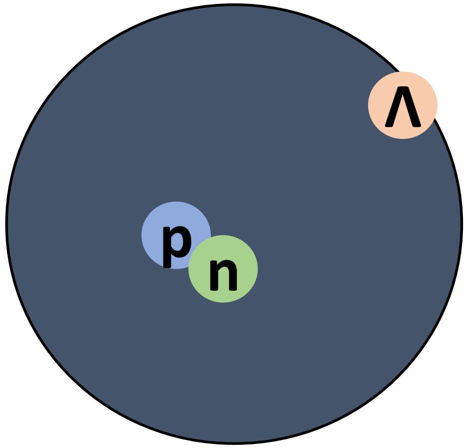
Hypernuclei: Motivation

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





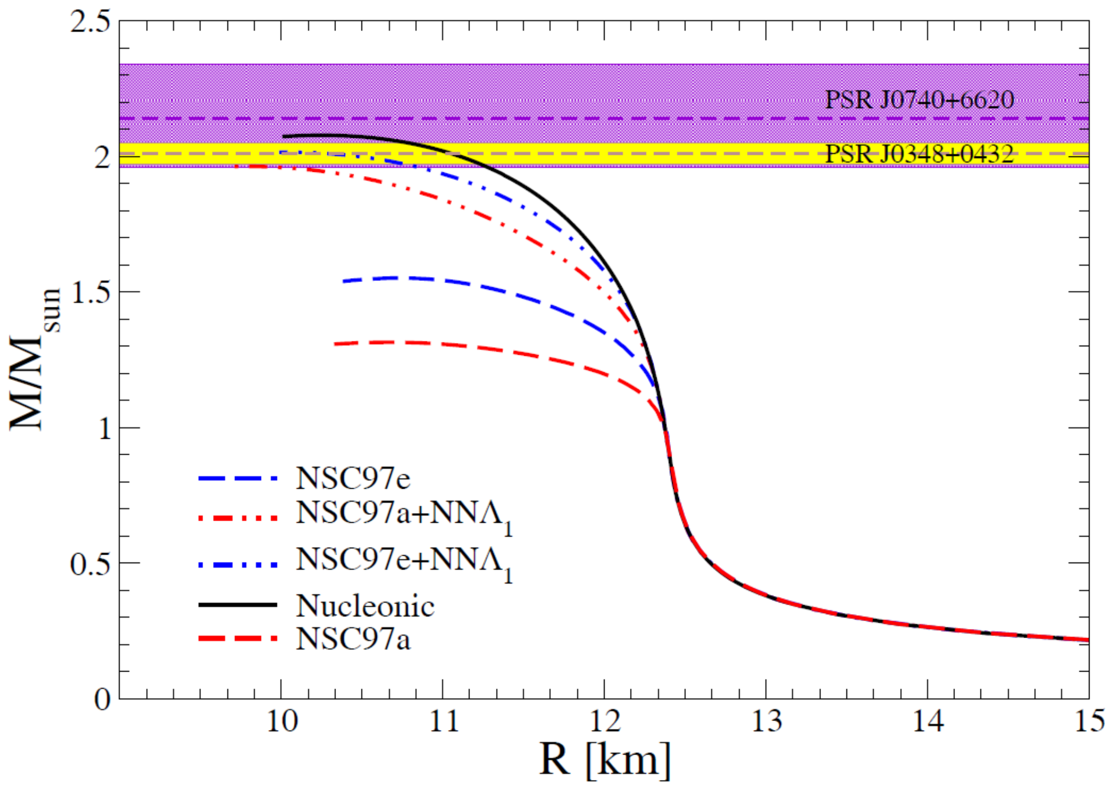
Hypernuclei: Motivation

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

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

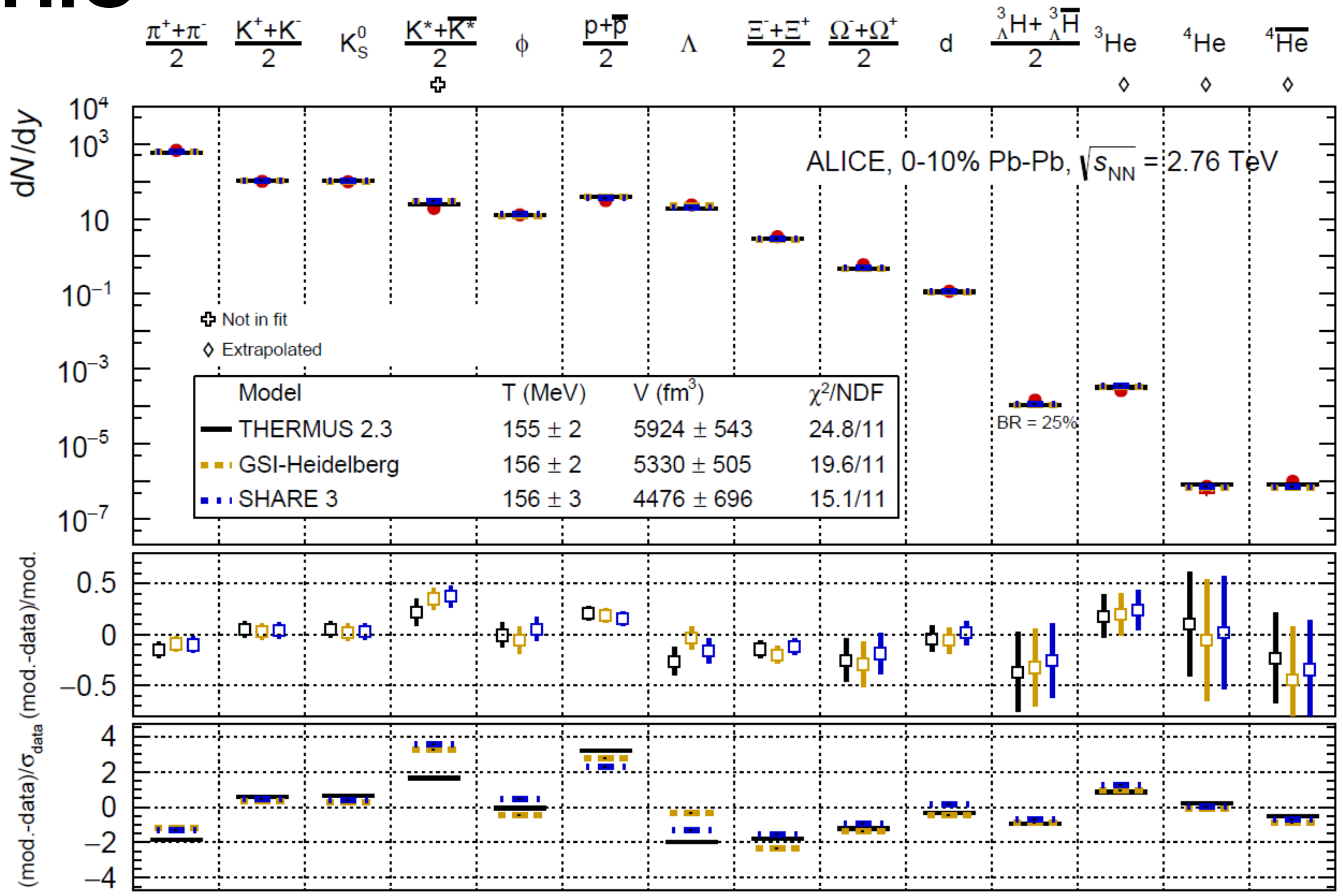
→ understanding of the Λ-N and Λ-Λ interaction



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

Particle production in HIC

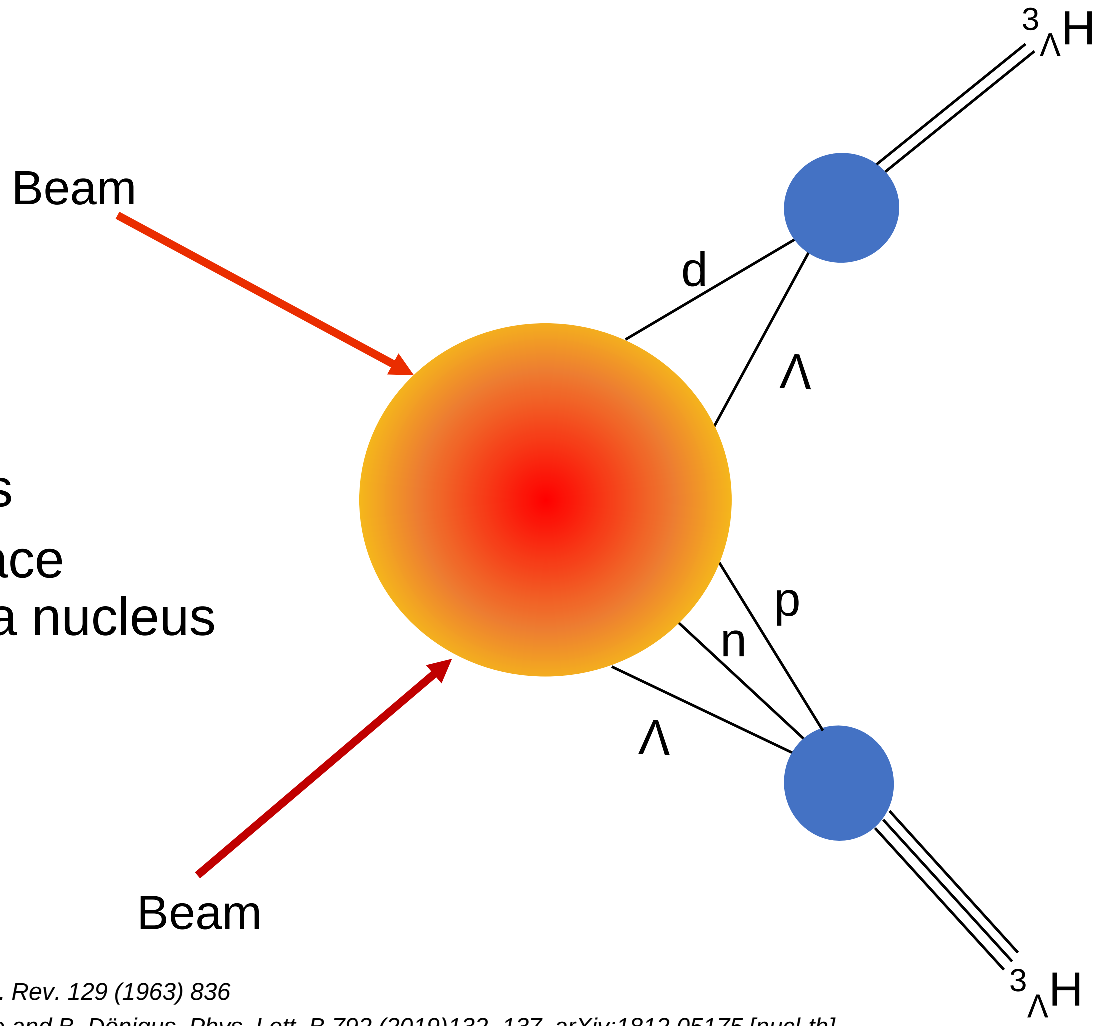
- In large colliding systems, the integrated yield of several particle species is well described over orders of magnitude by the Statistical Hadronization Model (SHM)
- SHM also takes into account the population of excited states by their spin degeneracy
- SHM assumes hadron abundances from statistical equilibrium at the common chemical freeze-out temperature T_{ch} = 156 MeV



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

Hypernuclei production

- 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
  - The closer hadrons in the phase-space → the higher the probability to form a nucleus



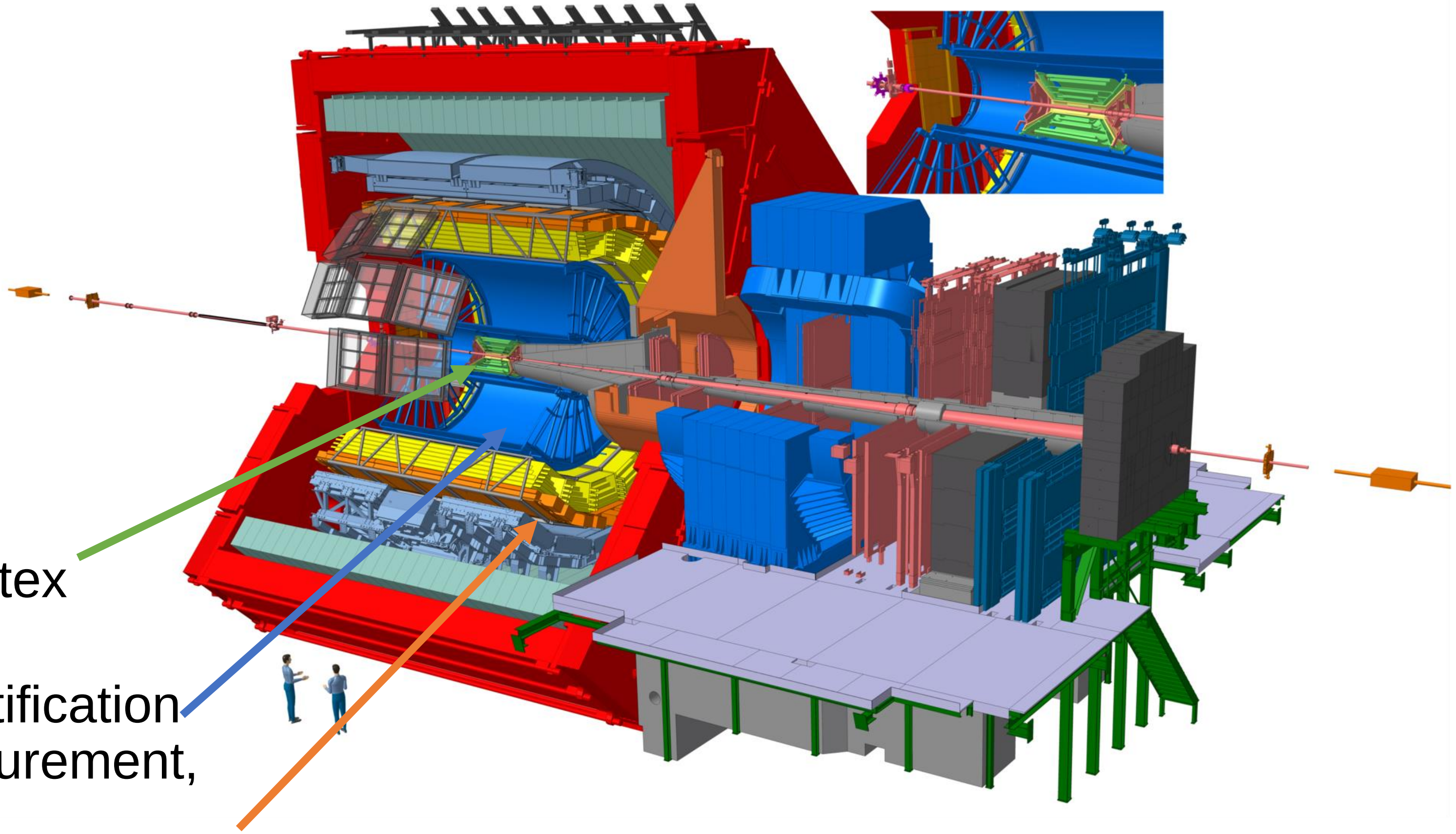
Butler et. Al., Phys. Rev. 129 (1963) 836

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

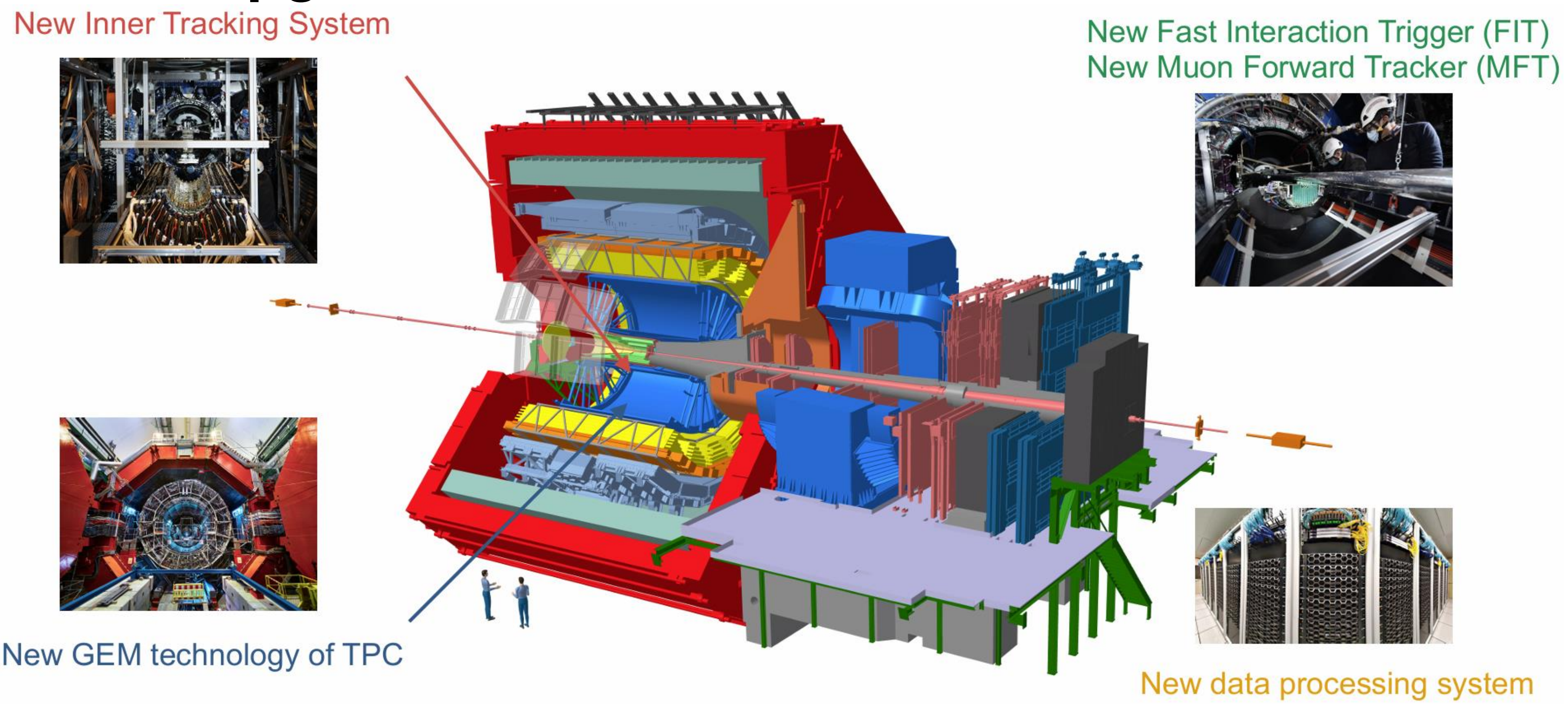
ALICE detector in Run 2

- 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



ALICE upgrades for Run 3



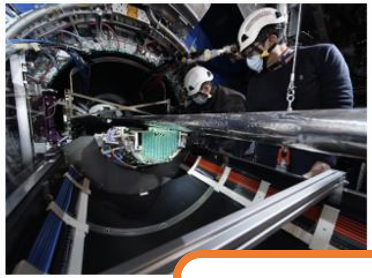
ALICE upgrades for Run 3

New Inner Tracking System

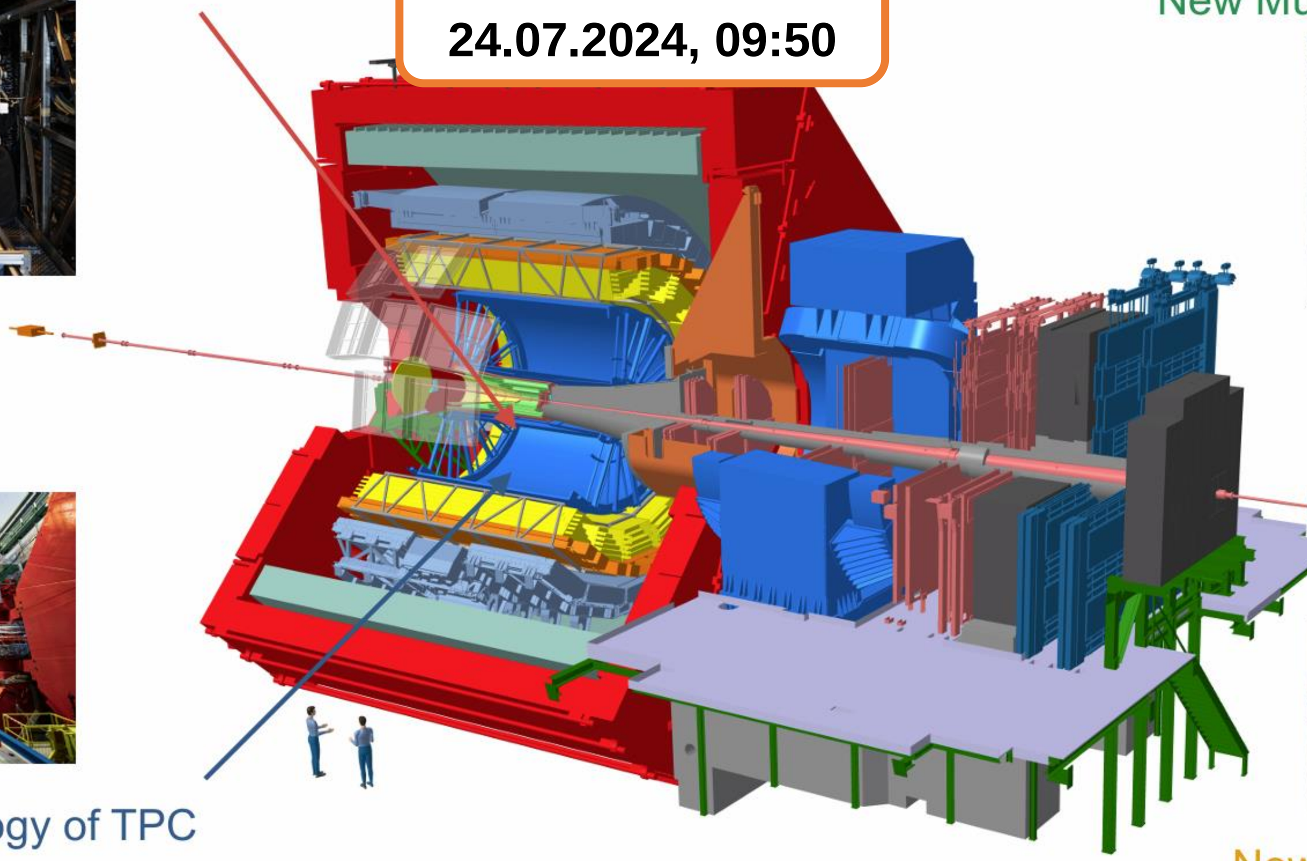
Kai Schweda
24.07.2024, 09:50

Yury Melikyan
19.07.2024, 08:48

New Fast Interaction Trigger (FIT)
New Muon Forward Tracker (MFT)



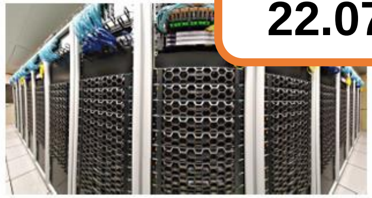
Jian Liu
18.07.2024, 10:45



Guillaume Batigne
20.07.2024, 16:45

David Rohr
22.07.2024, 17:05

New GEM technology of TPC

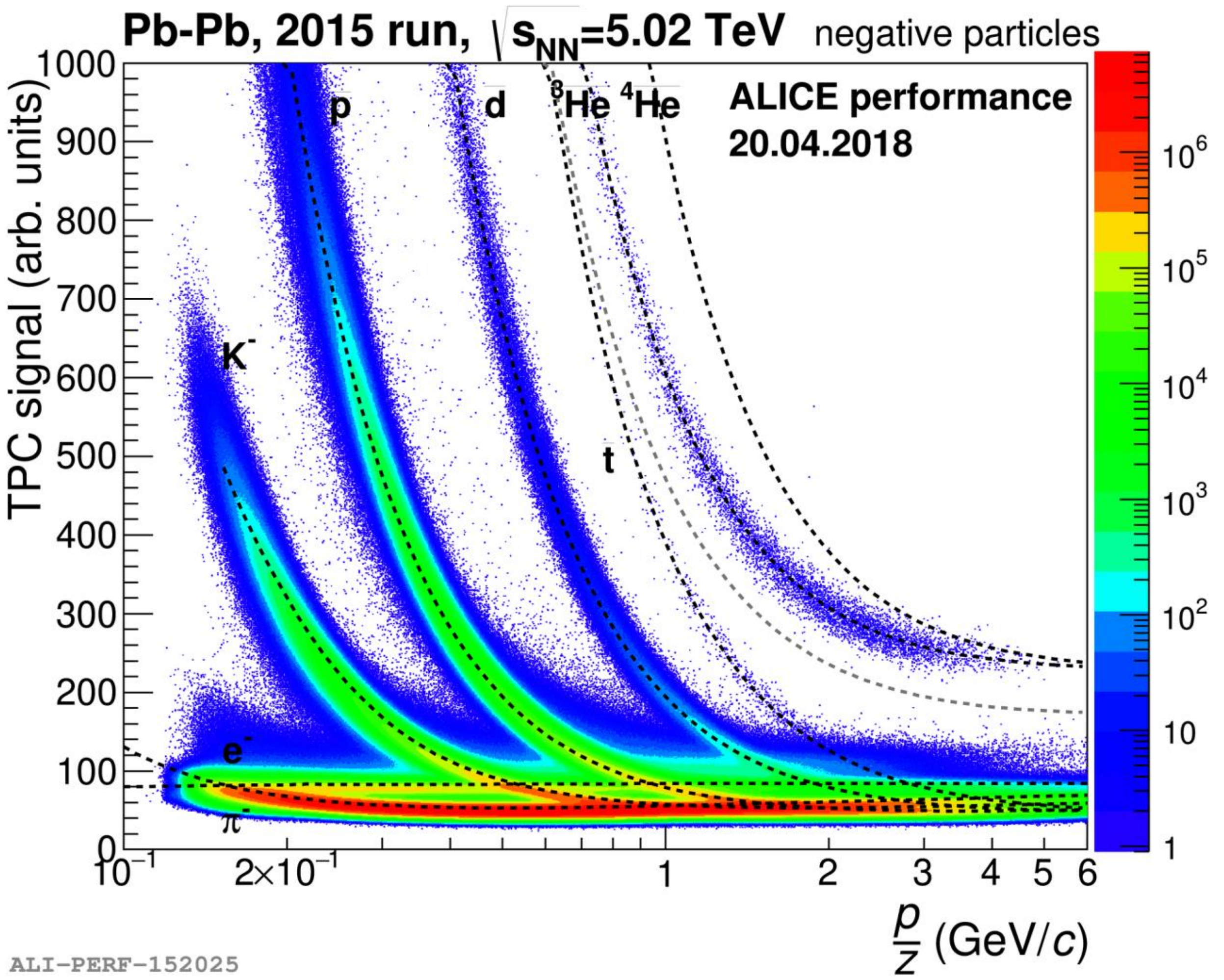


New data processing system

Hypernuclei reconstruction

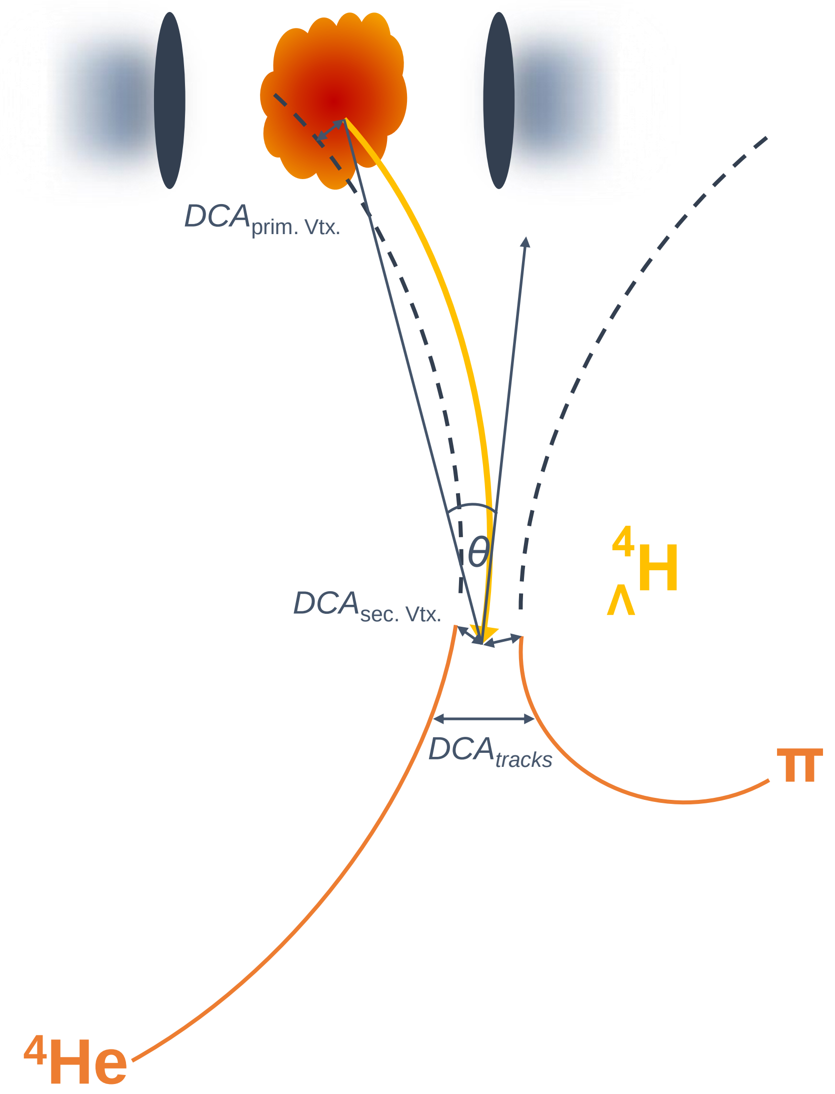
- **Step 1**: find and identify the daughter particle tracks
  - Using TPC PID via the specific energy loss
  - Excellent separation of different particle species

Particle	Decay mode	Branching Ratio
$^{3}_{\Lambda}H$	$^{3}He + \pi^{-}$ + c.c.	~25%
$^{4}_{\Lambda}H$	$^{4}He + \pi^{-}$ + c.c.	~55%
$^{4}_{\Lambda}He$	$^{3}He + p + \pi^{-}$ + c.c.	~29%



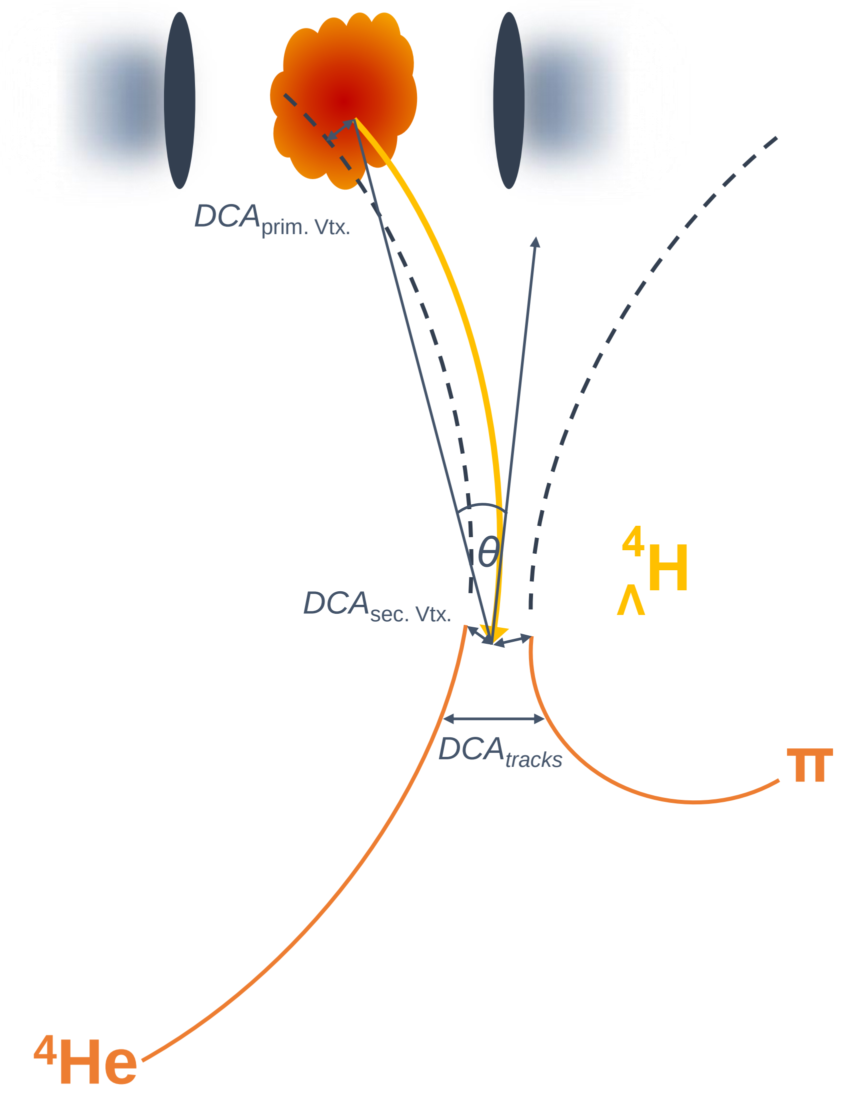
Hypernuclei reconstruction

- **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



Hypertriton production in Pb-Pb collisions

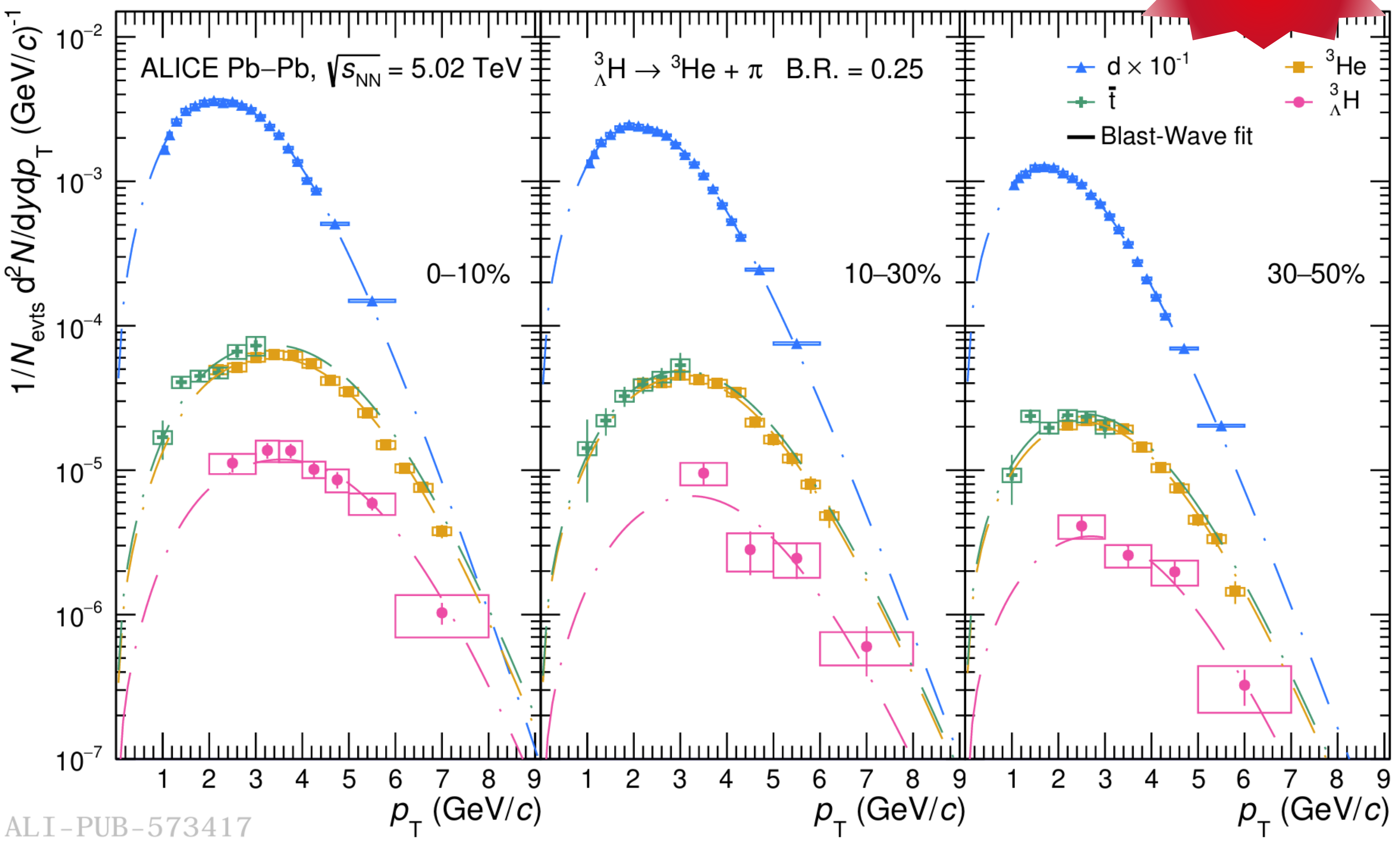
Do hypernuclei have similar freeze-out parameters as ordinary nuclei?

- First p_T-differential measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Performing a combined Blast-Wave fit to deuterons, tritons, helium-3 and ${}^{3}_{\Lambda}H$
- Parameters are compatible with the ones obtained from ordinary nuclei!

ALICE Collaboration, arXiv:2311.11758

ALICE Collaboration, arXiv:2405.19839

NEW

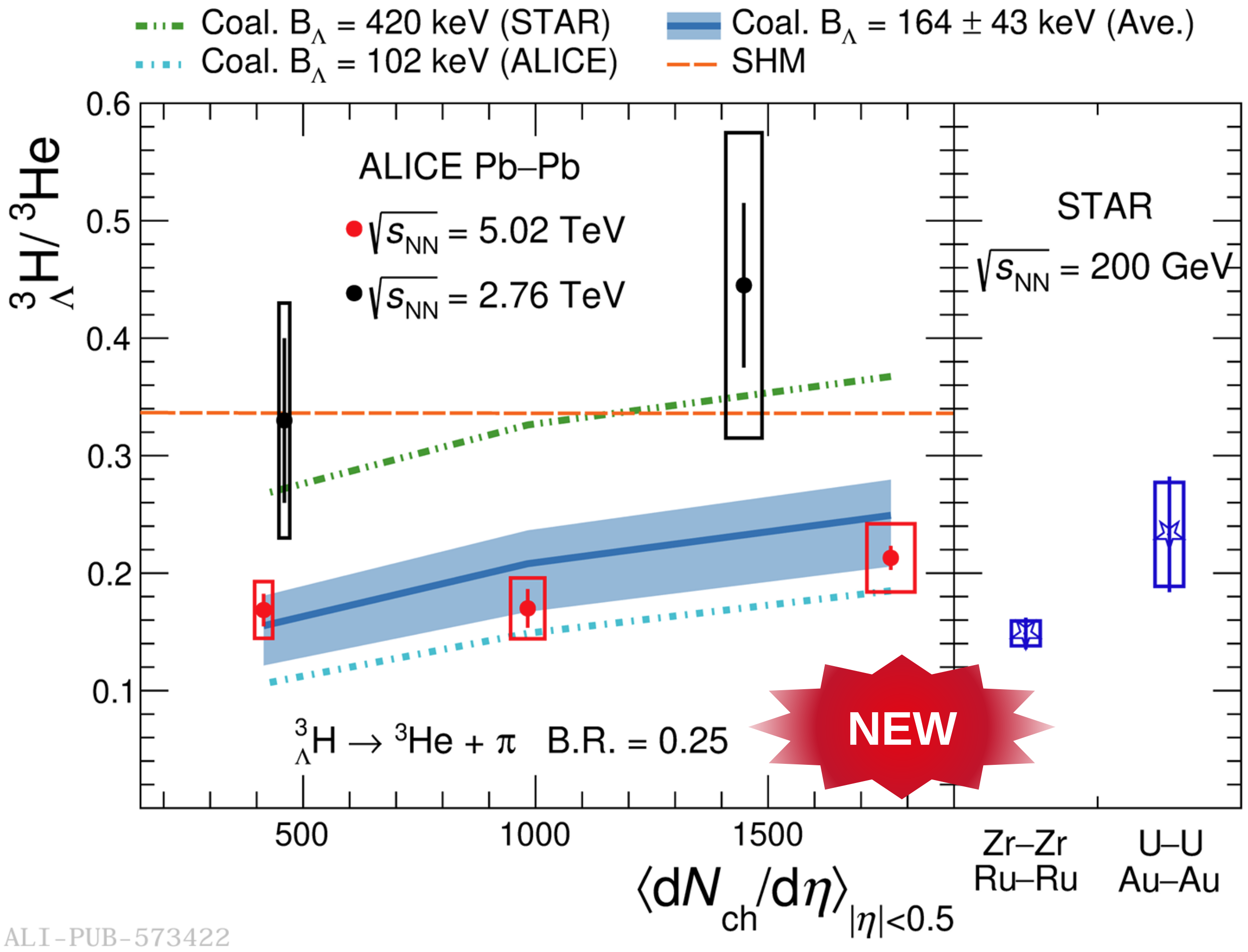


Hypertriton production in Pb-Pb collisions

Multiplicity dependence of the $^{3}_{\Lambda}H$ / ^{3}He ratio

- Consistent with Run 1 results within a 2σ confidence interval
- SHM prediction stays constant at large multiplicities, while coalescence prediction is more sensitive to multiplicities
- Well-described by the coalescence model, and compatible with the B_{Λ} value measured by ALICE
- Shows a suppression for the $^{3}_{\Lambda}H$ / ^{3}He ratio vs. the multiplicity as suggested by the STAR results

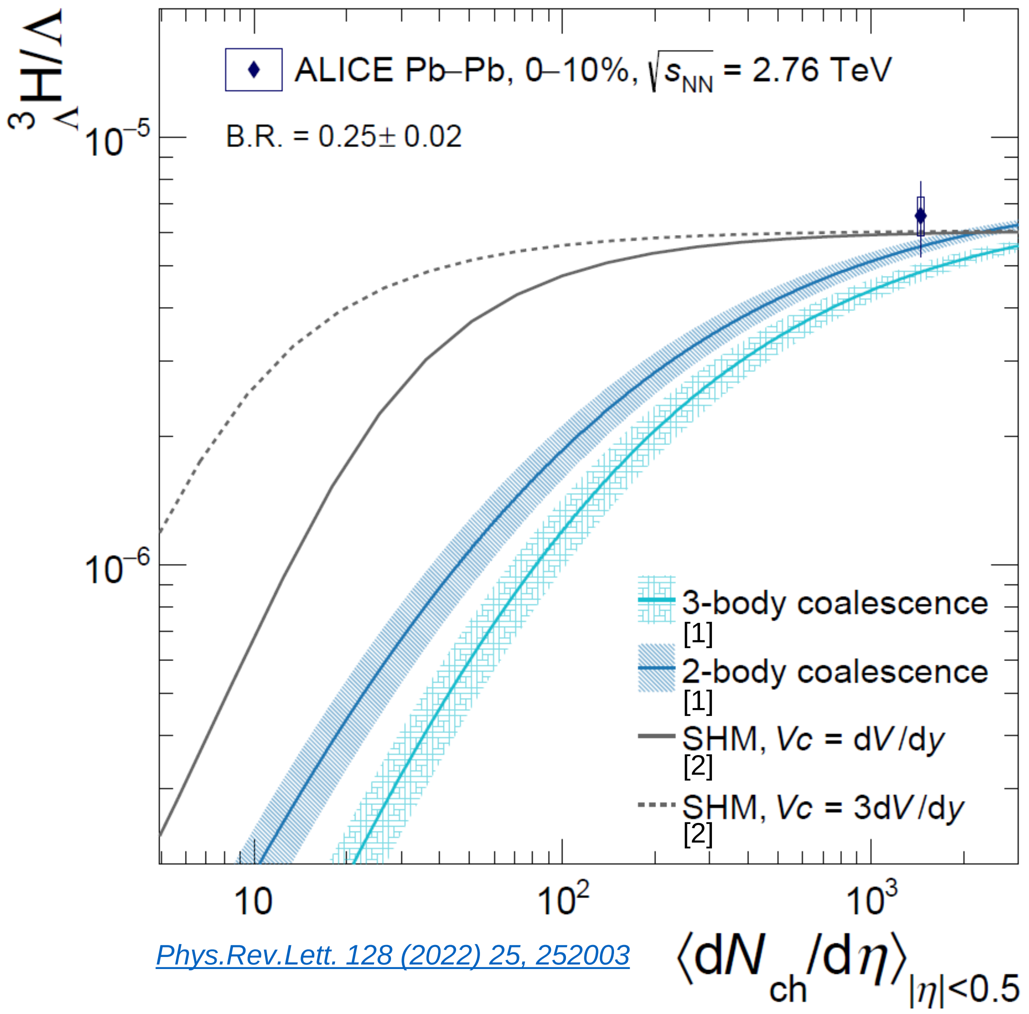
ALICE Collaboration, arXiv:2405.19839



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 → suppression due to canonical conservation of quantum numbers
  - In a coalescence picture large suppression of the production in small systems expected due to the large object size

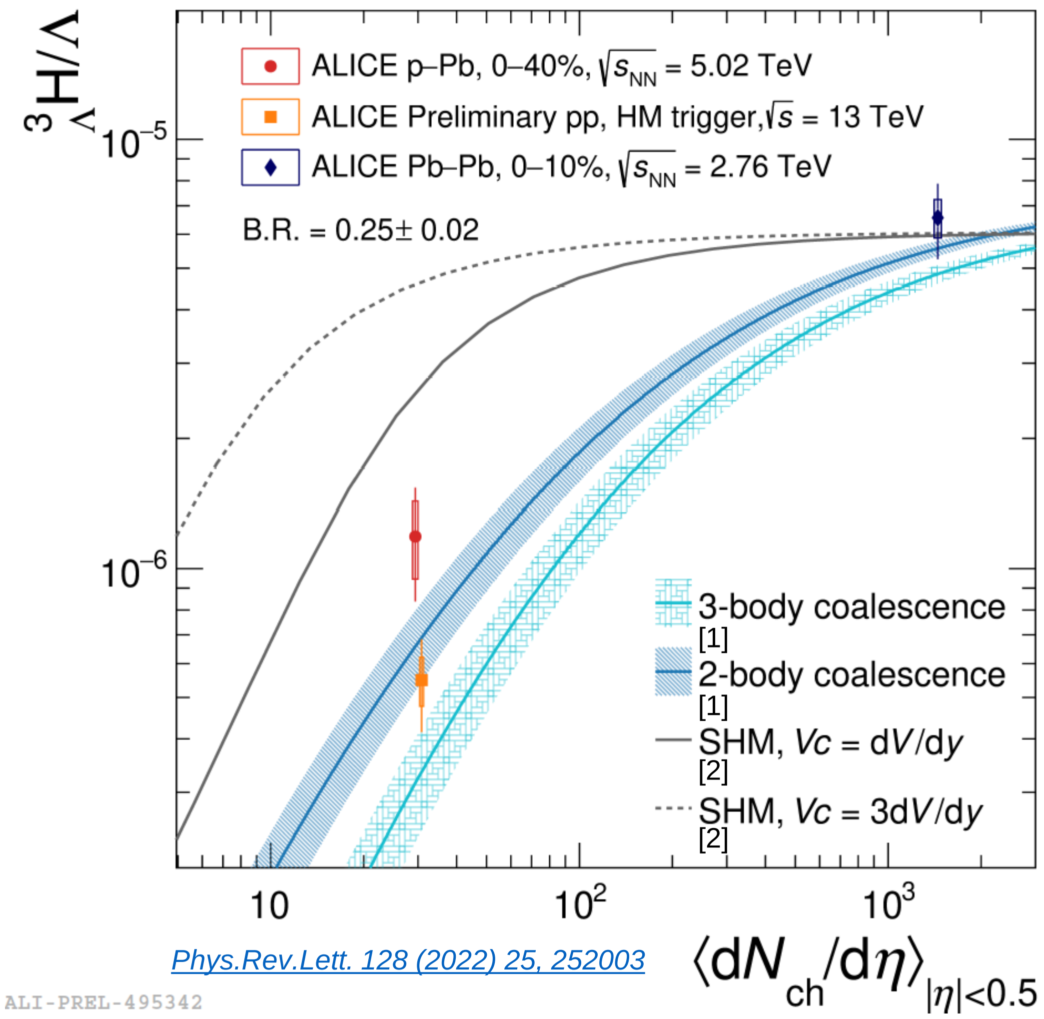


Phys.Rev.Lett. 128 (2022) 25, 252003

[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

- Two new measurements pp and p-Pb at different multiplicities
- Measurements slightly favour the two-body coalescence
- But do not exclude three-body coalescence



Phys.Rev.Lett. 128 (2022) 25, 252003

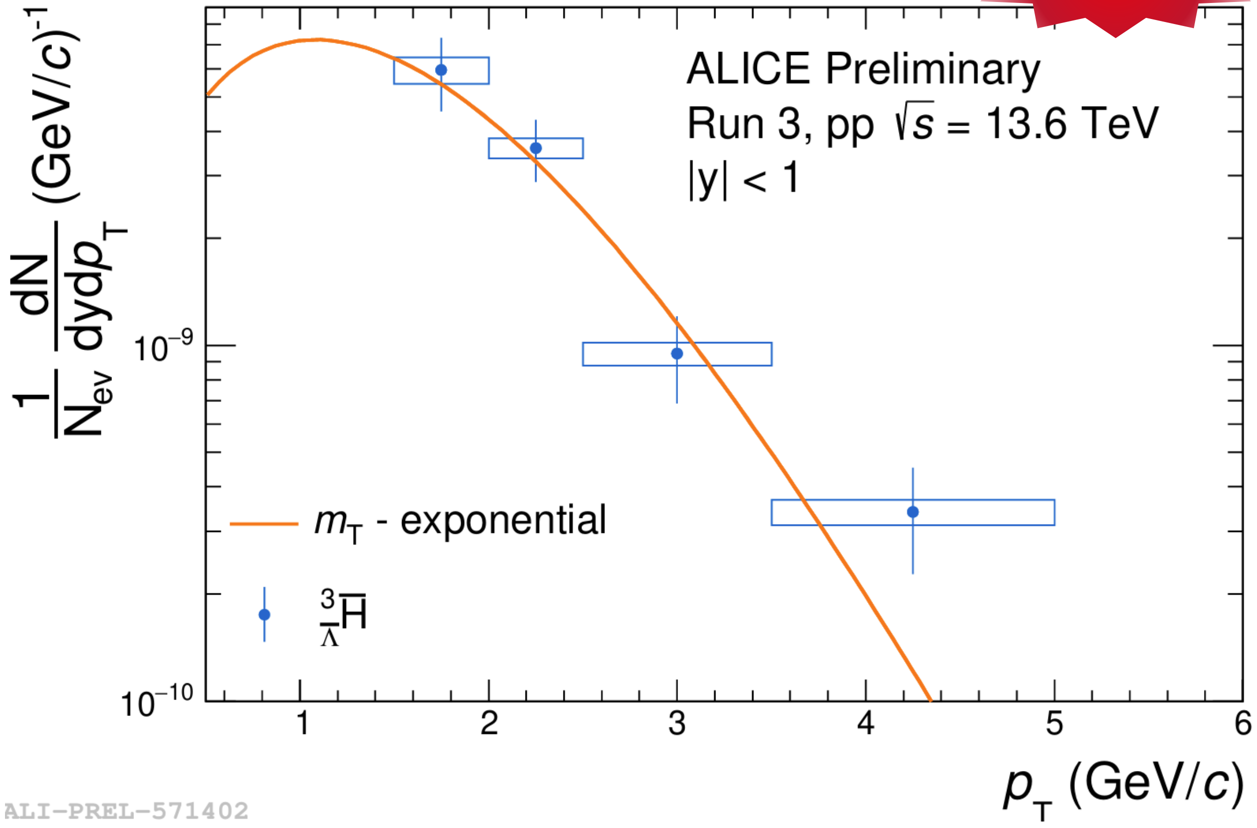
[1] K.-J. Sun, C.-M. Ko and B. Dönigus, Phys. Lett. B 792 (2019)132–137, arXiv:1812.05175 [nucl-th]
[2] V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B 785 (2018)171–174, arXiv:1808.05245 [hep-ph]

Hypertriton in small systems

First ever p_T-differential measurement of ${}^{3}_{\Lambda}H$ production in small collision systems using high statistics in Run 3 pp collisions at 13.6 TeV

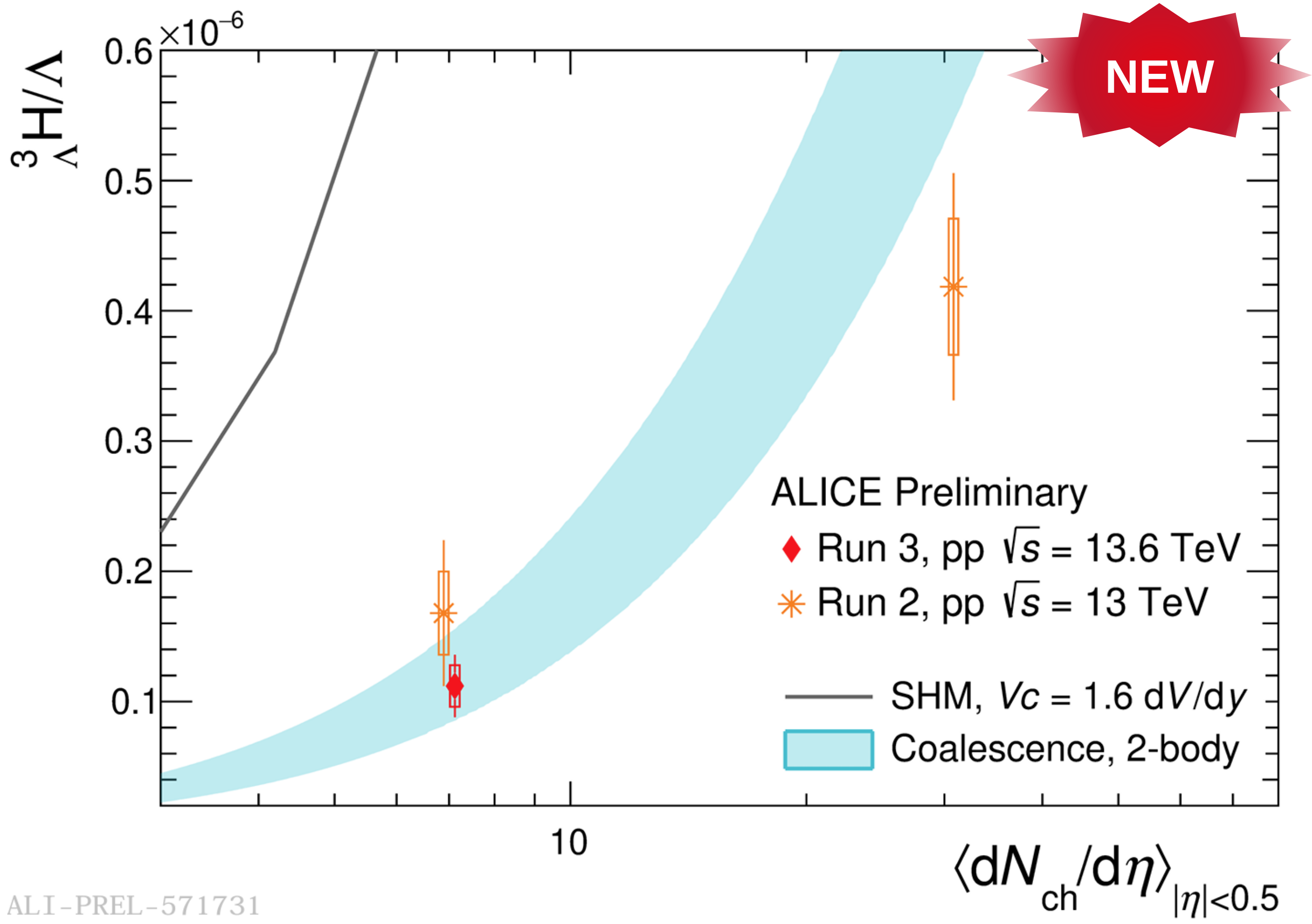
- Results obtained from antimatter
- Total yield estimated by extrapolating the p_T spectrum
- p_T – differential ${}^{3}_{\Lambda}H$ / ${}^{3}He$ ratio is sensitive to probe different production mechanisms

NEW



$^{3}_{\Lambda}H$ / Λ ratio

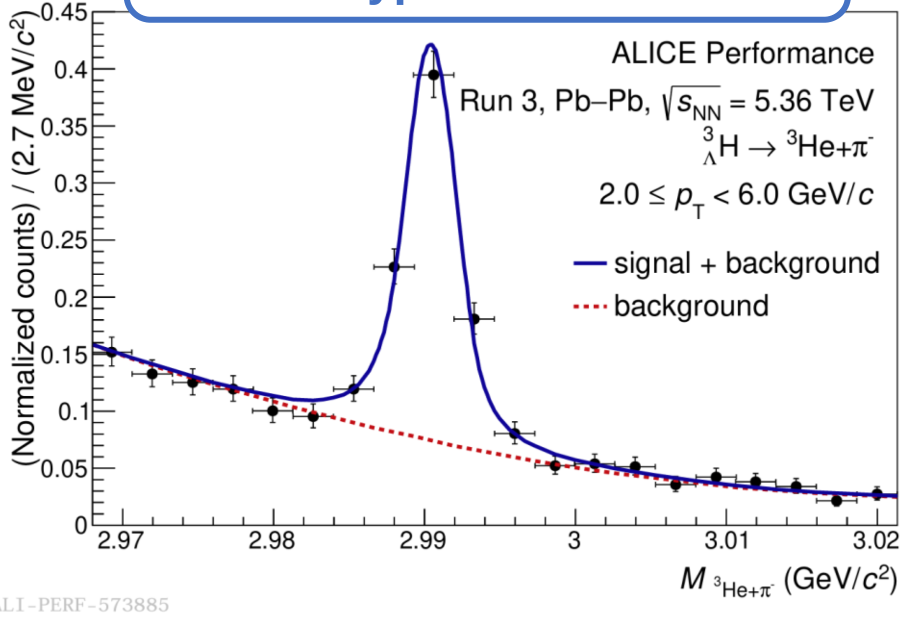
- Twice better precision w.r.t. Run 2
- Compatible with the Run 2 preliminary results
- New measurement at higher multiplicity also favours the two-body coalescence

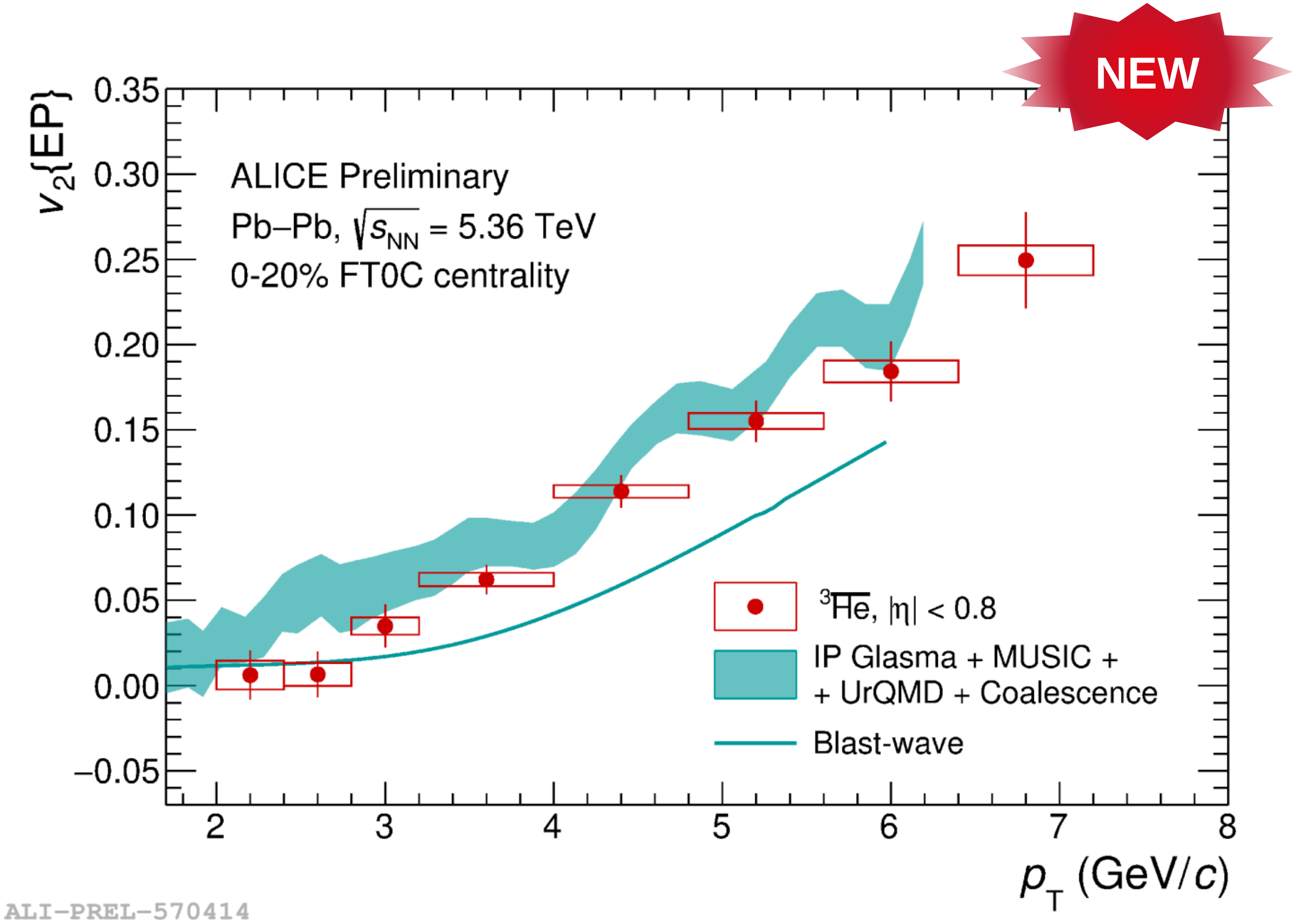


Hypernuclei flow

- Precise measurement of helium-3 elliptic flow in Run 3 Pb-Pb collisions at 5.36 TeV

Can we measure the flow of hypernuclei?



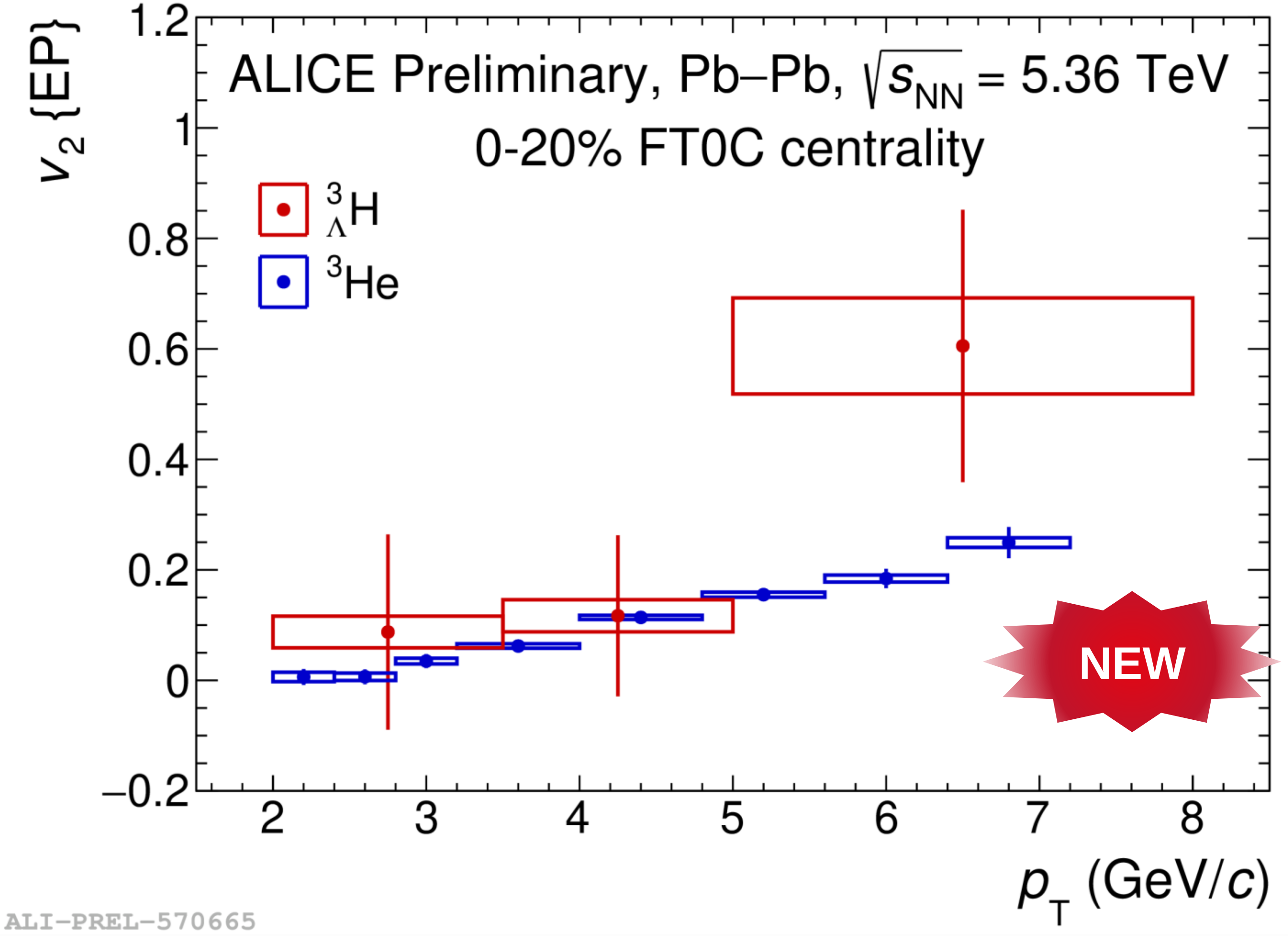


Hypernuclei flow

First measurement of $^{3}_{\Lambda}H$ elliptic flow in Run 3 Pb-Pb collisions at 5.36 TeV

- v_2 of the $^{3}_{\Lambda}H$ compared to helium-3
- Follows the same increasing trend with p_T (and centrality)

Luca Barioglio's talk today at 17:53



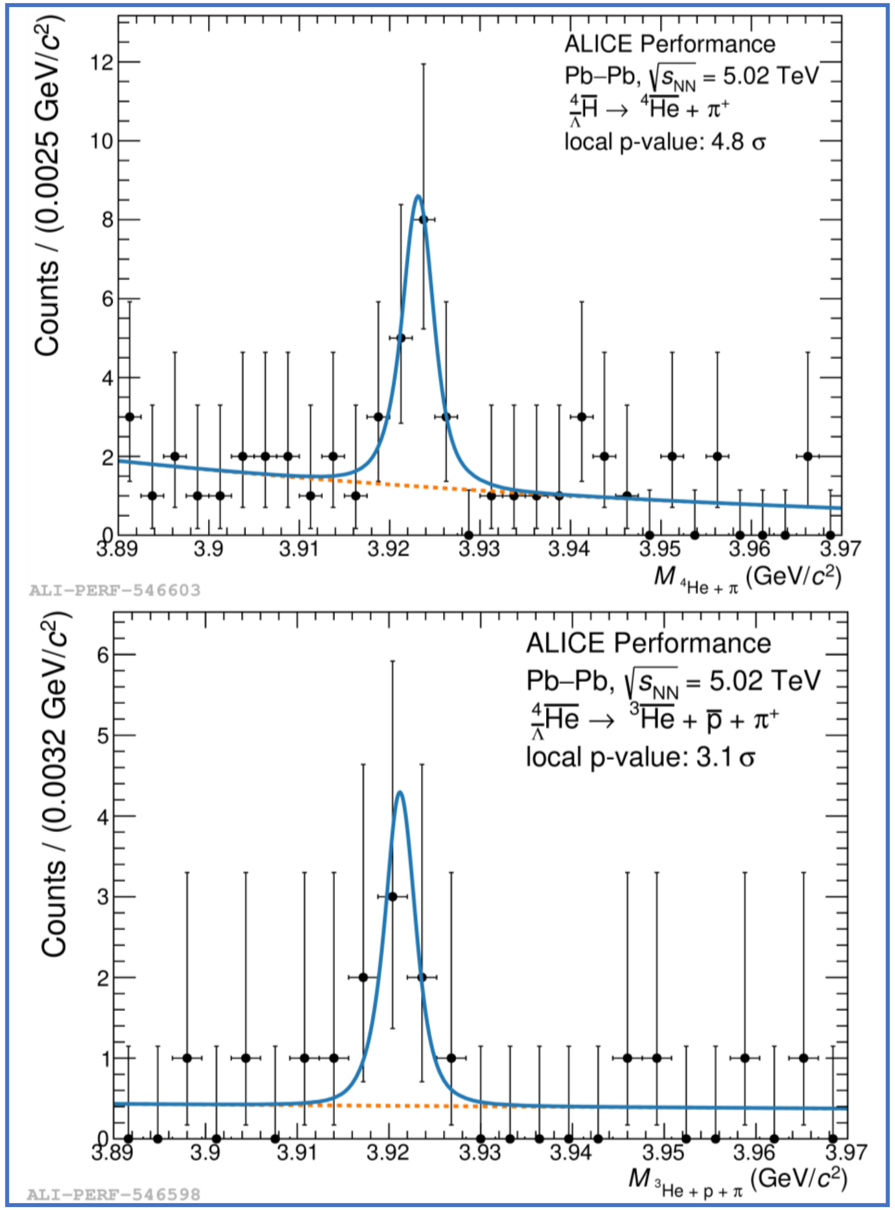
A = 4 hypernuclei in ALICE

- For the first time, we are able to reconstruct A = 4 (anti)hypernuclei at the LHC and determine their production yield in Run 2 Pb-Pb collisions at 5.02 TeV

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

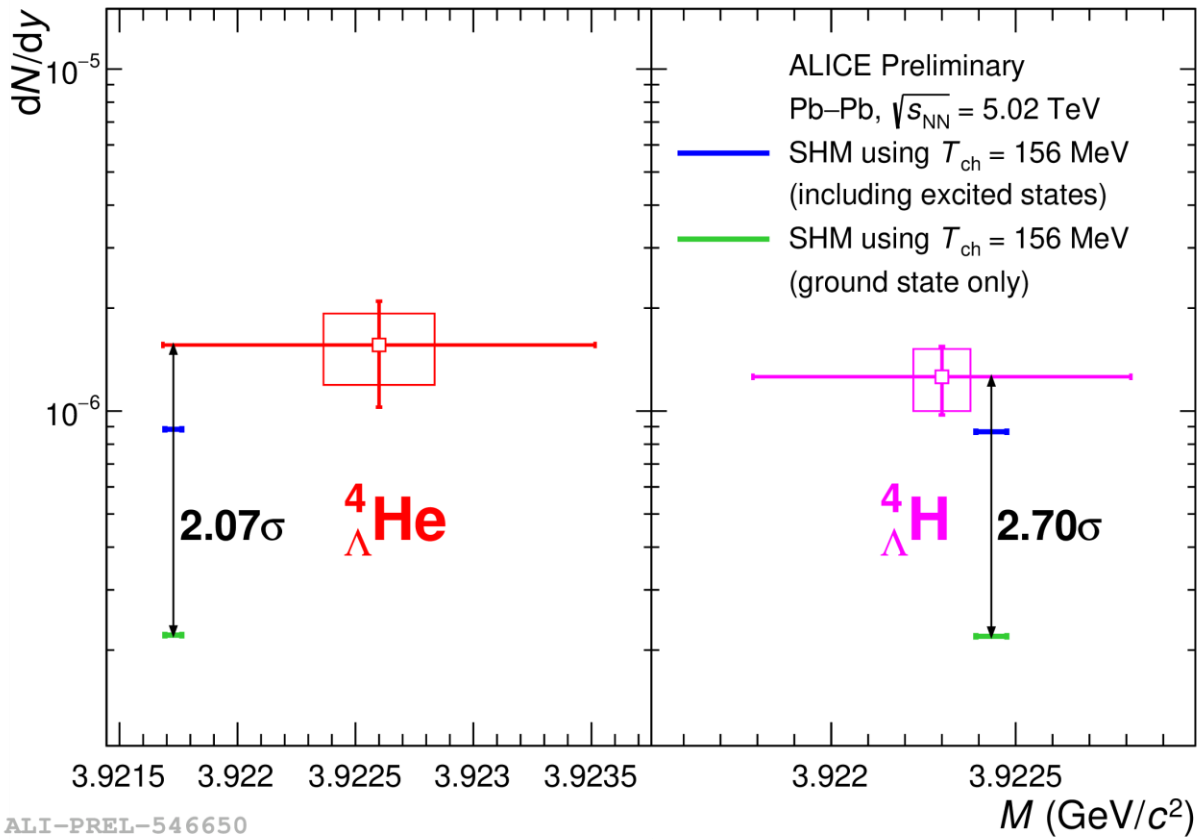
$$^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-} + \mathrm{c.c.}$$

First observation of $^{4}_{\Lambda}\overline{\mathrm{He}}$ ever!



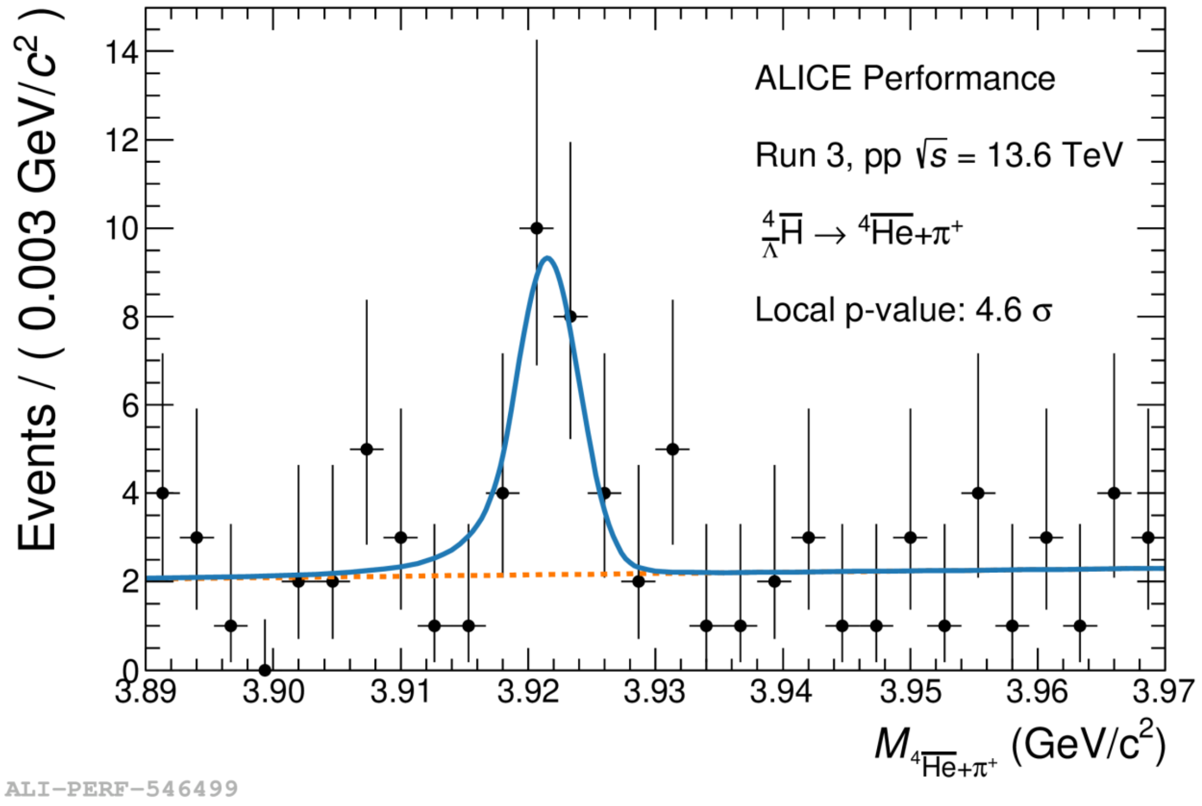
A = 4 hypernuclei in ALICE

- 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 SHM as a well working model for the prediction of hypernuclei yields
- 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)



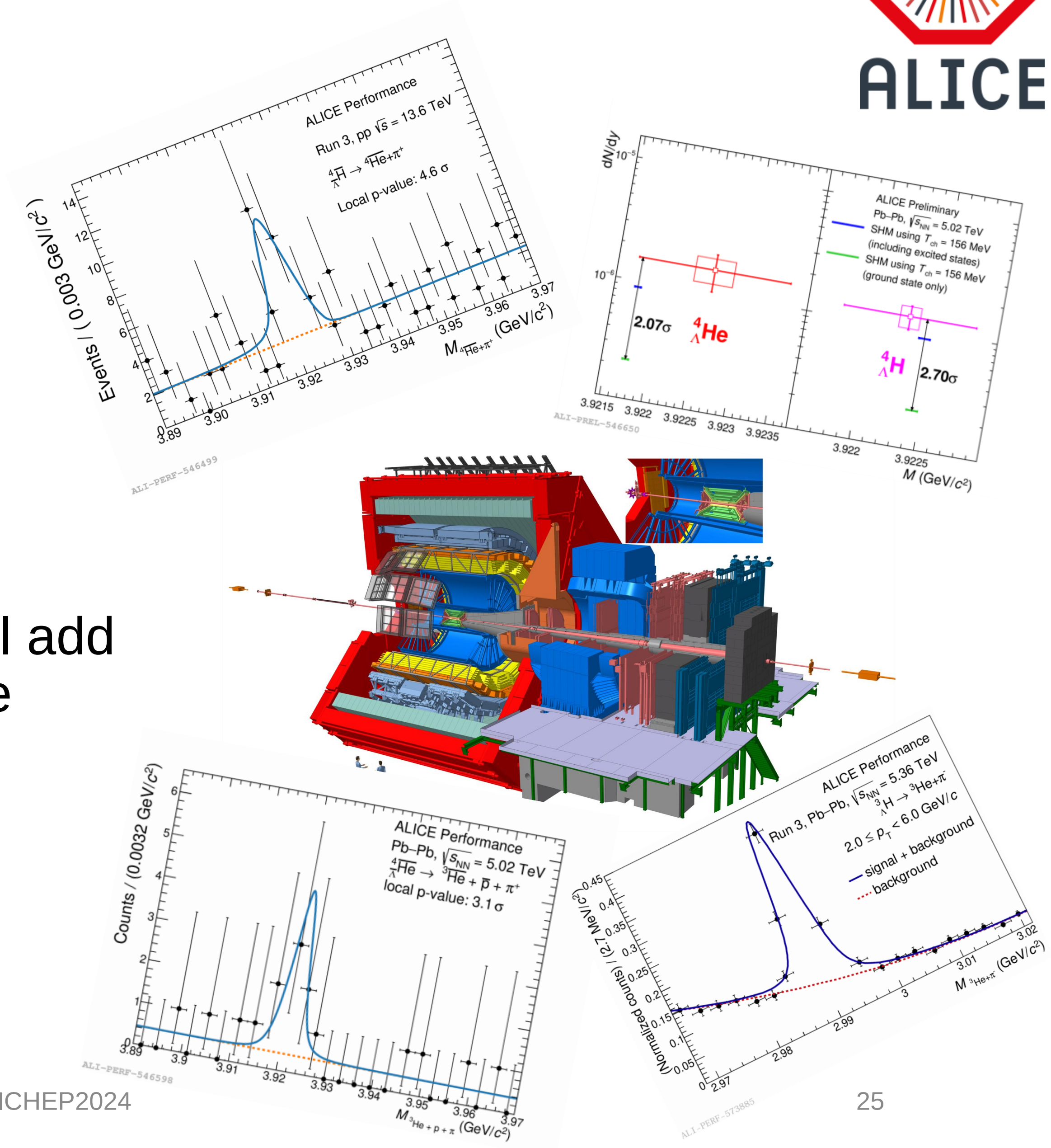
A = 4 hypernuclei in small systems

- 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

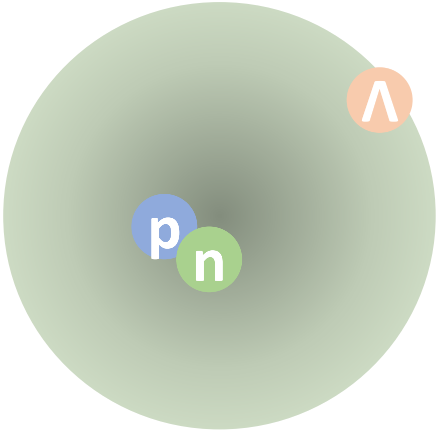
- ALICE is the perfect apparatus to study the production and properties of light (anti)(hyper)nuclei
- The latest results show small uncertainties and a good agreement with the theoretical predictions
- The ongoing Run 3 and upcoming Run 4 will add large statistics for the measurement of those particles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



Backup

Hypertriton

- Λ, p, n bound state
- Lightest known hypernucleus and very loosely bound
- Mass ≈ 2.991 GeV/c^2
- Λ-separation energy ≈ 100 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]



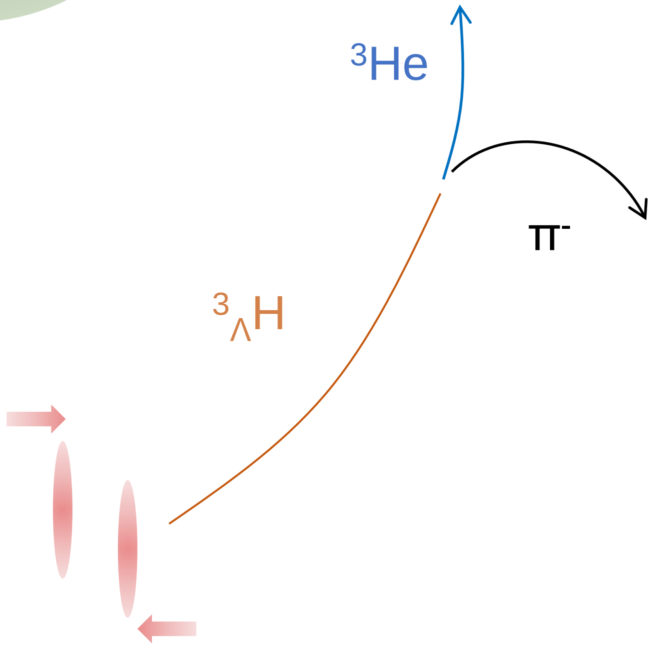
- Decay modes:

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

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

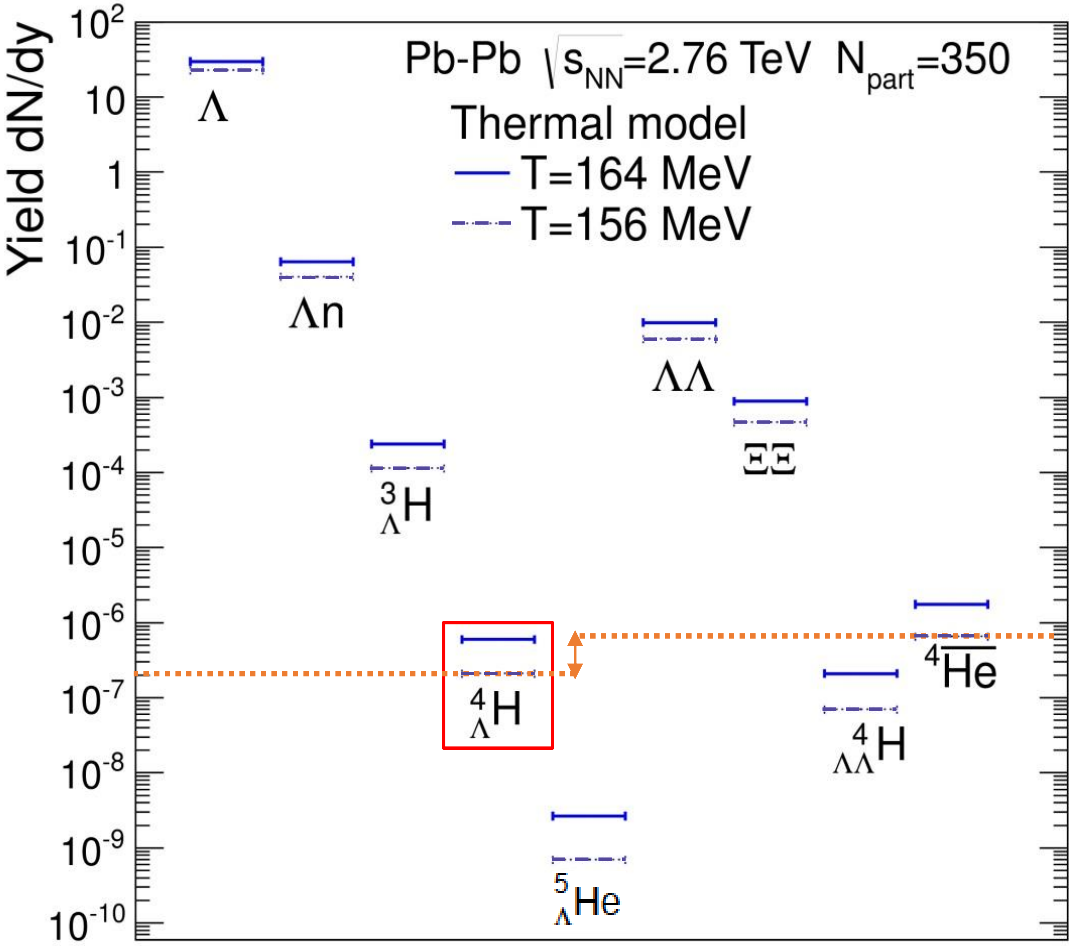
$^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$

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



A = 4 hypernuclei in ALICE

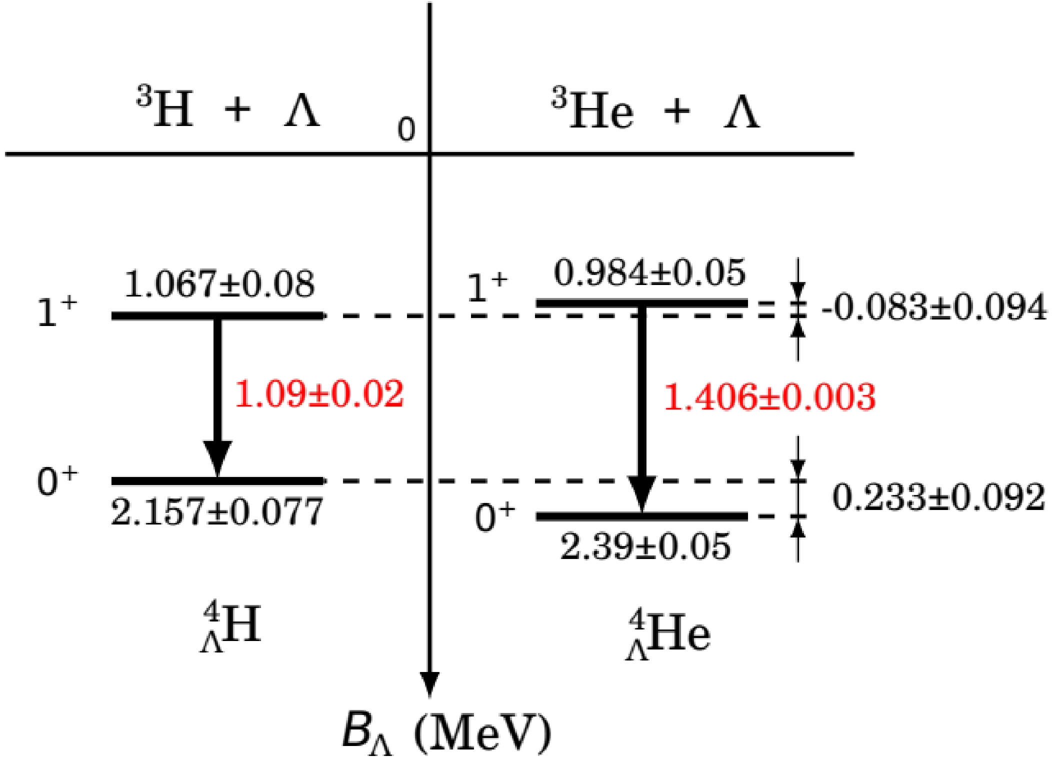
- Expectations for hypernuclei from the statistical hadronization model at T_{ch} = 156 MeV
- Penalty factor by adding one nucleon to a particle ≈ 300 in Pb-Pb collisions
- Further suppression due to strangeness content
- Comparing to only a few antialpha candidates in available Pb-Pb dataset → improbable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

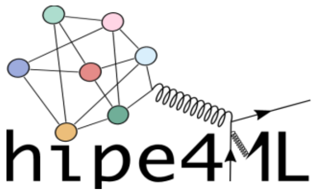
- A = 4 hypernuclei are more bound and each has an excited state
  Phys. Rev. Lett. 115, 222501 (2015)
- The yields of these hypernuclei are enhanced with respect to the ground state due to the feed-down from higher mass states
- Also the yields of the SHM scale with the spin-degeneracy
- Resulting in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



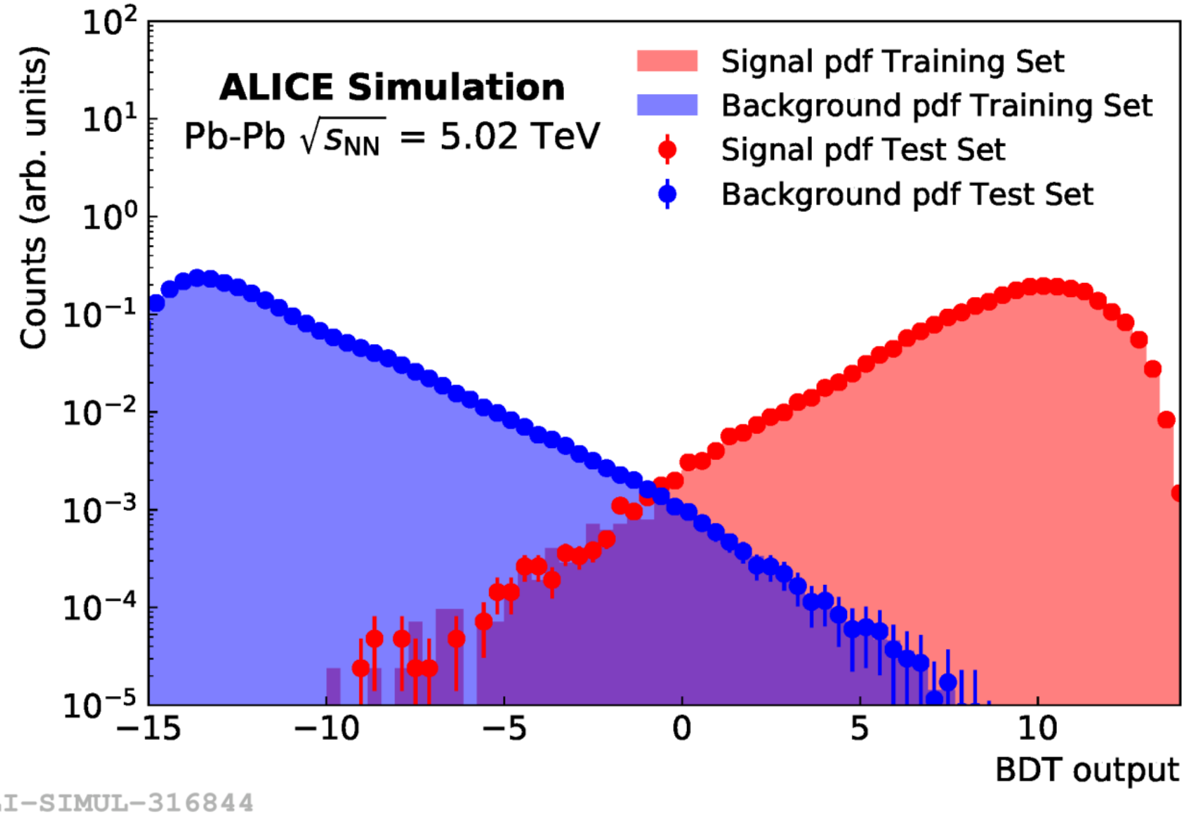
M. Schäfer, N. Barnea, A. Gal, Phys.Rev.C 106, L031001 (2022)

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



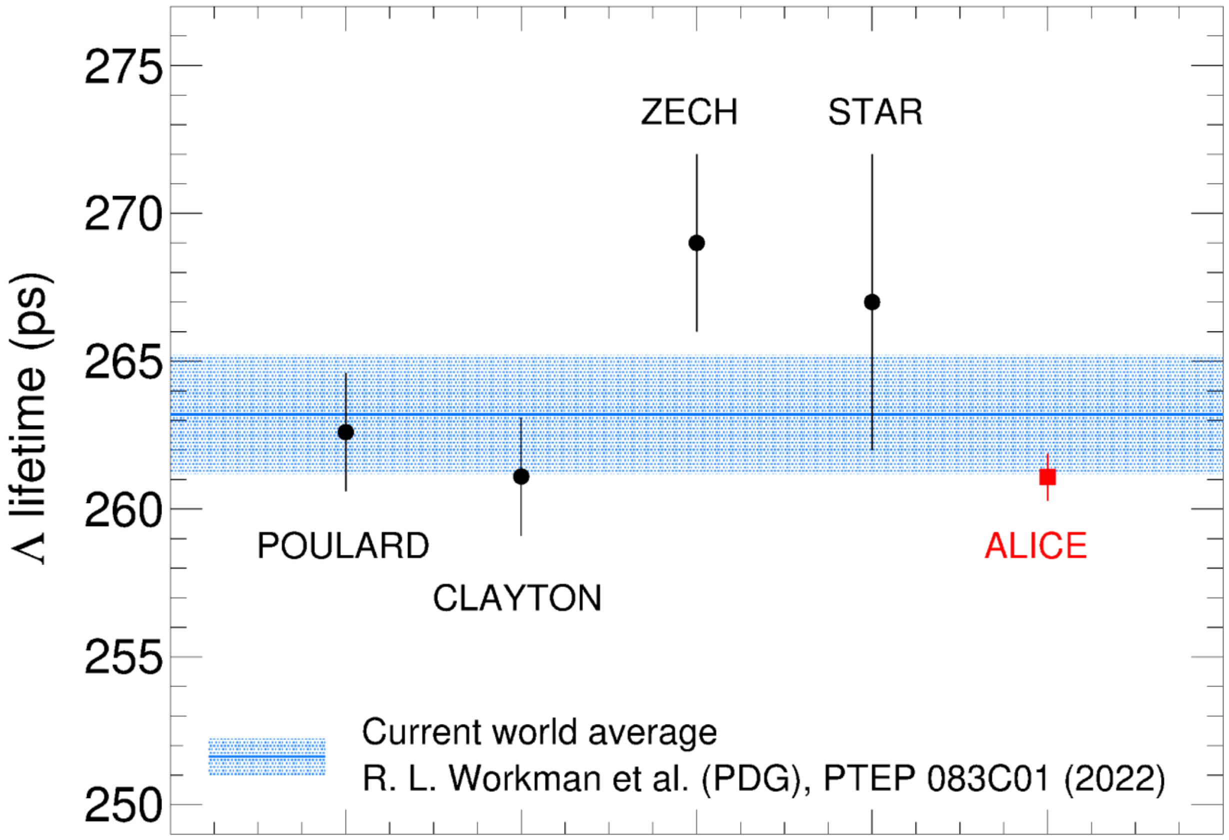
https://hipe4ml.github.io/



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 factor ~3 more precise than the PDG value

Phys. Rev. D 108, 032009 (2023)

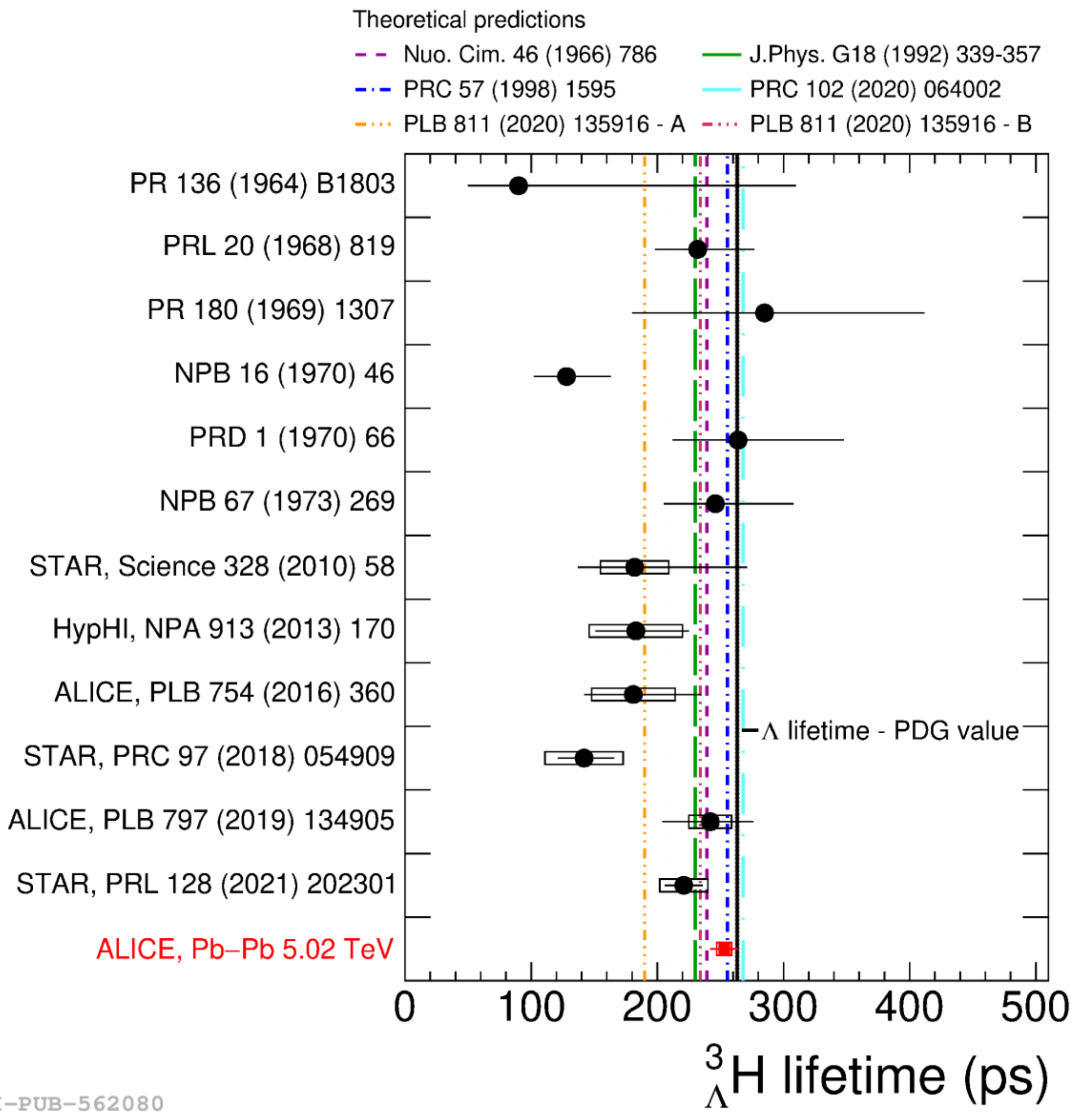


ALI-PUB-561575

Hypertriton lifetime

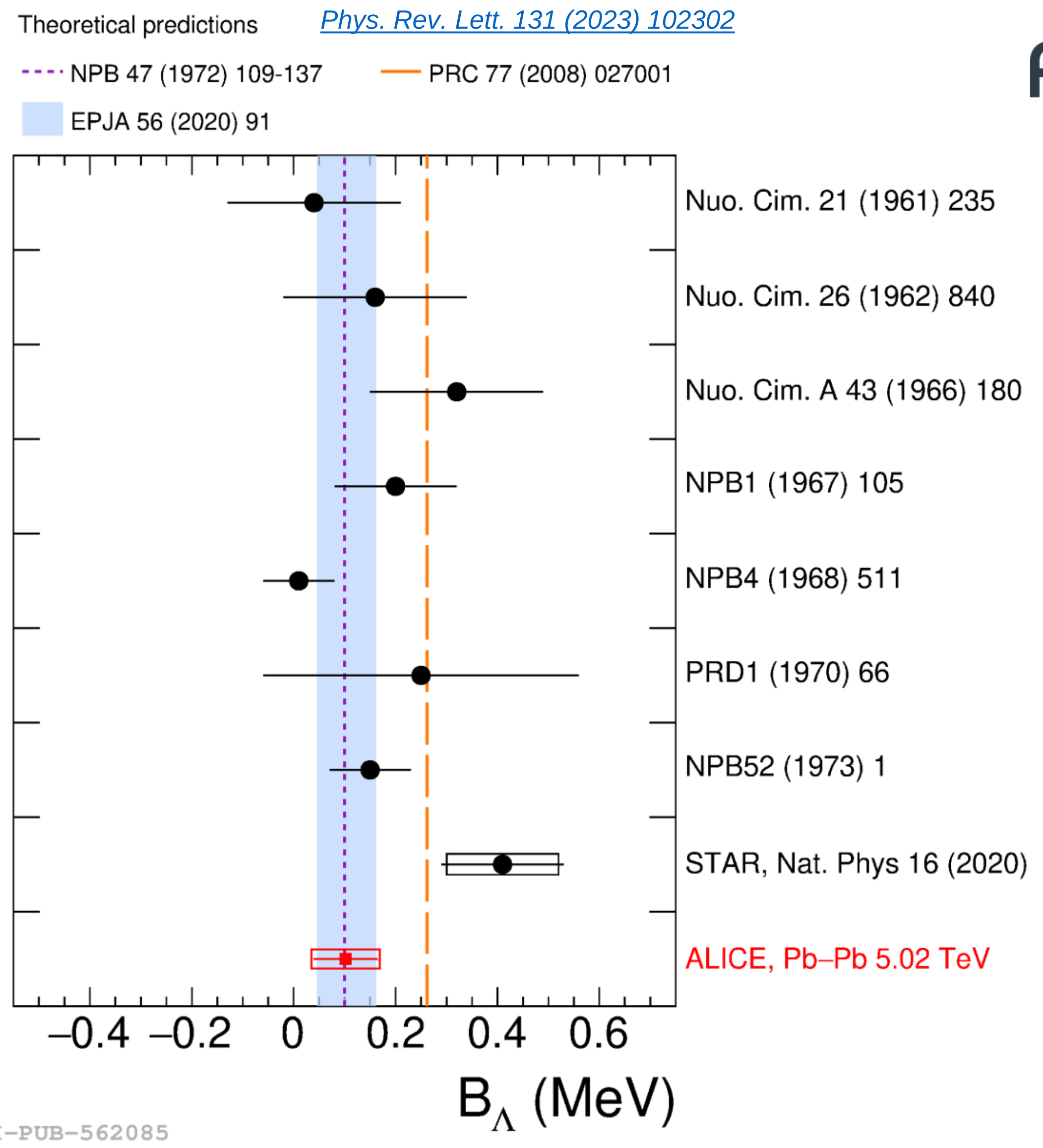
- Recent measurement in Run 2 Pb-Pb collisions at 5.02 TeV
- Is compatible with the free Λ lifetime within its uncertainties
- New result pushes the world average lifetime a little up

Phys. Rev. Lett. 131 (2023) 102302



Hypertriton binding energy

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

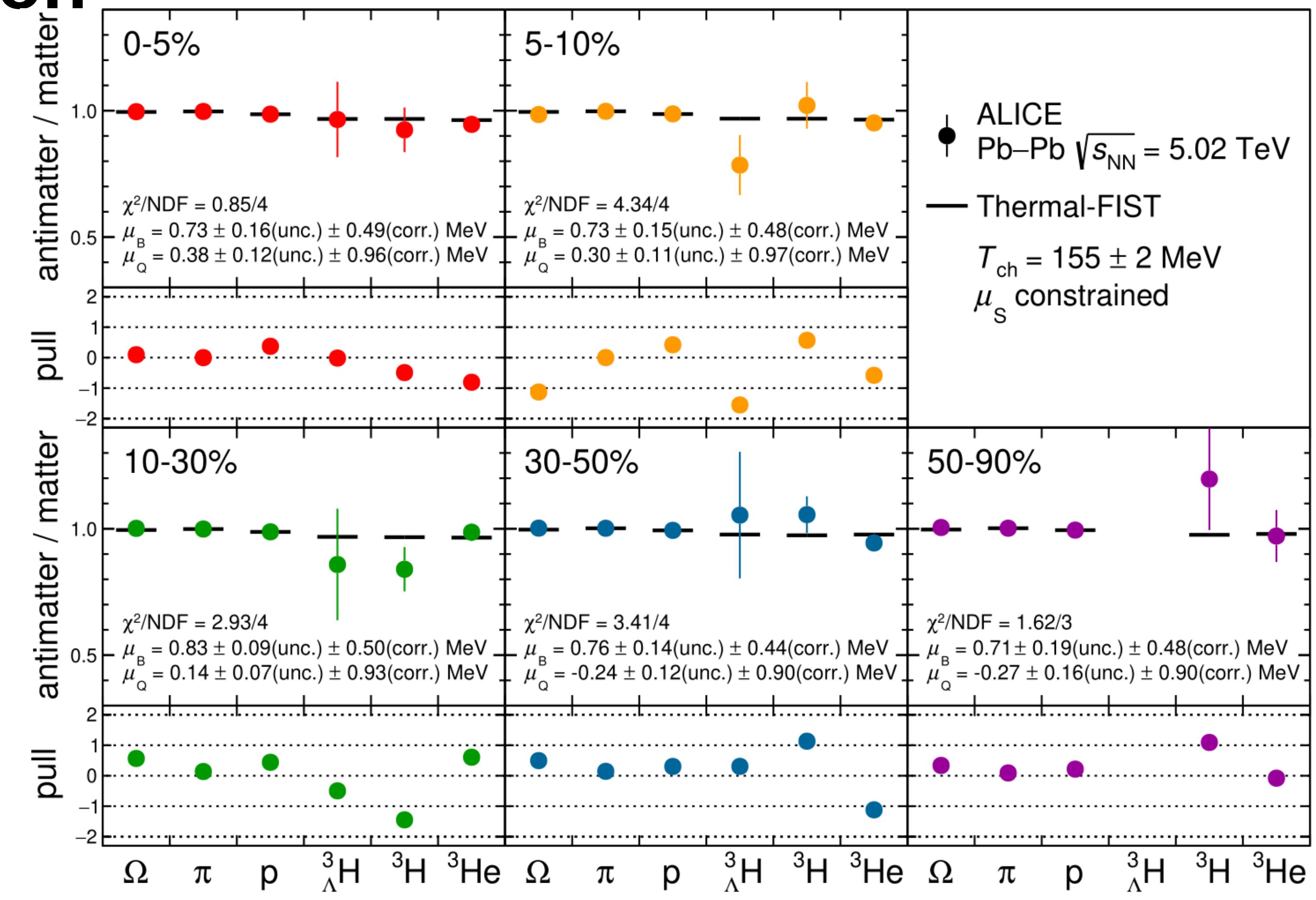


[NPB47(1972)] *R.H. Dalitz, R.C. Herndon, Y.C. Tang, Nuclear Physics B, Volume 47, Issue 1, 1972, Pages 109-137*
[arXiv:1711.07521] *Lonardoni, Diego and Pederiva, Francesco, arXiv:1711.07521 [nucl-th]*
[PRC77(2008)] *Fujiwara, Y. and Suzuki, Y. and Kohno, M. and Miyagawa, K., Phys. Rev. C 77, 027001*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

Hypertriton production

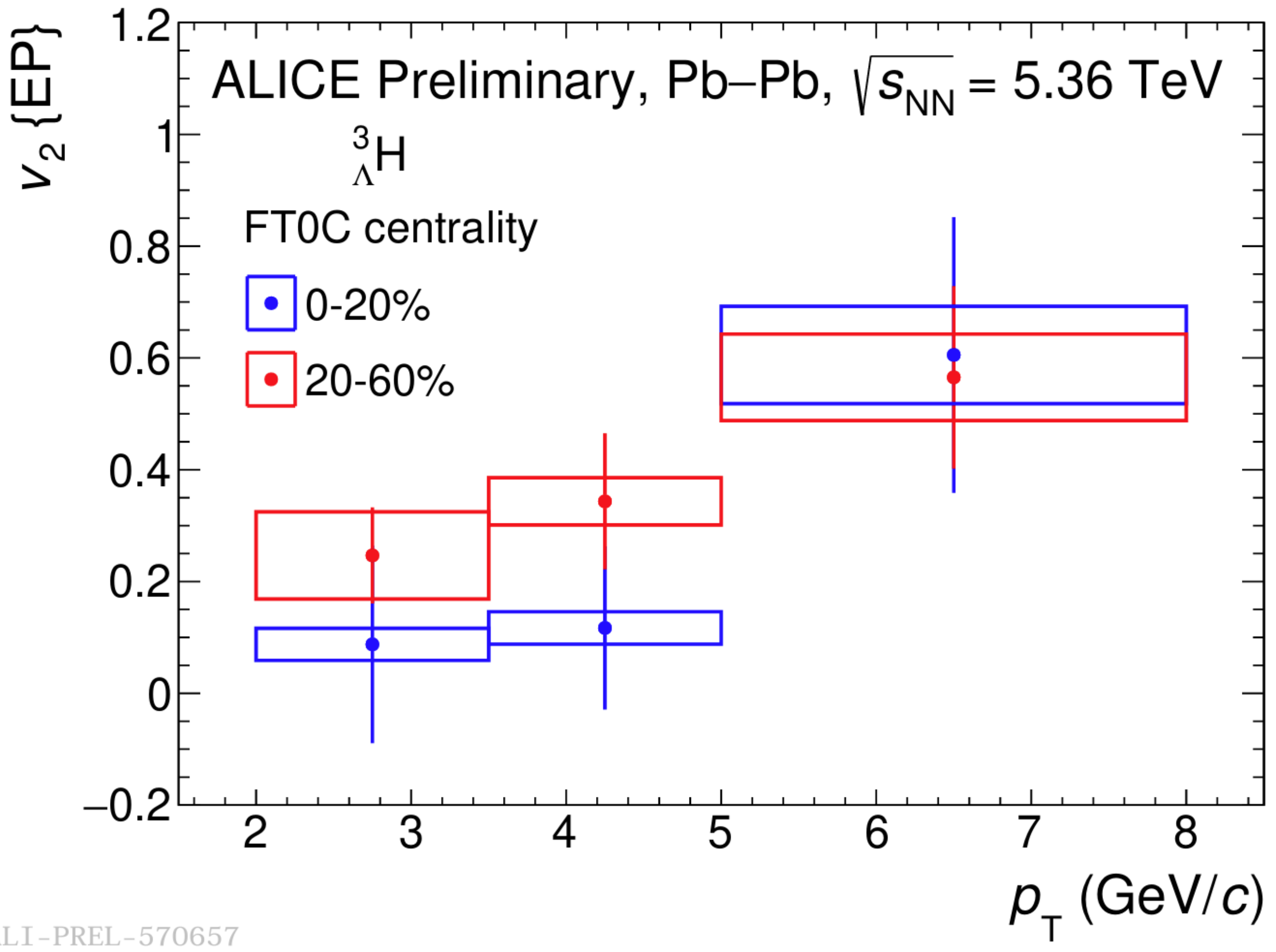
- Antiparticle to particle ratios compared to SHM predictions at T_{ch} = 155 ± 2 MeV and using the obtained μ_B for different centrality bins

arxiv:2311.13332 (accepted by PRL)



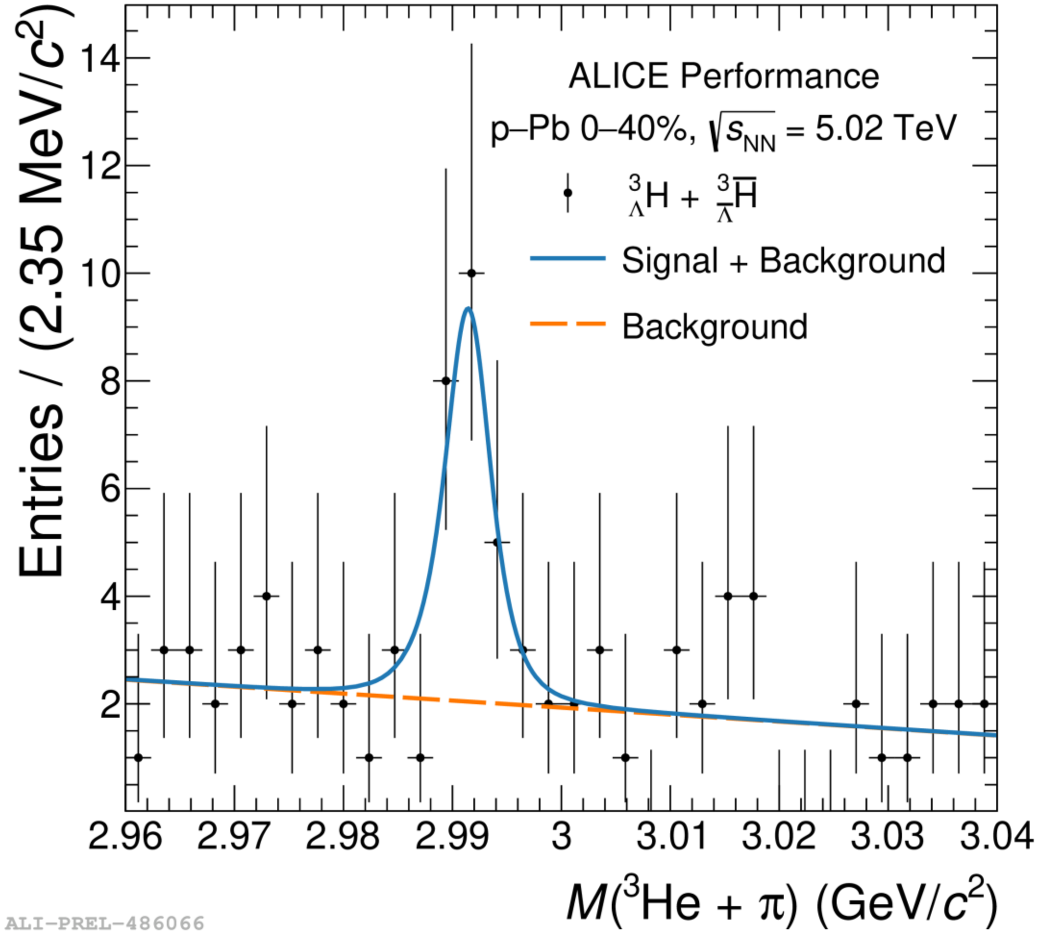
Hypertriton Flow

- Elliptic flow follows an increasing trend with centrality and p_T



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