SQM2024

ALICE

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

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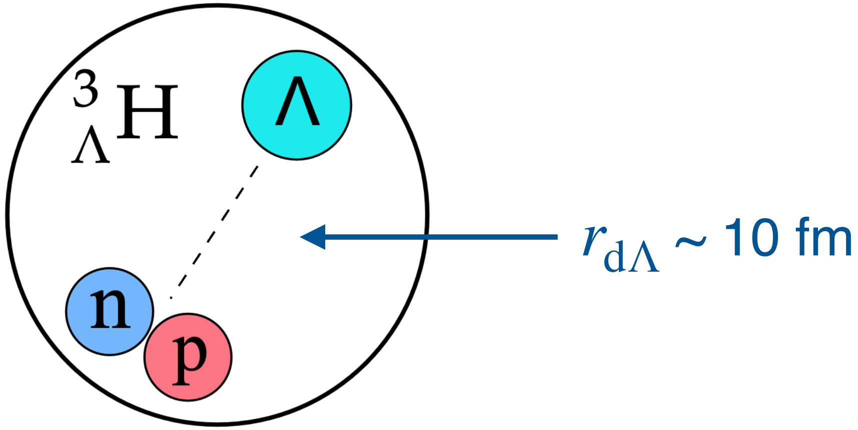
Hypernuclei

- Hypernuclei: bound states of nucleons and hyperons
  - Unique nuclear system can be used as probes to study hyperon-nucleon (Y-N) interaction (⇒hyperons in Neutron Star)

- The simplest case: hypertriton ($^{3}_{\Lambda}$H), consisting of a proton, a neutron, and a Λ hyperon



- But also a special case: small Λ binding energy

$^{3}_{\Lambda}$H: B_{Λ} ~ 100 keV, $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He: B_{Λ} ~ MeV

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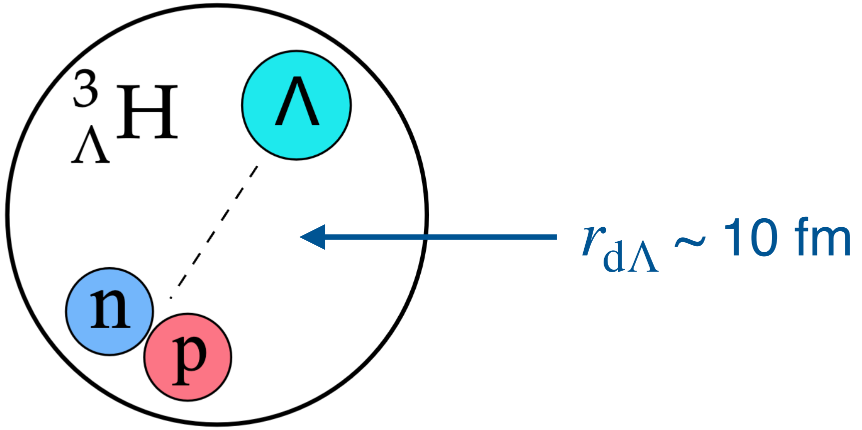

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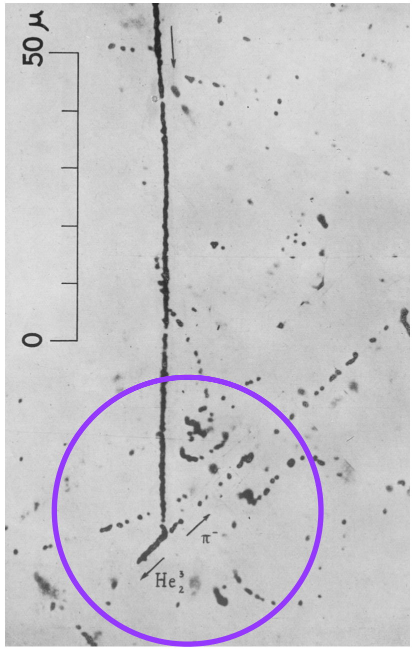
${}^{3}_{\Lambda}\mathrm{H}$: B_{Λ} ~ 100 keV, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$: B_{Λ} ~ MeV

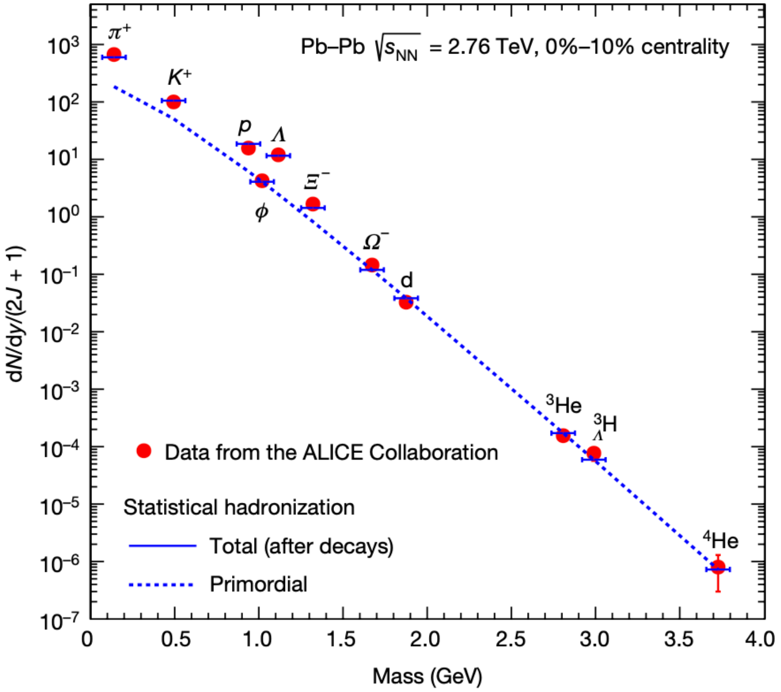
- The first hypernuclei were discovered in 1950s in cosmic ray experiments
- Need to be reconstructed by its decay products



Bonetti et al., Il Nuovo Cimento 11.2, (1954)

Production mechanism of nuclei

- SHM (statistical hadronization model):
  - Ideal hadron resonance gas in thermal equilibrium at the chemical freeze-out stage
  - $\mathrm{d}N/\mathrm{d}y \propto \exp(-m/T_{\mathrm{chem}})$



A. Andronic et al, Nature 561 (2018), 321–330

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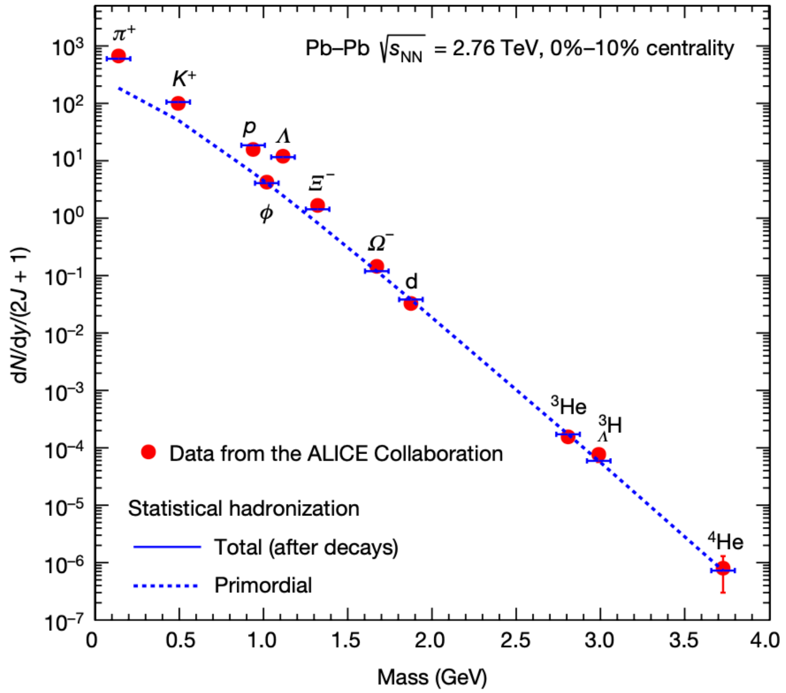
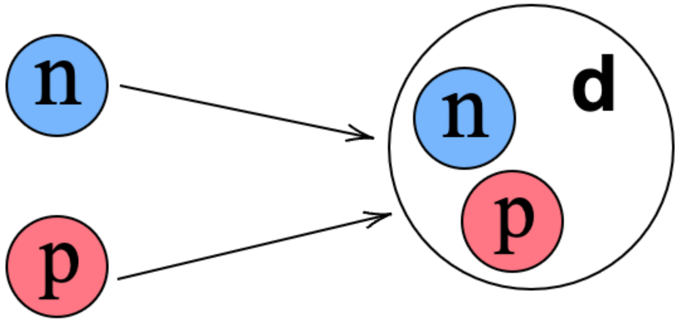


A. Andronic et al, Nature 561 (2018), 321–330

- Coalescence model
  - Nucleus production probability depends on the overlap of
    - Nucleus Wigner function
    - Nucleon distribution function in emission source
  - The closer hadrons in the phase-space ⇒ the higher probability to form a nucleus



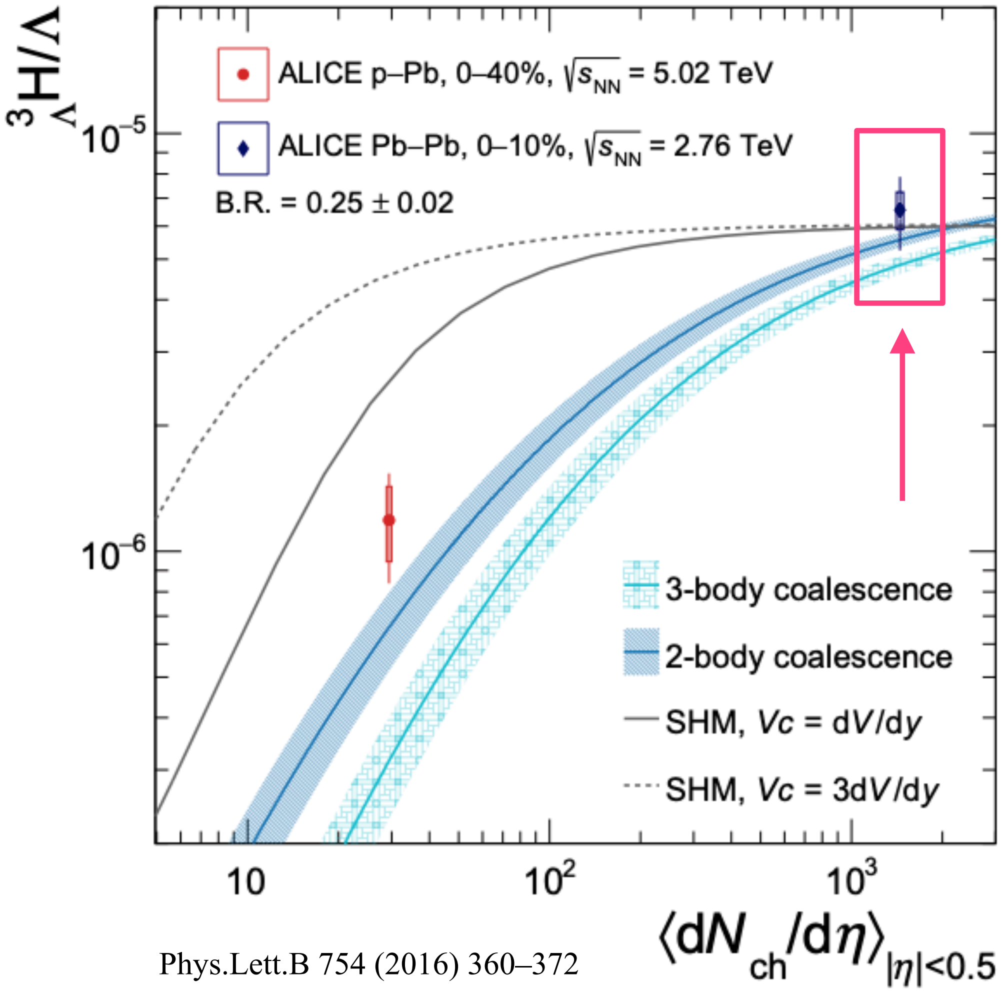
K. J. Sun et al., Phys.Lett.B 792 (2019), 132-137
D. N. Liu et al., arXiv:2404.02701

Production of hypernuclei in ALICE

- Probes for production mechanism with strangeness content and size dependence

➡ Pb-Pb 2.76 TeV with Run 1 data

  - Both models can describe the result due to large uncertainties



Phys.Lett.B 754 (2016) 360–372
Phys.Rev.Lett 128 (2022), 252003
V. Vovchenko et al., Phys.Lett.B 785 (2018), 171
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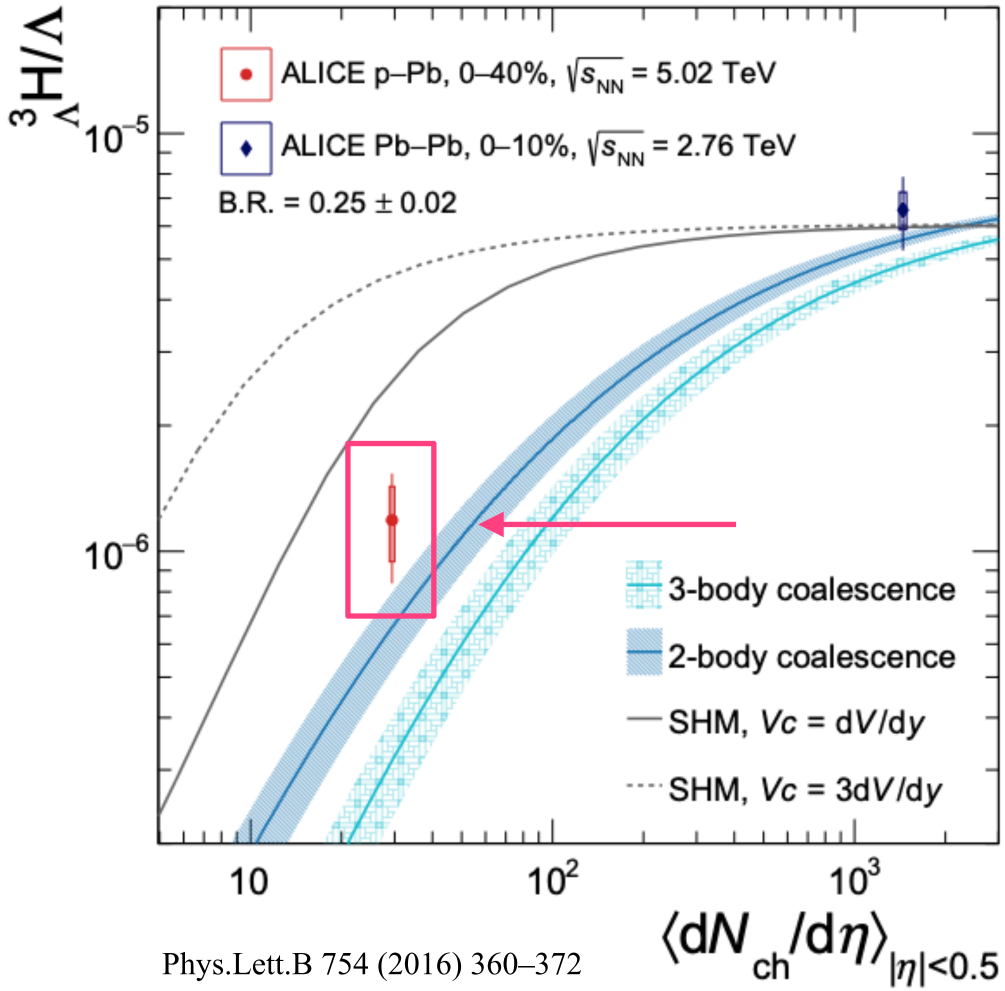
- Significant deviation for model predictions at low multiplicities
- In better agreement with 2-body coalescence model



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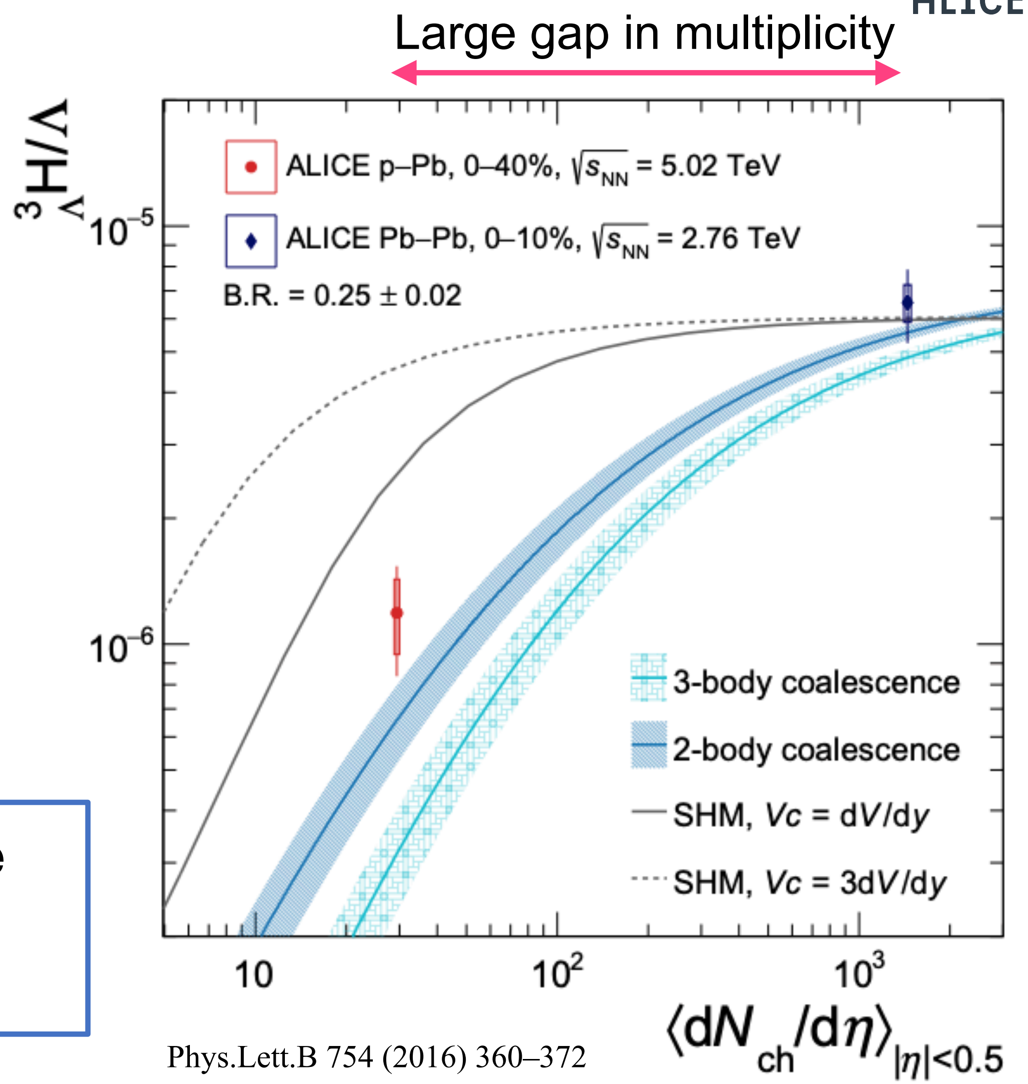

- Further analysis required to figure out the system size dependence
- Measurements of the production of other hypernuclei

Phys.Lett.B 754 (2016) 360–372
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V. Vovchenko et al., Phys.Lett.B 785 (2018), 171
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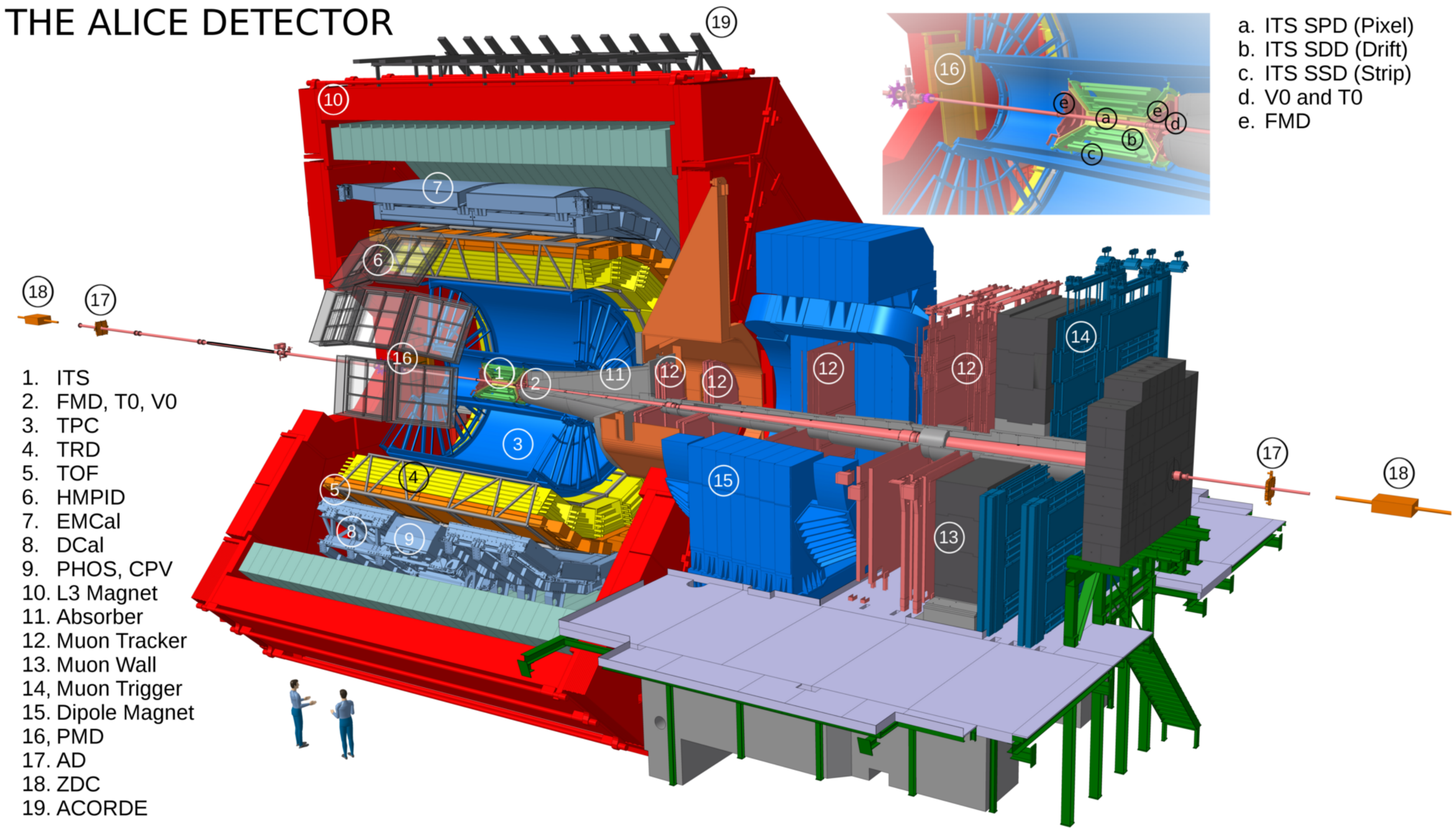
Hypernuclei with ALICE Run 2 Data

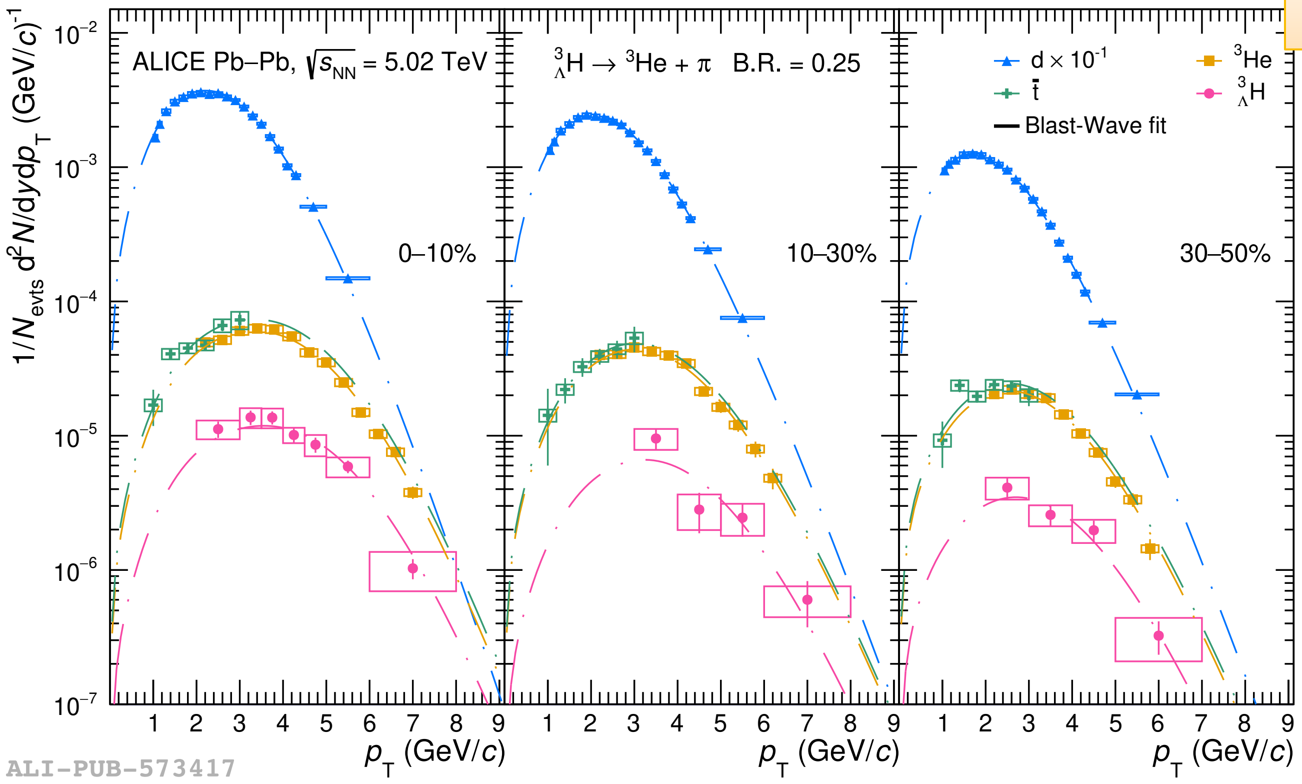
ALICE setup in Run 2

- V0 Detector
  - Centrality estimation
  - Trigger
- Inner Tracking System (ITS)
  - Reconstruct track and vertex
- Time Projection Chamber (TPC)
  - Tracking
  - PID by measuring specific energy loss
- Time-Of-Flight detector (TOF)
  - PID with time of flight



$^{3}_{\Lambda}H$ production in Pb-Pb collisions

ALICE Collaboration, arXiv:2405.19839



New!

- First measurement of p_T differential production of $^{3}_{\Lambda}H$ in Pb-Pb 5.02 TeV collisions

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

Centrality	$\langle\beta_T\rangle$	T (GeV)	n
0–10%	0.694 ± 0.003	0.103 ± 0.005	0.498 ± 0.009
10–30%	0.666 ± 0.003	0.132 ± 0.008	0.507 ± 0.012
30–50%	0.598 ± 0.005	0.152 ± 0.010	0.660 ± 0.022

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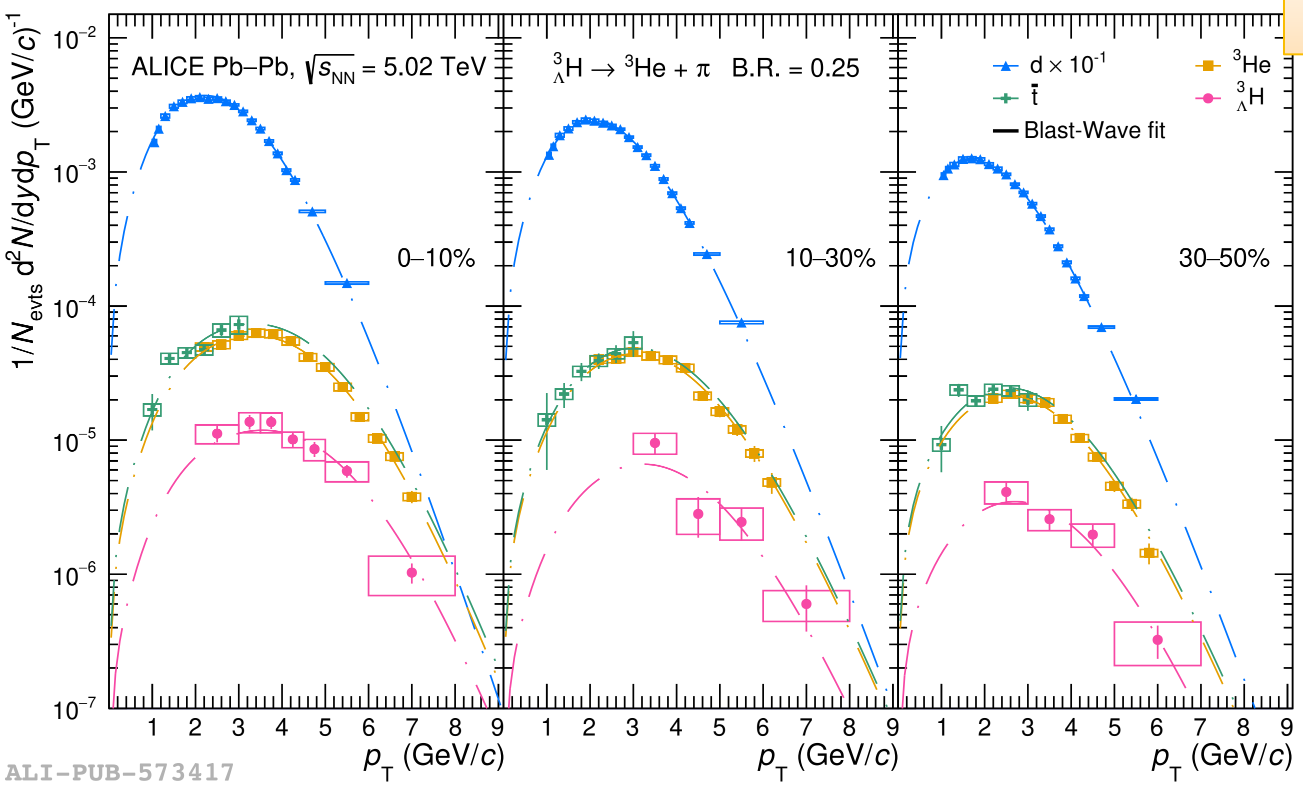

- First measurement of p_T differential production of $^{3}_{\Lambda}H$ in Pb-Pb 5.02 TeV collisions

✳ Combined Blast-Wave fit parameters compatible with the ones obtained from ordinary nuclei (d, t, ^{3}He, ^{4}He)

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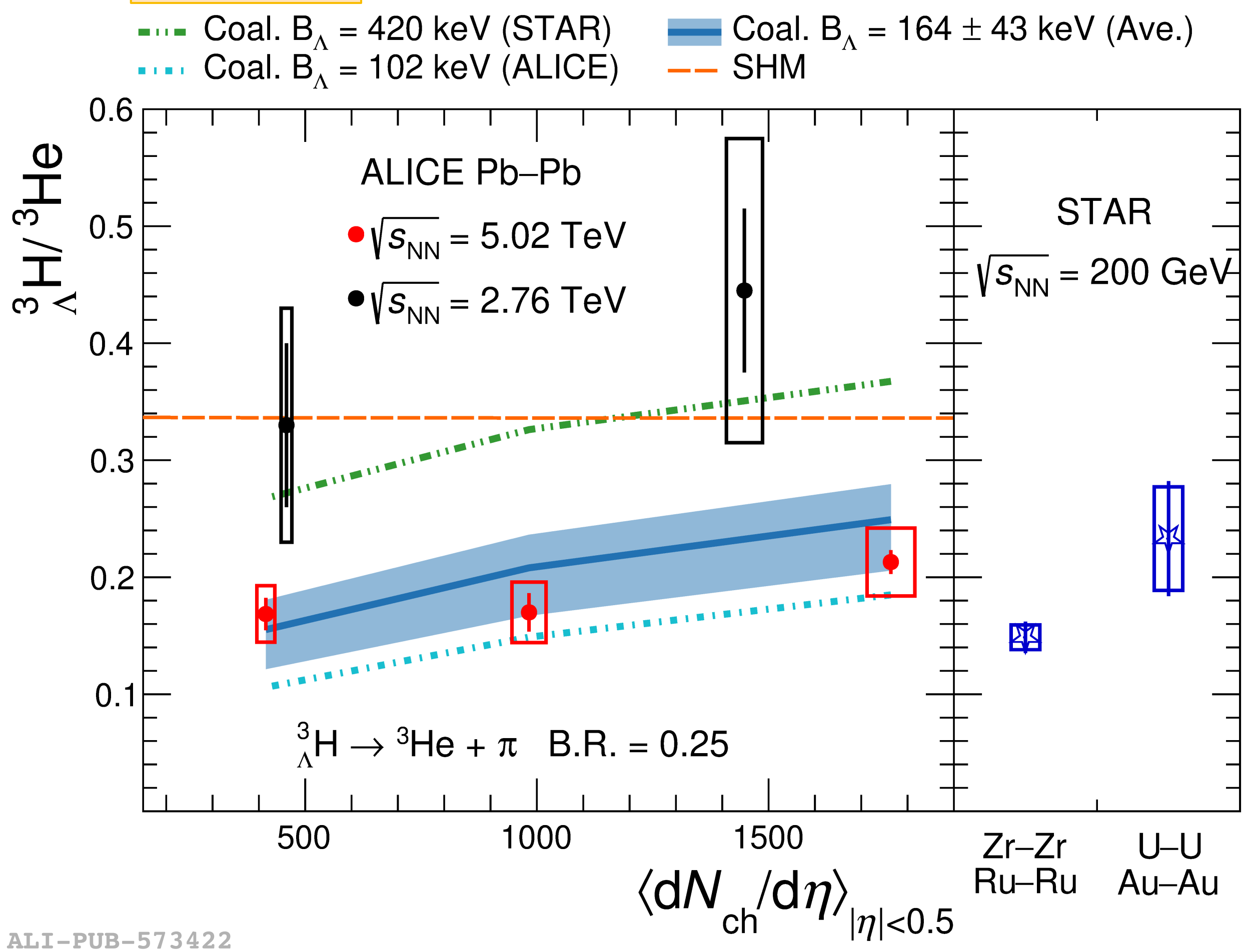
Blast-Wave fit parameters for nuclei in 0-10% Pb-Pb 5.02 TeV

	Fitted particles	$\langle\beta\rangle$	β_{max}	T_{kin} (MeV)	n	χ^2/ ndf
Fit C	d,t,^{3}He,^{4}He	0.684 ± 0.003	0.863 ± 0.005	108 ± 6	0.52 ± 0.02	44.5 / 37

ALICE Collaboration, arXiv:2311.11758

${}^{3}_{\Lambda}H / {}^{3}He$ in Pb-Pb collisions

New!



ALI-PUB-573422

- Multiplicity dependence of ${}^{3}_{\Lambda}H / {}^{3}He$ 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 ${}^{3}_{\Lambda}H / {}^{3}He$ ratio with smaller size of produced medium as suggested by the STAR results

ALICE Collaboration, arXiv:2405.19839
D. N. Liu et al., arXiv:2404.02701
STAR, arXiv:2310.12674

$^{3}_{\Lambda}H / ^{3}He$ in Pb-Pb collisions

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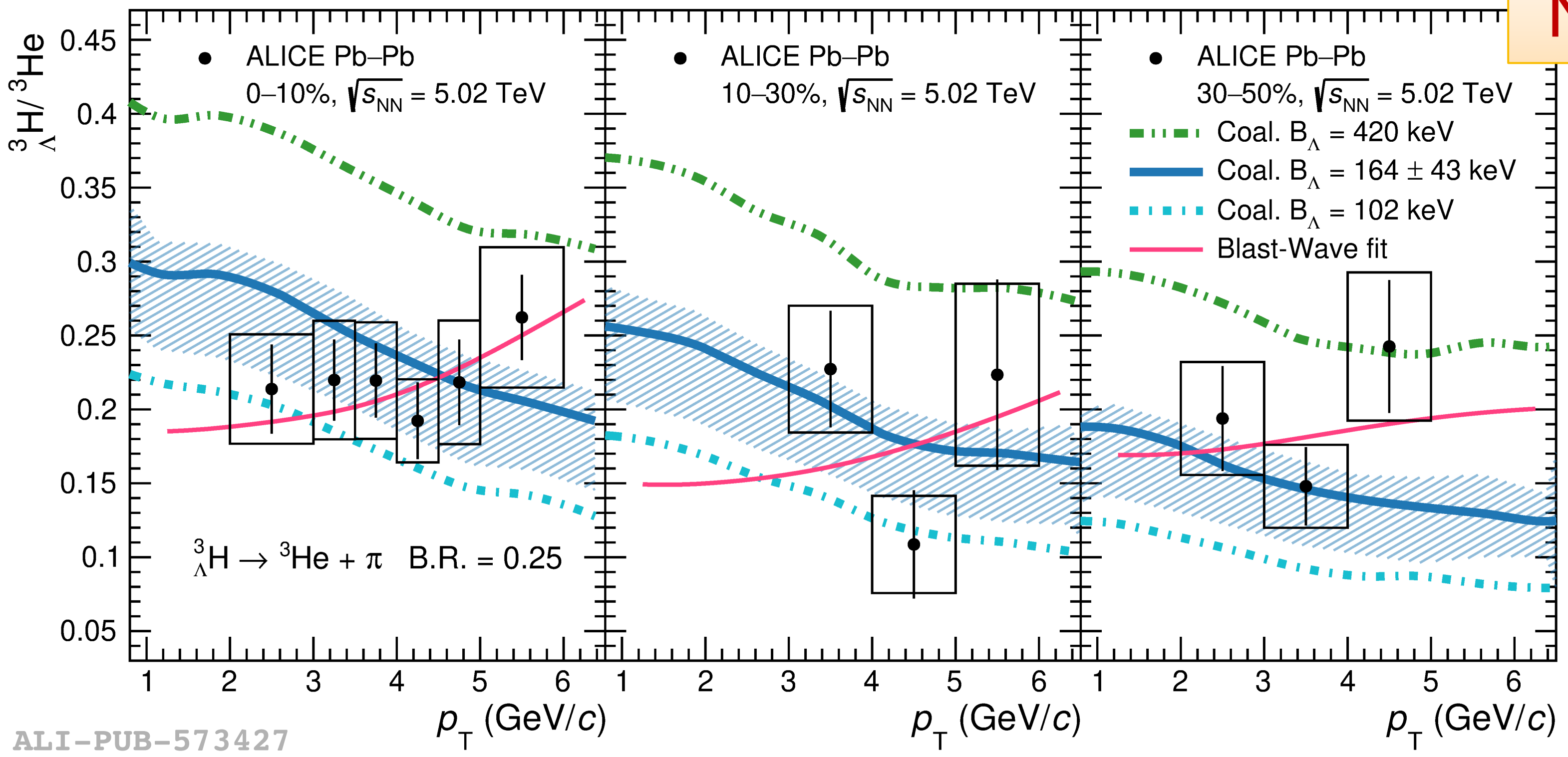
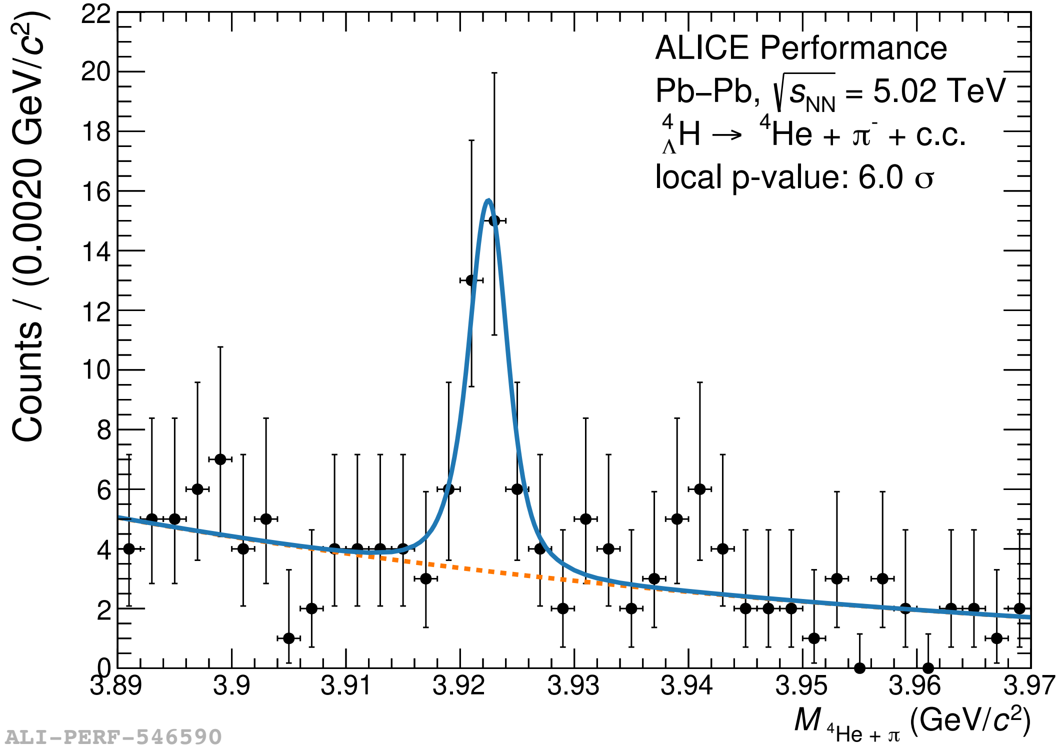


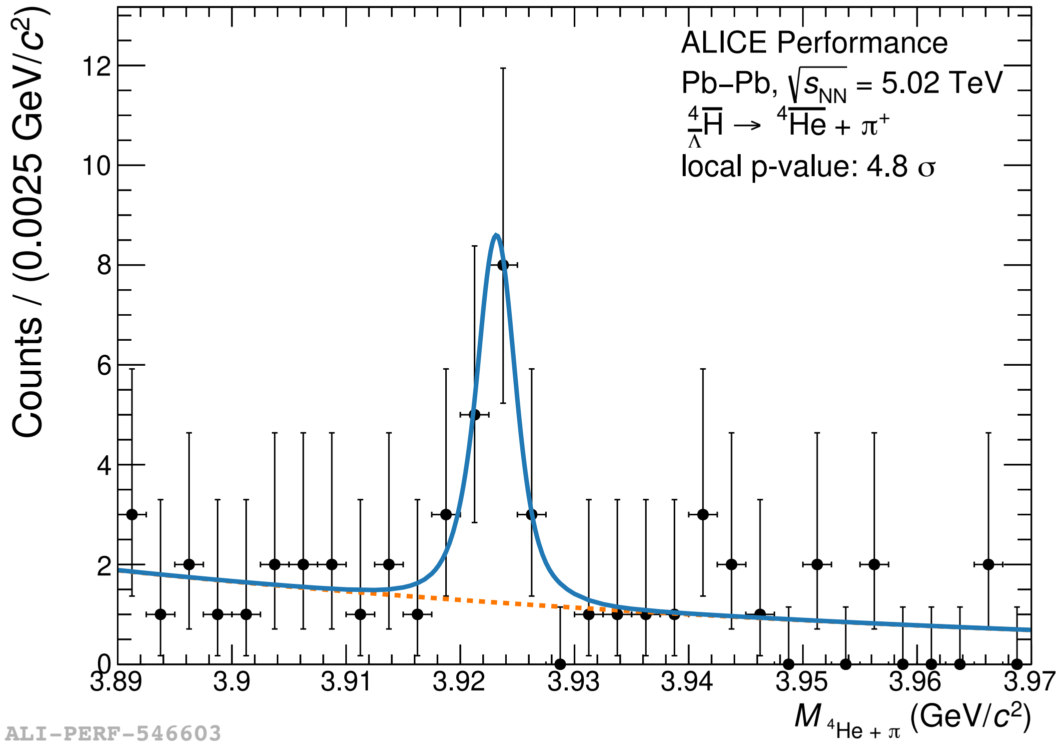
ALICE Collaboration, arXiv:2405.19839
D. N. Liu et al., arXiv:2404.02701

- p_{T}-dependence of $^{3}_{\Lambda}H / ^{3}He$ ratio
  - Different trends for Blast-Wave extrapolation and coalescence predictions
  - Hard to draw a conclusion with the current experimental uncertainties (doable in Run 3!)

${}^{4}_{\Lambda}\mathrm{H}$ signal in Pb-Pb collisions

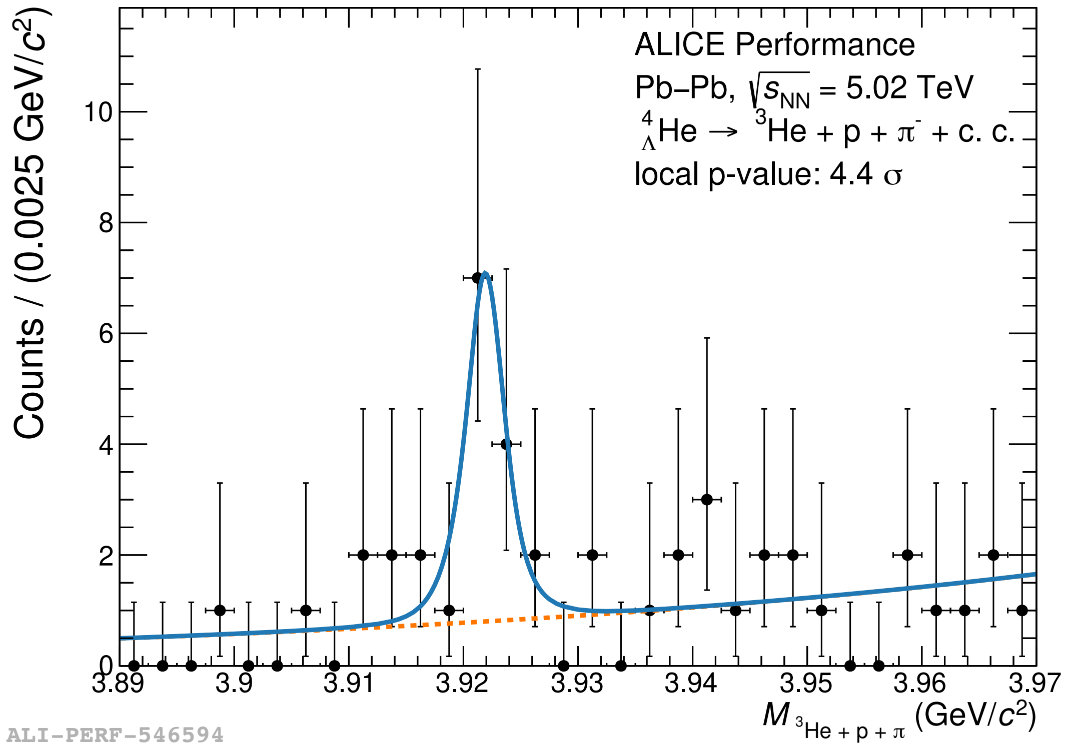
- First observation of ${}^{4}_{\Lambda}\mathrm{H}$ (${}^{4}_{\Lambda}\overline{\mathrm{H}}$) at LHC energies

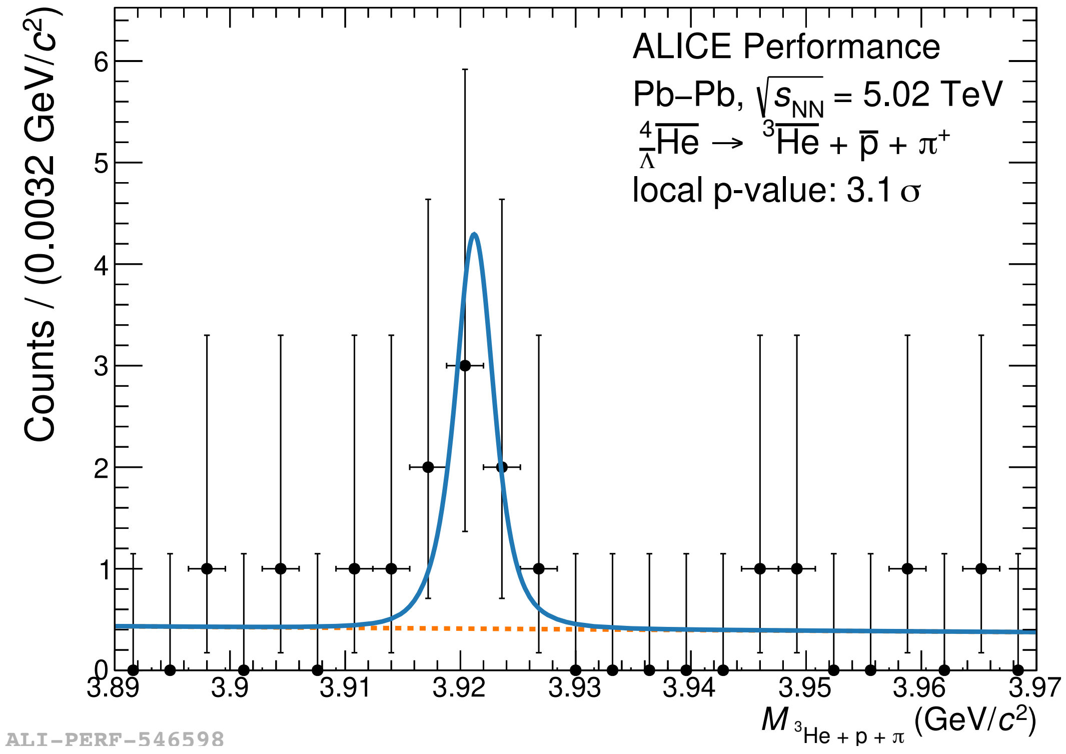




$^{4}_{\Lambda}$He signal in Pb-Pb collisions

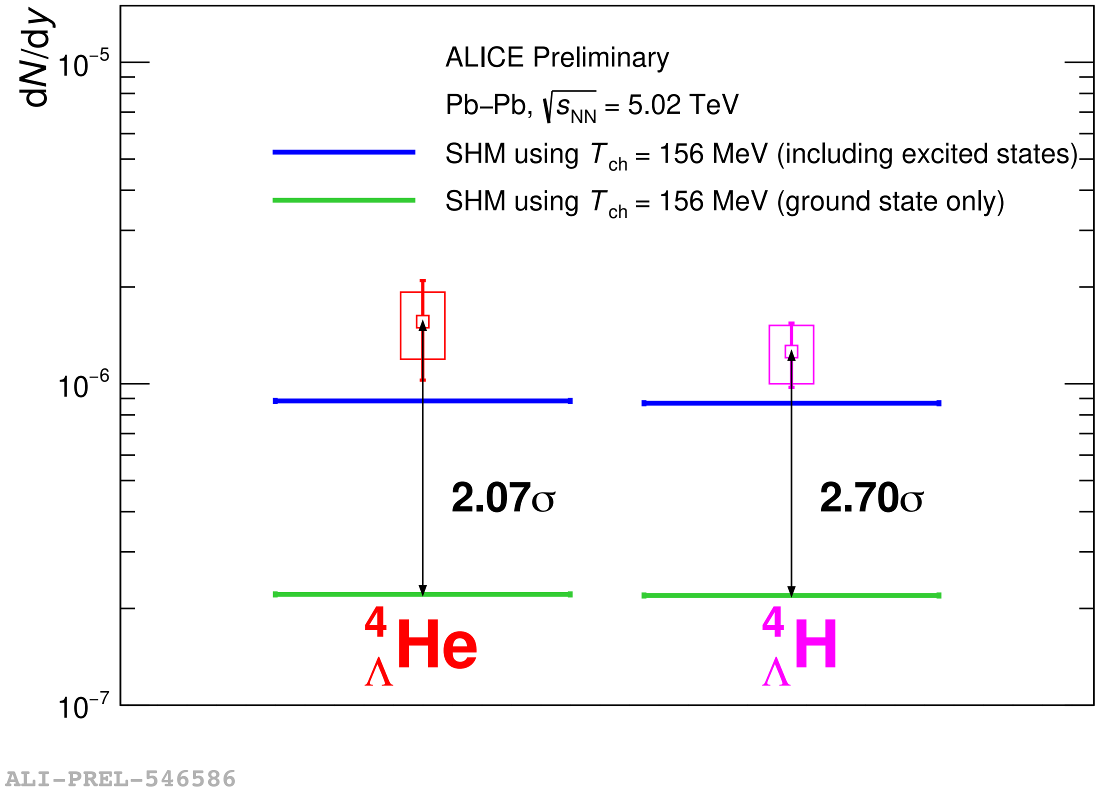
- First signal of $^{4}_{\Lambda}$He ($^{4}_{\Lambda}\overline{\text{He}}$) in heavy-ion collisions

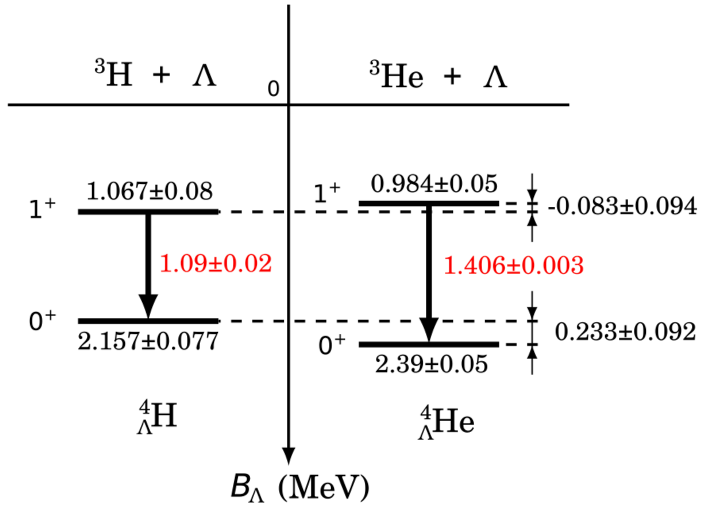




Production of A = 4 hypernuclei in Pb-Pb collisions

- Production of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$
  - The SHM expected yields are enhanced by a factor ~ 4 with excited states
  - Both are in agreement with SHM predictions including contributions from feed-down effects



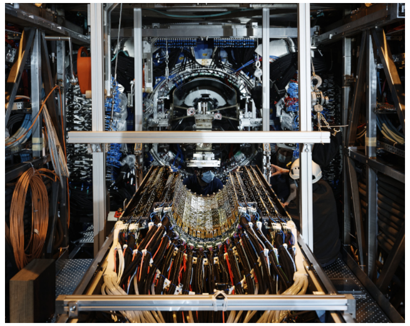


M. Schäfer et al., Phys. Rev. C 106 (2022), L031001

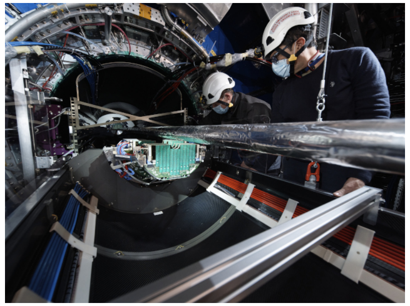
Hypernuclei with ALICE Run 3 Data

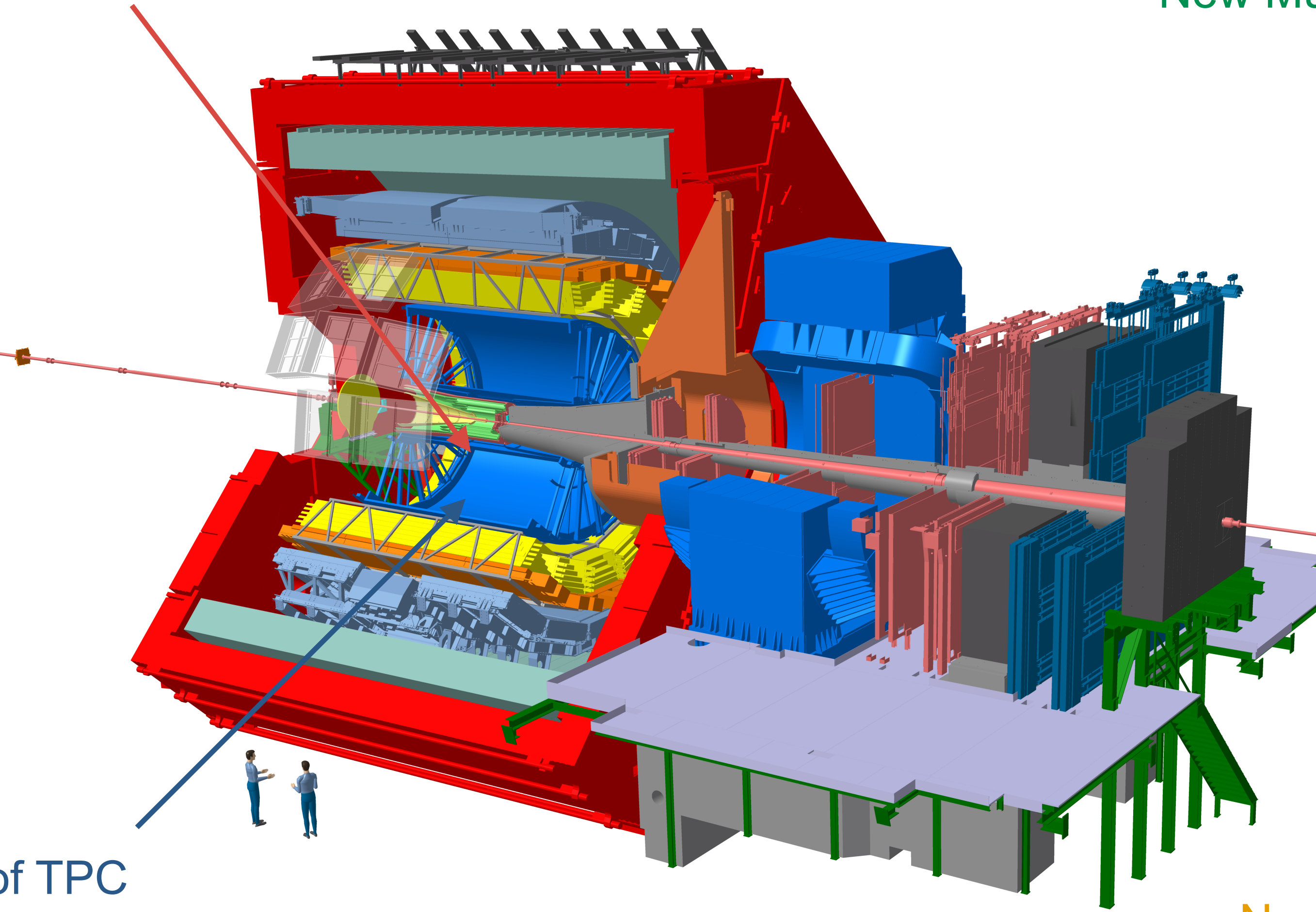
ALICE Upgrade for Run 3

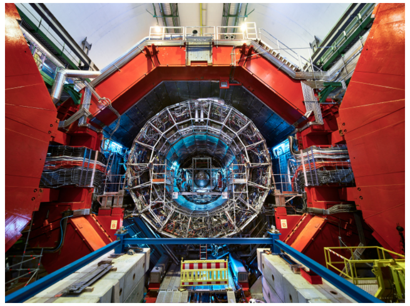
New Inner Tracking System



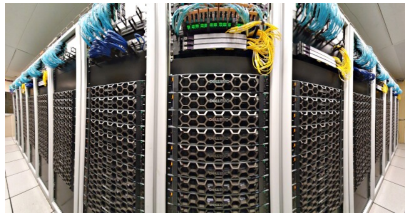
New Fast Interaction Trigger (FIT)
New Muon Forward Tracker (MFT)







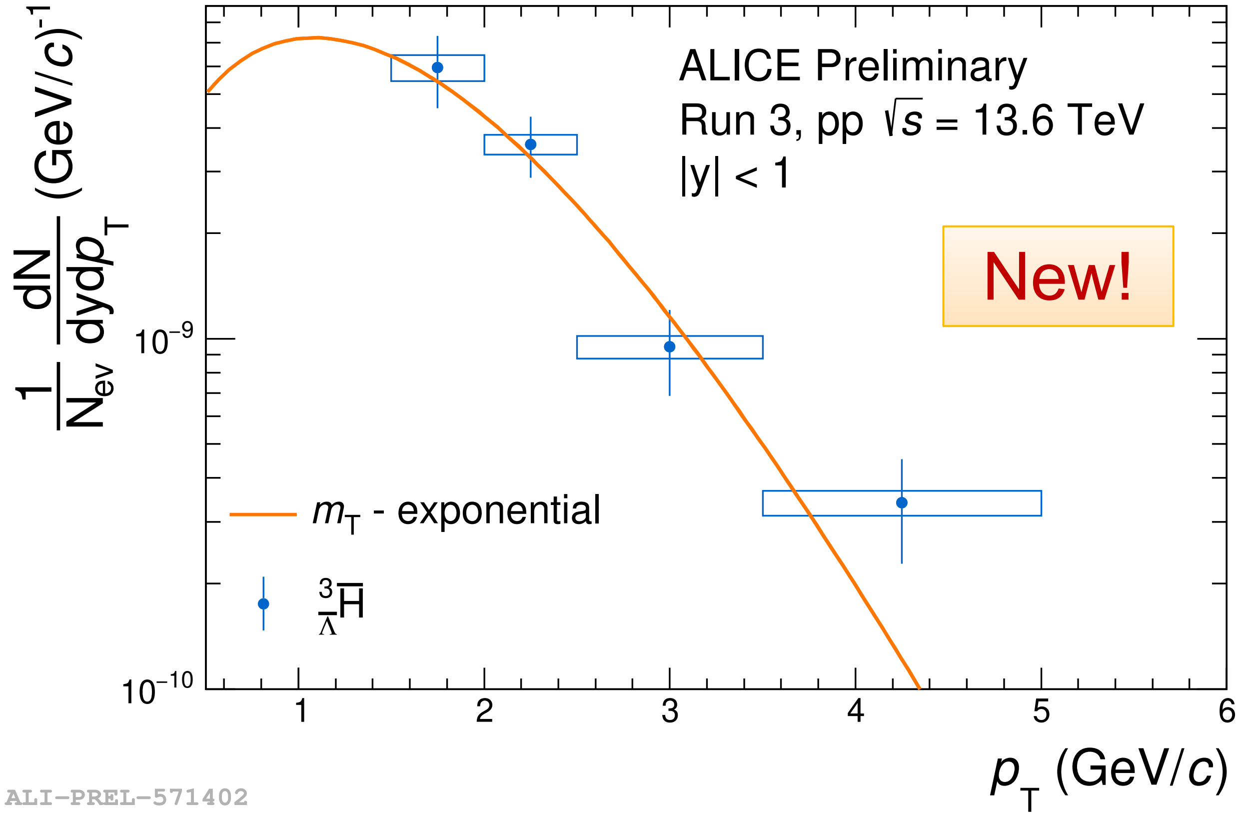
New GEM technology of TPC



New data processing system

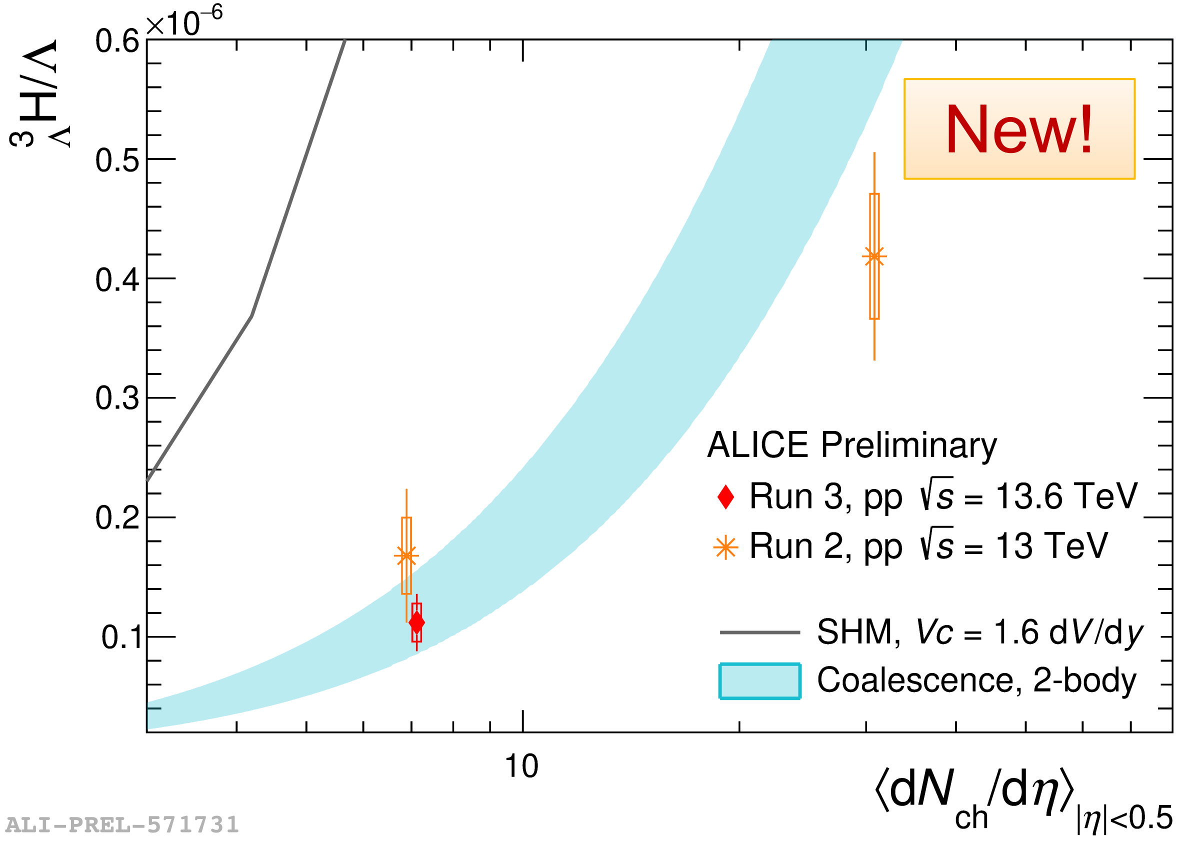
$^{3}_{\Lambda}H$ production in pp collisions

- First measurement of p_T differential production of hypertriton in pp 13.6 TeV collisions
  - Results obtained from antimatter analysis only
  - Total yield can be estimated by extrapolation of the p_T spectrum



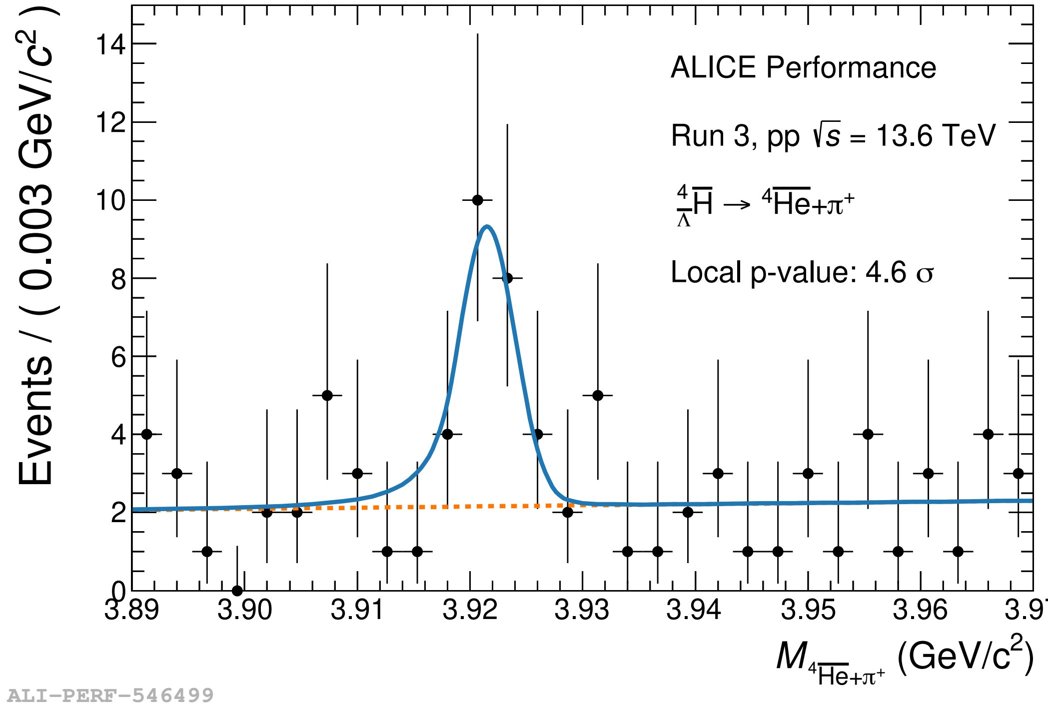
${}^{3}_{\Lambda}\mathrm{H} / \Lambda$ in pp collisions

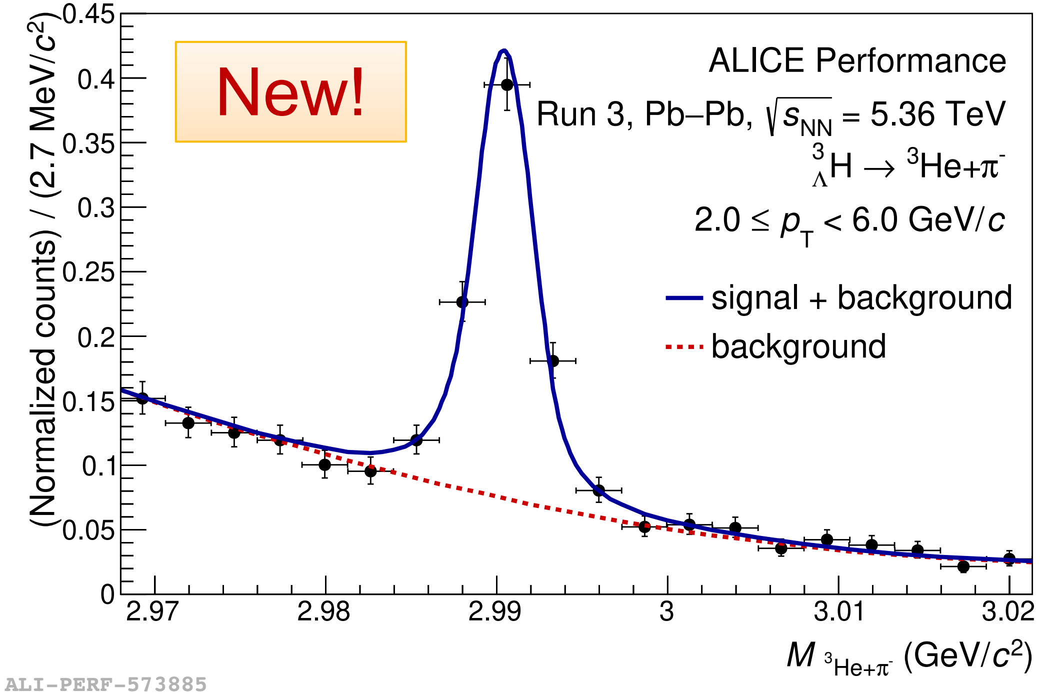
- ${}^{3}_{\Lambda}\mathrm{H} / \Lambda$ ratio in pp collisions
  - Twice better precision than Run 2
  - Compatible with Run 2 preliminary results and 2-body coalescence prediction



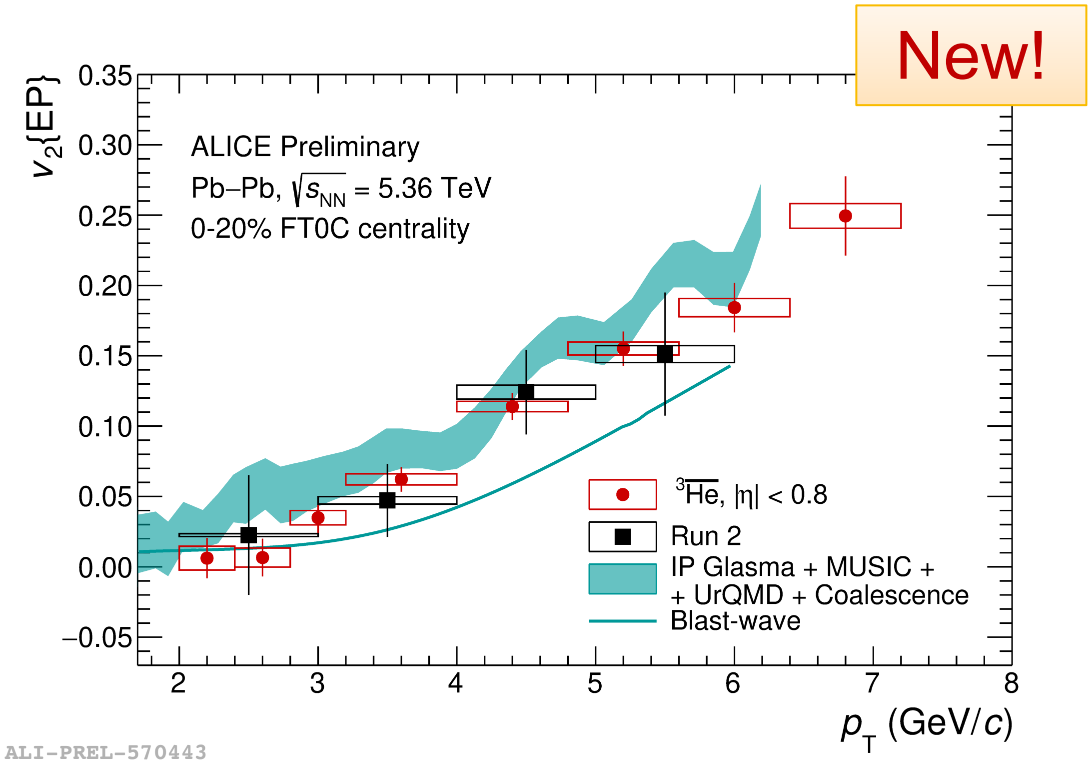
Performance with ALICE Run 3 data

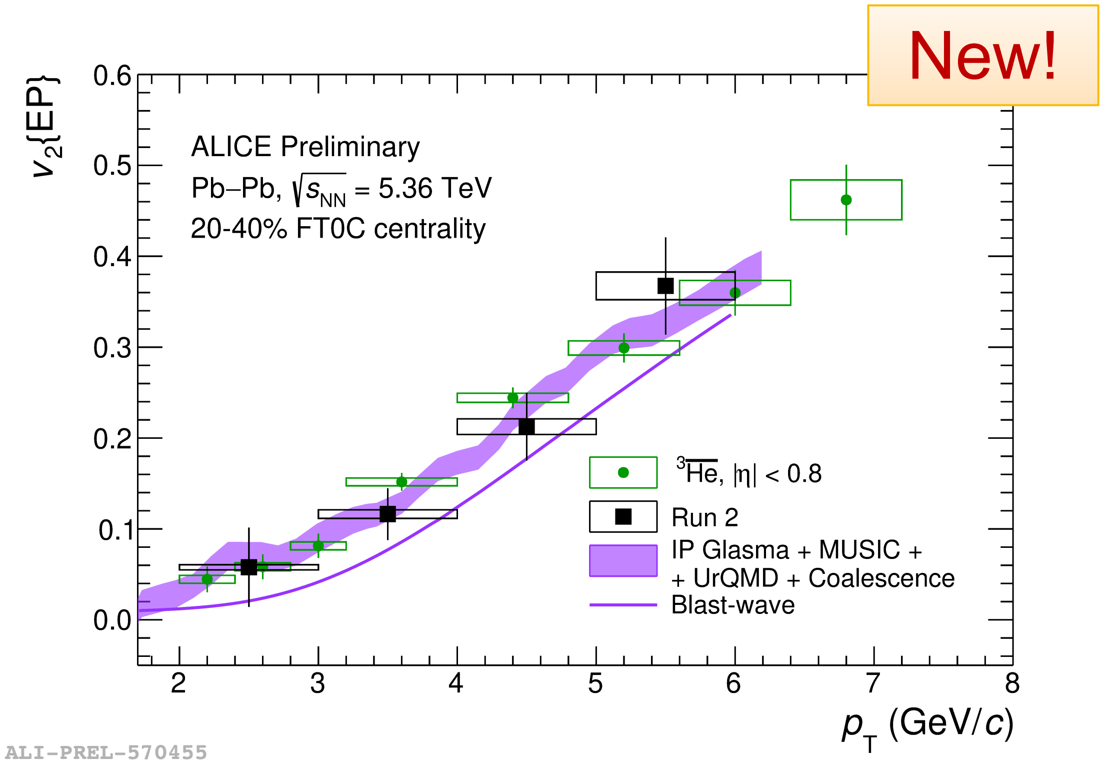
- Heavier hypernuclei (A = 4) measurable in pp collisions
- Significant hypertriton peak in Run 3 Pb-Pb collisions





Flow measurement in Run 3

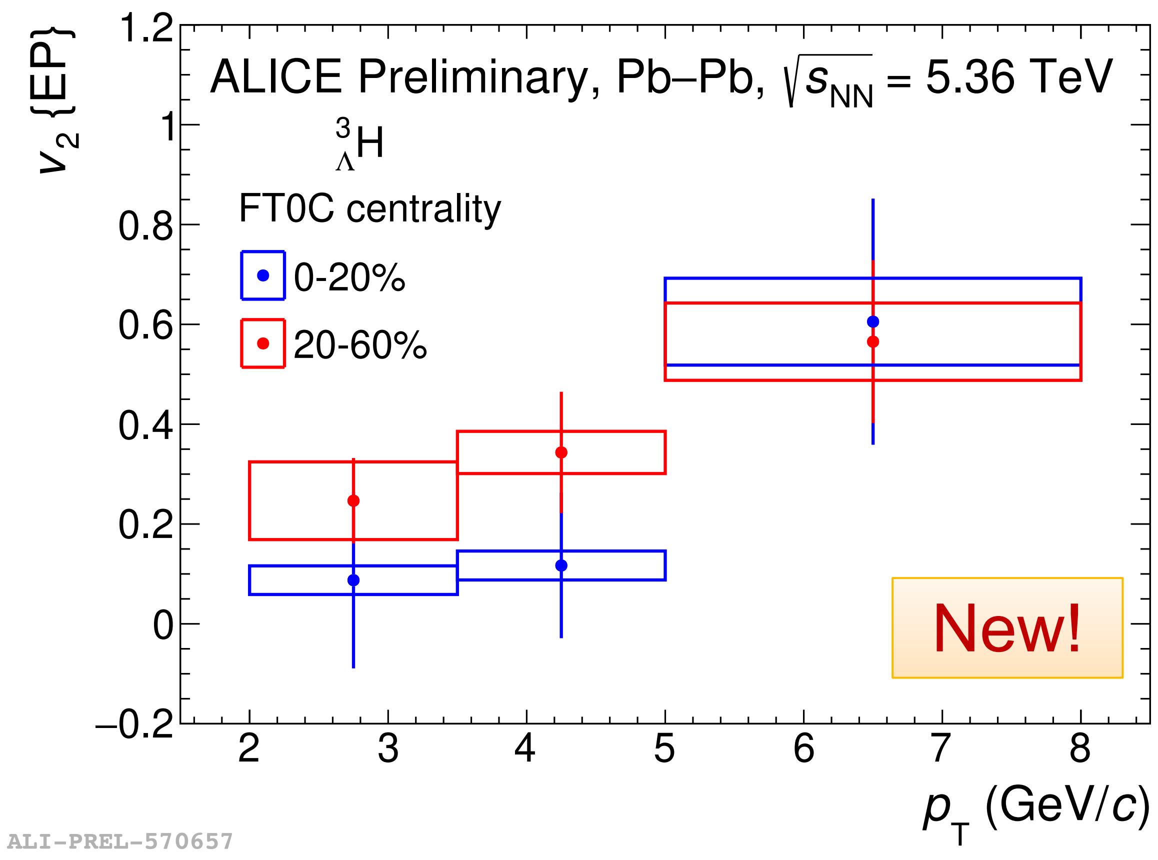




- More precise flow measurement of $^{3}\mathrm{He}$ in Run 3
- Can we measure the flow of $^{3}_{\Lambda}\mathrm{H}$?

Flow of ${}^{3}_{\Lambda}\mathrm{H}$ in Run 3 Pb-Pb collisions

- First measurement of elliptic flow of ${}^{3}_{\Lambda}\mathrm{H}$
- v_2 increases with both centrality and p_{T}



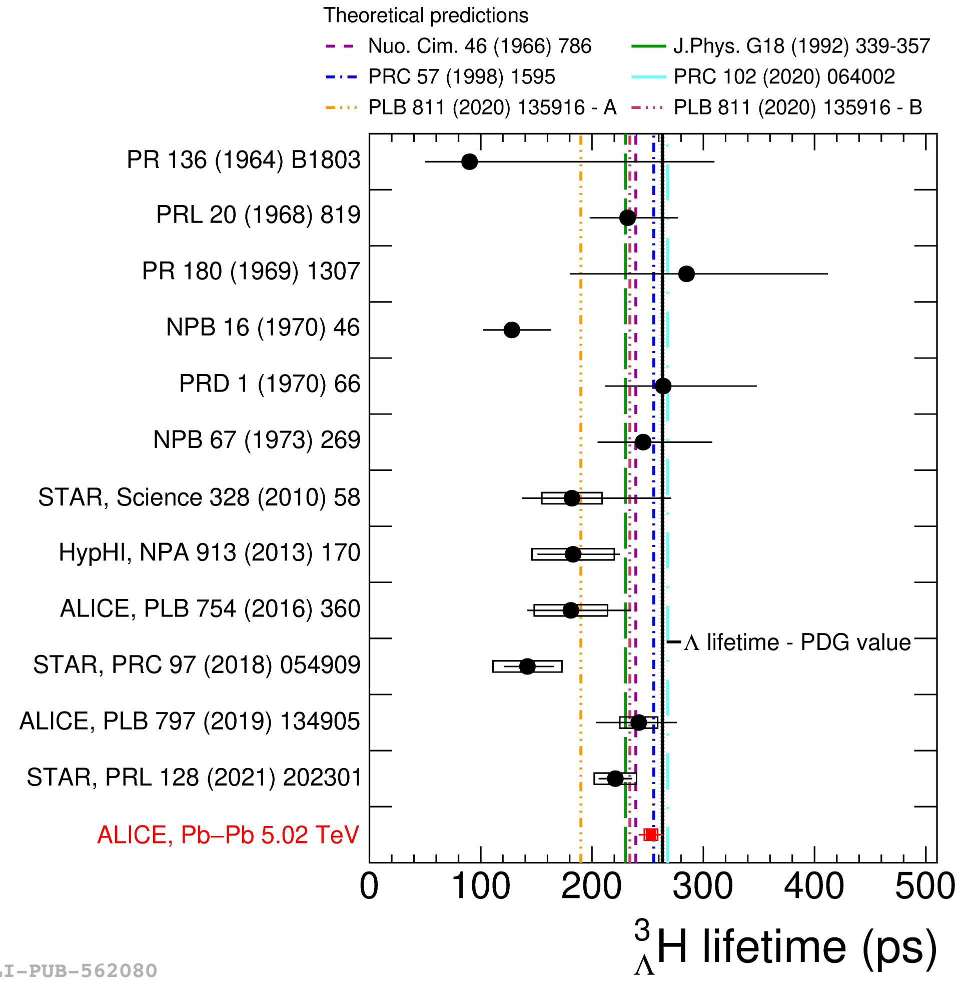
Summary

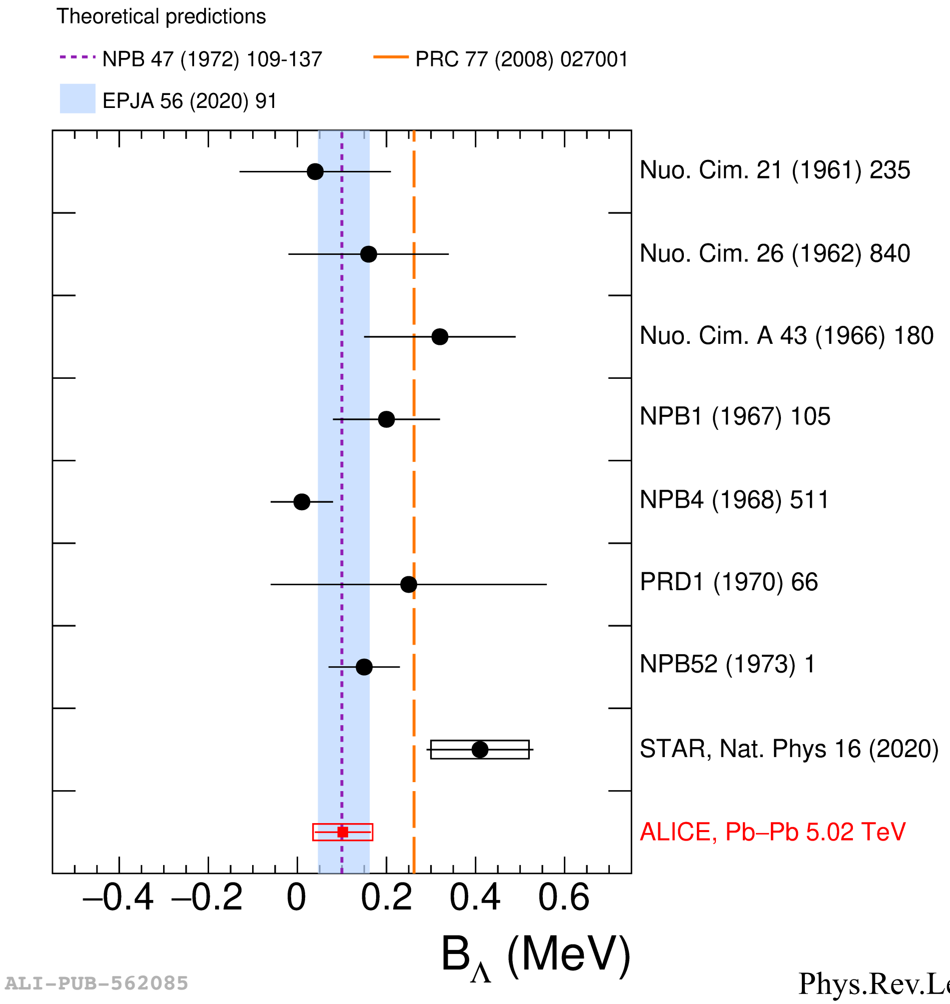
- New results of ${}^{3}_{\Lambda}\mathrm{H}$ yield with ALICE Run 2 and Run 3 data
  - First p_{T} differential measurements of hypertriton production in Pb-Pb 5.02 TeV and pp 13.6 TeV collisions
  - ${}^{3}_{\Lambda}\mathrm{H}\,/\,{}^{3}\mathrm{He}$ ratio as a probe to distinguish between different nucleosynthesis mechanisms of hypernuclei, in favor of coalescence model
- Observation of A = 4 hypernuclei with ALICE Run 2 data
  - In agreement of SHM in consideration of feed-down effects, populating the ground states for both ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$
- Outlook for the new Run 3 data:
  - Precise studies and more analyses with large statistics (target luminosity: 200 pb^{-1} for pp, 7 nb^{-1} for Pb-Pb)
  - Production of A = 4 hypernuclei in pp collisions

Thanks for your attention!

Backup

Properties of hypernuclei ($^{3}_{\Lambda}$H)

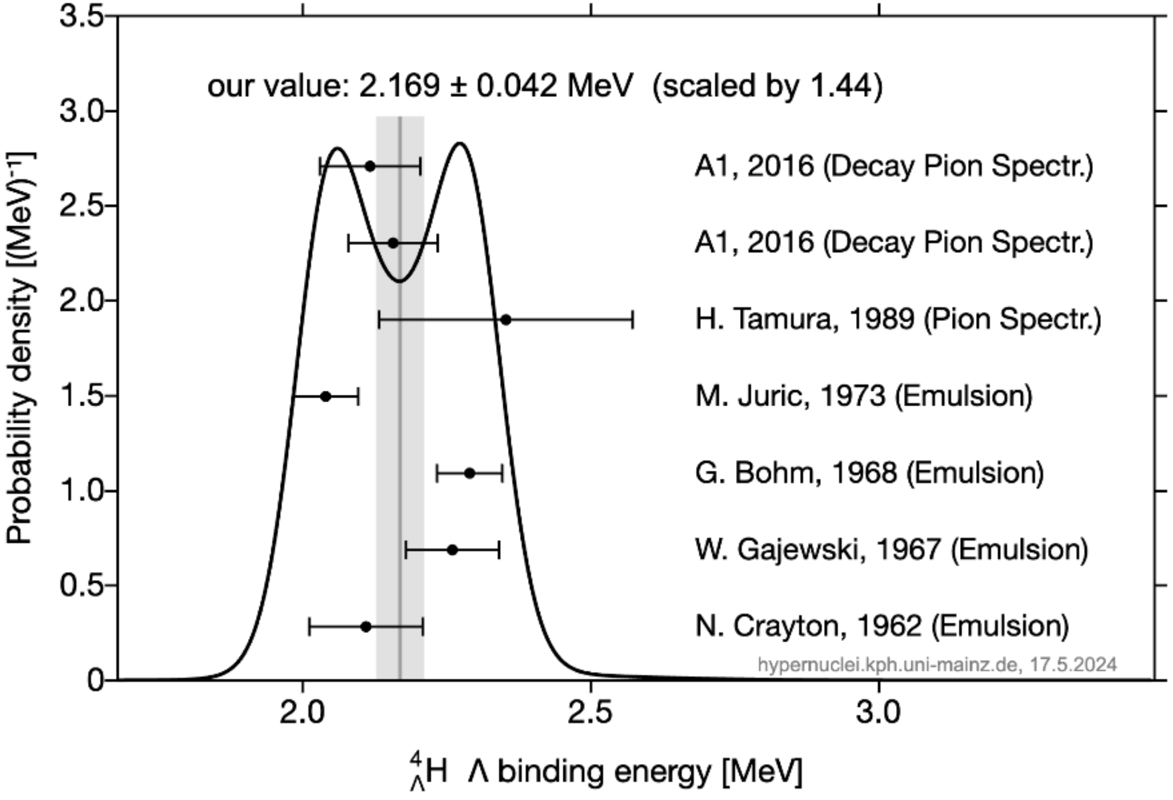


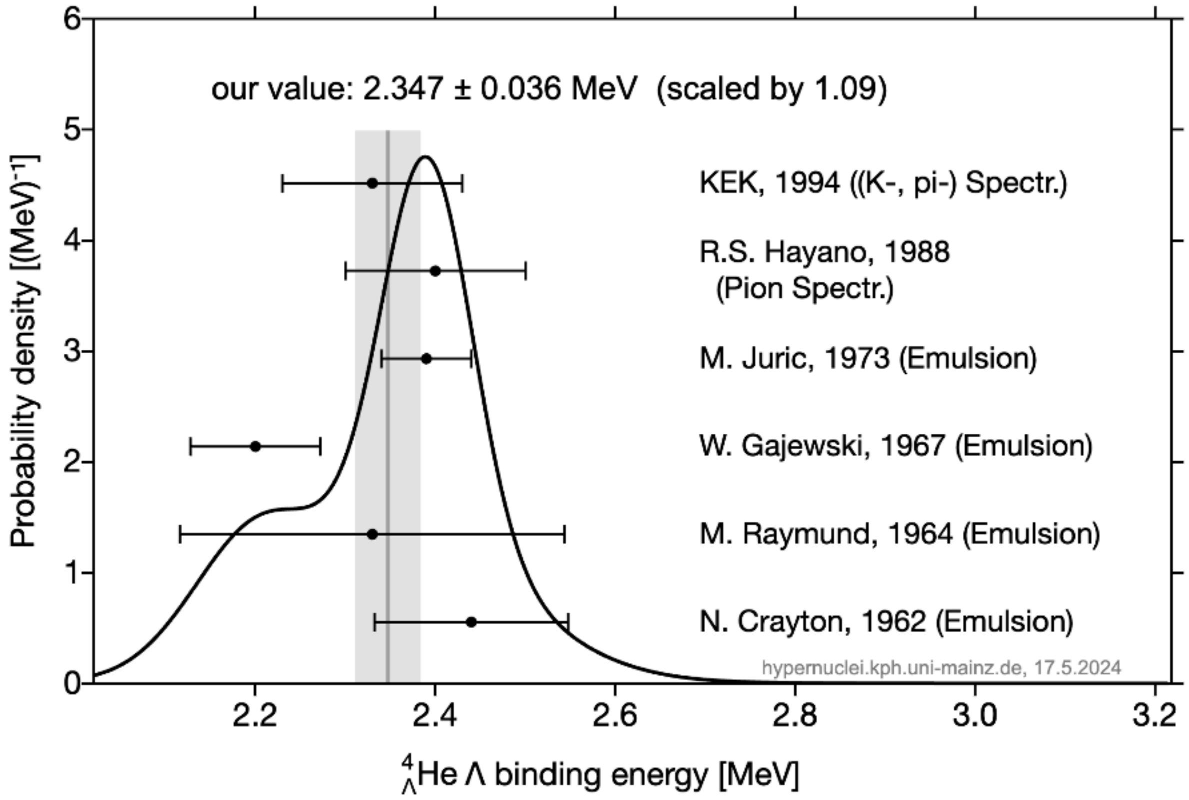


Phys.Rev.Lett 131 (2023) , 102302

- Recent measurements of $^{3}_{\Lambda}$H shows $\tau(^{3}_{\Lambda}\text{H}) \approx \tau(\Lambda)$, B_{Λ} ~ hundreds keV

Properties of hypernuclei (${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$)





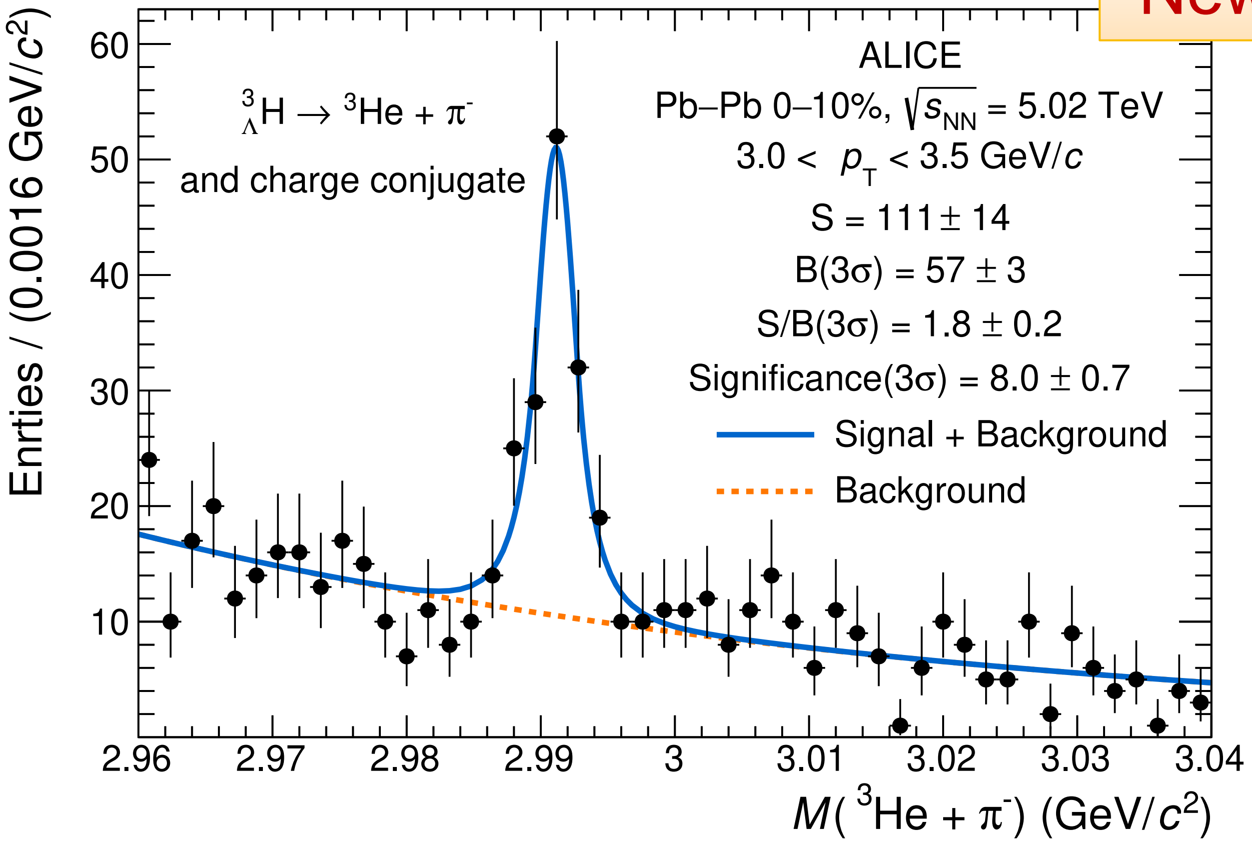
- Both ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ have a Λ binding energy of the order of MeV

The Hypernuclear Database, https://hypernuclei.kph.uni-mainz.de/

Invariant mass performance

- Hypertriton in Run 2 Pb-Pb collisions

New!

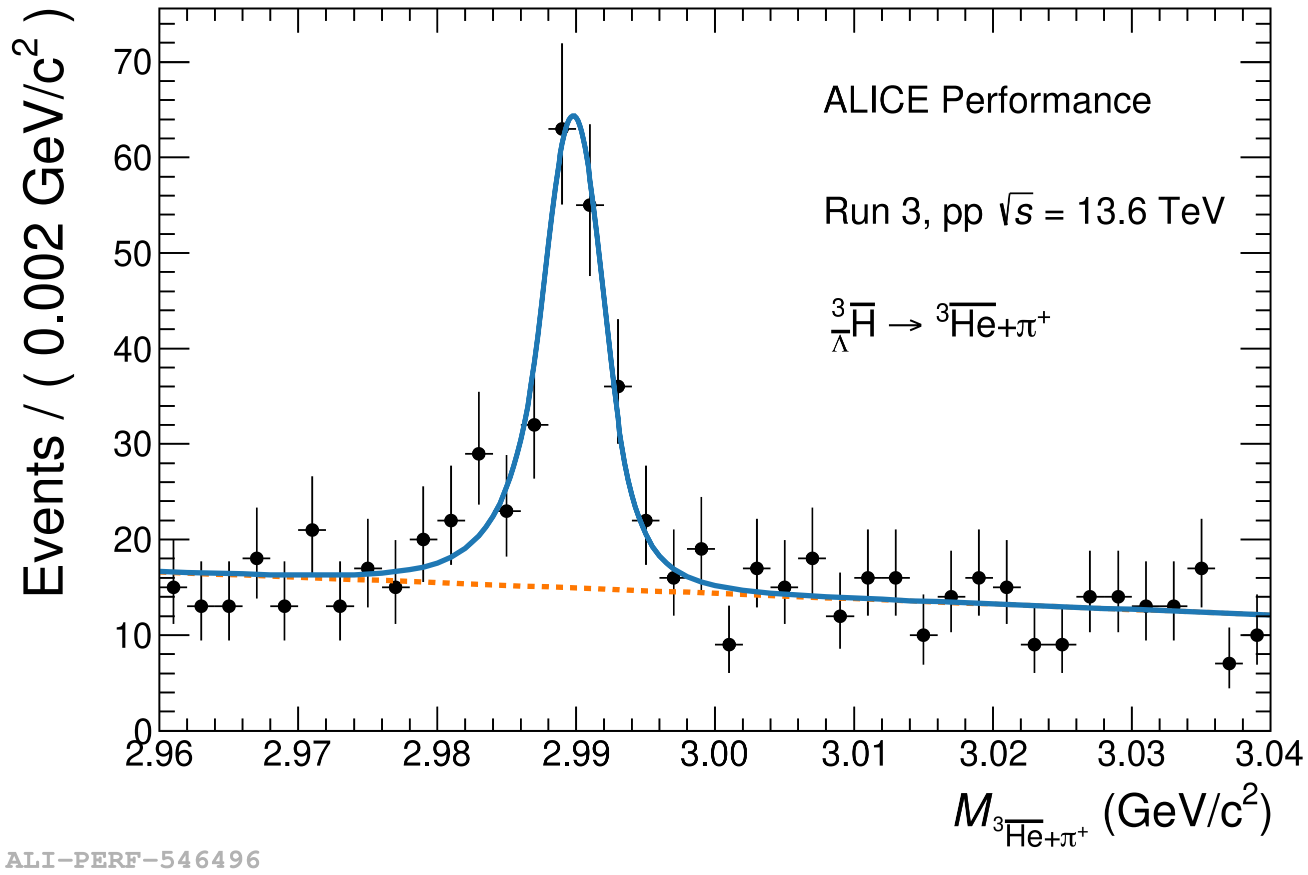


ALI-PUB-573412

ALICE Collaboration, arXiv:2405.19839

Invariant mass performance

- Hypertriton in Run 3 pp collisions



Reconstruction