Hypernuclei at the LHC

HYP Conference 2025, Tokyo

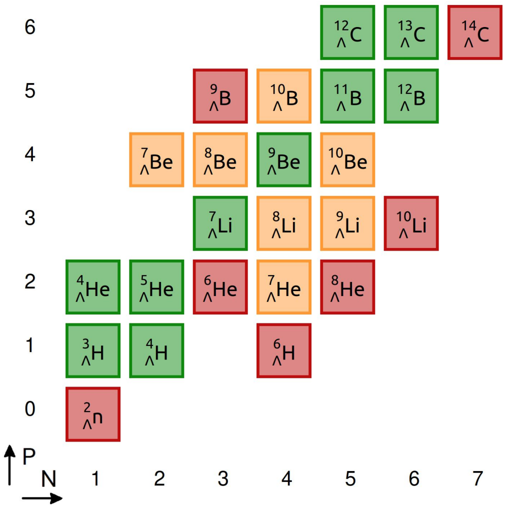
CERN

Francesco Mazzaschi

Hypernuclei

Hypernuclei: bound states of strange baryons (hyperons) and ordinary nuclei

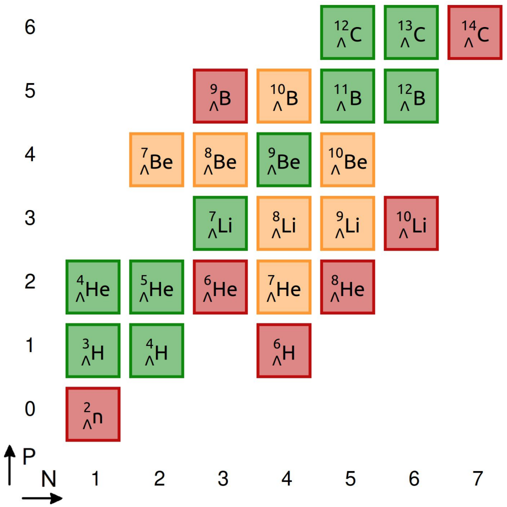
- Extend the nuclear chart to a third dimension
- Unique probes for studying the hyperon-nucleon interactions

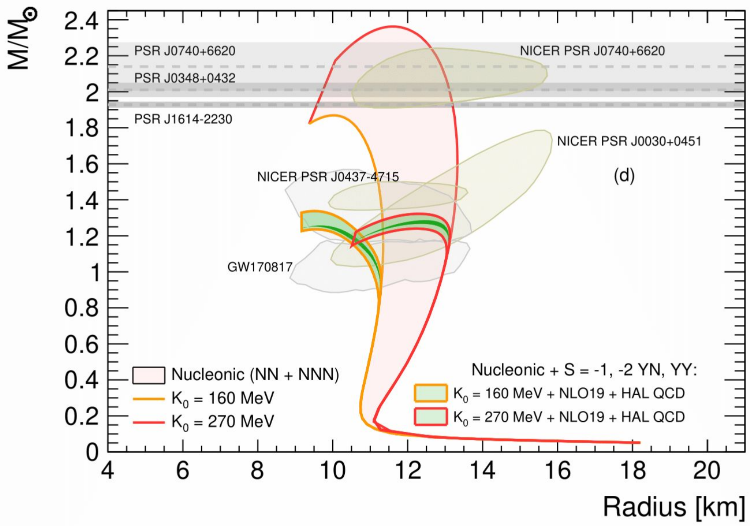


Hypernuclei

Hypernuclei: bound states of strange baryons (hyperons) and ordinary nuclei

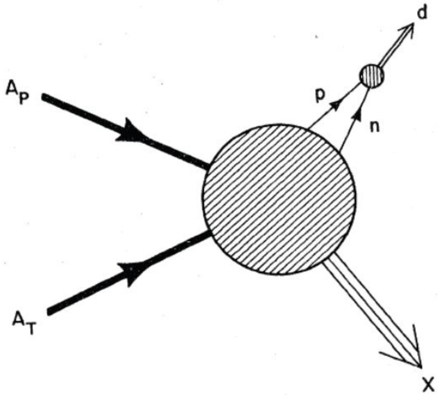
- Extend the nuclear chart to a third dimension
- Unique probes for studying the hyperon-nucleon interactions
    - Relevant also for astrophysics





Eur.Phys.J.A 61 (2025) 3, 59

(Hyper)Nucleosynthesis at the LHC



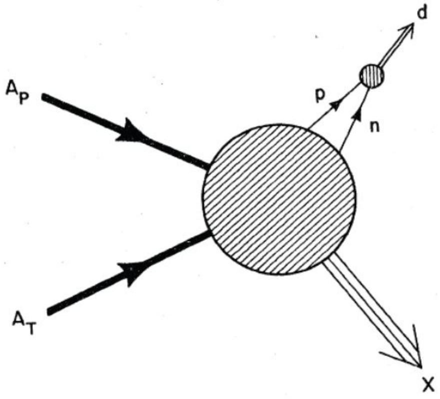
Coalescence

📕 Phys.Rev. C21, 1301 (1980)

Baryons close in phase space can form a nucleus

- Interplay between the configuration of the phase space of the nucleons and the wave function of the nucleus

(Hyper)Nucleosynthesis at the LHC



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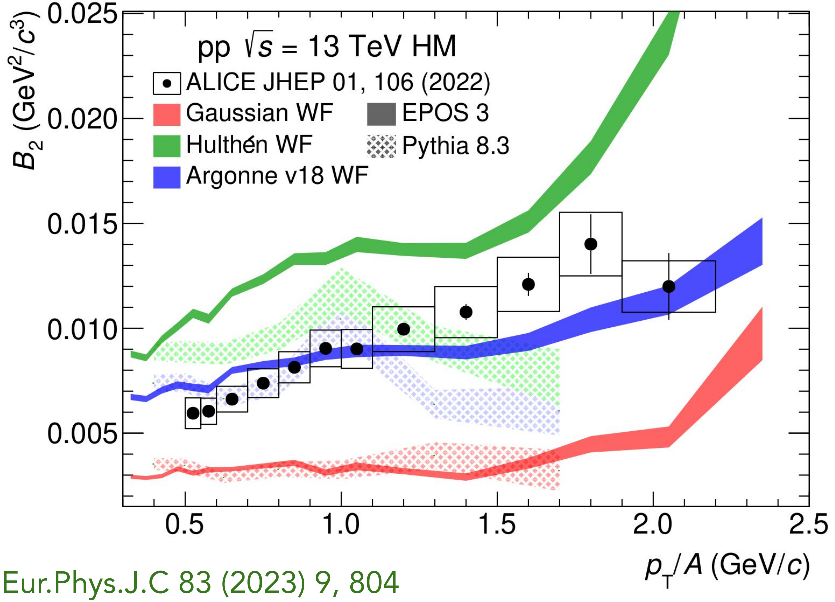
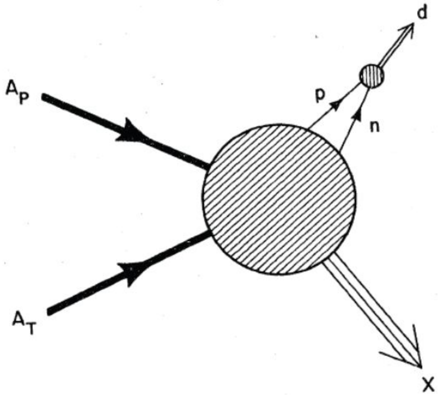


📕 Eur.Phys.J.C 83 (2023) 9, 804

(Hyper)Nucleosynthesis at the LHC



Coalescence

Phys.Rev. C21, 1301 (1980)

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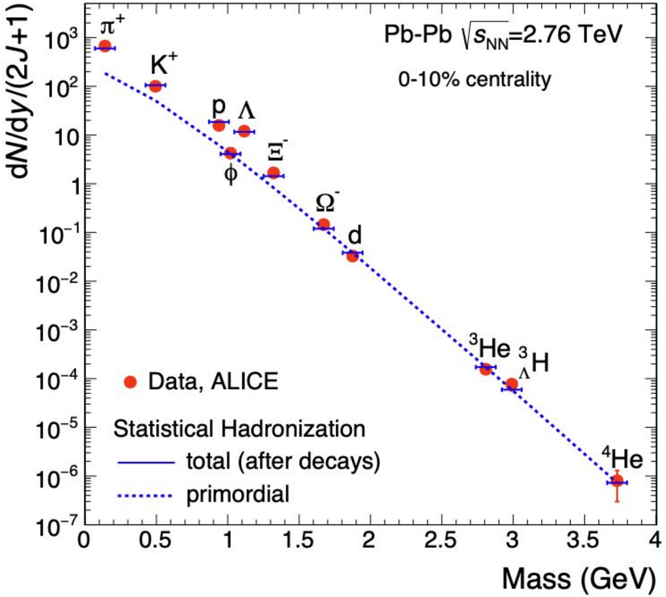
Thermal Models (SHMs)

Hadrons emitted from the interaction region in statistical equilibrium when the system reaches a limiting temperature T_{eq}

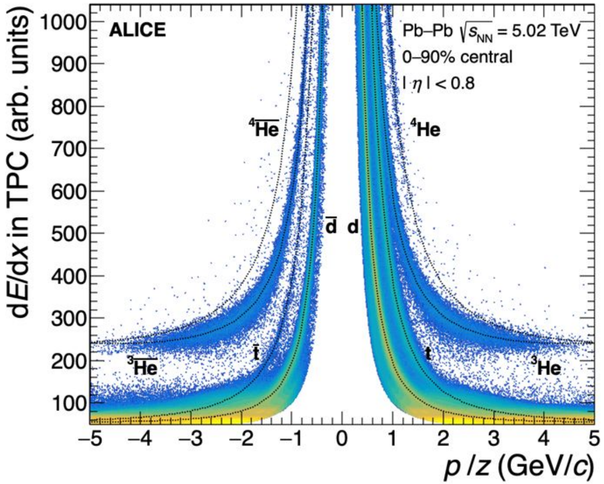
- Abundance of a species
  - ➢ $\propto \mathrm{Exp}(-M/T_{eq})$
- No dependency on the nuclear size



Nature 561 (2018) 7723, 321-330

How do we measure hypernuclei

Tracking and identification of the decay products



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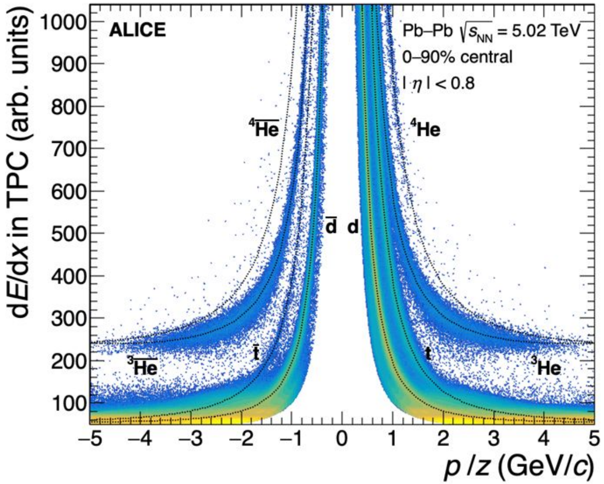
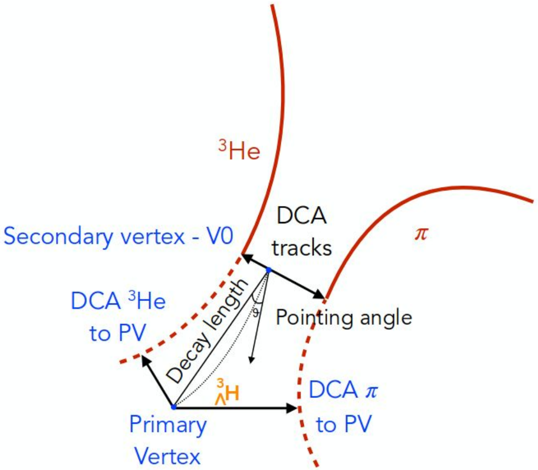
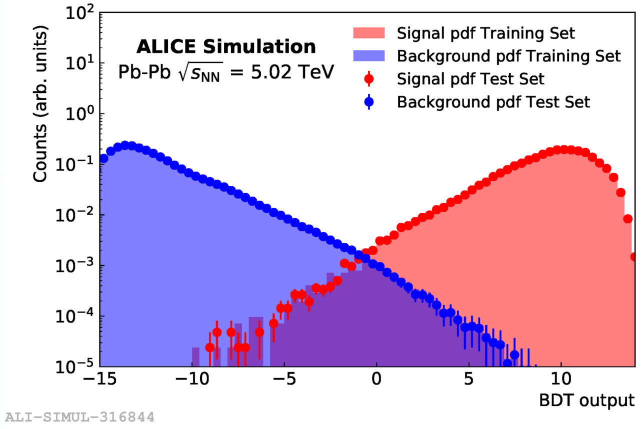




Decay vertex reconstruction and background suppression



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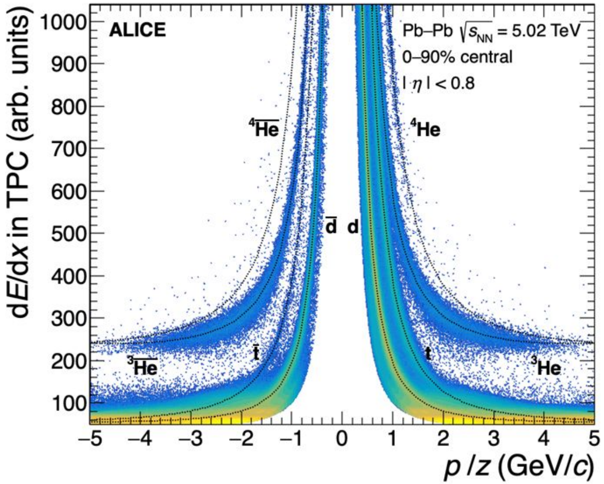

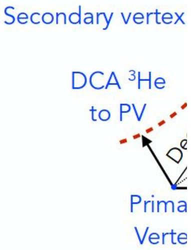

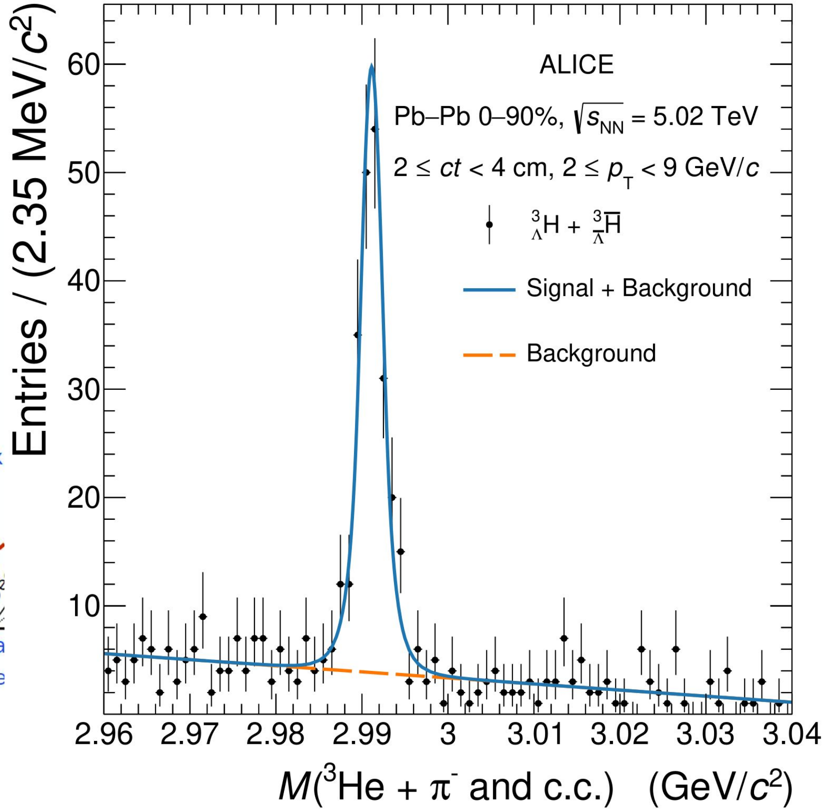

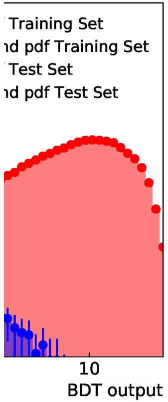


Where we are
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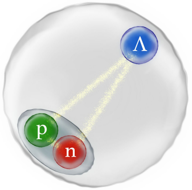
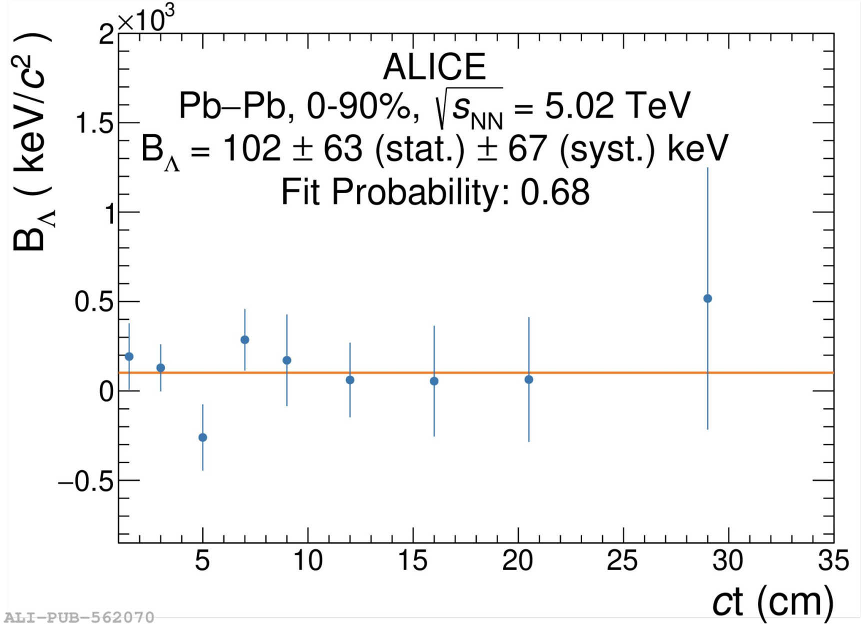
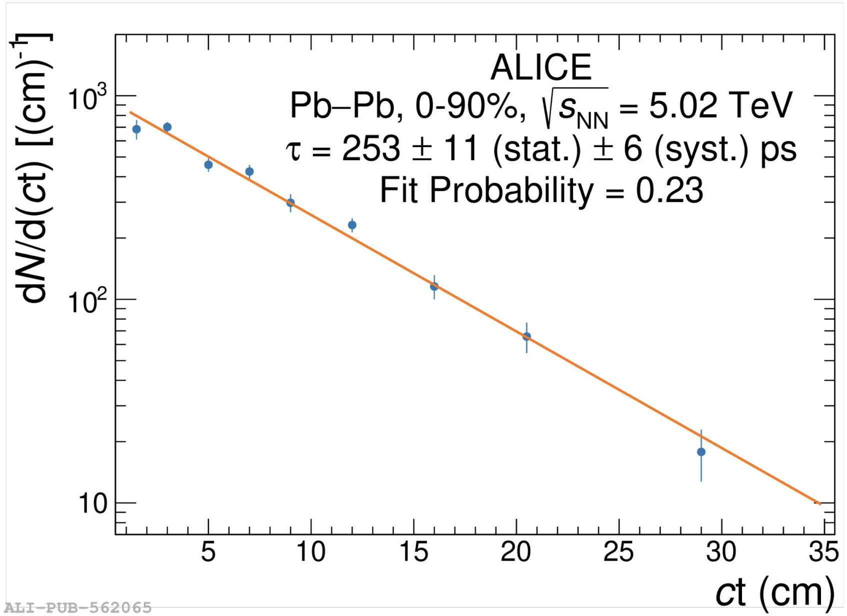
Hypertriton properties uncovered (${}^{3}_{\Lambda}\mathrm{H}$)



- ${}^{3}_{\Lambda}\mathrm{H}$ lifetime compatible within 1σ with free c lifetime, B_{Λ} ~ 100 keV
  - Weakly-bound nature of ${}^{3}_{\Lambda}\mathrm{H}$ confirmed, d-Λ radius ~ 10 fm

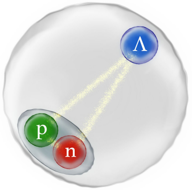




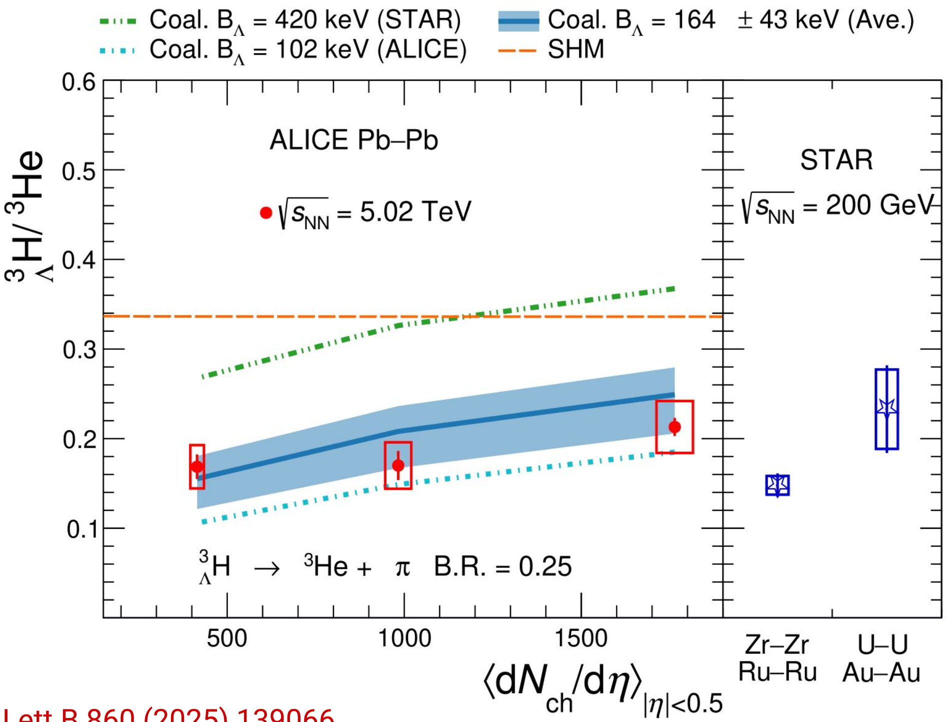
How does this reflect on its production?

Phys. Rev. Lett. 131, 102302 (2023)

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

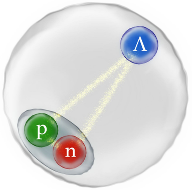


- First particle deviating from SHM description in Pb–Pb
  - Production mechanism sensitive to the ${}^{3}_{\Lambda}$H wave function

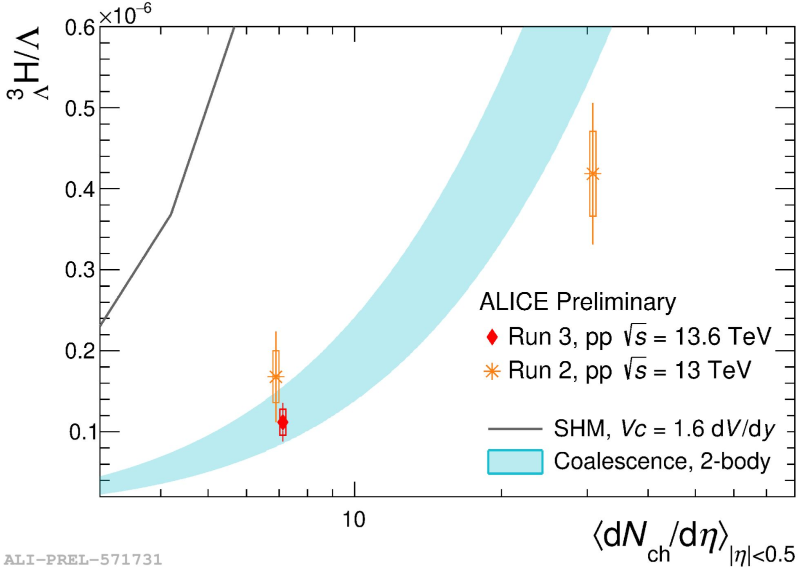


Phys.Lett.B 860 (2025) 139066

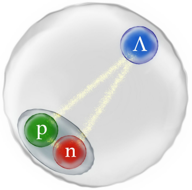
$^{3}_{\Lambda}$H in pp collisions



- In pp, particle emission size (~1 fm) << $^{3}_{\Lambda}$H average radius
  - Larger separation between coalescence and SHM
  - Production can be used to test the $^{3}_{\Lambda}$H wave function
  - LHC Run 3 pp dataset 100 times bigger than the previous ones



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



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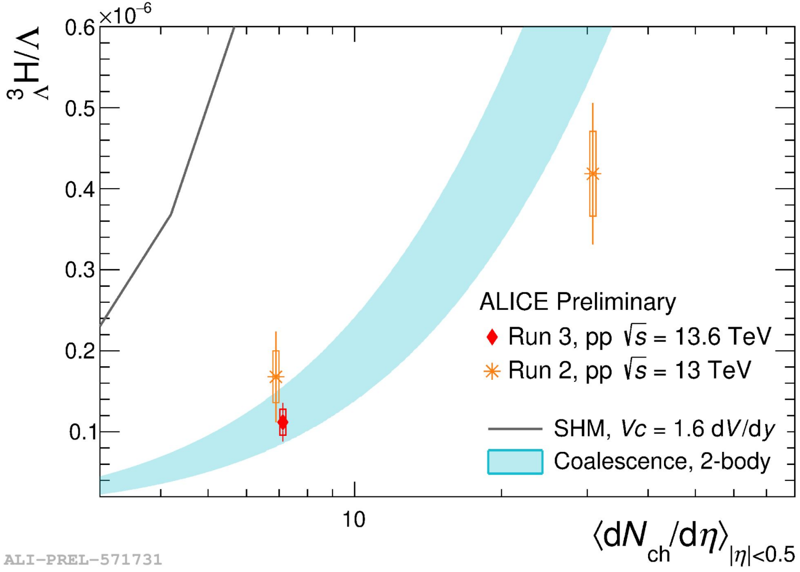
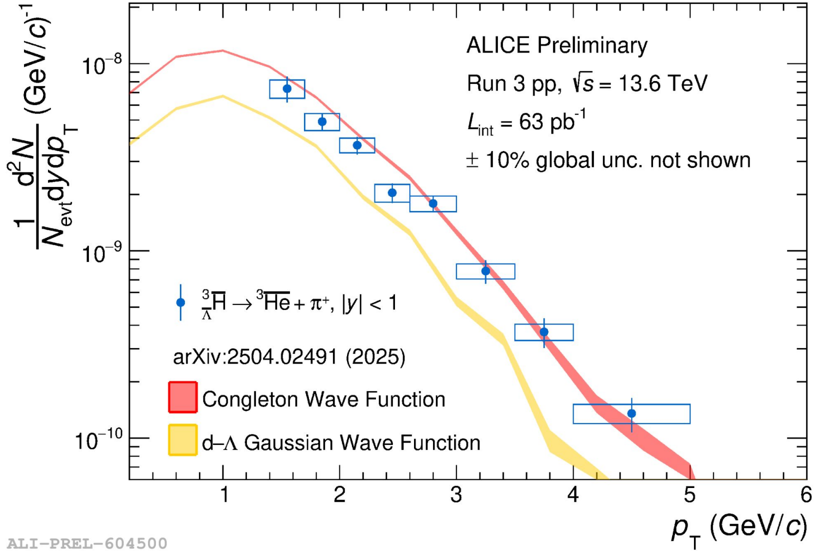
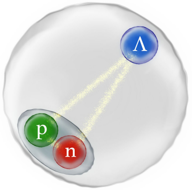


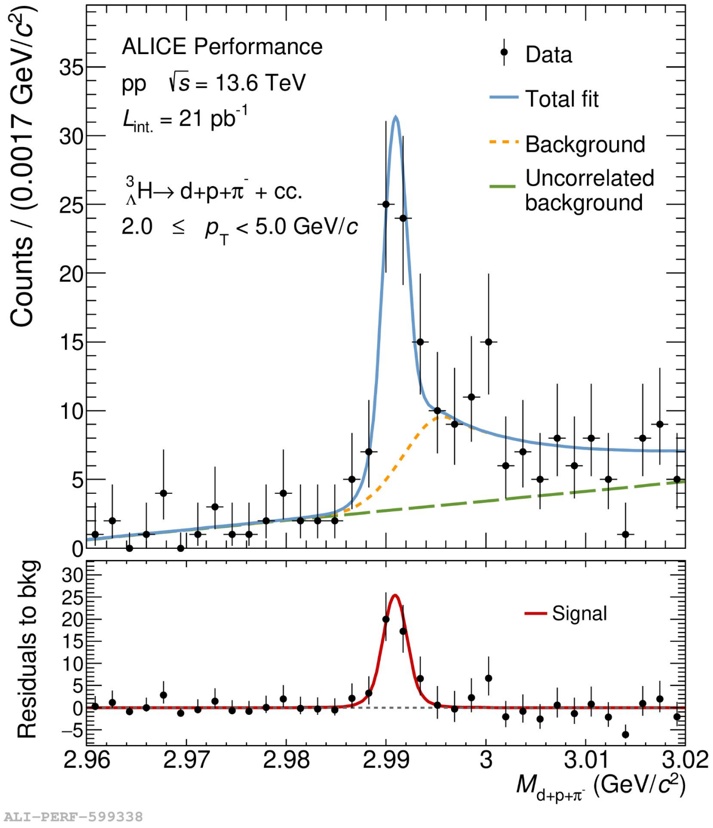


Ongoing $^{3}_{\Lambda}$H measurements

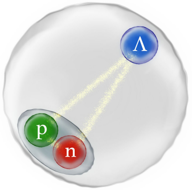


$^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$ decay

- Λ-d background modelled from data: correlated and uncorrelated background considered
- Precision R_3 measurement underway



Ongoing ${}^{3}_{\Lambda}H$ measurements



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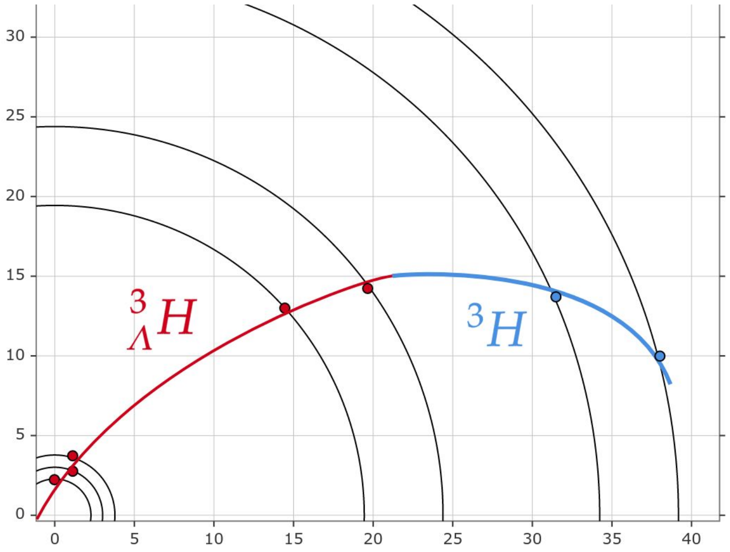
- Precision R_3 measurement underway

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

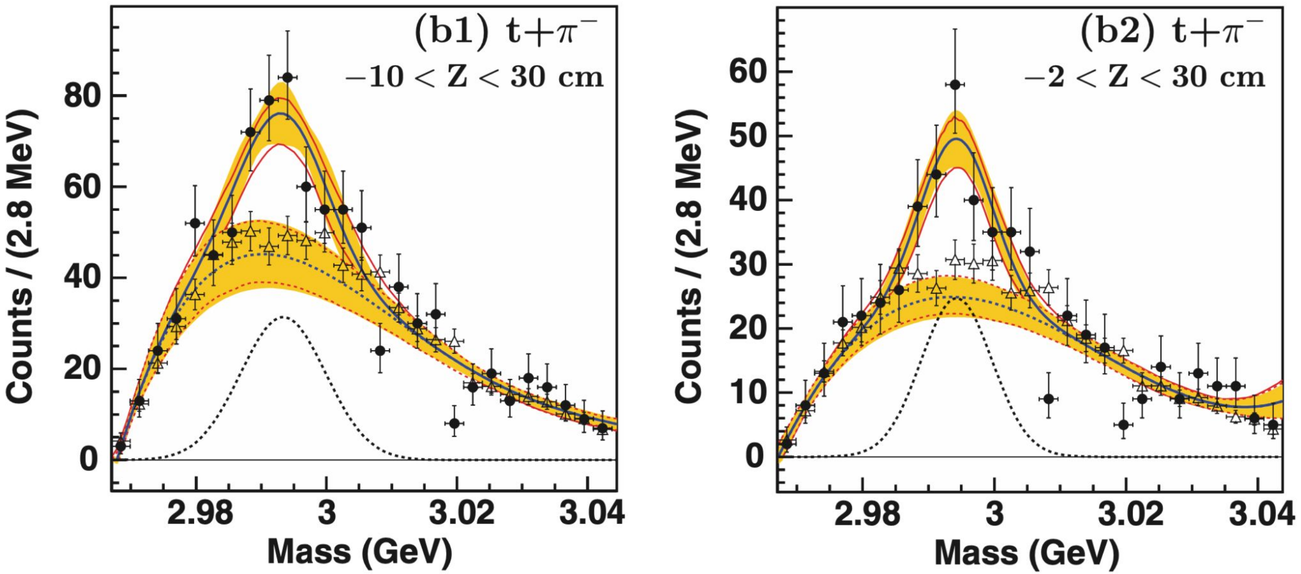
- Branching ratio never measured
  - expected to follow ΔI rule
- ${}^{3}_{\Lambda}H$ can be directly tracked into the ALICE Inner Tracking System!



More details in Y. Wang talk

Λnn searches

- Excess observed in the t + π^- final state observed by HypHi Collaboration [1]
- Λnn not bound according to most of the theorist [2, 3]



1 Phys. Rev. C 88, 041001
2 Phys. Lett. B 736, 93-97
3 Phys. Rev. C 89, 061302

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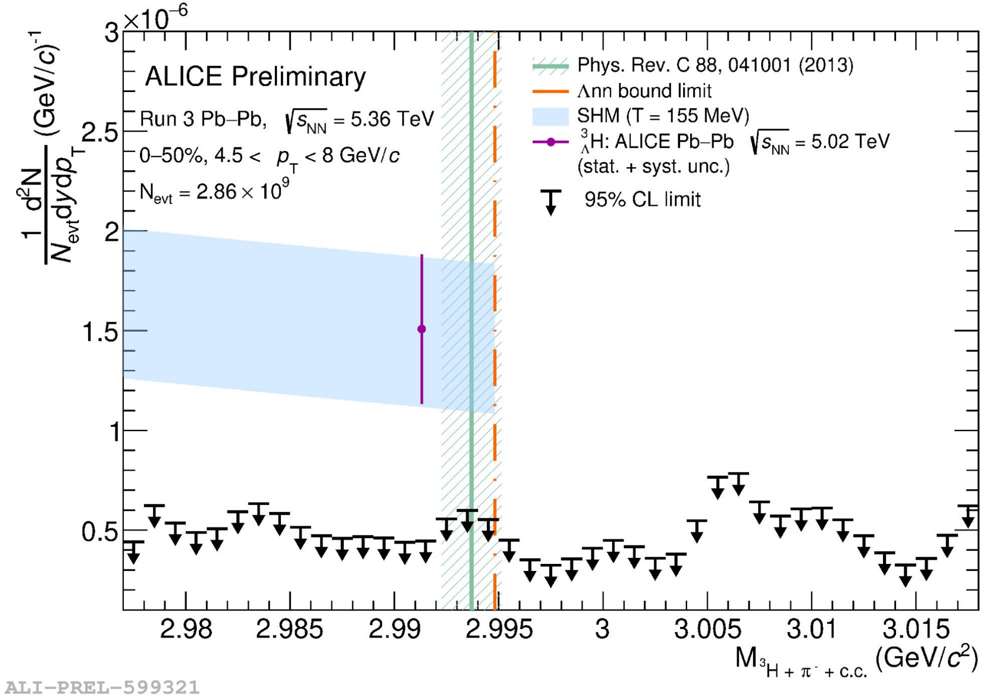
- Λnn not bound according to most of the theorist [2, 3]
- ALICE rules out the existence of a Λnn state stable under strong decay

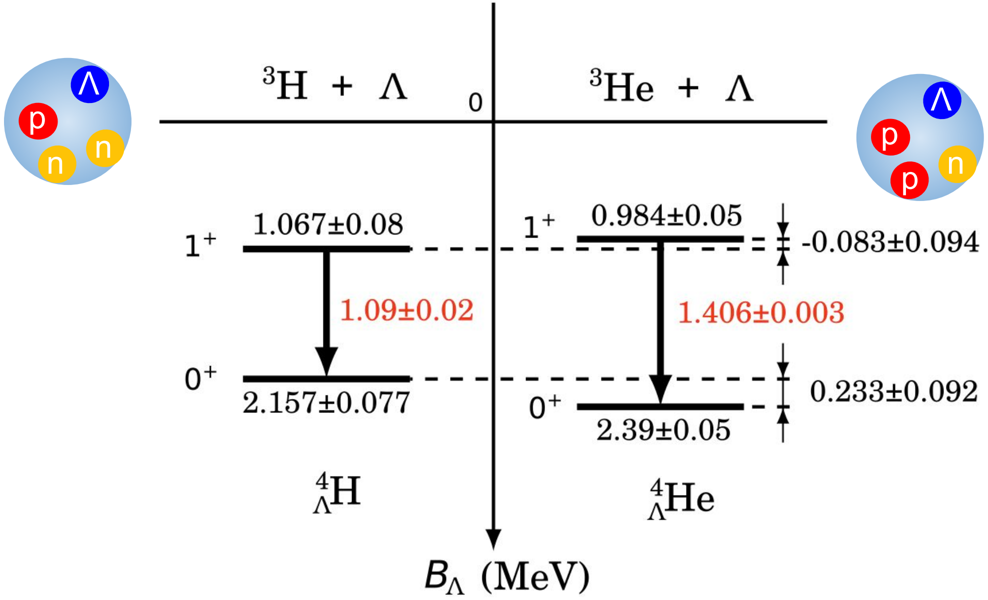


More details in M.P. Palhares talk

[1] Phys. Rev. C 88, 041001
[2] Phys. Lett. B 736, 93-97
[3] Phys. Rev. C 89, 061302

A = 4 Hypernuclei

- ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$ are expected to be compact states
  - ➢ SHM should give a good estimation of the yield
- And the SHM correctly describes the yield only when including the higher spin states

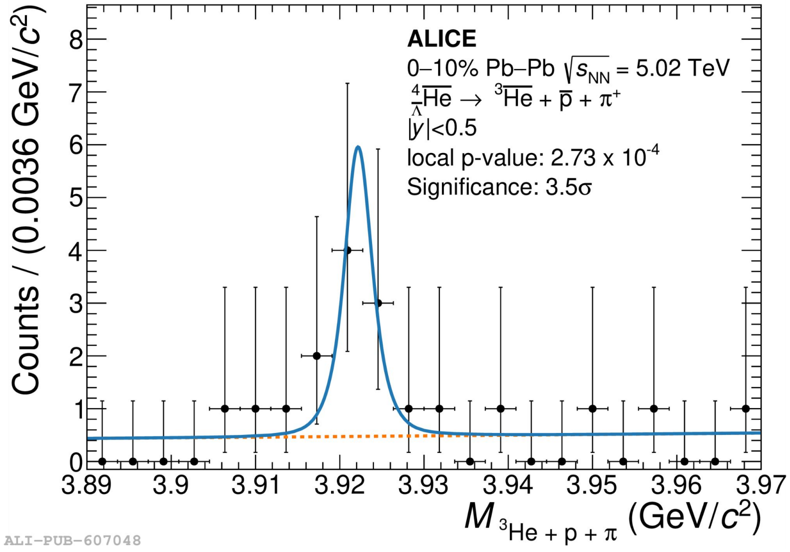


Phys.Rev.C 106, L031001 (2022)

A = 4 Hypernuclei

- First evidence of antimatter $^{4}_{\Lambda}$He hypernucleus

Run 2

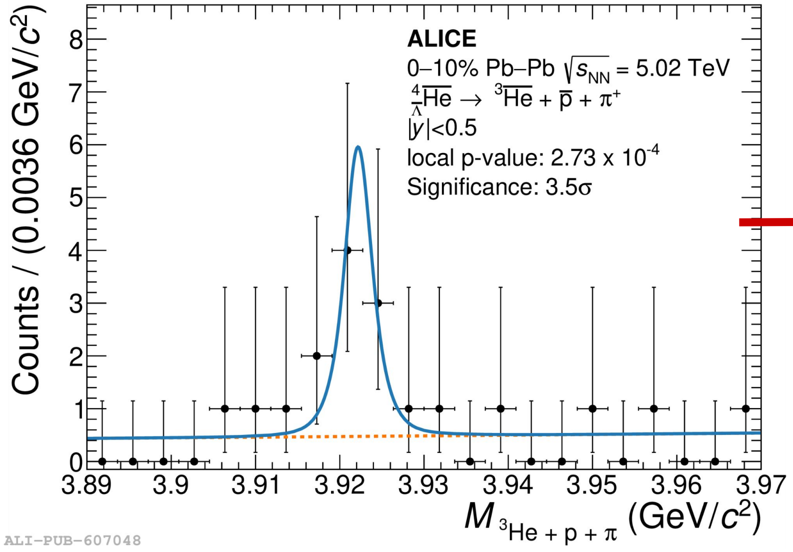


Phys. Rev. Lett. 134 (2025) 162301

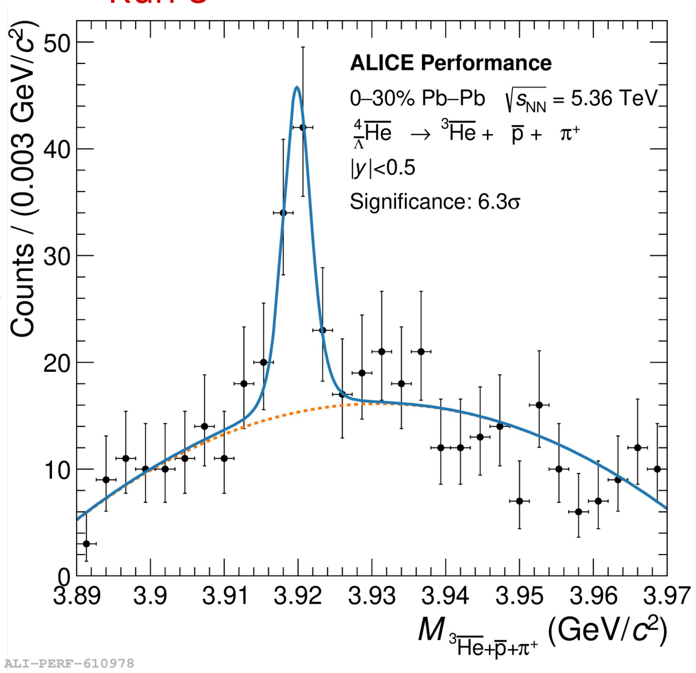
A = 4 Hypernuclei

- First ~~evidence~~ observation of antimatter $^{4}_{\Lambda}$He hypernucleus
  - ~~Significance > 5σ measured in Run 3~~

Run 2



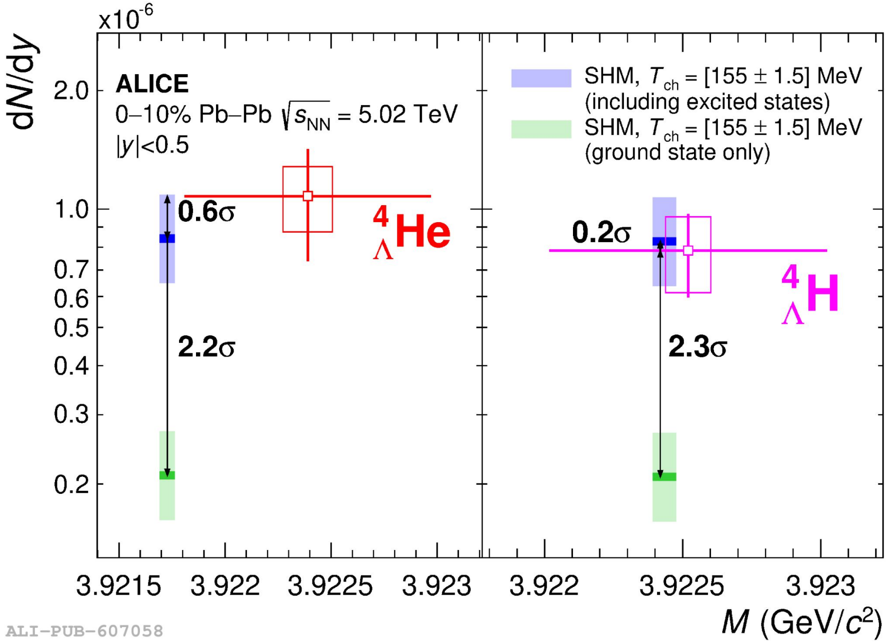
Run 3



📕 Phys. Rev. Lett. 134 (2025) 162301

A = 4 Hypernuclei

- First observation of antimatter ${}^{4}_{\Lambda}$He hypernucleus
- Significant deviation from SHM with ground state only
  - ➢ Nuclear properties inferred again starting from the production mechanism
  - ➢ Missing coalescence calculations, expected agreement with SHM



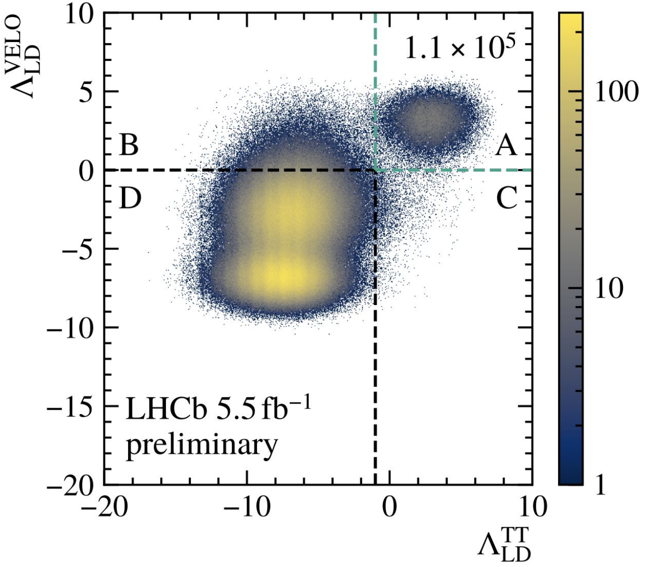
Factor twenty improvement in Run 3 will enable precise CSB measurements

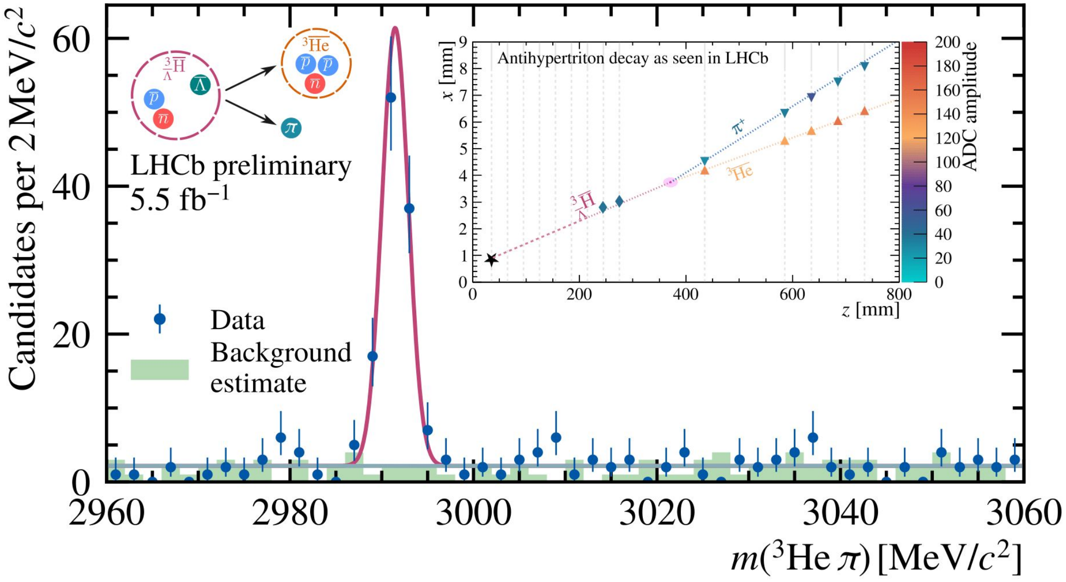
More details in
J. Ditzel poster

📕 Phys. Rev. Lett. 134 (2025) 162301

Hypernuclei in LHCb

- LHCb observed the (anti-)hypertriton on Run 2 pp data: [link]
  - ~ 100 anti-$^{3}_{\Lambda}$H analysing 5.5 fb^{-1}
  - Innovative methods for tagging nuclei
  - Allows for complementary measurements with ALICE in the forward region






Where do we go ?
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HYP Physics at the LHC

Pros

- Excellent detector calibration (from TeV to o(100) keV scale) and PID
- Measurement of antimatter counterparts, CPT tests in hypernuclear sector

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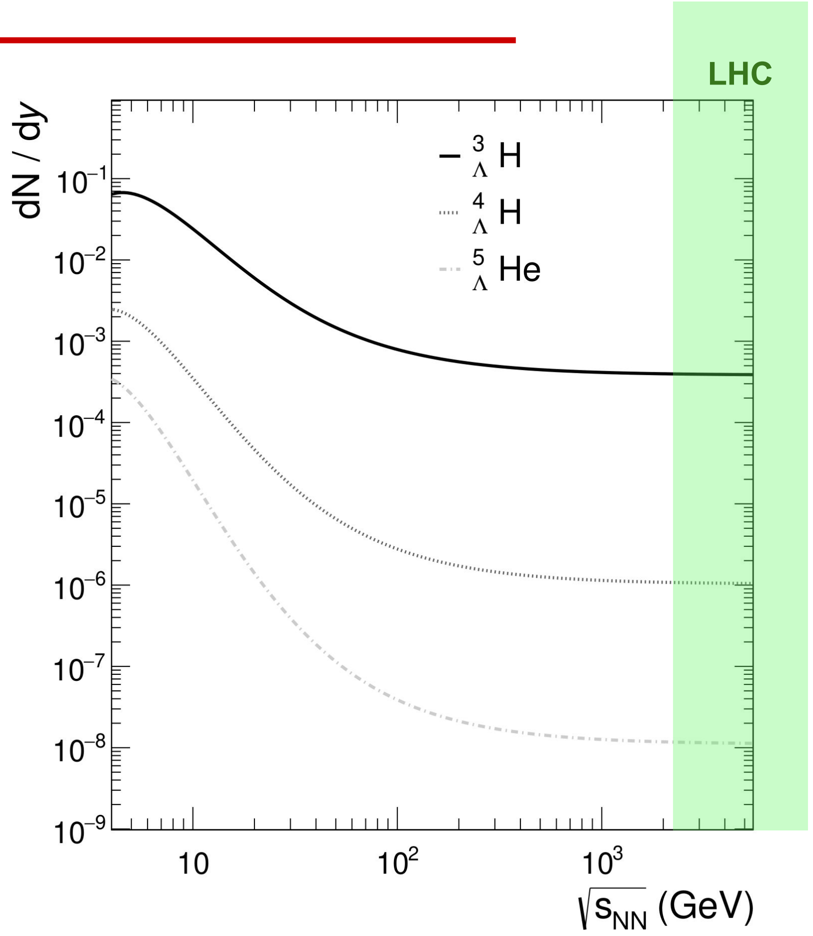
- Measurement of antimatter counterparts, CPT tests in hypernuclear sector

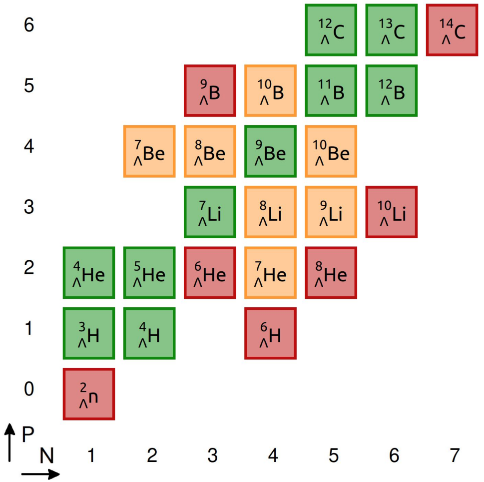
Cons

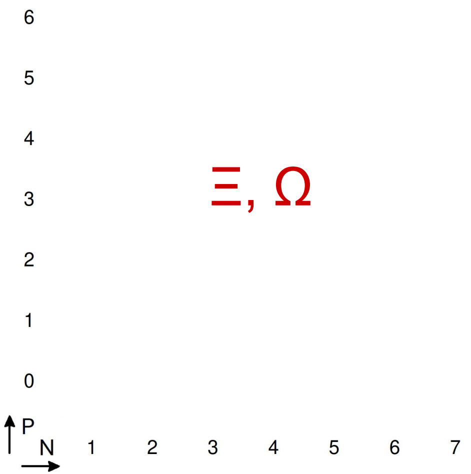
- Nuclear production peaks at low energies
  - A=5 hypernuclei out of reach
  - Competition from current and future low-energy experiments STAR BES, Hades, CBM, NA60+ ..

Where do we go ?



Beyond Λ - hypernuclei





- No data for light Ξ, Ω hypernuclei in spite of measured attractive interaction[1]
- lQCD calculations predict existence of Ω-dibaryons[2]

[1] Nature 588 (2020) 232-238
[2] Phys. Rev. Lett. 120, 212001

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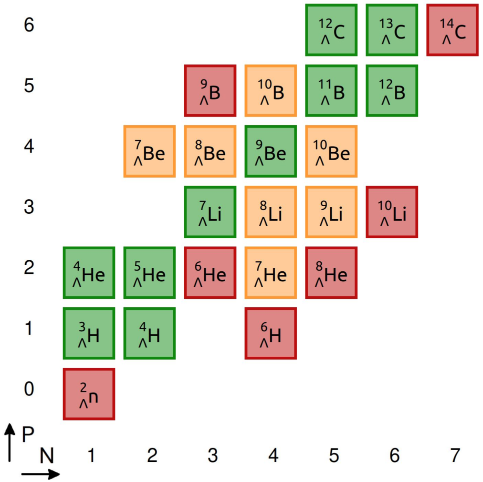

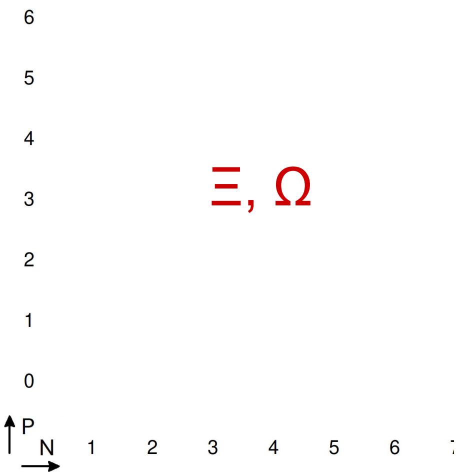

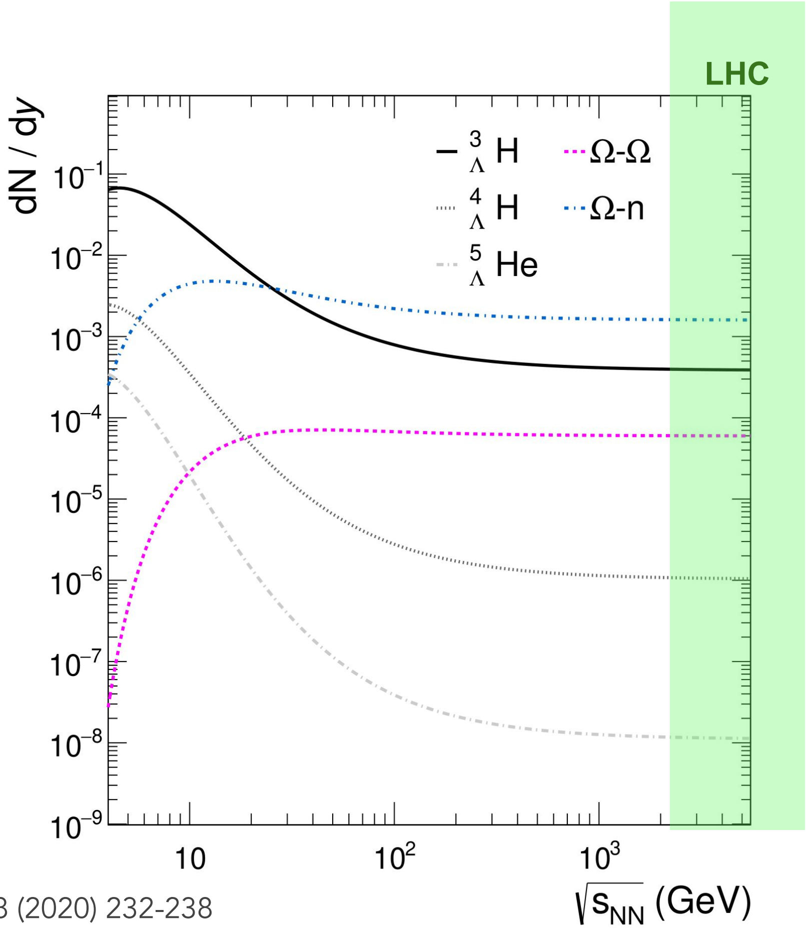

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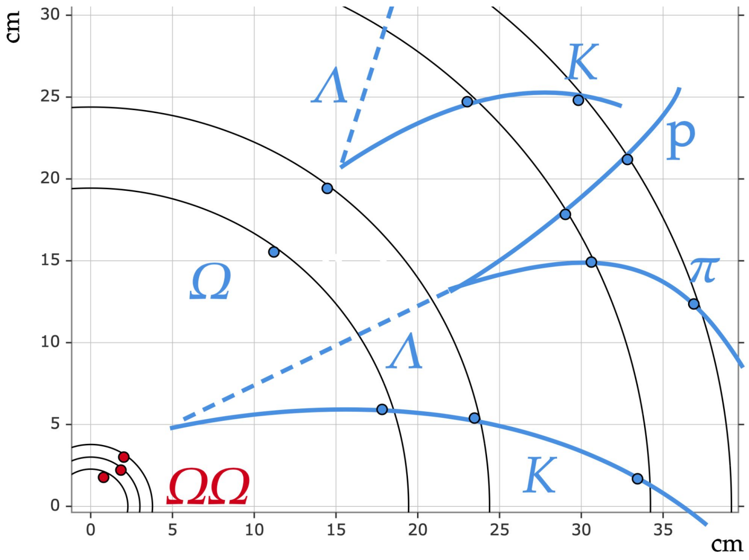
Multi-strange content makes these searches favourable at high-energies

[1] Nature 588 (2020) 232-238

[2] Phys. Rev. Lett. 120, 212001

Example: Ω-Ω

- Two ways to study these bound states at the LHC:
  - Femtoscopic correlation function
  - Search for the most probable decay, e.g. : Ω-Ω → Ω + K + Λ



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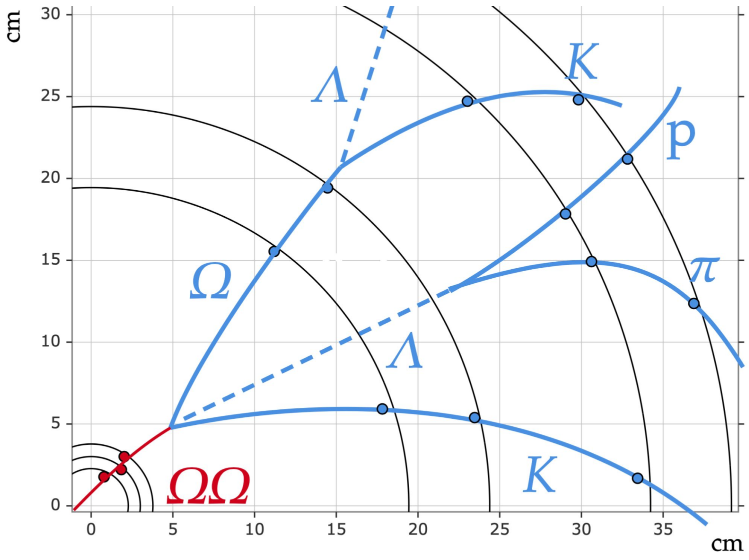
- ALICE Inner Tracking System enables strangeness tracking



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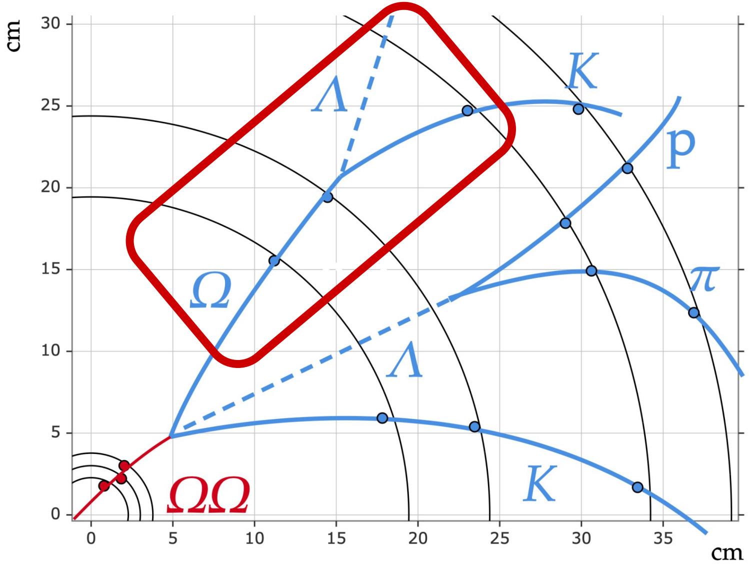
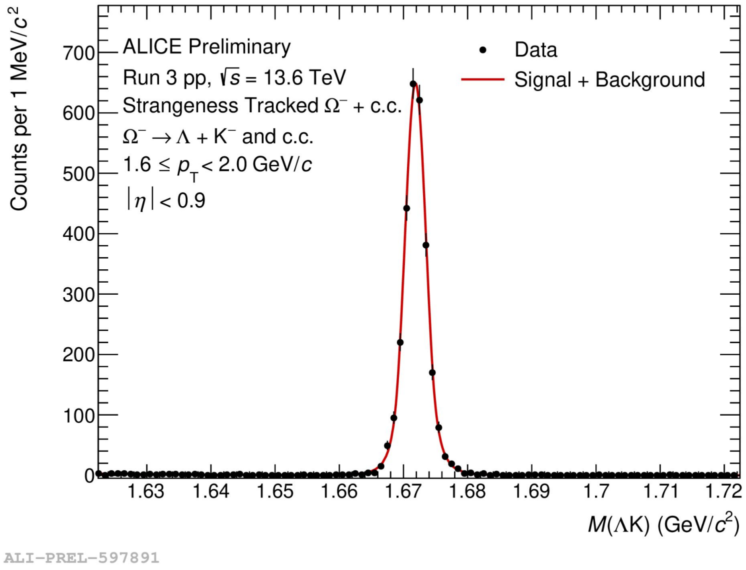




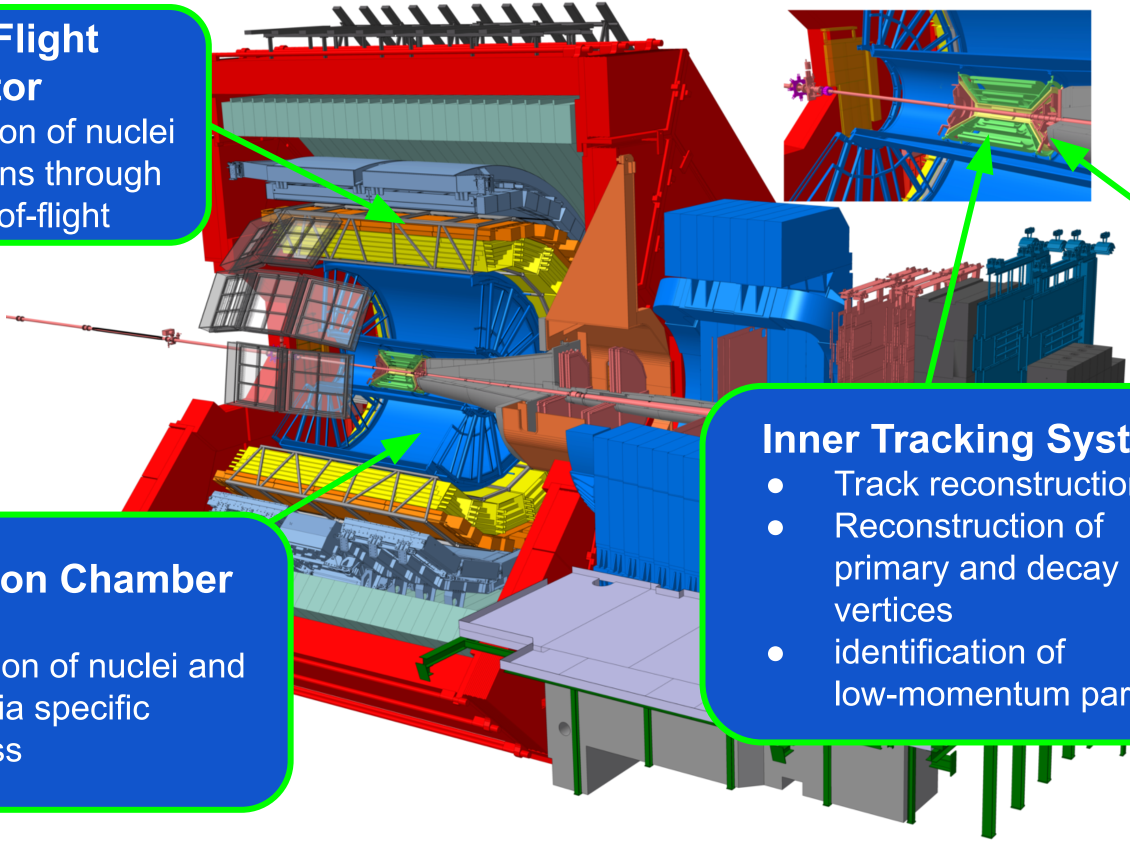
Summary

- New measurements and intense ongoing activities in the hypernuclear sector at the LHC
  - LHCb joining ALICE
- Opportunity in the future to extend the program beyond Λ hypernuclei

Thank you for your attention!

Backup

ALICE



Time-Of-Flight detector

- Identification of nuclei and hadrons through their time-of-flight

V0 detectors

- Trigger
- Centrality/multiplicity determination

Time Projection Chamber

- Tracking
- Identification of nuclei and hadrons via specific energy loss

Inner Tracking System

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