Recent Results in Hypernuclear Physics

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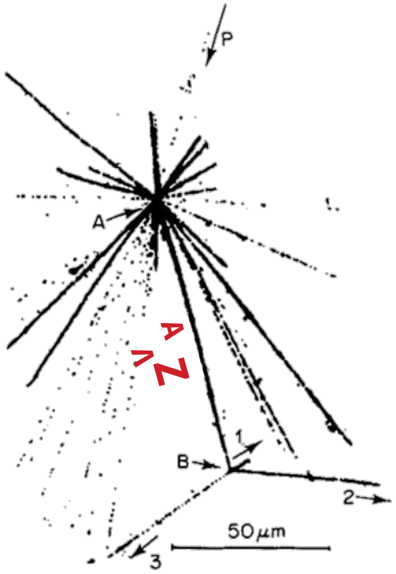
5th Workshop on Anti-Matter, Hyper-Matter and Exotica Production

Hypernuclei

- A hypernucleus is a nucleus which contains at least one hyperon (a baryon containing one or more strange quarks - Λ, Σ, Ξ,Ω) in addition to nucleons



First hypernuclear event observed in a nuclear emulsion by Marian Danysz and Jerzy Pniewski in 1952

Hypernuclei

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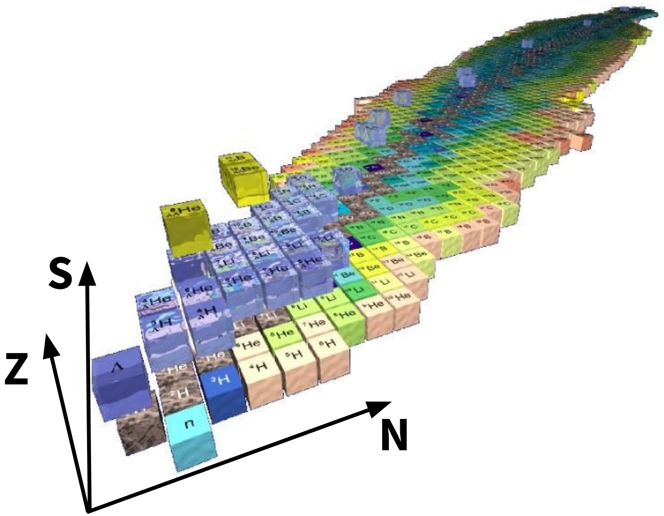
- Main goals of hypernuclear physics:
  - Extension of nuclear chart to a third dimension



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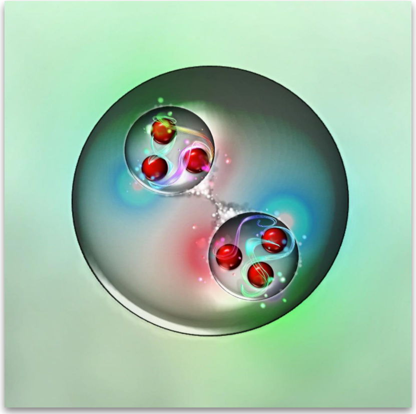
  - Study the structure of multi-strange systems



di-Omega dibaryon.
Image credit: Keiko Murano.

Hypernuclei

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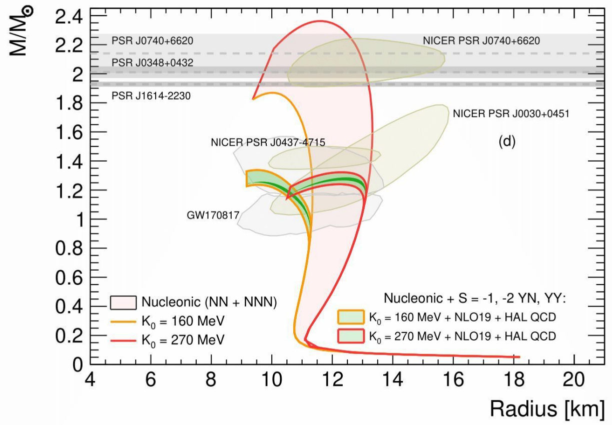
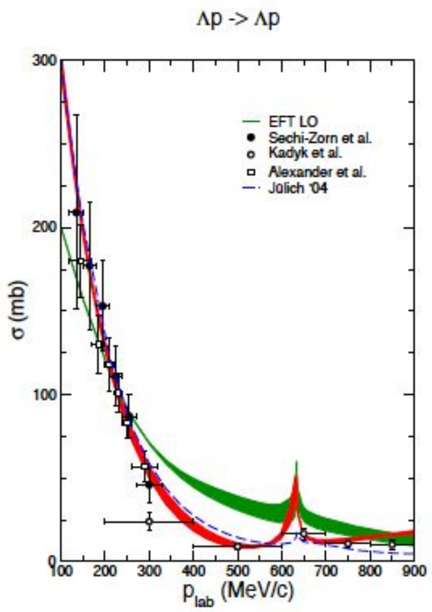
- Main goals of hypernuclear physics:
  - Extension of nuclear chart to a third dimension
  - Study the structure of multi-strange systems
  - Study nucleon-hyperon (N-Y) interaction:
    - Production of exotic bound states
    - Determination of the equation of state
    - Application to neutron stars:
      - Determination of NS properties
      - *Hyperon puzzle*: the problem of the strong softening of the EoS induced by the presence of hyperons which, although being energetically favorable, leads to values of M^{max} incompatible with the recent observations of $2M_{\odot}$ millisecond pulsars, is still an open issue



I. Vidaña et al., Eur.Phys.J.A 61 (2025) 3, 59

YN and YY interaction

- The main ingredients to understand the role of hyperons in NSs are the YN &YY interactions. But how much do we know to constrain them?
- Unfortunately, much less than in the pure nucleonic sector

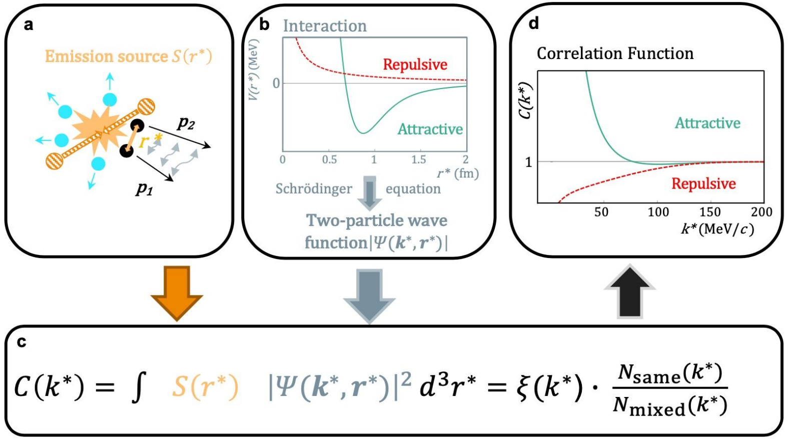


- Very few YN scattering data due to short lifetime of hyperons & low intensity beam fluxes
  - ΛN and ΣN: < 50 data points
  - ΞN very few events
- No YY scattering data exists

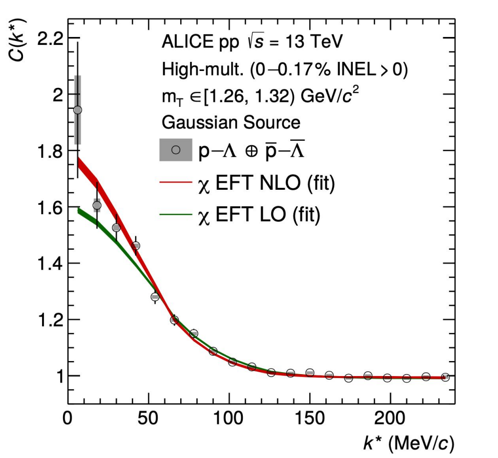
- NN: > 5000 data for E_{lab}<350 MeV

Constraints YN, YY & YNN interactions from Femtoscopy

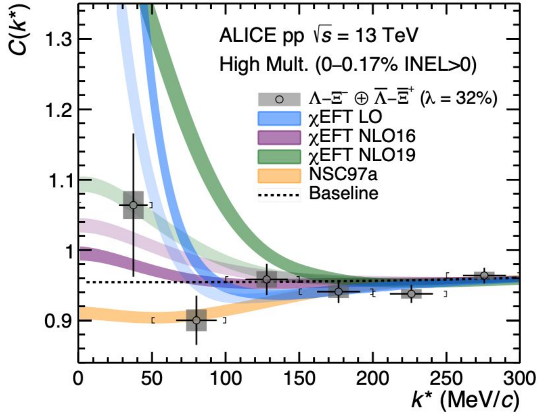
- New constraints on YN, YY, and YNN interactions obtained beyond traditional scattering data
  - Femtoscopy technique measures correlations of YN pairs and YNN triads in p–p and p–Pb collisions at the LHC (ALICE Collaboration)



ALICE collaboration, Nature 588, 232 (2021)



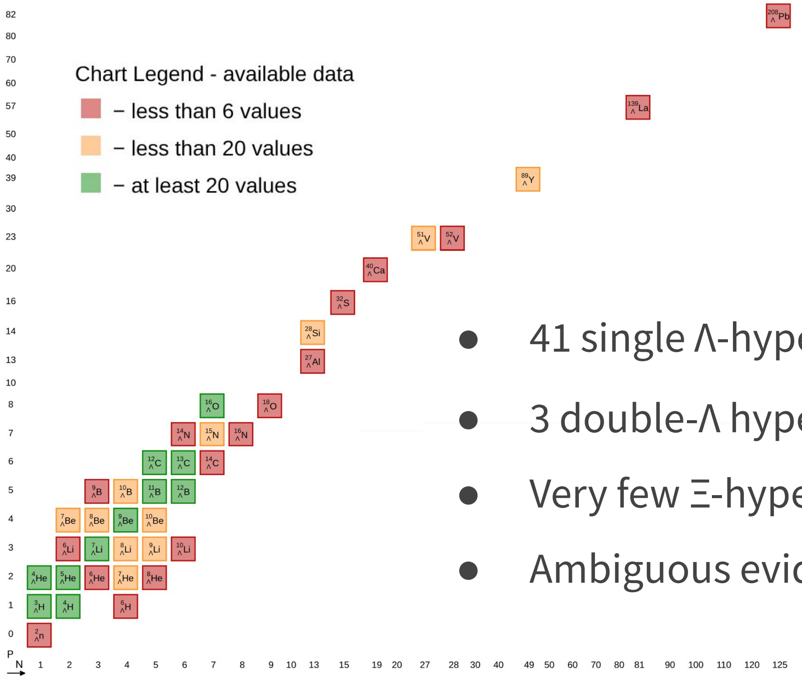
ALICE collaboration, PLB 811, 135849 (2020)



ALICE collaboration ,PLB 844, 137223 (2022)

Hypernuclei

- Alternative and complementary information can be obtained from the study of hypernuclei with the goal of relating hypernuclear observables with the underlying bare YN & YY interactions

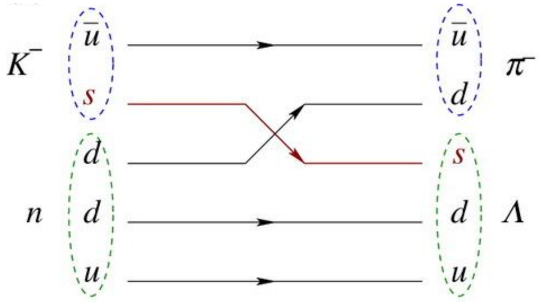


- 41 single Λ-hypernuclei → ΛN ***attractive*** ($U_\Lambda(\rho_0)$ ~ -30 MeV)
- 3 double-Λ hypernuclei → **weak** ΛΛ ***attraction*** ($\Delta B_{\Lambda\Lambda}$~ 0.67 MeV)
- Very few Ξ-hypernuclei → ΞN ***attractive*** ($U_\Xi(\rho_0)$??)
- Ambiguous evidence of Σ-hypernuclei → ΣN ***repulsive*** ($U_\Sigma(\rho_0)$ > +15 MeV) ?

Production of single-Λ hypernuclei

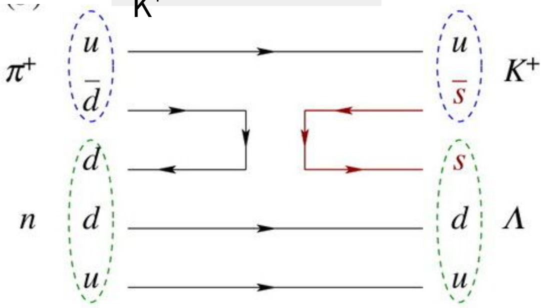
Strangeness exchange (BNL, KEK, JPARC)

$K^- + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$



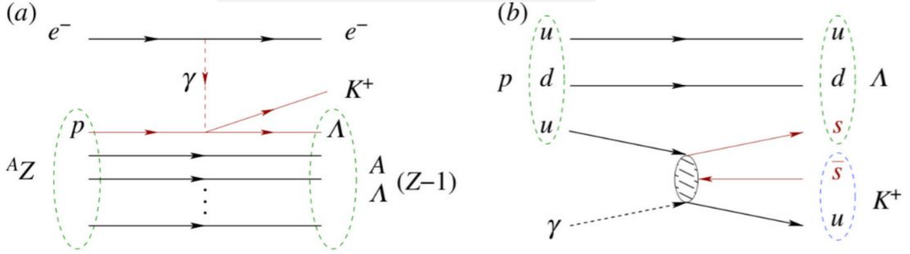
Associate production (BNL, KEK, GSI)

$\pi^+ + {}^AZ \rightarrow {}^A_\Lambda Z + K^+$



Electroproduction (JLAB, MAMI-C)

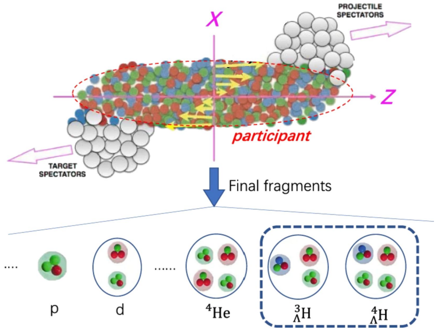
$e^- + {}^AZ \rightarrow e^{'} + K^+ + {}^A_\Lambda(Z\text{-}1)^-$



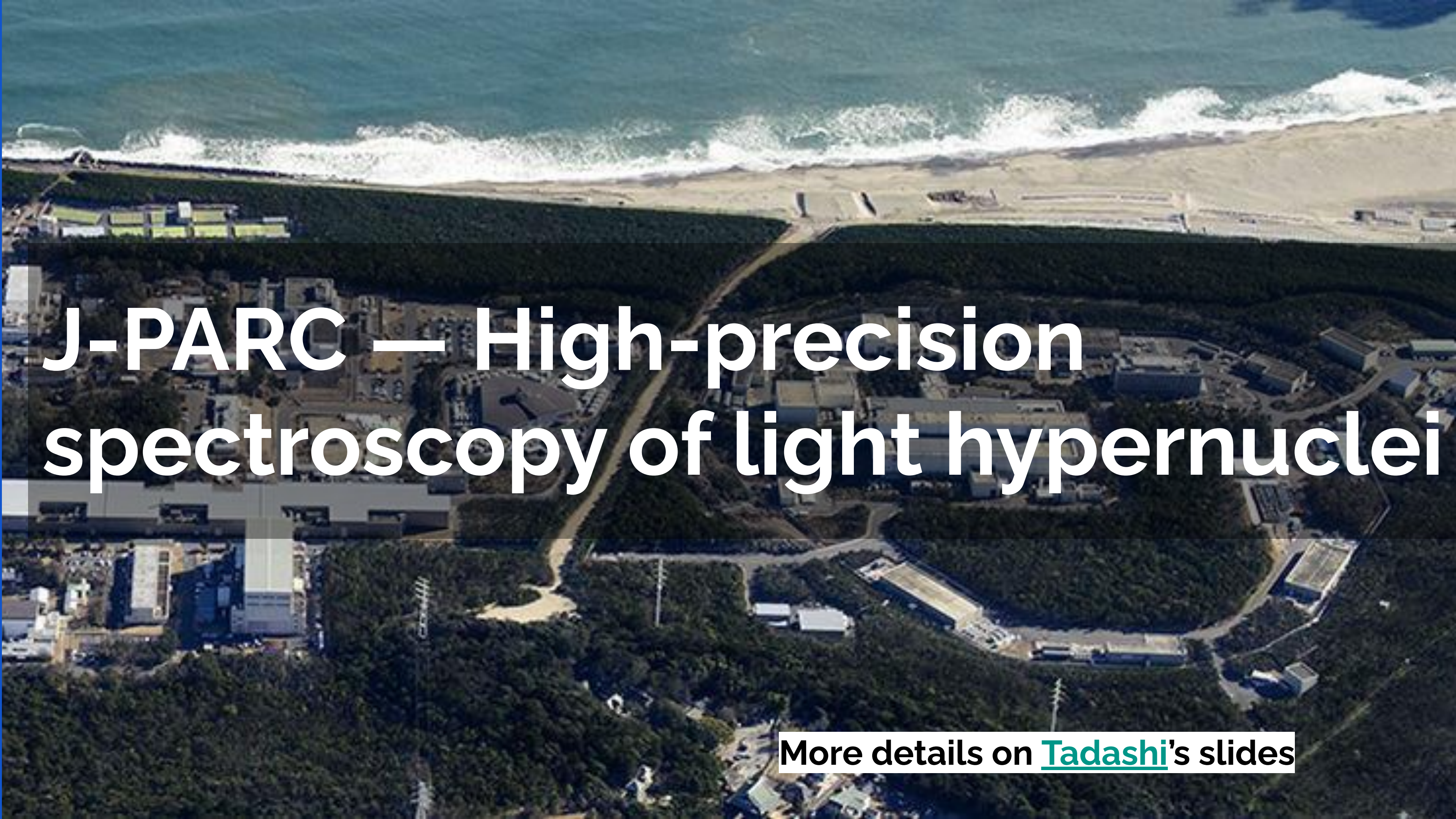
$e^- + {}^AZ \longrightarrow e^- + K^+ + {}^A_\Lambda(Z{-}1)$

$\gamma + p \longrightarrow K^+ + \Lambda$

Hypernuclei production in relativistic heavy ion collisions (GSI,RHIC,LHC)




GSI
Jefferson Lab
FAIR
mami
MAINZER MIKROTRON
CERN
BROOKHAVEN
NATIONAL LABORATORY
J-PARC



J-PARC — High-precision spectroscopy of light hypernuclei

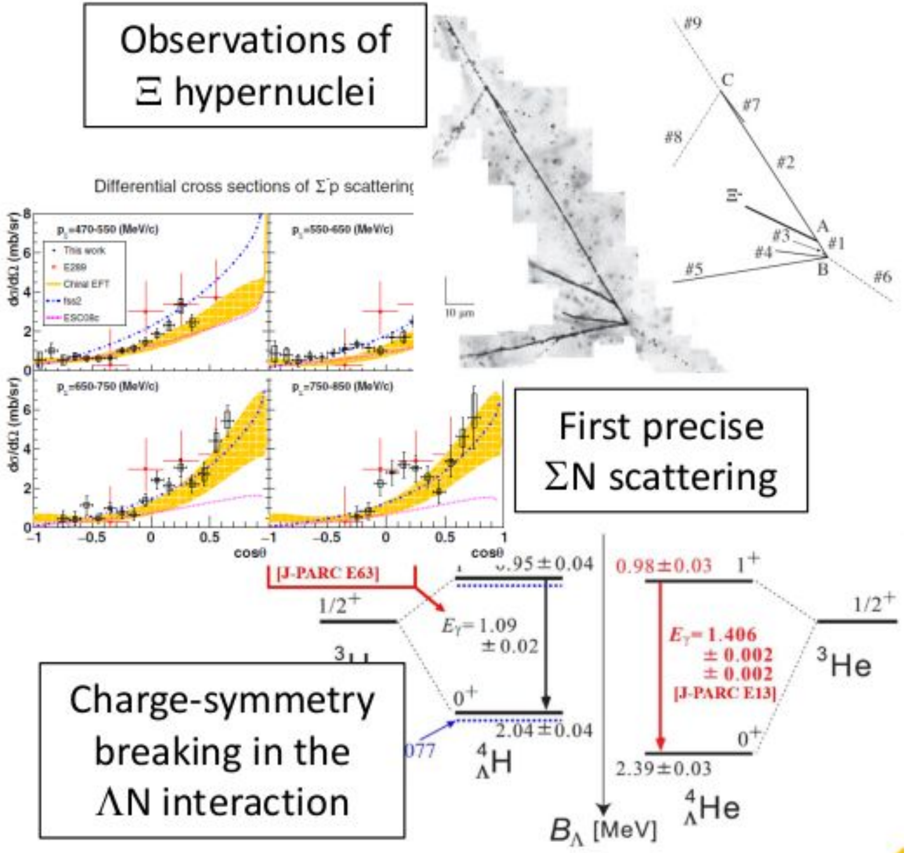
More details on Tadashi's slides

Hypernuclear physics at J-PARC

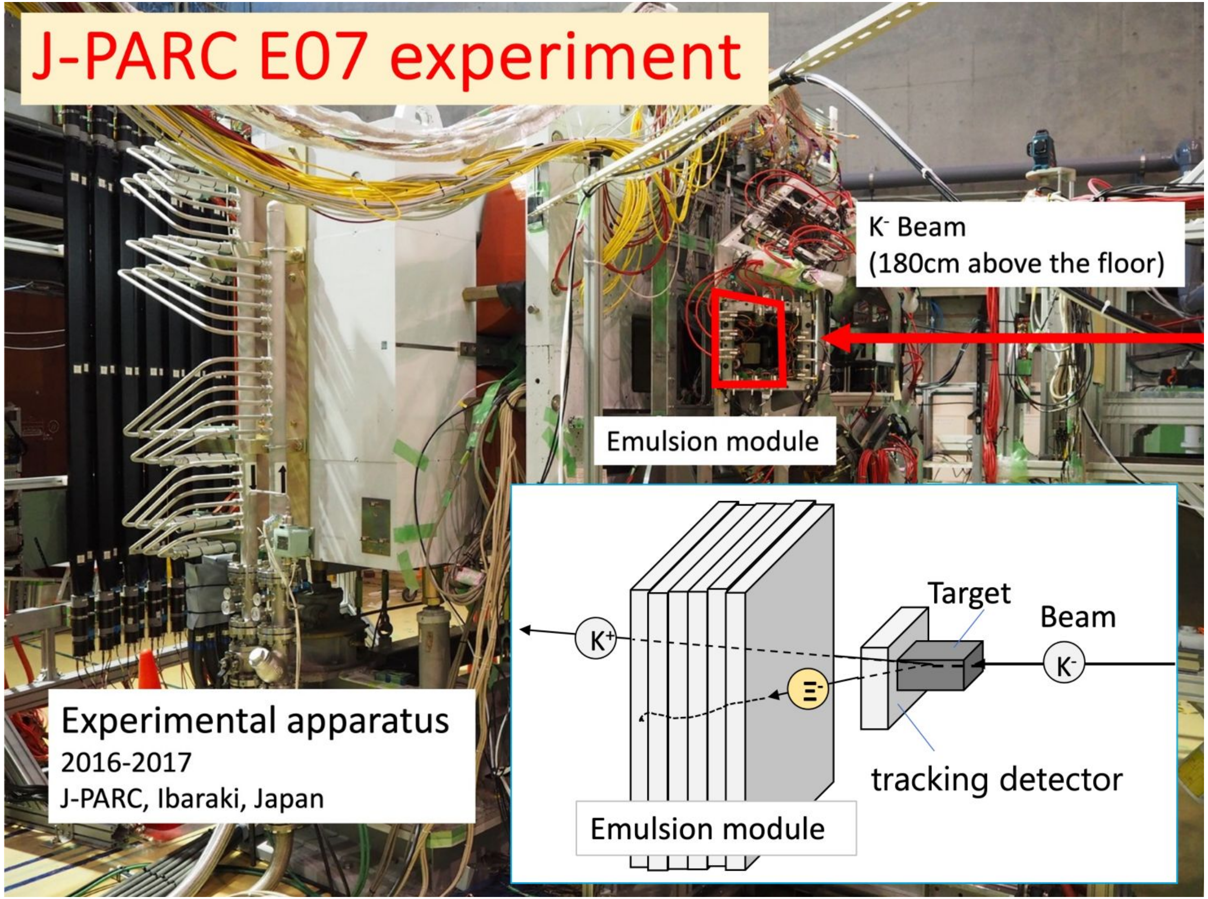
S. H. Hayakawa, PRL 126 (2021) 062501
M. Yoshimoto et al., PTEP 2021, 073D02

A lot of progress in hypernuclear research

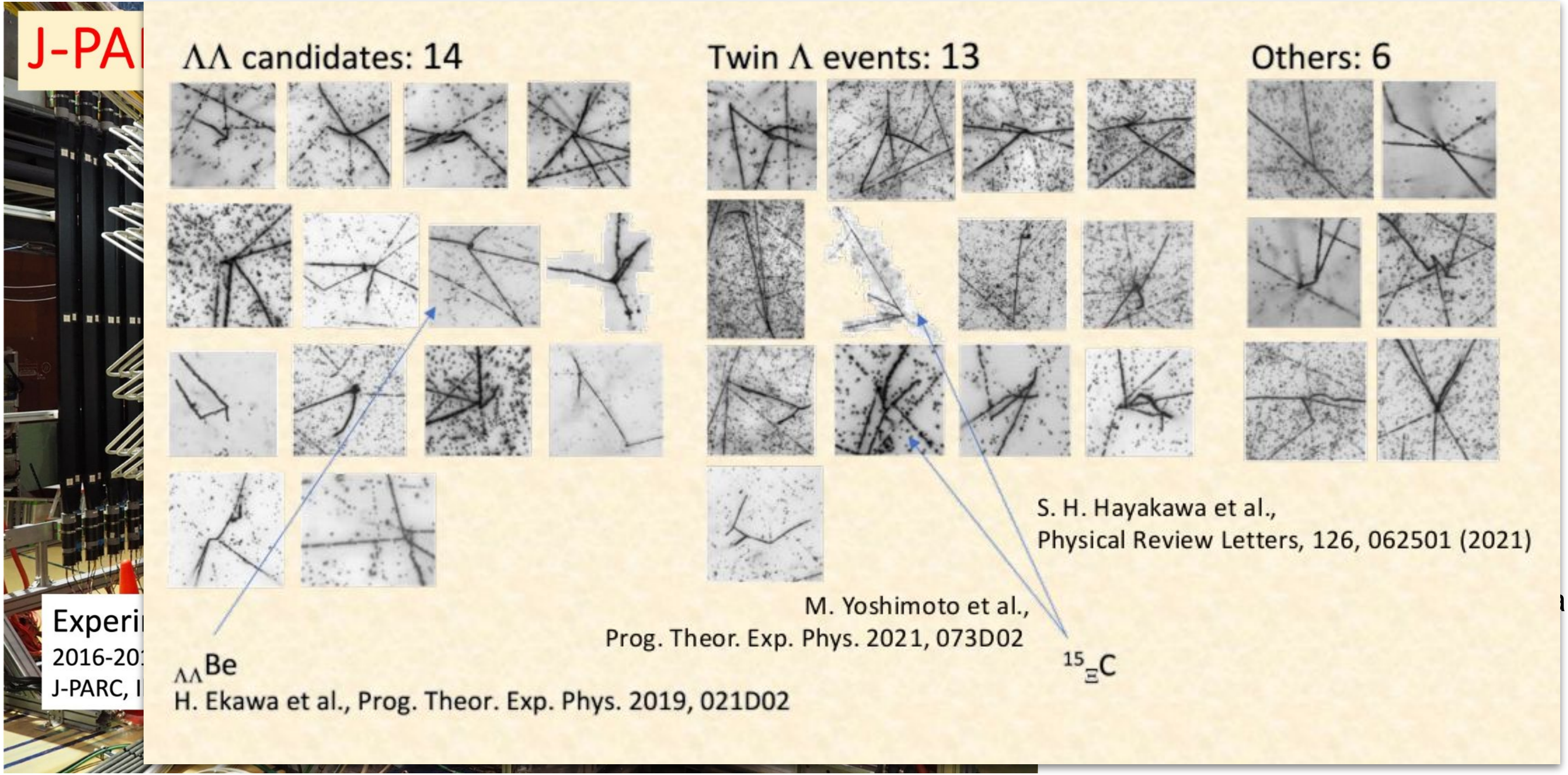
- High-resolution spectroscopic study of S=−2 hypernuclei
  - Access to ΞN (S=−2) interaction and deepened knowledge of ΛN, ΣN (S=−1) interactions
- Study of charge-symmetry breaking in the ΛN interaction
- Precise determination of ΣN scattering parameters



J-PARC E07 experiment

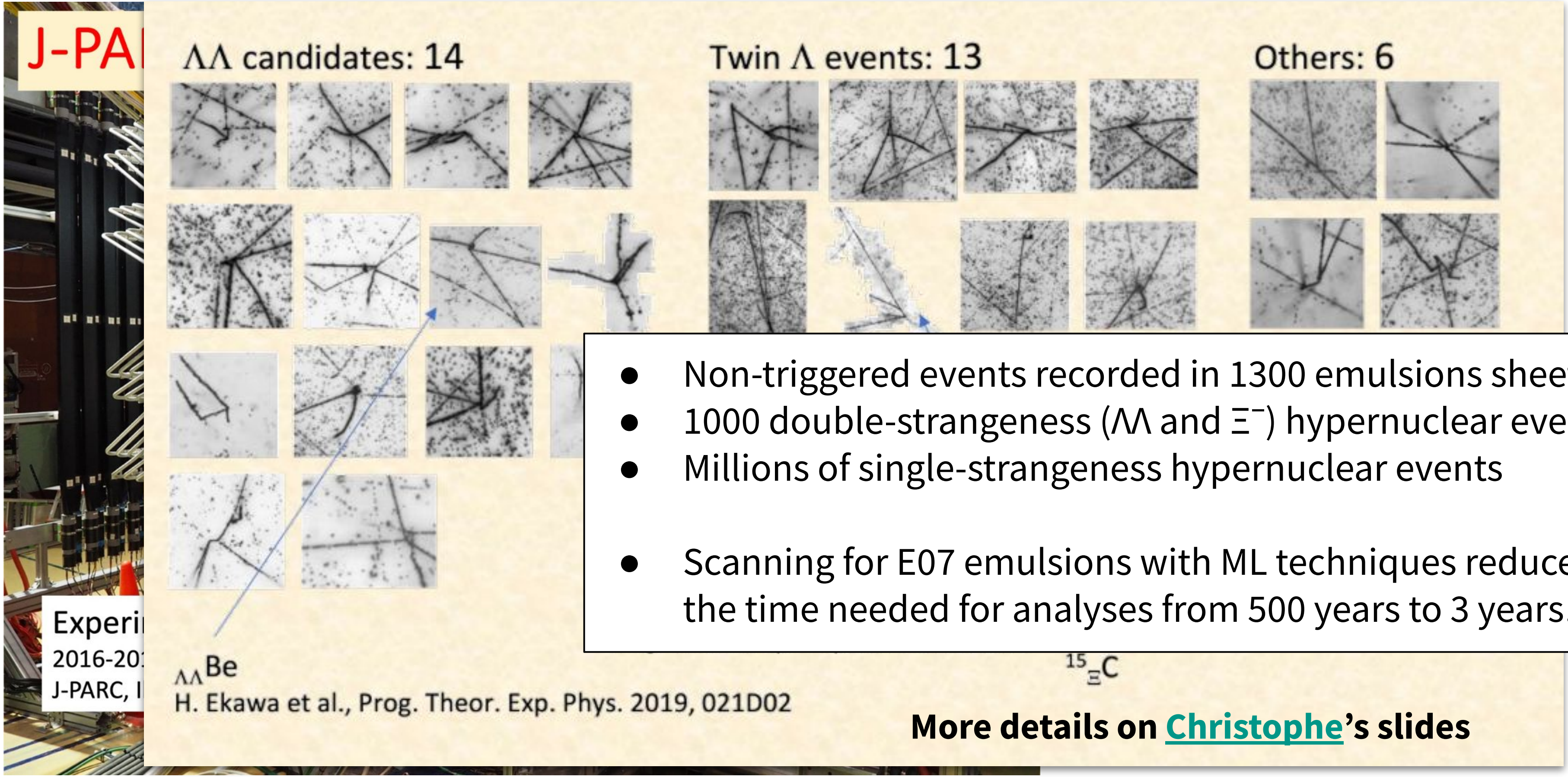


J-PARC E07 experiment



and

J-PARC E07 experiment

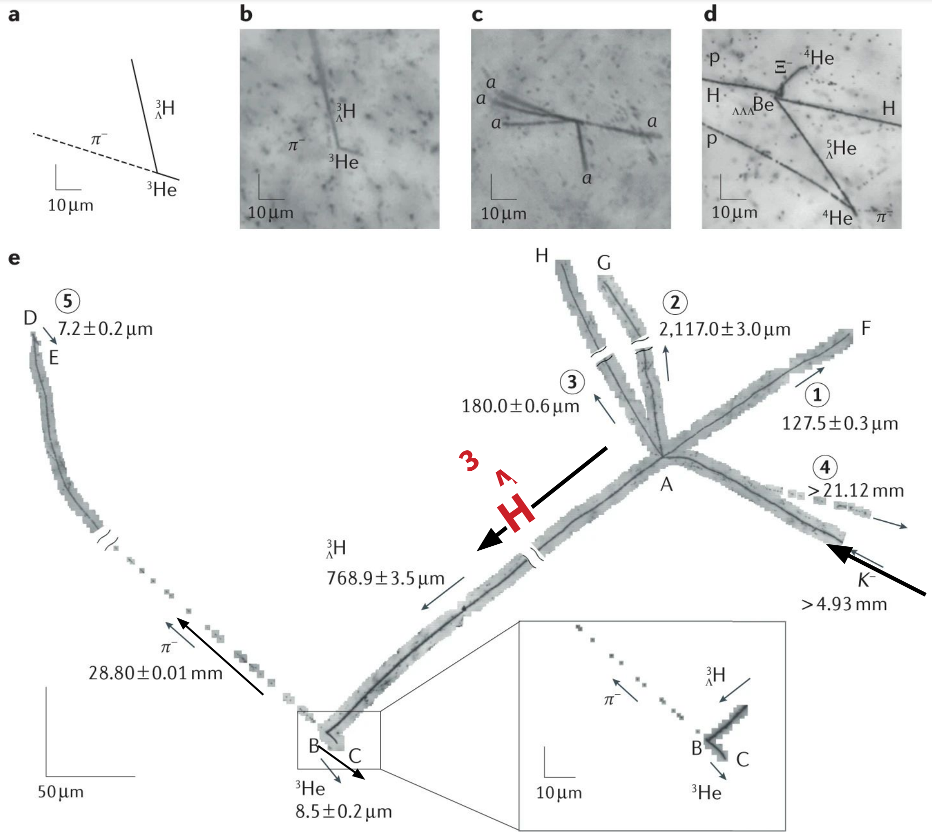


- Non-triggered events recorded in 1300 emulsions sheets
- 1000 double-strangeness (ΛΛ and Ξ^-) hypernuclear events
- Millions of single-strangeness hypernuclear events

- Scanning for E07 emulsions with ML techniques reduced the time needed for analyses from 500 years to 3 years!

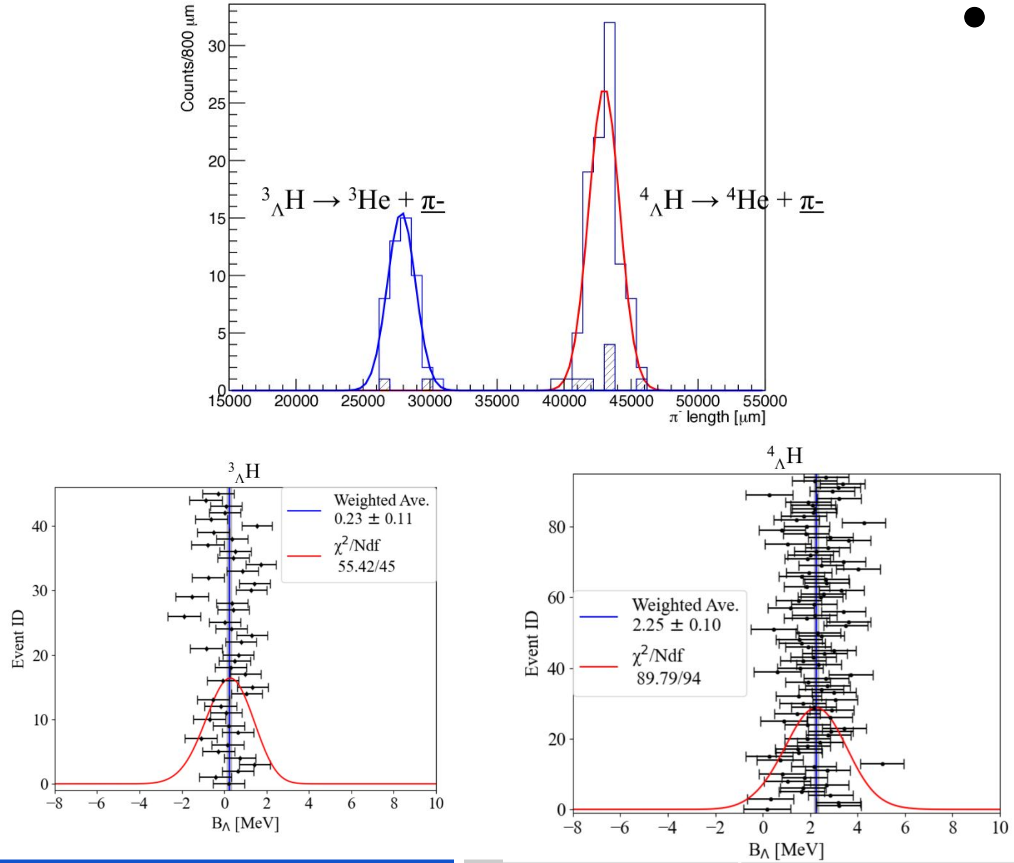
More details on Christophe's slides

Discovery of the first hypertriton event in E07 emulsions



Takehiko R. Saito et al., Nature Reviews Physics, 803-813 (2021)

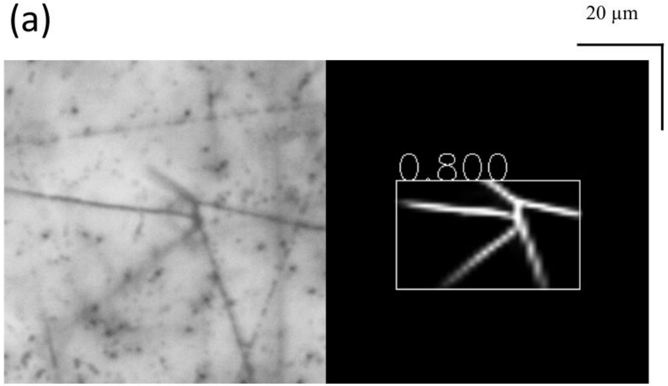
${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H binding energy

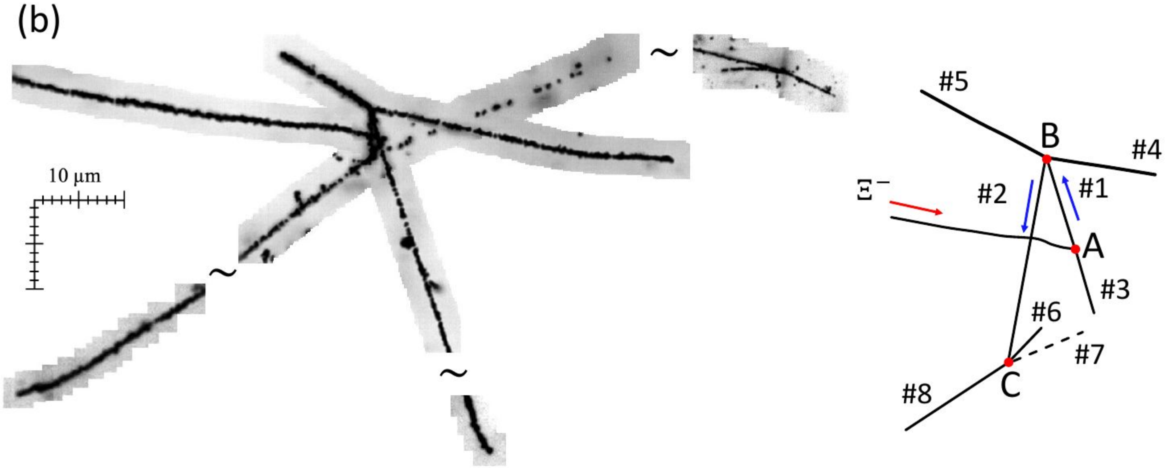


- ${}^{3}_{\Lambda}$H Binding energy:
  - Theory : 0.13 ± 0.05 MeV
  - STAR (2020): 0.41 ± 0.12 ± 0.11 MeV
  - ALICE (2023): 0.102 ± 0.063 ± 0.067 MeV
  - E07 (2025): 0.23 ± 0.11 MeV

📖G. Bohm et al., NPB 4 (1968) 511
📖M. Juric et al., NPB 52 (1973) 1
📖STAR Collaboration, Nat. Phys. 16 (2020) 409
📖ALICE Collaboration, Phys. Rev. Lett. 131, 102302 (2023)
📖A. Kasagi et al., PTEP 2025, 8 (2025)

Discovery of double-Λ hypernucleus: $^{13}_{\Lambda\Lambda}B$





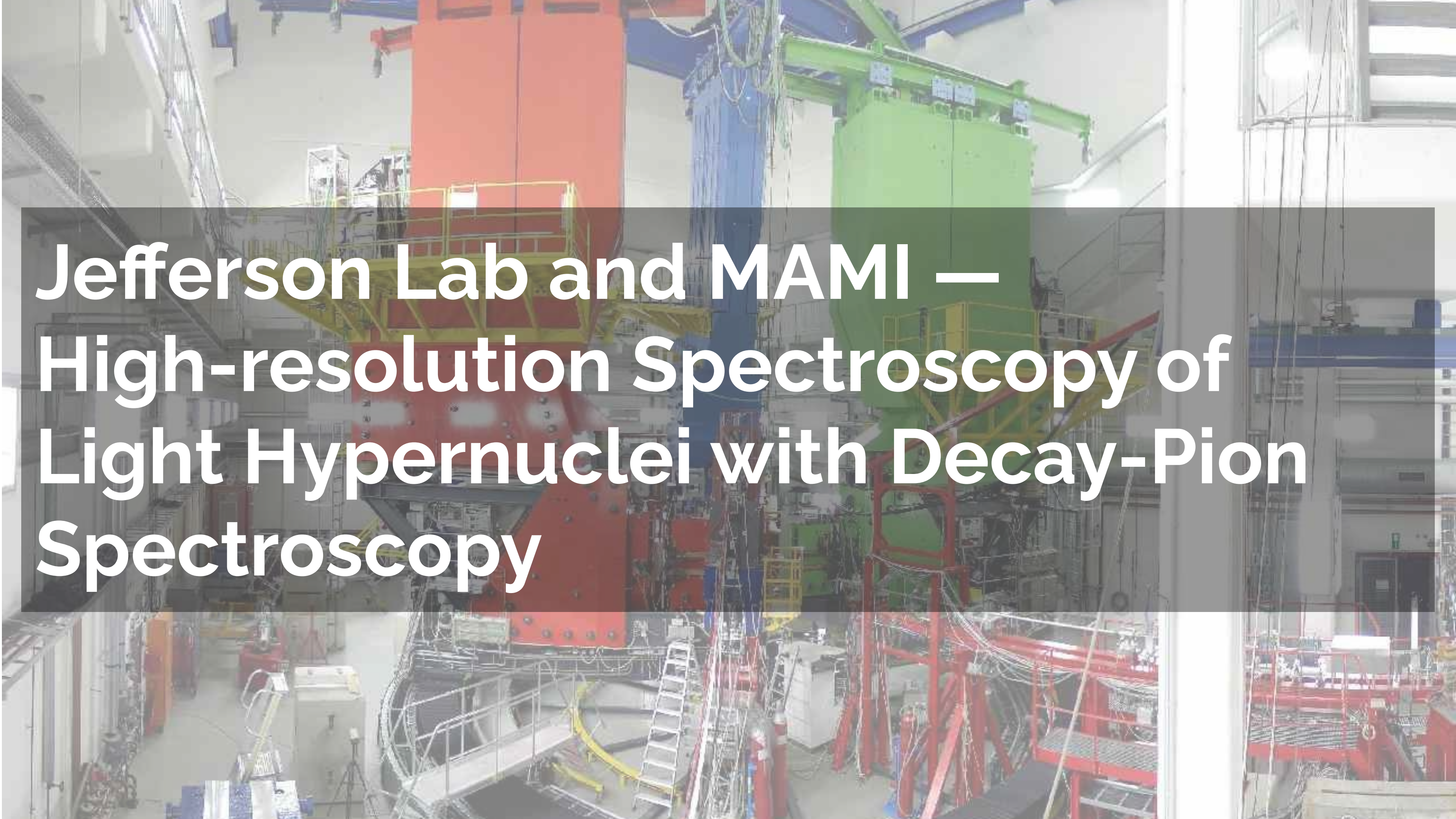
- $^{13}_{\Lambda\Lambda}B$: Uniquely identified
  - 2nd case in the history after E176 event

$B_{\Lambda\Lambda} = 25.57 \pm 1.18 \pm 0.07$ MeV

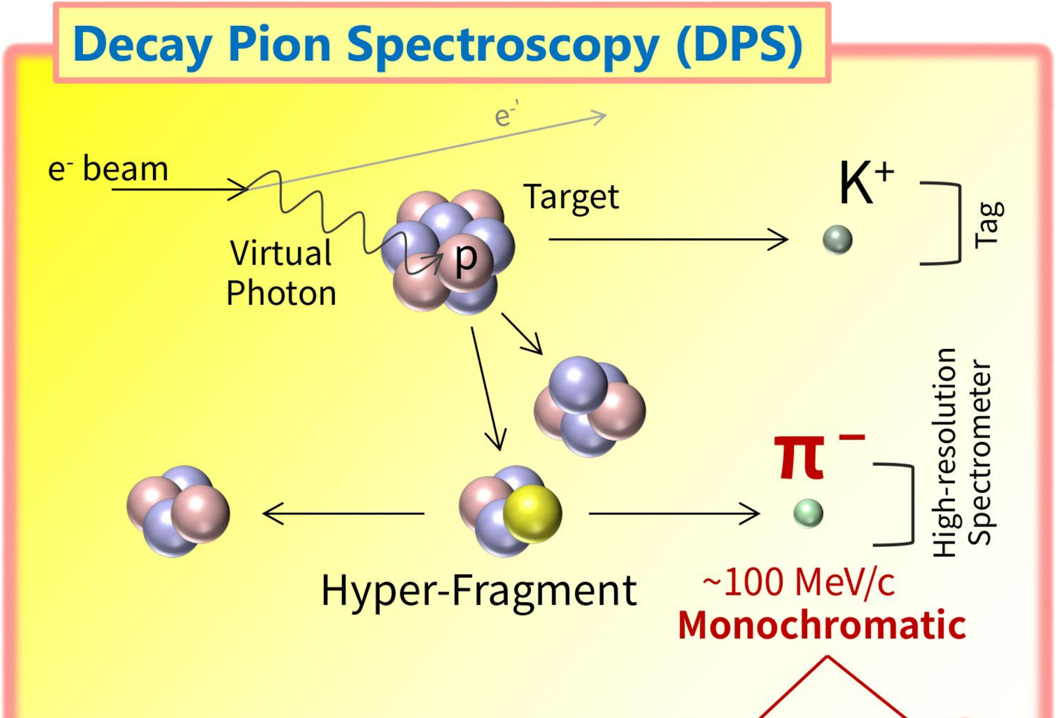
$\Delta B_{\Lambda\Lambda} = 2.83 \pm 1.18 \pm 0.14$ MeV

Yan He, et al., arXiv:2505.05802

Jefferson Lab and MAMI — High-resolution Spectroscopy of Light Hypernuclei with Decay-Pion Spectroscopy



Hypernuclei detection via π spectroscopy



$$M({}^{A}_{\Lambda}Z) = \sqrt{M({}^{A}(Z+1))^2 + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2}$$

- Hypernuclear Mass Spectroscopy with **high-resolution**, **high-precision**, **high-accuracy**
- Principle:
  - Measurement of monochromatic decay pion from hypernuclei stopped in the target emitting pion in two-body decay
    (e.g. ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$)
  - Identification from known (or expected) B_Λ
  - Tagging K^+ for background suppression from non-strangeness production

Possible hypernuclei & Expected Pion Momenta

- Specific decay pion momentum each hypernucleus
- Well known daughter particle masses
- Precise pion momentum → Precise hypernuclear ground-state mass

Example, ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$

$$M({}^{A}_{\Lambda}Z) = \sqrt{M({}^{A}(Z+1))^{2} + p_{\pi}^{2}} + \sqrt{M_{\pi}^{2} + p_{\pi}^{2}}$$

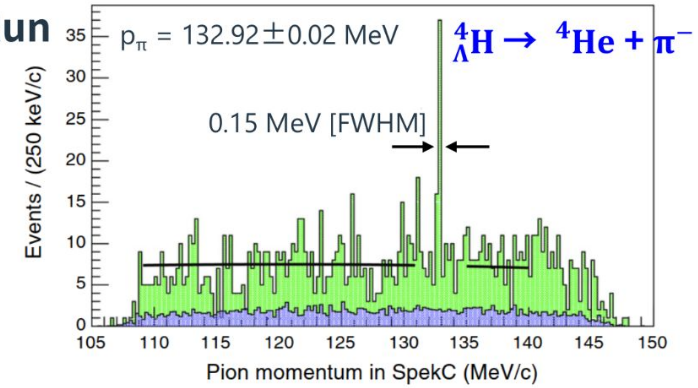
$M(\alpha)$	= 3727.3794118(11)	MeV/c²
$M(\pi)$	= 139.57039(18)	MeV/c²
$p(\pi)$	= 133.03(6)	MeV/c
$M({}^{4}_{\Lambda}H)$	= 3922.56(4)	MeV/c²

Hypernuclei	Decay mode	p_{π^-} (MeV/c)	comments
${}^{3}_{\Lambda}H$	${}^{3}He + \pi^{-}$	114.37	
${}^{4}_{\Lambda}H$	${}^{4}He + \pi^{-}$	133.03	
~~${}^{4}_{\Lambda}He$~~	~~${}^{4}Li + \pi^{-}$~~	~~98.17~~	Impossible 2-body decay
~~${}^{5}_{\Lambda}He$~~	~~${}^{5}Li + \pi^{-}$~~	~~99.26~~	Impossible 2-body decay
${}^{6}_{\Lambda}H$	${}^{6}He + \pi^{-}$	135.27	
${}^{6}_{\Lambda}He$	${}^{6}Li + \pi^{-}$	108.48	
~~${}^{6}_{\Lambda}Li$~~	~~${}^{6}Be + \pi^{-}$~~	~~-~~	No B_{Λ} data, above Sp
${}^{7}_{\Lambda}He$	${}^{7}Li + \pi^{-}$	115.10	
${}^{7}_{\Lambda}Li$	${}^{7}Be + \pi^{-}$	108.11	
~~${}^{7}_{\Lambda}Be$~~	~~${}^{7}C + \pi^{-}$~~	~~95.90~~	Impossible 2-body decay
${}^{8}_{\Lambda}He$	${}^{8}Li + \pi^{-}$	116.47	
${}^{8}_{\Lambda}Li$	${}^{8}Be + \pi^{-}$	124.20	
${}^{8}_{\Lambda}Be$	${}^{8}B + \pi^{-}$	97.19	No ${}^{8}B$(g.s) decay
${}^{9}_{\Lambda}Li$	${}^{9}Be + \pi^{-}$	121.31	
${}^{9}_{\Lambda}Be$	${}^{9}B + \pi^{-}$	96.98	
${}^{9}_{\Lambda}B$	${}^{9}C + \pi^{-}$	96.82	
${}^{10}_{\Lambda}Li$	${}^{10}Be + \pi^{-}$	-	No B_{Λ} data
${}^{10}_{\Lambda}Be$	${}^{10}B + \pi^{-}$	104.41	
${}^{10}_{\Lambda}B$	${}^{10}C + \pi^{-}$	100.49	
${}^{11}_{\Lambda}B$	${}^{11}C + \pi^{-}$	86.54	
${}^{12}_{\Lambda}B$	${}^{12}C + \pi^{-}$	115.87	
${}^{12}_{\Lambda}C$	${}^{12}N + \pi^{-}$	91.48	No ${}^{12}N$(g.s) decay
${}^{13}_{\Lambda}C$	${}^{13}N + \pi^{-}$	92.27	
${}^{14}_{\Lambda}C$	${}^{14}N + \pi^{-}$	101.20	
${}^{14}_{\Lambda}N$	${}^{14}O + \pi^{-}$	-	No B_{Λ} data
${}^{15}_{\Lambda}N$	${}^{15}O + \pi^{-}$	98.40	
${}^{16}_{\Lambda}N$	${}^{16}O + \pi^{-}$	106.23	
${}^{16}_{\Lambda}O$	${}^{16}F + \pi^{-}$	86.54	

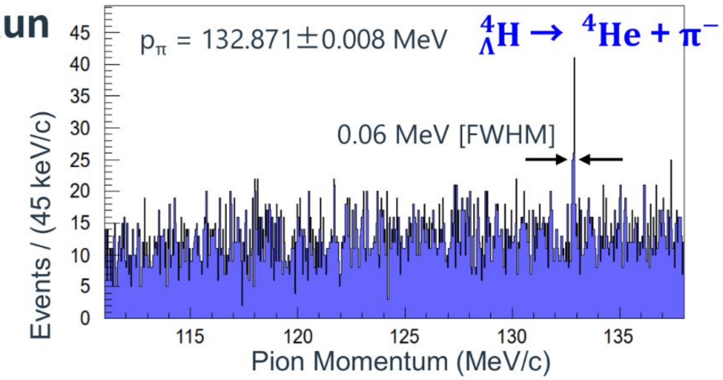
- ${}^{7}Li$ target (up to ${}^{7}_{\Lambda}He$)
- ${}^{9}Be$ target (up to ${}^{9}_{\Lambda}Li$)
- ${}^{12}C$ target (up to ${}^{12}_{\Lambda}B$)
- ${}^{16}O$ target (up to ${}^{16}_{\Lambda}O$)

$^{4}_{\Lambda}$H in DPS at MAMI

2012 Run



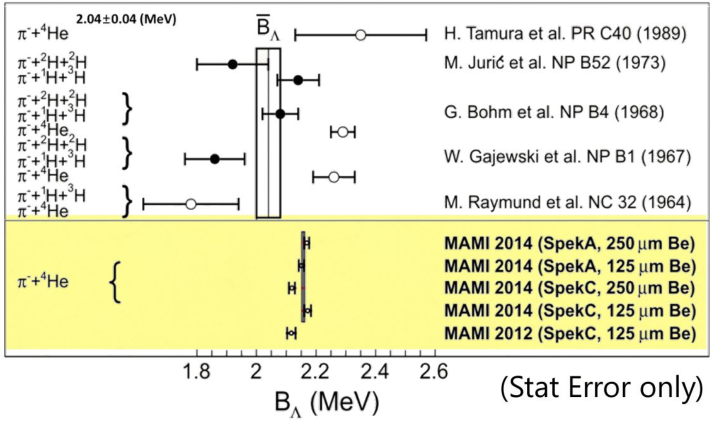
2014 Run



- Hypernuclear production with ^{9}Be target
- Two-body decay peak from $^{4}_{\Lambda}$H
- Excellent peak resolution thanks to high-resolution spectrometer & thin target

B_Λ ($^{4}_{\Lambda}$H)(MAMI 2012) = 2.12 ± 0.01 ± 0.09 (MeV)

B_Λ ($^{4}_{\Lambda}$H)(MAMI 2014) = 2.157 ± 0.005 ± 0.077 (MeV)

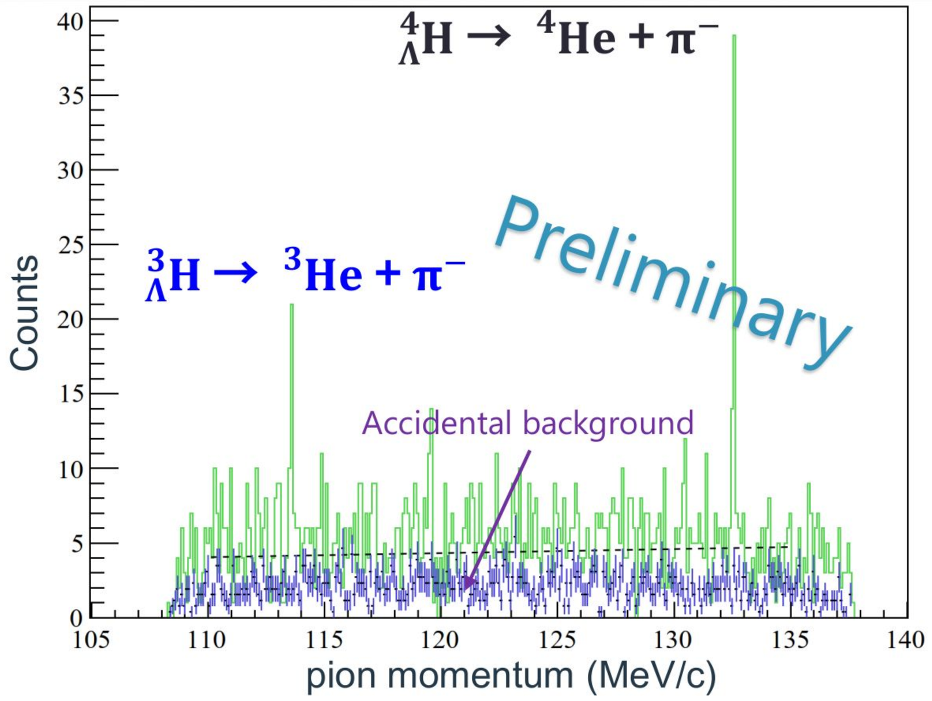


A1 Collaboration PRL 114 (2015) 232501

A1 Collaboration NPA 954 (2016) 149

Latest results of hypertriton data (MAMI)

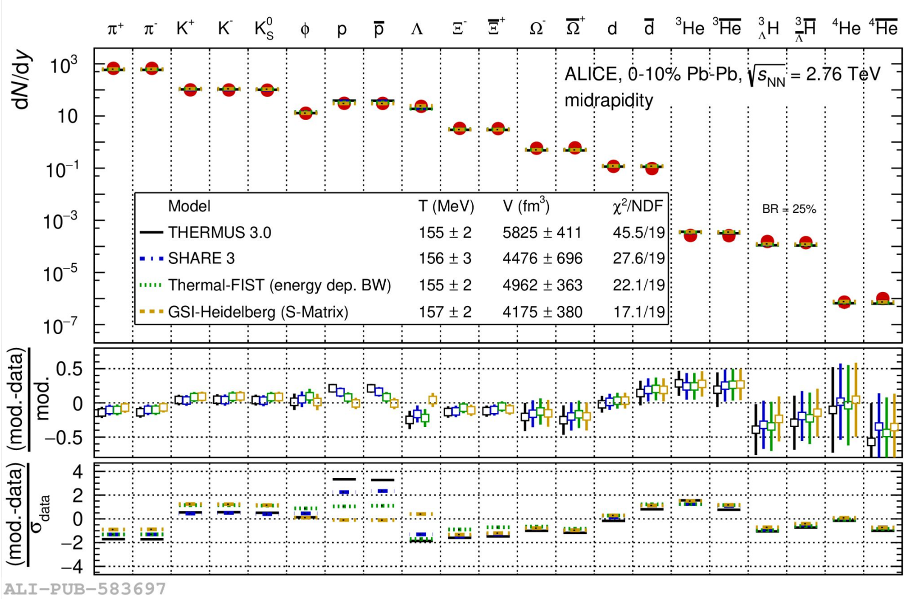
- Subsequence exp. was done in 2022:
  - Different target (Be → Li 2.7 g/cm^2)
- Finding two peaks on pion spectrum
  - ${}^4_\Lambda$H → ^{4}He+π^- (~133 MeV/c)
  - ${}^3_\Lambda$H → ^{3}He+π^- (~114 MeV/c)
- Reliable peak resolution
  - FWHM ~ 100 keV/c
- Statistical error:
  - ~ 10 keV/c
- Pion Yield:
  - ${}^4_\Lambda$H : ${}^3_\Lambda$H = 3 : 1



Results from heavy ion collisions

Production models

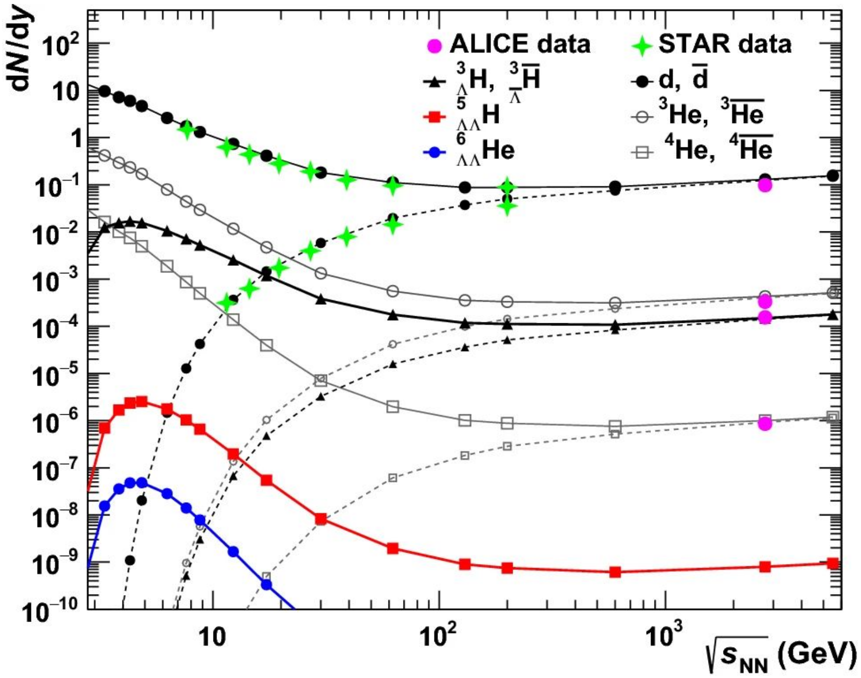
- Statistical hadronization models (SHMs)
  - describe the yields of light- flavoured hadrons by requiring thermal and hadron-chemical equilibrium
    - Parameters: (T, V, μ_B)
  - light (anti)(hyper)**nuclei** are treated as <u>**point-like objects**</u>



ALICE Collaboration Eur. Phys. J. C 84 (2024) 813

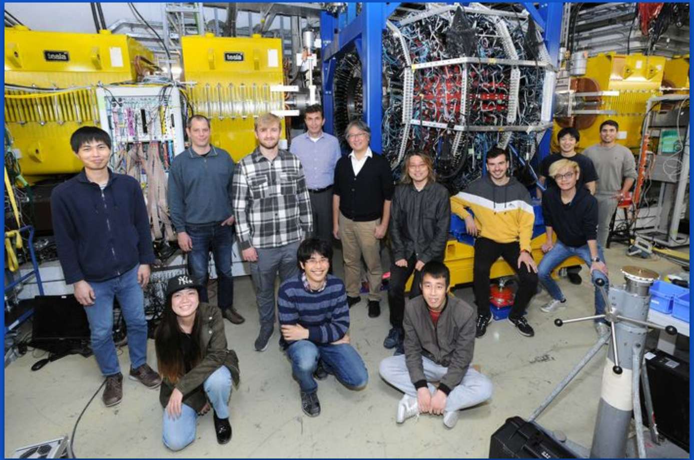
Production models: Statistical hadronization models

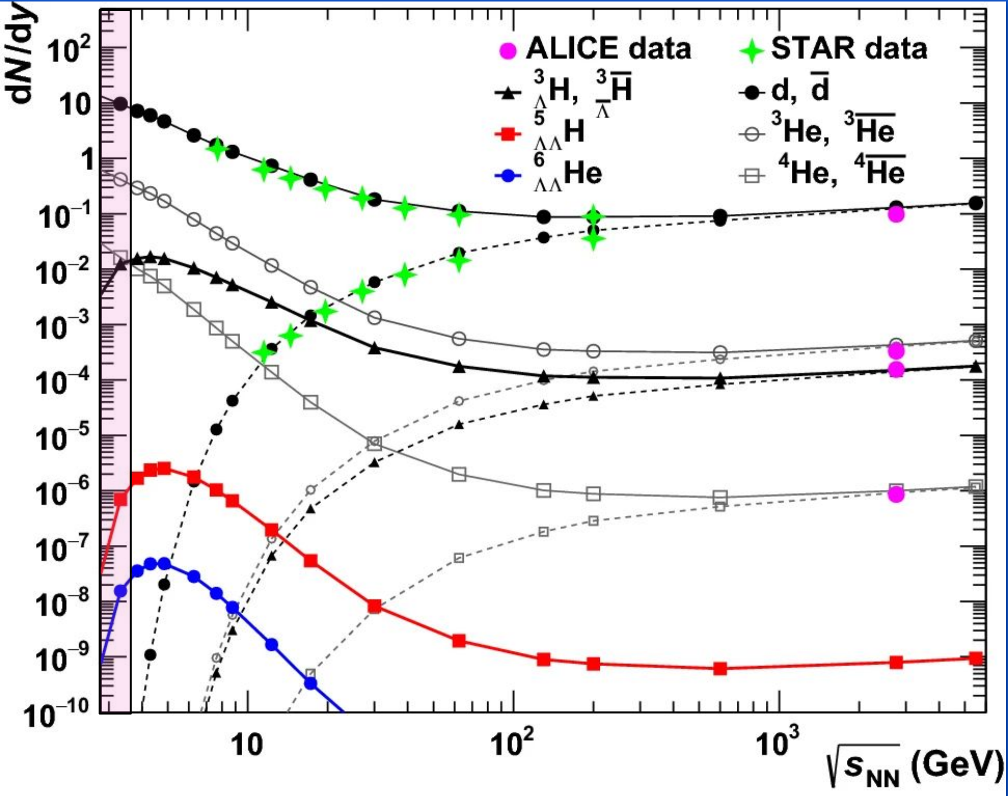
- Statistical hadronization models (SHMs)
  - describe the yields of light- flavoured hadrons by requiring thermal and hadron-chemical equilibrium
    - Parameters: (T, V, μ_B)
  - light (anti)(hyper)**nuclei** are treated as **point-like objects**
- Internal structure of hypernuclei plays no role
  - The heavier it is, the harder it is to produce
    - The strong enhancement at low energies, can be attributed to an interplay of the temperature dependence, baryochemical potential and canonical effects



B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al, PLB 697 (2011)203

WASA-FRS HypHI (GSI)

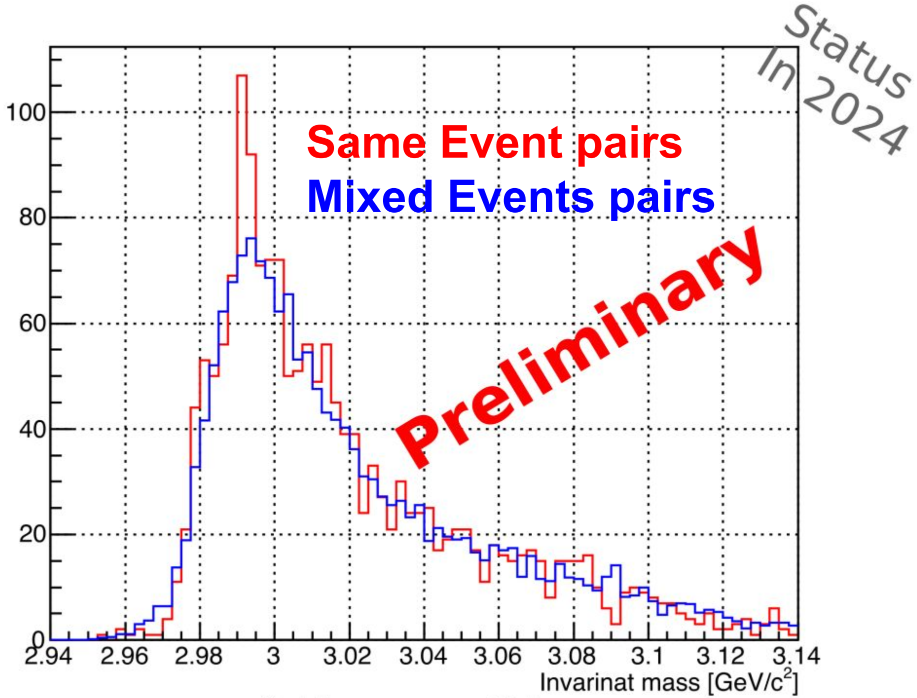




More details on [Christophe]'s slides

Light hypernuclei identification

- Fixed target, Reaction : ^{6}Li+ ^{12}C @ 1.96 AGeV or $\sqrt{s_{NN}}$ = 2.7 GeV



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

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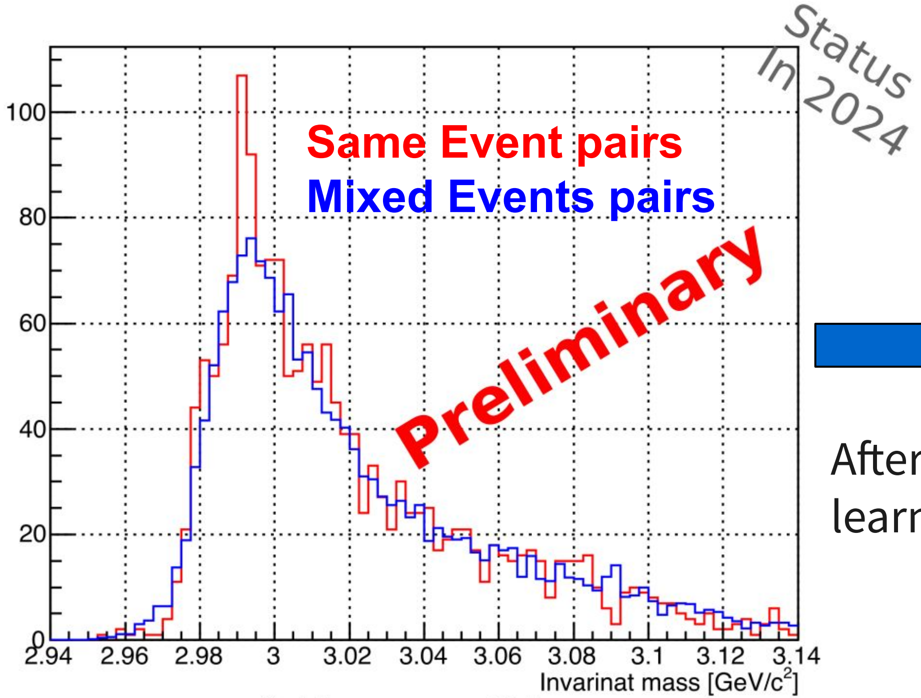
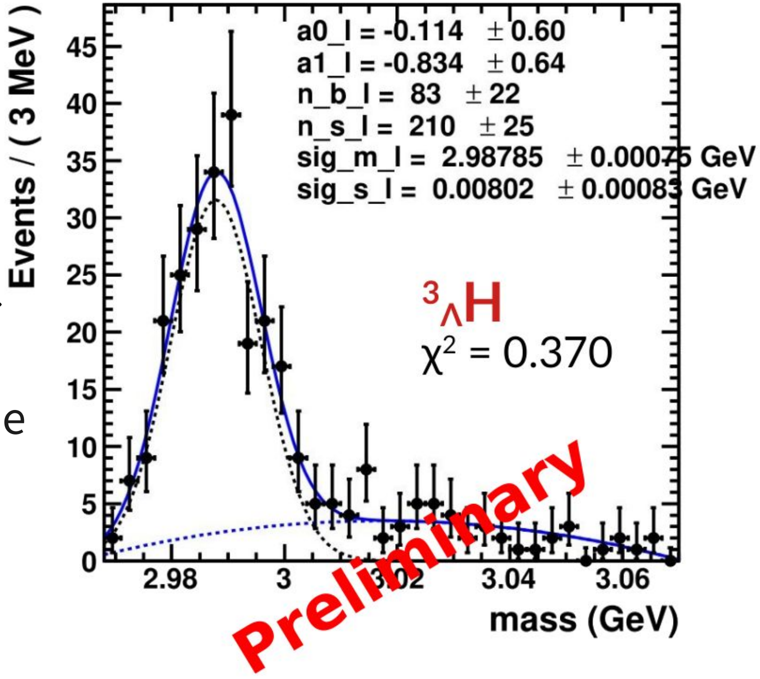
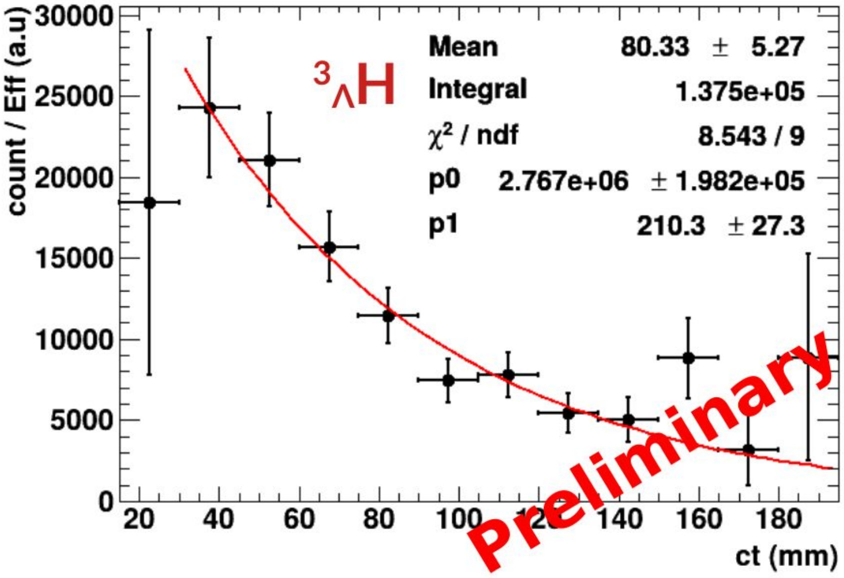


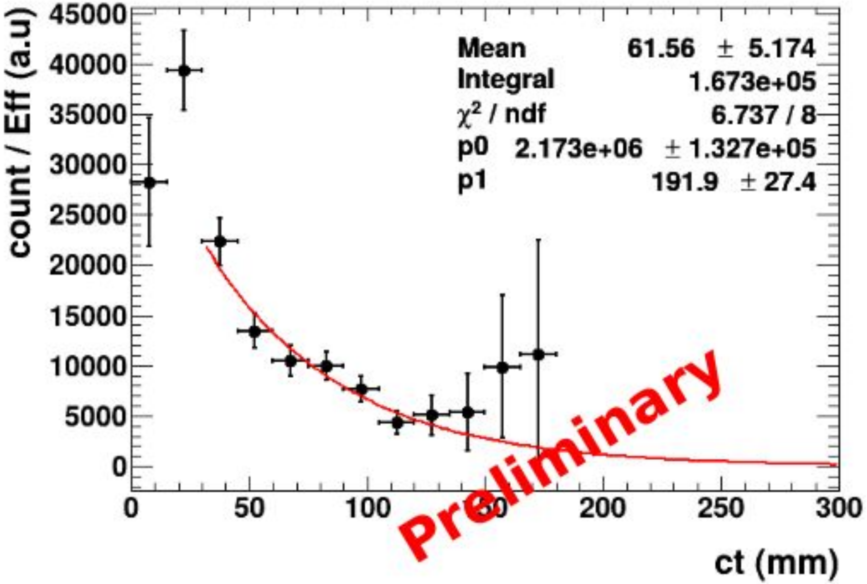
$^{3}_{\Lambda}H \rightarrow \pi^{-} + {}^{3}He$

After machine learning



Light hypernuclei lifetime determinations





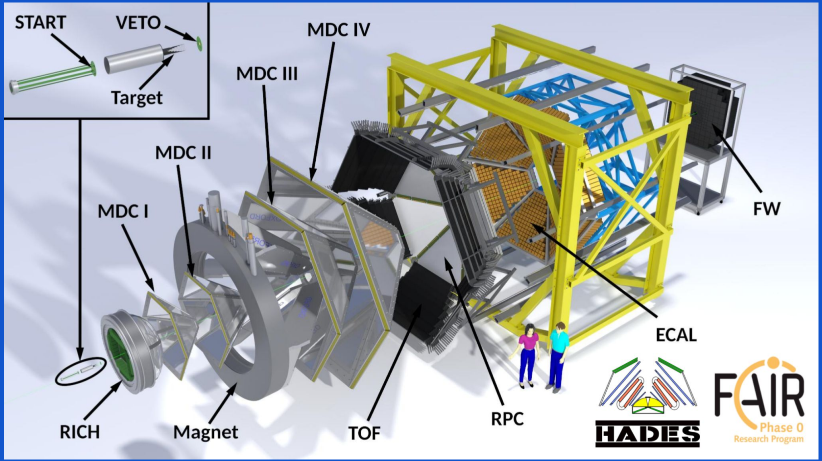
$^{3}_{\Lambda}H \rightarrow$ Threshold > 0.97

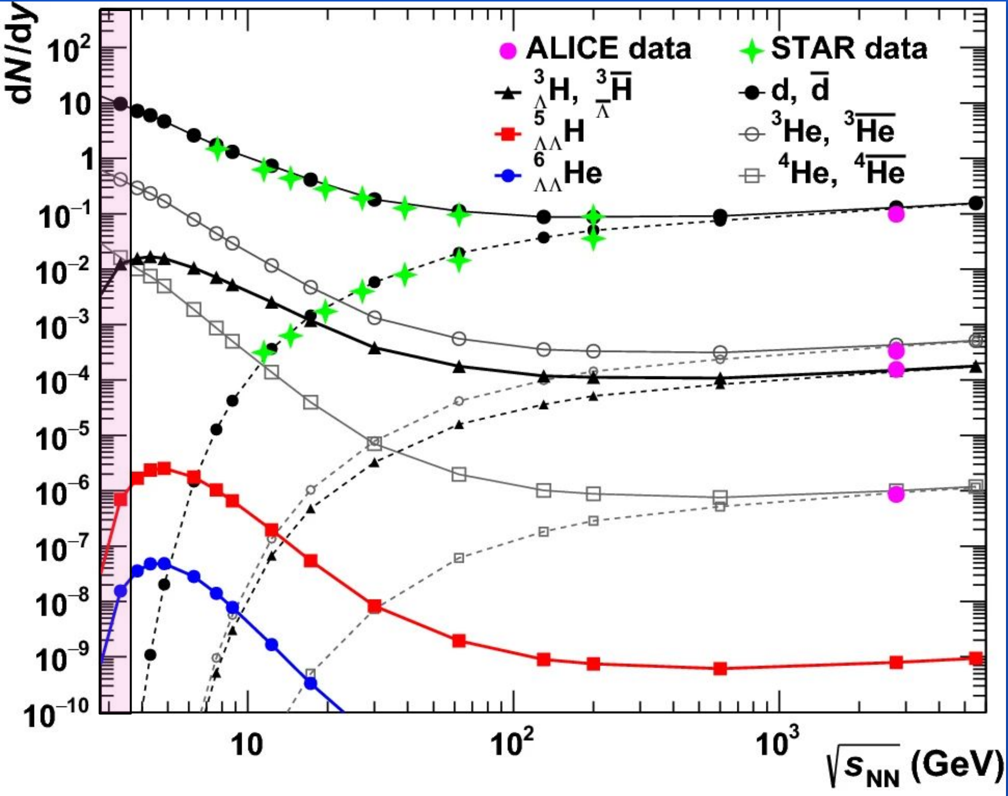
τ = 210 ± 27 ps

$^{4}_{\Lambda}H \rightarrow$ Threshold > 0.95

τ = 192 ± 27 ps

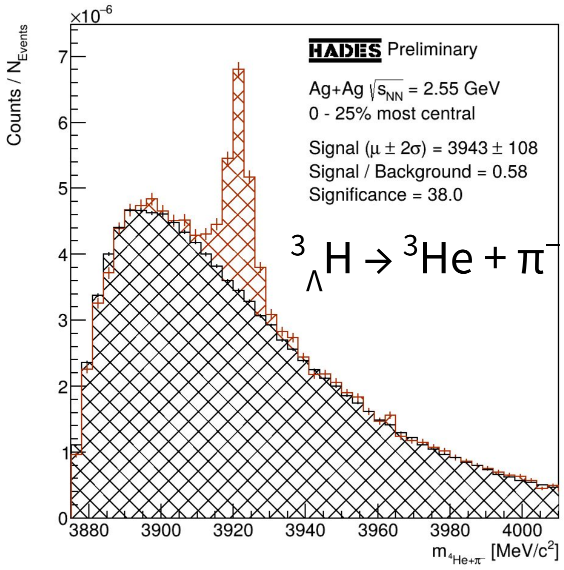
HADES EXPERIMENT (GSI)

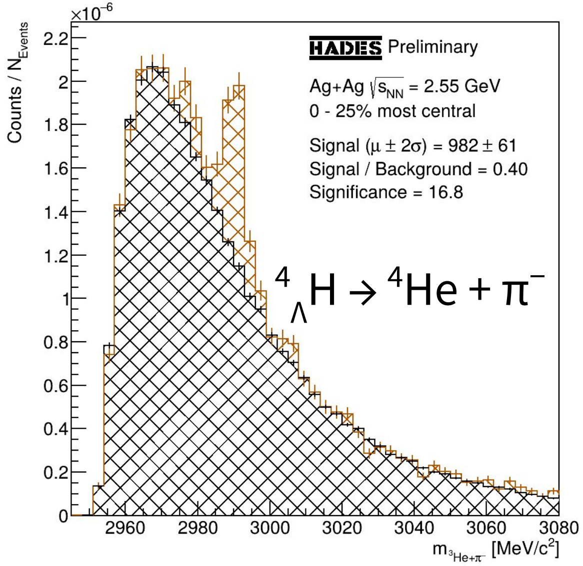




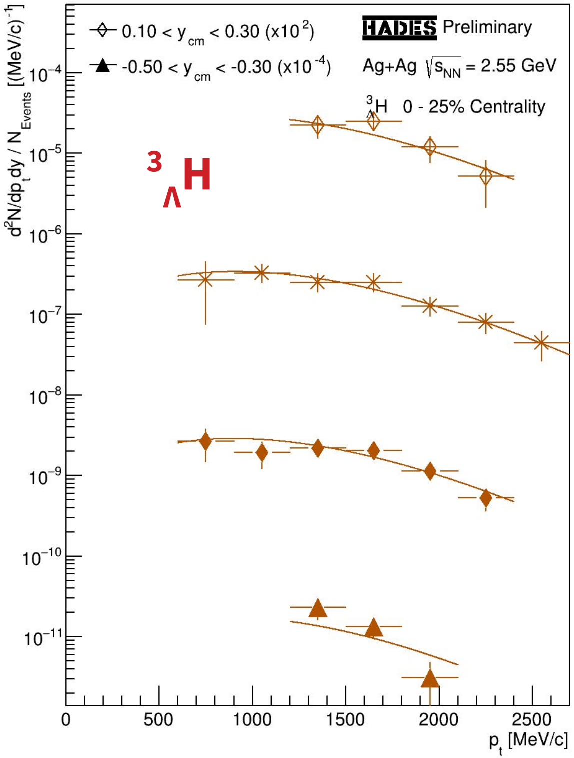
Hypernuclei from Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV

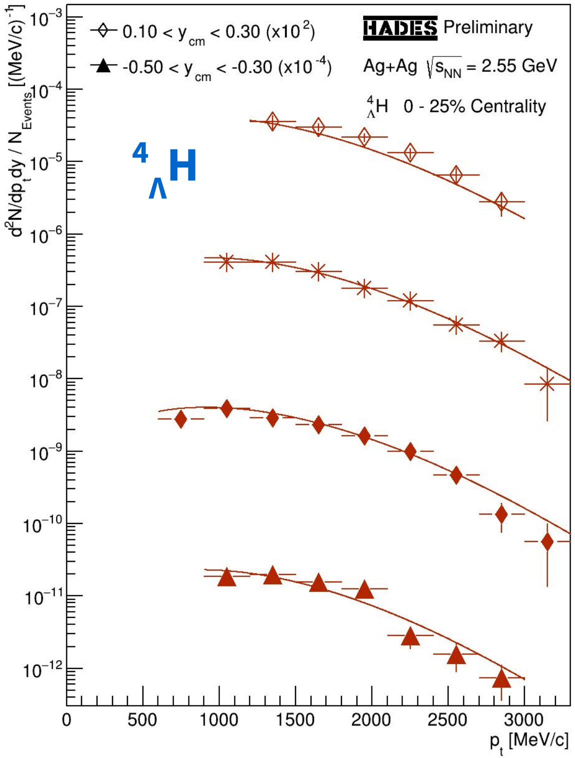
- Significant signals in the two-body-decay channels
- Three-body-decay channels more challenging due to increased combinatorial background
- Multi-differential analysis of Hypernuclei production possible





Light hypernuclei production



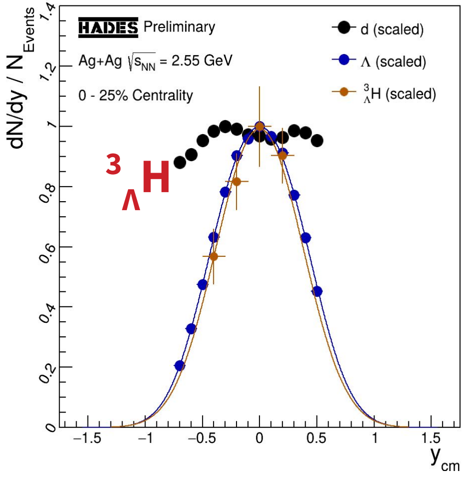


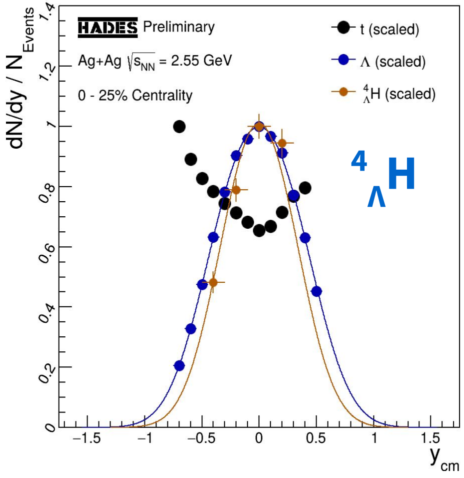
Production as a function of transverse momentum and rapidity

Hypernuclei production mechanism

- Compare rapidity distributions of **light nuclei**, **hyperons** and **hypernuclei**

- Rapidity distributions of **light nuclei** (d, t) have a "**coalescence-like**" behavior
- Rapidity distributions of **Λ** have a "**thermal-like**" behavior
- Rapidity distributions of **hypernuclei** have similar shape as the ones of **Λ**





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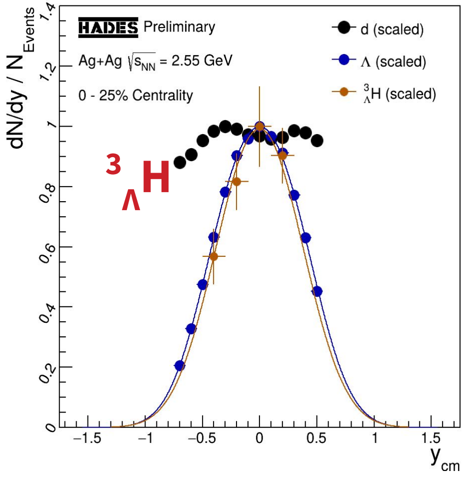
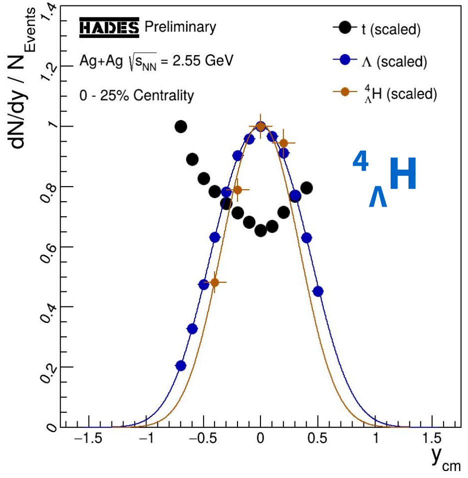
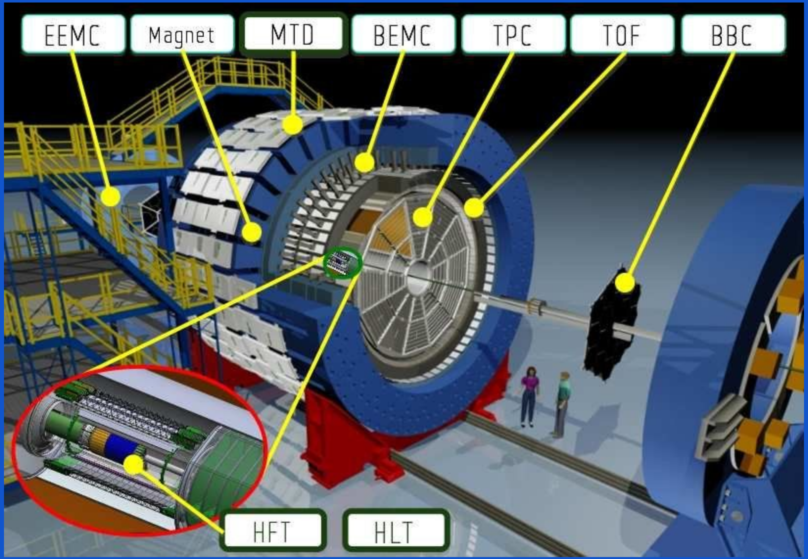
- Hypernuclei produced via coalescence $d + \Lambda \rightarrow {}^{3}_{\Lambda}H$, $t + \Lambda \rightarrow {}^{4}_{\Lambda}H$ would be influenced by rapidity distributions of both d/t and Λ inheriting "coalescence-like" and "thermal-like" features

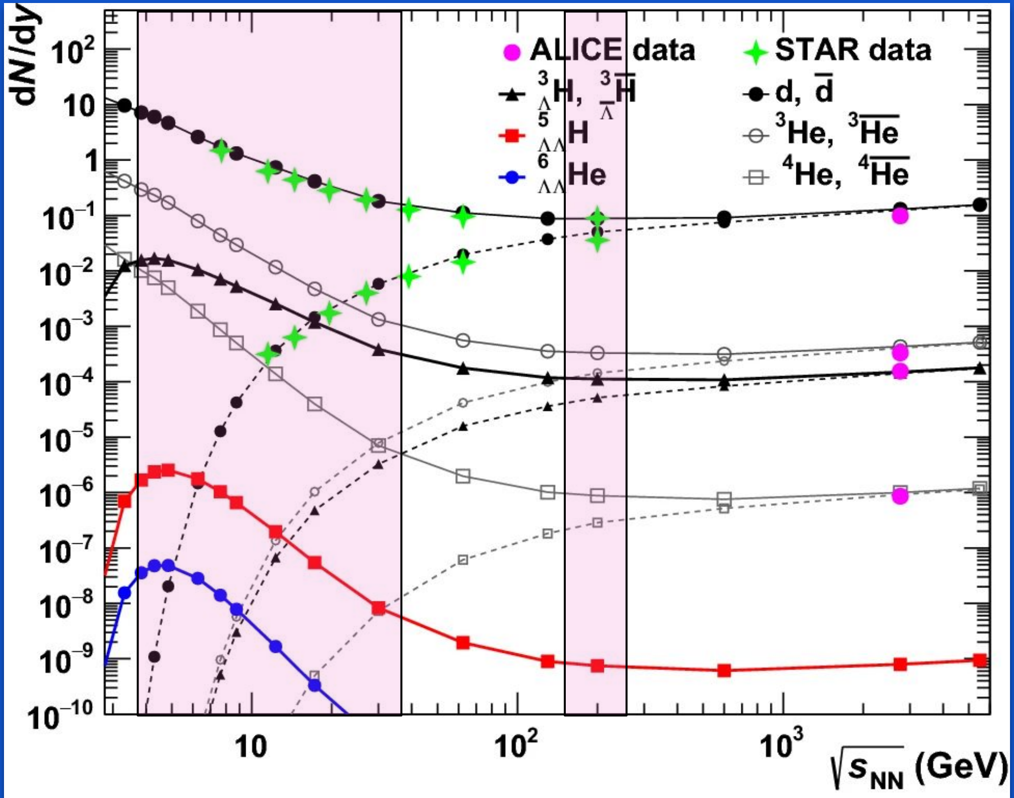




- More narrow rapidity distributions of hypernuclei hint towards "thermal-like" effects to be dominant, but statistical uncertainties are still large

STAR experiment (RHIC)

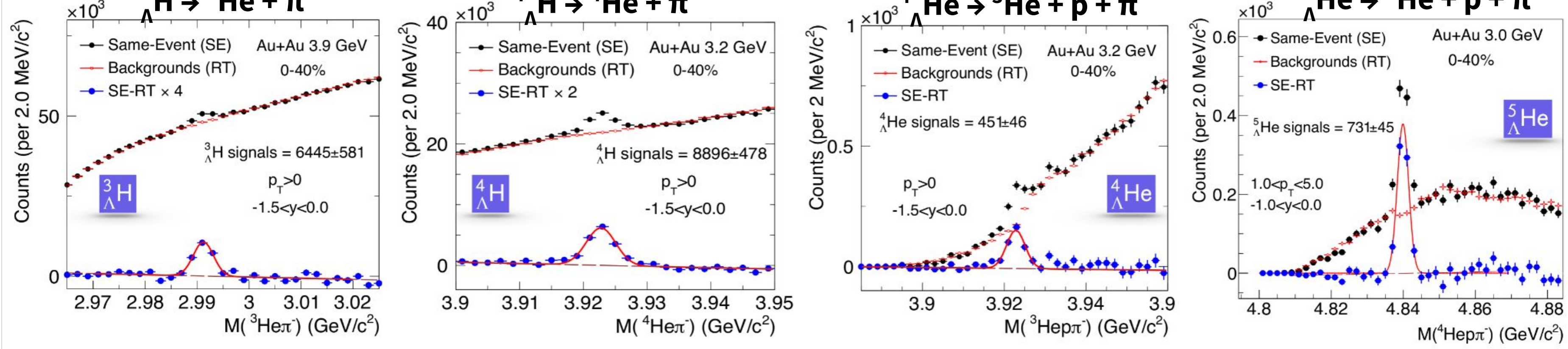


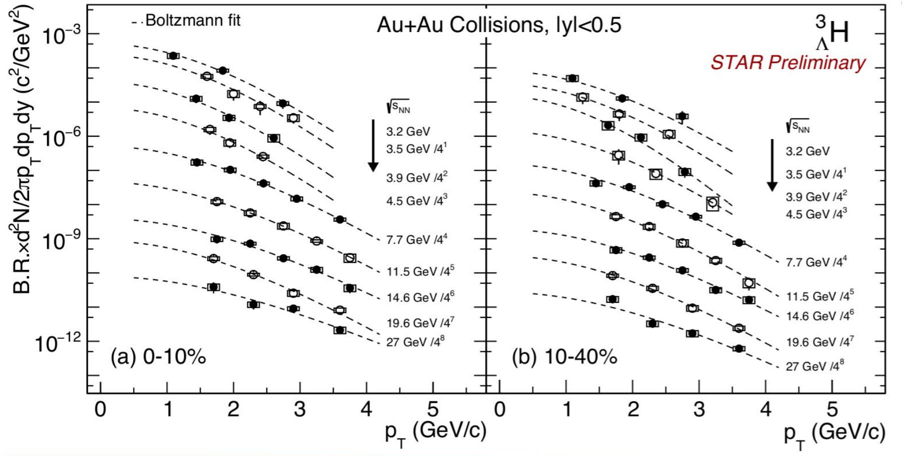


More details on Yixuan's slides

Hypernuclei reconstruction and p_T-spectra

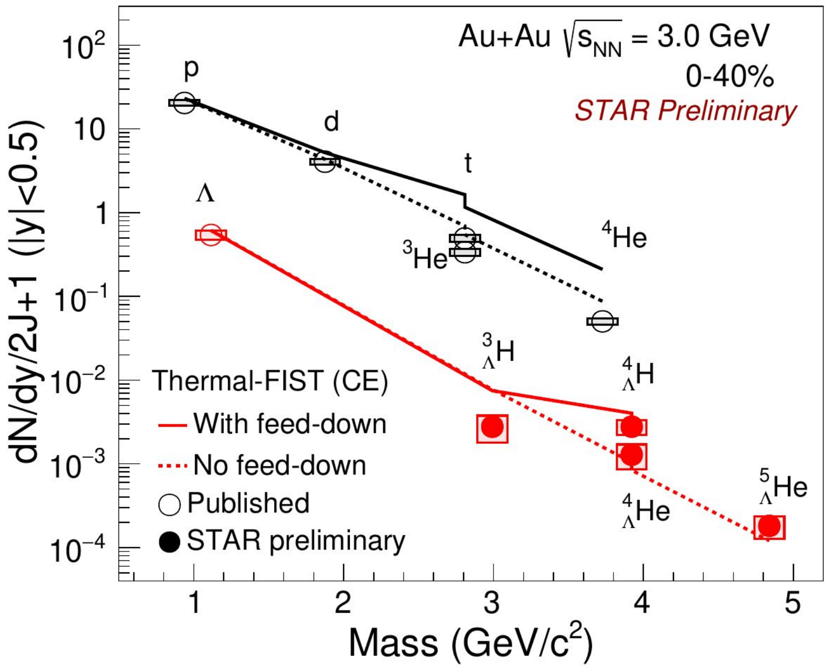
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ $^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$ $^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^{-}$ $^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$





- Large production of hypernuclei with A = 2,4, and 5
- Multi-differential analysis as a function of p_T, energy and rapidity

Particle yield comparison with Thermal model at 3 GeV



- Thermal model predicts approximate exponential dependence of yields/(2J+1) vs A
- Light nuclei overestimated by thermal model with feed-down from unstable nuclei
- Model overestimate $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He after including feed-down from excited states

$$^{4}_{\Lambda}\mathrm{H}^{\star}\ (1^{+}) \rightarrow {}^{4}_{\Lambda}\mathrm{H}\ (0^{+}) + \gamma$$
$$^{4}_{\Lambda}\mathrm{He}^{\star}(1^{+}) \rightarrow {}^{4}_{\Lambda}\mathrm{He}\ (0^{+}) + \gamma$$

STAR Collaboration, PRC 110, 054911 (2024)
STAR Collaboration, PRL 128, 202301 (2022)
STAR Collaboration, JHEP 10 (2024) 139
STAR Collaboration, PLB 834, 137449 (2022)

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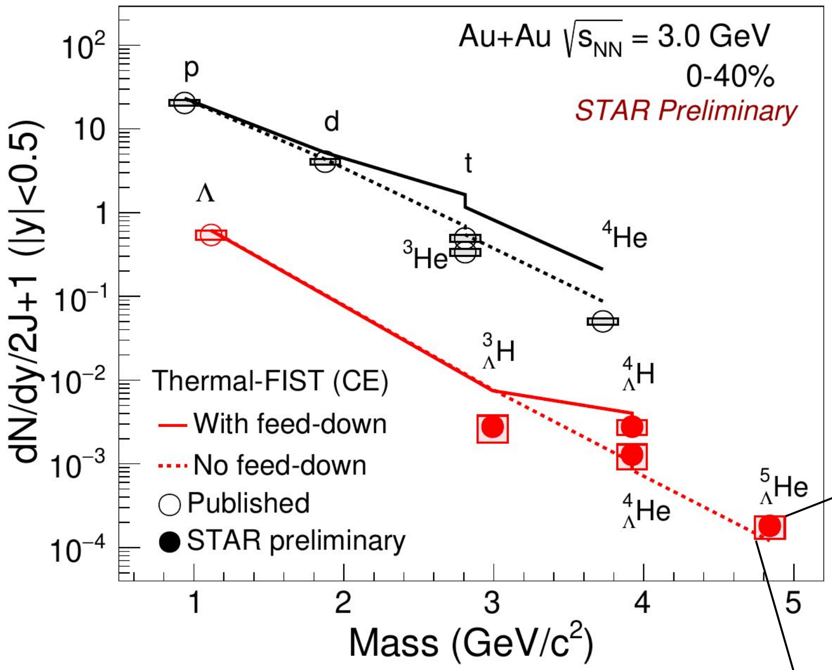

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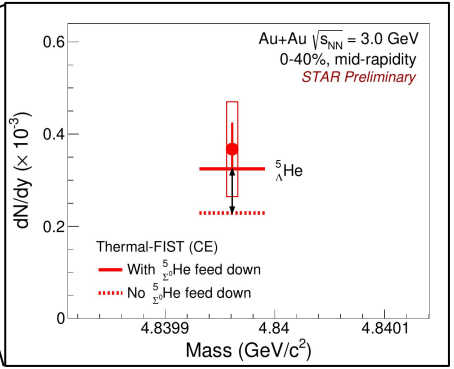


First hint for the possible feed down from $^5_{\Sigma^0}\mathrm{He} \rightarrow {}^5_\Lambda\mathrm{He} + \gamma$

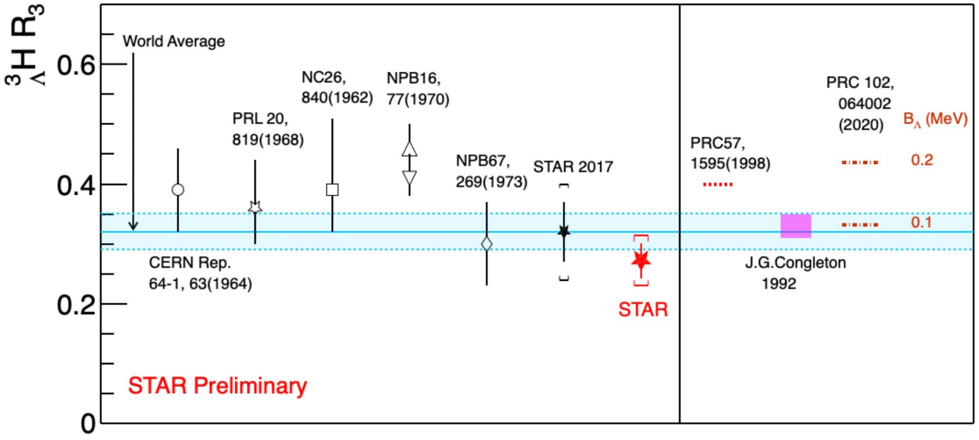
STAR Collaboration, PRC 110, 054911 (2024)
STAR Collaboration, PRL 128, 202301 (2022)
STAR Collaboration, JHEP 10 (2024) 139
STAR Collaboration, PLB 834, 137449 (2022)

R_3 determination using STAR data

- Calculations propose that R_3 ($^3_\Lambda H$) may be sensitive to B_Λ
- B_Λ: Λ separation energy
- $B_\Lambda(^3_\Lambda H) = M(d) + M(\Lambda) - M(^3_\Lambda H)$

$$R_3 = \frac{B.R.(^3_\Lambda H \to {}^3He + \pi^-)}{B.R.(^3_\Lambda H \to p + d + \pi^-) + B.R.(^3_\Lambda H \to {}^3He + \pi^-)}$$

STAR: $R_3 = 0.272 \pm 0.030 \pm 0.042$



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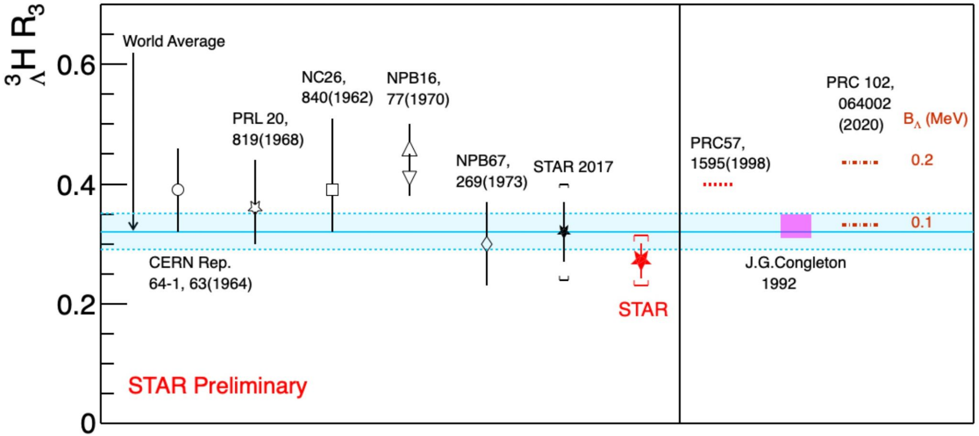
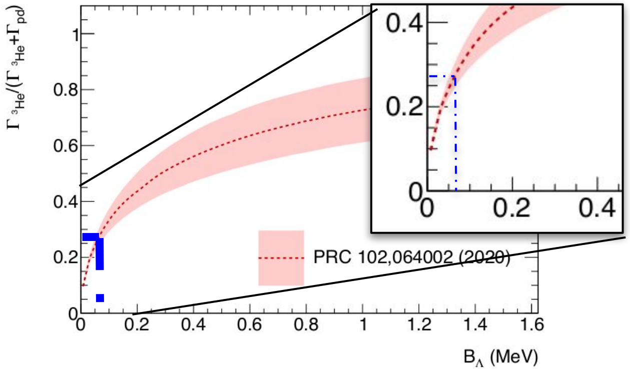
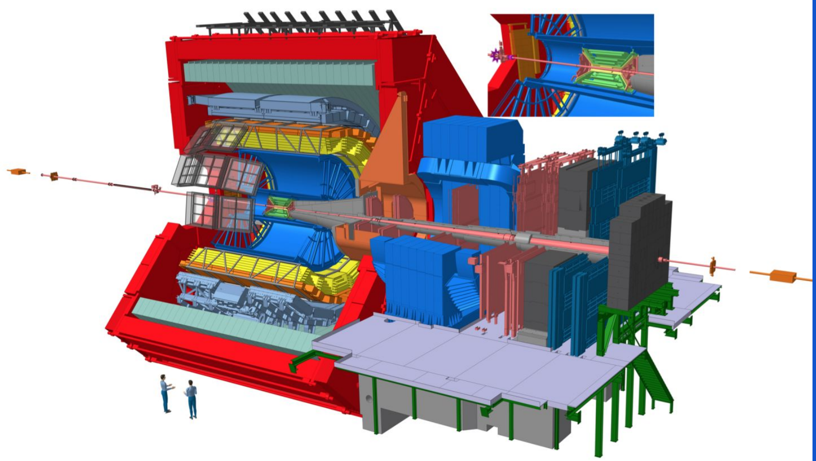


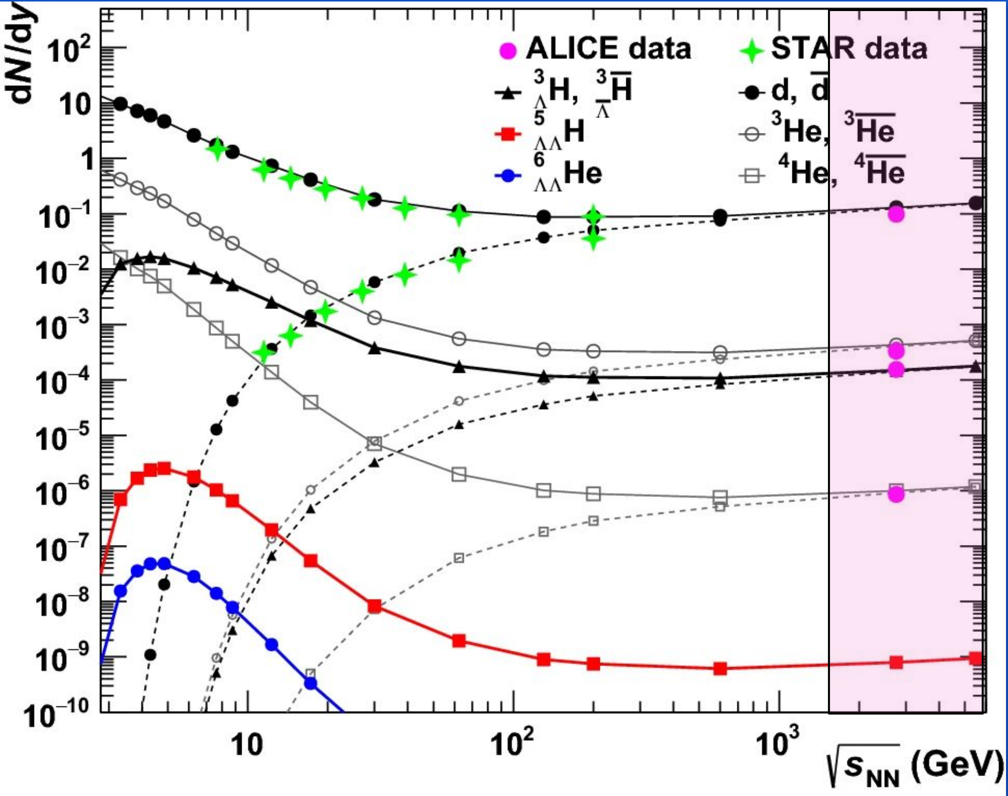


F. Hildenbrand et al, PRC 102, 064002 (2020)

STAR new R_3 data favors small binding energy of $^{3}_{\Lambda}H$

ALICE experiment (LHC)

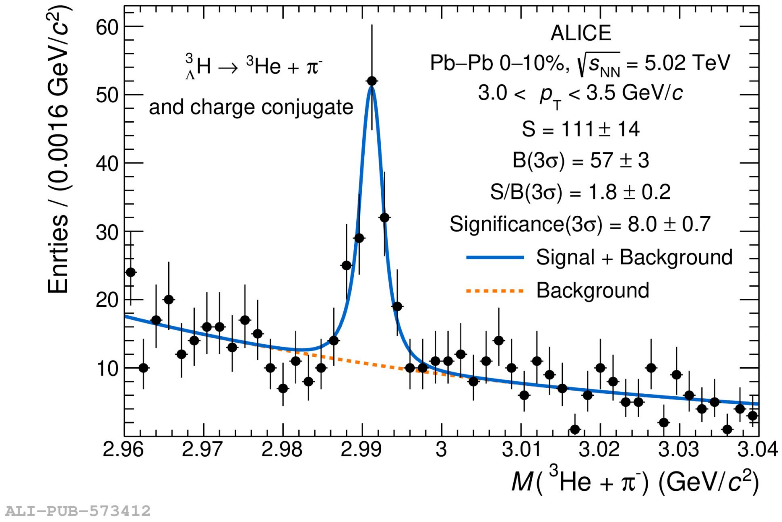




More details on [Mario](#)'s slides

Hypertriton production in Pb–Pb

- ${}^{3}_{\Lambda}$H has been measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



ALICE Collaboration, PLB 860, 139066 (2025)

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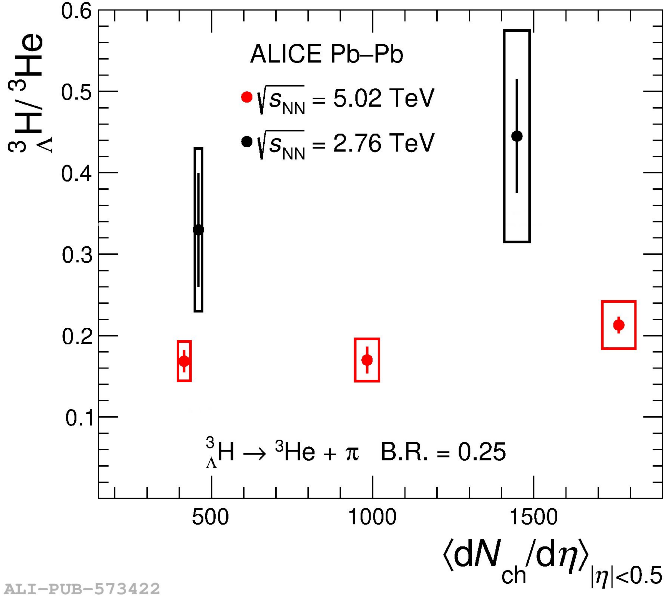

ALICE Collaboration, PLB 860, 139066 (2025)

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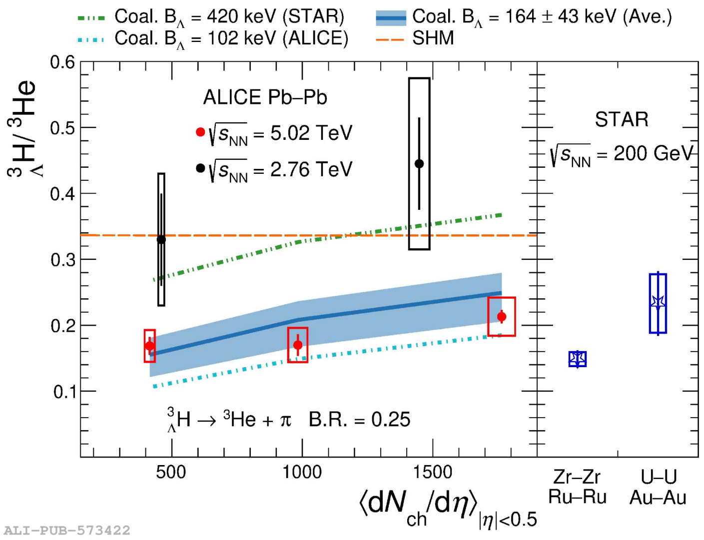

ALICE Collaboration, PLB 860, 139066 (2025)

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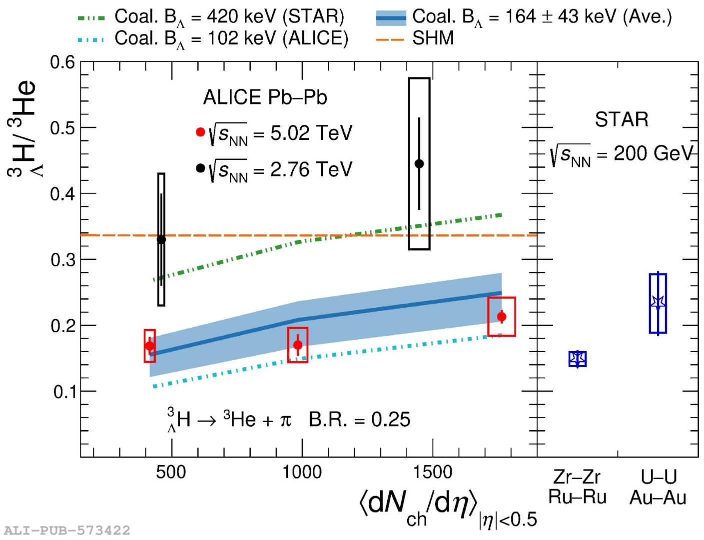
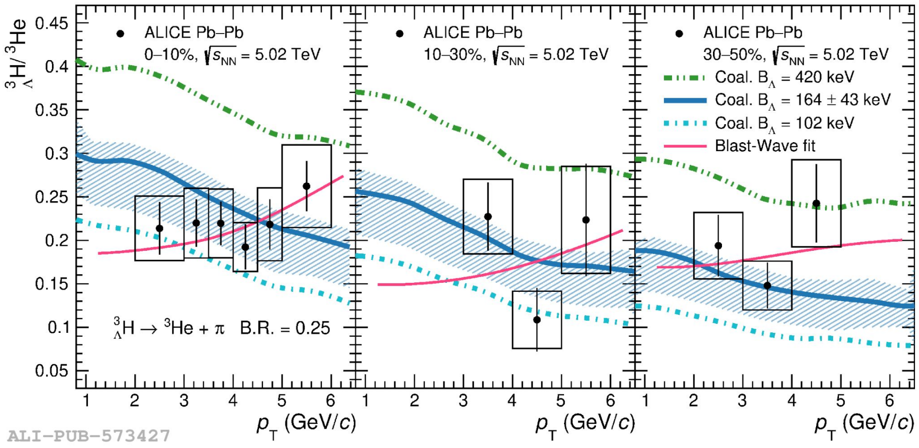




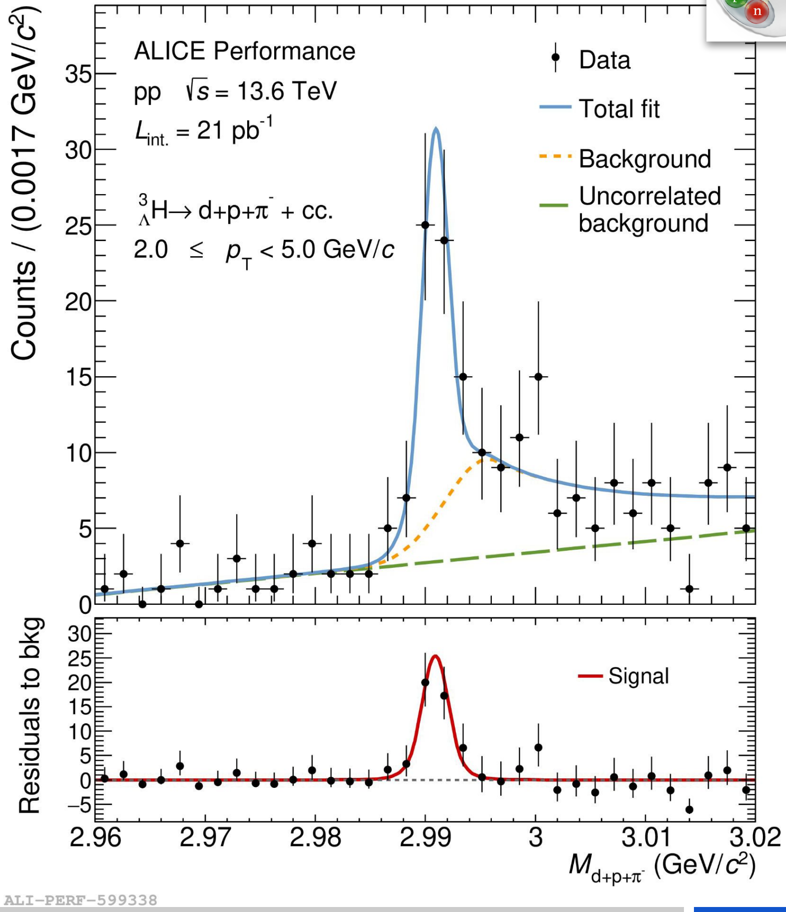
- p_T-differential measurement is also in agreement with **blast-wave** with common parameters with other nuclei
  - Large statistical uncertainties → Ongoing p_T-differential analyses with Run 3 data are fundamental to disentangle the two models

ALICE Collaboration, PLB 860, 139066 (2025)

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

- $^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$
  - Λ-d background modelled from data: correlated and uncorrelated background considered
  - Precision R_3 measurement underway

More details on Carolina's slides



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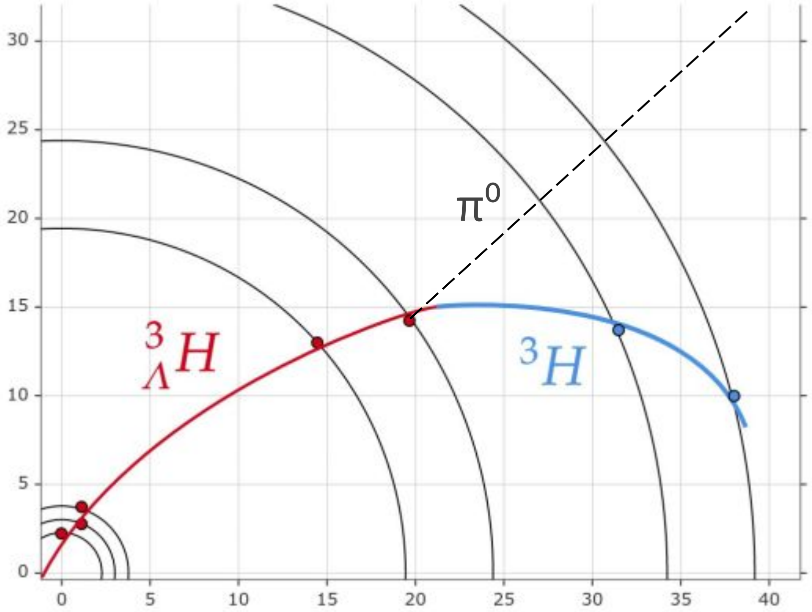
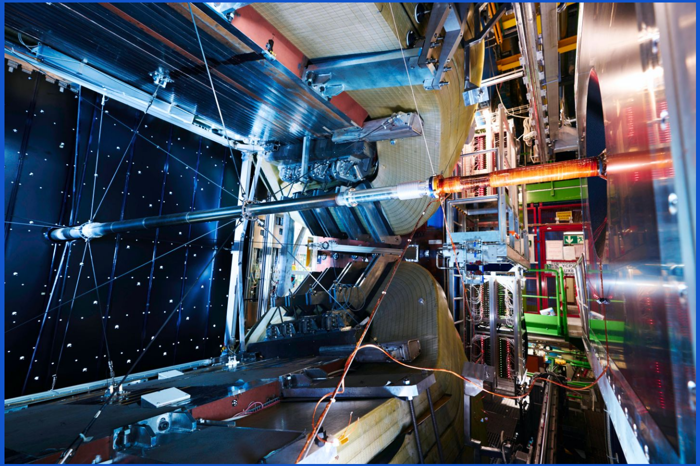
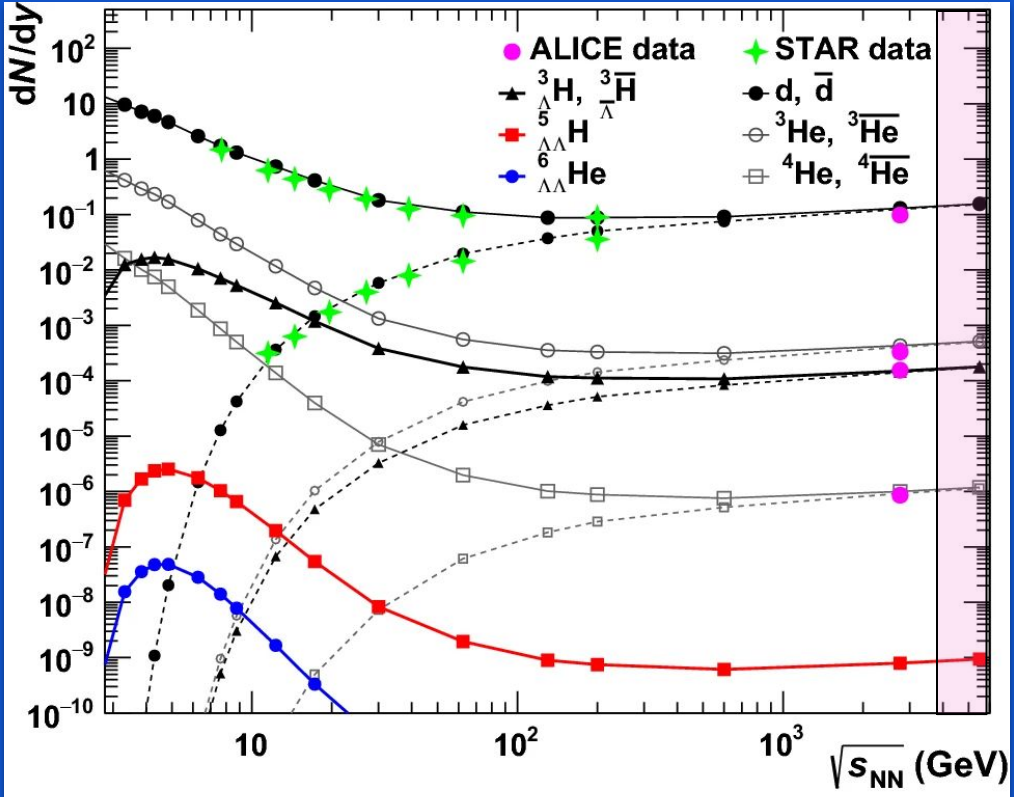


- $^{3}_{\Lambda}H \rightarrow {}^{3}H + \pi^{0}$ decay
  - Branching ratio never measured expected to follow ΔI rule
  - $^{3}_{\Lambda}H$ can be directly tracked into the ALICE innermost detector (ITS)

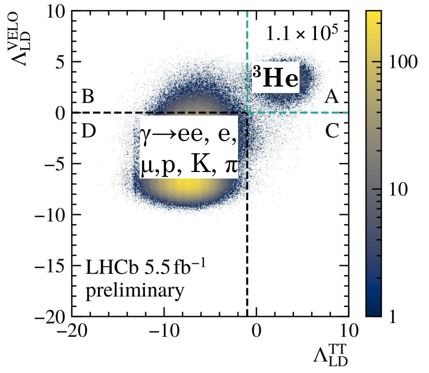
LHCb experiment (LHC)

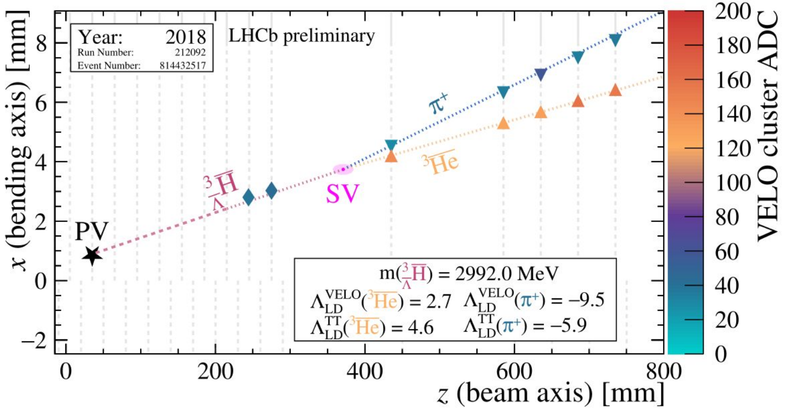


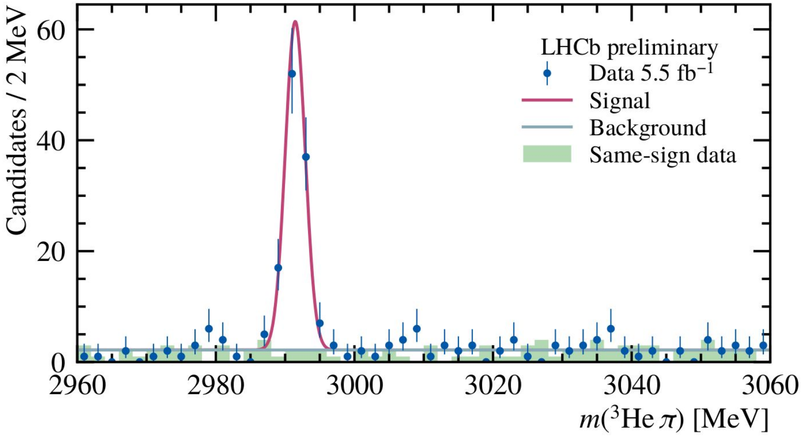


Hypernuclei in LHCb

- 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

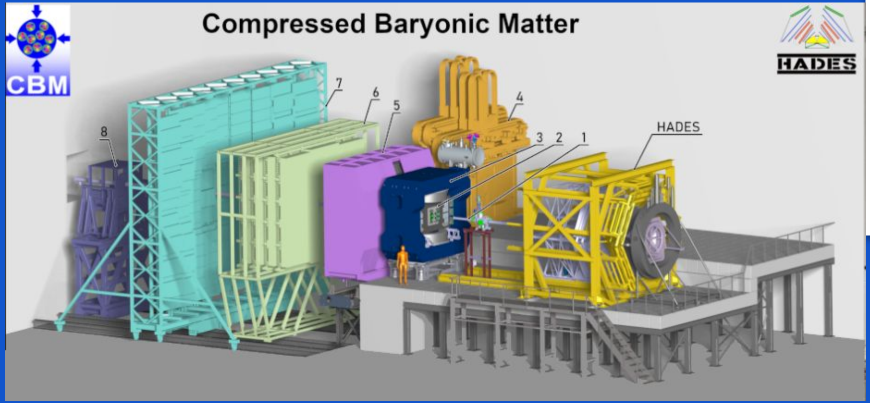


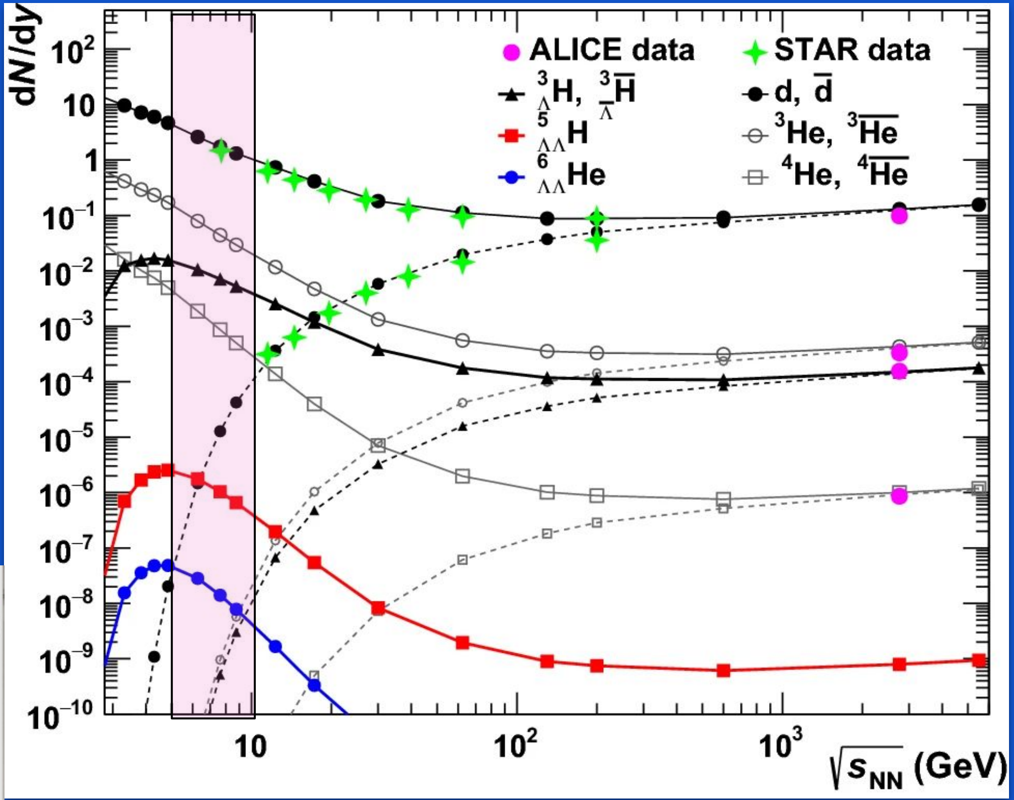




Future perspective

CBM (FAIR @ GSI)

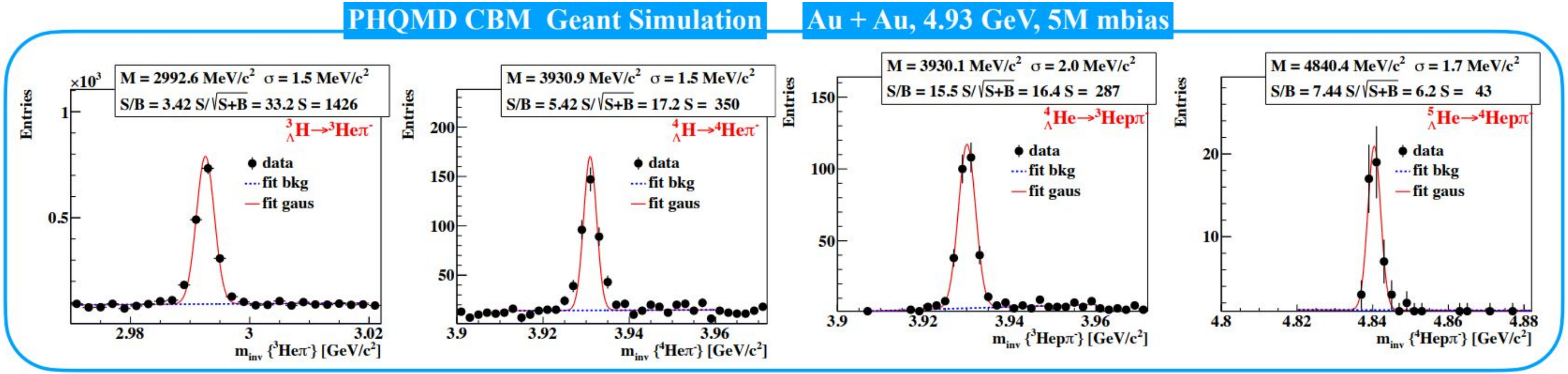




More details on Yingjie's slides

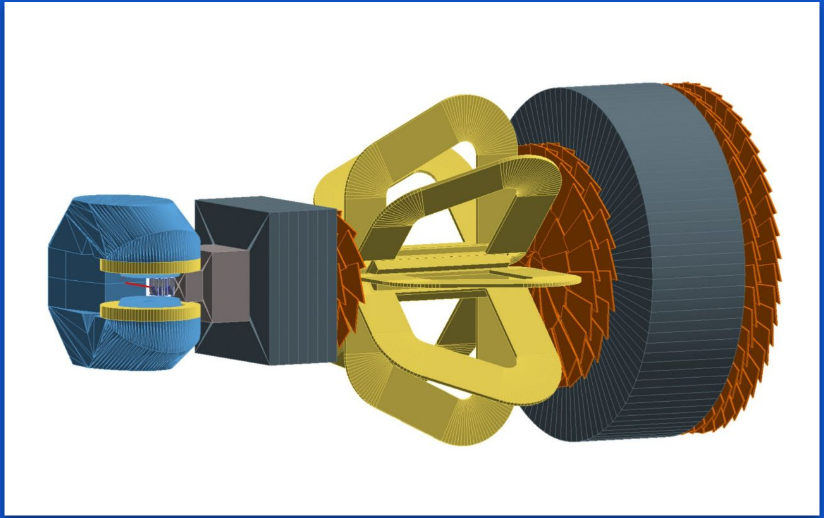
CBM

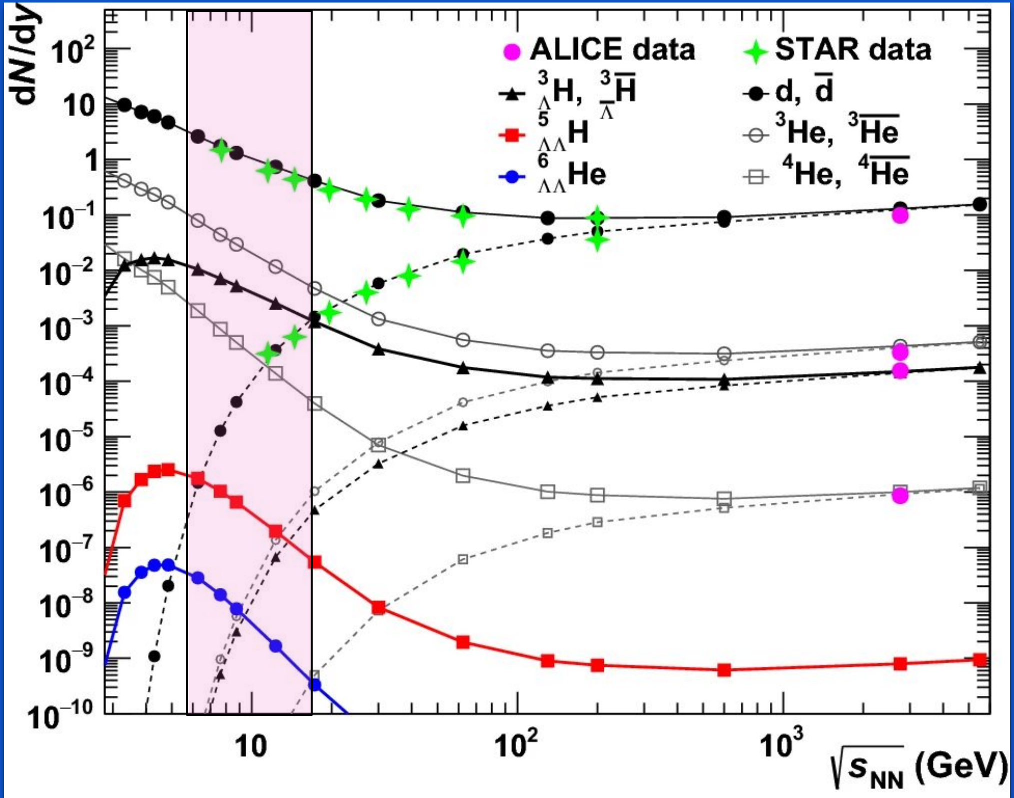
- Optimal beam energies for hypernuclei production
- Excellent vertexing and particle identification
- High interaction rates capability enabling raresignal studies, including double-Λ hypernuclei



Physics data taking by 2028!

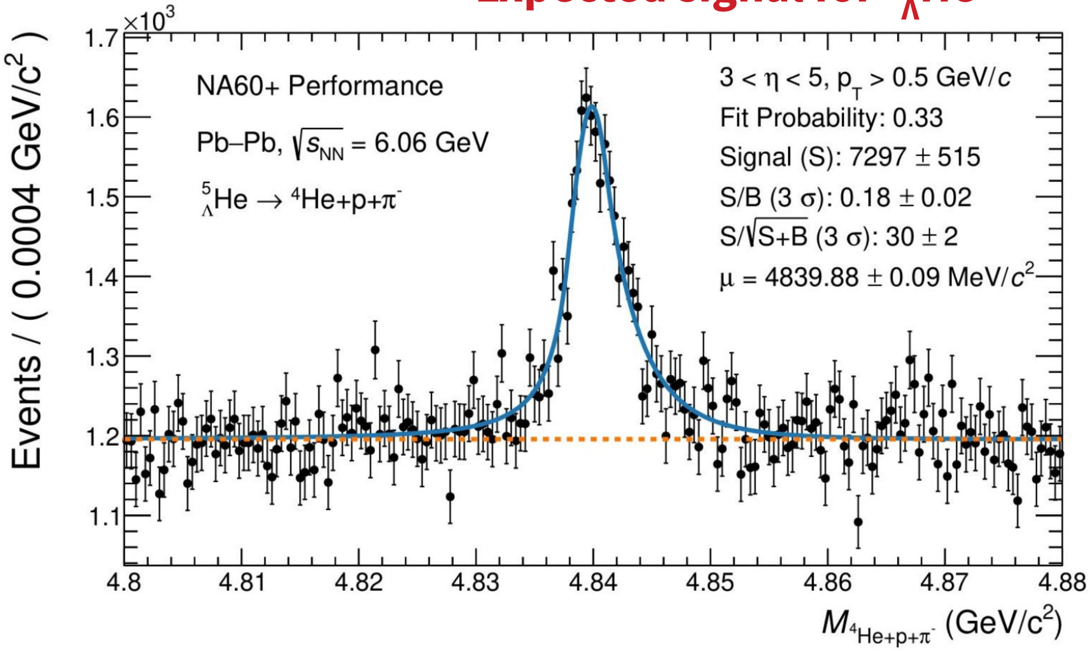
NA 60+ (SPS)





dN/dy
ALICE data
STAR data
$^{3}_{\Lambda}H$, $^{3}_{\bar{\Lambda}}\bar{H}$
d, $\bar{d}$
$^{5}_{\Lambda\Lambda}H$
^{3}He, $^{3}\overline{He}$
$^{6}_{\Lambda\Lambda}He$
^{4}He, $^{4}\overline{He}$
$\sqrt{s_{NN}}$ (GeV)

Expected signal for $^{5}_{\Lambda}He$



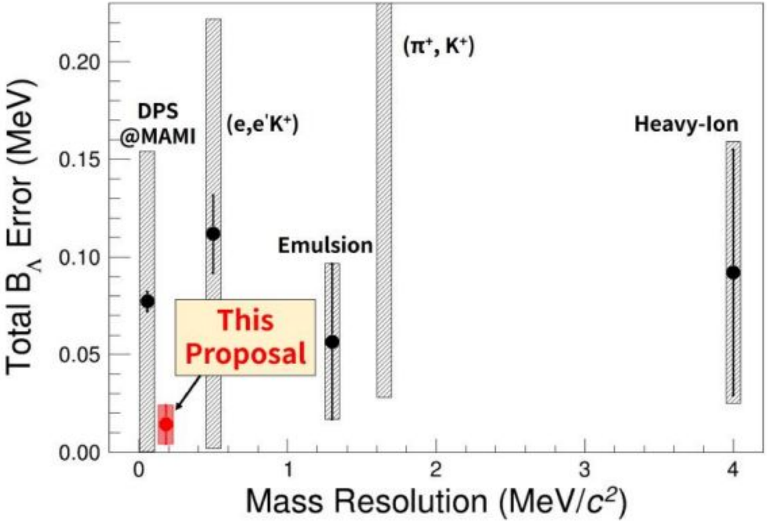
- Fixed-target experiment proposed at the CERN SPS
- Beam energy scan at 6-17 GeV
- Energy + rate combination is unique
- Large (hyper)nuclei production
  - Identification in the tracker

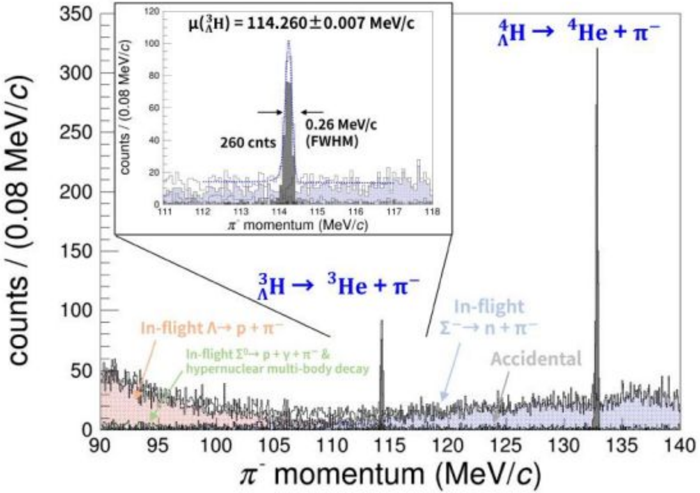
- High precision measurement of the properties of Λ hypernuclei
- Possible discovery of light Ξ and Σ hypernuclei

Data taking over 7 years from 2029

Hypernuclear program at JLab

- Several experiments have been proposed (See Guido's slide for more details)
- E12-20-013A/E12-15-008A
  - High resolution Decay Pion Spectroscopy (DPS)



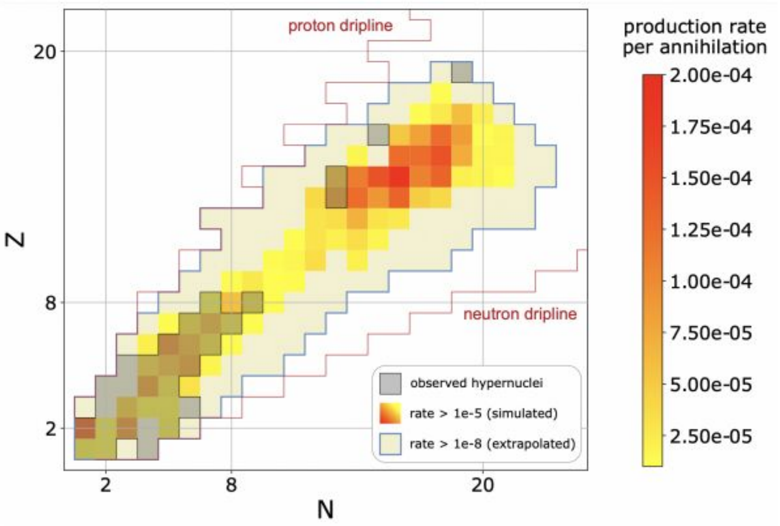


Li target

Expected resolution on B_Λ reduced by a factor ~ 10!

Other ways to produce and study hypernuclei

- Hypernuclei production from antiprotonic atoms: **HYP̄ER** (Proposed to start by ~2030):
  - Antiproton capture (simulated with GiBUU and ABLA07) produces hypeHYP̄ERrnuclei through surface annihilations and kaon–nucleon interactions
  - About 1% of annihilations result in hypernuclei formation, opening new opportunities to explore the hypernuclear landscape.



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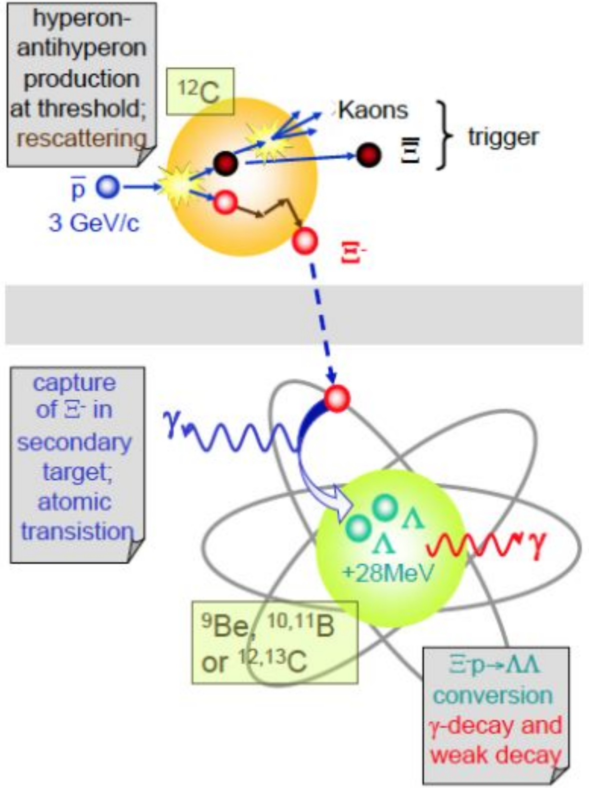
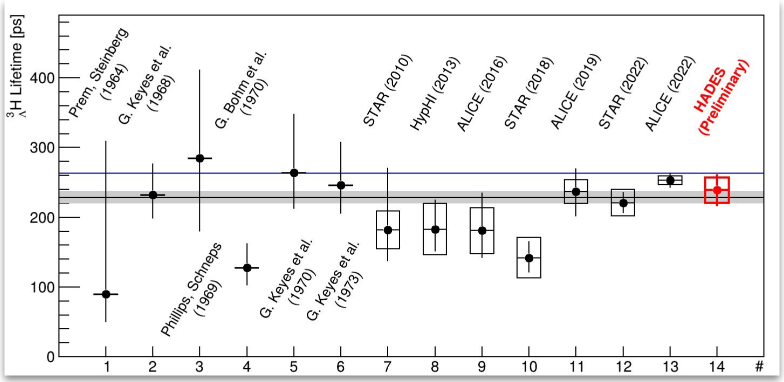
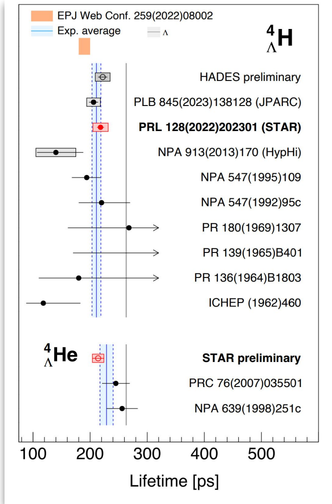
- High-energy-antiproton-induced production:
  - High-energy antiprotons (studied by the **P̄ANDA** experiment at FAIR) are proposed as a powerful tool to produce hypernuclei through collisions and capture of strange baryons.
  - The PANDA program (phases 2–3, **beyond 2040**) aims to enable the production and spectroscopy of double-Λ hypernuclei.

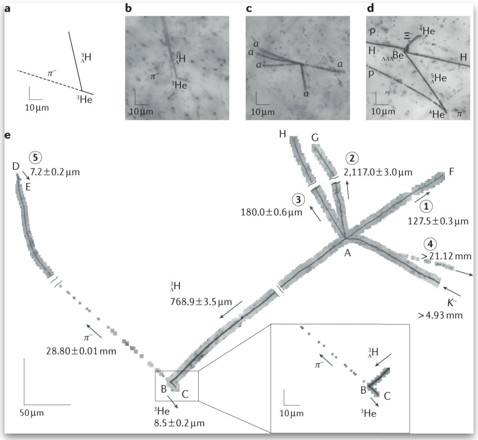


Conclusions

- **Major advances** in precision hypernuclear measurements (lifetimes, binding energies, new species)
- **New discoveries**: double-Λ and anti-hypernuclei observed at modern facilities
- **Models improving**, but further input needed to constrain YN / YY interactions
- **Future experiments** (CBM, NA60+, JLab, HYP̄ER, P̄ANDA) will expand the hypernuclear landscape and probe the hyperon puzzle

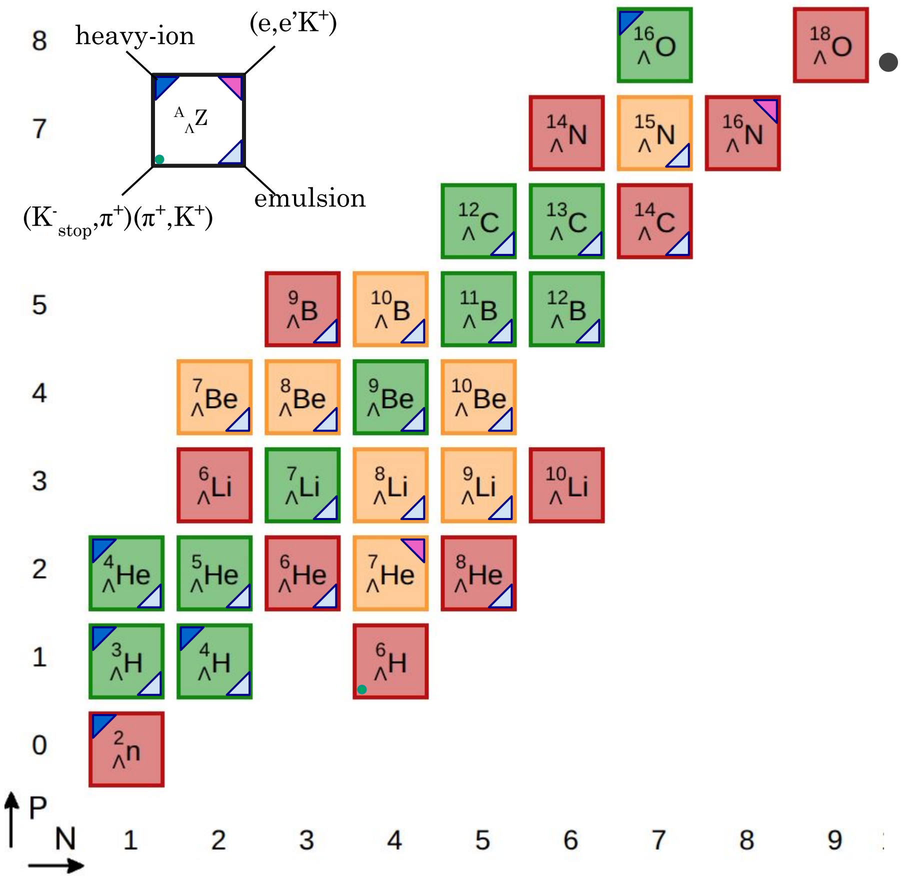






Backup slides

Production of single-Λ hypernuclei and limitations



- Challenges:
  - low production rates, short lifetime (~200 ps)
  - Missing mass and pion spectroscopy restricted to few hypernuclei
  - Ultra-relativistic heavy-ion collision cannot reach more than A=4-5

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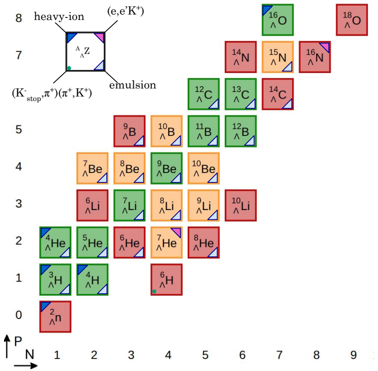

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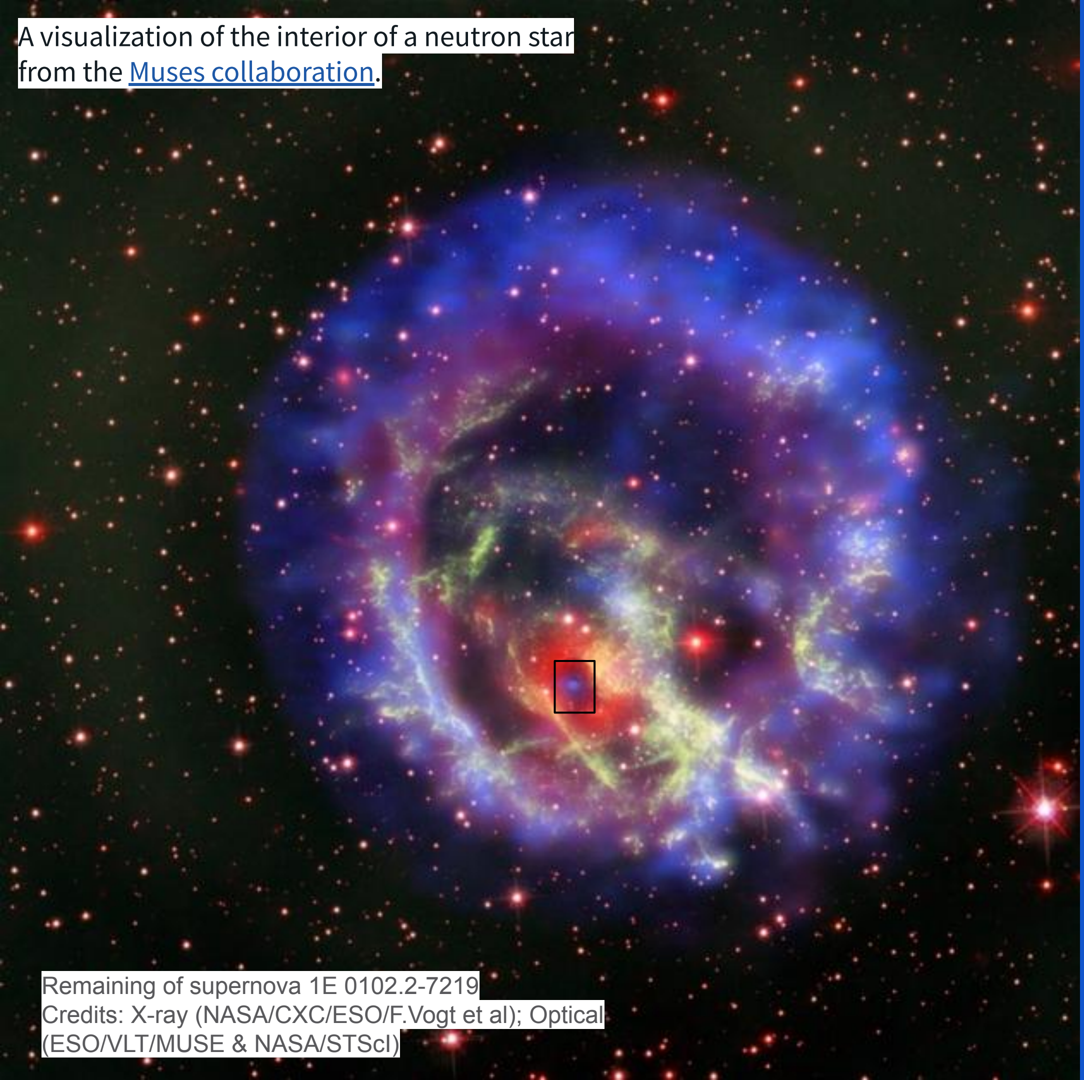
Production	Main lab(s)	Hypernuclei	Excited states	Ground state binding	Ground state lifetime
In-flight (K^-, π^-)	CERN (90s), BNL	$Z_Y = Z_i - 1$	✓	✓	✗
Stopped (K^-, π^-)	CERN (70s), LNF-INFN, KEK, BNL	$Z_Y = Z_i - 1$	✓	✓	✗
(π^+, K^+)	KEK, BNL	$(A, Z)_Y = (A, Z)_i$	✓	✓	✗
$(e, e'K^+)$	JLAB, Mainz	$Z_Y = Z_i - 1$			
Heavy-ion (GeV)	GSI/FAIR, HIAF	Potentially many	✗	✓ 3 MeV	✓ Sys.
Relativistic HI (100 GeV - 13 TeV)	RHIC, ALICE (CERN)	$A_Y \leq 4$	✗	✓	✓ Sys.∼ 10 ps
Λ, Ξ from in-flight $\bar{p}$	PANDA (FAIR)	$(A, Z)_Y = (A, Z)_i$	✓	✗	✗
Stopped $\bar{p}$	HYPER (CERN)	Potentially many	✓	✓	✓$\leq$ 40 ps

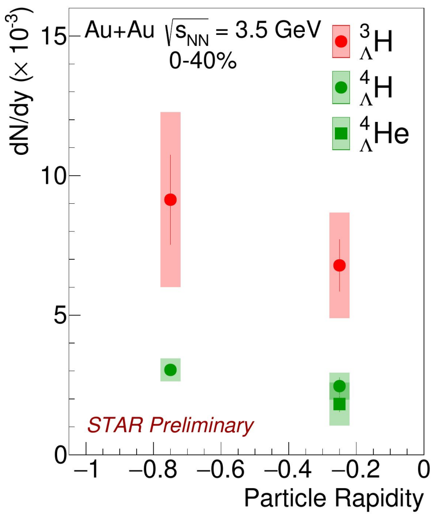
A visualization of the interior of a neutron star from the Muses collaboration.

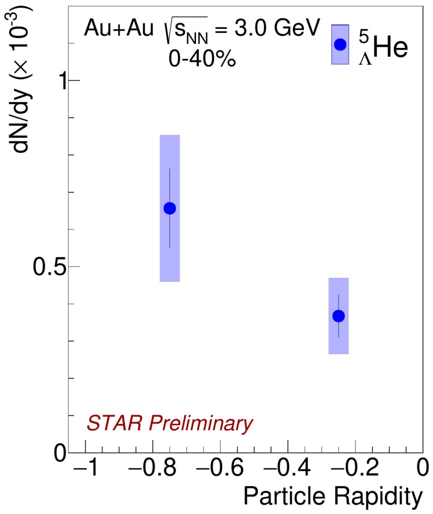


Remaining of supernova 1E 0102.2-7219
Credits: X-ray (NASA/CXC/ESO/F.Vogt et al); Optical (ESO/VLT/MUSE & NASA/STScI)

Neutron Stars

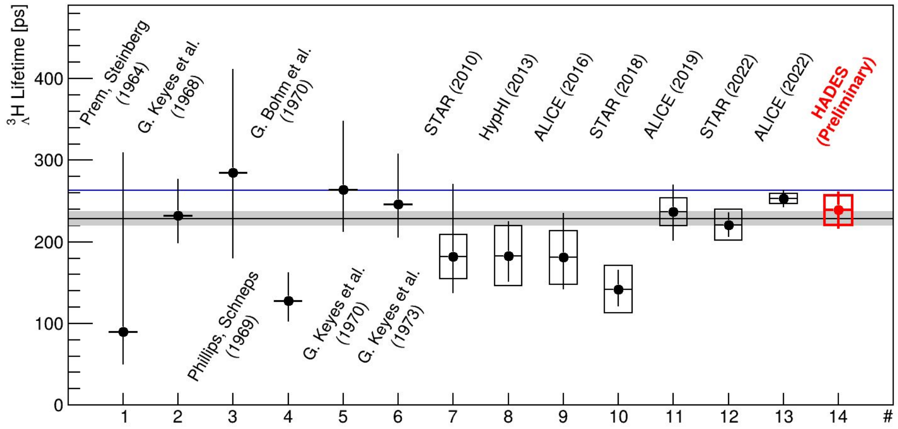
Hypernuclei production as a function of rapidity

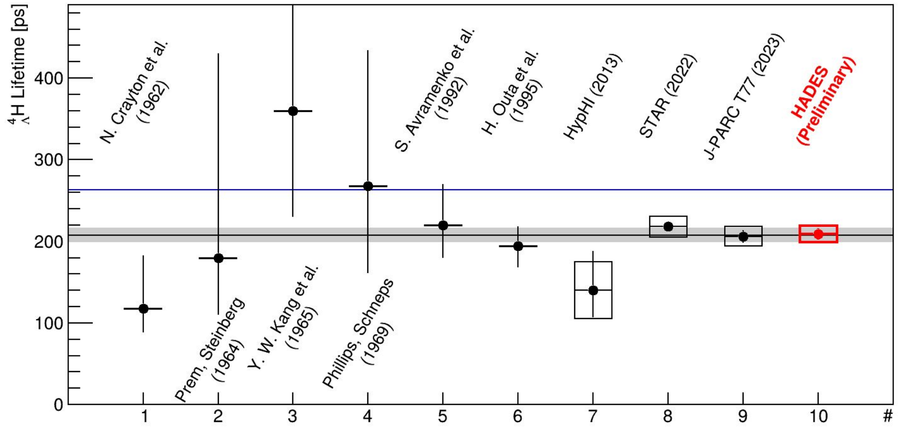




- Significant hypenuclei production at target rapidity, more pronounced for heavier hypernuclei
- Spectator matter matters at target rapidity

Hypernuclei Lifetimes



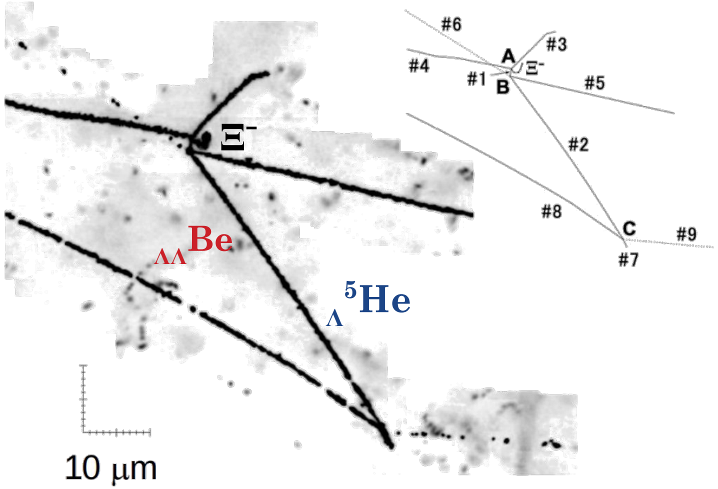


- $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H Lifetime measurement contribute to world data on hypernuclei lifetimes
- Lifetime of $^{3}_{\Lambda}$H = (239 ± 23 ± 18) ps compatible with free Λ
- Lifetime of $^{4}_{\Lambda}$H = (209 ± 7 ± 10) ps compatible with earlier measurements
- Extensive uncertainty evaluation performed

Production of double-Λ hypernuclei

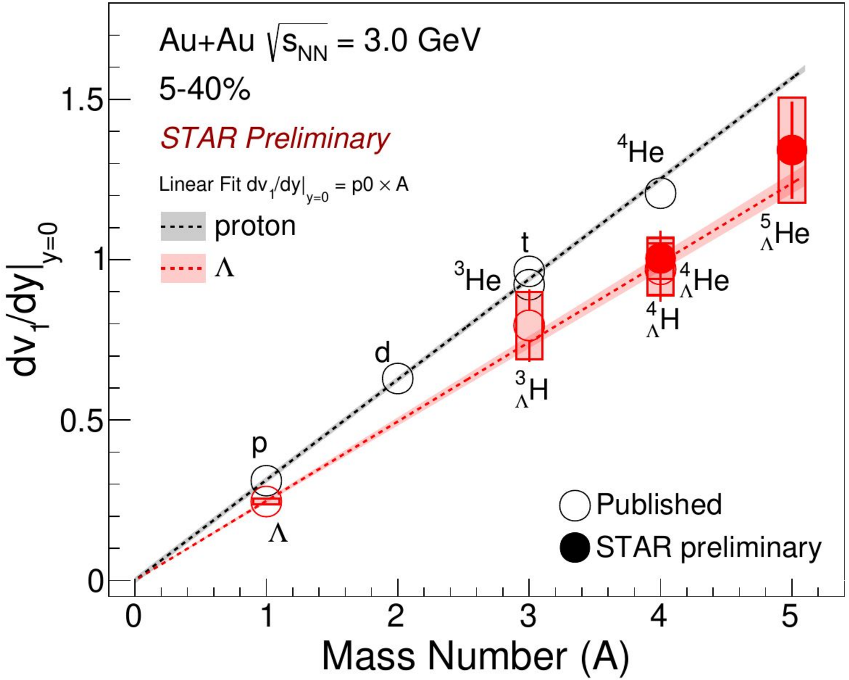
- Best systems to investigate the properties of S = - 2 baryon–baryon interaction
- Contrary to single-Λ hypernuclei they are produced in a two-step process:
  - Ξ^- production in process like
    - (K^-,K^+) reaction (BNL, KEK)
      - $K^- + p \rightarrow \Xi^- + K^+$
  - Proton-antiproton reaction (GSI/FAIR)
    - $p + \bar{p} \rightarrow \Xi^- + \Xi^+$
  - Ξ^- captured in an atomic orbit interacts with the nuclear core producing two Λ's
    - $\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5$ MeV

H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02 (2019)



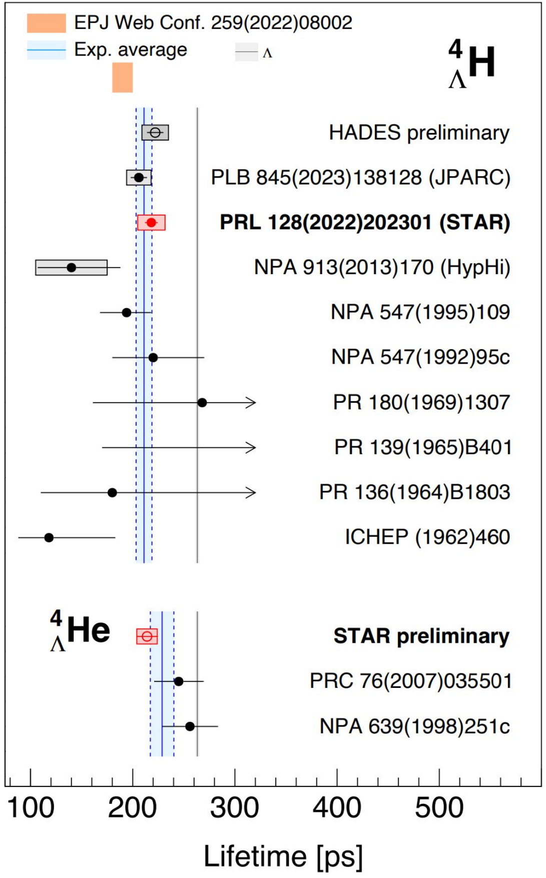
$$^{16}\mathrm{O} + \Xi^- \rightarrow (^{10}_{\Lambda\Lambda}\mathrm{Be},\ ^{11}_{\Lambda\Lambda}\mathrm{Be},\ ^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_\Lambda\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$

Directed Flow at 3 GeV



- Light nuclei mid-rapidity v_1 slope increase linearly with atomic mass number A
- Hypernuclei v_1 slope systematically lower than light nuclei of similar A, and compatible with Λ atomic mass number scaling (Similarly to HADES results)

$^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He lifetimes



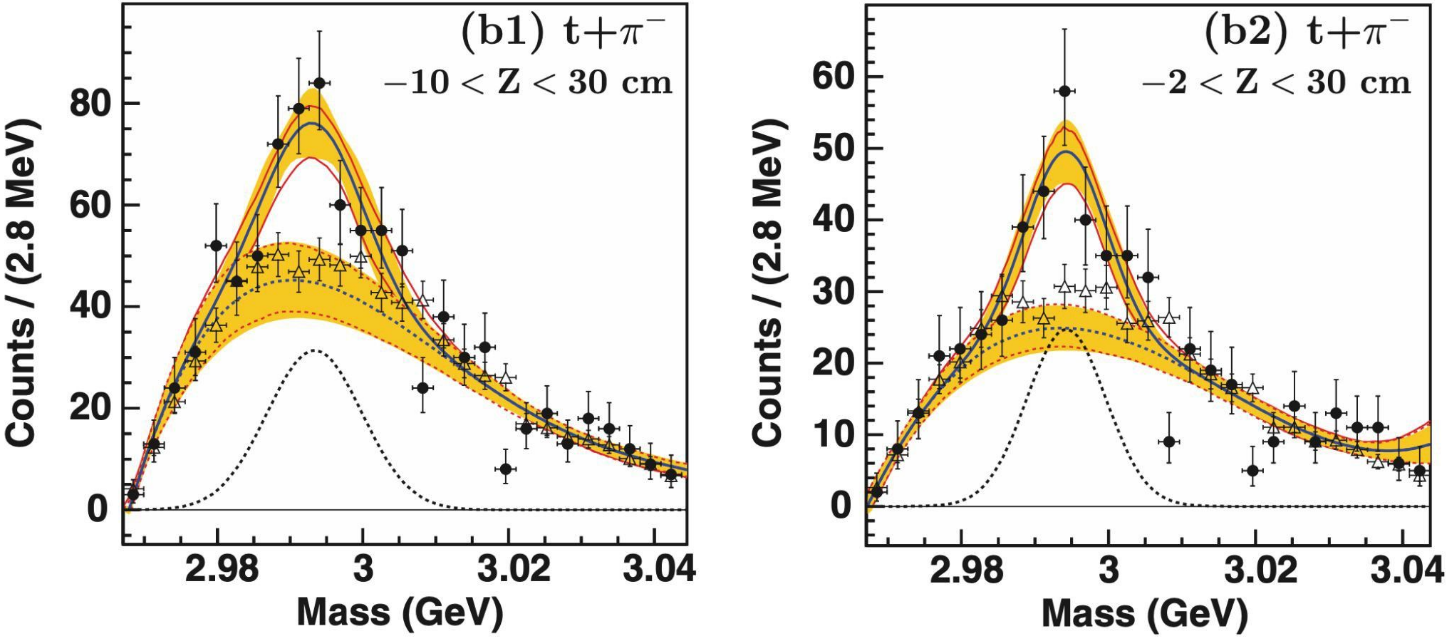
- STAR averaged results from $\sqrt{s_{NN}}$ = 3.2, 3.5, and 3 GeV:
  - $\tau(^{4}_{\Lambda}He)$ = 12 ± 10 (stat.) ± 10 (syst) ps
    - Most precise measurement of $\tau(^{4}_{\Lambda}He)$

- $\tau(^{4}_{\Lambda}H)/\tau(^{4}_{\Lambda}He)$= 0.92 ± 0.06, consistent within 2.5 σ with theoretically estimated value 0.74 ± 0.04 applying the isospin rule

A. Gal, EPJ Web Conf., 259, 08002 (2022)

Λnn searches

- Excess observed in the $t + \pi^-$ final state observed by HypHi Collaboration
- Λnn not bound according to most of the theorist



HypHI Collaboration, Phys. Rev. C 88, 041001 A Gal, H Garcilazo, Phys. Lett. B 736, 93-97 E. Hiyama et al. Phys. Rev. C 89, 061302

Λnn searches

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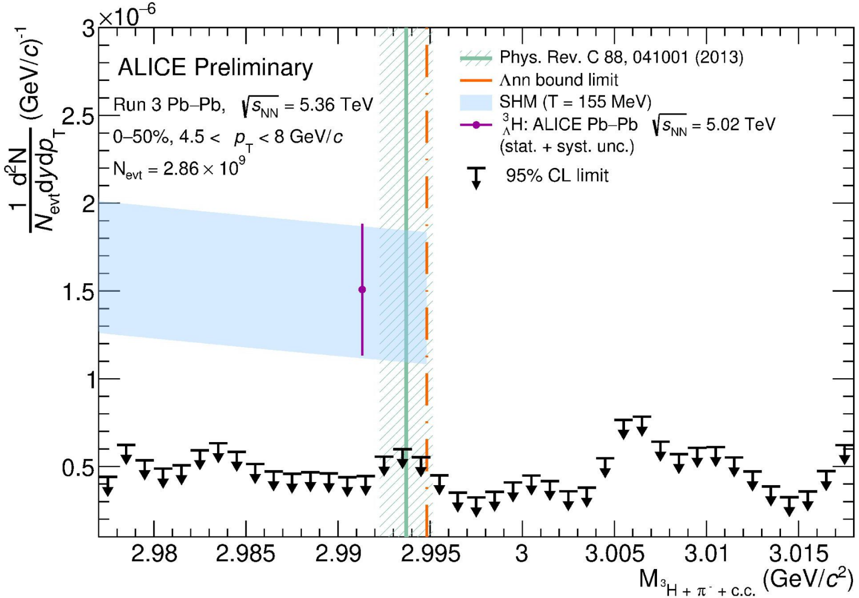
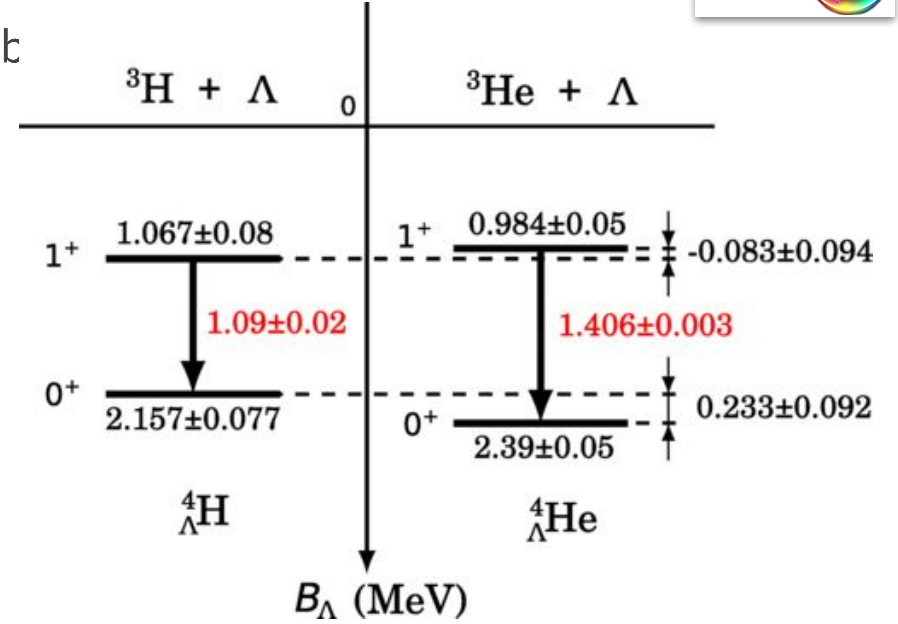
- Λnn not bound according to most of the theorist
- ALICE rules out the existence of a Λnn state stable under weak decay



📖 HypHI Collaboration, Phys. Rev. C 88, 041001 📖 A Gal, H Garcilazo, Phys. Lett. B 736, 93-97 📖 E. Hiyama et al. Phys. Rev. C 89, 061302

Hypernuclei with A = 4

- SHM predicts hypernuclei with A = 4 in Pb–Pb
  - they are rare:
    - penalty factor for increasing A: ~ 300
    - suppression due to strangeness content
- Some factors may enhance the yield (x 4):
  - larger binding energy wrt A = 3
  - existence of excited states $\frac{dN}{dy} \propto 2J+1$
  - spin degeneracy



M. Schäfer et al., PRC 106, L031001 (2022)

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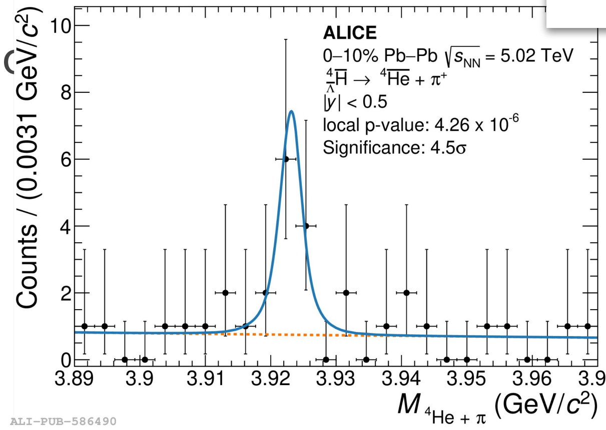
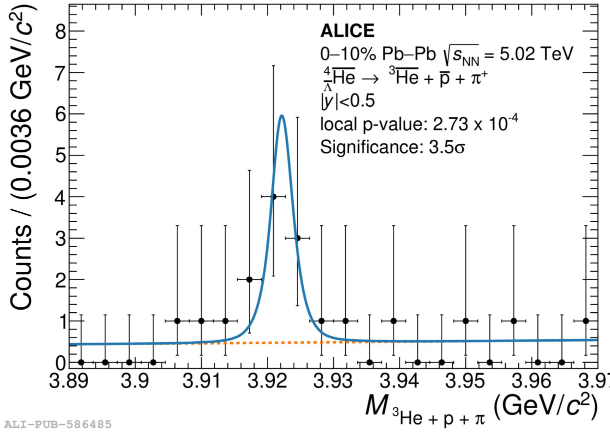
- In Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV, ALICE has observed:
  - ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$
  - ${}^{4}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$





📖 ALICE Collaboration, Phys. Rev. Lett. 134 (2025) 162301

Hypernuclei with A = 4

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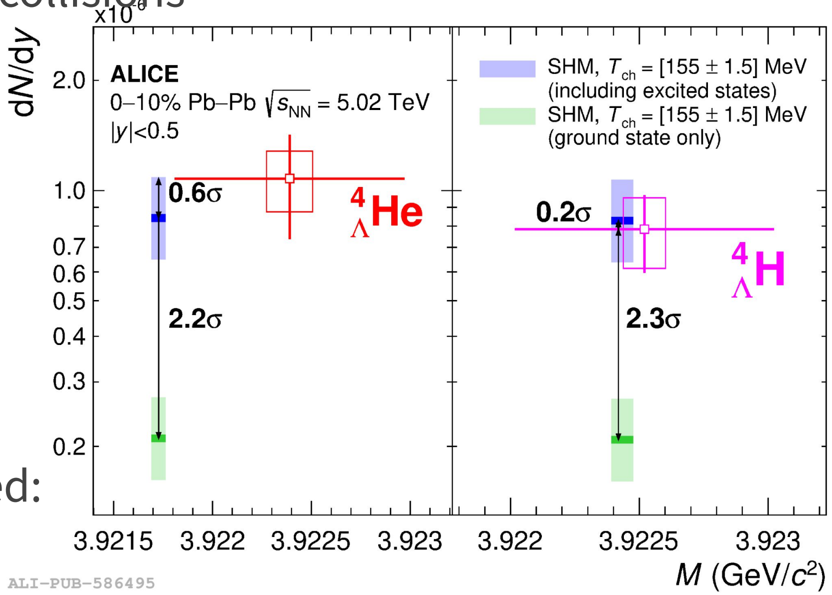
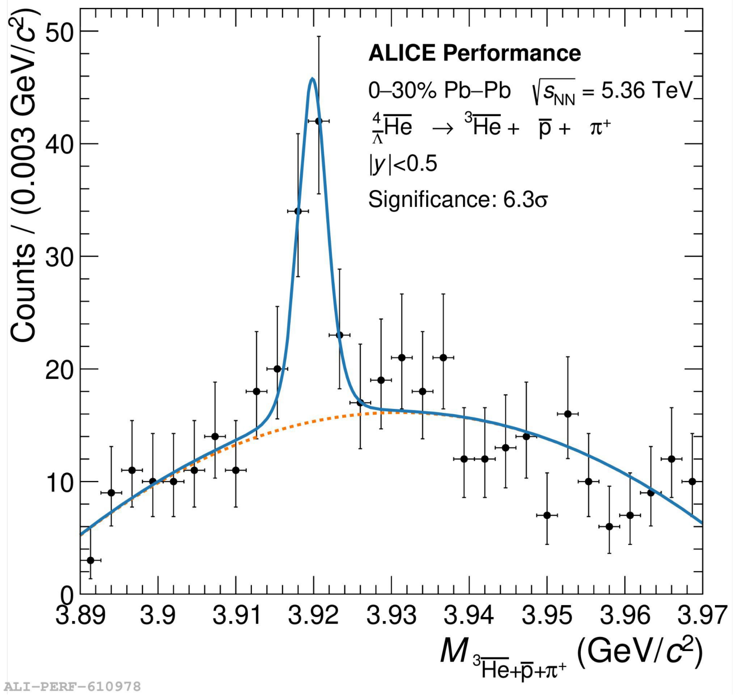
- Yields in agreement with **SHM** prediction that includes feed-down from excited states

➢ **SHM describes hypernuclei with A = 4 well**



New results for A = 4 Hypernuclei

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



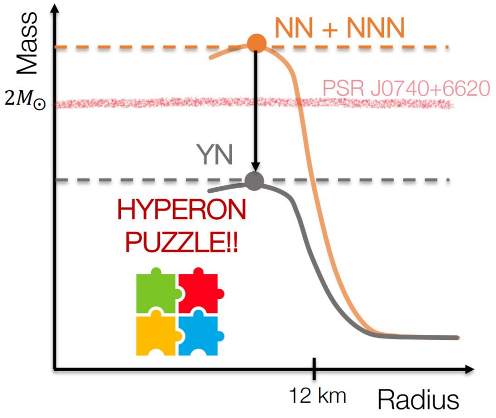
- Factor 20 improvement in Run 3 will enable precise CSB measurements

Production of single-Σ and single-Ξ hypernuclei

- Production of single-Σ hypernuclei mechanisms similar to the ones considered for Λ hypernuclei like, e.g., strangeness exchange (K^-,$p^\pm$). However, their existence has not been experimentally confirmed yet without ambiguity, suggesting that the Σ nucleon interaction is most probably repulsive.
- Single-Ξ hypernuclei can be produced by means of (K^-, K^+) & proton-antiproton reactions
  - A first analysis of $^{12}C(K^-, K^+)^{12}_{\Xi^-}Be$ reaction indicated an attractive Ξ-nucleus interaction of the order of about -14 MeV, but an independent analysis of the (K^- , K^+) Ξ production spectrum on ^{12}C found instead an almost zero Ξ-nucleus potential
  - A deeply bound state of the $\Xi^- - {}^{14}N$ system with a binding energy of 4.38 ± 0.25 MeV has been observed. Future Ξ-hypernuclei production experiments are being planned at JPARC

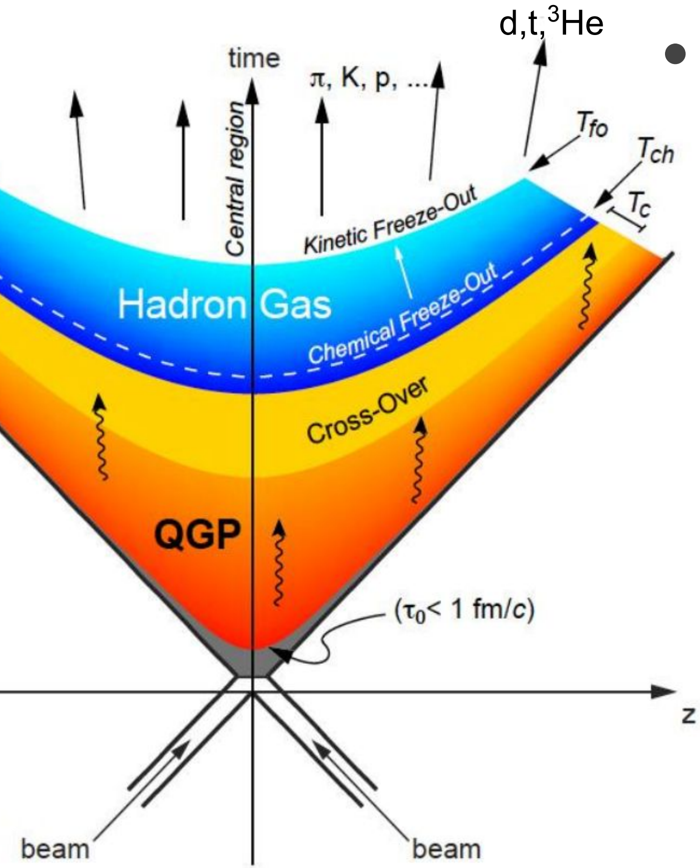
The Hyperon Puzzle

- Hyperons are expected to appear in the core of neutron stars at r~ (2-3)$r_\odot$ when μ_N is large enough to make the conversion of N into Y energetically favorable
- **But,** the relieve of Fermi pressure due to its appearance leads to a softer EoS and, therefore, to a reduction of the mass to values incompatible with recent observations



- **Any reliable EoS of dense matter should predict Mmax [EoS] > 2$M_\odot$ NS**
  - Can hyperons be present in the interior of neutron stars in view of this stringent constraint ?
  - Three-body ΛNN repulsive forces to stiffen EoS:
    - How much repulsion? → Model-dependent → Need for more experimental constraints
  - More exotics scenarios possible as well

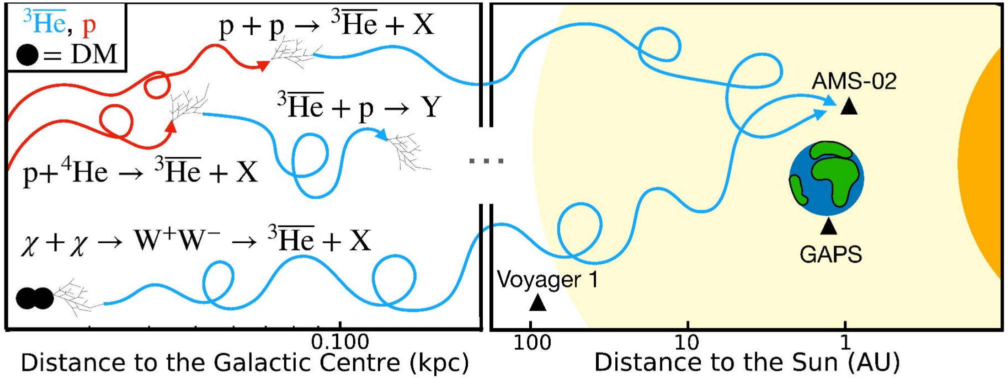
Light nuclei in heavy-ion collisions



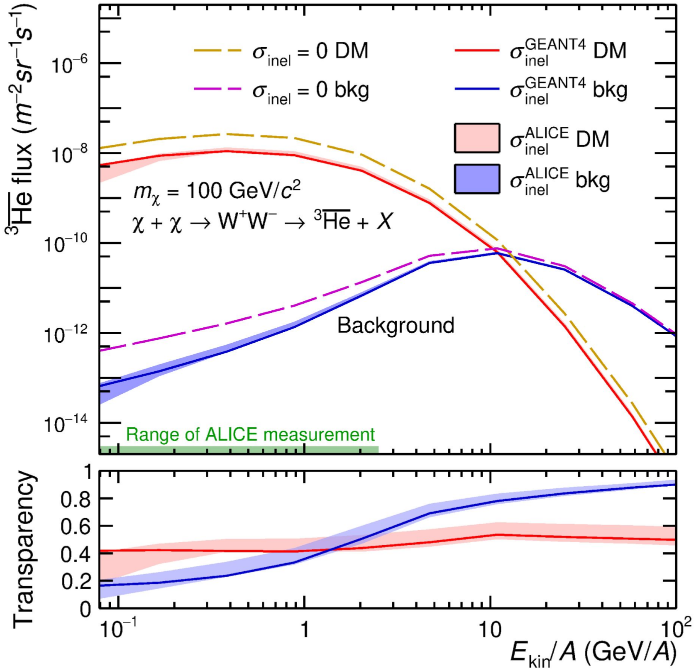
- The study of light (anti)(hyper)nuclei is very important:
  - Production mechanism is not well understood
    - How/when do they form?
      - “early” at chemical freeze-out (thermal production)
      - or “late” at kinetic freeze-out (coalescence)?
    - Do they suffer for the dissociation by rescattering?
  - Low binding energy (few MeV) "Snowballs in hell": nuclei formation is very sensitive to chemical freeze-out conditions and to the dynamics of the emitting source
  - Baseline for exotic bound state searches
  - Light nuclei measurements in high energy physics can be used to estimate the background of secondary anti-nuclei in dark matter search

Antinuclei production

- Antinuclei can be a sign of Dark Matter annihilation:
  - Background: production in the collisions between cosmic rays (CR) and the interstellar medium (ISM) (pp and p-A collisions)
    - Nuclei production must be known very well!



ALI-PUB-532052



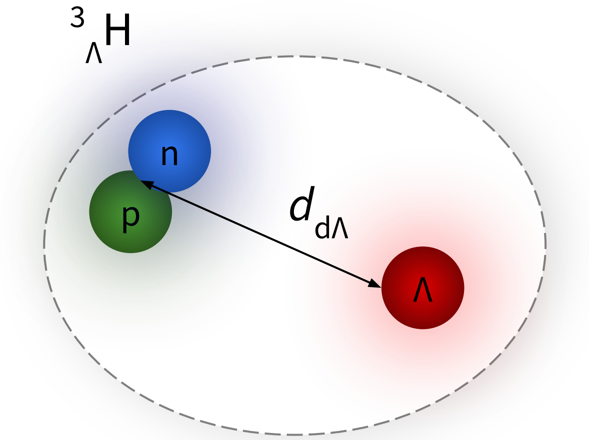
ALI-PUB-532056

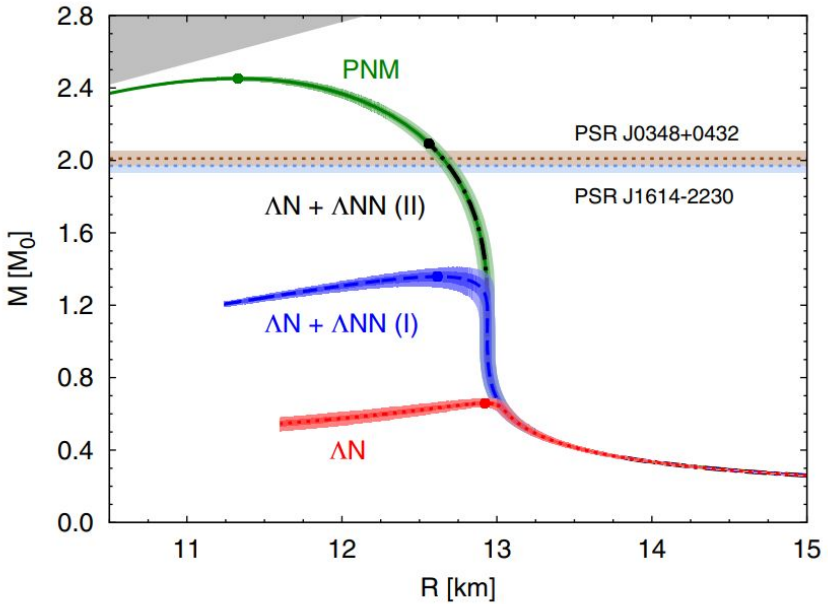
📖 M. Korsmeier et al, Phys. Rev. D 97, 103011

📖 Nature Phys. 19 (2023) 1, 61-71

Hypernuclei production

- Hypernuclei can be used to study nucleon-hyperon (N-Y) interaction
  - Production of exotic bound states
  - Determination of the equation of state
    - Application to neutron stars



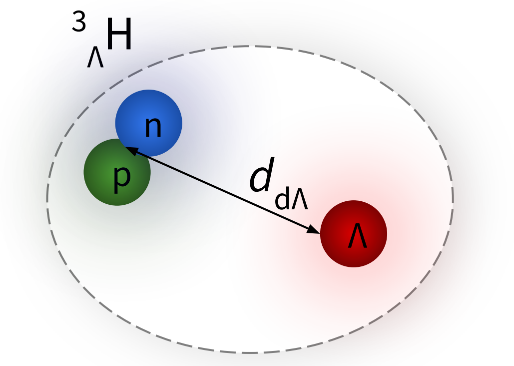


D. Lonardoni et al., PRL 114, 092301 (2015)

D. Logoteta et al., EPJA 55 (2019) 11, 207

Hypertriton production

- Lightest known hypernucleus consisting of (p, n, Λ)
- Mass = 2.991 GeV/c^2
- $B_\Lambda = 0.13 \pm 0.05$ MeV ($B_d = 2.2$ MeV, $B_t = 8.5$ MeV, $B_{3He} = 7.7$ MeV)
- ${}^3_\Lambda$H has a large size:
  - $d_{d-\Lambda} = 10.79$ fm, r (d) = 1.96 fm



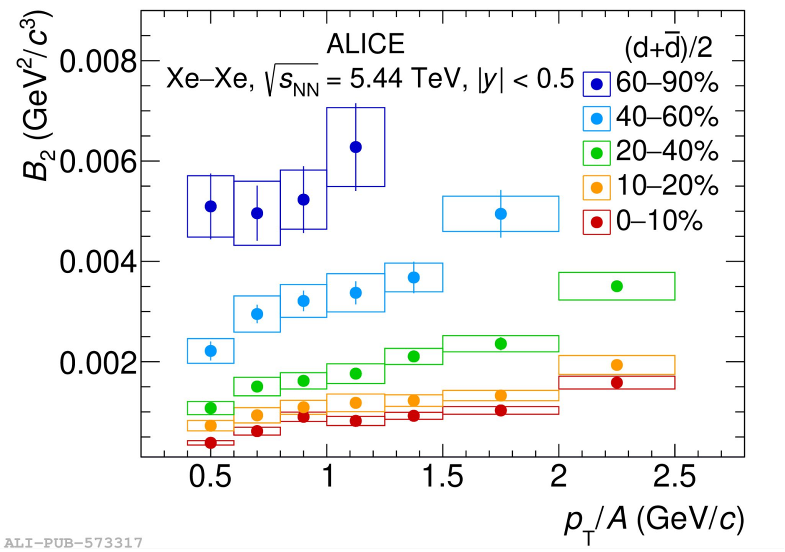
https://hypernuclei.kph.uni-mainz.de/

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

Production models: Coalescence

- **Coalescence**
  - Nuclei are formed by nucleons emitted at freeze-out hypersurface
  - Coalescence calculations incorporate the **size of nuclei**
    - convolution between nucleon phase-space distribution and Wigner function of the nucleus

- Coalescence parameter $\boldsymbol{B_A}$, related to formation probability via coalescence:



$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

J. I. Kapusta, PRC 21, 1301 (1980)

Mahlein et al., EPJC 83 (2023) 9, 804