Results on light hypernuclei in the WASA-FRS and E07 emulsion experiments

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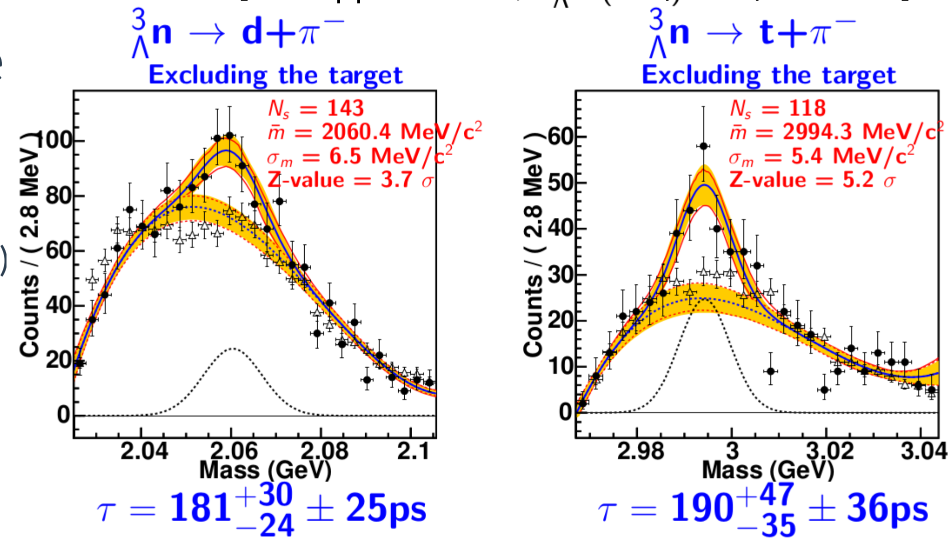
For ML-Emulsion collaboration & WASA-FRS / Super-FRS Experiment collaboration

Current puzzles for light hypernuclei: $^{3}_{\Lambda}$H & $^{3}_{\Lambda}$n

- **In our first experiment, HypHI Phase 0:**
  Two puzzling observations were made:
  - Possible signal of nnΛ bound state
    - <u>All theoretical calculations show negative results</u>
      - E. Hiyama et al., Phys. Rev. C89 (2014) 061302(R)
      - A. Gal et al., Phys. Lett. B736 (2014) 93
      - H. Garcilazo et al., Phys. Rev. C89 (2014) 057001
      - and much more publication

[C. Rappold et al., PRC 88 (2013) 041001]



  - Short lifetime of $^{3}_{\Lambda}$H :
    - Our published value : 183 $^{+43}_{-32}$ ps [C. Rappold et al., Nucl. Phys. A 913 (2013) 170]
    - Plus other recent measurements : Combined lifetime analysis excludes all current models of $^{3}_{\Lambda}$H [C. Rappold et al., Phys. Lett. B 728, 543 (2014)]

Current puzzles for light hypernuclei: $^{3}_{\Lambda}H$ & $^{3}_{\Lambda}n$

- **Yet the puzzles deepen :**
  - Over the years more data from ALICE and STAR experiments :

    More tension on the combined lifetime measurements

    - ALICE : 181^{+54}_{-39} ps → 237^{+34}_{-38} ps → 253 ± 11 ps
    - STAR : $155\ ^{+25}_{-22}$ ps → $142\ ^{+24}_{-21}$ ps → 221 ± 15 ps
    - HypHI : 183^{+42}_{-32} ps

    [PLB 128 (2019) 134905]
    [PRL 131 (2023) 102302]
    [PRL 128 (2022) 202301]

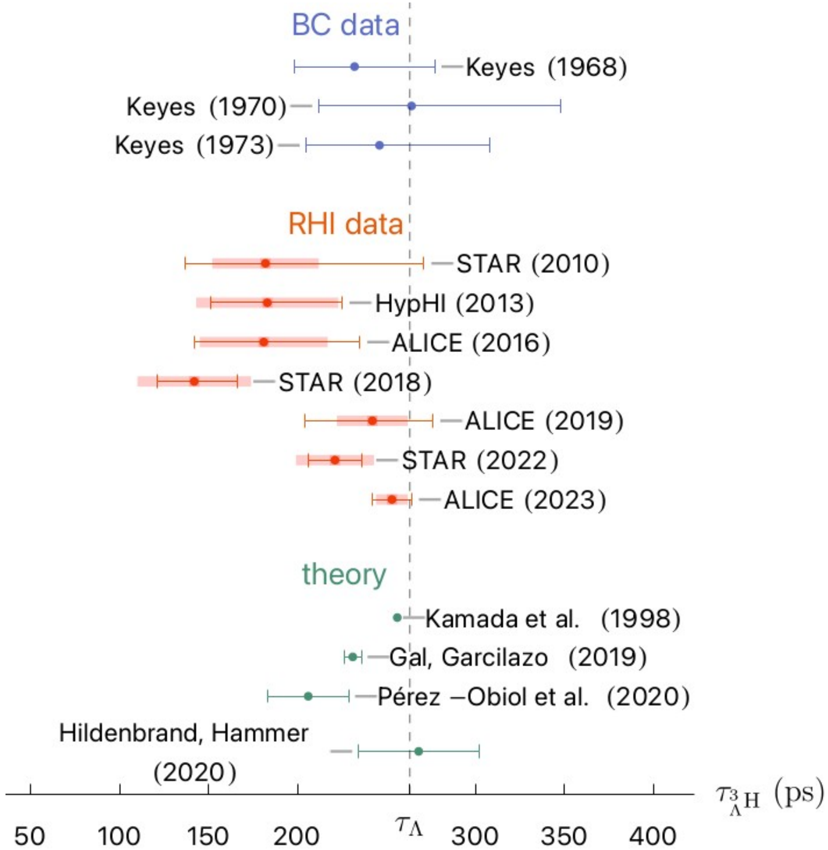
    We will provide one very precise data point with our new WASA-FRS experiment

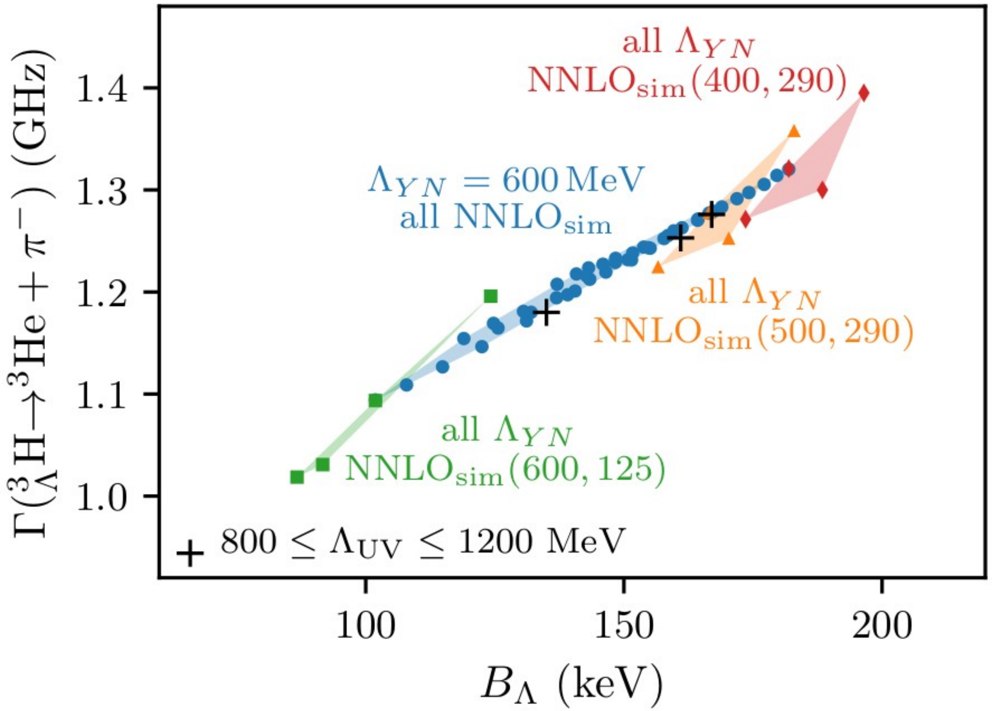
  - Hot topics in nuclear experiments:
    - STAR, ALICE, J-PARC, ELPH, HADES, HYDRA and WASA-FRS

  - <u>Still no clear theoretical explanation for the short lifetime, is it ?</u>

Current puzzles for light hypernuclei: $^3_\Lambda$H & $^3_\Lambda$n

- **Hypertriton: bound state of p, n, Λ0**
  - New data from HI collisions conflicting with theory





[D. Gazda et al., Phys. Rev. C 109, 024001 (2024)]

Current puzzles for light hypernuclei: $^{3}_{\Lambda}H$ & $^{3}_{\Lambda}n$

- **Yet the puzzles deepen :**
  - Binding energy of hypertriton :

nature physics

LETTERS

https://doi.org/10.1038/s41567-020-0799-7

Check for updates

Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

The STAR Collaboration*

The Λ binding energy, B_Λ, for $^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\Lambda}\overline{\mathrm{H}}$ is calculated using the mass measurement shown in equation (1). We obtain

$$\boxed{B_\Lambda = 0.41 \pm 0.12(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}} \quad (3)$$

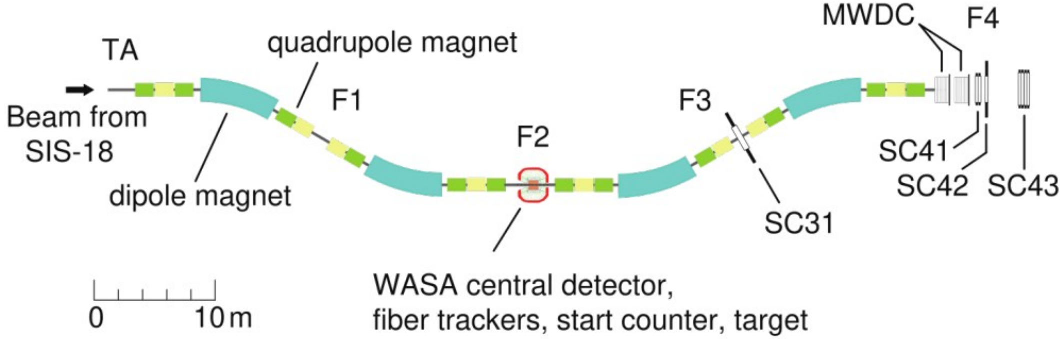
  - Previously accepted value: $B_\Lambda = 0.13 \pm 0.05$ MeV
  - And still : ALICE measured a Λ binding energy of :
    - $B_\Lambda = 0.102 \pm 0.063 \pm 0.067$ MeV [Phys. Rev. Lett. 131 (2023) 102302]

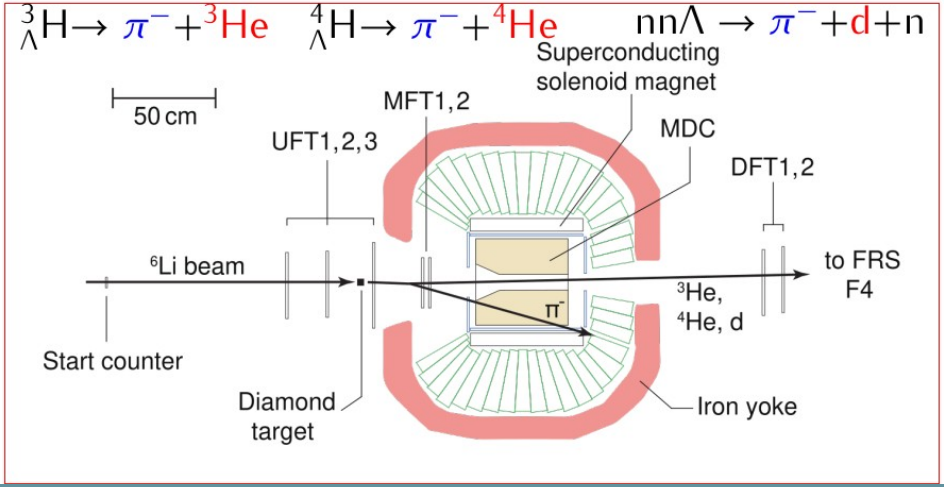
Deep learning in study of those puzzles

- **Our contributions to solve : 2 experiments to measure**

→ Lifetime & radius:

WASA-FRS experiment at GSI-FAIR

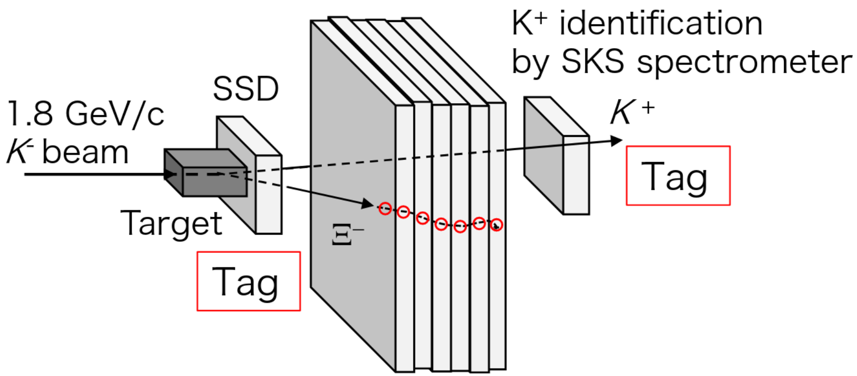


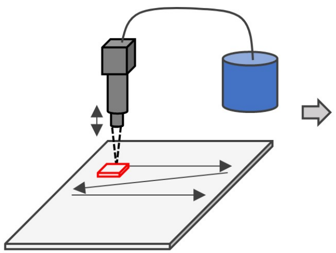


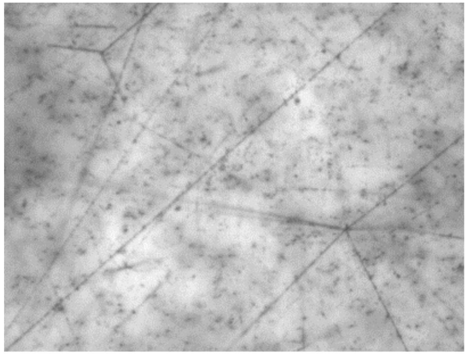
→ Binding energy:

E07 experiment at JPARC

Emulsion-Counter hybrid method

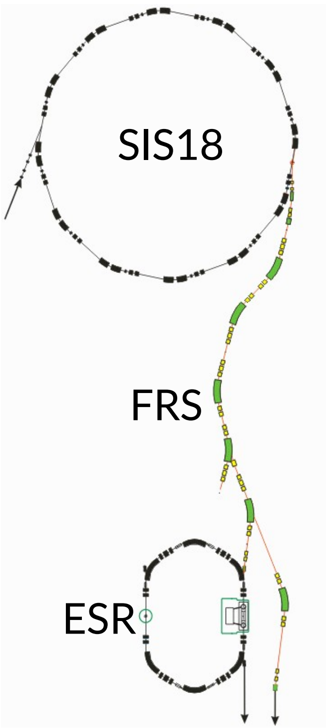


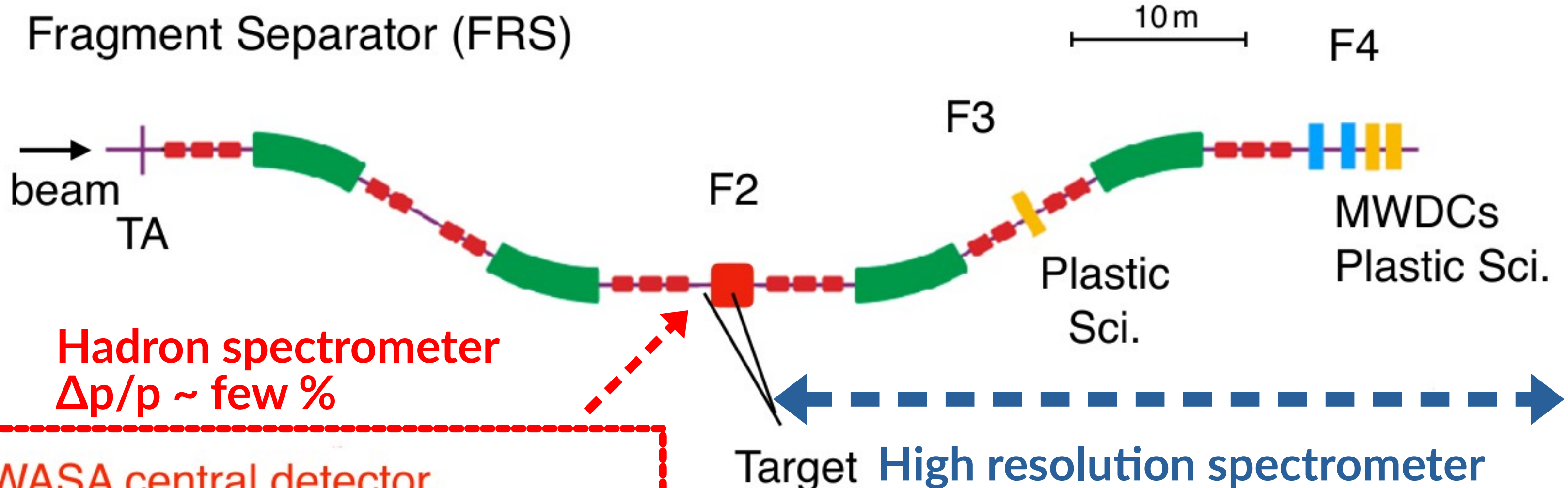




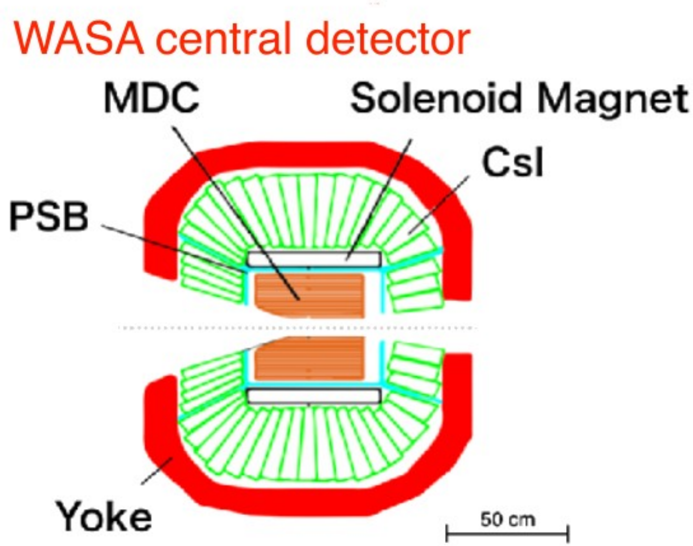
WASA-FRS Experimental campaign: Jan. – March 2022

GSI facility





Hadron spectrometer
$\Delta p/p$ ~ few %



High resolution spectrometer
$\Delta p/p = 10^{-4}$

Two experiments took place:

- η'-mesonic nuclei spectroscopy
- Hypernuclei spectroscopy

2 of 10 key topic of SuperFRS EC

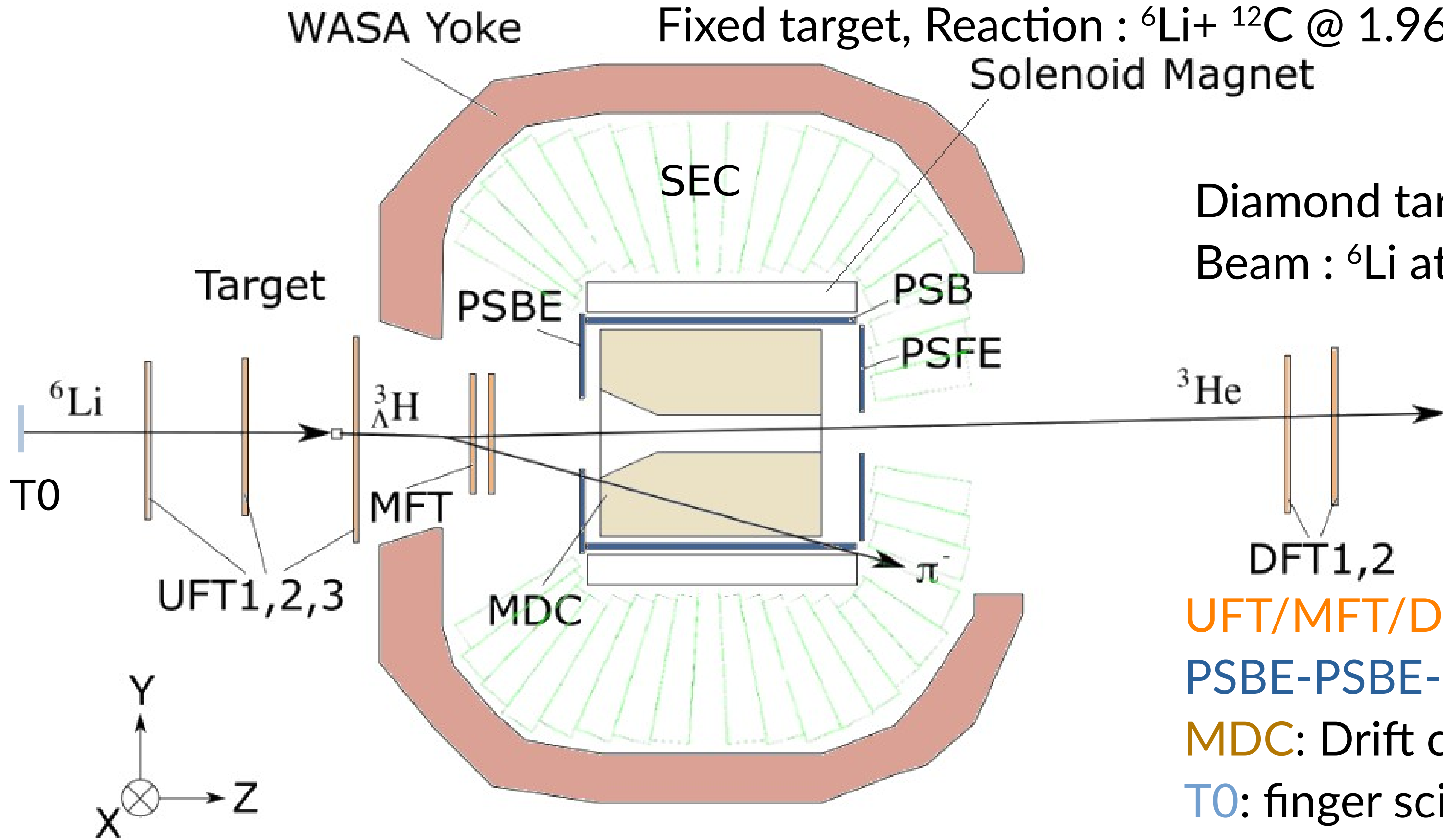
Super-FRS EC

Experimental apparatus: WASA-FRS HypHI

- **At the middle focal plane of FRS:**

$^{3}_{\Lambda}\mathrm{n} \rightarrow \mathrm{d}+\pi^{-}+(\mathrm{n})$ $\quad$ $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}+\pi^{-}$ $\quad$ $^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He}+\pi^{-}$

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

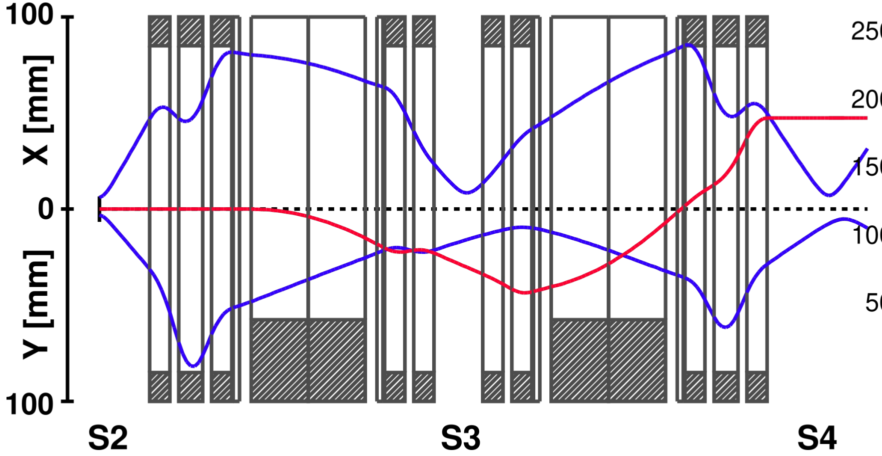


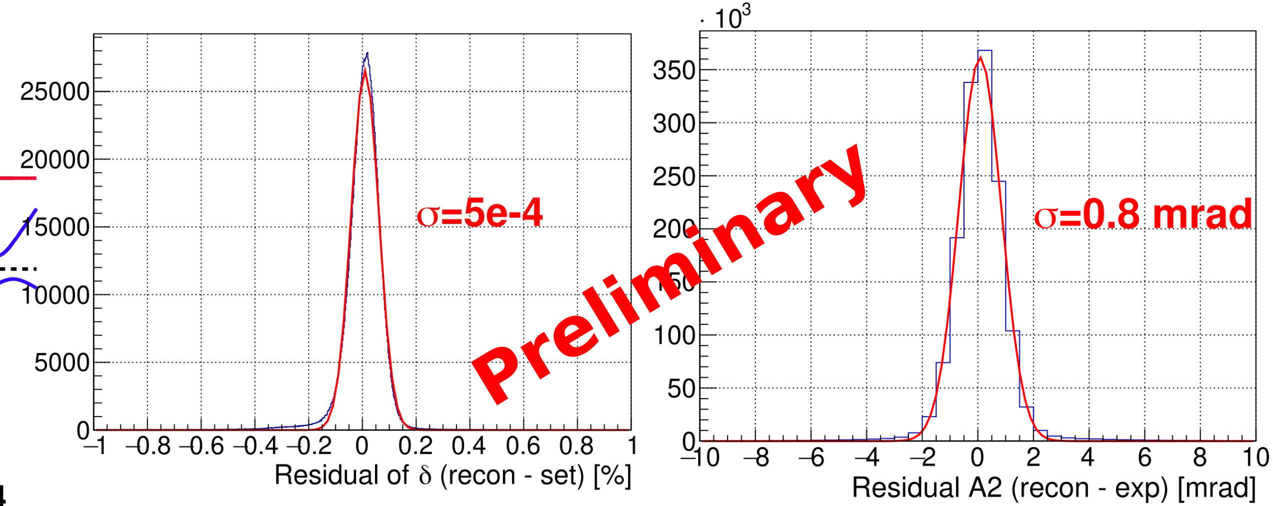
Diamond target: 9.87 g/cm²
Beam : ^{6}Li at 1.96 *A*GeV ~ 2 x 10^{7}/s

UFT/MFT/DFT: Fiber Trackers
PSBE-PSBE-PSFE: Plastic scintillators
MDC: Drift chambers base on straw tubes
T0: finger scintillators
SEC: CsI crystal calorimeter

Data analysis: Tracking & PID

- **Analysis of high resolution spectrometer for fragments:**
  - Momentum analysis : High acceptance & high resolution
    → Needs ion-optics calibration: Several datasets with fixed parameters





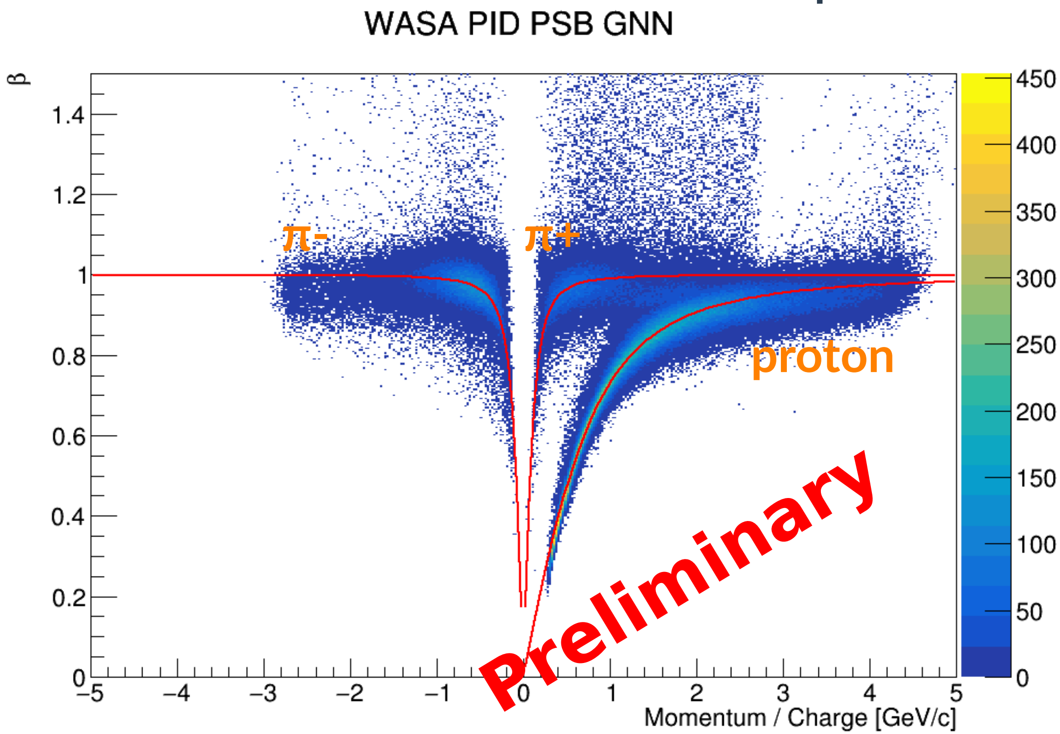
E. Liu's PhD thesis

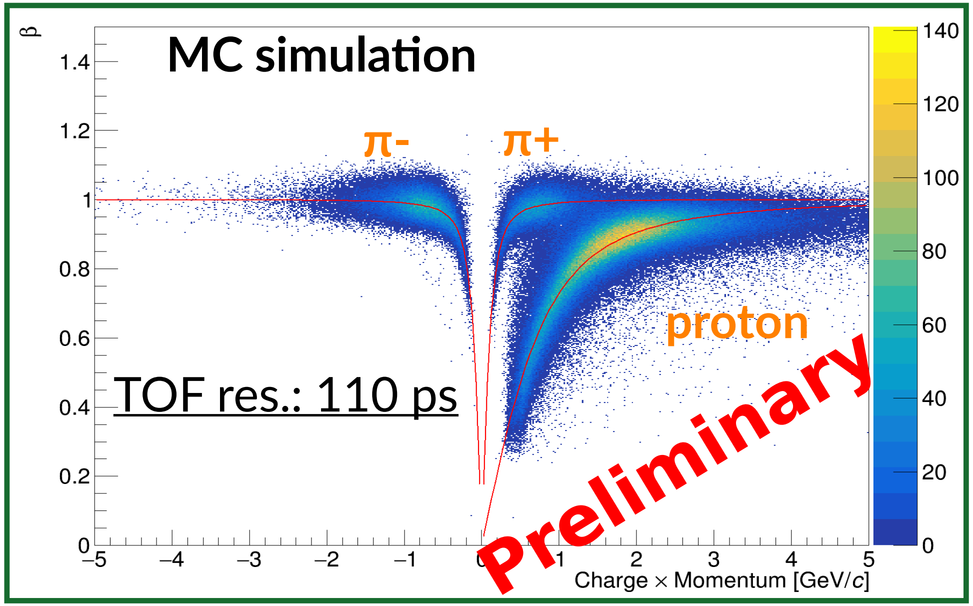
After correction and ion-optics up to second order :

- A momentum resolution for fragments : 5 10^{-4}
- Position & angular resolutions : [x,y] ~ 0.2 mm & [a, b] ~ 0.8 and 0.7 mrad

Data analysis: Tracking & PID

- **Analysis of WASA central system for hadron measurements :**
  - PID at S2 middle focal plane of FRS:



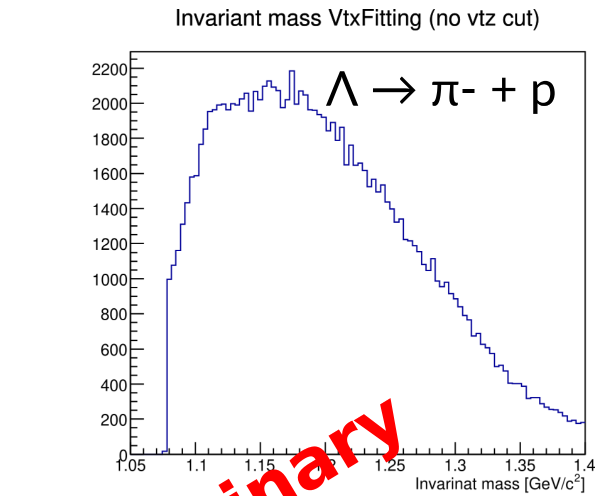


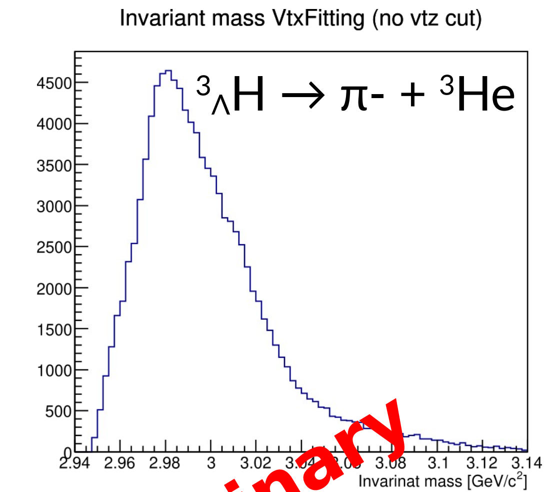
→Improved the track finding with Graph Neural Network:
Estimator resolutions: momentum 8.8%, angular 2.3 mrad

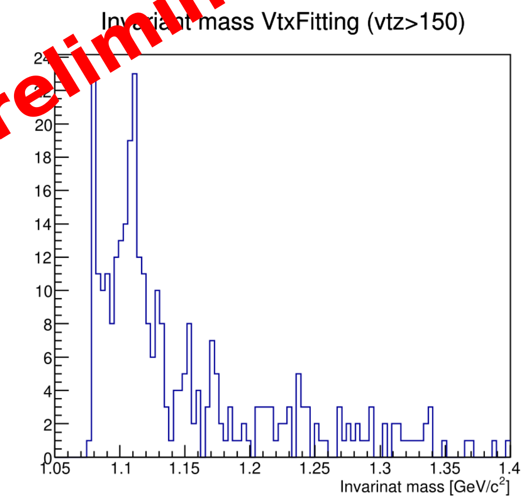
[H. Ekawa et al., Eur. Phys. J. A 59, 103 (2023)]

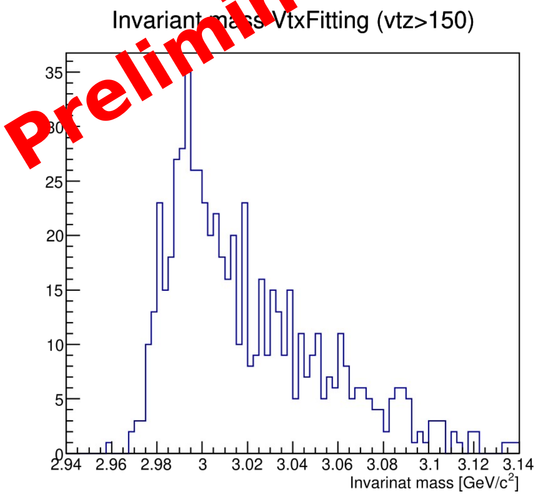
Data analysis: Hypernuclei identification

- **Invariant mass at 15 cm behind the target:**



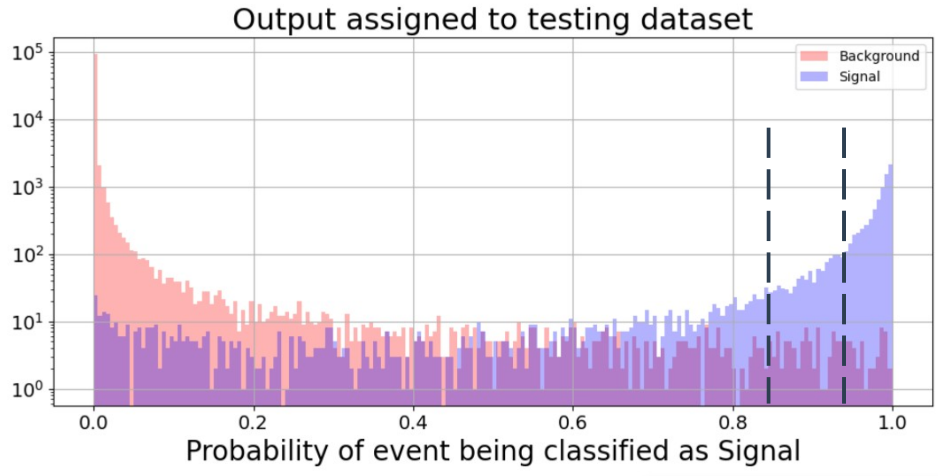


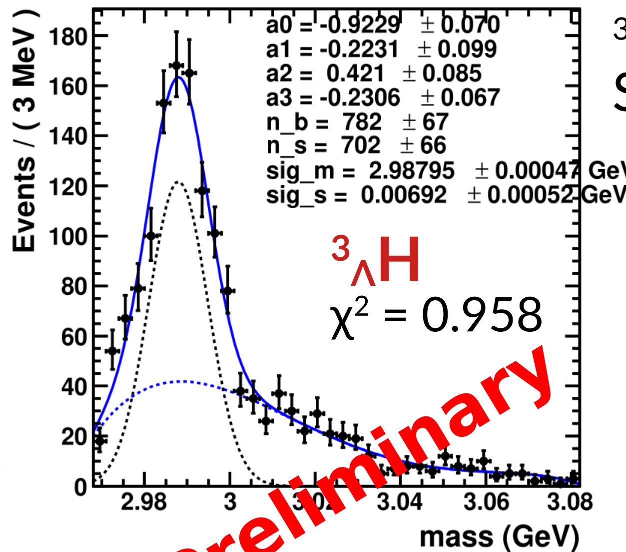




Data analysis: ML for S/B improvement

- Use of Boosted Decision Tree, XGBoost:



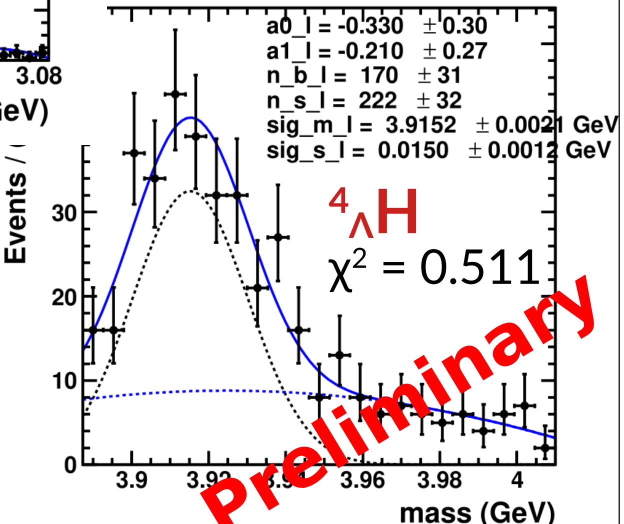


$^{3}_{\Lambda}H \rightarrow$ Thr: 0.85
S = 702 ± 66

Training data:

- <u>**Uncorrelated to**</u> invariant mass & lifetime
  → **no bias**
- Physical observables: geometry of decay vertex & hit patterns & π- hit multiplicity detectors

$^{4}_{\Lambda}H \rightarrow$ Thr: 0.95
S = 222 ± 32



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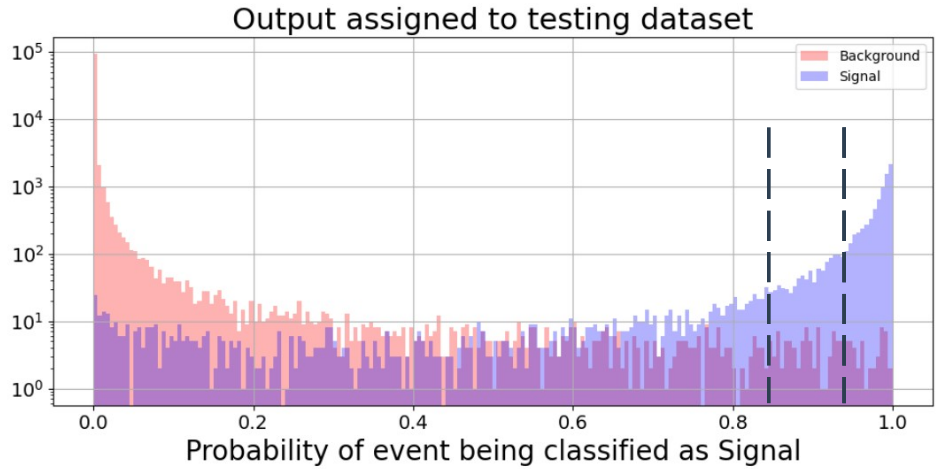
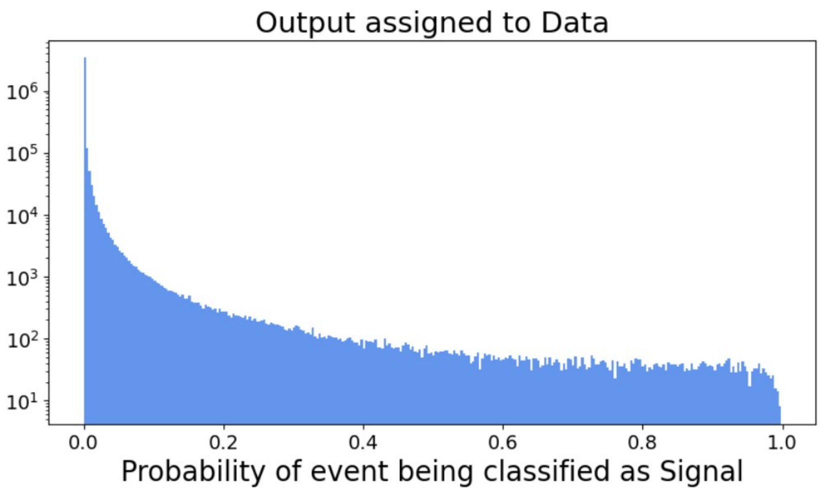
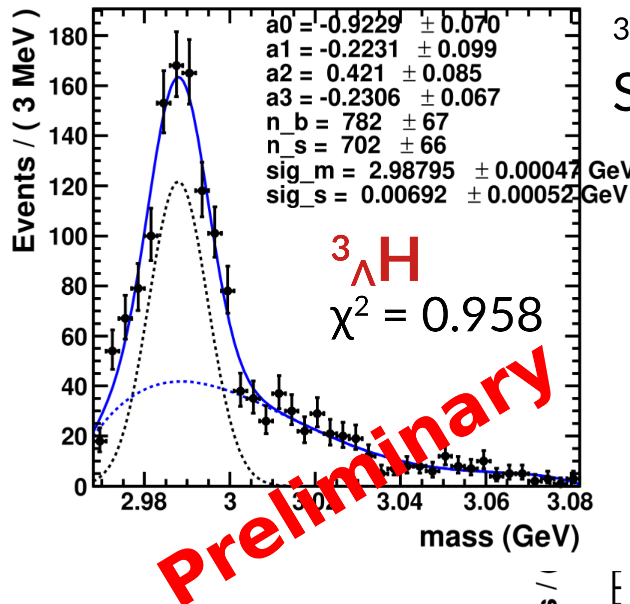
- Use of Boosted Decision Tree, XGBoost:







$^{3}{}_{\Lambda}H \rightarrow$ Thr: 0.85
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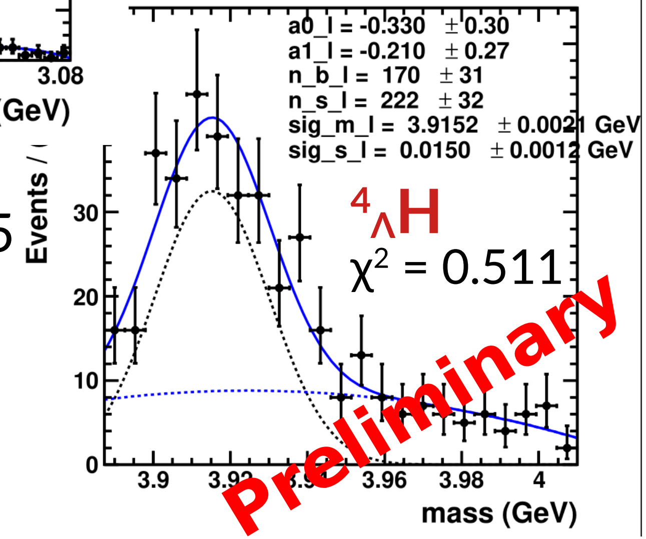
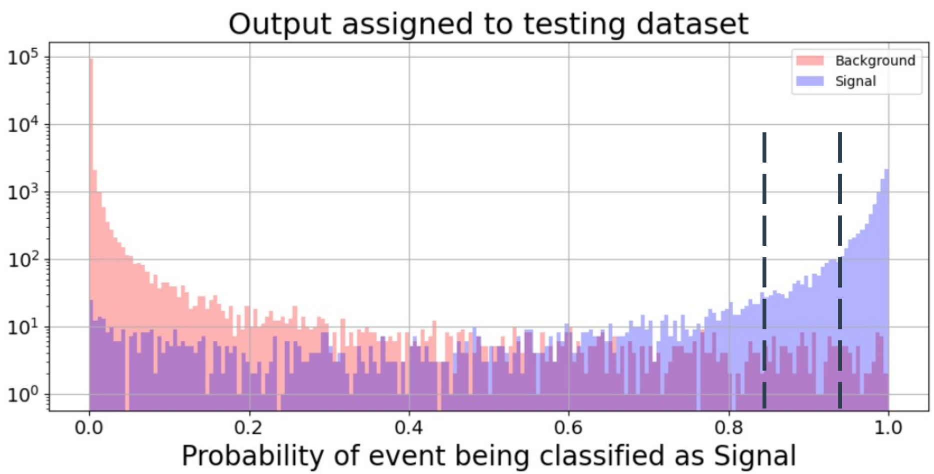
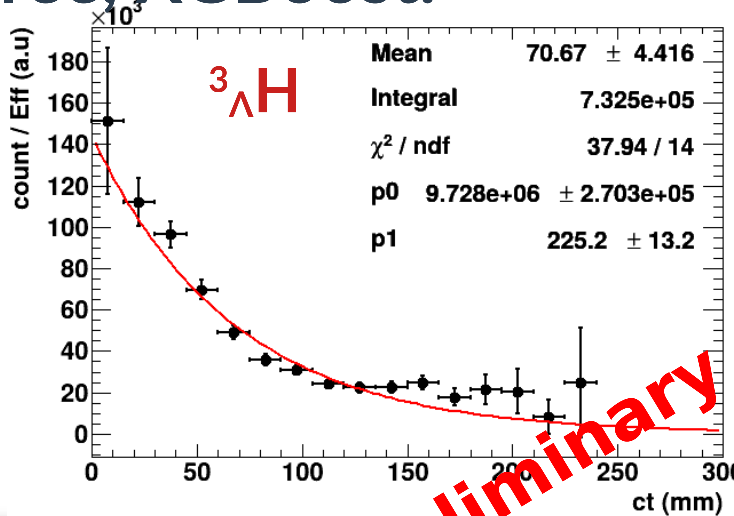


Data analysis: ML for S/B improvement

- Use of Boosted Decision Tree, XGBoost:

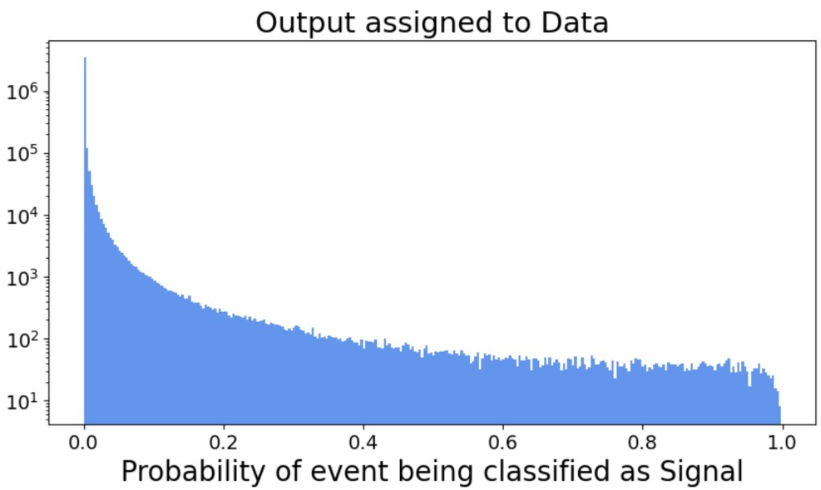




$^{3}_{\Lambda}$H → Thr: 0.85

τ = 225 ± 13 ps

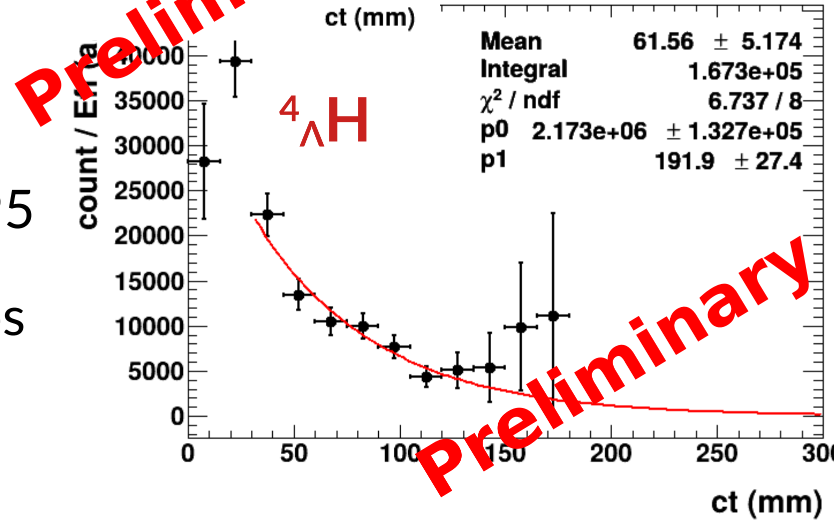
World avg: 237 $^{+10}_{-9}$ ps



$^{4}_{\Lambda}$H → Thr: 0.95

τ = 192 ± 28 ps

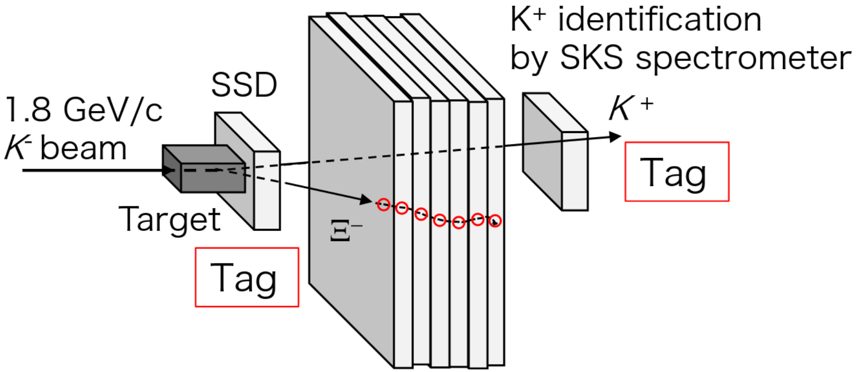
World avg: 208 $^{+10}_{-12}$ ps

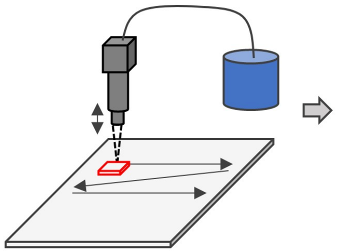


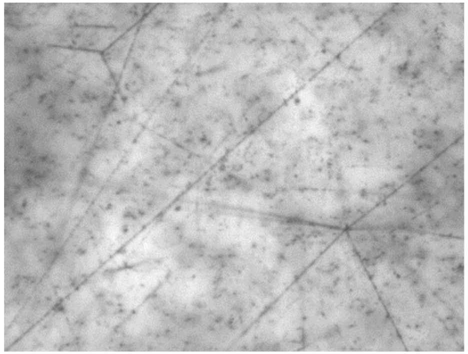
E07 experiment with machine learning

- **E07 experiment at JPARC:**

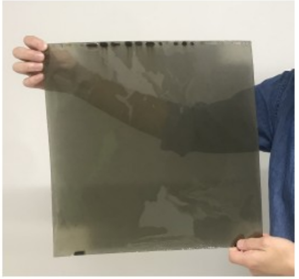
Emulsion-Counter hybrid method







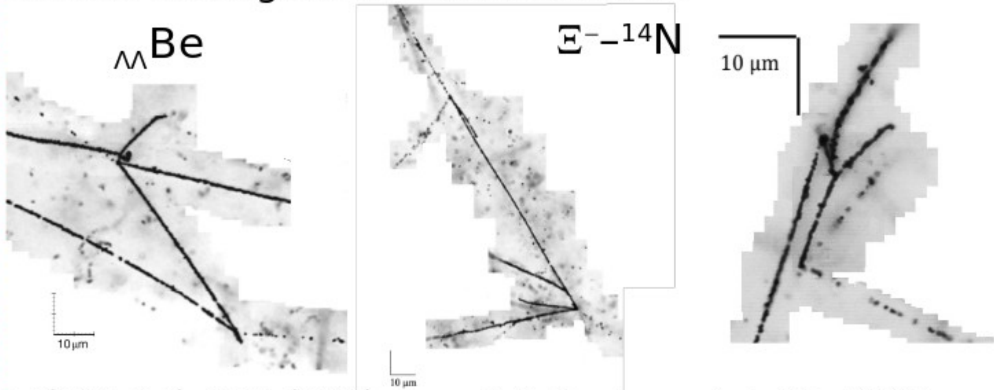
E07 nuclear emulsion



(35 cm × 35 cm × 0.6 mm)

- With trigger →
- Without trigger:
  - S=-1: 10^6 events (3 <= A <= 15)
  - S=-2: 10^3 events
  - Data: 150 PB → 560 years

Double-strangeness candidates: 33

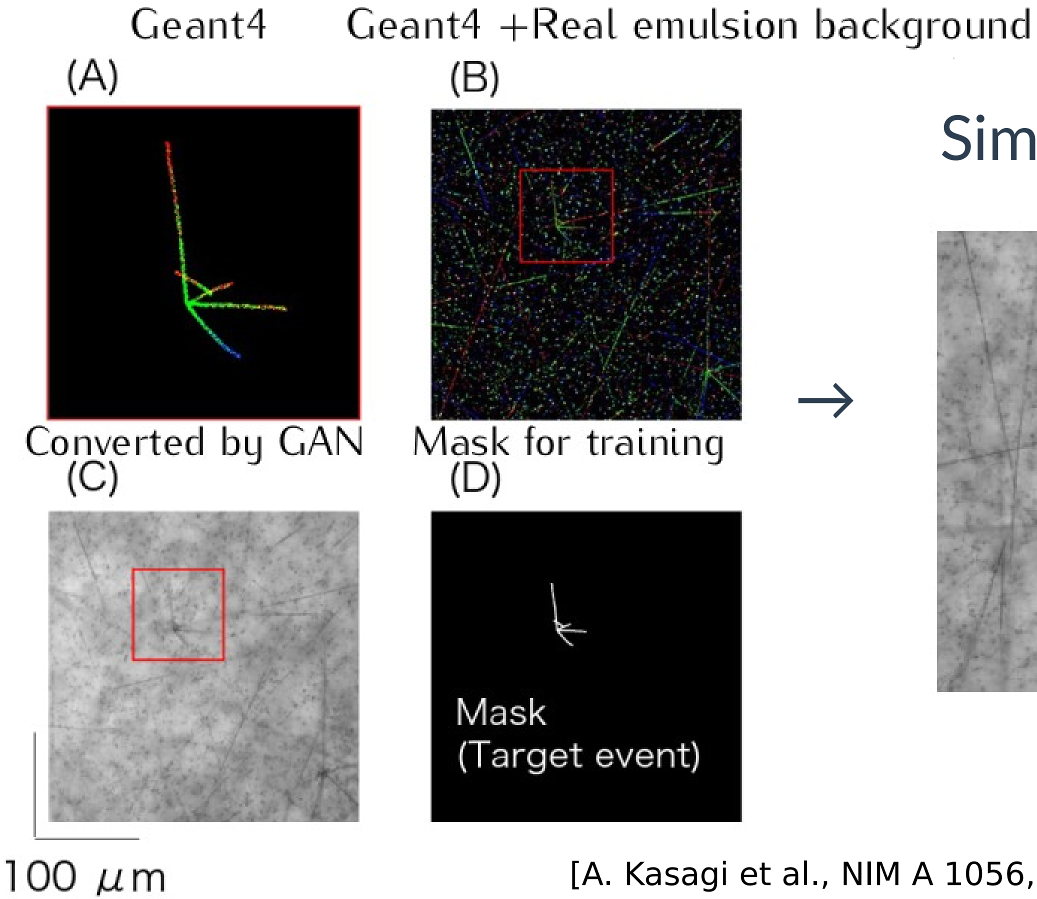


H. Ekawa et al., PTEP, (2019)
A.N.L. Nyaw et al., BSPIJ, (2020)

S. H. Hayakawa et al., PRL, (2021)
M. Yoshimoto et al., PTEP, (2021)

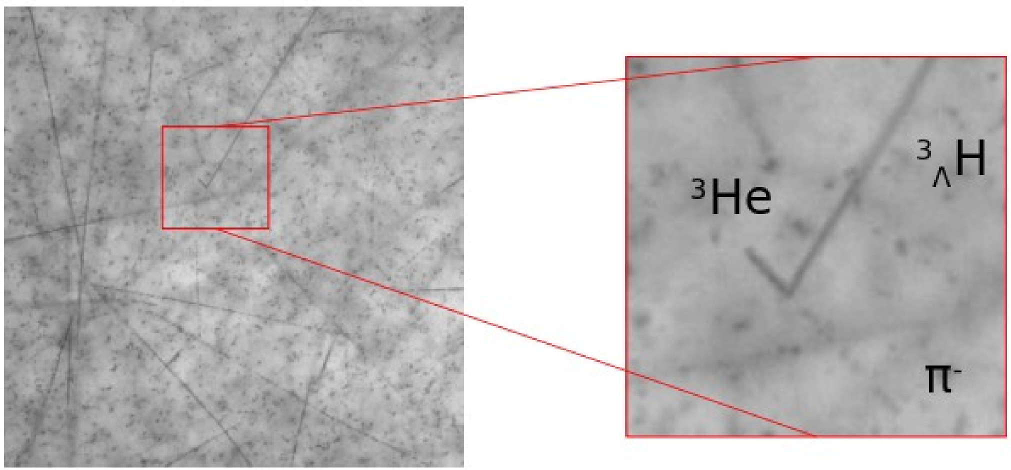
Hypernuclear Event Search with Machine Learning

- **Production training data:**
  - surrogate images from MC simulation + GAN



→

Simulated image:

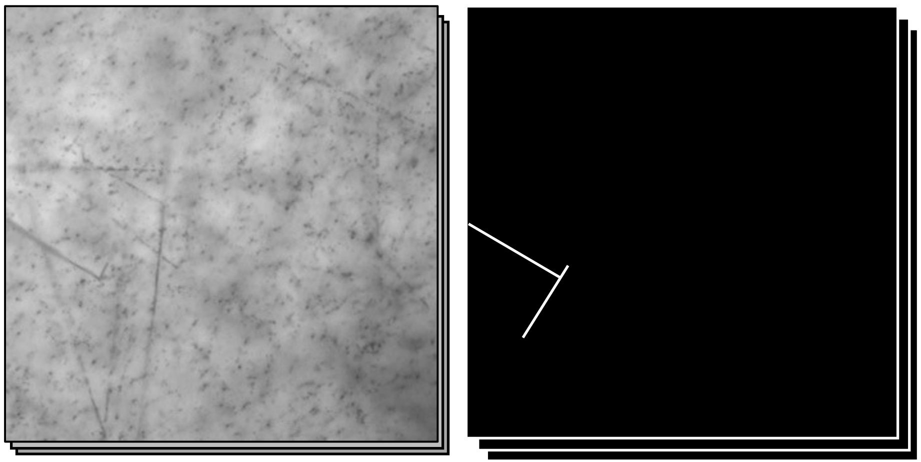


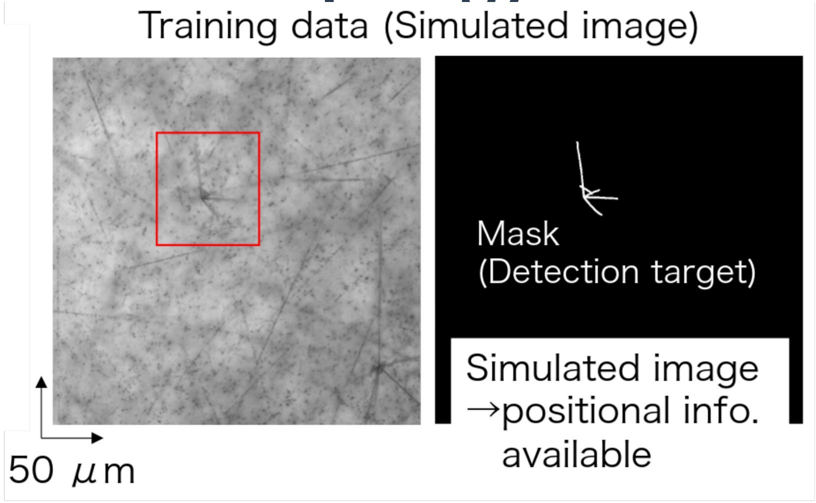
[A. Kasagi et al., NIM A 1056, 168663 (2023)]

Hypernuclear Event Search with Machine Learning

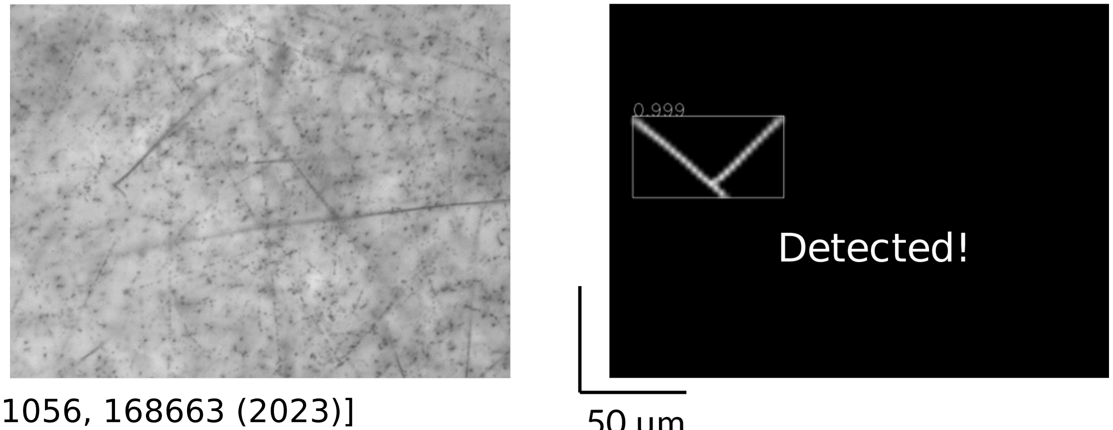
- **Object detection model for $^{3}_{\Lambda}H$ event topology**
  - Mask R-CNN model:

Simulation





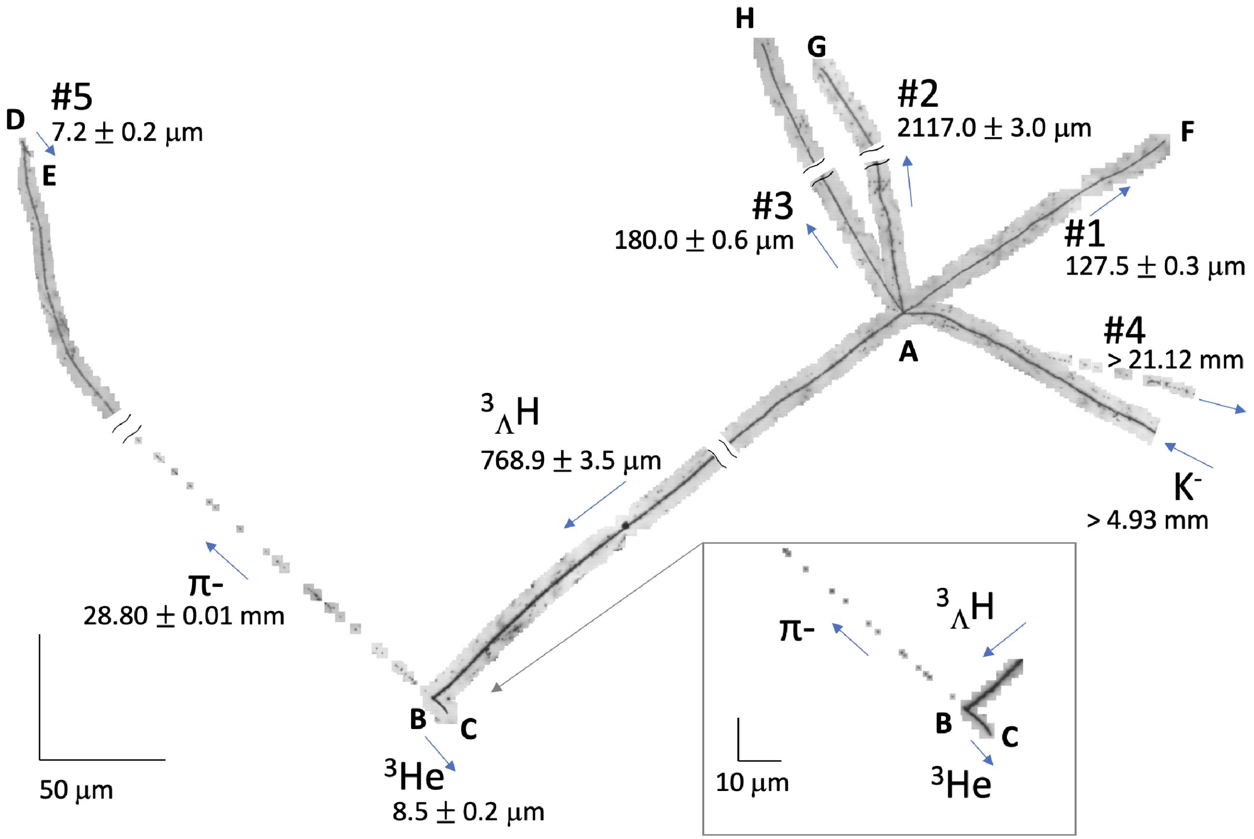
Mask R-CNN Model on Real Data



[A. Kasagi et al., NIM A 1056, 168663 (2023)]

Hypernuclear Event Search with Machine Learning

- **First $^{3}_{\Lambda}H$ found with Deep learning model:**



Current status:
Found in 0.6% of the data:

- 49 $^{3}_{\Lambda}H$
- 163 $^{4}_{\Lambda}H$

Statistical error on binding energy: ~ 100 keV
→ improve with more statistics

Systematic error on binding energy: ~ 14 keV

[T. Saito et al., Nat. Rev. Phys. 3, 803 (2021)]

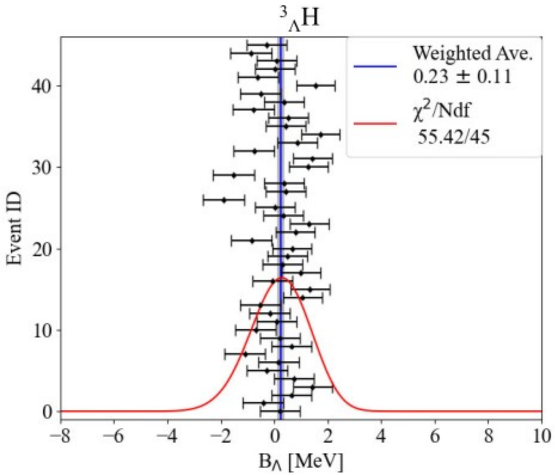
Event analysis from the ML topology search

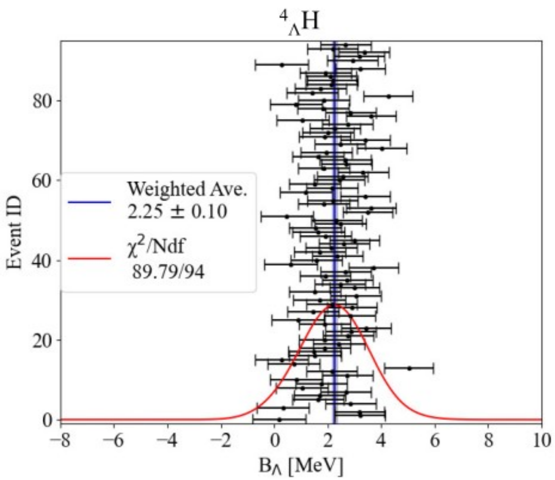
- **Statistical Results:**

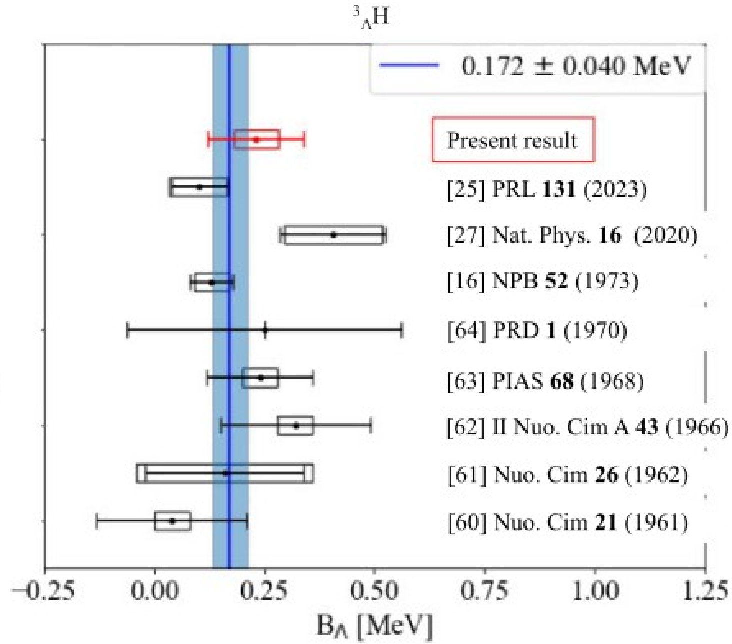
[A Kasagi et al., Prog. Theor. Exp. Phys. 8, 083D01 (2025)]

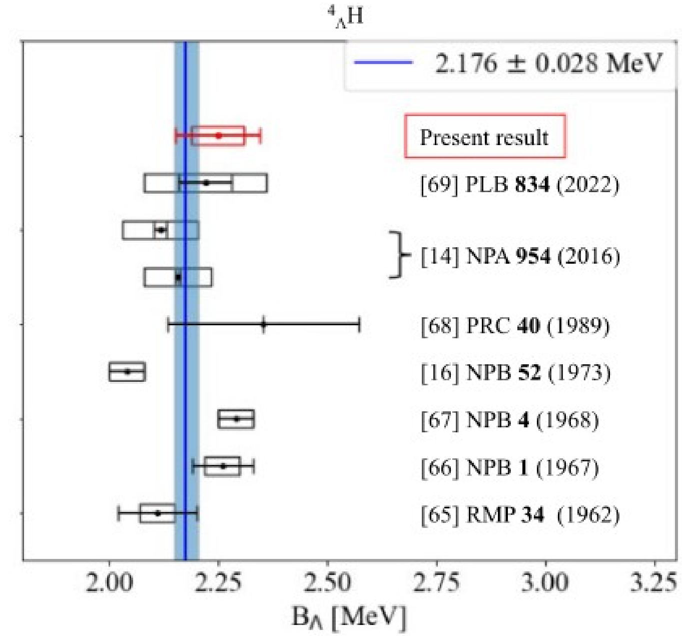
$$({}^{3}_{\Lambda}\mathrm{H})\ \ B_{\Lambda} = 0.23 \pm 0.11(\mathrm{Stat.}) \pm 0.05(\mathrm{Syst.})\ \mathrm{MeV},$$

$$({}^{4}_{\Lambda}\mathrm{H})\ \ B_{\Lambda} = 2.25 \pm 0.10(\mathrm{Stat.}) \pm 0.06(\mathrm{Syst.})\ \mathrm{MeV}.$$







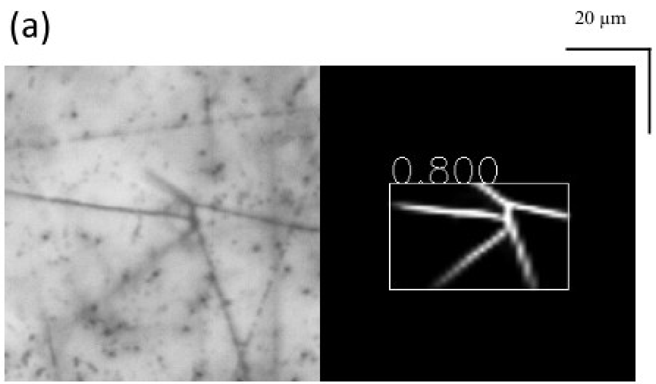


- New calibration method based on μ+ & ATIMA
- Systematic uncertainties: 50 – 60 keV
- & More data coming → new statistical analysis possible now !

Event analysis from the ML topology search

- Discovery of 13ΛΛB and uniquely identified:
  - Second ΛΛ-hypernucleus after NAGARA event after 24 years !

(a)

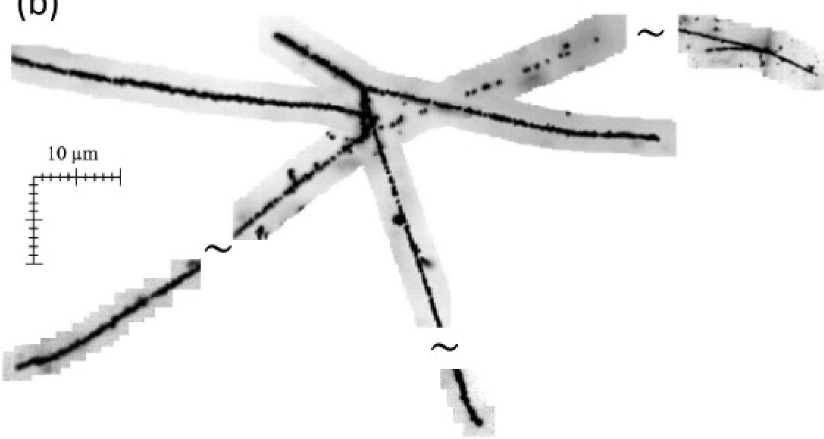


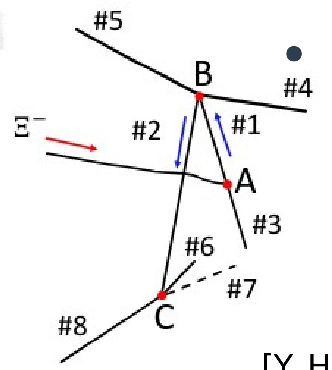
v.A: $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{13}_{\Lambda\Lambda}\mathrm{B} + p + n$

v.B: ${}^{13}_{\Lambda\Lambda}\mathrm{B} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + t + {}^{3}\mathrm{He} + 2n$

v.C: ${}^{5}_{\Lambda}\mathrm{He} \quad \rightarrow \; {}^{4}\mathrm{He} \;\; \pi^- \quad p$

(b)





- Binding energy of 2Λ:

$$B_{\Lambda\Lambda} = 25.57 \pm 1.18(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})\mathrm{MeV}$$

- ΛΛ interaction energy:

$$\Delta B_{\Lambda\Lambda} = 2.83 \pm 1.18(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\mathrm{MeV}$$

[Y. He et al., *Under review Nat. Comm.* arXiv:2505.05802]

Summary

- **Steps for tackling ${}^{3}_{\Lambda}H$ and nnΛ puzzles:**
  - **HypHI WASA-FRS at GSI:**
    - The experiment took place 2022, it was very successfully !
    - Analysis is advancing: ${}^{3}_{\Lambda}H$ & ${}^{4}_{\Lambda}H$ hypernuclei identified
    - Lifetime measurement obtained → study systematics uncertainties
    - Search of nnΛ & ${}^{9}_{\Lambda}C$
  - **E07 emulsion at JPARC with deep learning:**
    - Analysis with DL pipeline is fixed and statistics on hypernuclear topologies are accumulating.
    - ${}^{3}_{\Lambda}H$ & ${}^{4}_{\Lambda}H$ found → their binding energy extracted
    - Extending the search for more decay topologies:
      - New double strangeness hypernuclei uniquely identified

Acknowledgment

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