IEM

CSIC

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

HENP

High Energy Nuclear Physics

GSI

Super-FRS EC

Hypernuclear Studies through Machine Learning

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

13/11/2025

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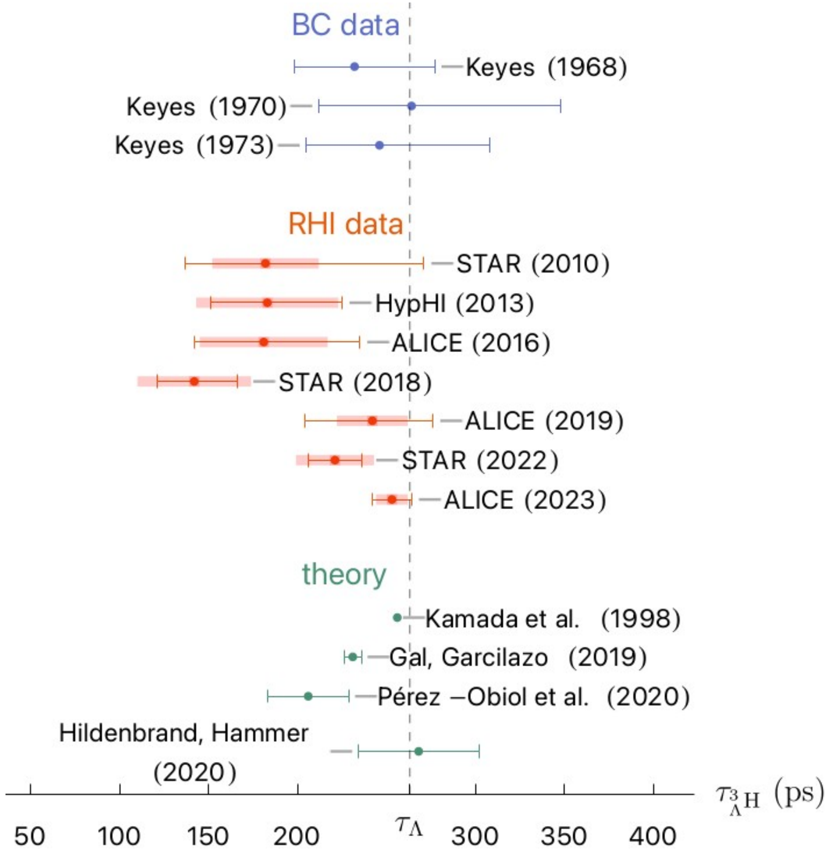
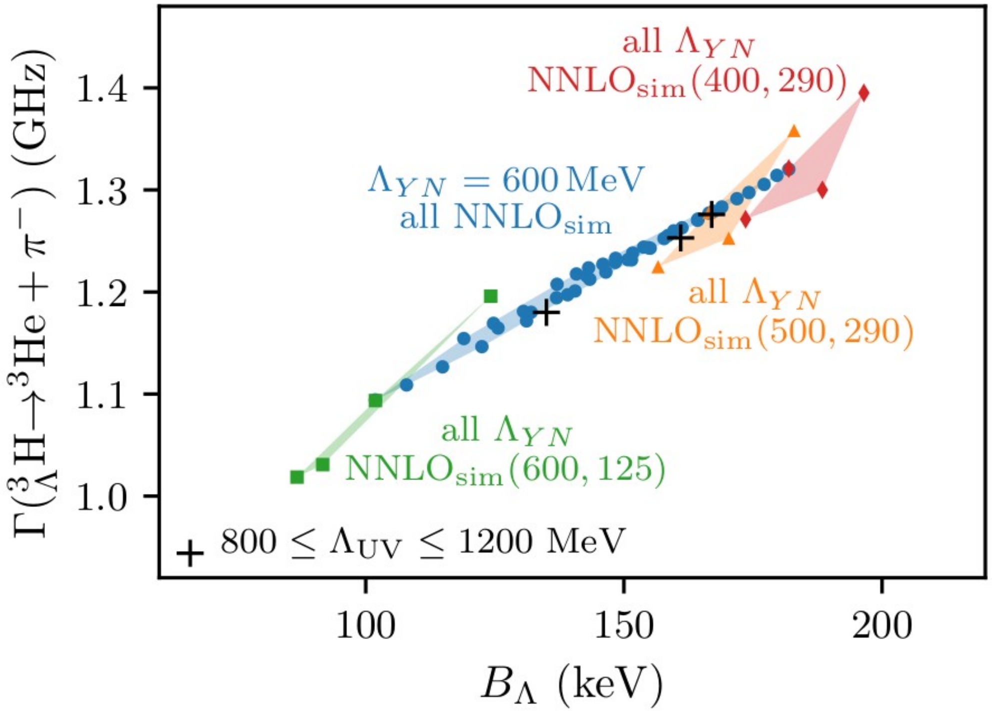
For ML-Emulsion collaboration & WASA-FRS / Super-FRS Experiment collaboration

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

- **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 :**
  - 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: ${}^{3}_{\Lambda}H$ & ${}^{3}_{\Lambda}n$

- **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

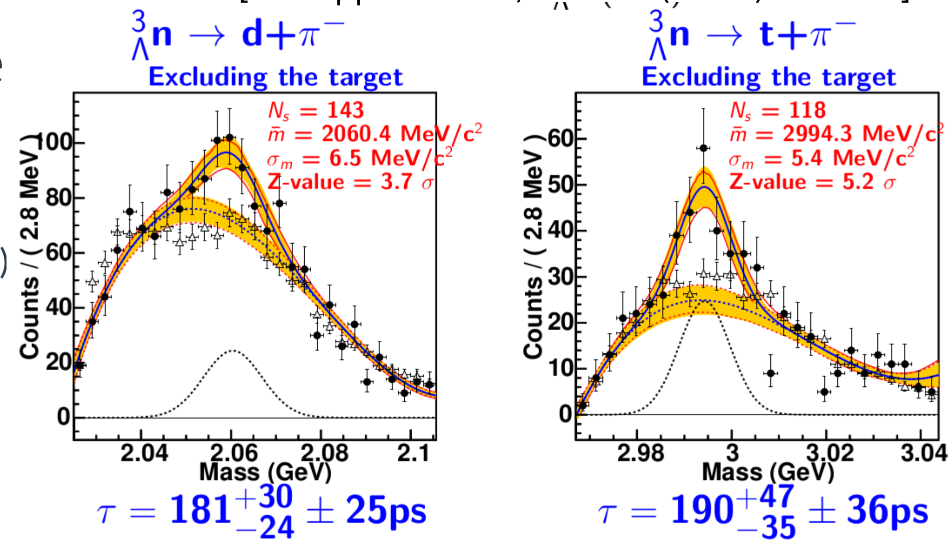
$$B_{\Lambda} = 0.41 \pm 0.12(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV} \quad (3)$$

  - 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]

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]



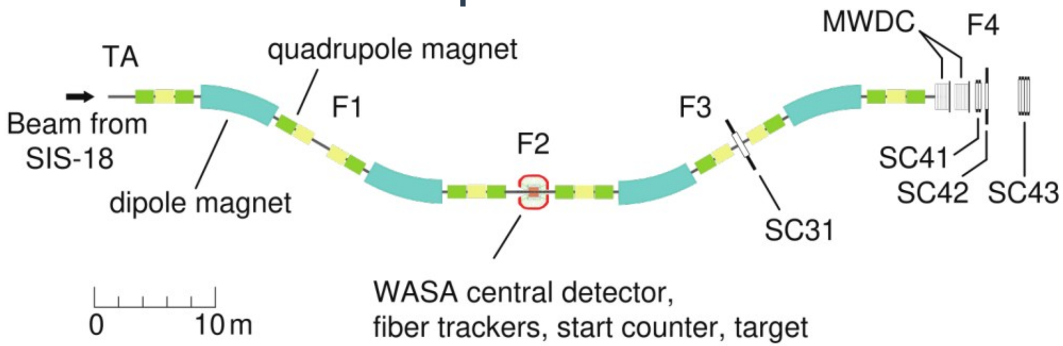
  - Short lifetime of $^{3}_{\Lambda}H$:
    - Our published value : 183 $^{+43}_{-32}$ ps [C. Rappold et al., Nucl. Phys. A 913 (2013) 170]
    - Plus other recent measurements : Combined lifetime analysis excludes all current models of $^{3}_{\Lambda}H$ [C. Rappold et al., Phys. Lett. B 728, 543 (2014)]

Deep learning in study of those puzzles

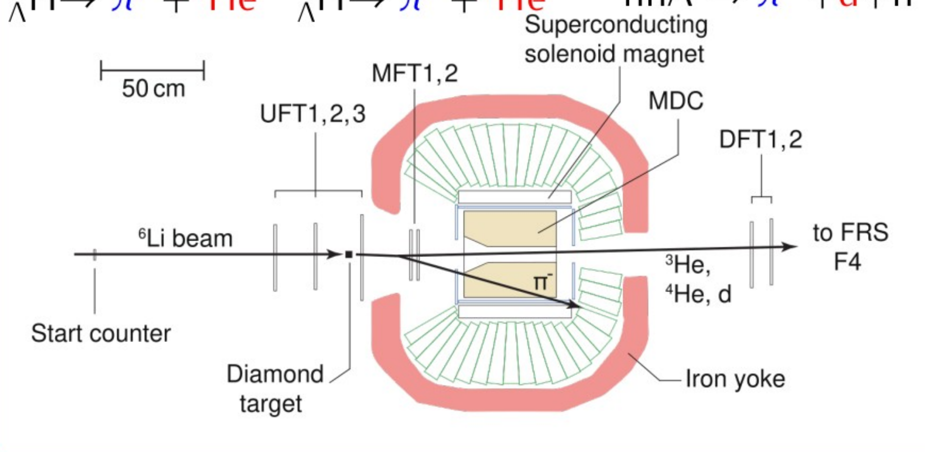
- **Our contributions to solve : 2 experiments to measure**

→ Lifetime & radius:

WASA-FRS experiment at GSI-FAIR



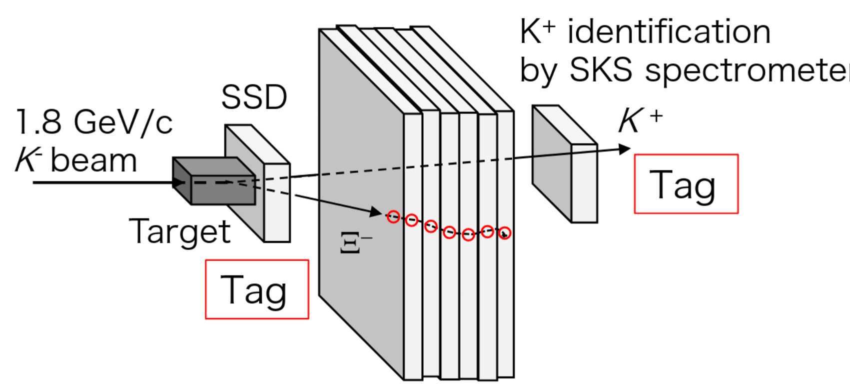
$^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^{-} + {}^{3}\mathrm{He}$ $\quad ^{4}_{\Lambda}\mathrm{H} \rightarrow \pi^{-} + {}^{4}\mathrm{He}$ $\quad \mathrm{nn}\Lambda \rightarrow \pi^{-} + \mathrm{d} + \mathrm{n}$

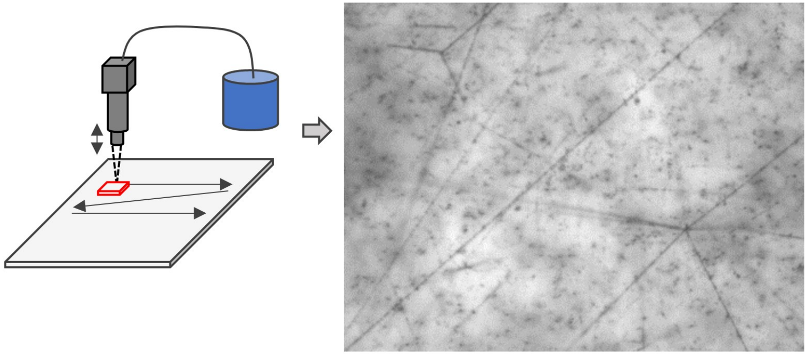


→ Binding energy:

E07 experiment at JPARC

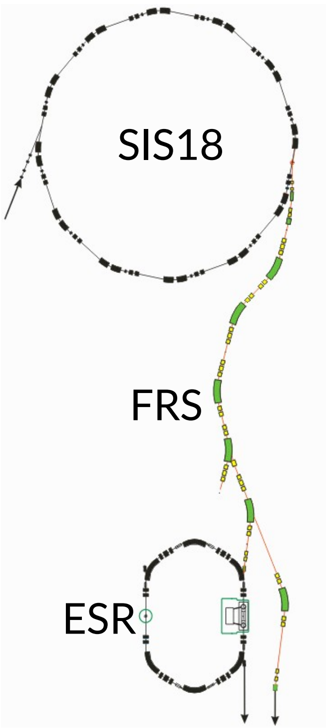
Emulsion-Counter hybrid method

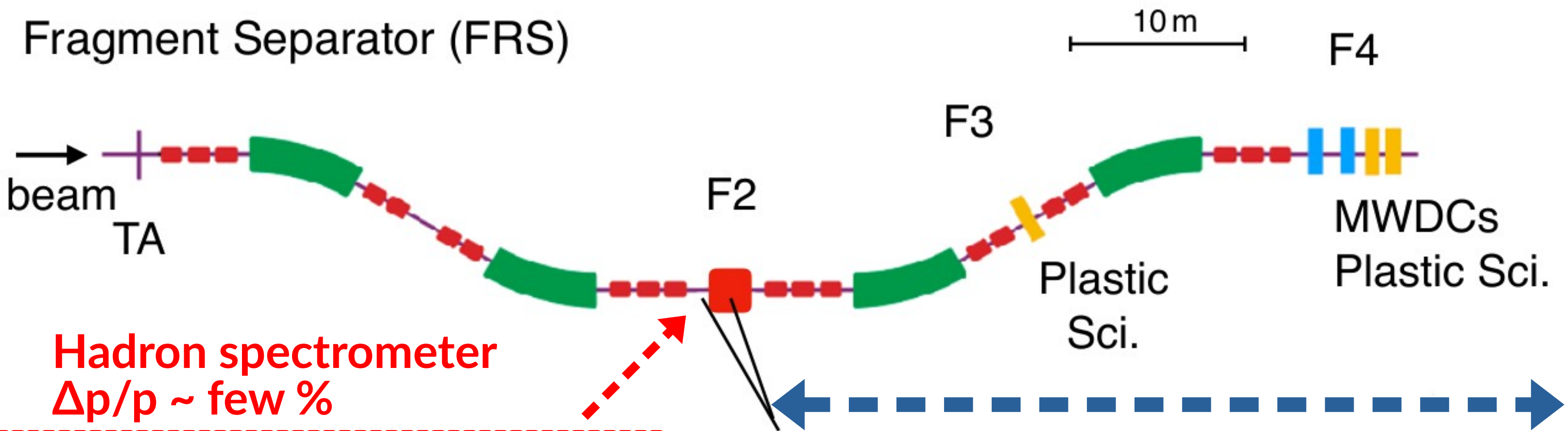




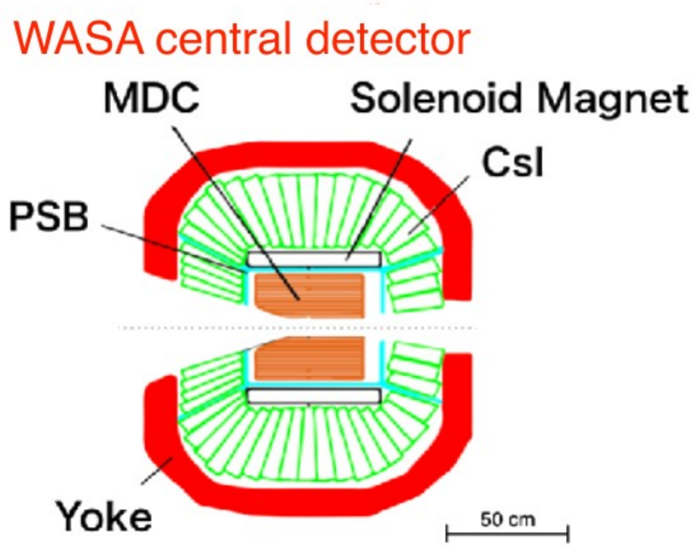
WASA-FRS Experimental campaign: Jan. – March 2022

GSI facility





Hadron spectrometer
Δp/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

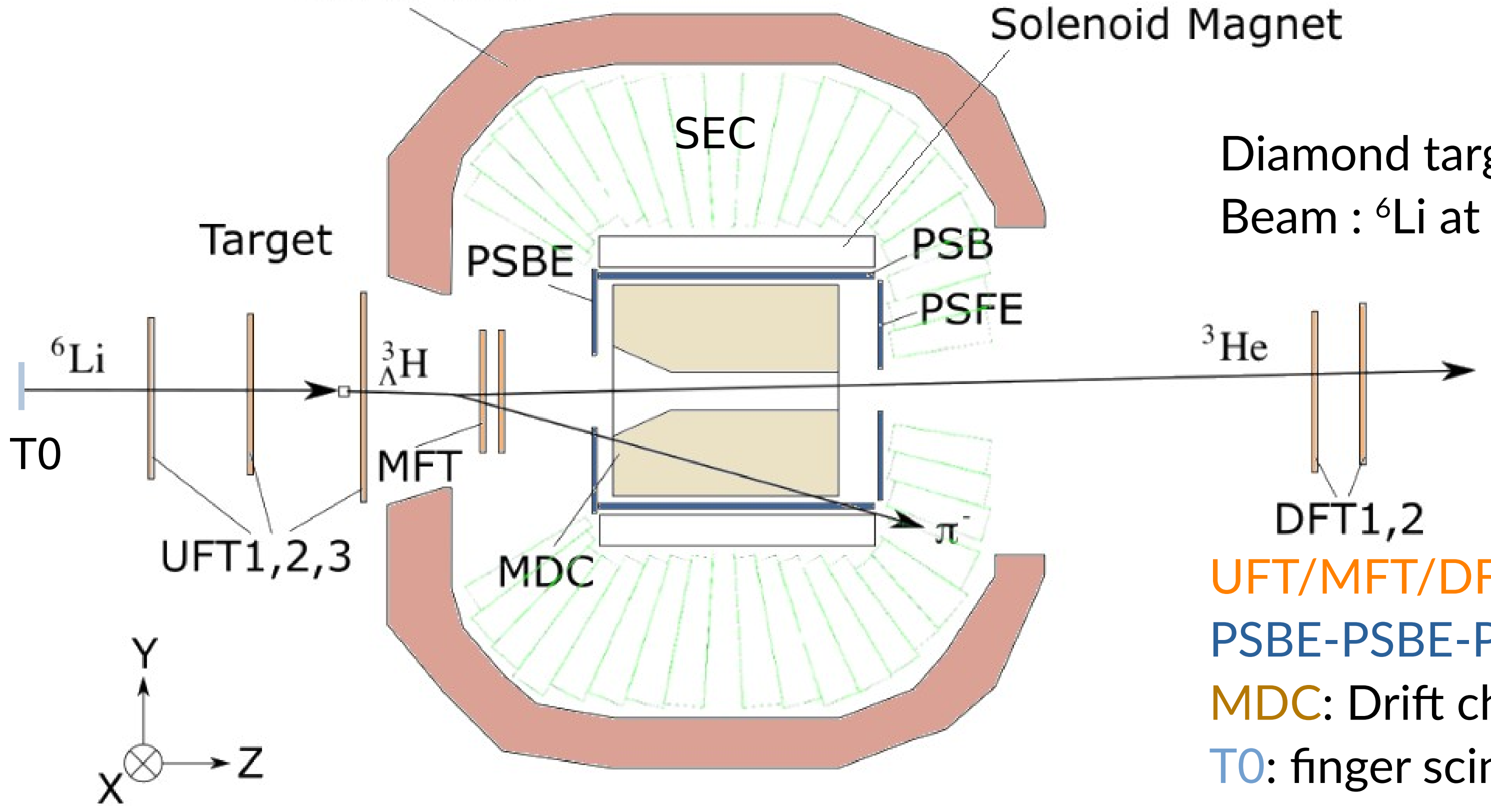
Super-FRS EC

Experimental apparatus: WASA-FRS HypHI

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

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

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

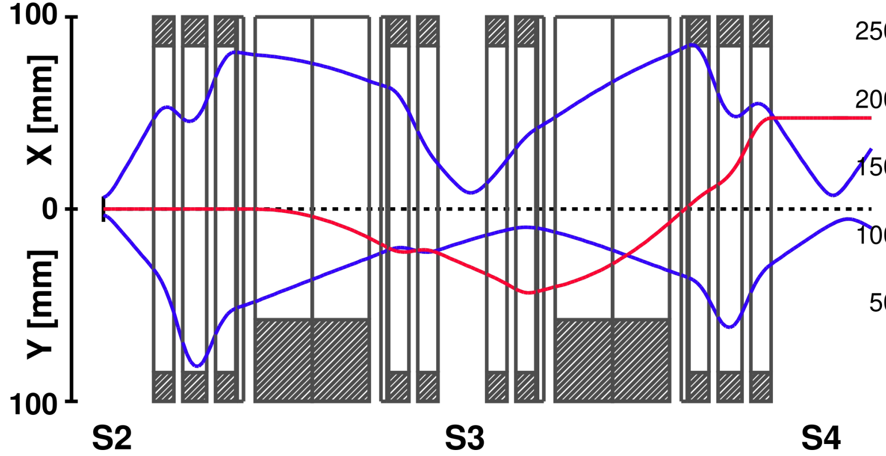
MDC: Drift chambers base on straw tubes

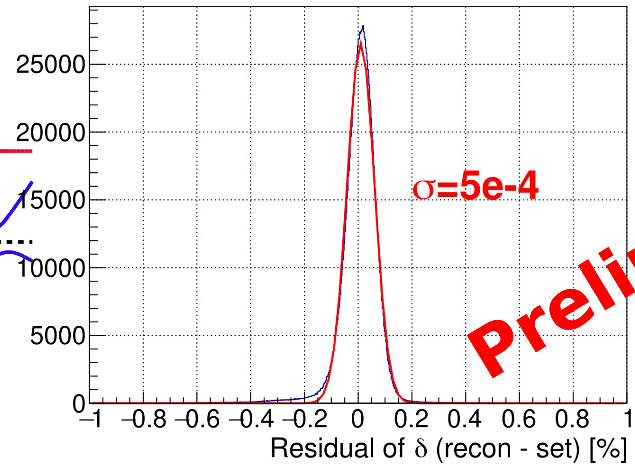
T0: finger scintillators

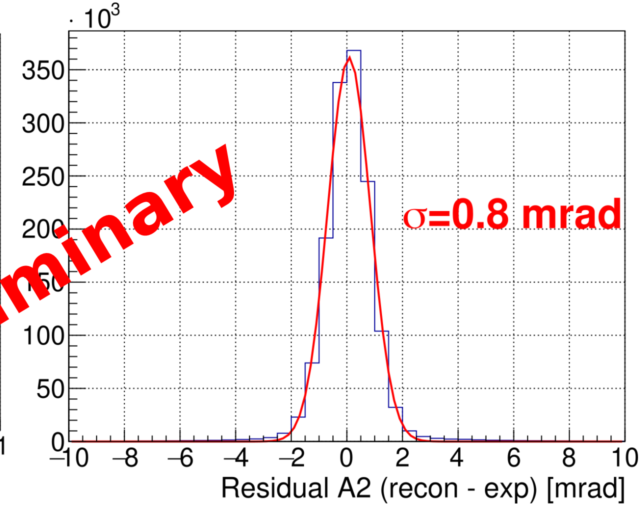
SEC: CsI crystal calorimeter

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







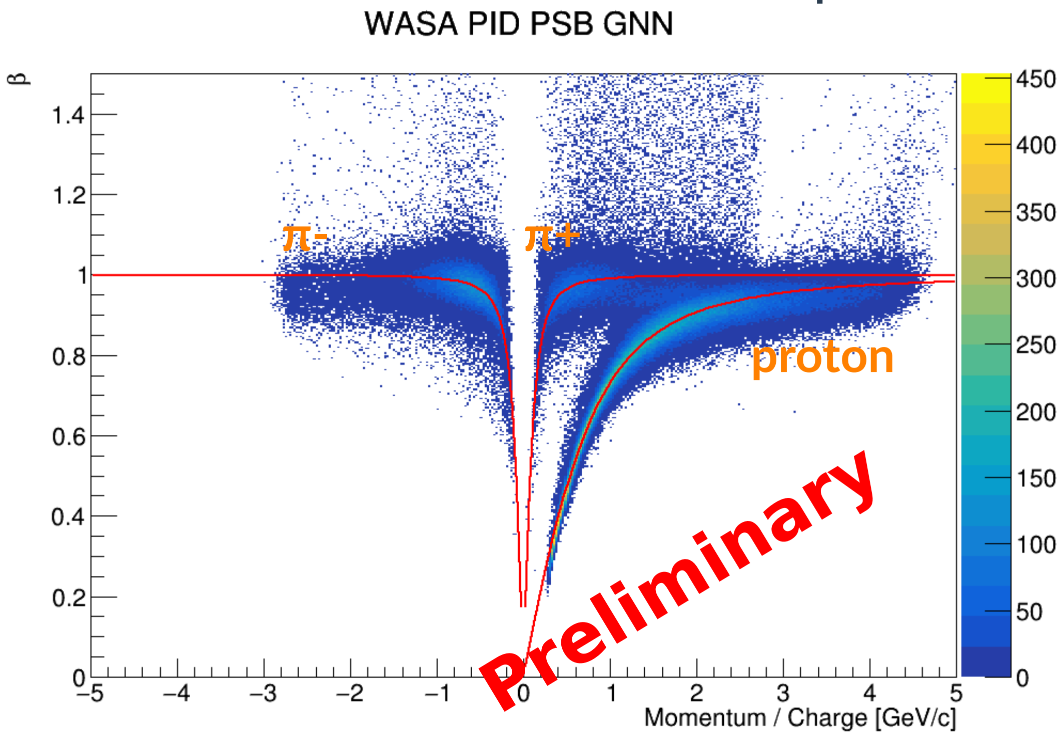
E. Liu's PhD thesis

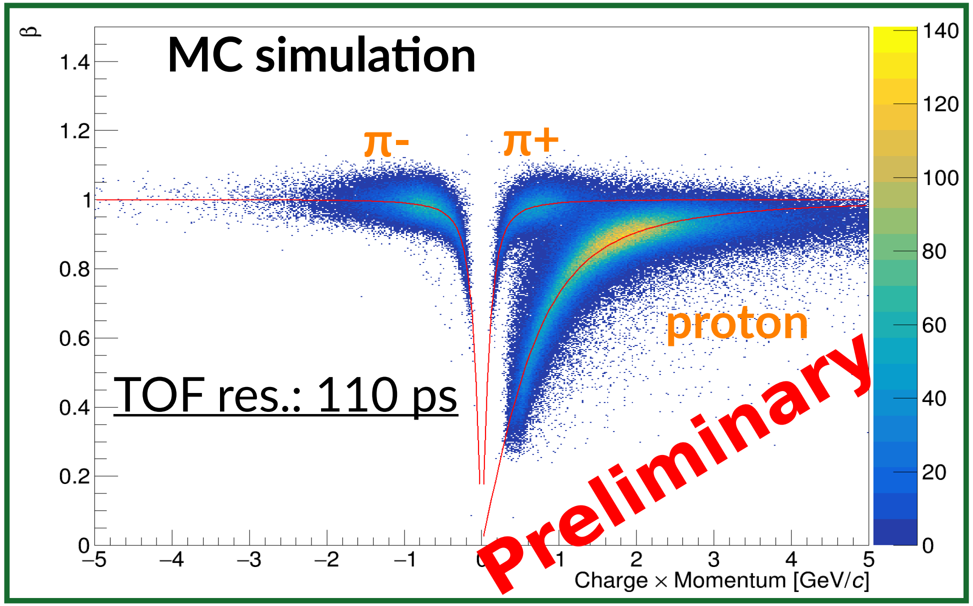
After correction and ion-optics up to second order :

- 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:



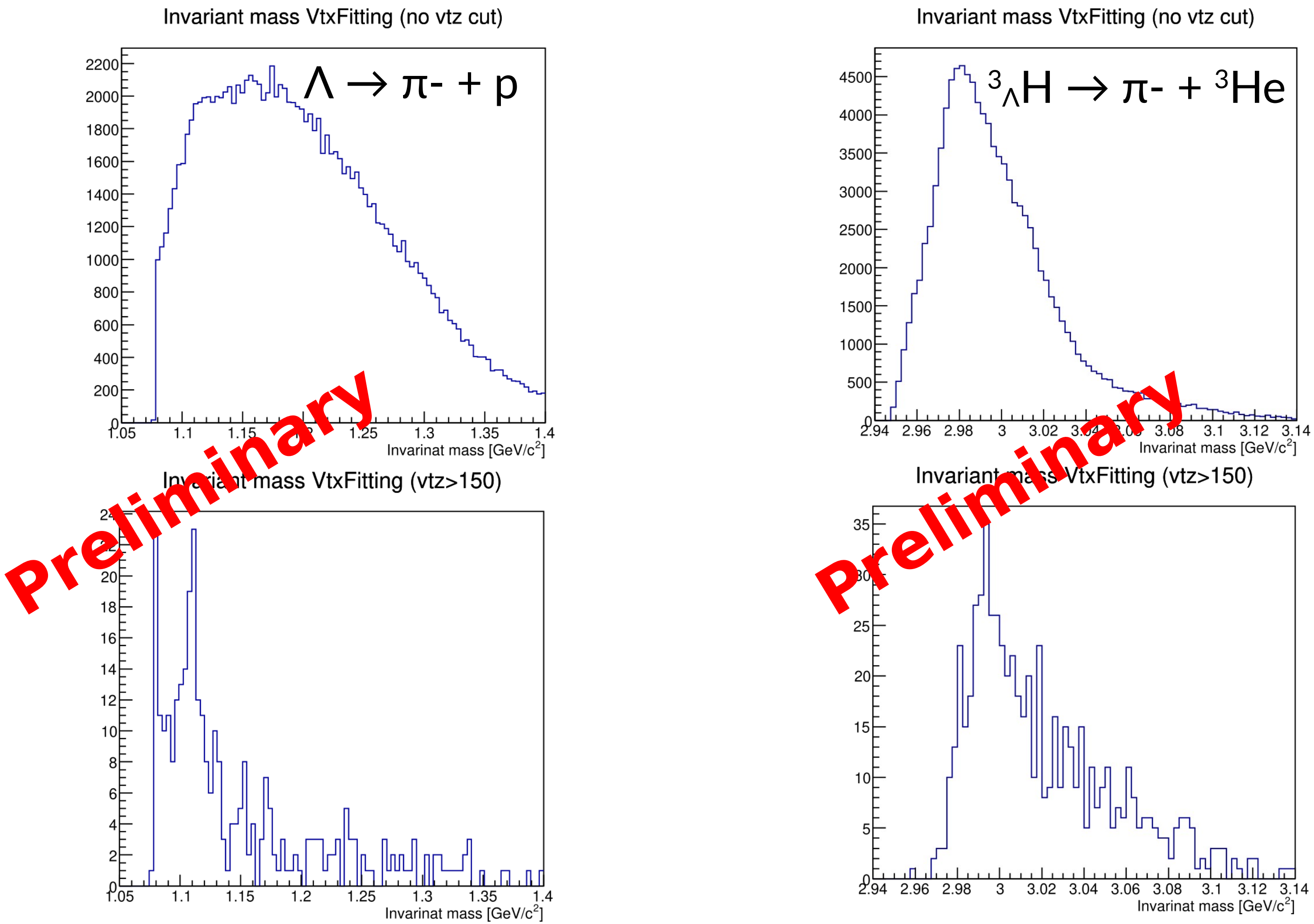


→Improved the track finding with Graph Neural Network:
Estimator resolutions: momentum 8.8%, angular 2.3 mrad

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

Data analysis: Hypernuclei identification

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



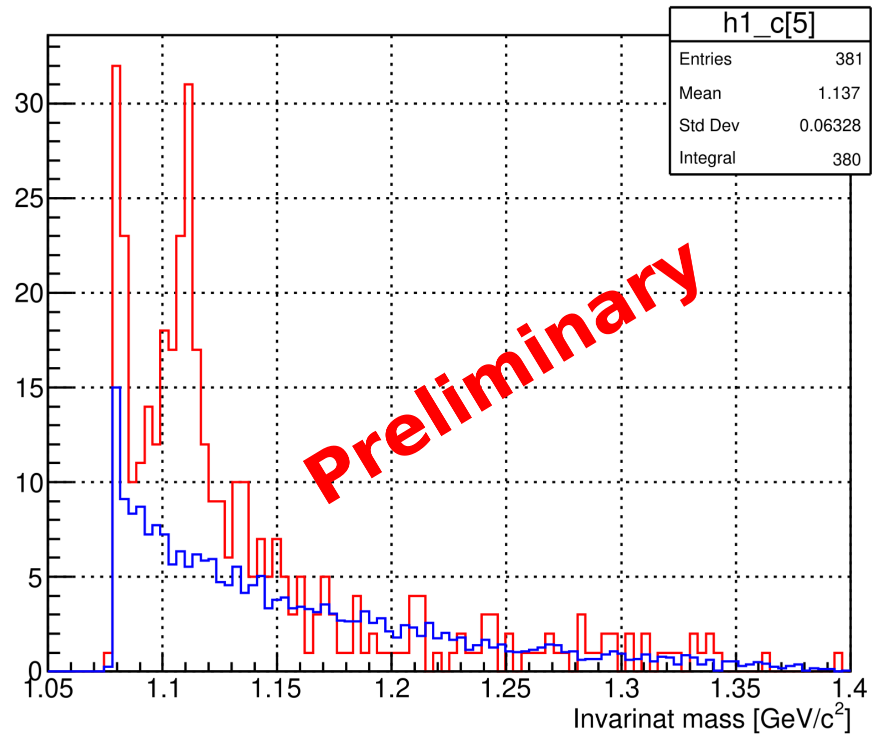
Data analysis: Hypernuclei identification

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

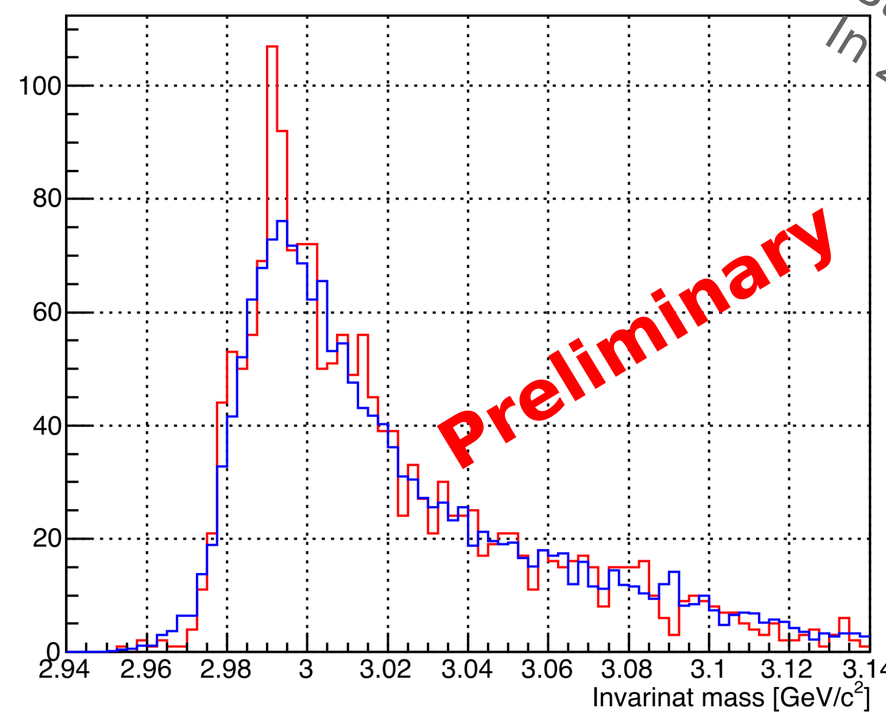
Red → real event | Blue → mixed event: π- Event #n + p | ^{3}He Event #n+1

Secondary vertex Z pos > 150 mm

Status In 2024



$\Lambda \rightarrow \pi^- + p$



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

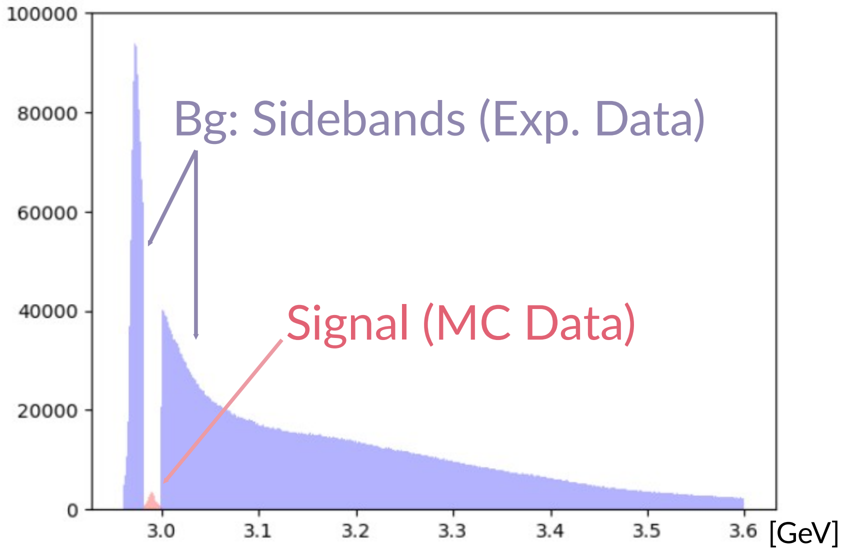
~ S - B = 51 ± 26 events

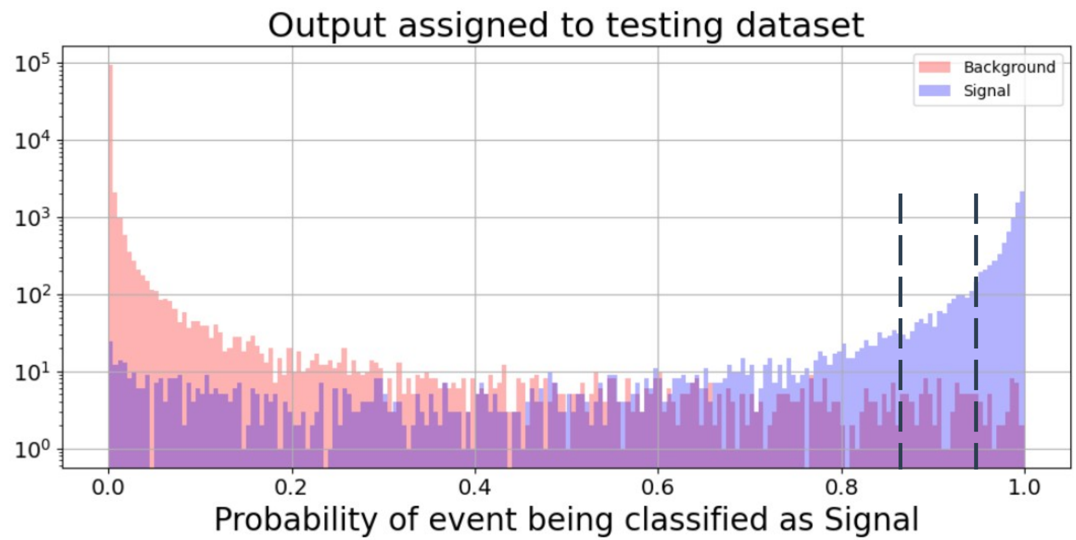
Data analysis: ML for S/B improvement

- **Use of Boosted Decision Tree, XGBoost:**

binary classifier → identify Signal ($^{3}_{\Lambda}H$) and exclude Background (anything else)

Training data:





- <u>**Uncorrelated to**</u> invariant mass & lifetime → **no bias**

- Physical observables: geometry of decay vertex & hit patterns & π- hit multiplicity detectors

Data analysis: ML for S/B improvement

- **Use of Boosted Decision Tree, XGBoost:**

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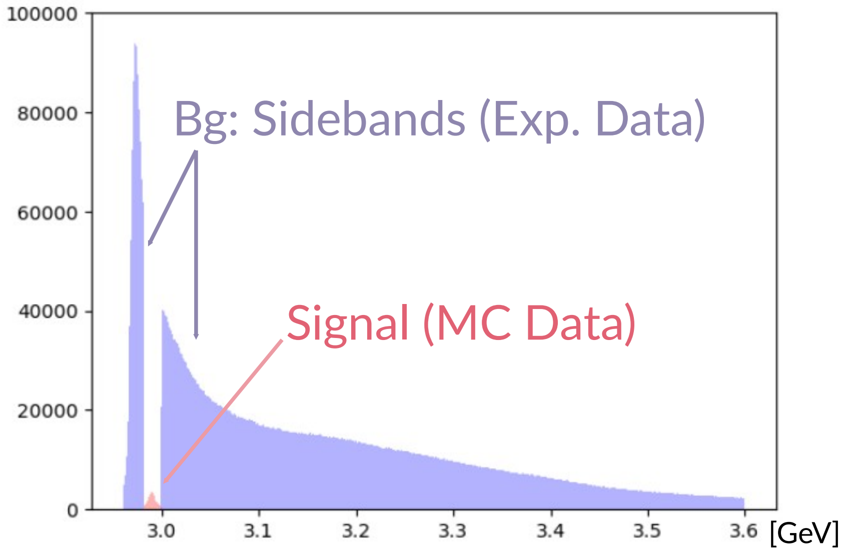
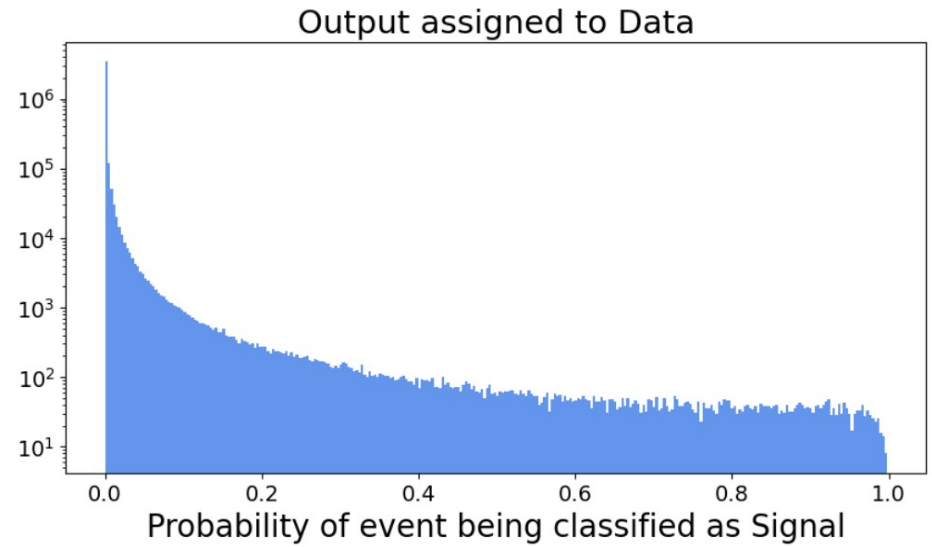


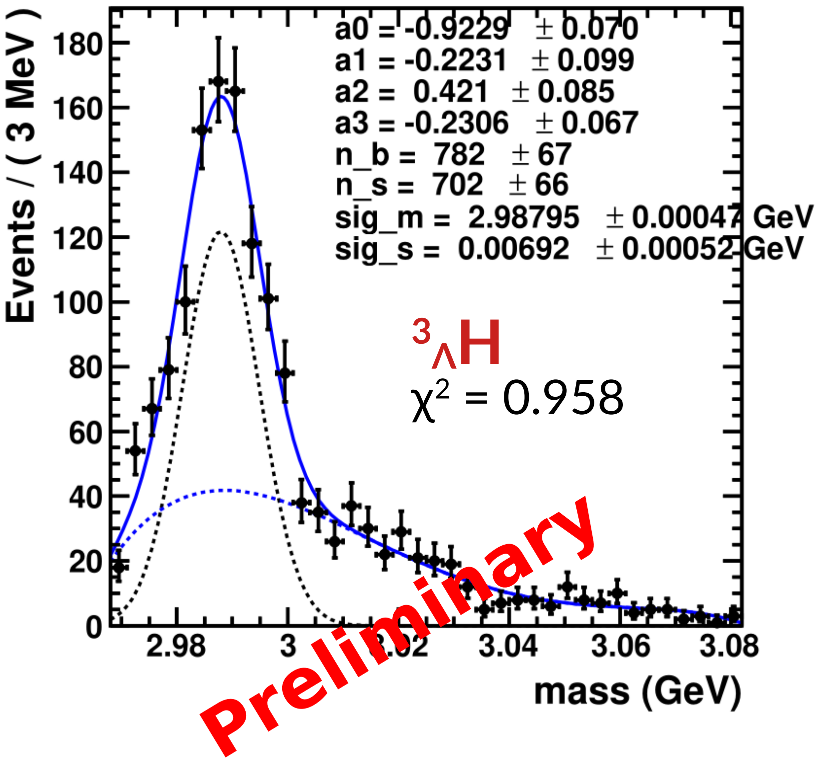


- **Uncorrelated to** invariant mass & lifetime → **no bias**

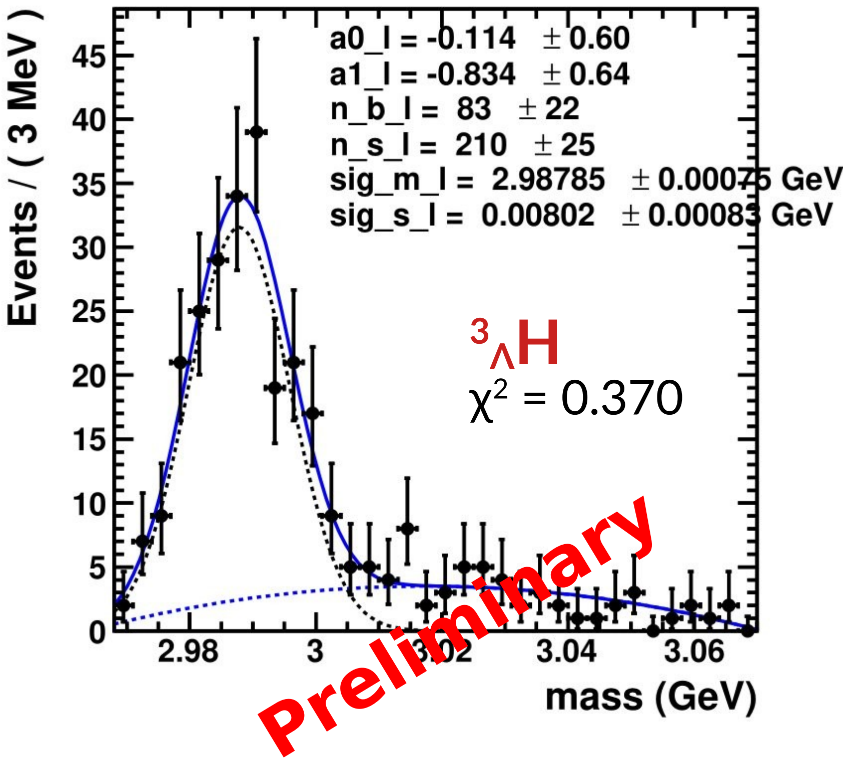
- Physical observables: geometry of decay vertex & hit patterns & π- hit multiplicity detectors

Data analysis: ML for S/B improvement

- Trained Model for $^{3}_{\Lambda}H$ discrimination:



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

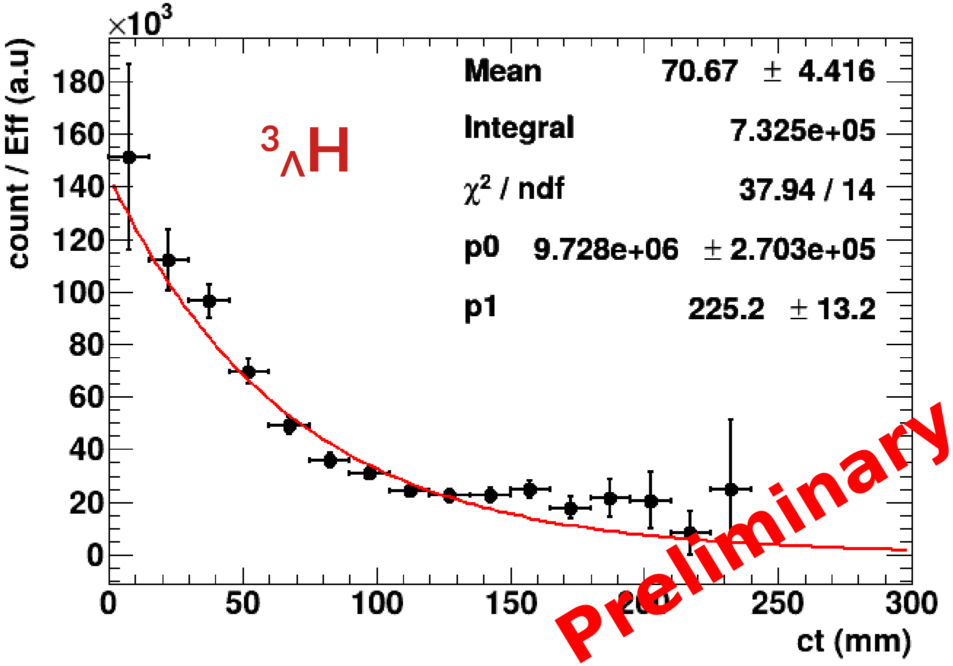


$^{3}_{\Lambda}H \rightarrow$ Threshold > 0.97
S = 210 ± 25

FAIR Phase 0 Research Program

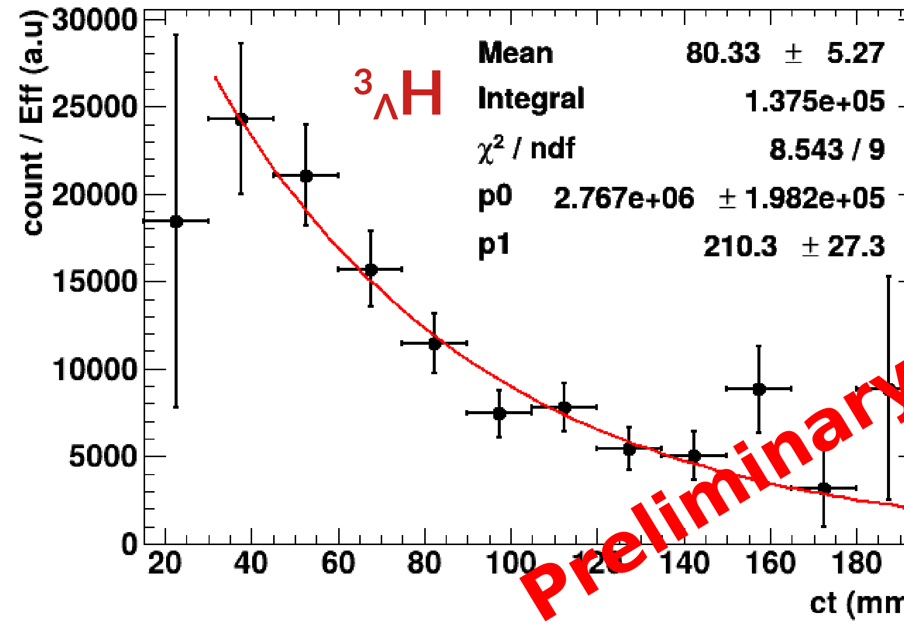
Data analysis: ML for S/B improvement

- Trained Model for $^{3}_{\Lambda}H$ discrimination:



$^{3}_{\Lambda}H \rightarrow$ Threshold > 0.85

τ = 225 ± 13 ps



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

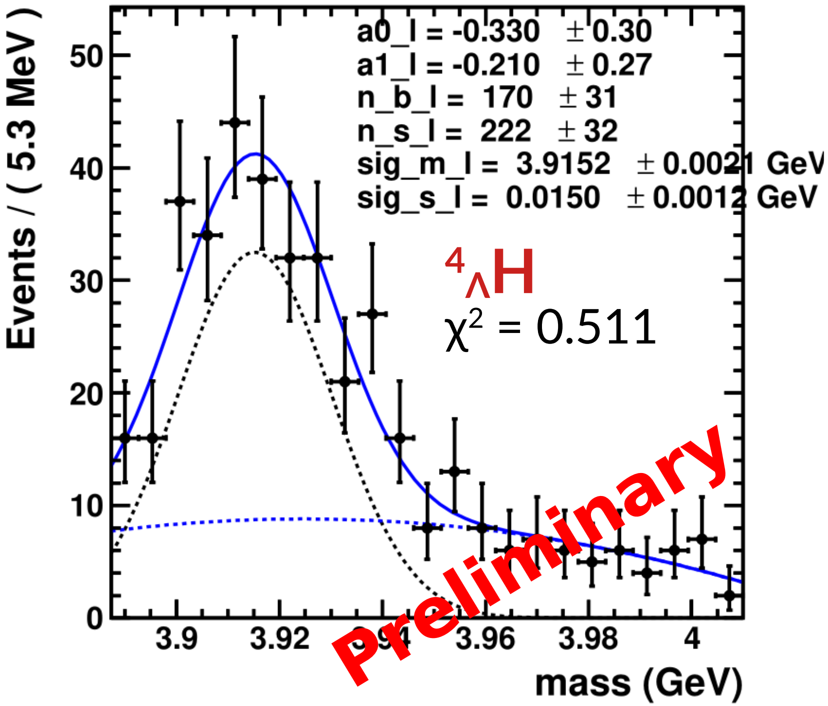
τ = 210 ± 27 ps

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

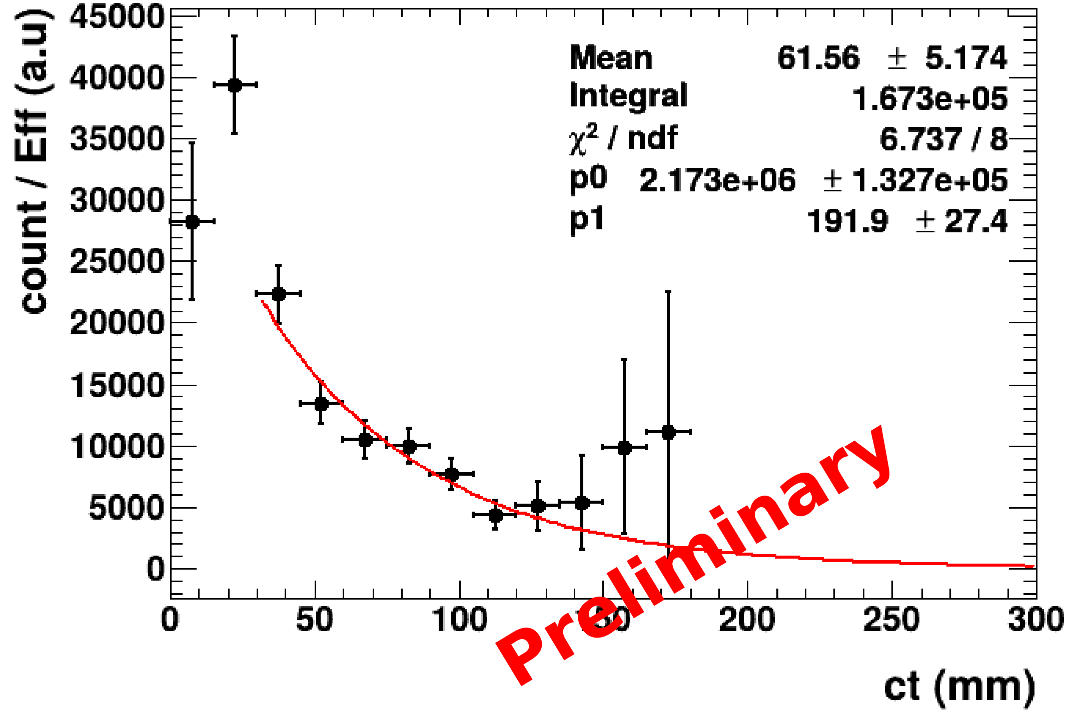
Phase 0
Research Program

Data analysis: ML for S/B improvement

- **Trained Model for $^{4}_{\Lambda}H$ discrimination:**



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

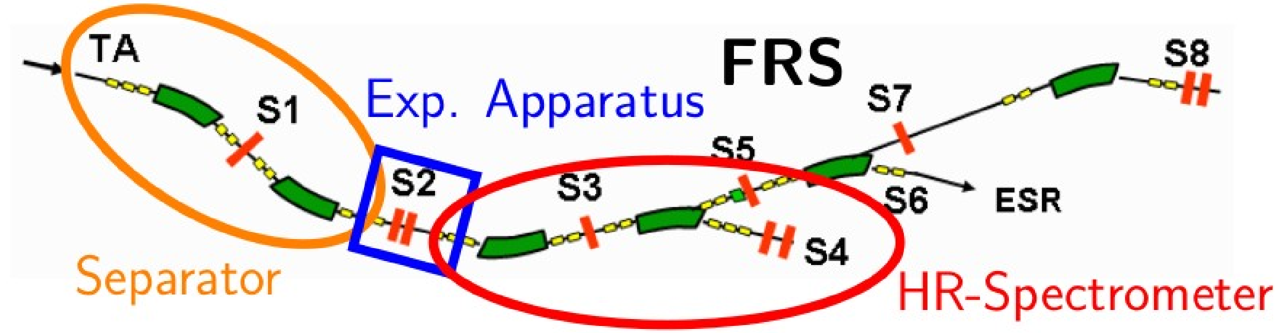


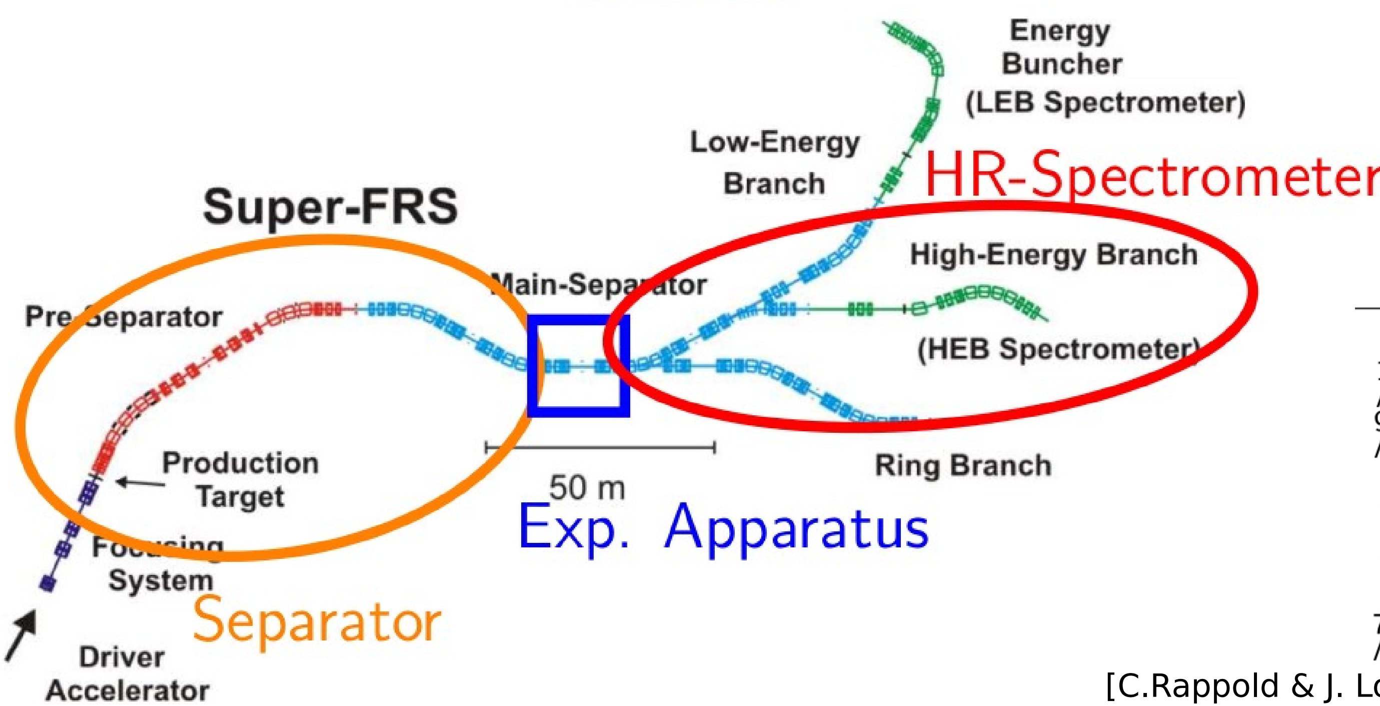
World avg:
208^{+10}_{-12} ps

$^{4}_{\Lambda}H \rightarrow$ Threshold > 0.95
τ = 192 ± 27 ps

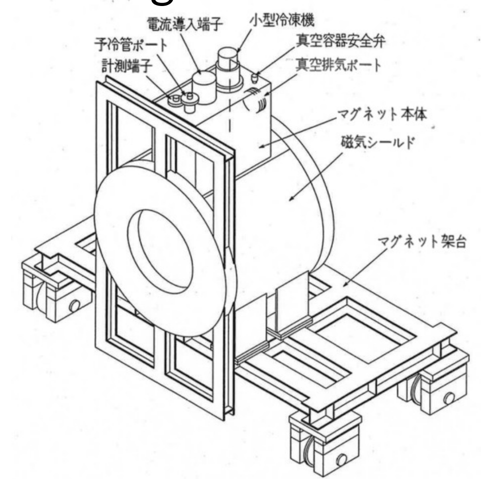
FAIR Phase 0 Research Program

Future of WASA-FRS HypHI @ GSI-FAIR





New magnet from RCNP



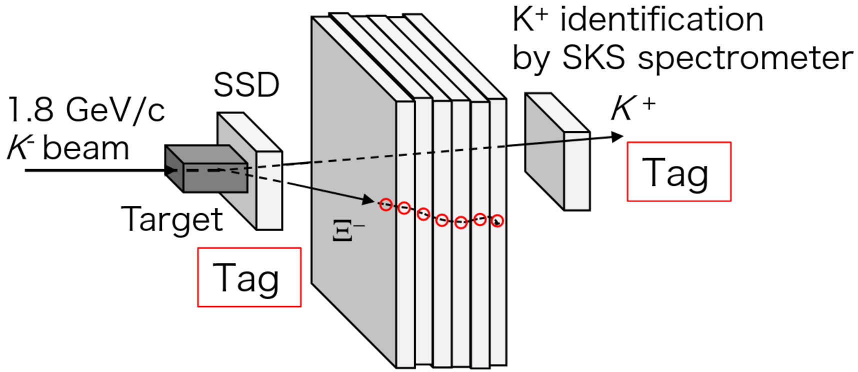
Reaction		Target (cm)	2^{nd} beam
${}^{9}_{\Lambda}\mathrm{C}$	${}^{14}\mathrm{N}+{}^{9}\mathrm{Be}$	5.5	${}^{12}\mathrm{N}$
${}^{11}_{\Lambda}\mathrm{B}$	${}^{20}\mathrm{Ne}+{}^{9}\mathrm{Be}$	2	${}^{17}\mathrm{F}$
${}^{9}_{\Lambda}\mathrm{Be}$	stable beam		${}^{16}\mathrm{O}$
${}^{5}_{\Lambda}\mathrm{Li}$	${}^{12}\mathrm{C}+{}^{9}\mathrm{Be}$	6	${}^{10}\mathrm{C}$
${}^{6}_{\Lambda}\mathrm{Li}$	${}^{14}\mathrm{N}+{}^{9}\mathrm{Be}$	5.5	${}^{12}\mathrm{N}$
${}^{9}_{\Lambda}\mathrm{Li}$	${}^{16}\mathrm{O}+{}^{9}\mathrm{Be}$	5.5	${}^{14}\mathrm{O}$
${}^{7}_{\Lambda}\mathrm{He}$	${}^{20}\mathrm{Ne}+{}^{9}\mathrm{Be}$	2	${}^{17}\mathrm{F}$

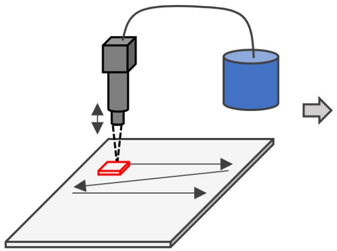
[C.Rappold & J. López-Fidalgo, PRC 94 (2016) 044616]
[S. Escrig & C.Rappold, Particles 8 (2025) 2, 54]

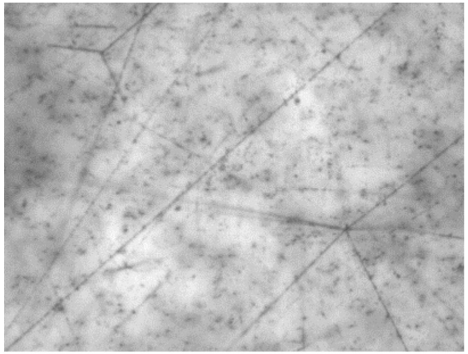
E07 experiment with machine learning

- **E07 experiment at JPARC:**

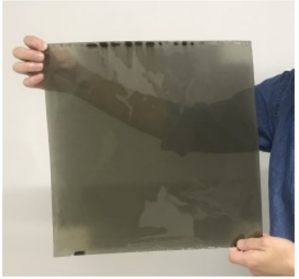
Emulsion-Counter hybrid method







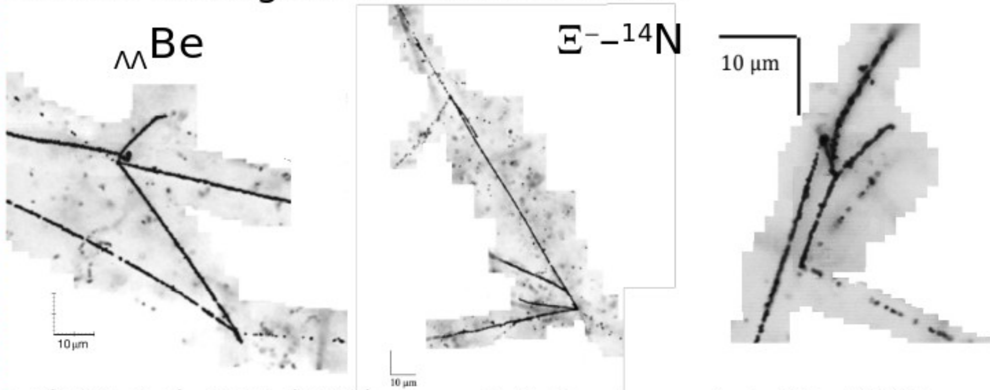
E07 nuclear emulsion



(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

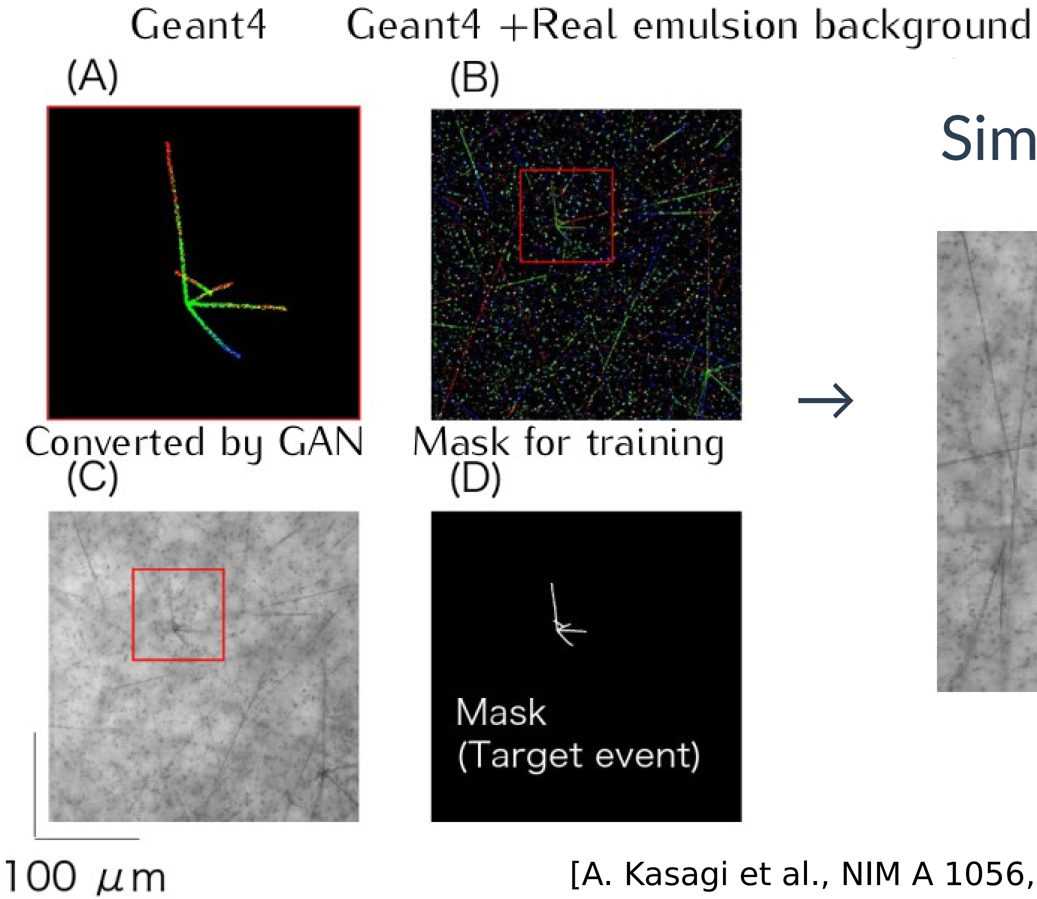


H. Ekawa et al., PTEP, (2019)
A.N.L. Nyaw et al., BSPIJ, (2020)

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

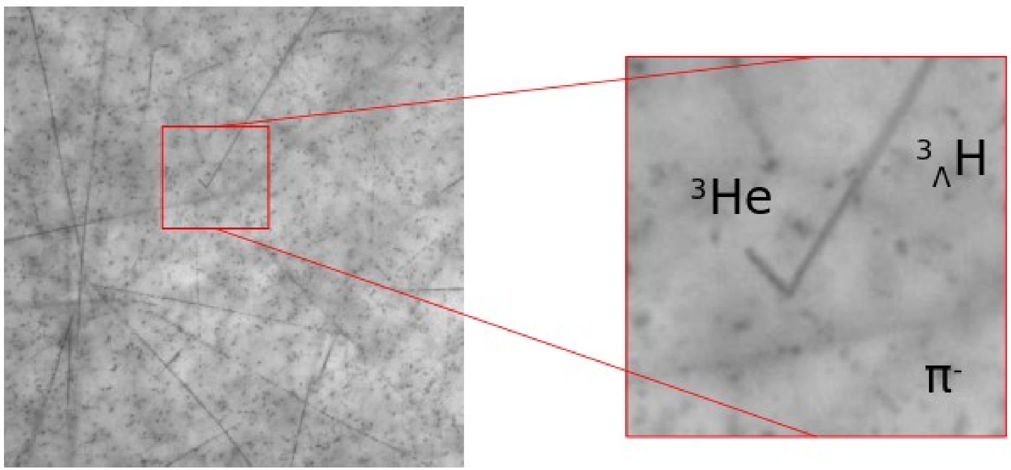
Hypernuclear Event Search with Machine Learning

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



→

Simulated image:

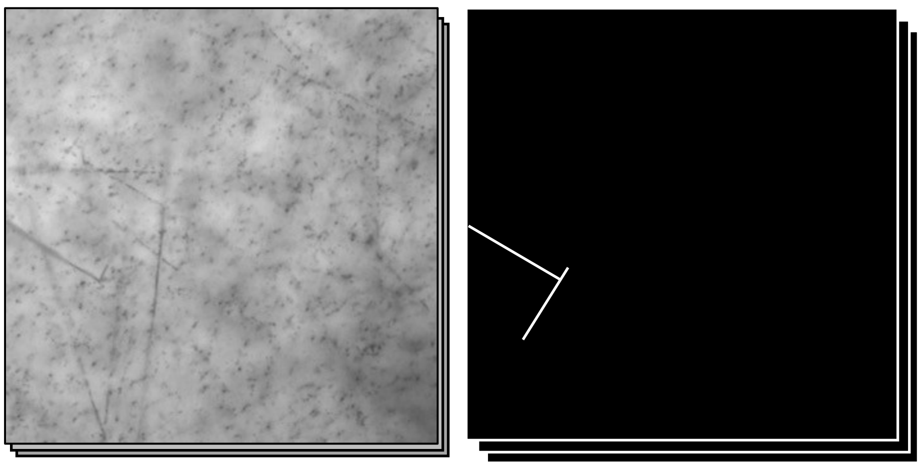


[A. Kasagi et al., NIM A 1056, 168663 (2023)]

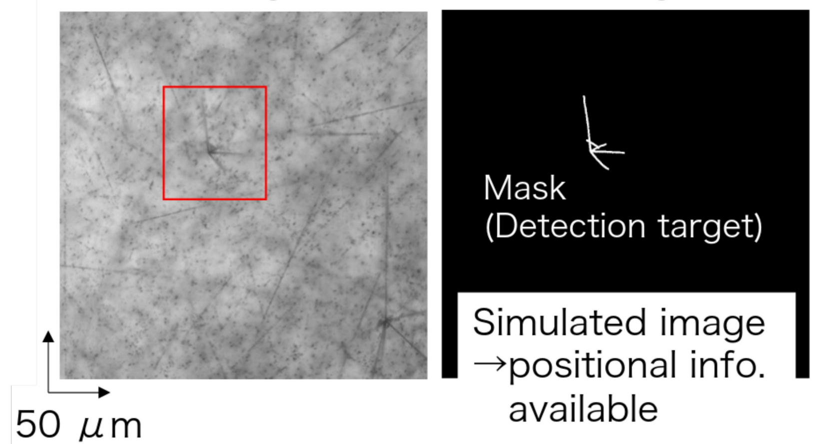
Hypernuclear Event Search with Machine Learning

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

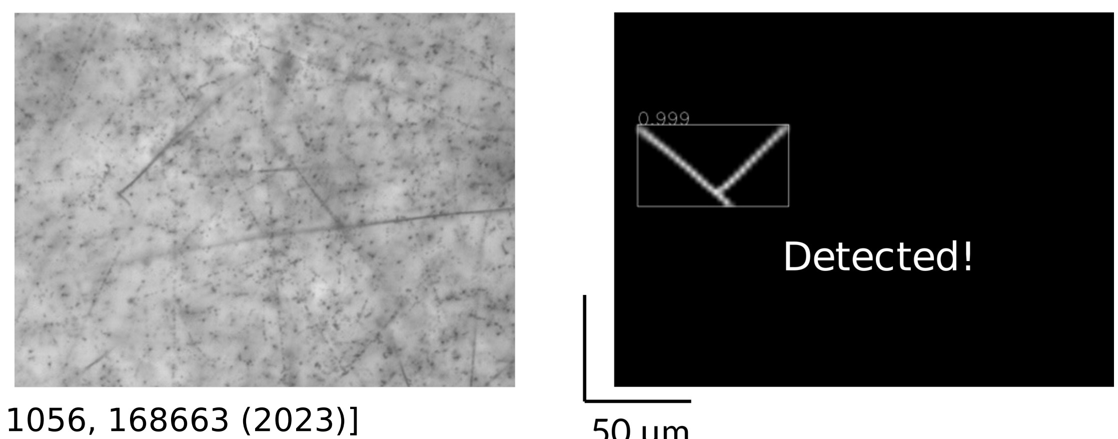
Simulation



Training data (Simulated image)



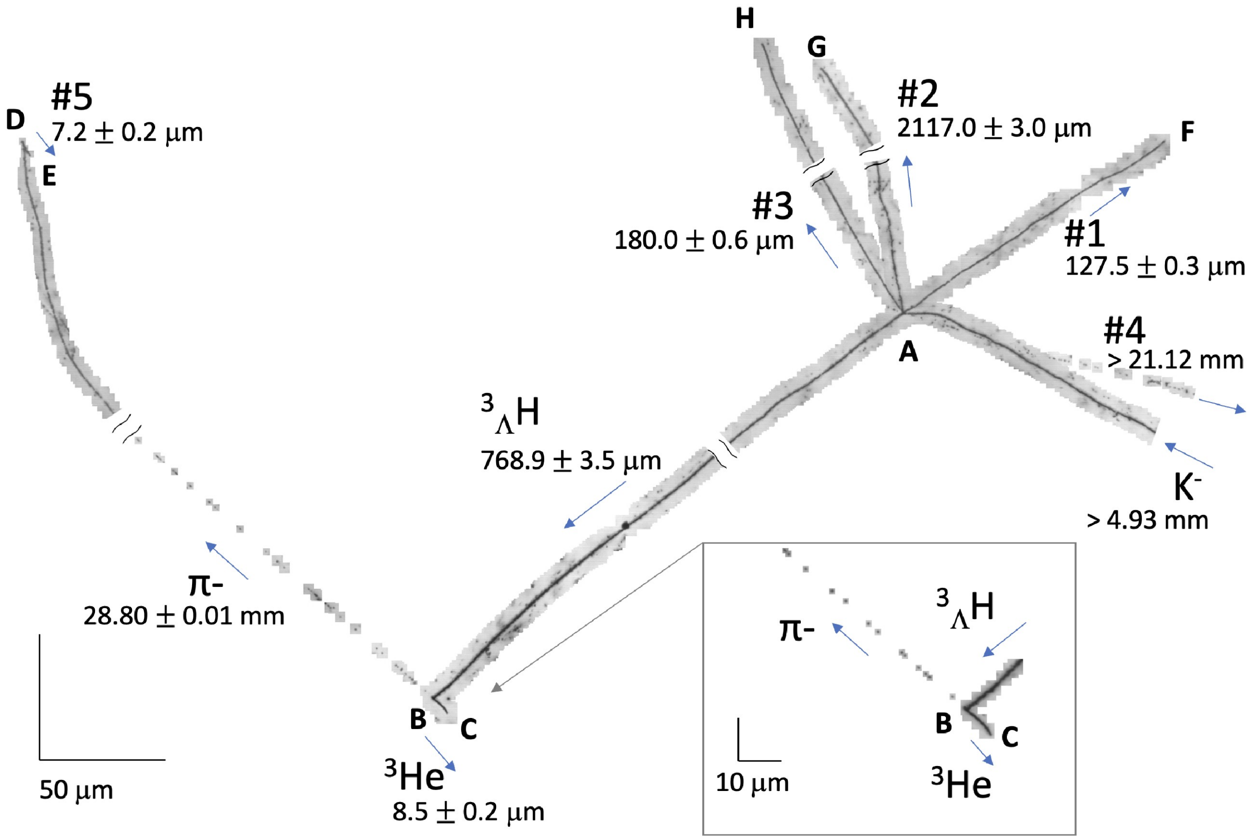
Mask R-CNN Model on Real Data



[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)]

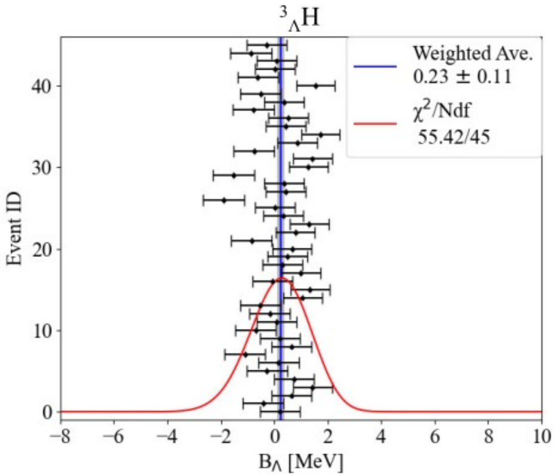
Event analysis from the ML topology search

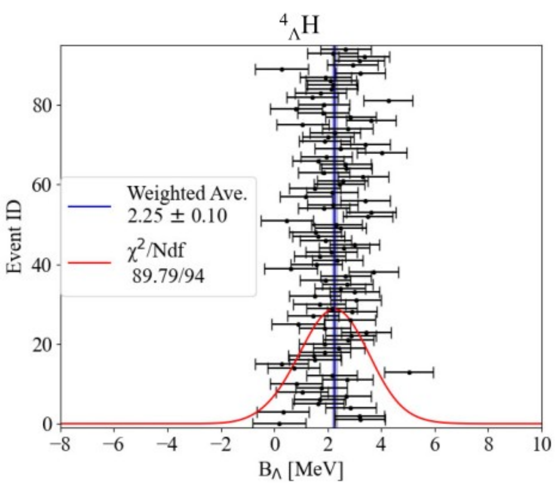
- **Statistical Results:**

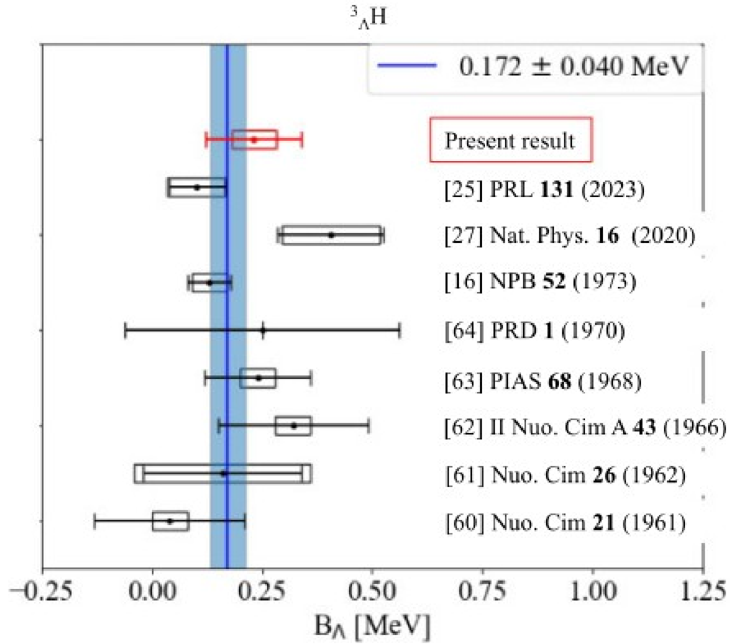
[A Kasagi et al., Prog. Theor. Exp. Phys. 8, 083D01 (2025)]

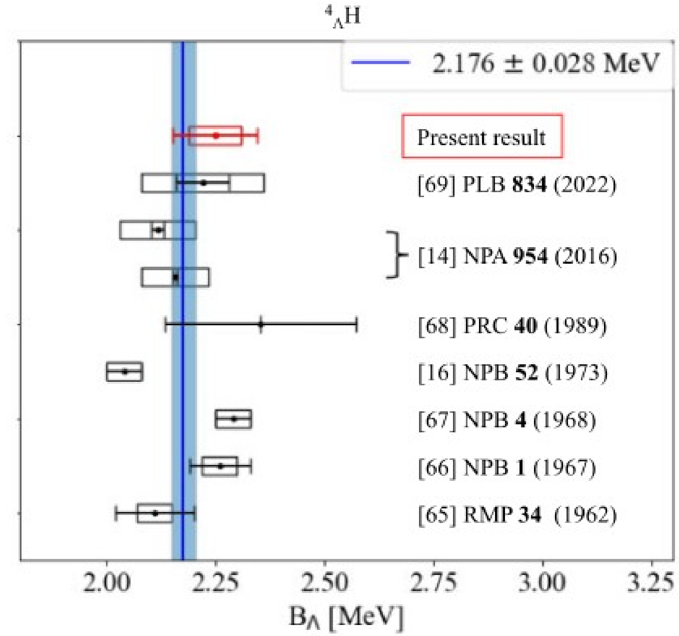
$$({}^{3}_{\Lambda}\mathrm{H})\ \ B_{\Lambda} = 0.23 \pm 0.11(\mathrm{Stat.}) \pm 0.05(\mathrm{Syst.})\ \mathrm{MeV},$$

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









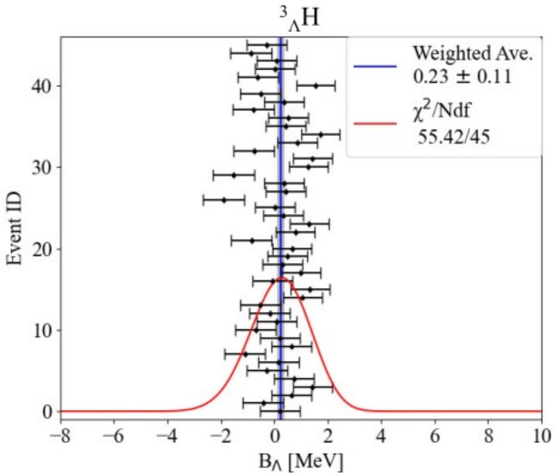
- New calibration method based on μ+ & ATIMA
- Systematic uncertainties: 50 – 60 keV
- & More data coming → new statistical analysis possible now !

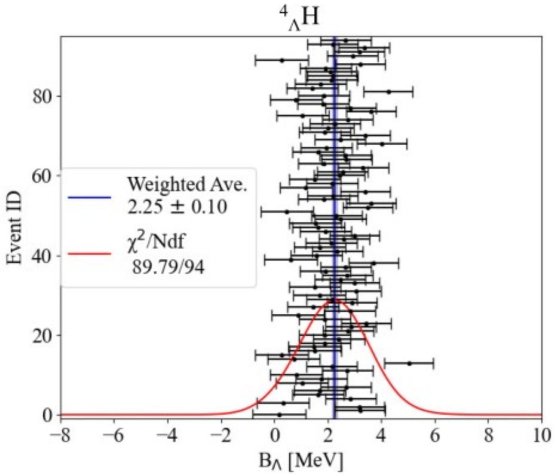
Event analysis from the ML topology search

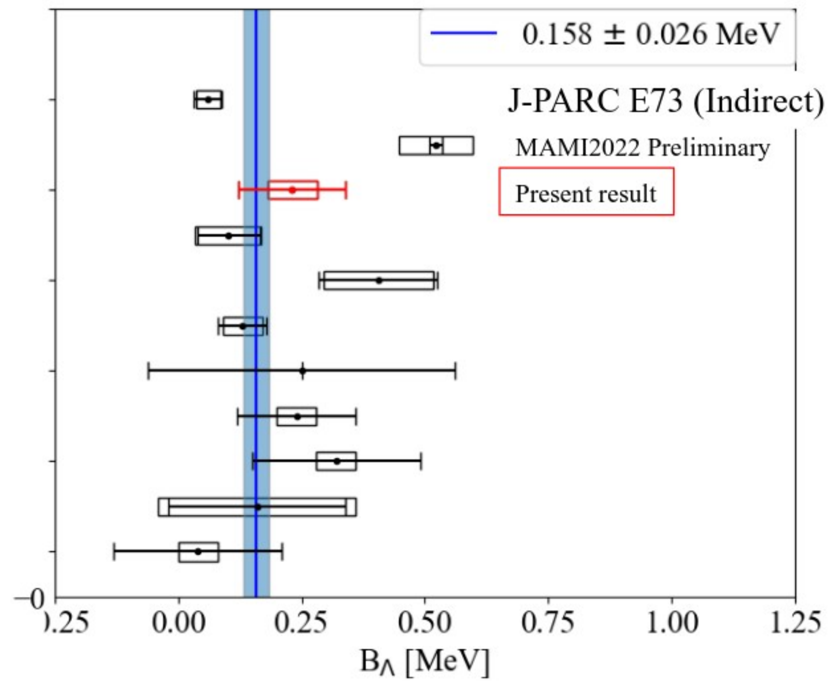
- **Statistical Results:**

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

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







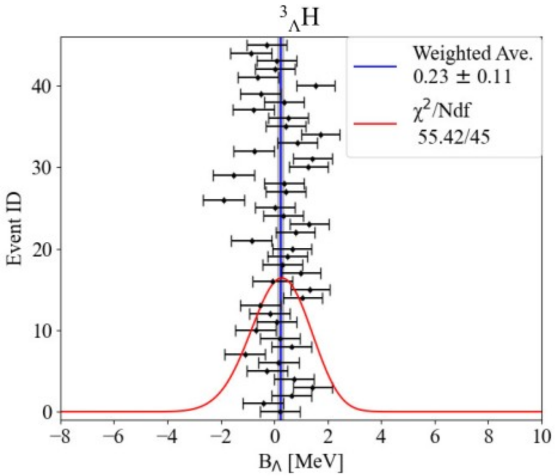
- New data for $^{3}_{\Lambda}$H from HYP2025:
  - MAMI(2022): > 500 keV → Deeper binding ?
- More Precise data needed: Emulsion analysis only 0.6% of data

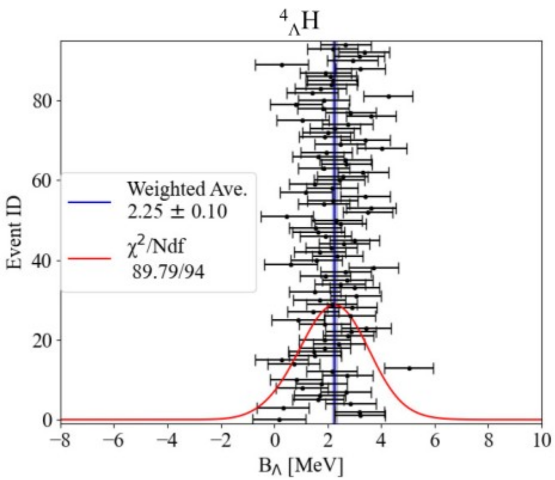
Event analysis from the ML topology search

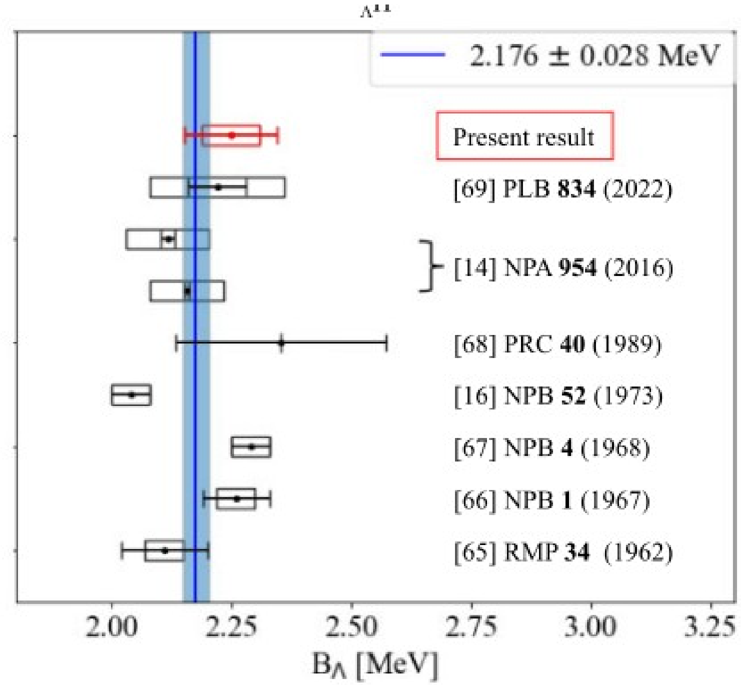
- **Statistical Results:**

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

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



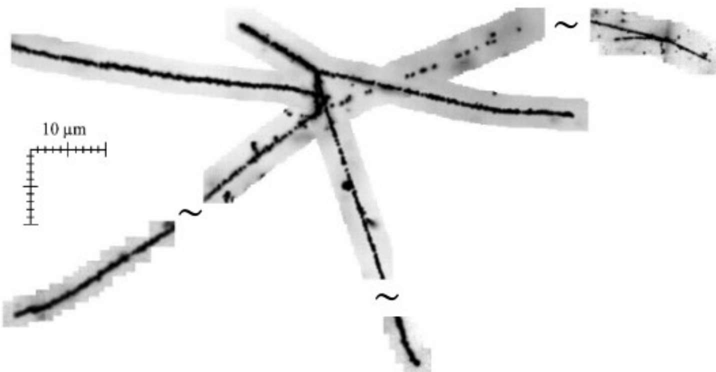


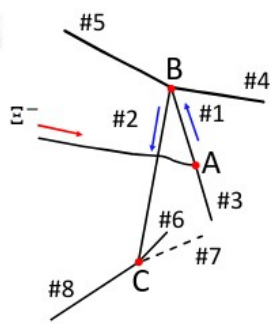


- Gap from Juric et.al, [16] ?
  - World Ave. with only 2-body decay → 2.23 ± 0.03 MeV
- $\Delta B_{\Lambda}(A = 4)$: 350 keV → 160 keV
  - So what about CSB in ${}^{4}_{\Lambda}\mathrm{H} \leftrightarrow {}^{4}_{\Lambda}\mathrm{He}$?

Event analysis from the ML topology search

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





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

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

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

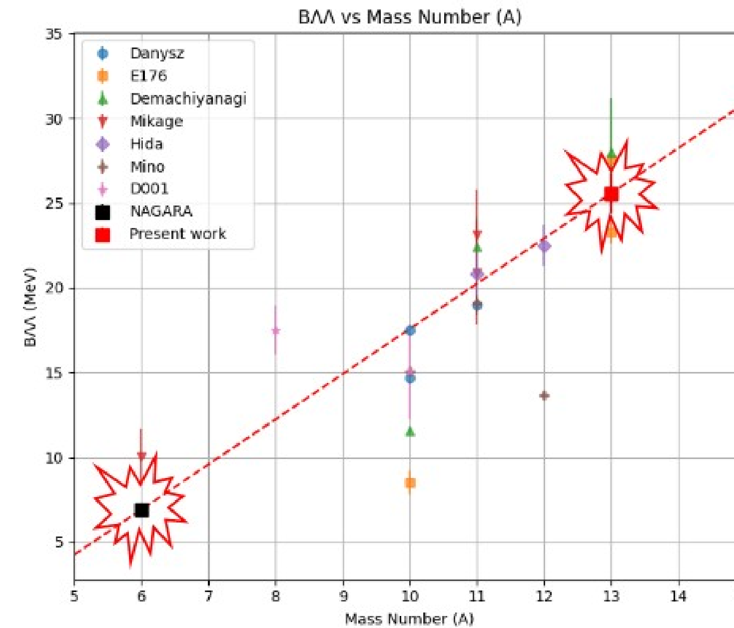
- **Binding energy of 2Λ:**

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

- **ΛΛ interaction energy:**

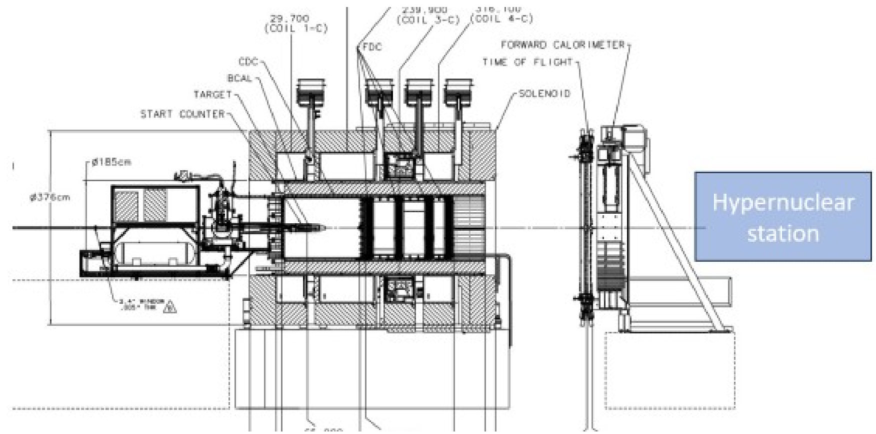
$$\Delta B_{\Lambda\Lambda} = 2.83 \pm 1.18(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\mathrm{MeV}$$

[Y. He et al., _Accepted in Nat. Comm._ arXiv:2505.05802]



New experiment @ KLF - JLab

- **New Experiment with K_L beam approved at JLab:**
  - Hypernuclear station with emulsions behind GlueX setup



- **No beam tracks in the emulsion**
  - No background from beam track → much cleaner images
- **High quality data with 3 x 10^3 K_L/s over 2 years (400 days)**
  - 2.3 times more than J-PARC E07 : 2.3k double-strangeness hypernuclei

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 & ${}^{9}_{\Lambda}B$
    - New Experiment in planing (> 2028) for proton- and neutron-rich hypernuclei
  - **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
    - New Experiment at KLF@JLab (from 2027): Emulsion station with K_L