Status of the lifetime and binding energy measurements for light hypernuclei in the WASA-FRS and E07 emulsion experiments

23rd International Conference on Few-Body Problems in Physics

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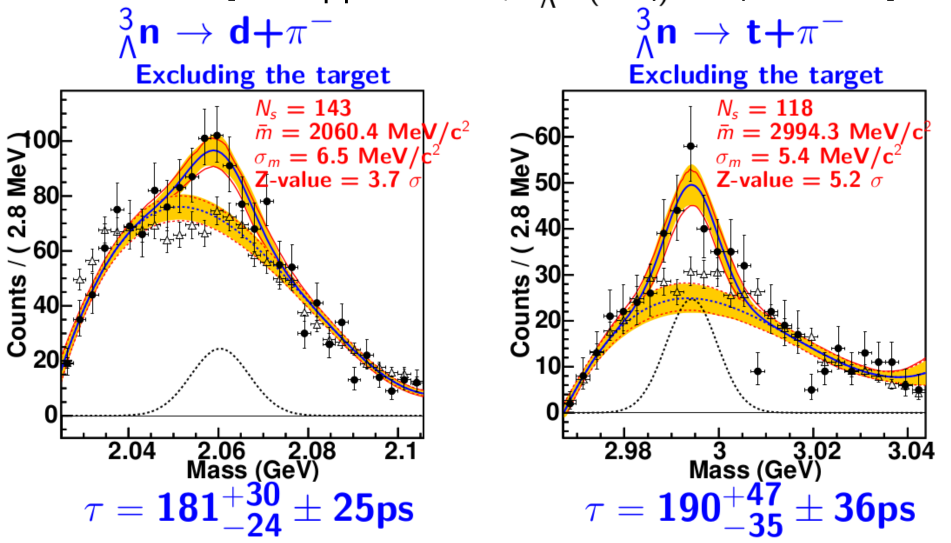
For ML-Emulsion collaboration & WASA-FRS / Super-FRS Experiment collaboration

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
    - All theoretical calculations show negative results
      - 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 [PLB 128 (2019) 134905]
    - STAR : 155^{+25}_{-22} ps → 142^{+24}_{-21} ps → 221 +- 15 ps [PRL 128 (2022) 202301]
    - HypHI : 183^{+42}_{-32} ps

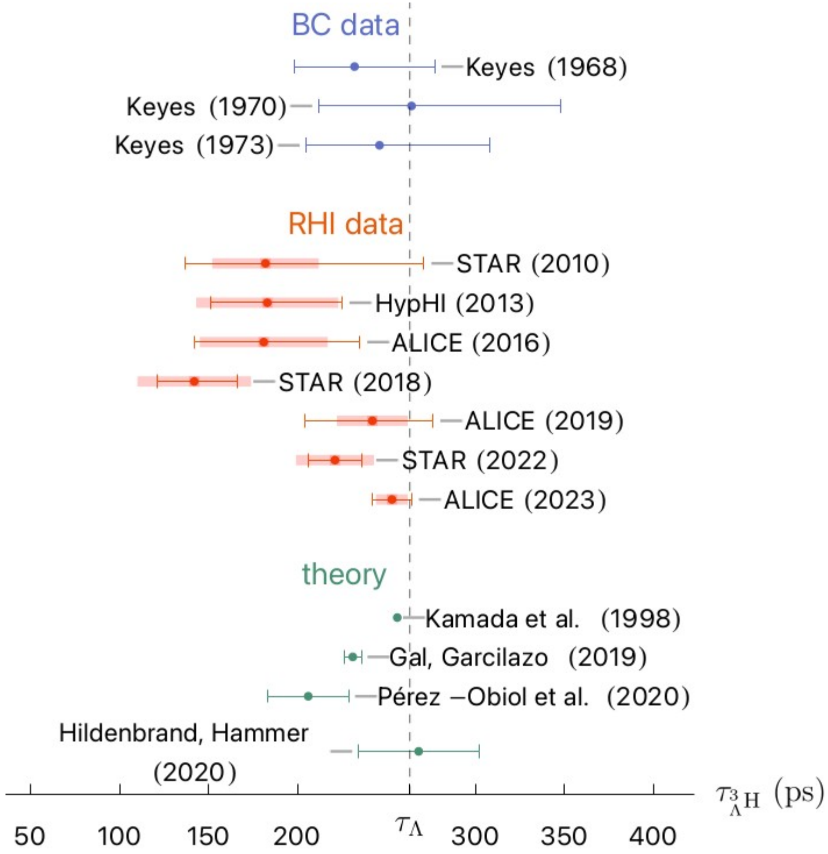
    We will provide one very precise data point with our new WASA-FRS experiment

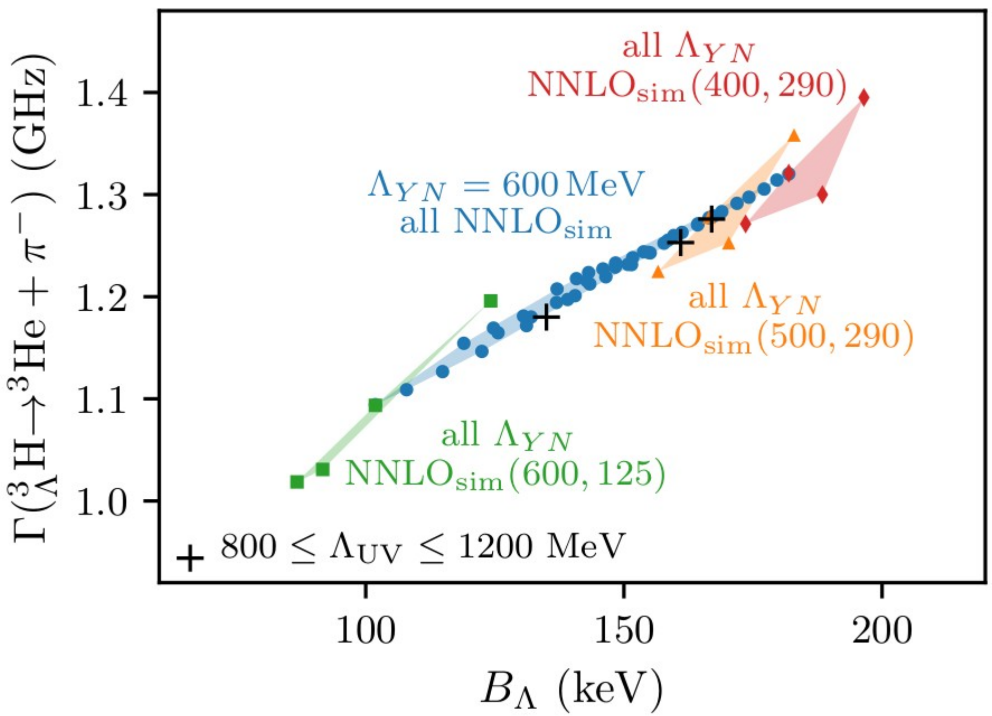
  - Hot topics in nuclear experiments:
    - STAR, ALICE, J-PARC, ELPH, HADES, HYDRA and WASA-FRS

  - <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 $^3_\Lambda H$ and $^3_{\bar\Lambda}\overline{H}$ is calculated using the mass measurement shown in equation (1). We obtain

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

  - Previously accepted value: $B_\Lambda = 0.13 \pm 0.05$ MeV
  - And still : ALICE measured a Λ binding energy of :
    - $B_\Lambda = 0.072 \pm 0.063 \pm 0.36$ MeV

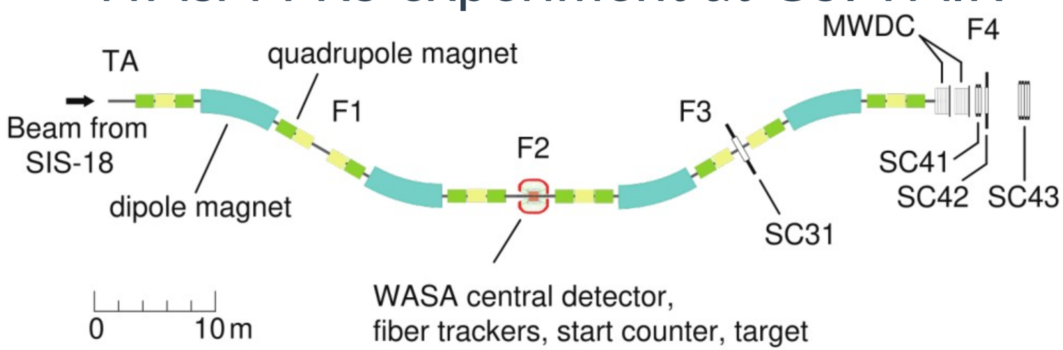
[arXiv:2209.07360]

Deep learning in study of those puzzles

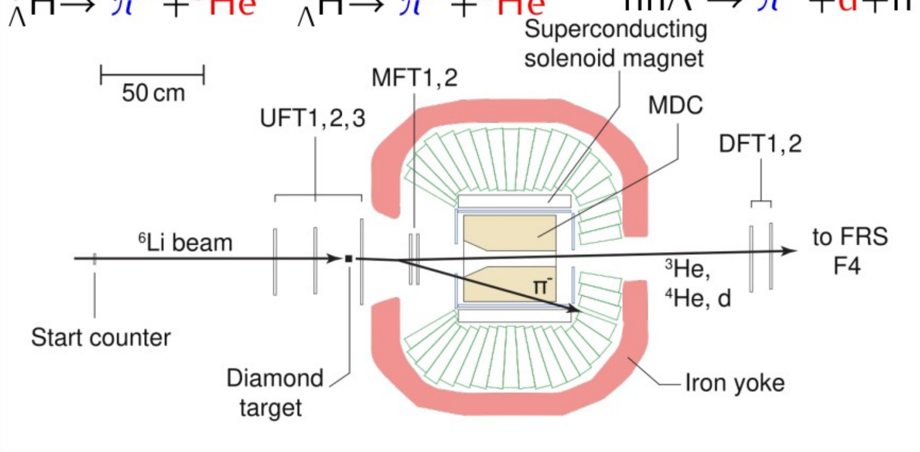
- **Our contributions to solve : 2 experiments to measure**

→ Lifetime & radius: **→ Binding energy:**

WASA-FRS experiment at GSI-FAIR

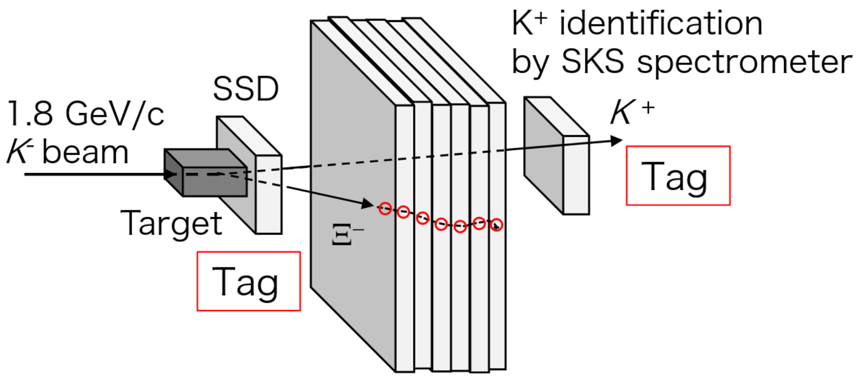


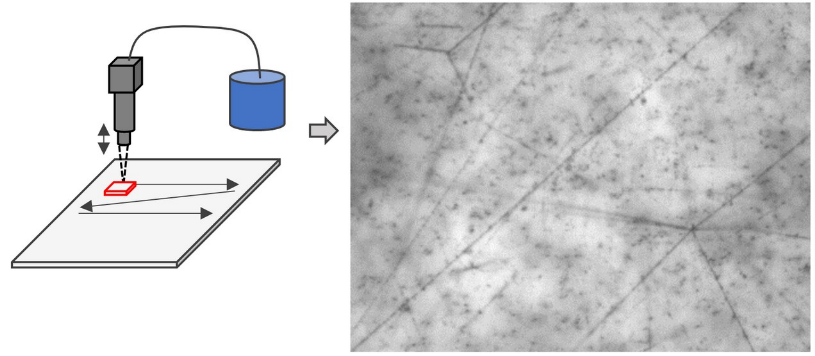
${}^3_\Lambda H \to \pi^- + {}^3He$ ${}^4_\Lambda H \to \pi^- + {}^4He$ $nn\Lambda \to \pi^- + d + n$



E07 experiment at JPARC

Emulsion-Counter hybrid method

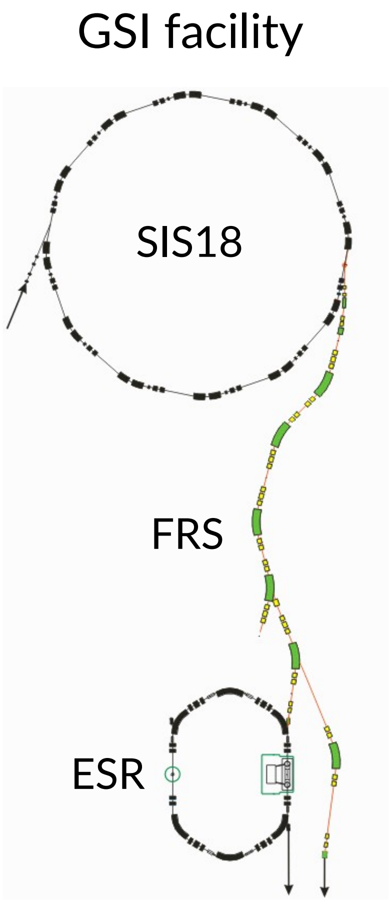


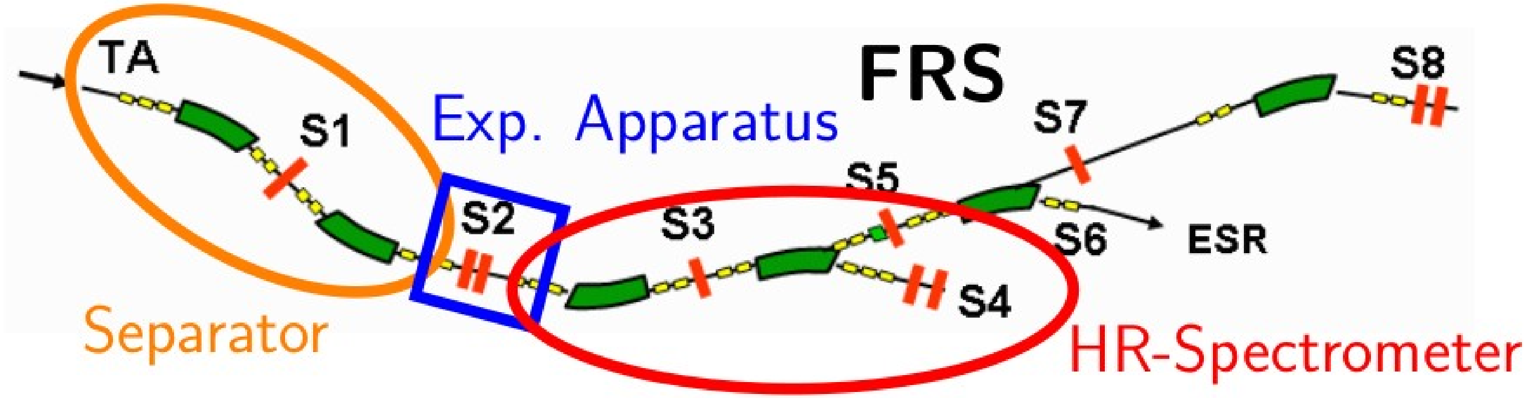


WASA-FRS experiment

- **Future of HypHI project : Exotic hypernuclei / strangeness cluster**
  - Use of heavy ion and RI beam to study hypernuclei at FRS & SuperFRS
    - Hypernuclei toward the proton and neutron drip lines with Exotic beam
    - $\Lambda - \Sigma$ coupling in the nuclear matter
    - Lifetime of exotic hypernuclei
    - Chance to repeat the observation of nnΛ
  - Why @ FRS / SuperFRS ?
    - High momentum resolution for forward fragments :
      - 10^{-4} δp / p optimal
    - Exotic hypernuclei ; Need RI beam
      - With high energy ~ 2 *AGeV*
      - With high intensity
    - Can optimize each data taking for one decay / species

WASA-FRS Experiment : Concept & Layout





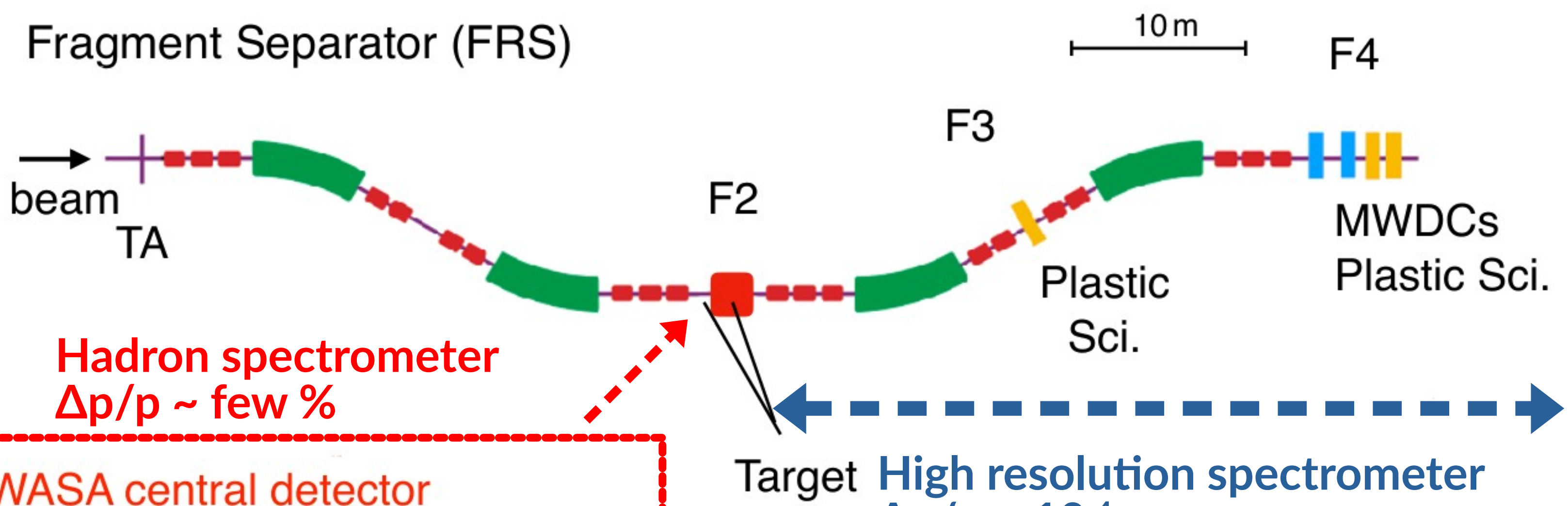
- **We had the opportunity to use WASA central detectors :**

  → Moved to GSI in 2019

  → Placed in S2 in 2021

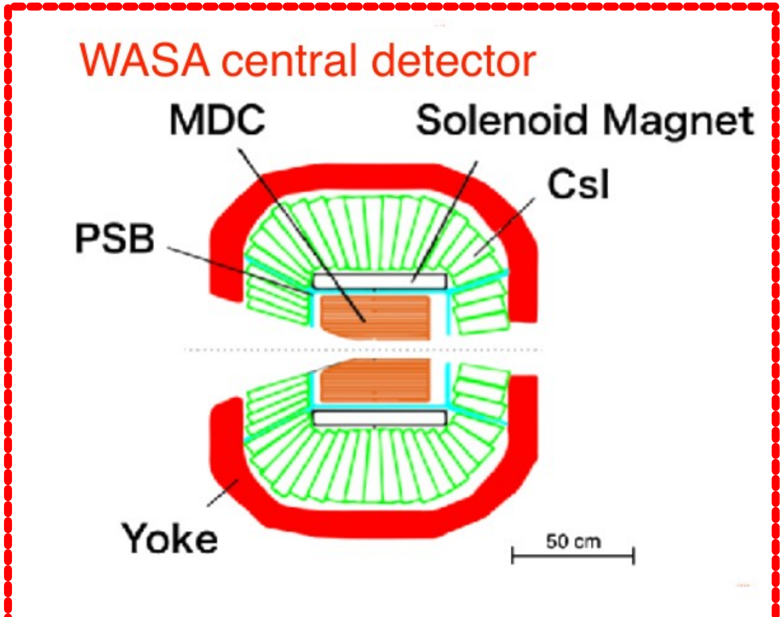
- Since 2019, preparation work of the WASA setup with new detectors & new readouts & cryogenics system

WASA-FRS Experimental campaign: Jan. – March 2022



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

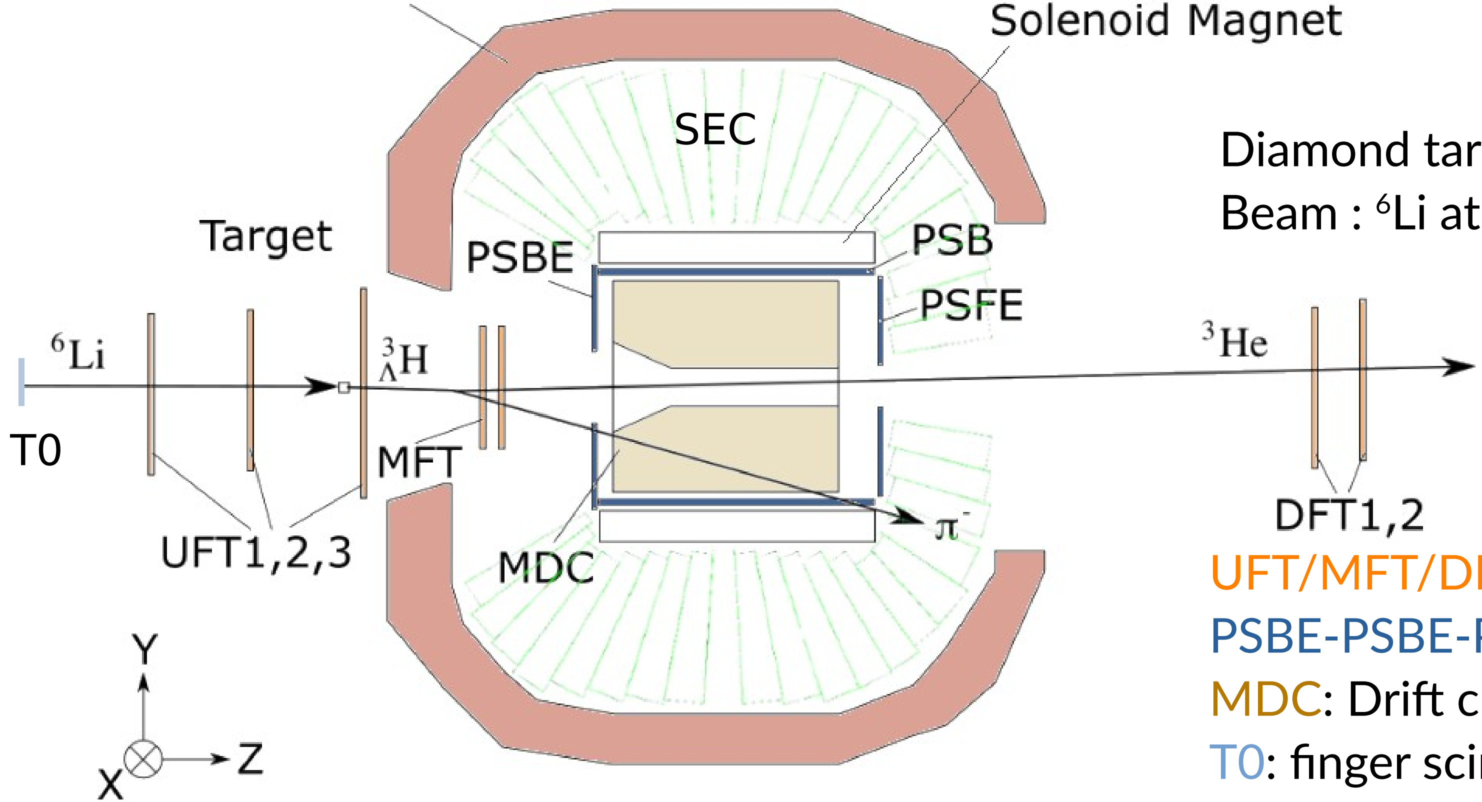
Super-FRS EC

Experimental apparatus: WASA-FRS HypHI

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

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

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

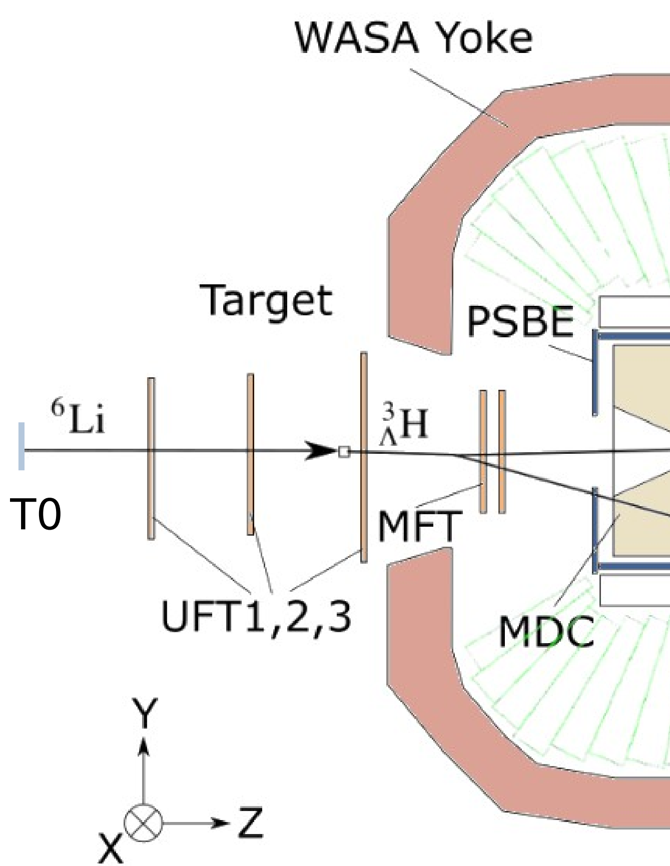
T0: finger scintillators

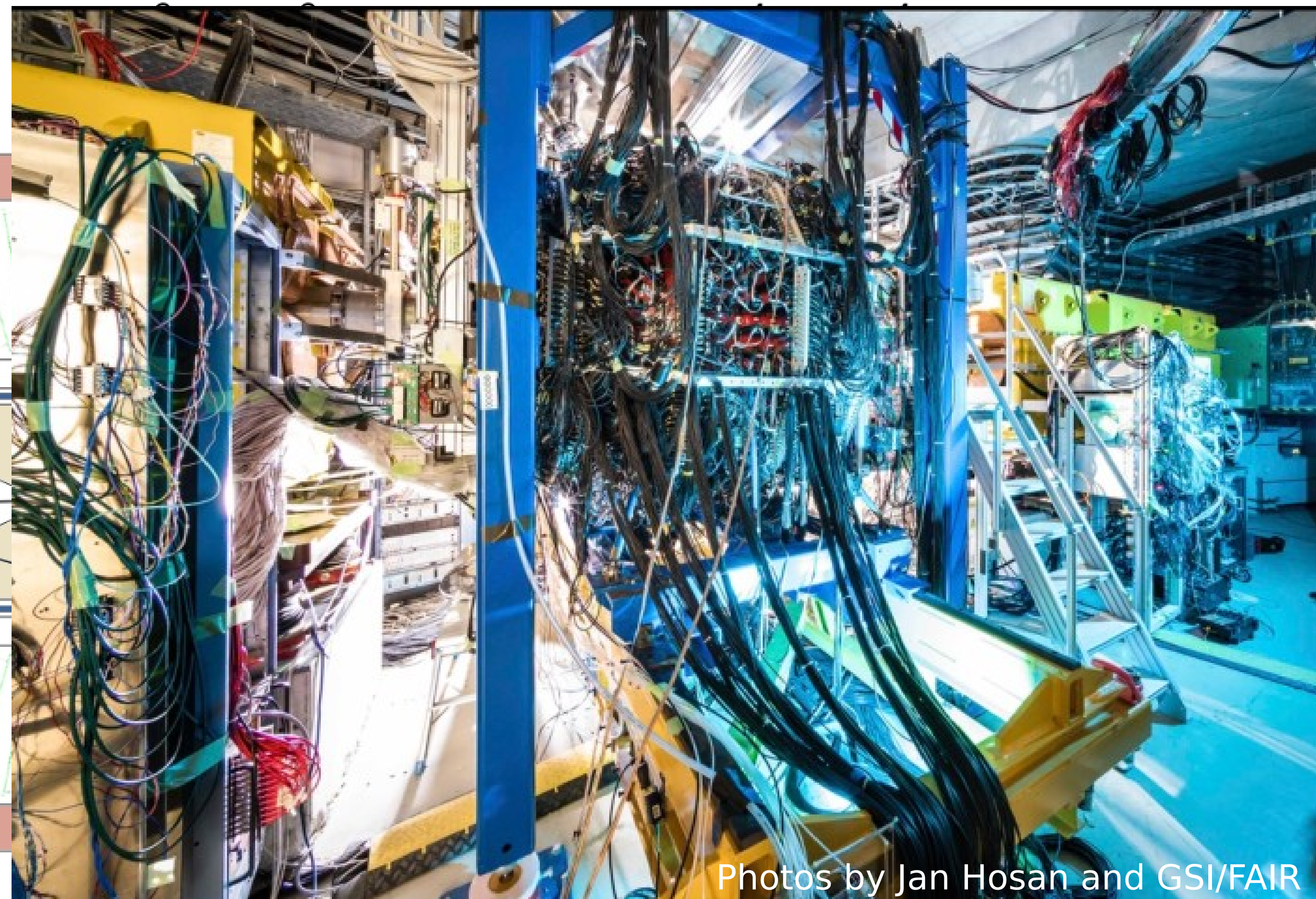
SEC: CsI crystal calorimeter

Experimental apparatus: WASA-FRS HypHI

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

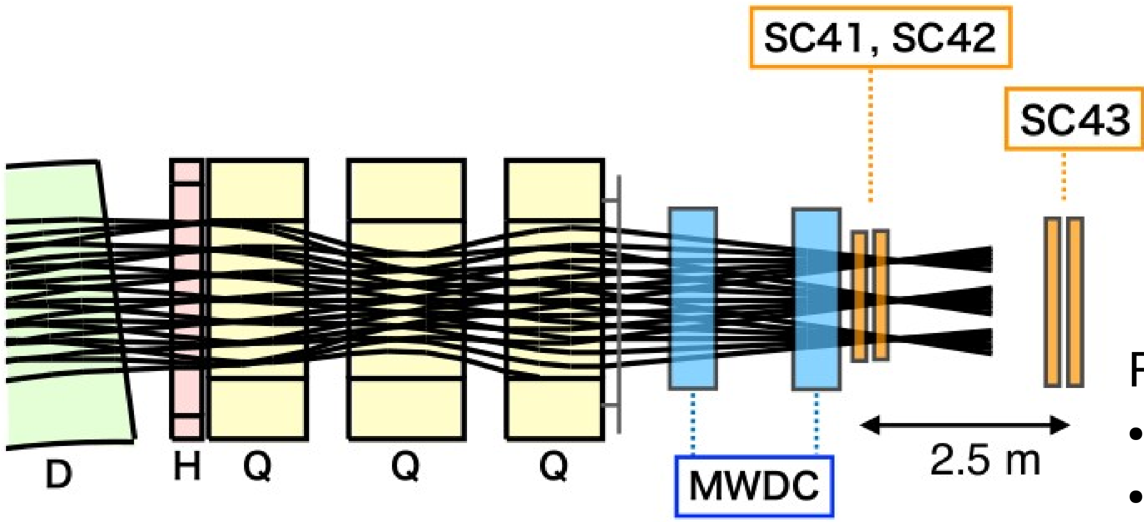
$${}^{3}_{\Lambda}\mathrm{n} \rightarrow \mathrm{d}+\pi^{-}+(\mathrm{n})$$





Experimental apparatus: WASA-FRS HypHI

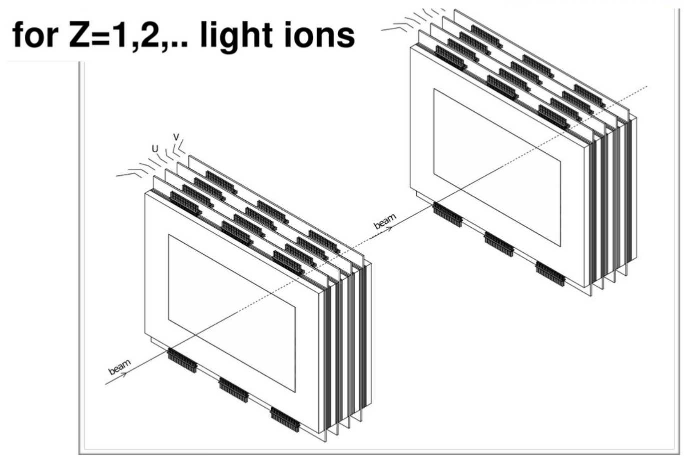
- At the final focal plane of FRS:

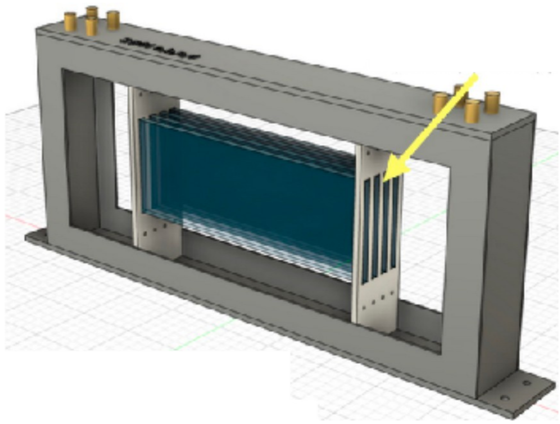


MWDC: Multi-Wire Drift Chamber

SC: stacked scintillator

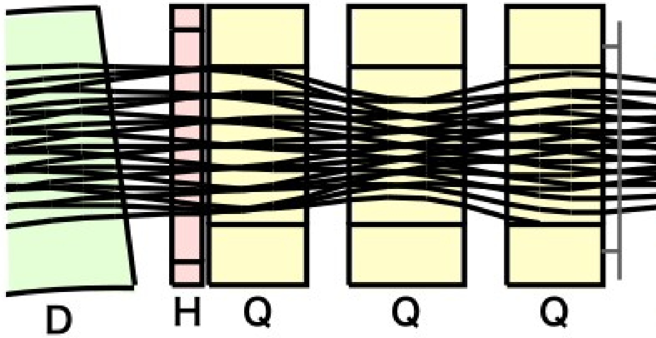
For Z=1 and Z=2 ion measurements:
- Tracking of focal plan → Bρ
- TOF

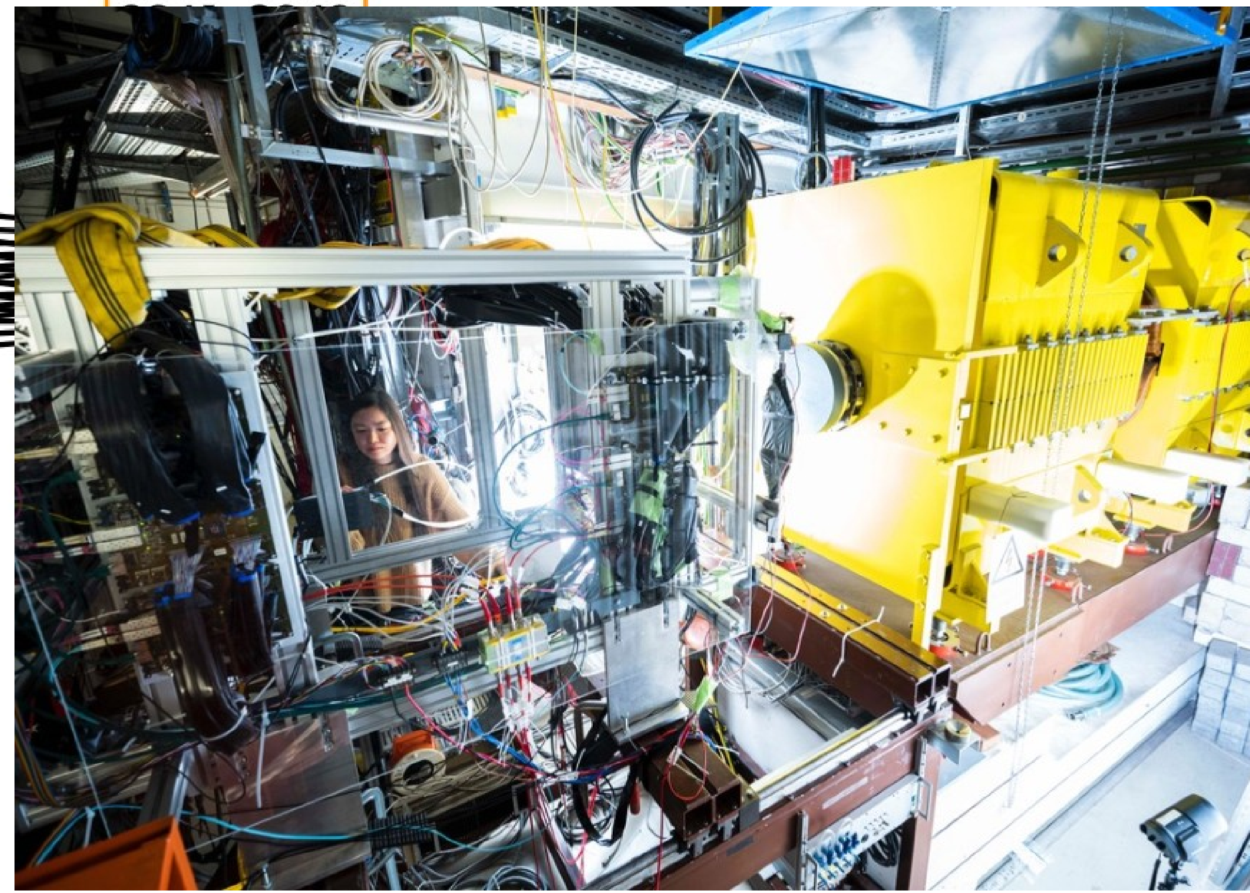




Experimental apparatus: WASA-FRS HypHI

- At the final focal plane of FRS:



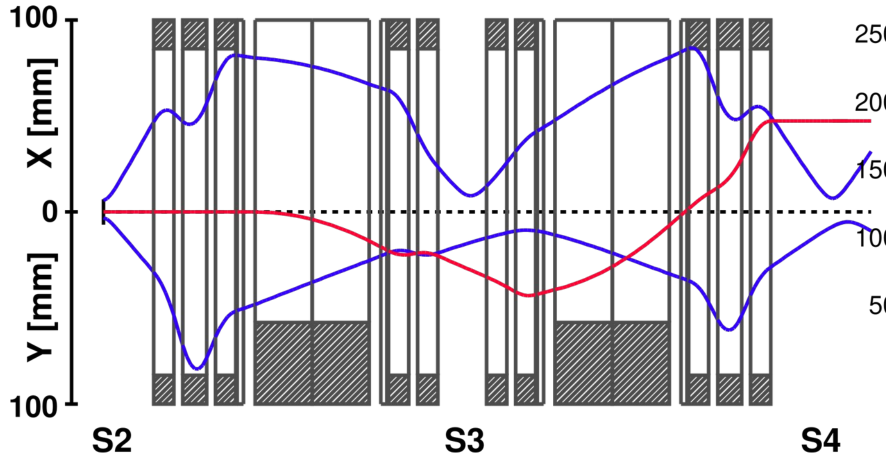


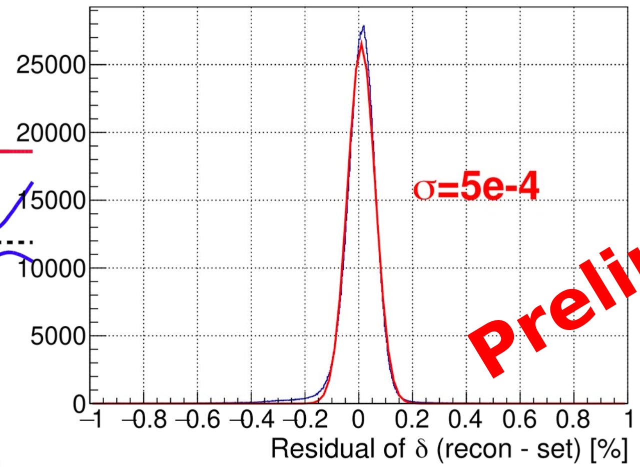
Photos by Jan Hosan and GSI/FAIR

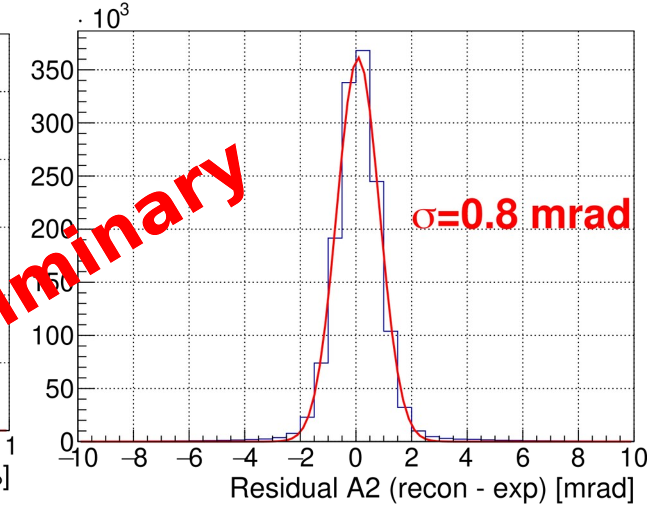
Preliminary data analysis

- **Analysis of high resolution spectrometer for fragments:**
  - Momentum analysis : High acceptance & high resolution

    → Needs ion-optics calibration: Several datasets with fixed parameters







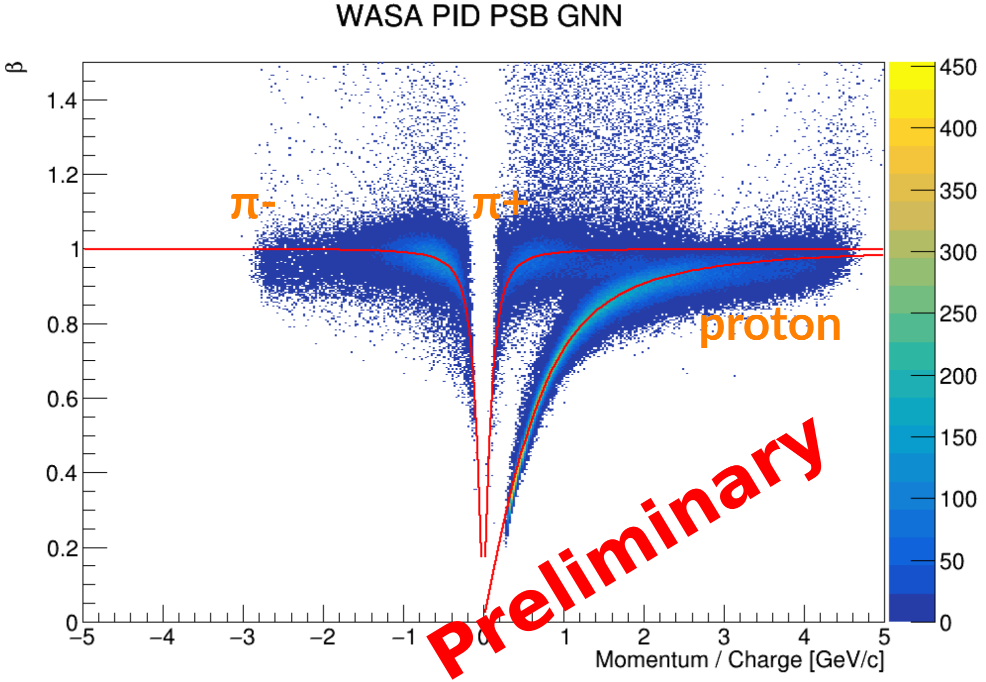
E. Liu's PhD thesis

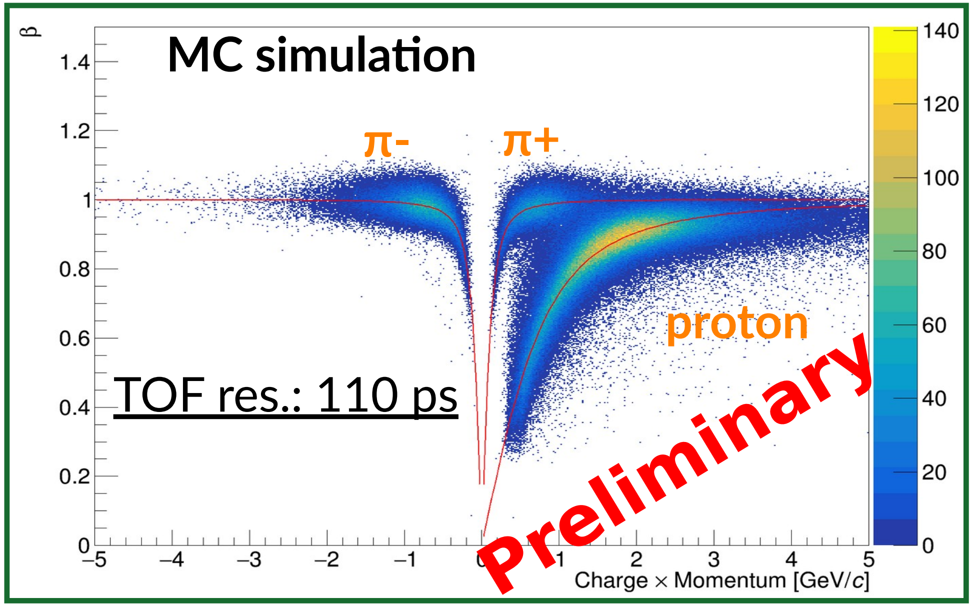
After correction and ion-optics up to second order :

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

Preliminary data analysis

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



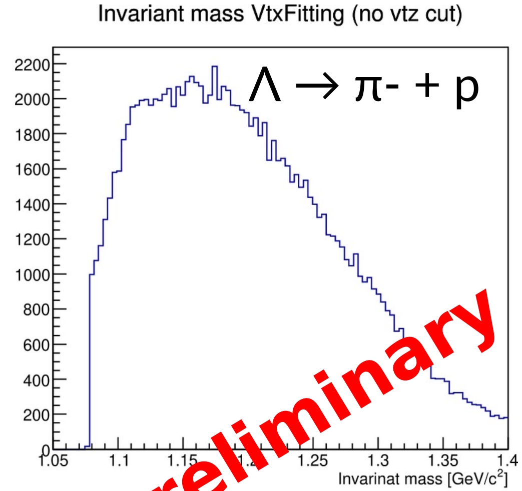


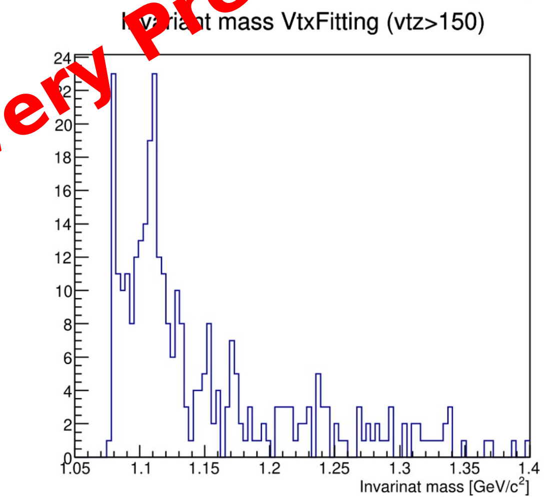
→Improved the track finding with Graph Neural Network:
Estimator resolutions: momentum 8.8%, angular 2.3 mrad

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

Preliminary data analysis

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

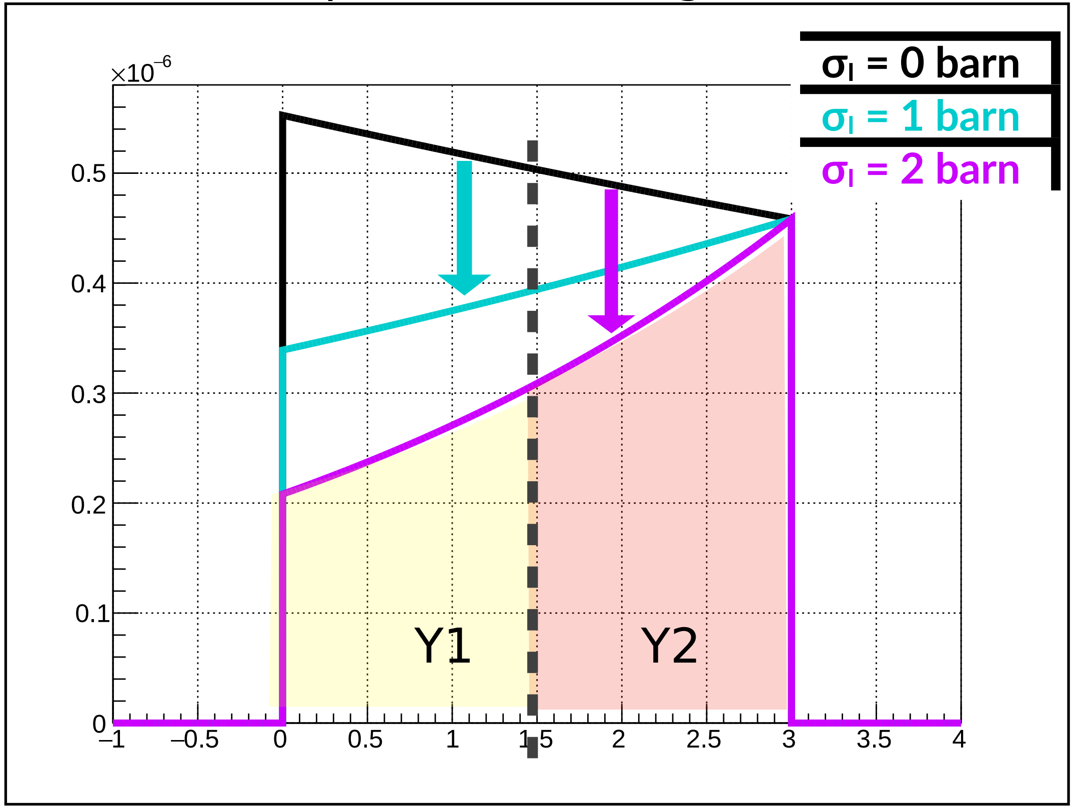




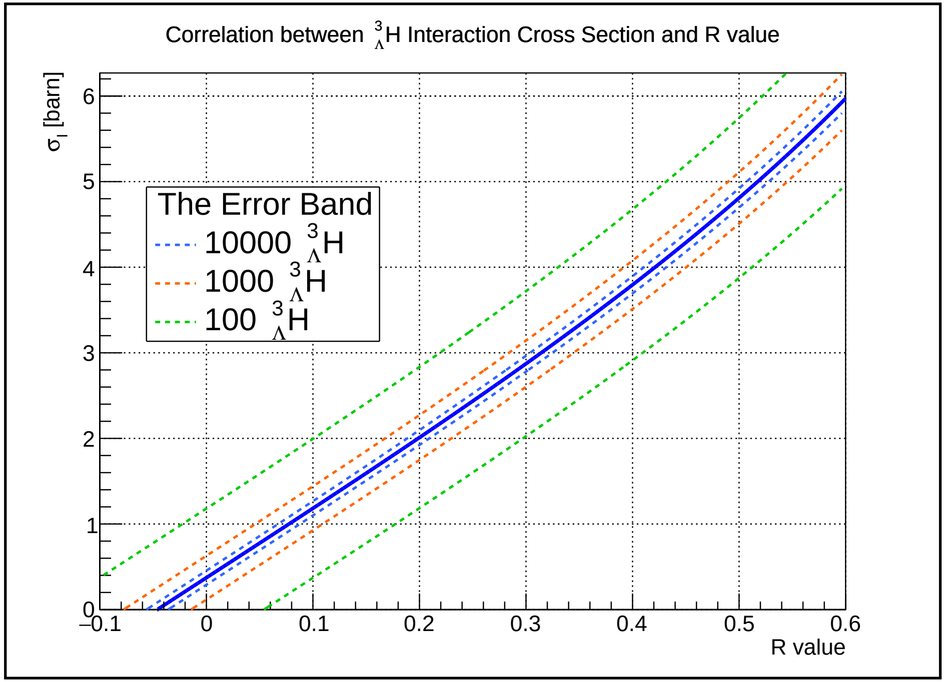
Preliminary data analysis

- **Analysis of Radius of products with WASA-FRS:**

Distribution of production position of observed products in target



$$\sigma_{I(^{3}_{\Lambda}H)}(R) = \frac{2\ln\frac{1+R}{1-R}}{T \cdot N_v} + \sigma_{I(^{6}Li)} - \frac{1}{\tau\gamma\beta c \cdot N_v}$$

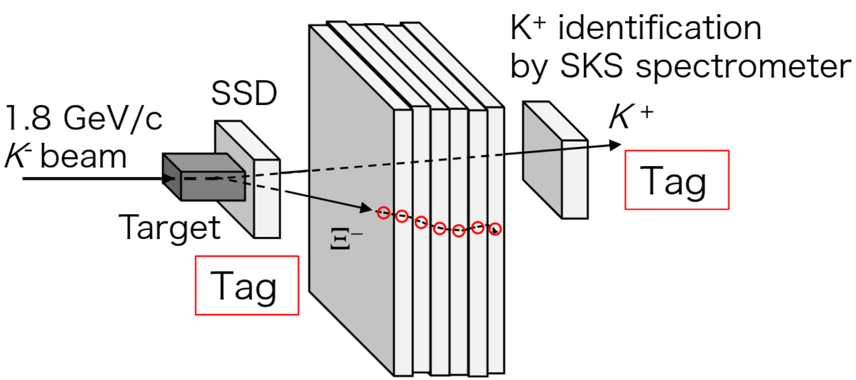


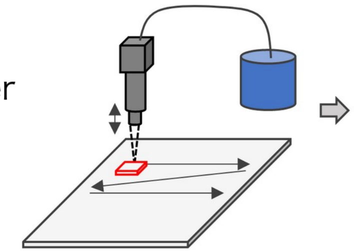
[Y. Gao et al., in preparation for publication]

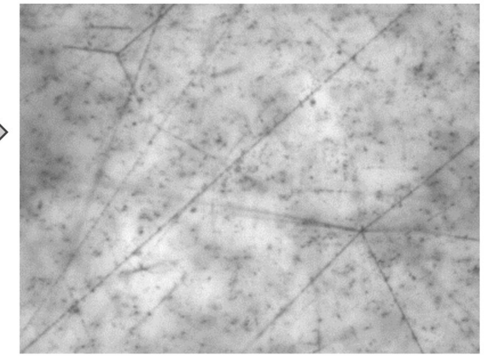
E07 experiment with machine learning

- **E07 experiment at JPARC:**

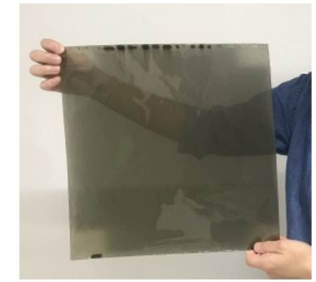
Emulsion-Counter hybrid method







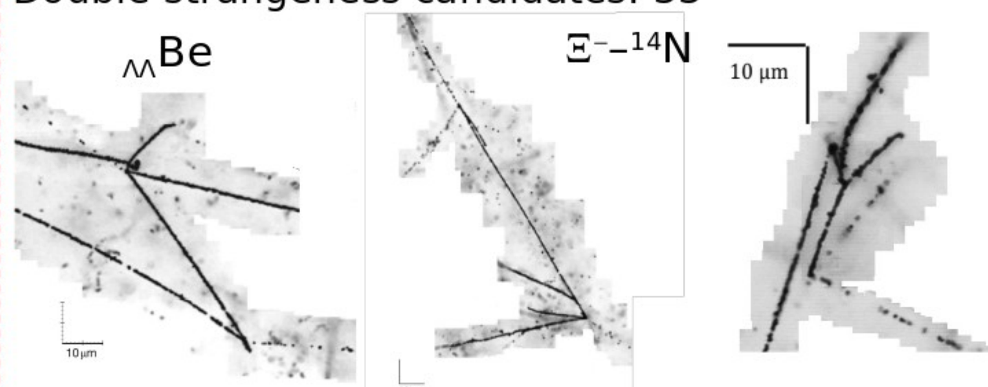
E07 nuclear emulsion



(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

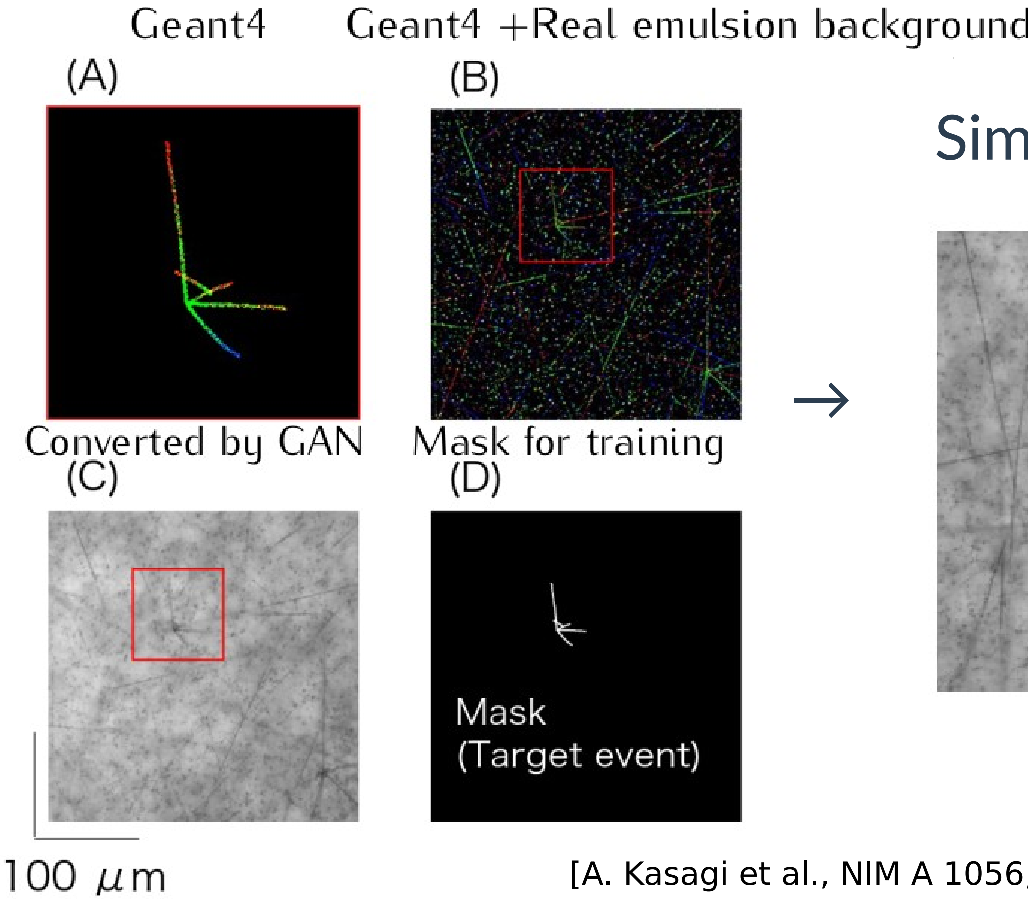
Double-strangeness candidates: 33



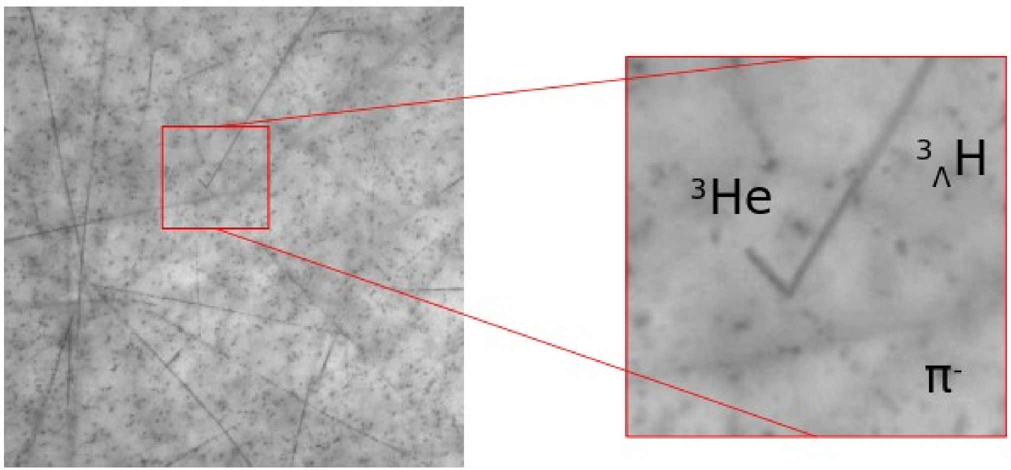
H. Ekawa et al., PTEP, (2019)
A.N.L. Nyaw et al., BSPIJ, (2020)
S. H. Hayakawa et al., PRL, (2021)
M. Yoshimoto et al., PTEP, (2021)

Hypernuclear Event Search with Machine Learning

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



Simulated image:

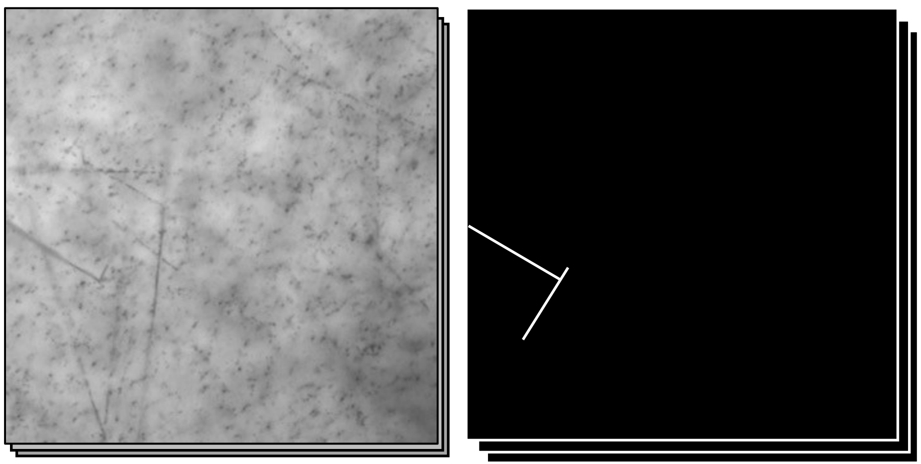


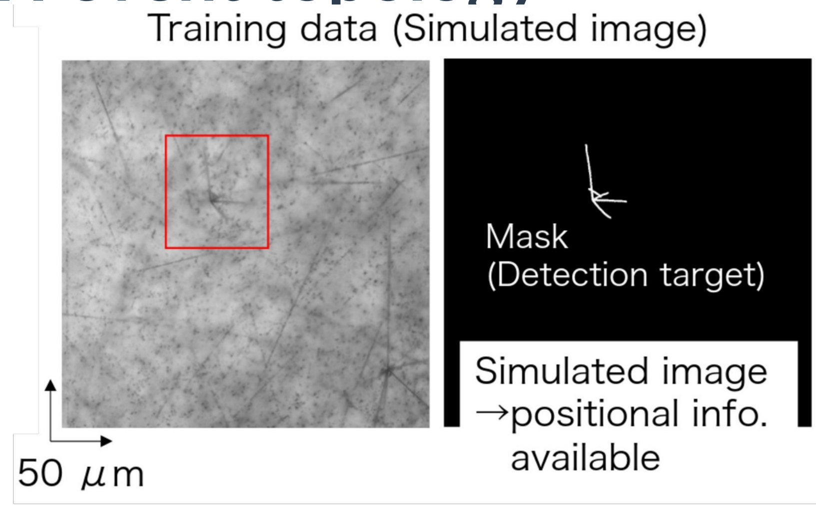
[A. Kasagi et al., NIM A 1056, 168663 (2023)]

Hypernuclear Event Search with Machine Learning

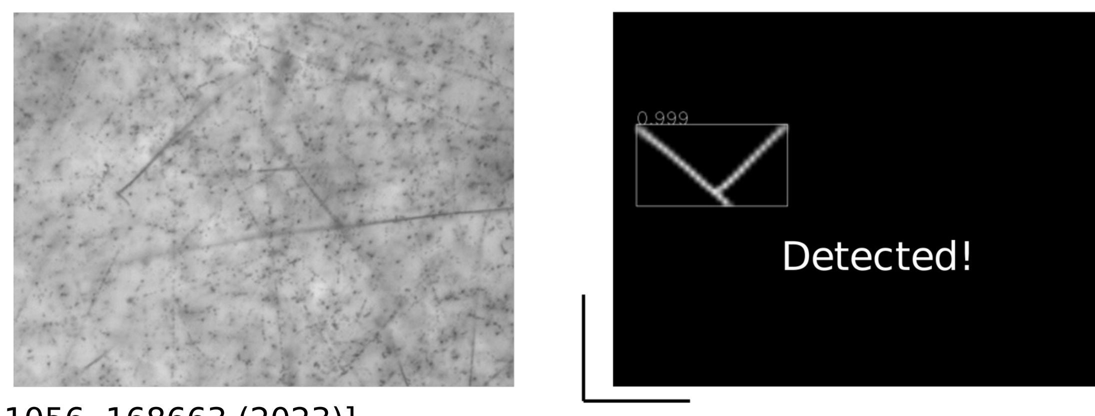
- **Object detection model for $^{3}_{\Lambda}$H event topology**
  - Mask R-CNN model:

Simulation





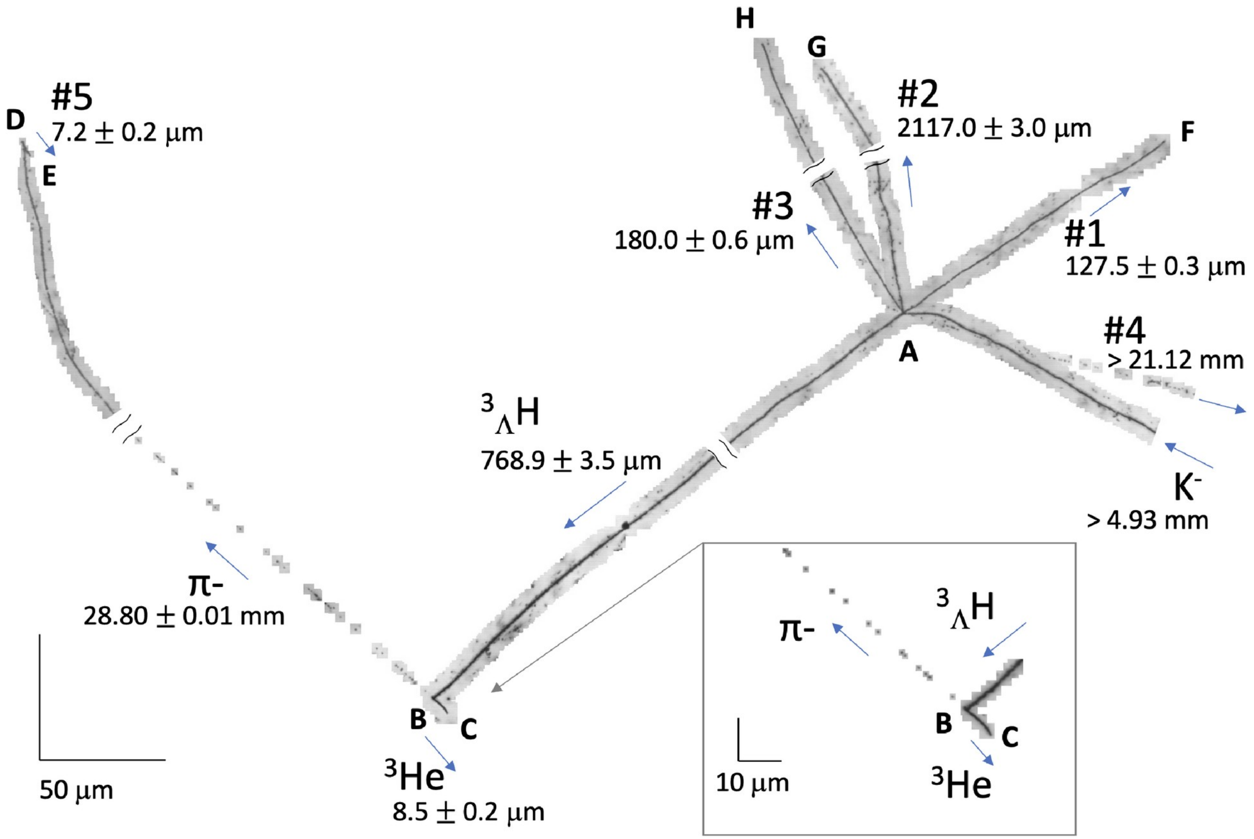
Mask R-CNN Model on Real Data



[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 $^{4}_{\Lambda}H$

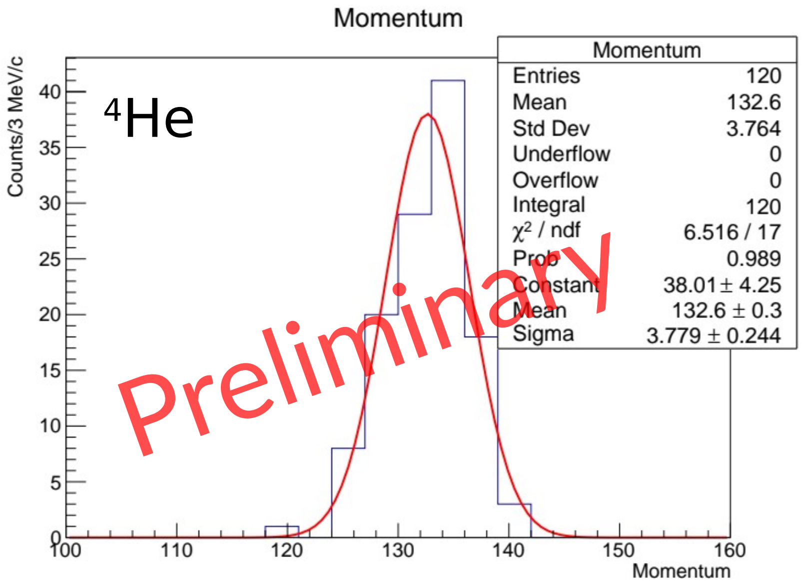
Statistical error on binding energy: ~ 100 keV
→ improve with more statistics

Systematic error on binding energy: ~ 14 keV

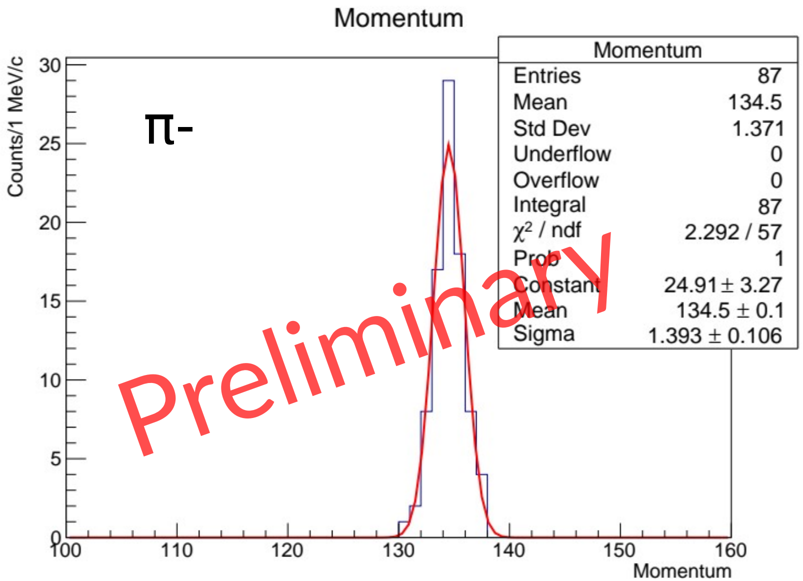
[T. Saito et al., Nat. Rev. Phys. 3, 803 (2021)]

Event analysis from the ML topology search

- **Calibration of the range – energy:**
  - Measure of all the ranges of the decay daughters
  - Translates measured range into kinetic energy
- **$^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^-$**



132.650 ± 0.345 MeV/c

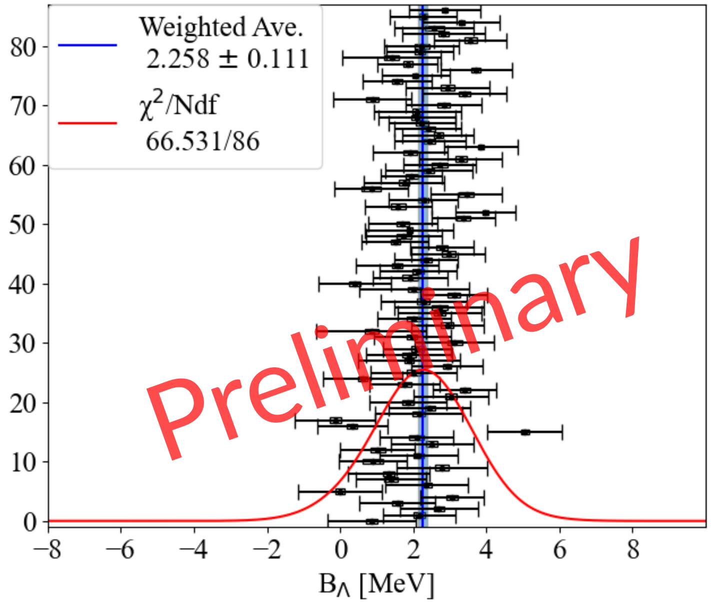


134.453 ± 0.149 MeV/c

Event analysis from the ML topology search

- **Calibration of the π- range:**
  - Ref. from MAMI-C ($^{4}_{\Lambda}H \rightarrow \pi^- + {}^{4}He$) [A1 collaboration, Nucl. Phys. A 954, 149 (2016)]
    - $P_{\pi-}$ = 132.851 ± 0.011 (stat.) ± 0.101 (syst.) MeV/c

$^{4}_{\Lambda}H$



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

Summary

- **Steps for tackling $^{3}_{\Lambda}H$ and nnΛ puzzles:**
  - **HypHI WASA-FRS:**
    - The experiment took place beginning 2022, it was very successfully !
    - Currently, the analysis is advancing:
    - Calibrations carrying-on & track finding / fitting / vertexing R&D
      → Hypernuclear events are under reconstruction
    - Lifetime & radius measurement soon
  - **E07 emulsion with deep learning:**
    - Analysis with DL pipeline is fixed and statistics on hypernuclear topologies are accumulating.
    - Light hypernuclei found: their binding energy extracted.
    - Extenting the search for more decay topologies:
      - three-body decay & double strangeness hypernuclei
      - Candidates already found and kinematics study ongoing