Current results on light hypernuclei in the WASA-FRS HypHI experiment

15th International Conference on Hypernuclear and Strange Particle Physics

HYP2025

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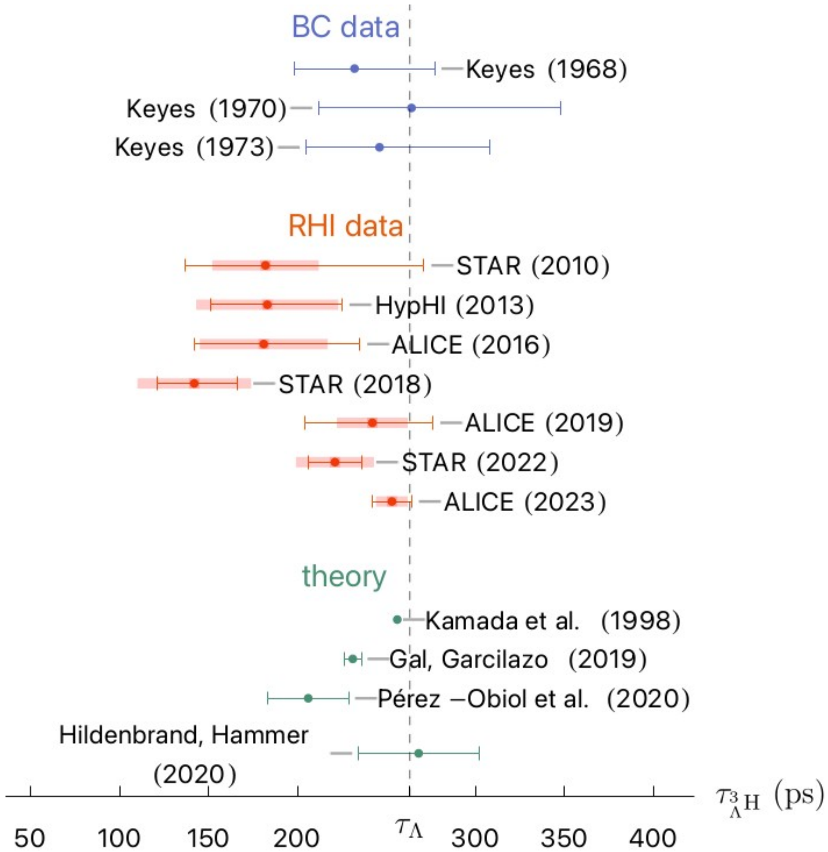
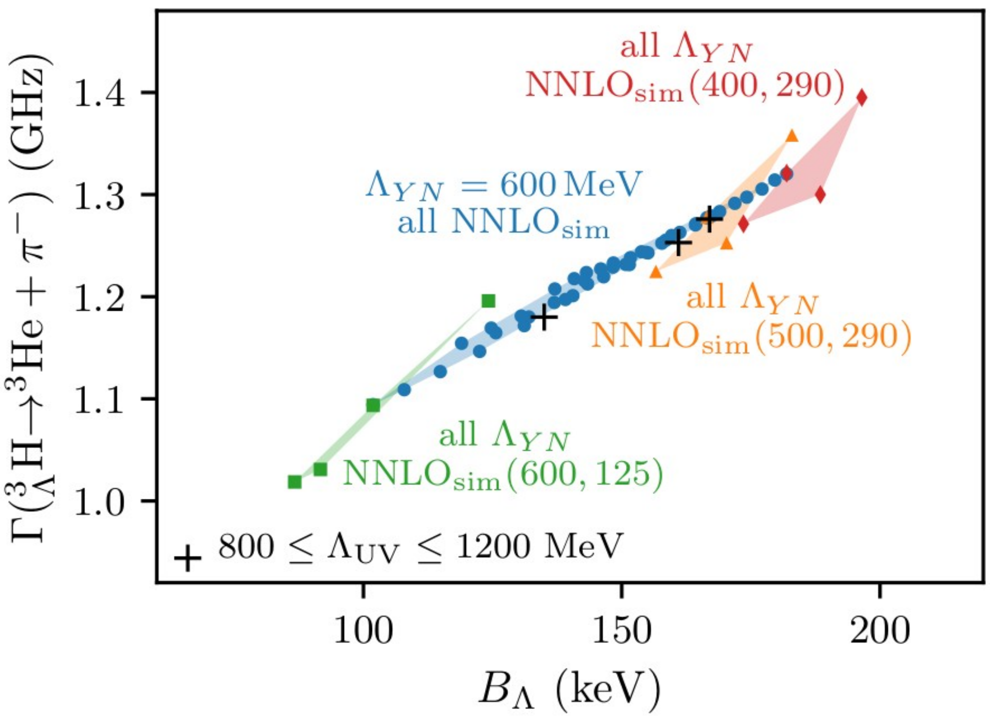
For WASA-FRS & Super-FRS Experiment collaboration

Current puzzles for light hypernuclei:

- **Hypertriton:**
  - New data from HI collisions conflicting with theory





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

Current puzzles for light hypernuclei:

- **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

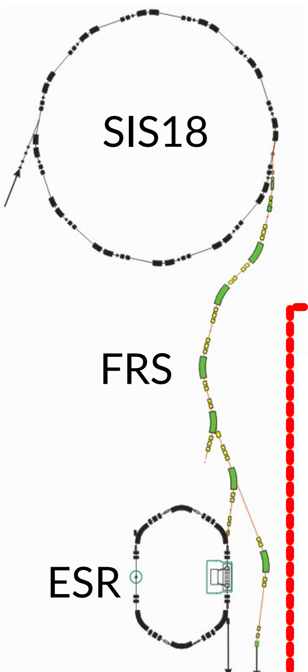
$$\boxed{B_\Lambda = 0.41 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})\ \text{MeV}} \qquad (3)$$

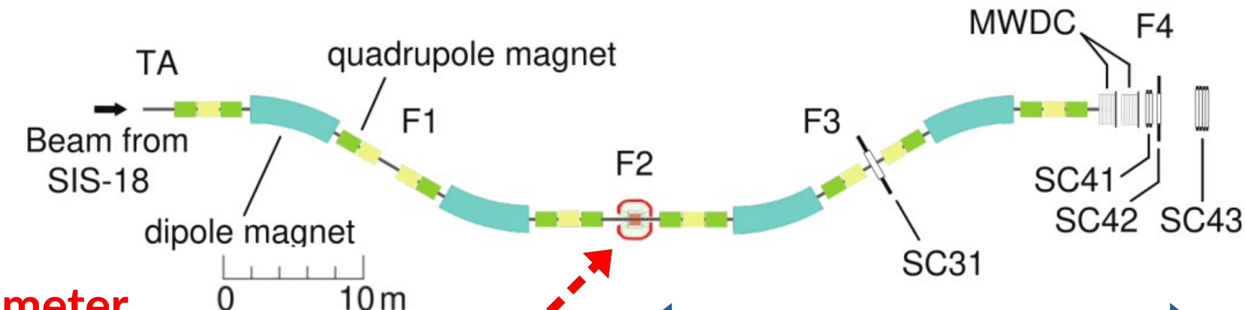
  - Previously accepted value: $B_\Lambda = 0.13 \pm 0.05$ MeV
  - And still : ALICE measured a Λ binding energy of :
    - $B_\Lambda = 0.102 \pm 0.063 \pm 0.067$ MeV [Phys. Rev. Lett. 131 (2023) 102302]
  - And in 2025 the E07 emulsion + ML measured :
    - $B_\Lambda = 0.23 \pm 0.11 \pm 0.05$ MeV [A Kasagi et al., Prog. Theor. Exp. Phys. 8, 083D01 (2025)]

WASA-FRS Experimental campaign: Jan. – March 2022

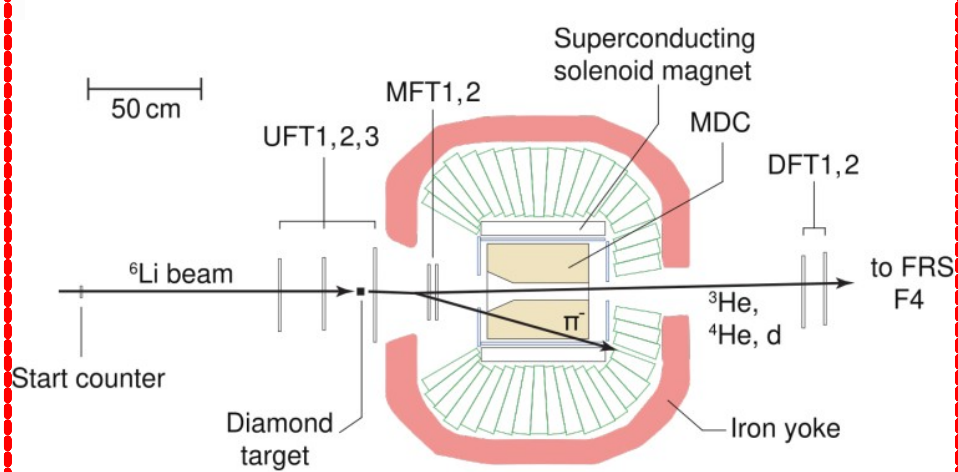
- Our contributions to solve : measure Lifetime & Radius

GSI facility





Hadron spectrometer
Δp/p ~ few %



High resolution spectrometer
Δp/p = 10^{-4}

Two experiments took place:

- η'-mesonic nuclei spectroscopy
- Hypernuclei spectroscopy

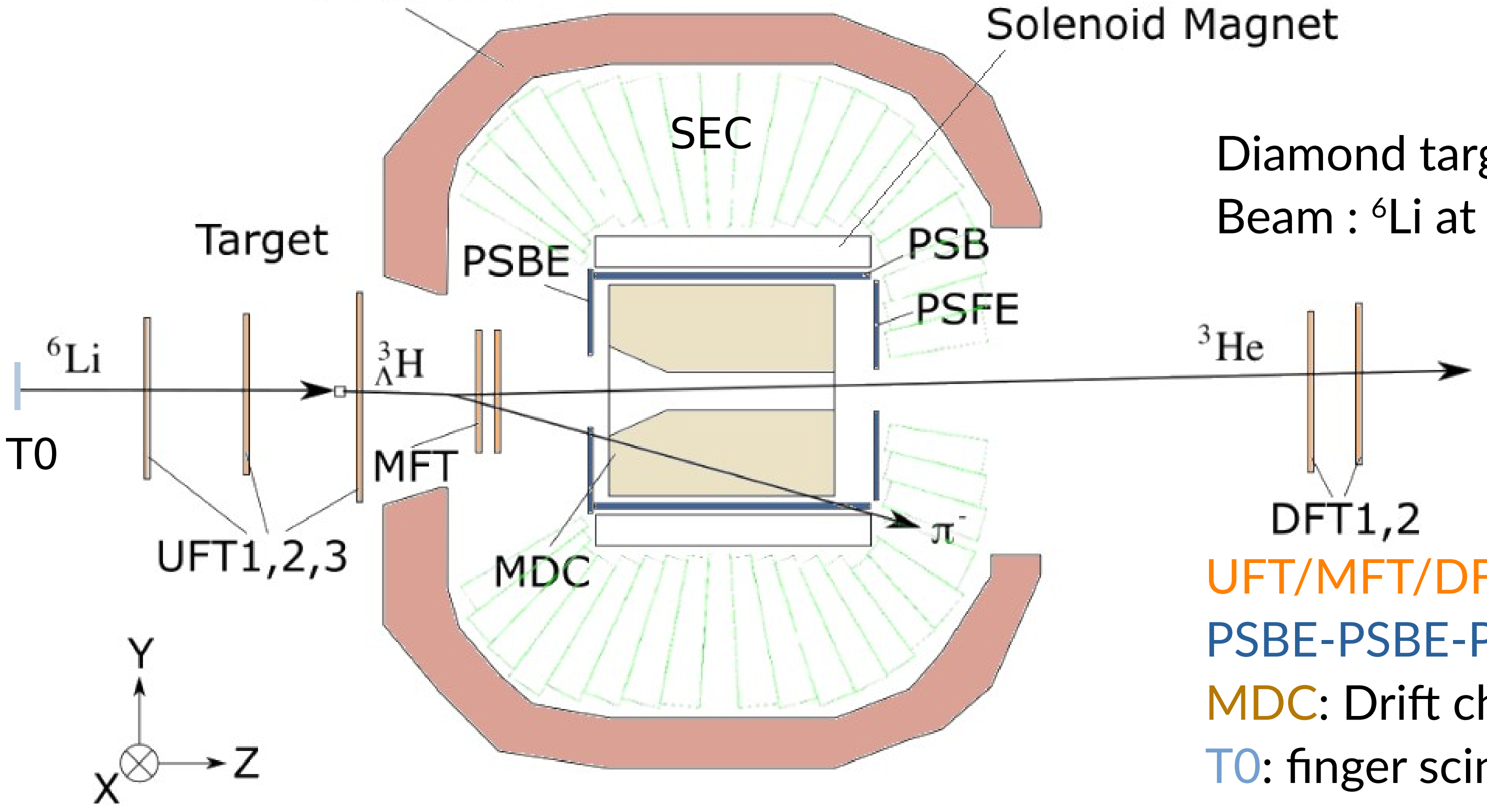
2 key topic of FAIR-Phase 0 of SuperFRS EC

Super-FRS EC

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

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

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 taking

Run	Period	Data size
Commissioning run	28th Jan. - 7th Feb.	7 TB
Physics run for HypHI	10th Mar. - 19th Mar.	48 TB

Acquired data:

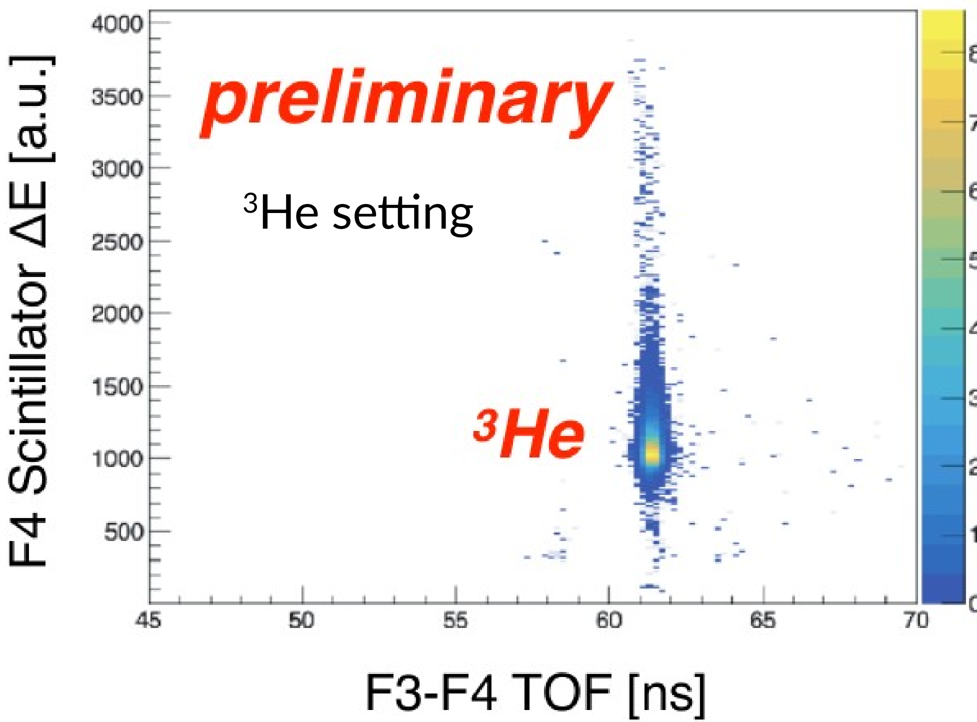
DAQ & Trigger system: Hybrid event triggered based on timestamp system

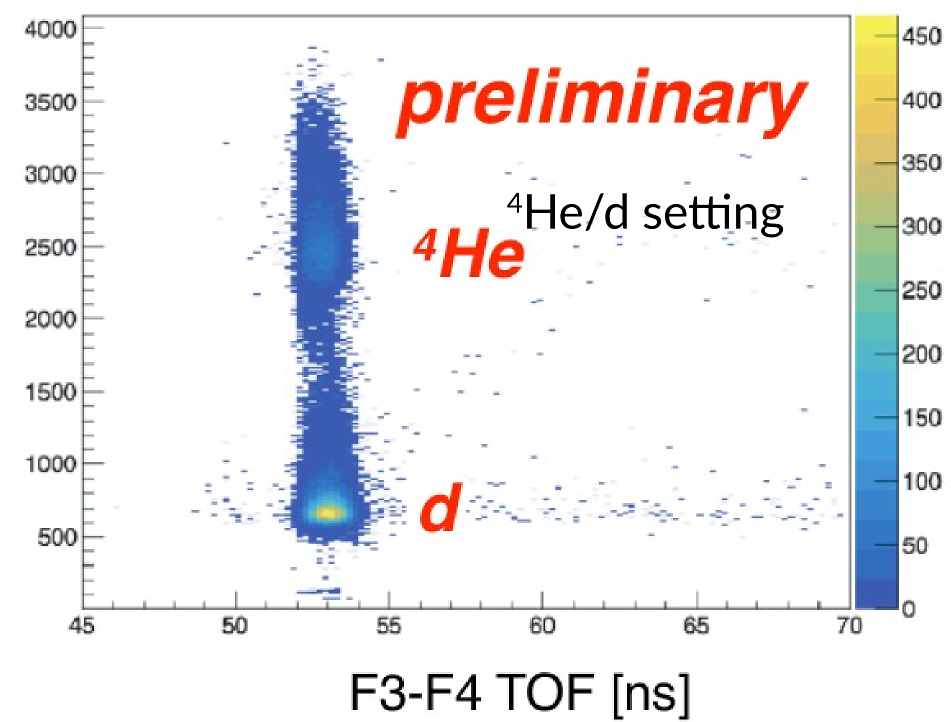
→ Bρ acceptance S2-S4 at 2% Δp/p & TOF S3-S4 & ΔE selection at S4

Beam	Fragment at S4	Amount	Time	Accepted trigger rate	
6Li beam	^{3}He	3.3×10^{8}	40.9 hours	2.6 kHz	$^{3}_{\Lambda}$H
	^{4}He	0.9×10^{8}	43.9 hours	1.8 kHz	$^{4}_{\Lambda}$H
	d	1.8×10^{8}			nnΛ
	p (mid-rap.)	5.3×10^{6}	3.2 hours	0.68 kHz	Λ
12C beam	^{3}He	1.0×10^{8}	13.5 hours	2.4k Hz	$^{3}_{\Lambda}$H
	^{9}C	2.4×10^{5}			$^{9}_{\Lambda}$B

Particle identification: already from last report

- **Analysis of high resolution spectrometer for fragments:**
  - PID at S4 final focal plane of FRS:

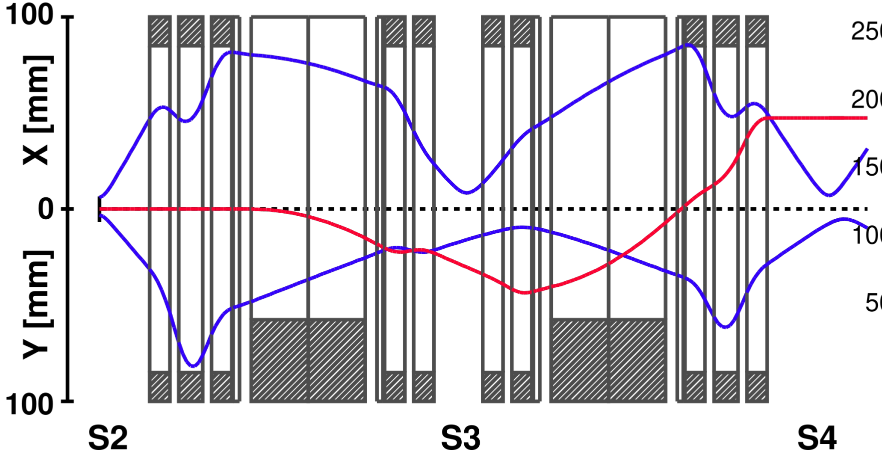


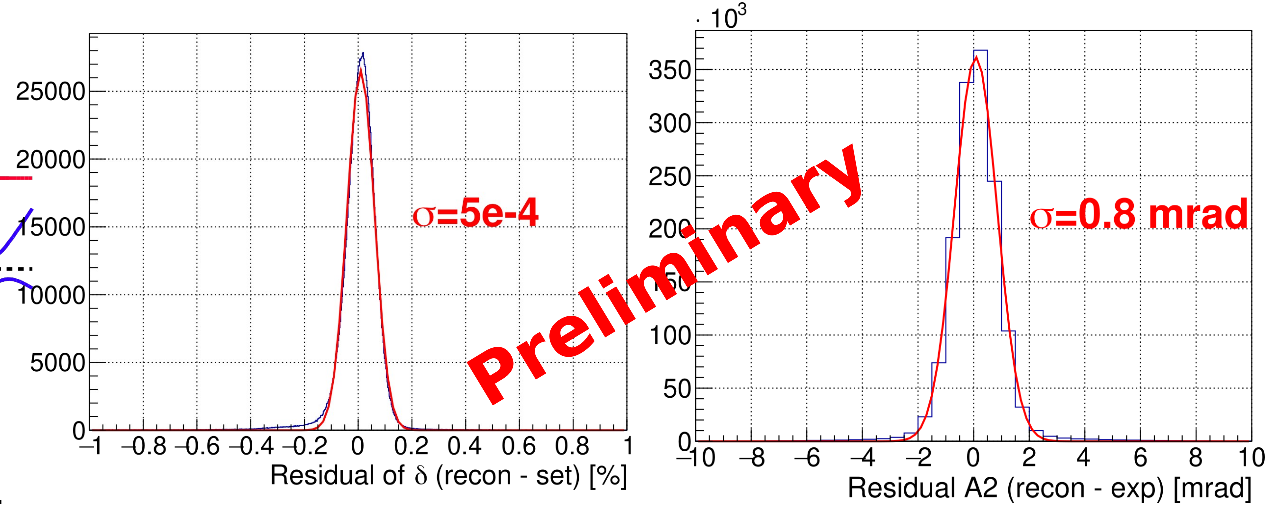


Data analysis: Tracking & PID

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

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





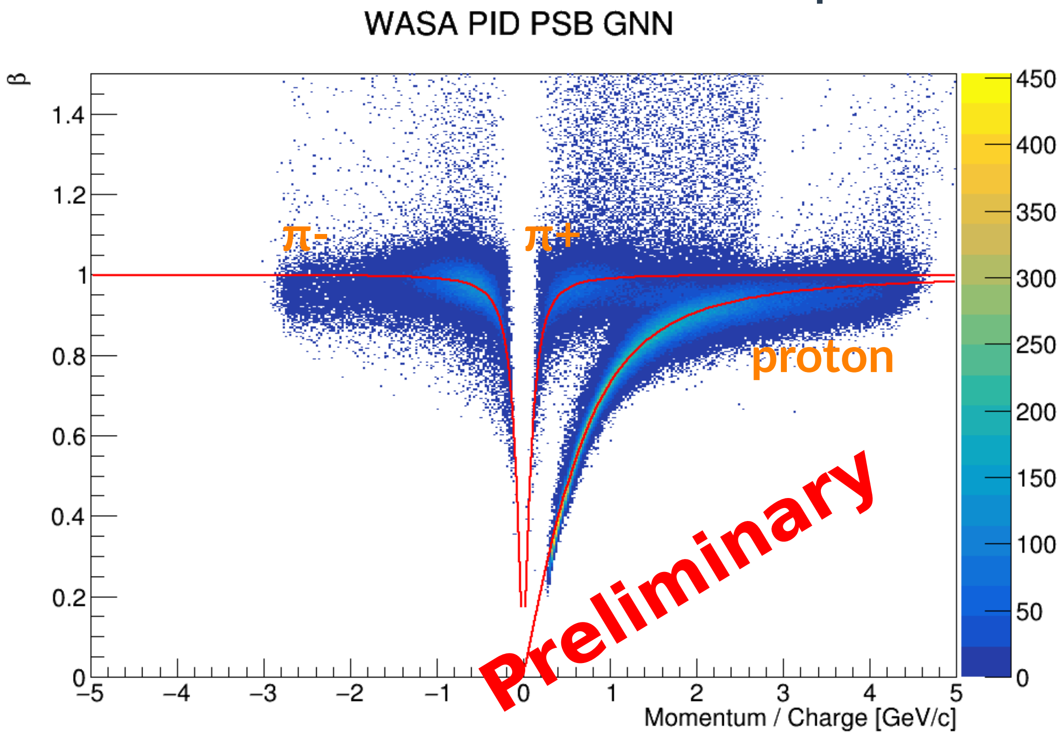
E. Liu's PhD thesis

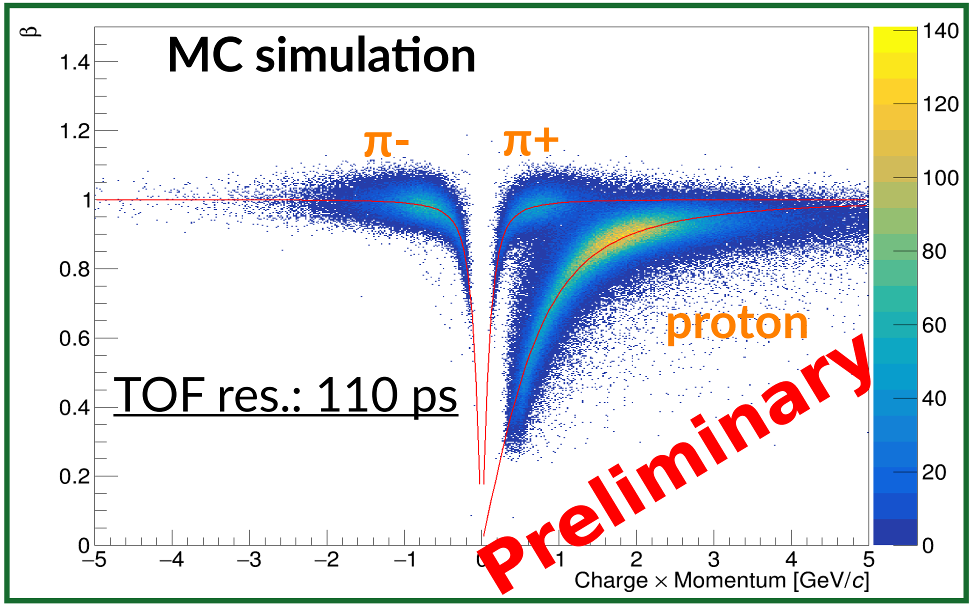
After correction and ion-optics up to second order :

- 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:



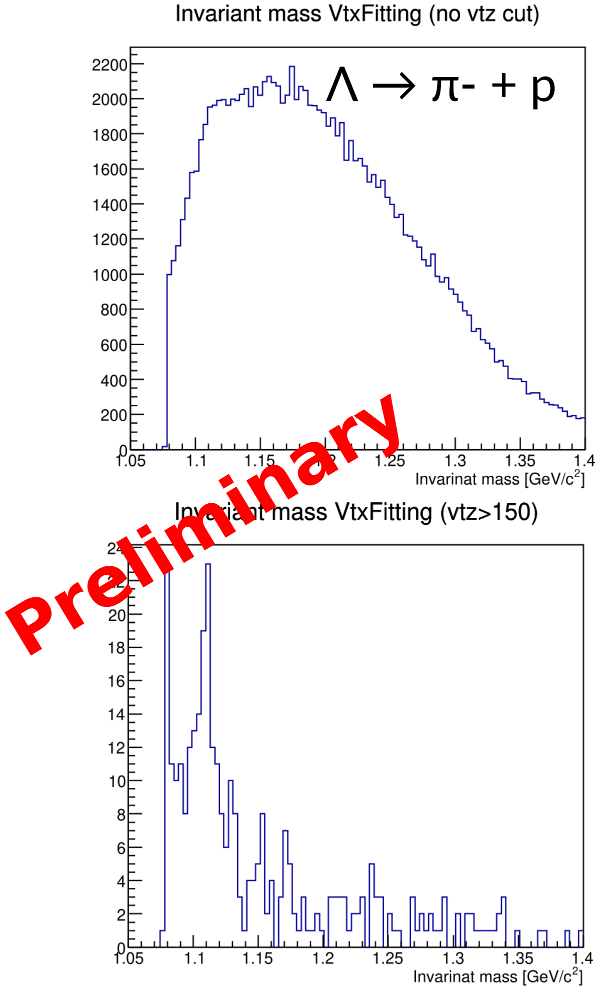


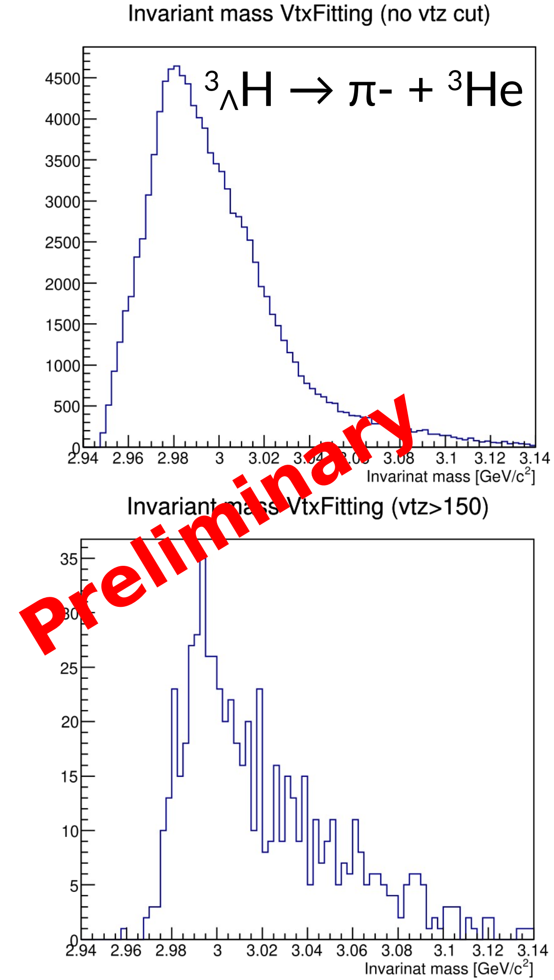
→Improved the track finding with Graph Neural Network:
Estimator resolutions: momentum 8.8%, angular 2.3 mrad

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

Data analysis: Hypernuclei identification

- Invariant mass at 15 cm behind the target:





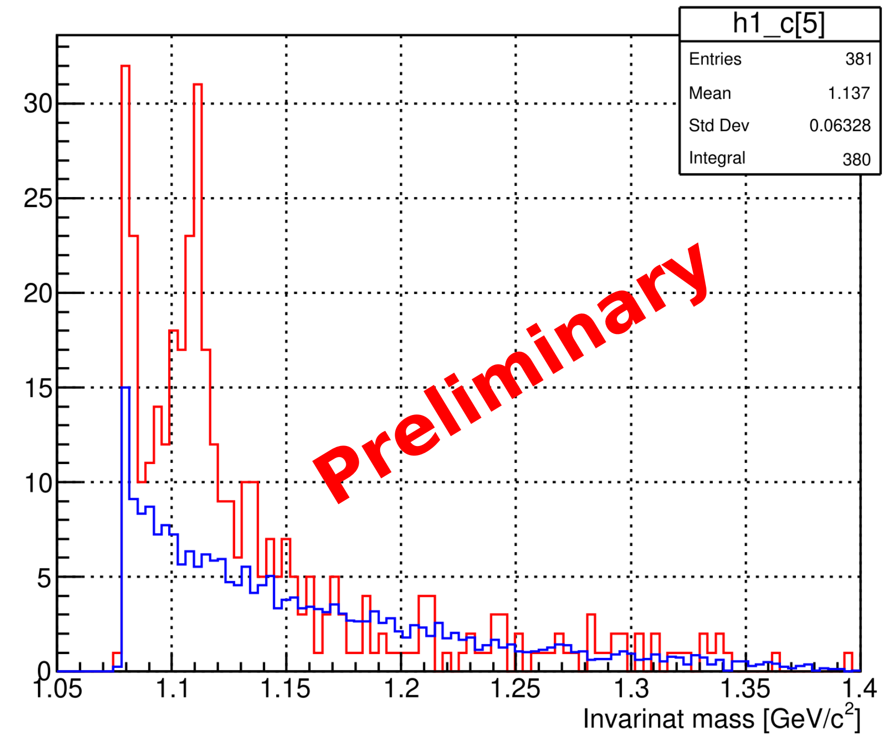
Data analysis: Hypernuclei identification

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

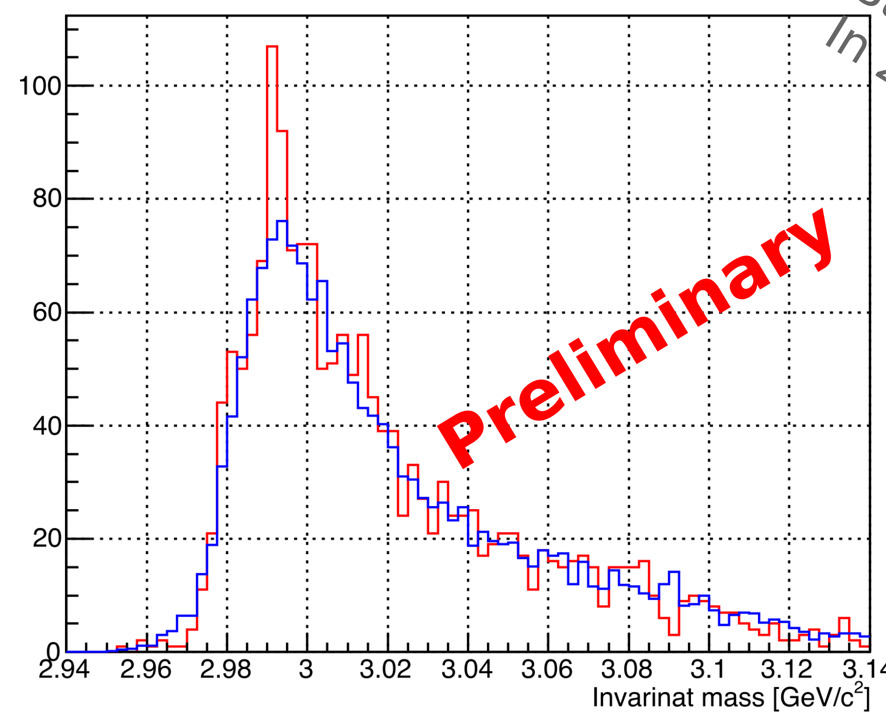
Red → real event | Blue → mixed event: π- Event #n + p | ^{3}He Event #n+1

Secondary vertex Z pos > 150 mm

Status
In 2024



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



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

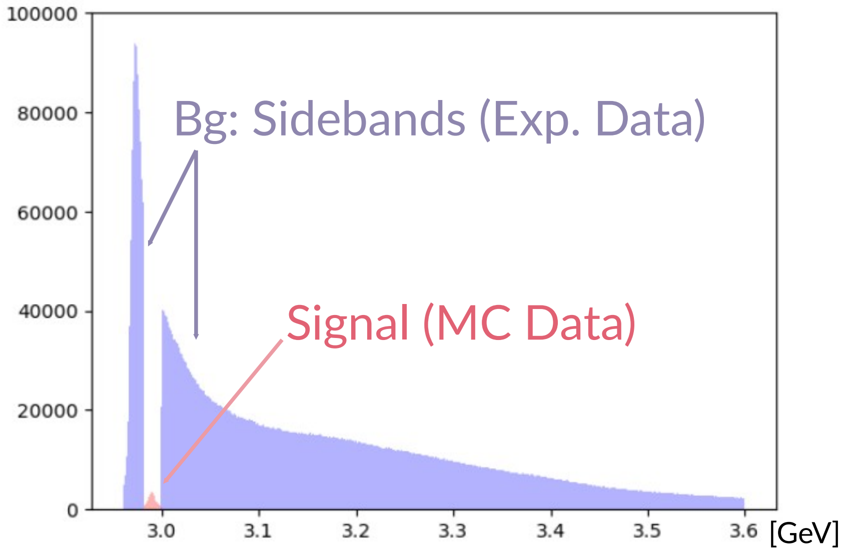
~ S - B = 51 ± 26 events

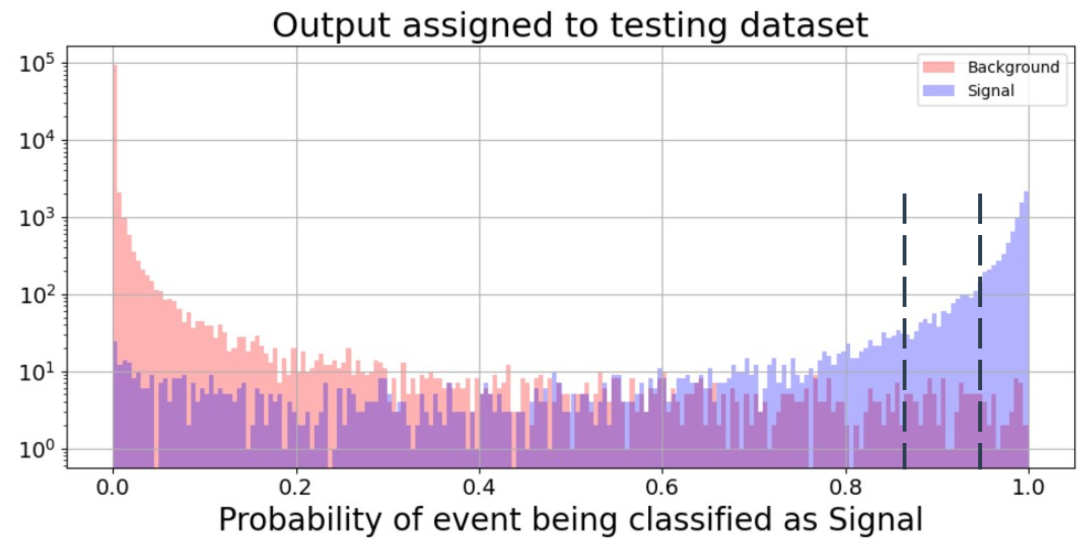
Data analysis: ML for S/B improvement

- 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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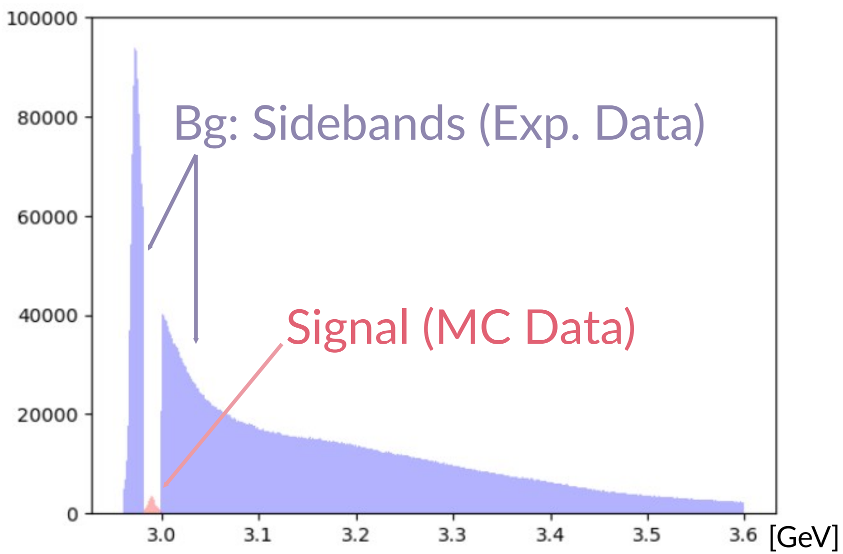
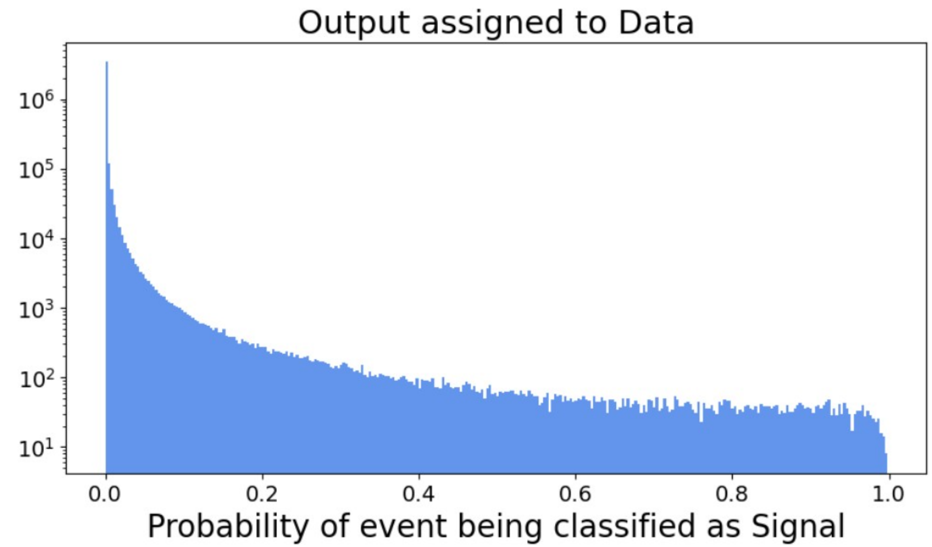


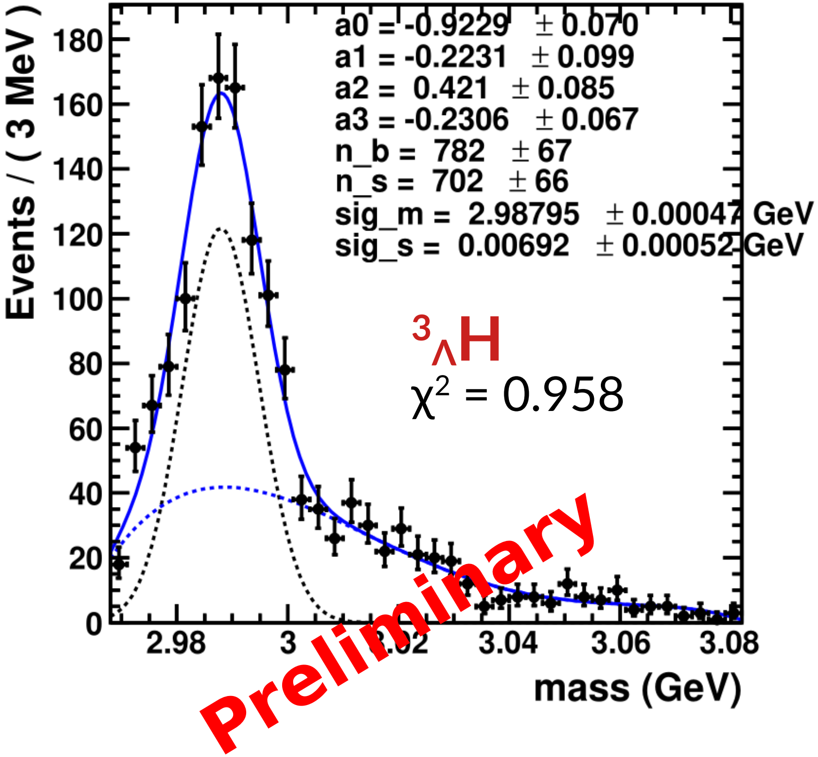


- **<u>Uncorrelated to</u>** invariant mass & lifetime → **no bias**

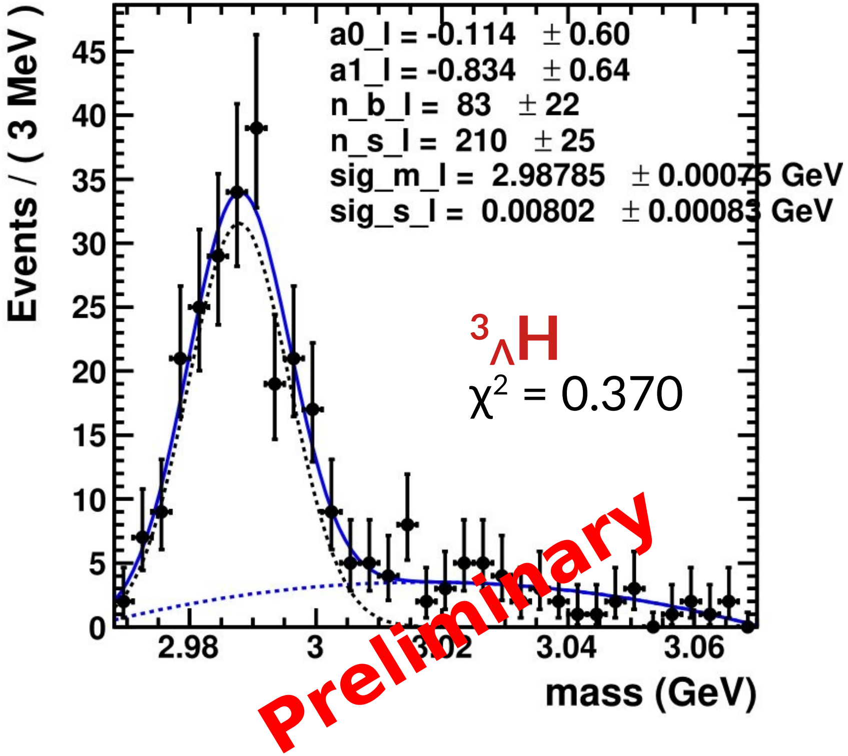
- Physical observables: geometry of decay vertex & hit patterns & π- hit multiplicity detectors

Data analysis: ML for S/B improvement

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



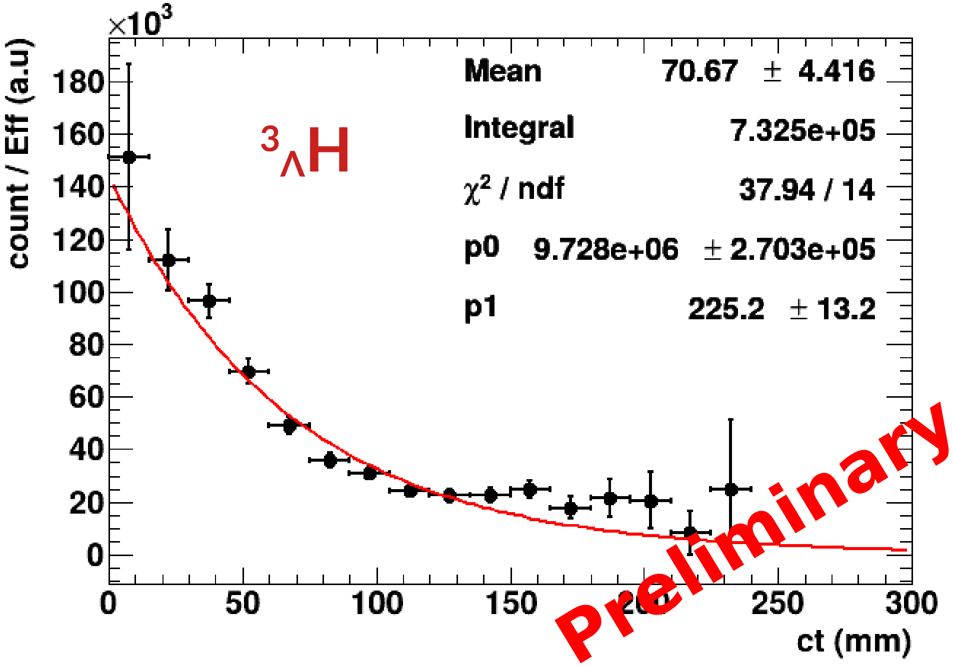
$^{3}_{\Lambda}H \rightarrow$ Threshold > 0.85
S = 702 ± 66

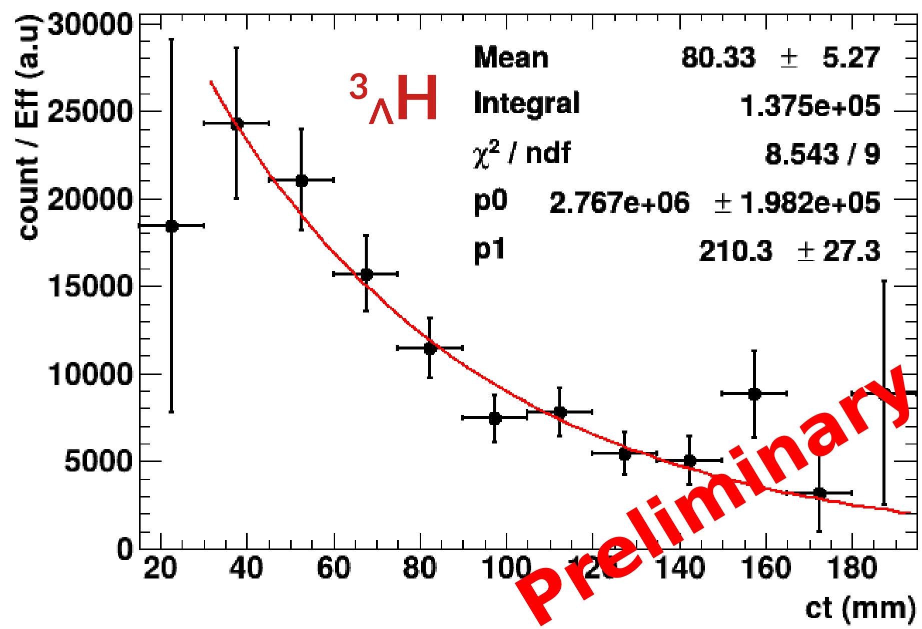


$^{3}_{\Lambda}H \rightarrow$ Threshold > 0.97
S = 210 ± 25

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

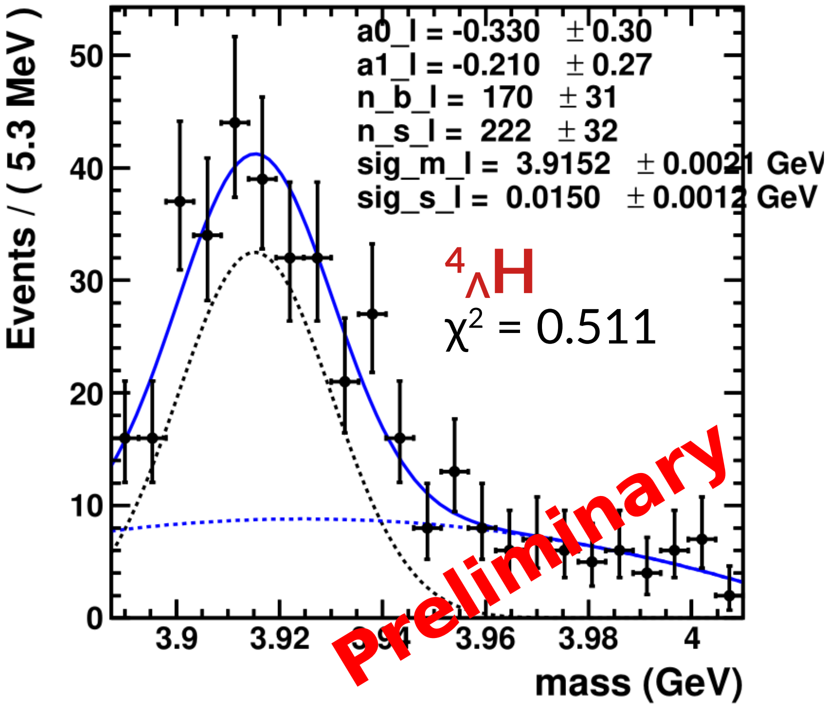
$^{3}_{\Lambda}H \rightarrow$ Threshold > 0.97

τ = 210 ± 27 ps

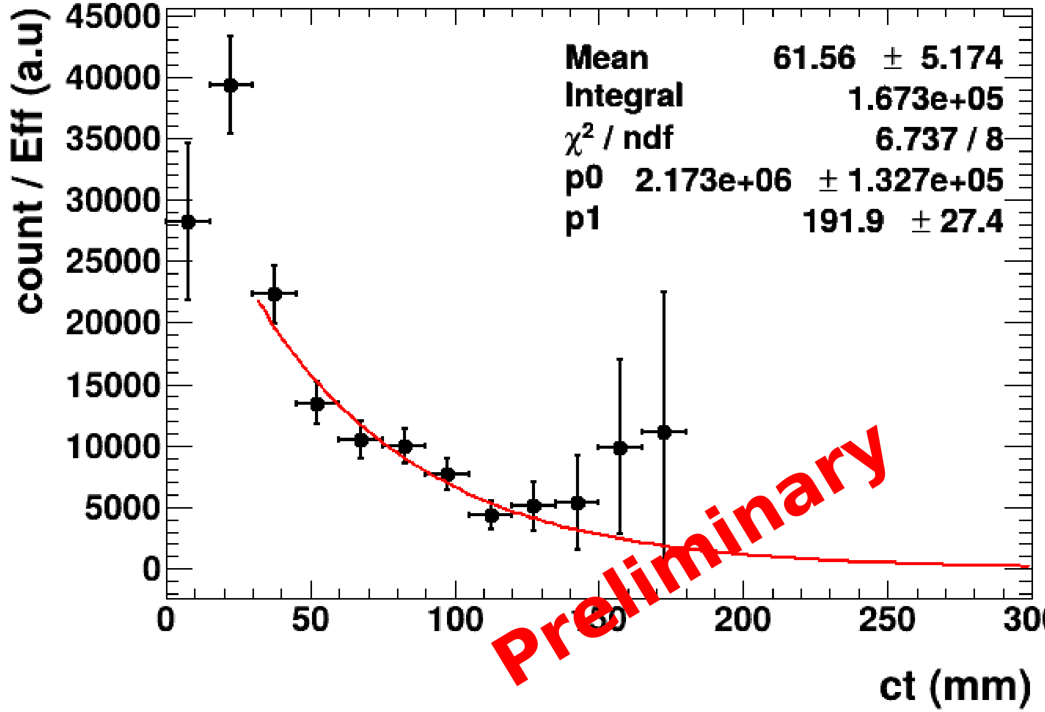
World avg:
237^{+10}_{-9} ps

Phase 0
Research Program

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



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



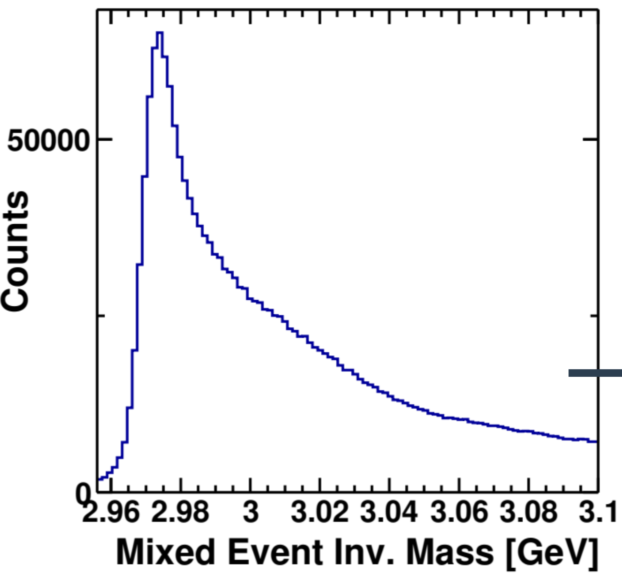
World avg:
$208\ ^{+10}_{-12}$ ps

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

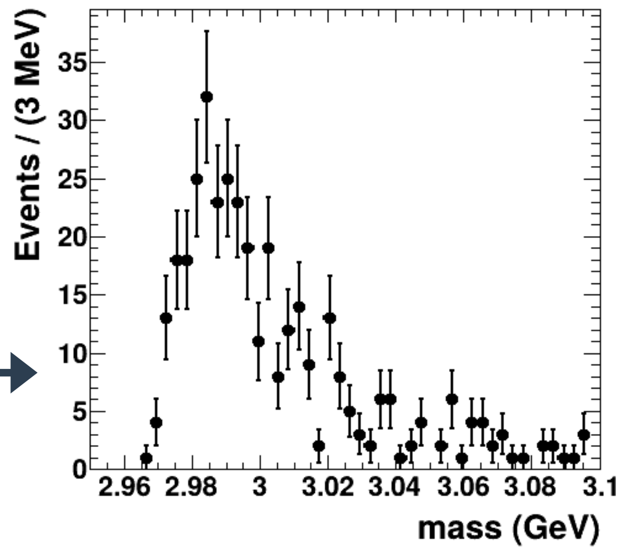
FAIR Phase 0 Research Program

Data analysis: ML for S/B improvement

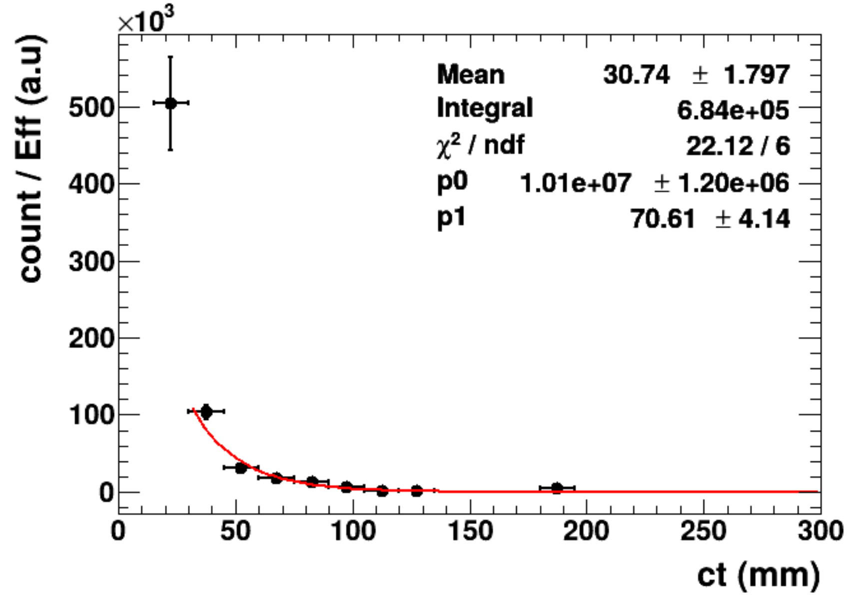
- **Cross Check: trained a model on mixed event of $^{3}_{\Lambda}H$**
  - No real signal in the dataset : mixed π+ + ^{3}He fake signal
    → check if ML can fake a real mass peak & lifetime



Threshold > 0.97



No mass peak of $^{3}_{\Lambda}H$
→ Background peak

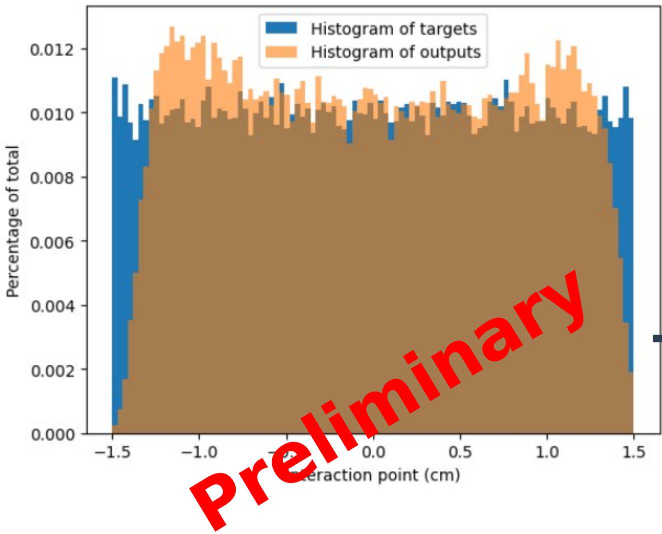


Very short lifetime → 70 ps
→ Background decay distribution

  - & additional training / checks were done !

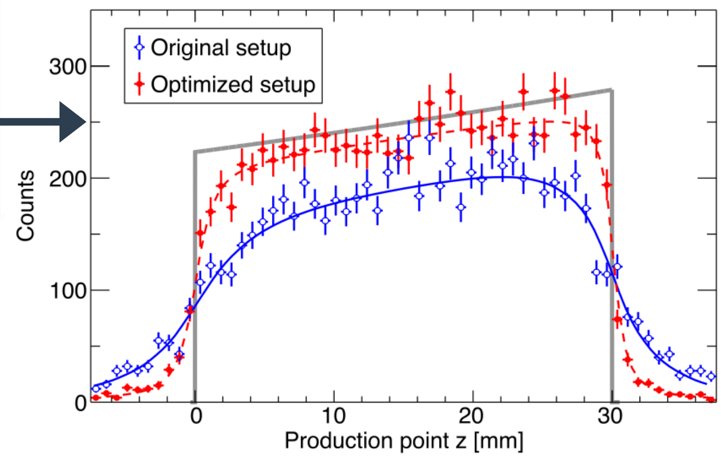
Data analysis: ML for S/B improvement

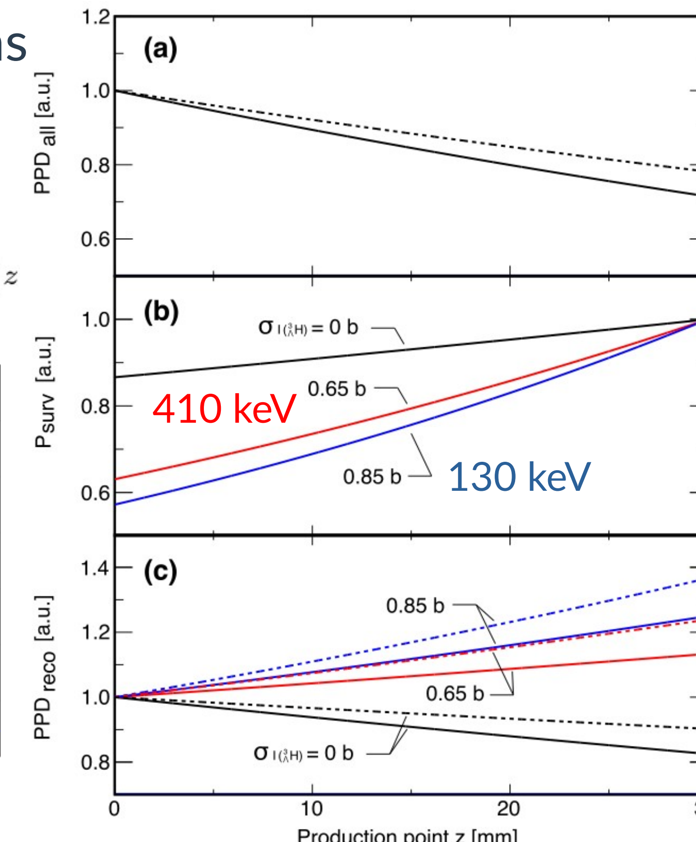
- **Analysis of Radius of products with WASA-FRS:**
  - Foundational model based on Transformer arch. (~ GPT3)
    - For estimator of event topology in NN collisions



Res ~ 0.45 mm → 2 mm

$$\mathrm{PPD}_{\mathrm{reco}}(z) \propto \mathrm{PPD}_{\mathrm{all}}(z) \cdot P_{\mathrm{surv}}(z)$$
$$\propto e^{\left(n\sigma_{I(^3_\Lambda \mathrm{H})} + \frac{1}{\gamma\beta c\tau} - n\sigma_{I(^6\mathrm{Li})}\right) z}$$





[Y. Gao et al., Ch. Phys. C 50, (2026) *in-press*]

Summary

- **HypHI WASA-FRS experiment at GSI:**
  - Steps for tackling $^{3}_{\Lambda}H$ and nnΛ puzzles:
  - 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
    - With trained ML models → study of radius possible
  - Search of nnΛ in d + π- reconstruction
  - In the ^{12}C+^{12}C dataset: Search for $^{9}_{\Lambda}B \rightarrow {}^{9}C + \pi^-$
- **In Future with new solenoid @ SuperFRS at FAIR:**
  - Proton- and neutron-rich hypernuclei accessible with RI beam

The WASA-FRS collaboration (only core members)

- <u>High Energy Nuclear Physics Laboratory, RIKEN, Japan</u>
  - H. Ekawa, Y. Gao, Y. He, A. Kasagi, E. Liu, A. Muneem, M. Nakagawa, T.R. Saito, Y. Tanaka, A. Yanai, J. Yoshida, H. Wang
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