Studies of Hypernuclei with HI-beams, Nuclear Emulsions and Machine Learning

Take R. Saito for **the WASA-FRS HypHI collaboration**, **the Super-FRS Experiment Collaboration**, and the **Emulsion-ML collaboration**

High Energy Nuclear Physics Laboratory,

Cluster for Pioneering Research,

***RIKEN**,*

Japan

HRS-HYS Research Group
(High ReSolution - HYpernuclear Spectroscopy),

FRS/NUSTAR department,

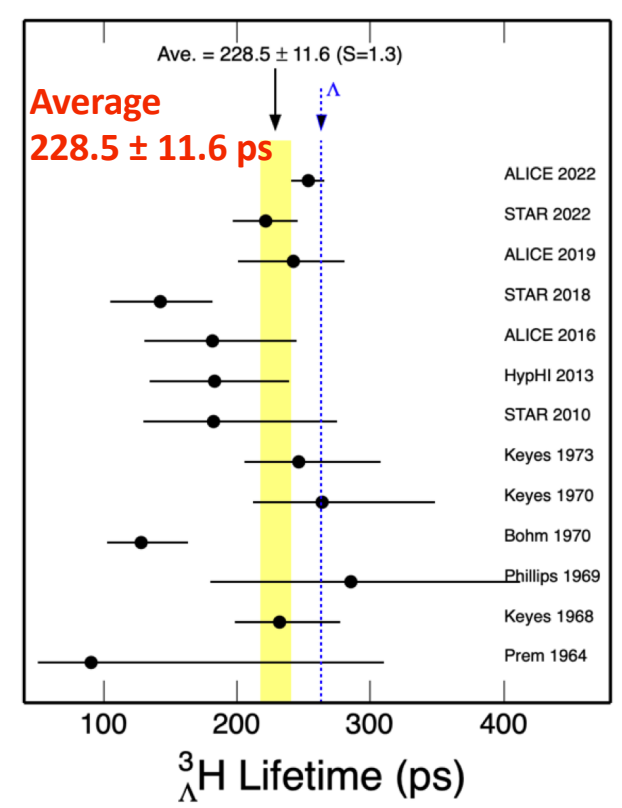
***GSI Helmholtz Center for Heavy Ion Research**,*

Germany

EMMI Workshop: Bound states and particle interactions in the 21st century ,
Trieste, Italy , 3rd - 6th July 2023

Recent hot topics for few-body hypernuclei

On hypertriton



Talk by Zhangbu Xu on Monday

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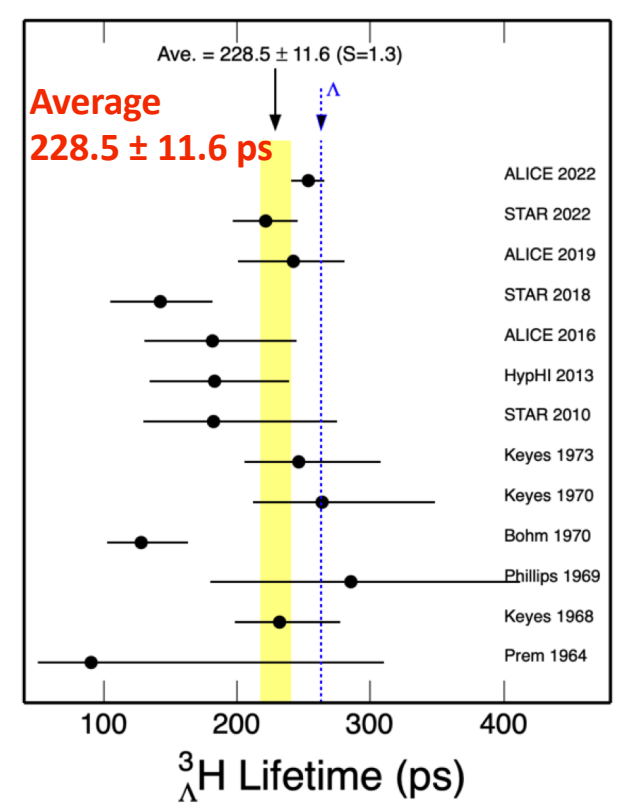

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$^{3}_{\Lambda}$H Binding energy

$B_\Lambda(^{3}_{\Lambda}H)$: 0.13 ± 0.05 MeV

G. Bohm et al., NPB **4** (1968) 511

M. Juric et al., NPB **52** (1973) 1

STAR (2020)

0.41 ± 0.12 ± 0.11 MeV

STAR Collaboration,

Nat. Phys. **16** (2020) 409

ALICE

0.072 ± 0.063 ± 0.036 MeV

arXiv.2209.07360 (2022)

talk by Chiara Pinto on Monday

0.102 ± 0.063 MeV

Talk by Stefania Bufalino

in the Hadron2023 conf. (2023)

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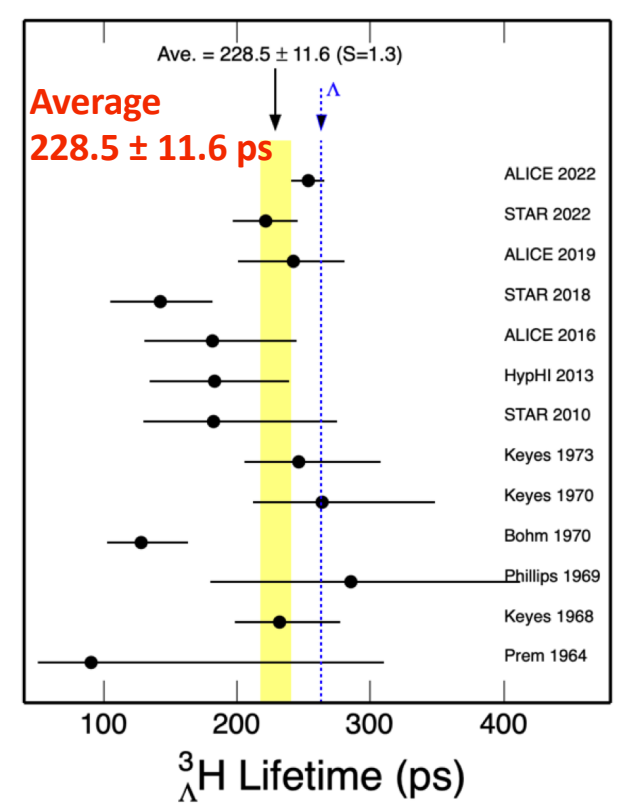

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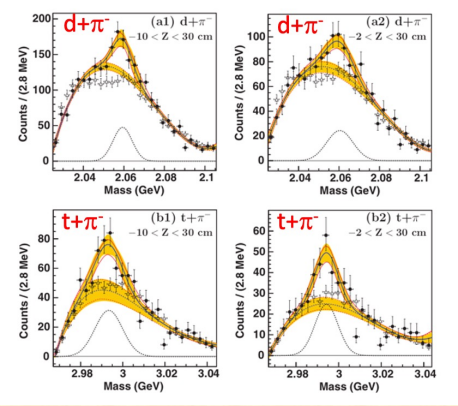
On Λnn



HypHI., PRC 88 (2013) 041001

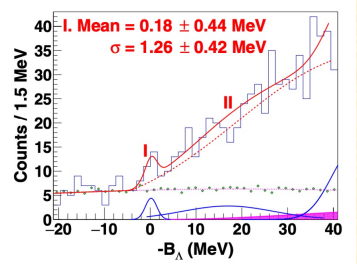


FIG. 5. The enlarged mass spectrum around the Λ*nn* threshold. Two additional Gaussians were fitted together with the known contributions (the accidentals, the Λ quasifree, the free Λ, and the ^{3}He contamination). The one at the threshold is for the small peak, while the broad one is for the additional strength above the predicted quasifree distribution.

JLab E12-17-003., PRC 105 (2022) L051001

Talk by Liguang Tang on Wednesday

Our projects

With heavy-ion beams

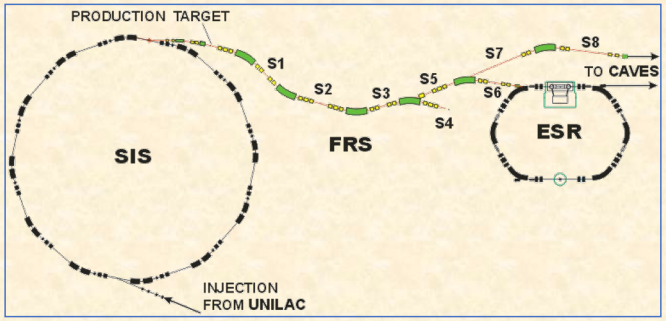
- Lifetime of light hypernuclei including hypertriton
- Λnn states

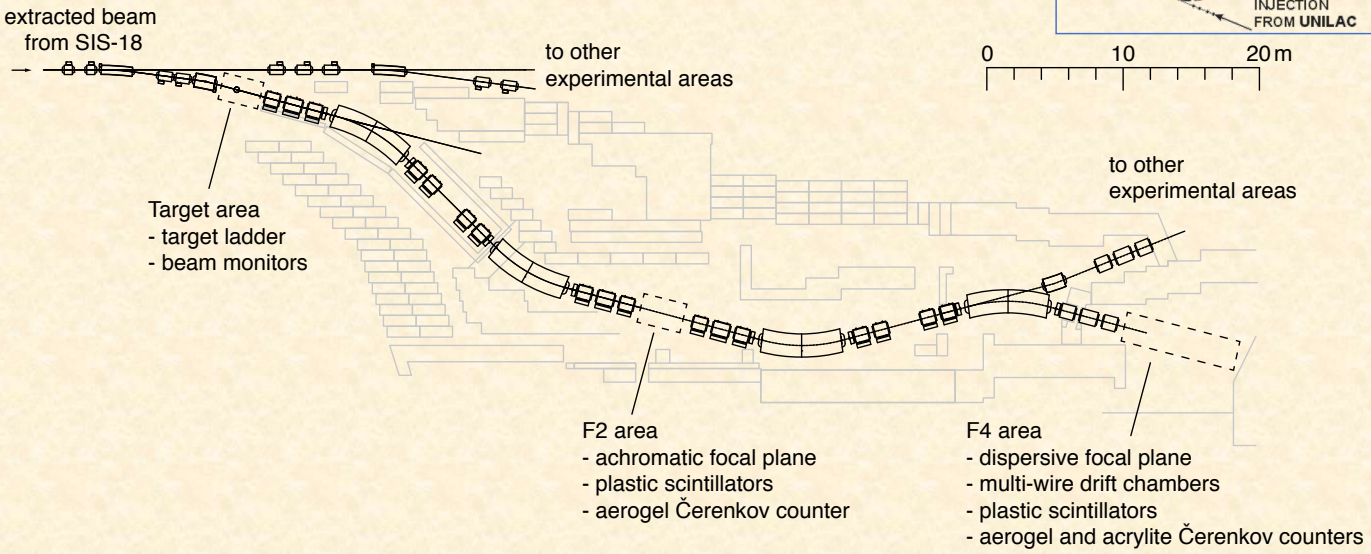
With nuclear emulsions

- Binding energy of hypernuclei
  - Single-strangeness hypernuclei
    - ✓Stopped two-body decays
    - ✓Multi-body decays
  - Double-strangeness hypernuclei

Machine learning

The novel technique with FRS at GSI





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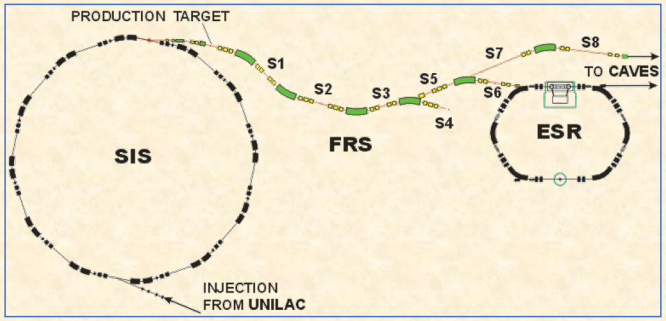

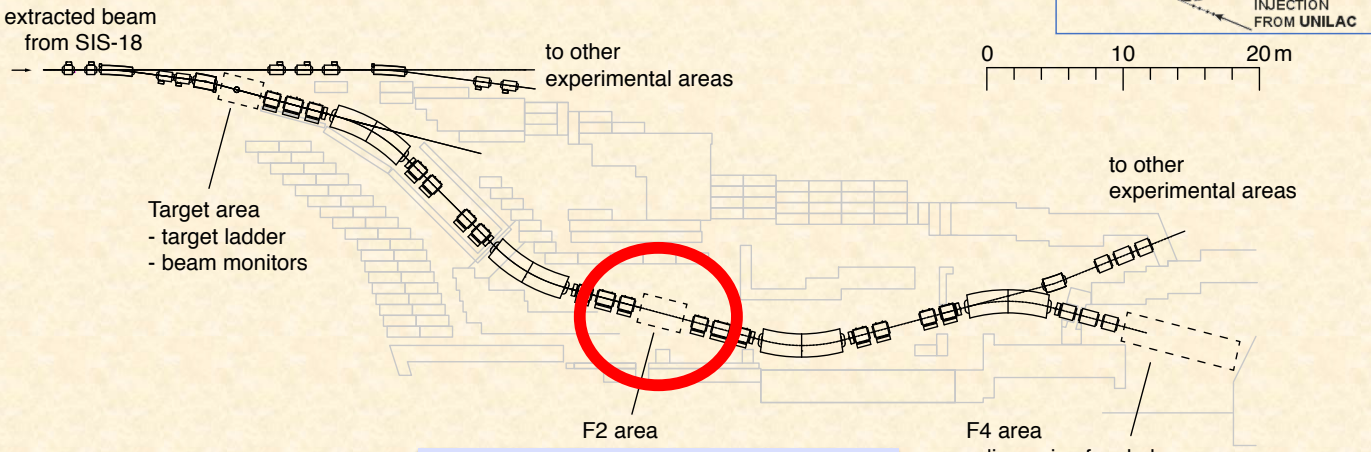

$^{3}_{\Lambda}H \rightarrow \pi^- + {}^{3}He$

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

$nn\Lambda \rightarrow \pi^- + d + n$

With $^{6}Li + ^{12}C$ at 2 A GeV

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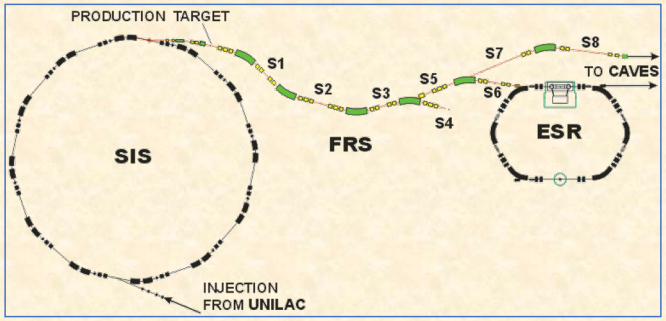

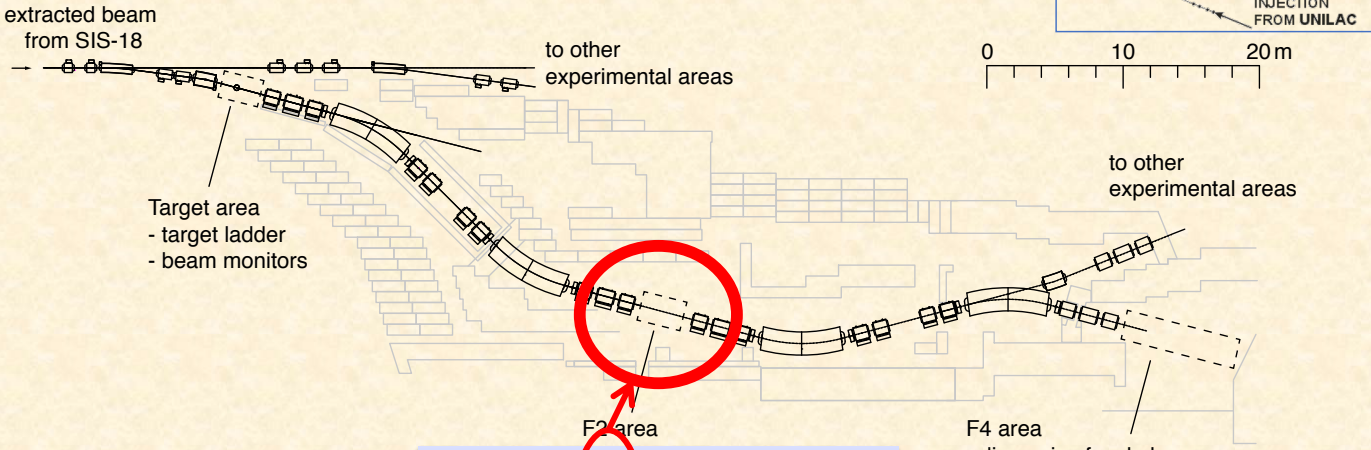

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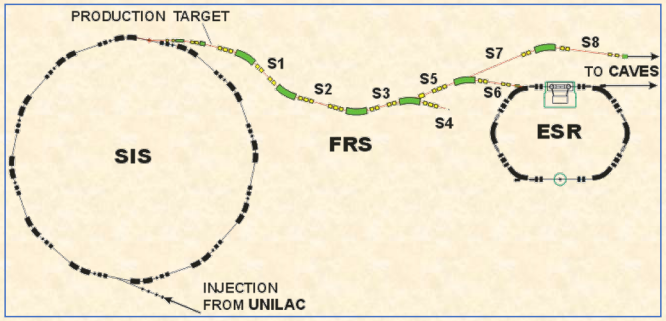

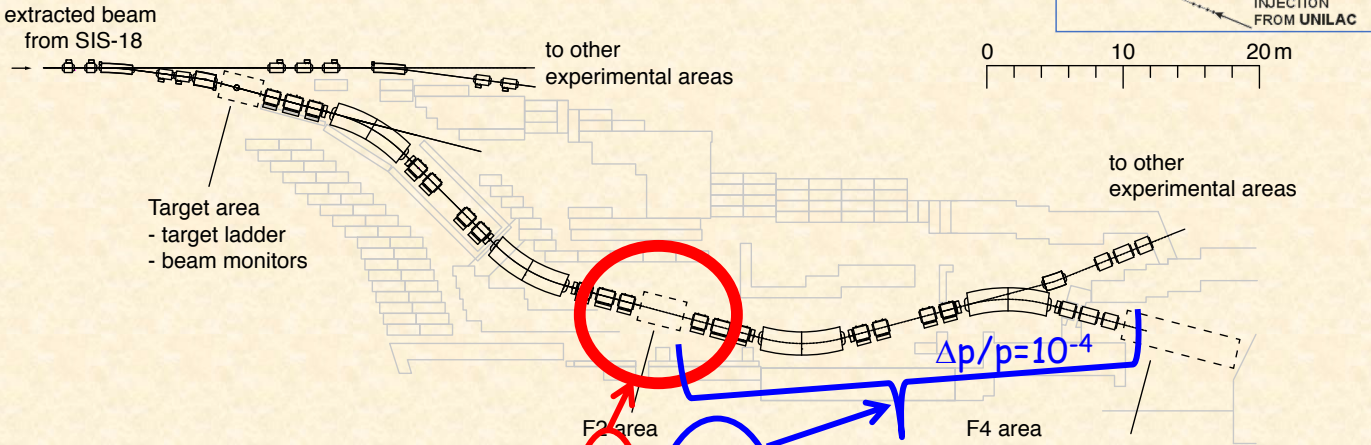

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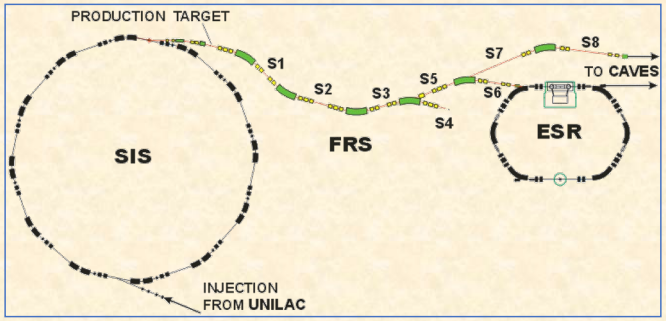

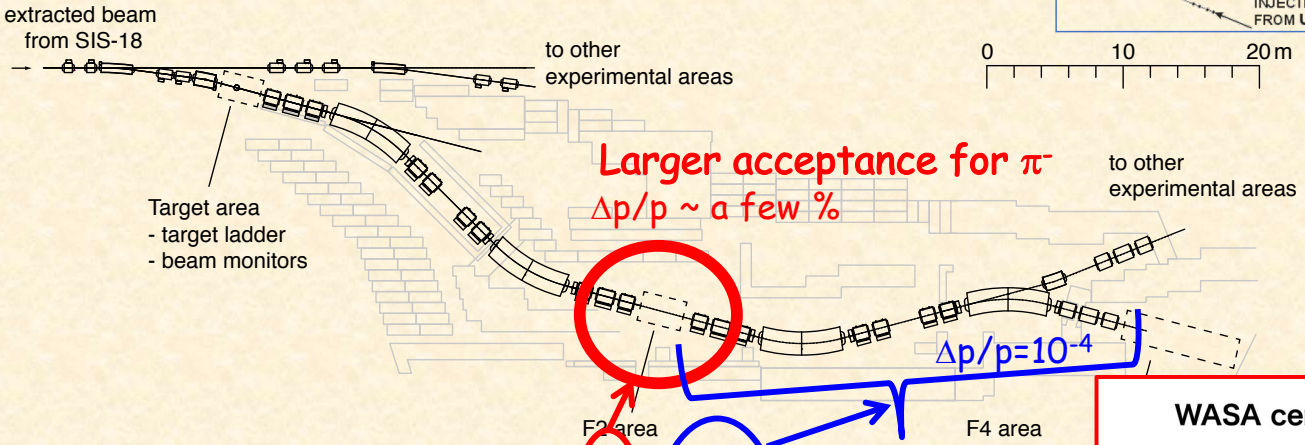

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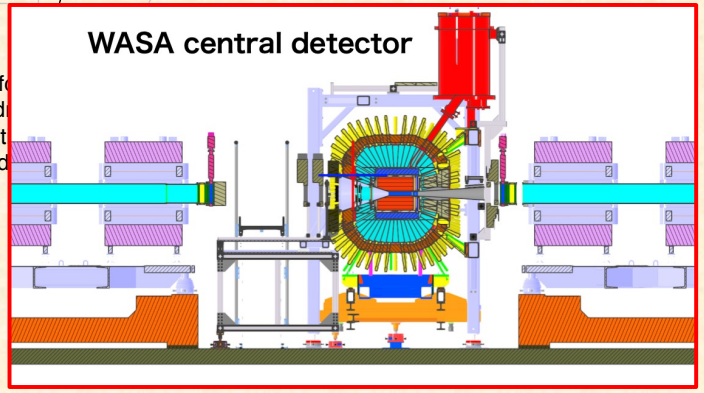
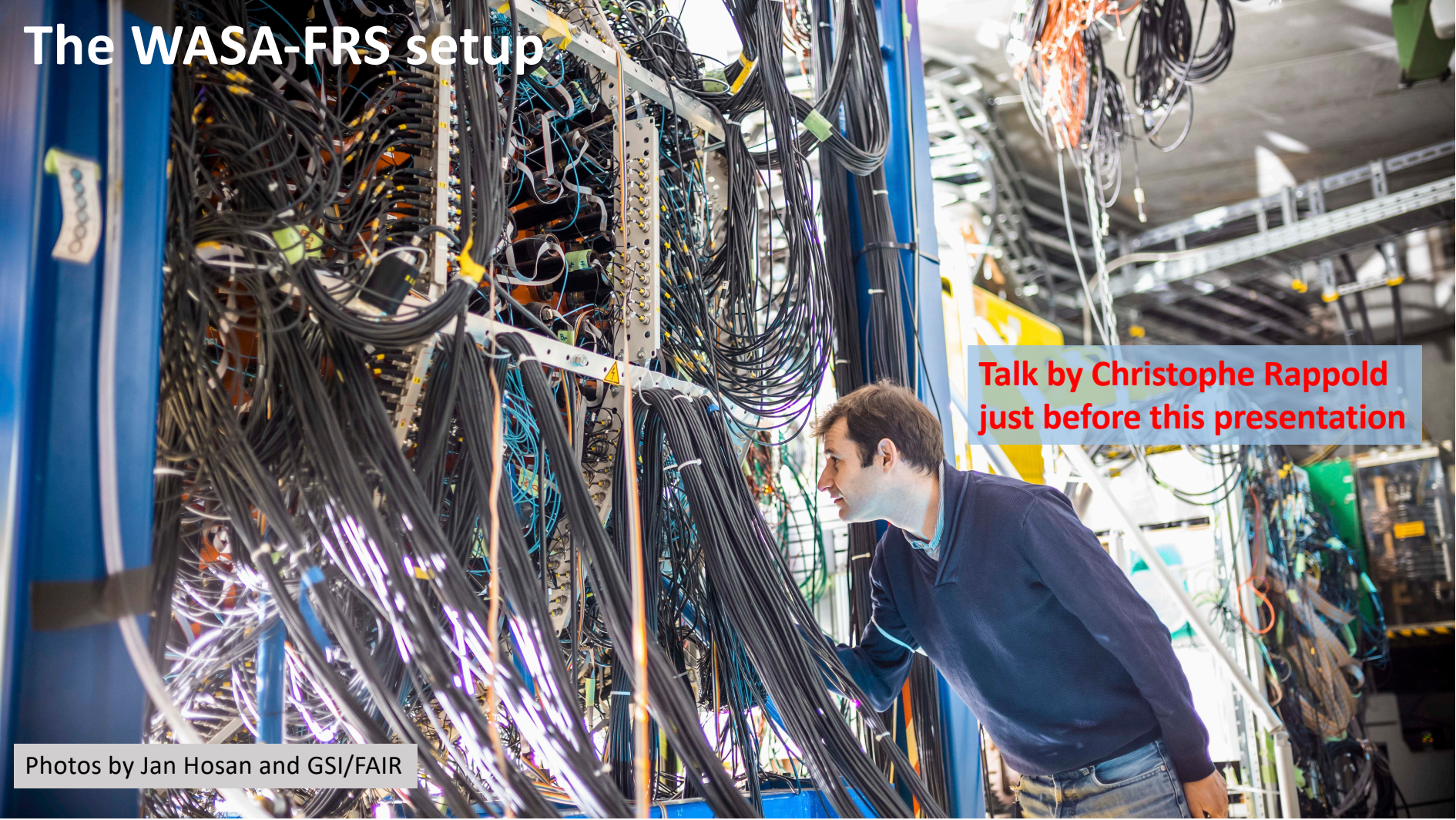


The WASA-FRS setup



Talk by Christophe Rappold just before this presentation

Photos by Jan Hosan and GSI/FAIR

The WASA-FRS collaboration

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Author list of the EMIS2022 proceedings

Part of the WASA-FRS collaboration

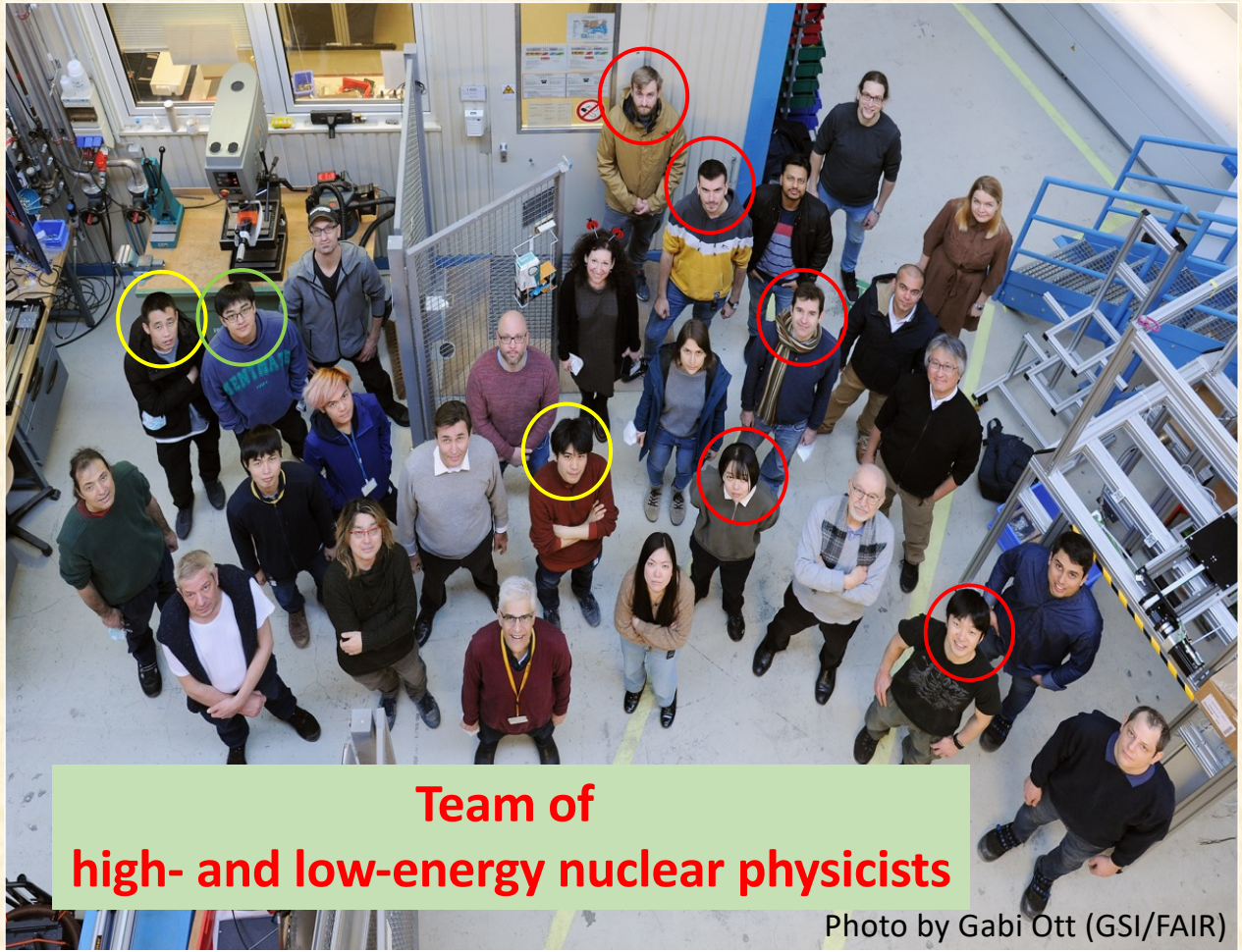


Photo by Gabi Ott (GSI/FAIR)

Data taking (January – March 2022)

Run	Period	Data size
Commissioning run	28th Jan. - 7th Feb.	7 TB
Physics run for η' nuclei	22nd Feb. - 28th Feb.	40 TB
Physics run for HypHI	10th Mar. - 19th Mar.	48 TB

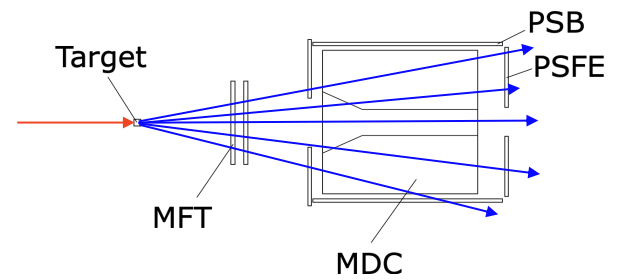
92 % of the prop.

Acquired data for S447 (hypernuclei)

Beam	Fragment at S4	Amount	Time	Accepted trigger rate	
^{6}Li beam	^{3}He	3.3×10^{8}	40.9 hours	2600 Hz	$^{3}_{\Lambda}$H
	^{4}He	0.9×10^{8}	43.9 hours	1800 Hz	$^{4}_{\Lambda}$H
	deuteron	1.8×10^{8}			nnΛ
	proton (mid-rapidity)	5.3×10^{6}	3.2 hours	680 Hz	Λ
^{12}C beam	^{3}He	1.0×10^{8}	13.5 hours	2400 Hz	$^{3}_{\Lambda}$H
	^{9}C	2.4×10^{5}			$^{9}_{\Lambda}$B

Graph Neural Network (GNN) for WASA

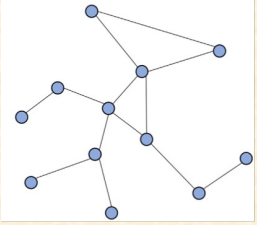
Track Finding

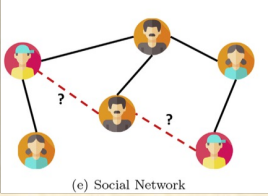


- Multi particles in HI reaction
- Combinatorial background

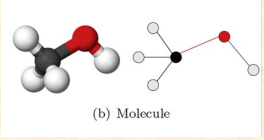
Track Finding with Graph Neural Network (GNN)

Graph





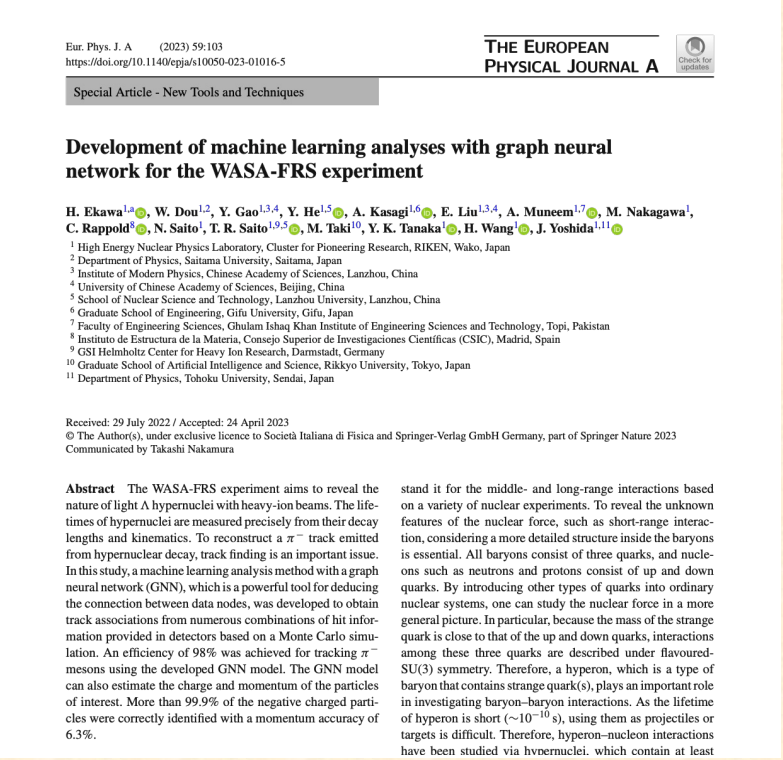
(e) Social Network



(b) Molecule

- Node : Data point
- Edge : Connection

Jie Zhou *et al.*, AI Open 1 (2020) 57–81



Eur. Phys. J. A (2023) 59:103
https://doi.org/10.1140/epja/s10050-023-01016-5

THE EUROPEAN PHYSICAL JOURNAL A

Special Article - New Tools and Techniques

Development of machine learning analyses with graph neural network for the WASA-FRS experiment

H. Ekawa[1,a], W. Dou[1,2], Y. Gao[1,3,4], Y. He[1,5], A. Kasagi[1,6], E. Liu[1,3,4], A. Muneem[1,7], M. Nakagawa[1], C. Rappold[8], N. Saito[1], T. R. Saito[1,9,5], M. Taki[10], Y. K. Tanaka[1], H. Wang[1], J. Yoshida[1,11]

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Communicated by Takashi Nakamura

Abstract The WASA-FRS experiment aims to reveal the nature of light Λ hypernuclei with heavy-ion beams. The lifetimes of hypernuclei are measured precisely from their decay lengths and kinematics. To reconstruct a π^- track emitted from hypernuclear decay, track finding is an important issue. In this study, a machine learning analysis method with a graph neural network (GNN), which is a powerful tool for deducing the connection between data nodes, was developed to obtain track associations from numerous combinations of hit information provided in detectors based on a Monte Carlo simulation. An efficiency of 98% was achieved for tracking π^- mesons using the developed GNN model. The GNN model can also estimate the charge and momentum of the particles of interest. More than 99.9% of the negative charged particles were correctly identified with a momentum accuracy of 6.3%.

stand it for the middle- and long-range interactions based on a variety of nuclear experiments. To reveal the unknown features of the nuclear force, such as short-range interaction, considering a more detailed structure inside the baryons is essential. All baryons consist of three quarks, and nucleons such as neutrons and protons consist of up and down quarks. By introducing other types of quarks into ordinary nuclear systems, one can study the nuclear force in a more general picture. In particular, because the mass of the strange quark is close to that of the up and down quarks, interactions among these three quarks are described under flavoured-SU(3) symmetry. Therefore, a hyperon, which is a type of baryon that contains strange quark(s), plays an important role in investigating baryon–baryon interactions. As the lifetime of hyperon is short ($\sim 10^{-10}$ s), using them as projectiles or targets is difficult. Therefore, hyperon–nucleon interactions have been studied via hypernuclei, which contain at least

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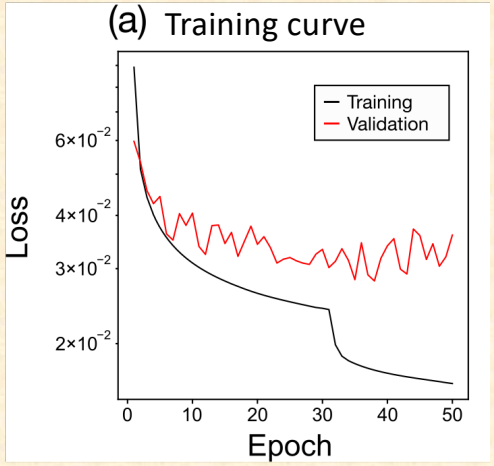
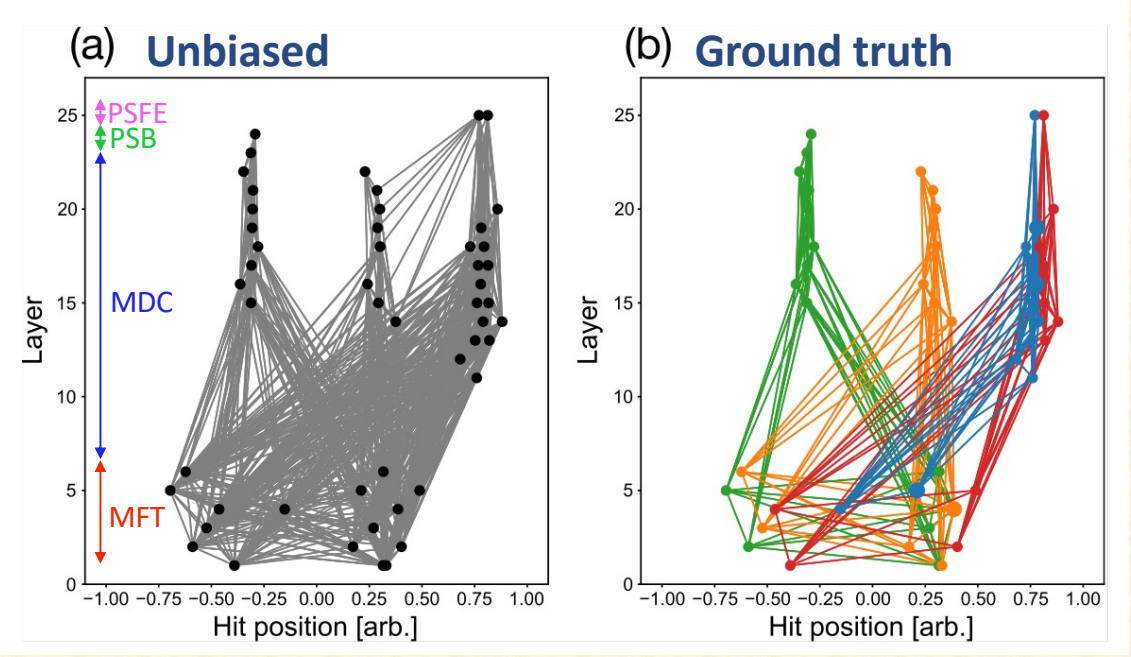
H. Ekawa et al., Eur. Phys. J. A (2023) **59**, 103
DOI : 10.1140/epja/s10050-023-01016-5

GNN: Node clustering

Machine Learning

- PyTorch + PyTorch Geometric
- Monte Carlo (MC) simulation
  - Training, Validation, Test
- Learning object
  - Edge : ON / OFF
  - Node : Shared / Not-Shared

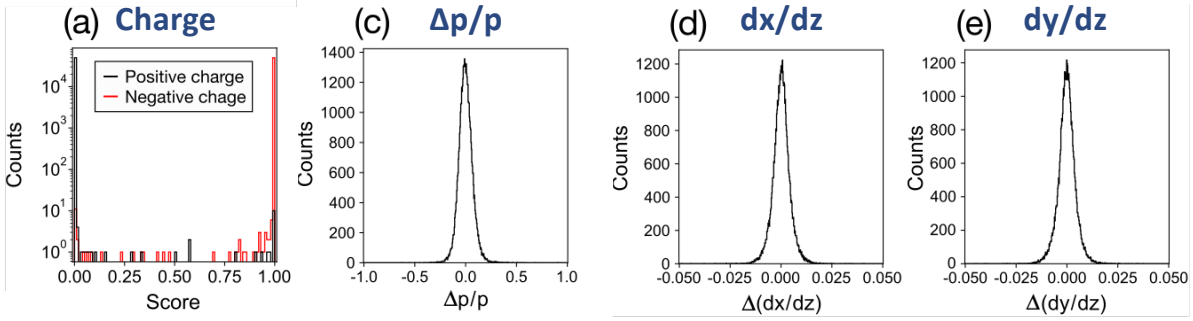




H. Ekawa et al., Eur. Phys. J. A (2023) **59**, 103

GNN: Performance with MC

Data size	Clustering efficiency for π^-	Clustering efficiency for others	Training time [h/epoch]
100k	96.3%	95.1%	0.6
300k	97.4%	96.2%	2.0
1M	98.1%	97.1%	7.5



Data size	Eff.	False-positive	$\frac{\Delta p}{p}$	$\Delta \frac{dx}{dz}$ [mrad]	$\Delta \frac{dy}{dz}$ [mrad]	Training time[h/epoch]
500k	99.70%	0.07%	9.9%	6.1	6.0	0.2
1M	99.82%	0.04%	8.5%	5.3	5.3	0.4
2M	99.92%	0.03%	6.8%	4.1	4.1	0.8
4M	99.95%	0.04%	6.3%	3.7	3.7	1.5

cf. Kalman filter

Δp/p : 9.9 %

Δ(dx/dz), Δ(dy/dz) : 3.0 mrad

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

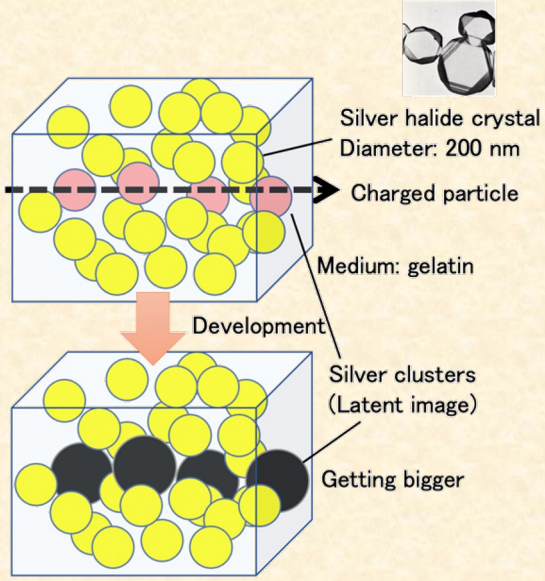
How about
the hypernuclear binding energy?

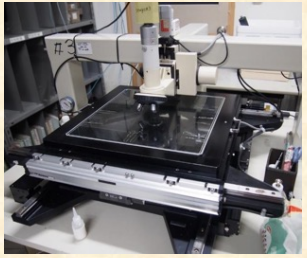
Nuclear Emulsion:

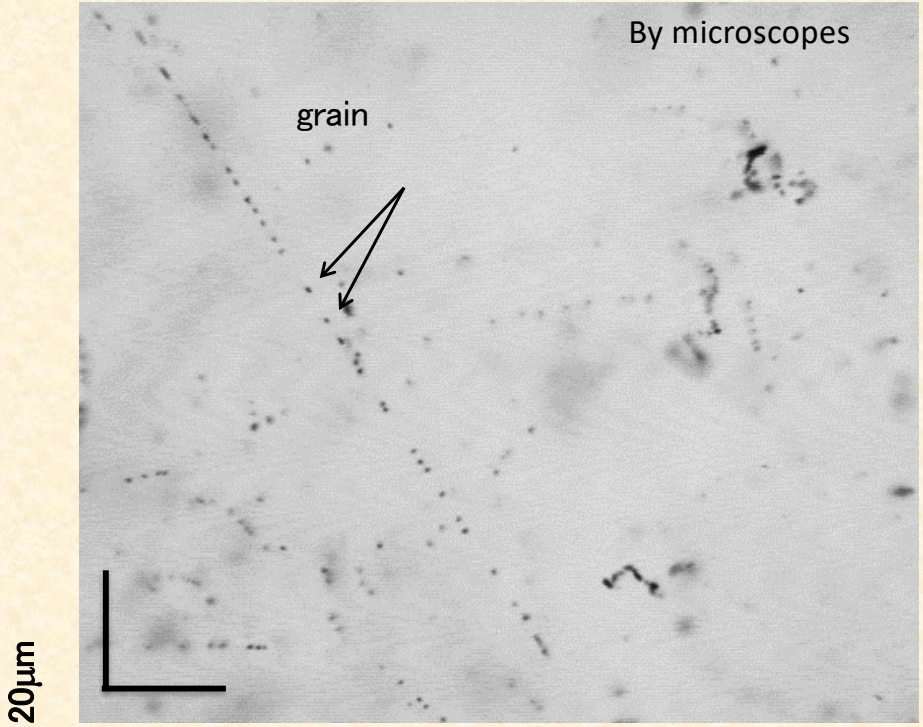
Charged particle tracker with

the best spatial resolution

(easy to be < 1 μm, 11 nm at best)

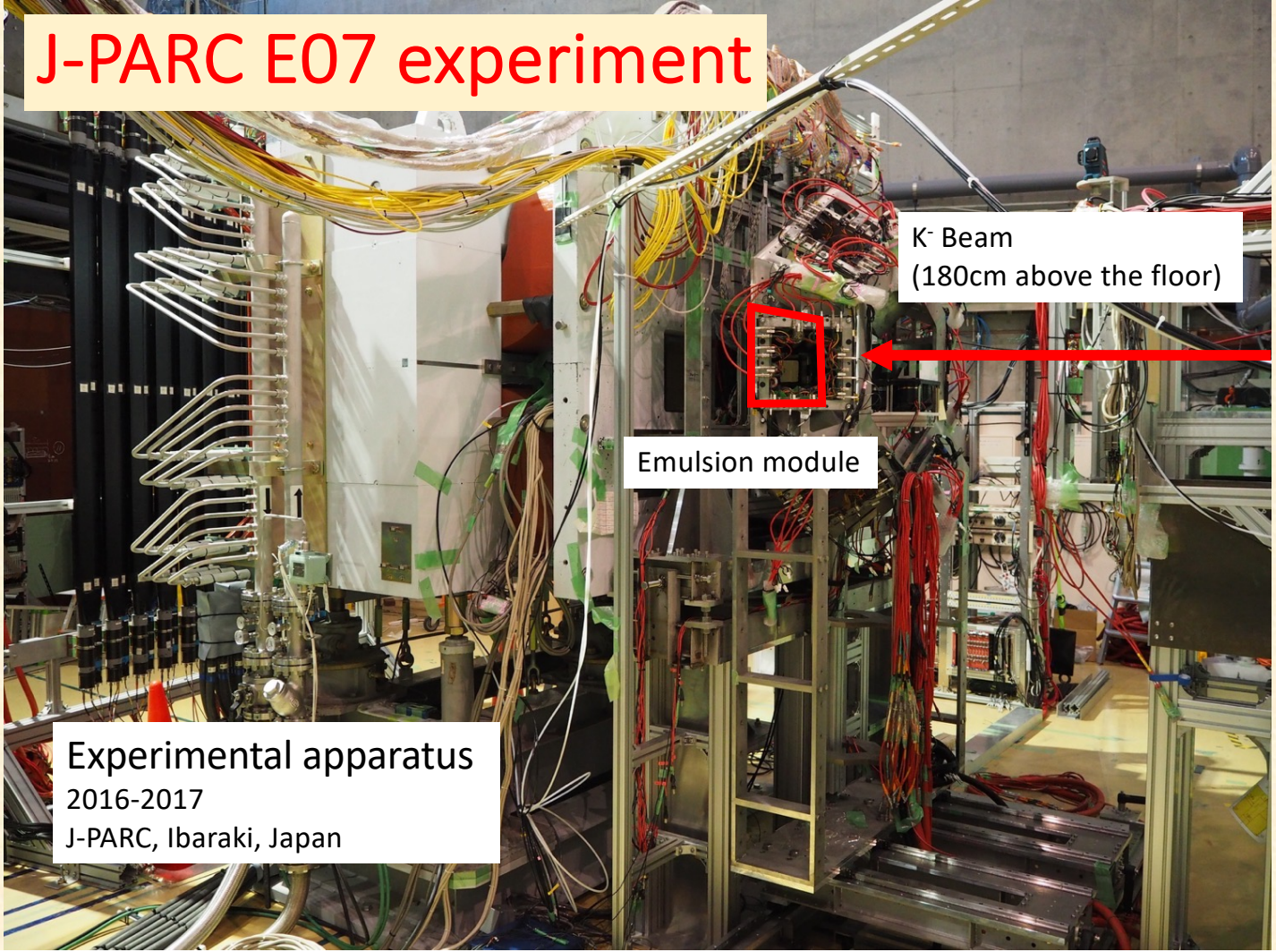






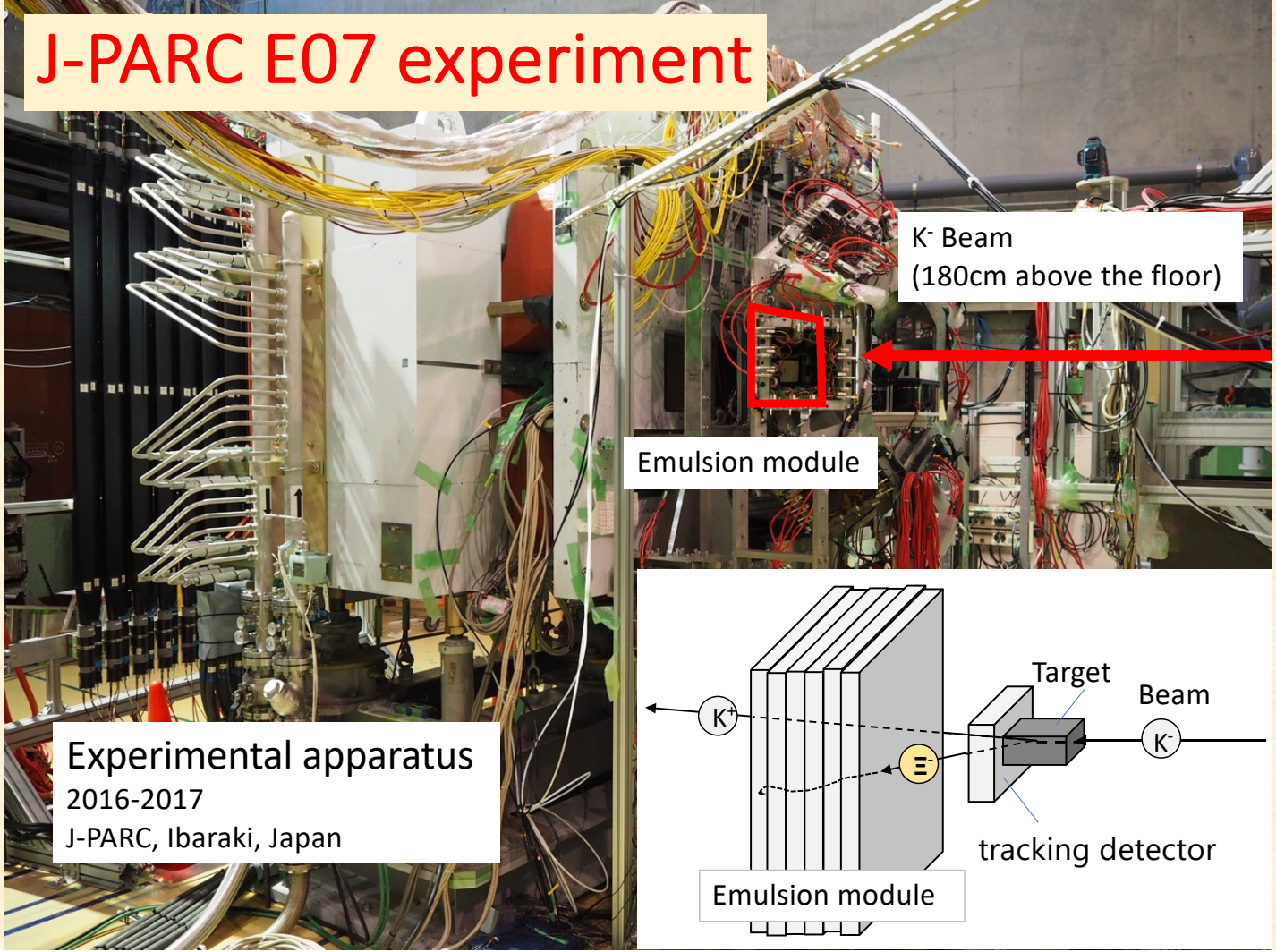
J-PARC accelerator facility

J-PARC E07 experiment

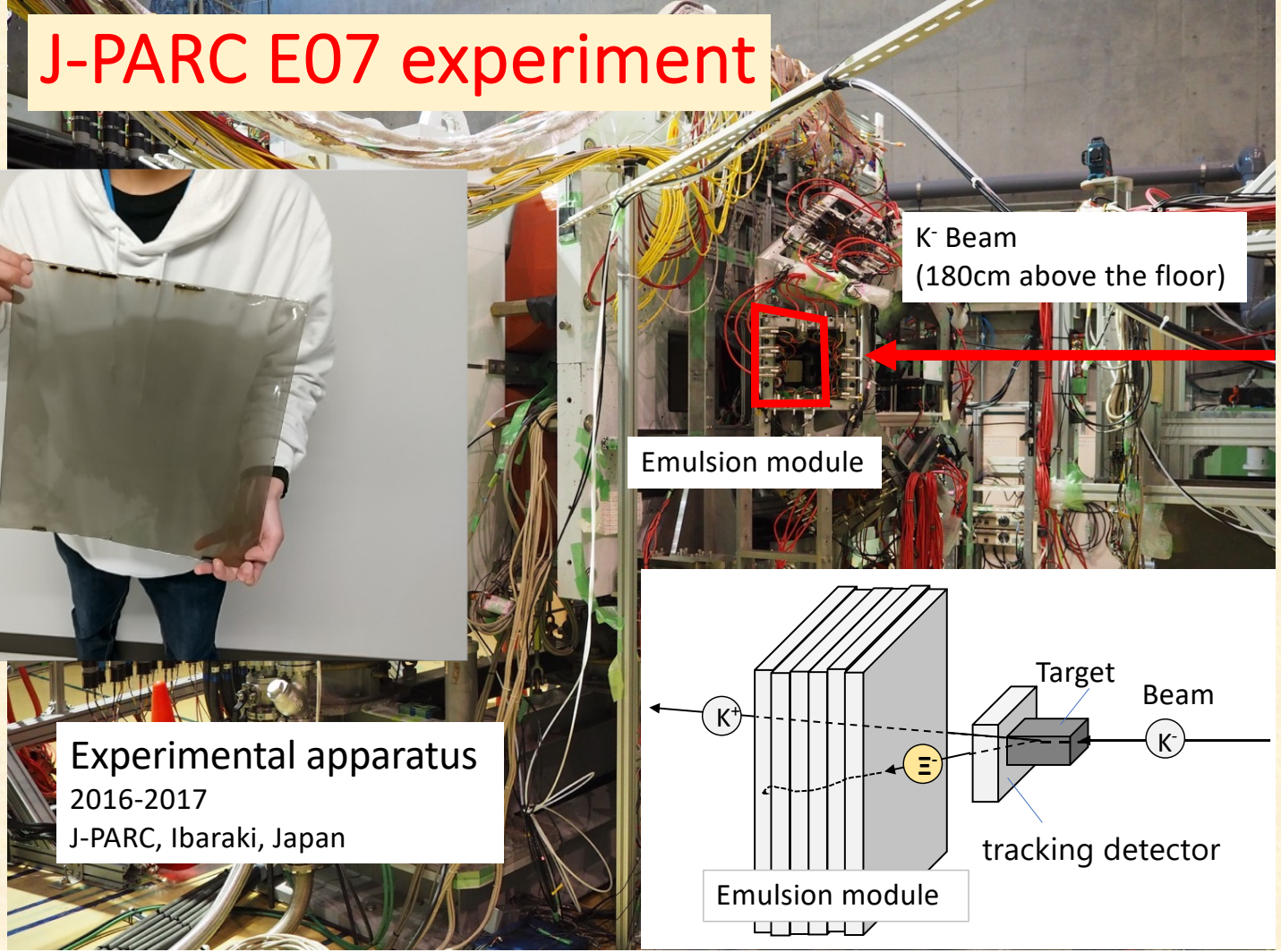


Experimental apparatus
2016-2017
J-PARC, Ibaraki, Japan

J-PARC E07 experiment



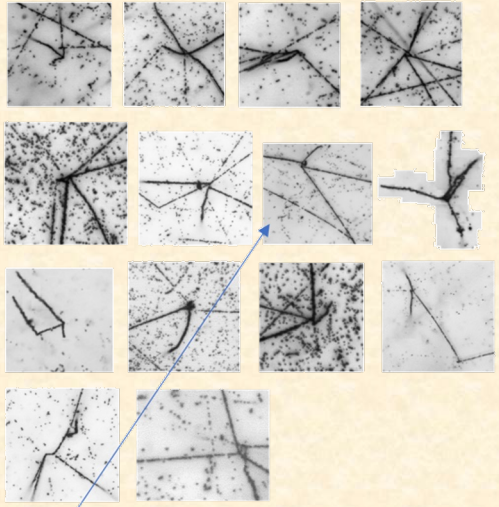
J-PARC E07 experiment



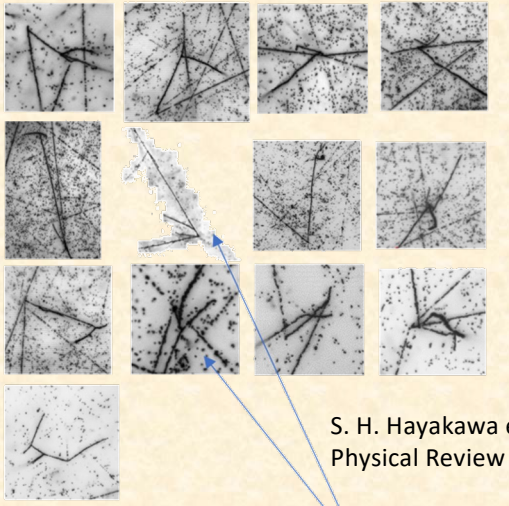
Experimental apparatus
2016-2017
J-PARC, Ibaraki, Japan

Results from J-PARC E07 (Hybrid method)

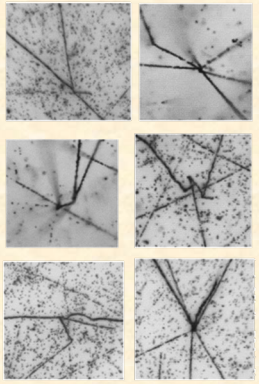
$\Lambda\Lambda$ candidates: 14



Twin Λ events: 13



Others: 6



S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

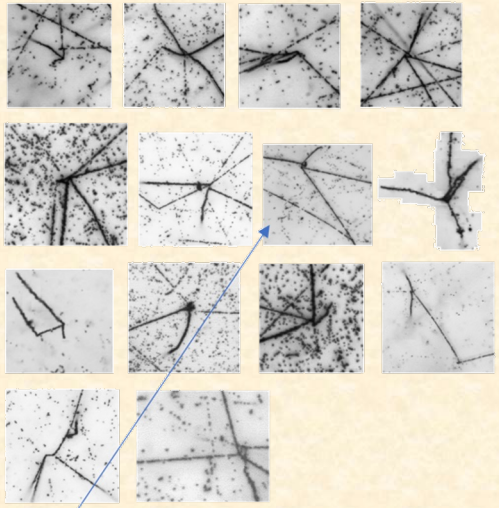
M. Yoshimoto et al.,
Prog. Theor. Exp. Phys. 2021, 073D02

$^{15}_{\Xi}C$

$^{\Lambda\Lambda}Be$
H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

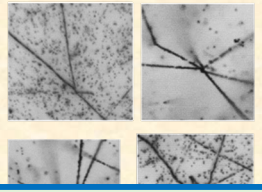
Results from J-PARC E07 (Hybrid method)

ΛΛ candidates: 14



Twin Λ events: 13

Others: 6



Non-triggered events recorded in 1000 emulsions sheets

- 1000 double-strangeness (ΛΛ- and Ξ-) hypernuclear events
- Millions of single-strangeness hypernuclear events

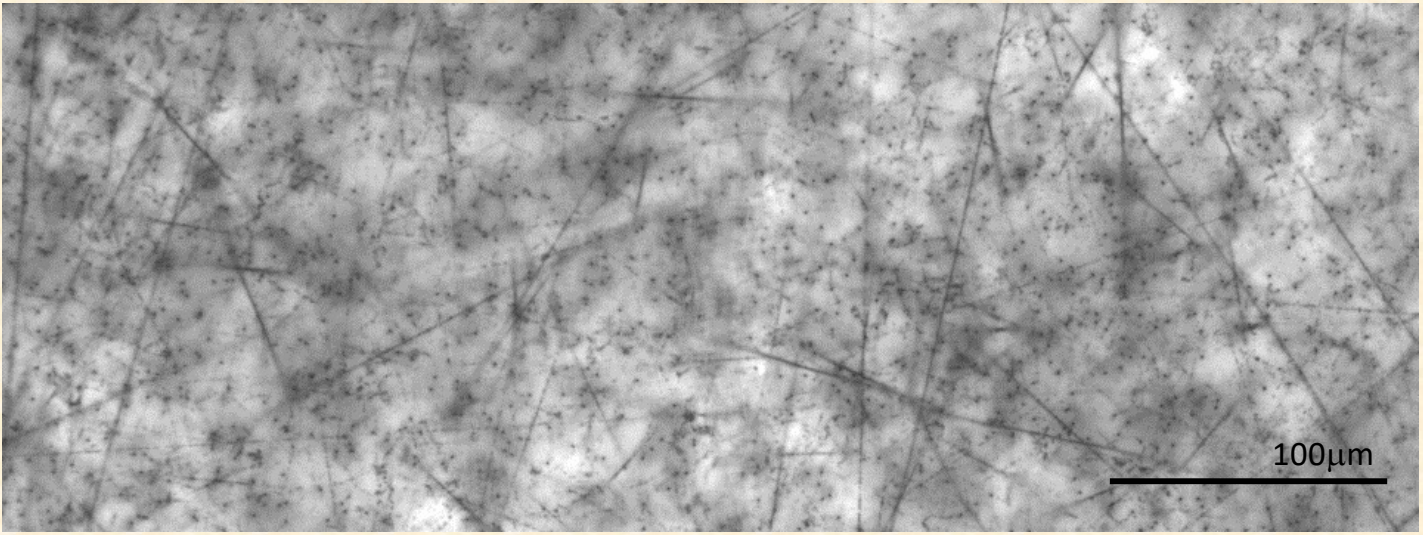
Overall scanning of all emulsion sheets
(35 X 35 cm^2 X 1000)

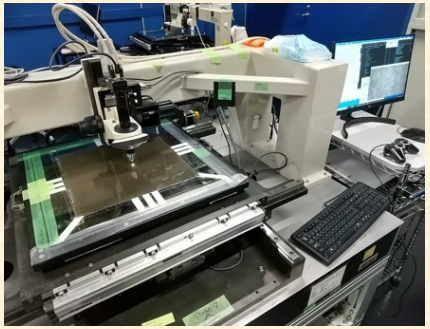
M. Yoshimoto
Prog. Theor. Exp. Phys. 2021, 073D02

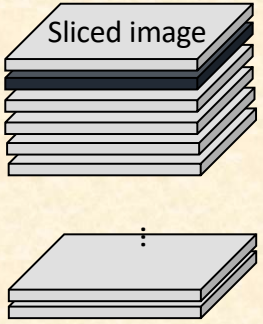
$^{15}_{\Xi}$C

$^{\Lambda\Lambda}$Be
H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

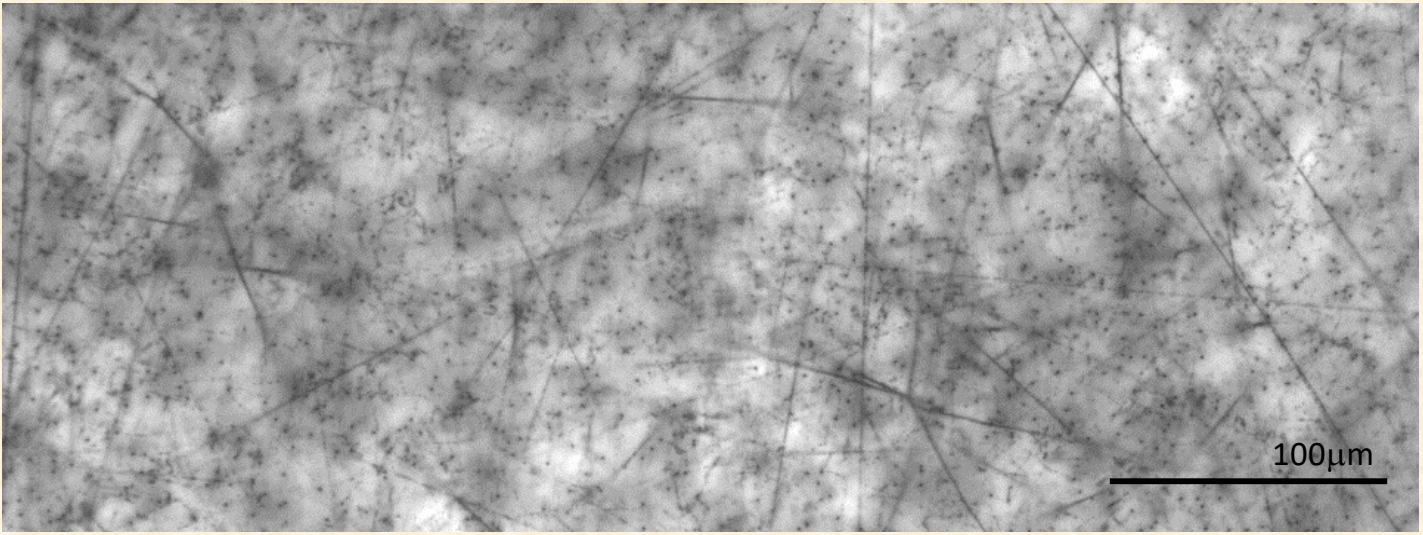
Overall scanning for E07 emulsions

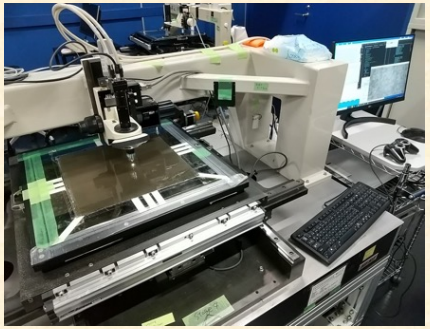


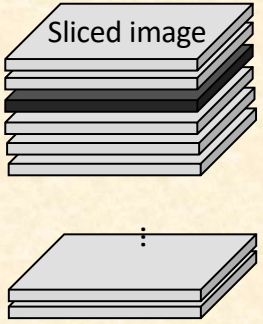




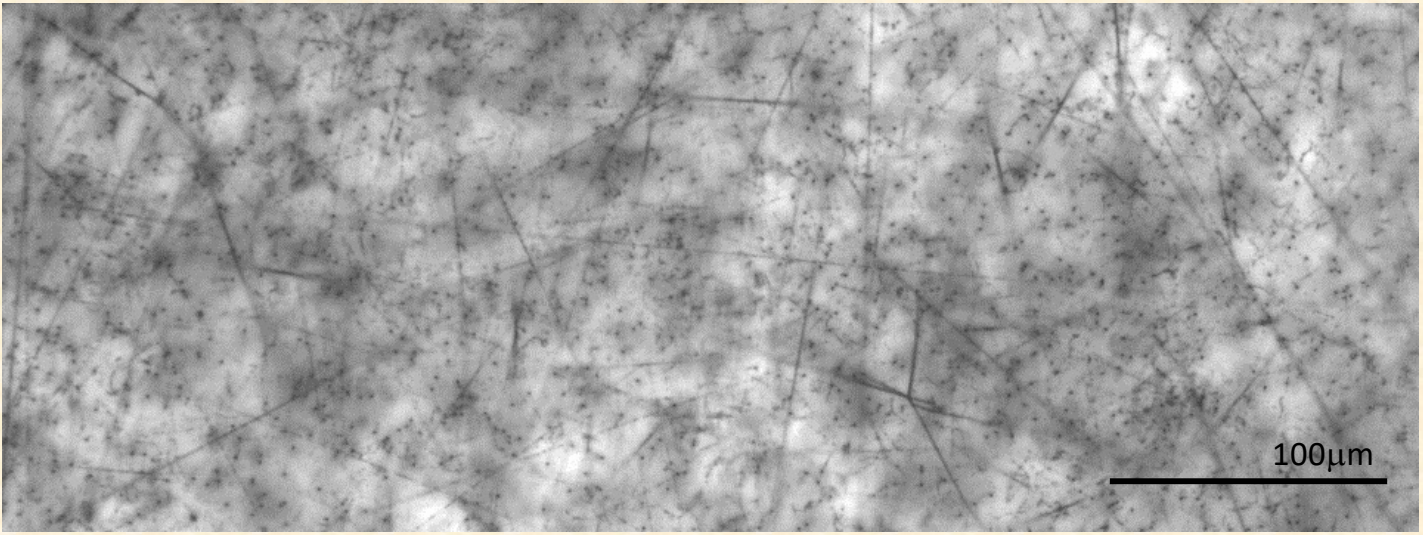
Overall scanning for E07 emulsions

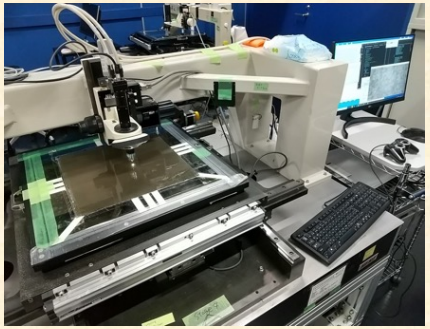


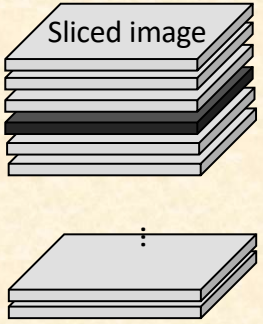




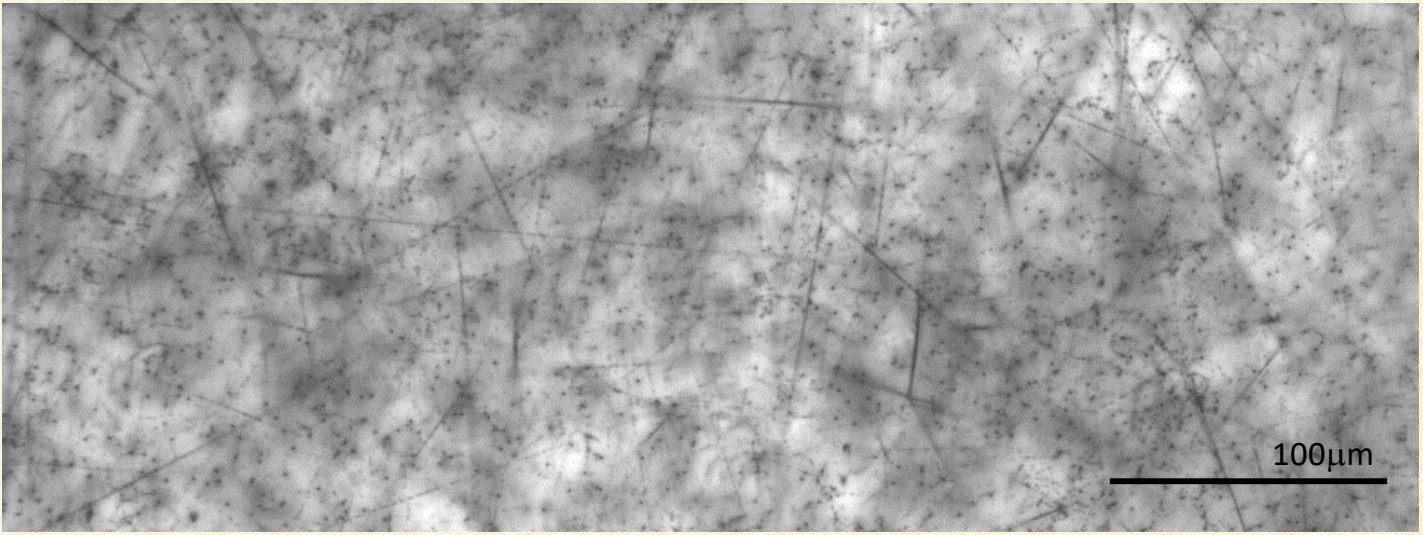
Overall scanning for E07 emulsions

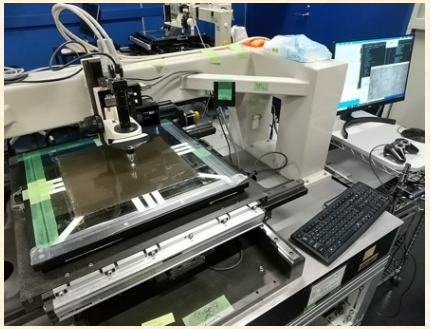


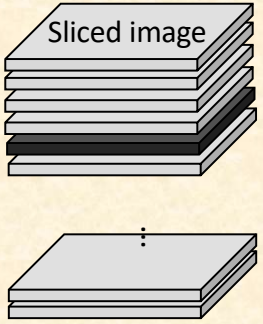




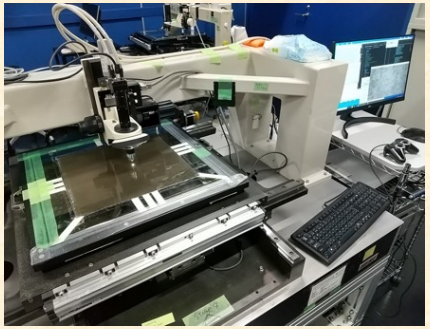
Overall scanning for E07 emulsions







Overall scanning for E07 emulsions



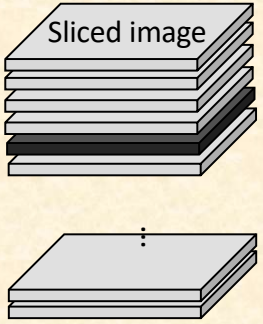
Data size:
- 10^7 images per emulsion (100 T Byte)
- 10^{10} images per 1000 emulsions (100 P Byte)

Number of background tracks:
- Beam tracks: $10^4/mm^2$
- Nuclear fragmentations: $10^3/mm^2$

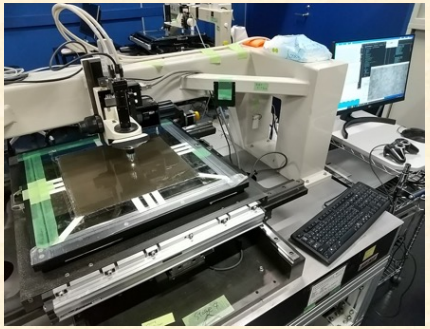
Current equipments/techniques with visual inspections

560 years

100μm



Overall scanning for E07 emulsions



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Number of background tracks:
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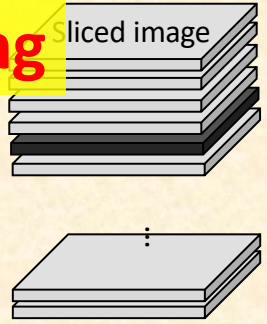
- Nuclear fragmentations: $10^3/mm^2$

Current equipments/techniques with visual inspections

560 years

3 years

Machine Learning



Millions of single-strangeness hypernuclei
1000 double strangeness hypernuclei (formerly only 5)

Setup for analyzing emulsions at the High Energy Nuclear Physics Laboratory in RIKEN

- Hypernuclear physics
- Neutron imaging

Challenges for Machine Learning Development

MOST IMPORTANT:

- **Quantity and quality of training data**

However,

No existing data for hypertriton with emulsions for training

Our approaches:

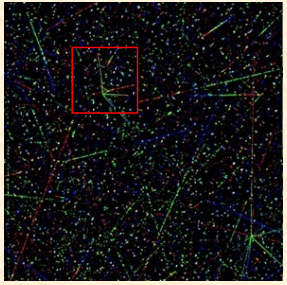
Producing training data with

- Monte Carlo simulations
- Image transfer techniques

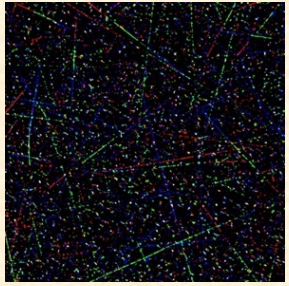
Production of training data

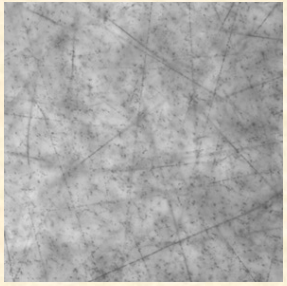
Monte Carlo simulations and GAN(Generative Adversarial Networks)

Binarized tracks from MC simulations
+ background from the real data



Imitated
emulsion image





Binarized (like for simulations)

Real emulsion image

GAN: pix2pix

Ayumi Kasagi. Ph.D. thesis (2023)
A. Kasagi et al., submitted to NIM A

Production of training data

Monte Carlo simulations and GAN(Generative Adversarial Networks)

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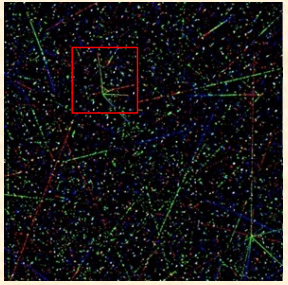
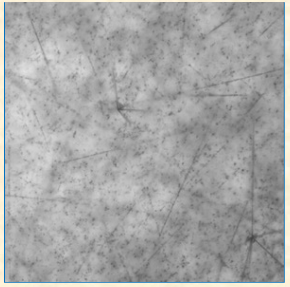
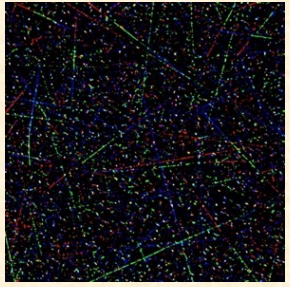
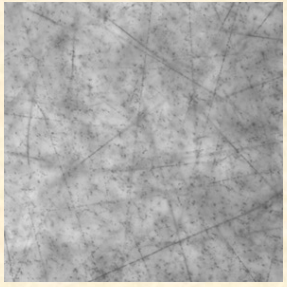


Produced training data







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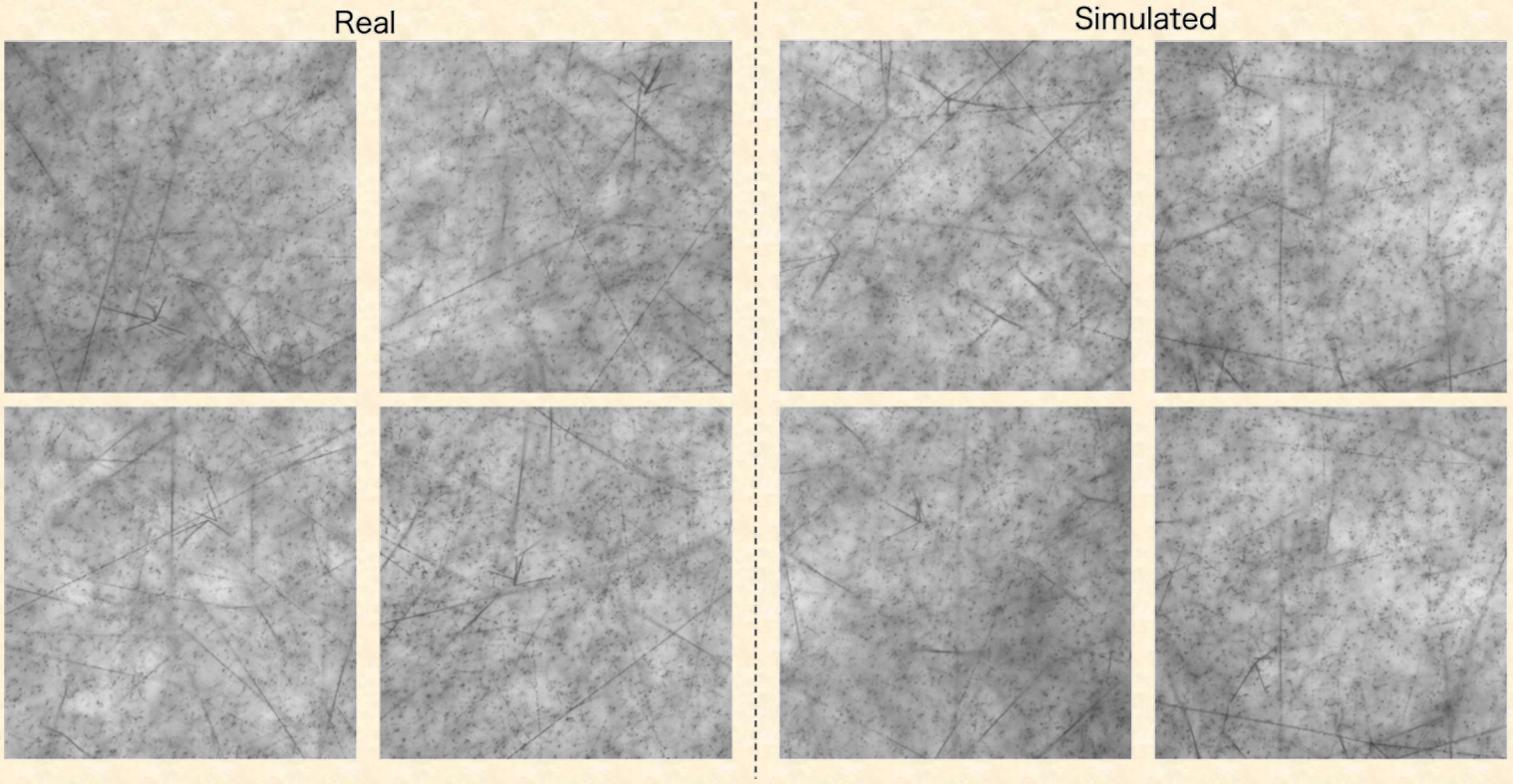
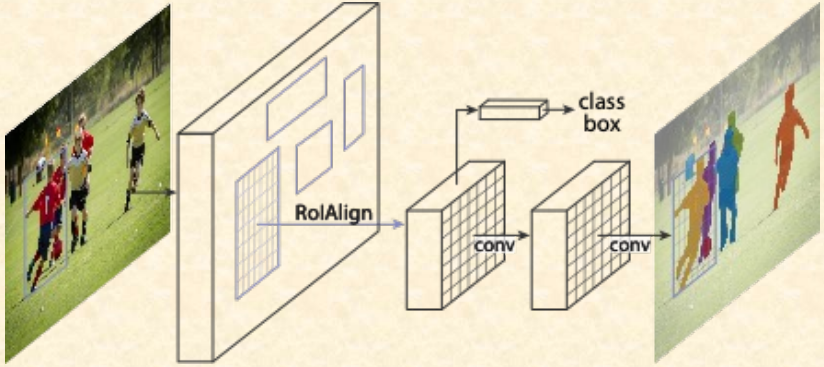
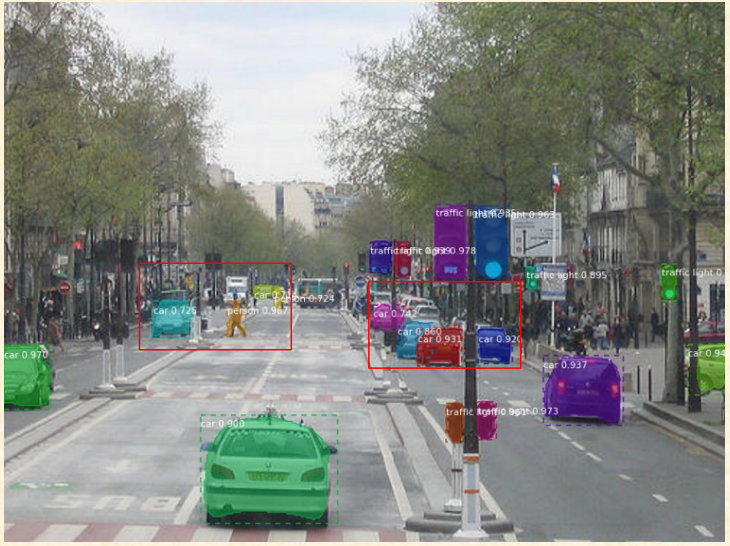


Detection of hypertriton events

With Mask R-CNN model

K. He, et al., arXiv https://arxiv.org/ abs/1703.06870 (2017).





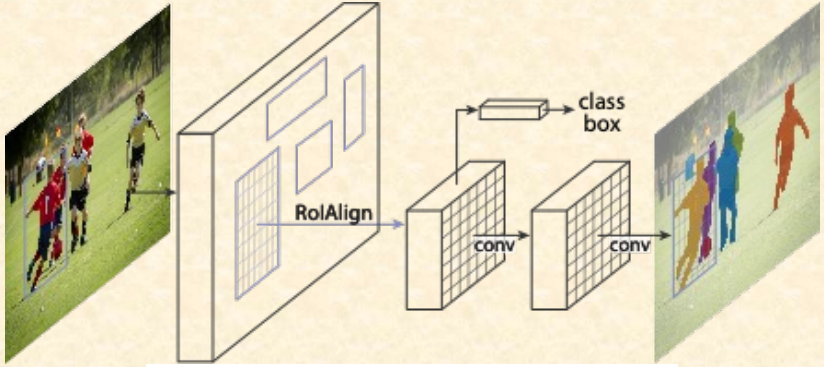
Detection of each object

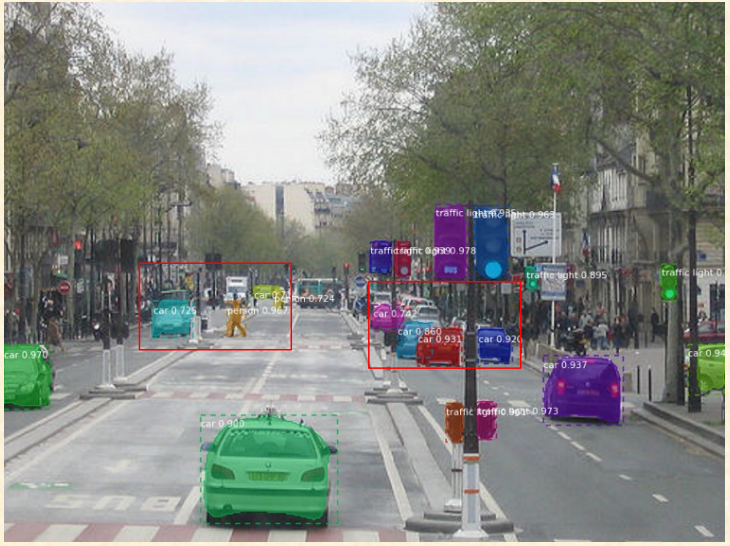
At large object density

Detection of hypertriton events

With Mask R-CNN model

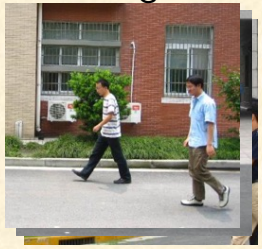
K. He, et al., arXiv https://arxiv.org/ abs/1703.06870 (2017).





Example of training dataset

Image



Mask

A Pedestrian dataset

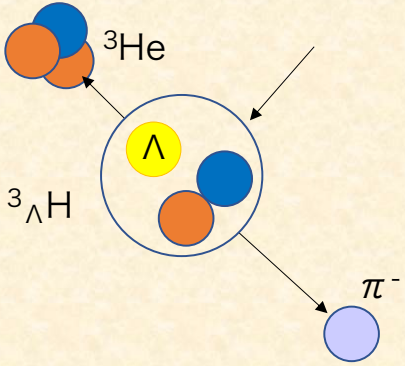
https://www.cis.upenn.edu/~jshi/ped_html/

Detection of each object

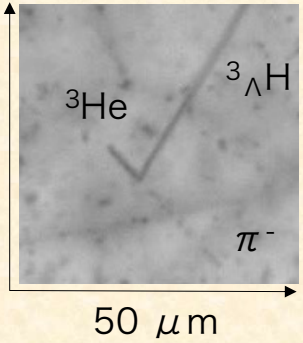
At large object density

Hypertriton search with Mask R-CNN

Two body decay of $^{3}_{\Lambda}H$

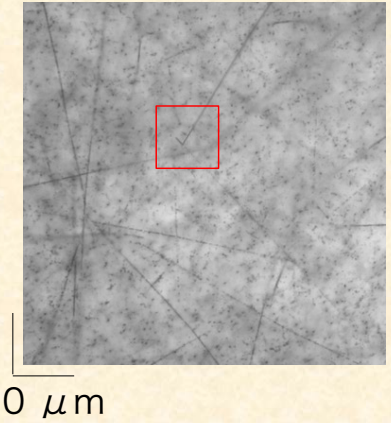


Simulated image

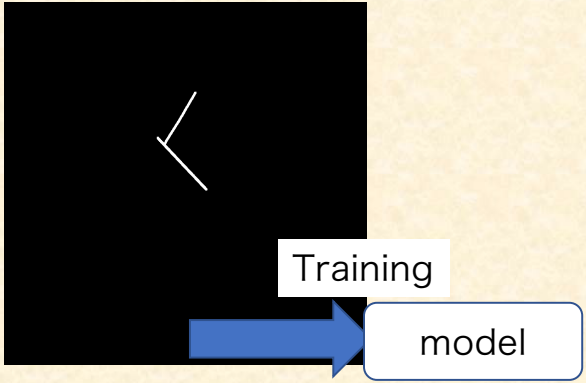


Training dataset (Simulated images)

Image



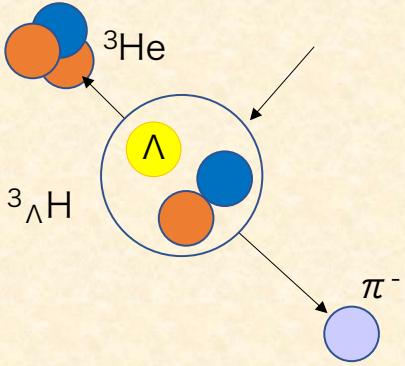
Mask



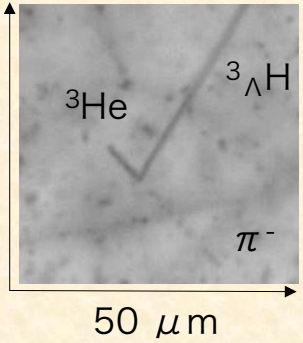
Ayumi Kasagi. Ph.D. thesis (2023)
A. Kasagi et al., submitted to NIM A

Hypertriton search with Mask R-CNN

Two body decay of $^{3}{}_{\Lambda}H$

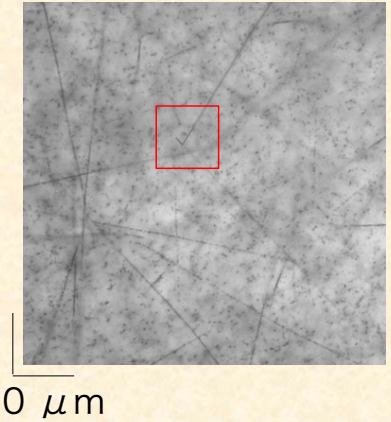


Simulated image

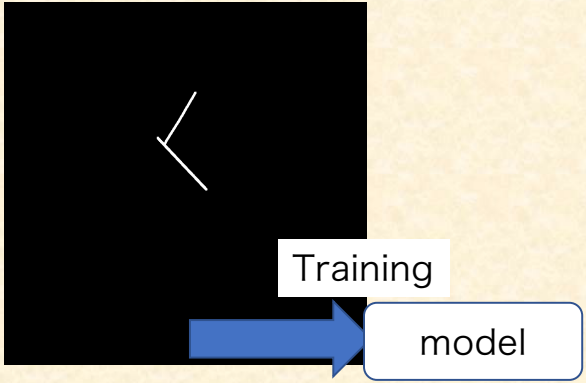


Training dataset (Simulated images)

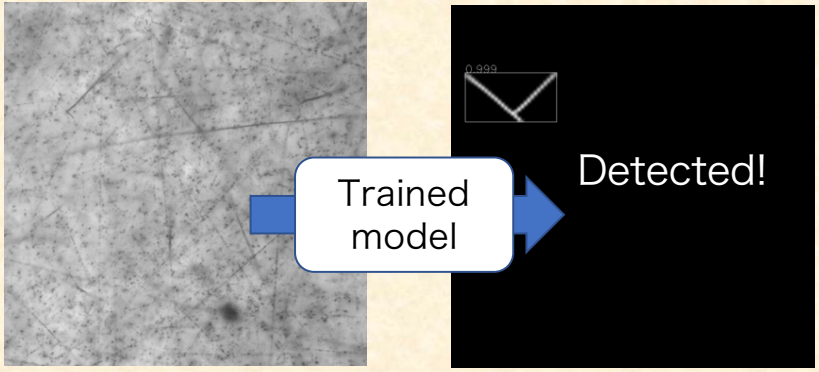
Image



Mask

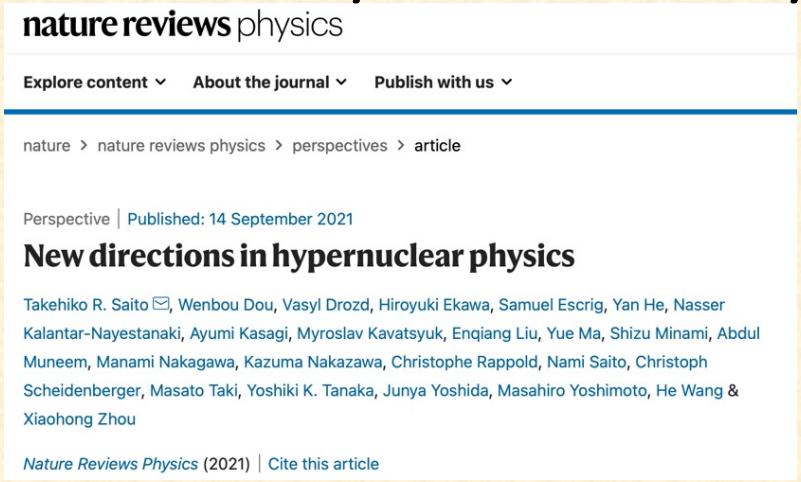


Real image



Ayumi Kasagi. Ph.D. thesis (2023)
A. Kasagi et al., submitted to NIM A

Discovery of the first hypertriton event in E07 emulsions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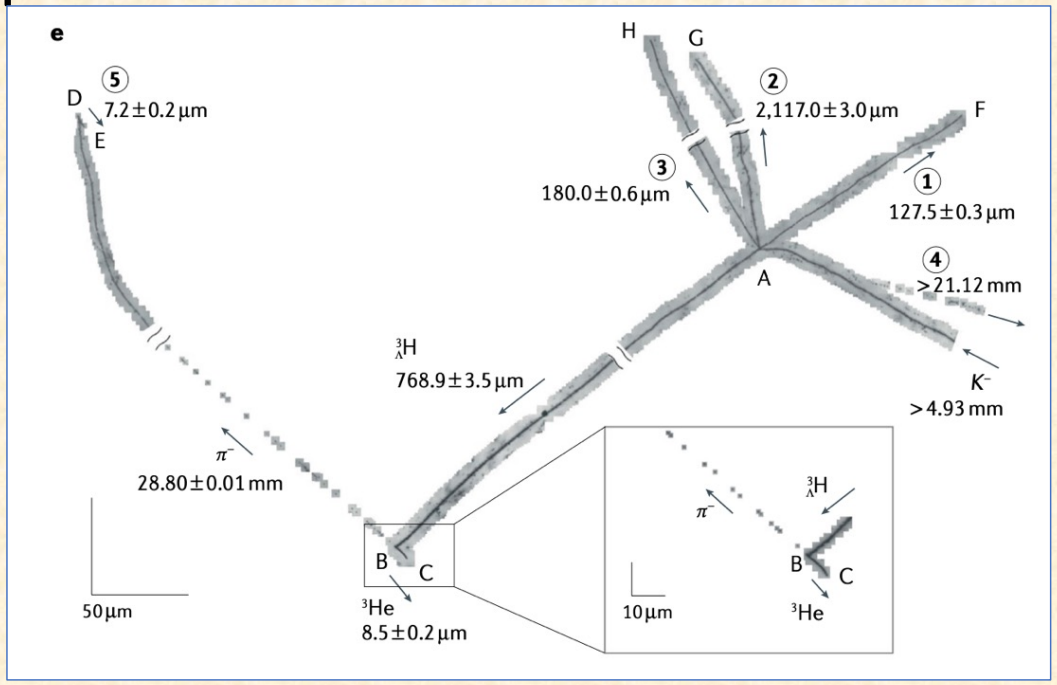
Perspective | Published: 14 September 2021

New directions in hypernuclear physics

Takehiko R. Saito, Wenbou Dou, Vasyl Drozd, Hiroyuki Ekawa, Samuel Escrig, Yan He, Nasser Kalantar-Nayestanaki, Ayumi Kasagi, Myroslav Kavatsyuk, Enqiang Liu, Yue Ma, Shizu Minami, Abdul Muneem, Manami Nakagawa, Kazuma Nakazawa, Christophe Rappold, Nami Saito, Christoph Scheidenberger, Masato Taki, Yoshiki K. Tanaka, Junya Yoshida, Masahiro Yoshimoto, He Wang & Xiaohong Zhou

Nature Reviews Physics (2021) | Cite this article

TRS et al., Nature Reviews Physics, 803-813 (2021)
Cover of December 2021 issue



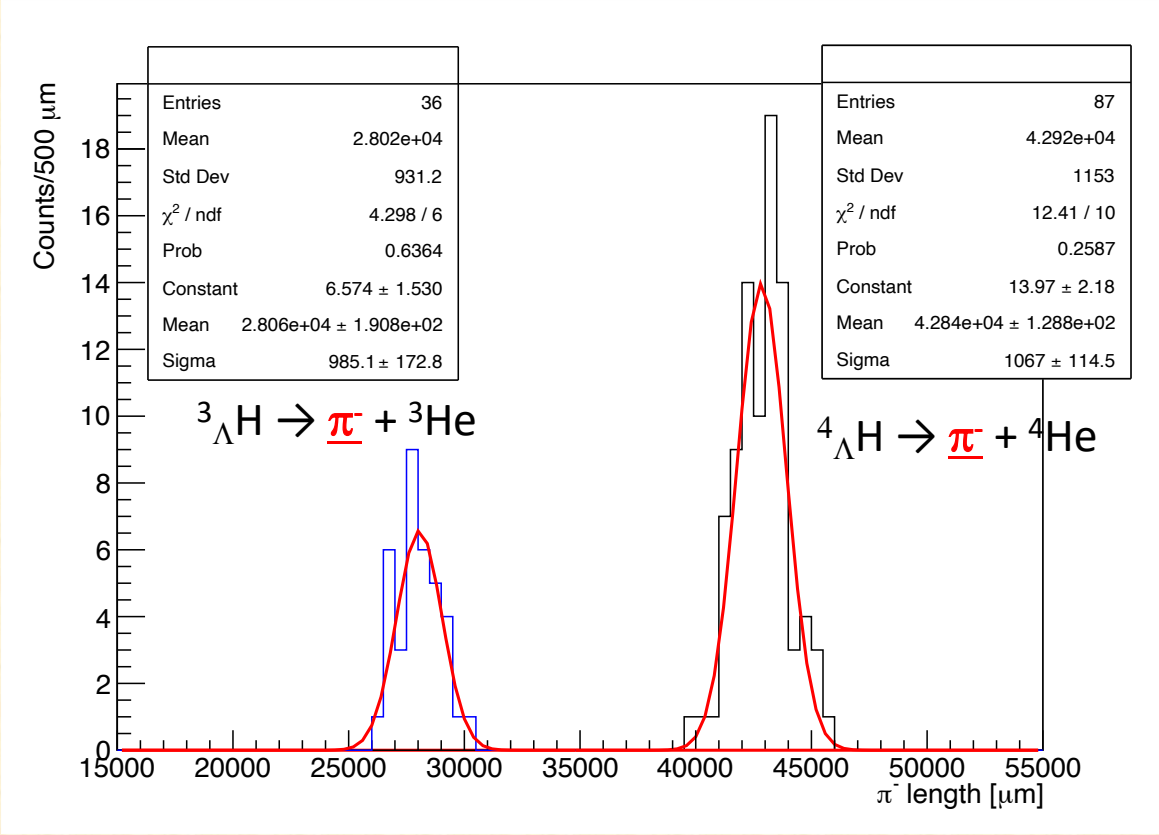
Guaranteeing the determination of the hypertriton binding energy SOON

Precision: 28 keV

E. Liu et al., EPJ A57 (2021) 327

Ayumi Kasagi. Ph.D. thesis (2023)
A. Kasagi et al., submitted to NIM A

Identification of hypertriton and $^{4}_{\Lambda}H$ by π^- track length



Ayumi Kasagi. Ph.D. thesis (2023)

Current status

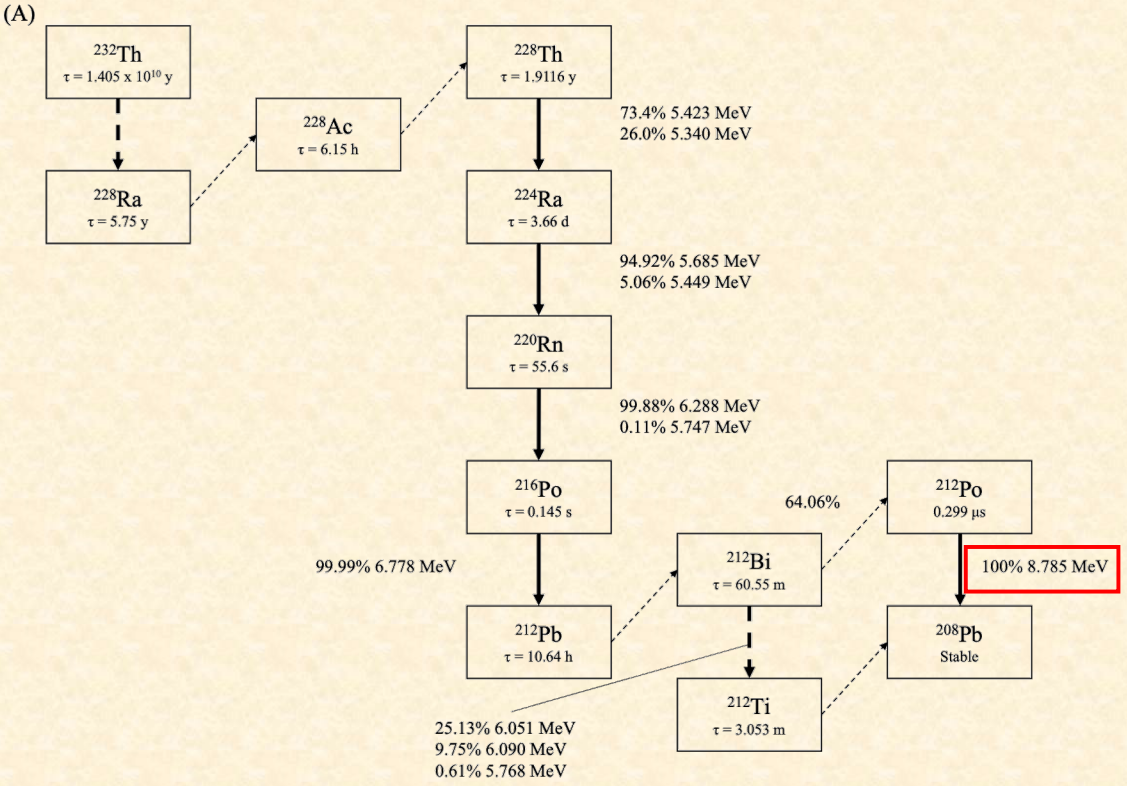
No. events: 174 (<u>0.4% of the entire E07 data</u>)

- $^{3}_{\Lambda}$H: 36
- $^{4}_{\Lambda}$H: 138 (Identified: 87 + Penetrated: 51)

Calibrated events: 143

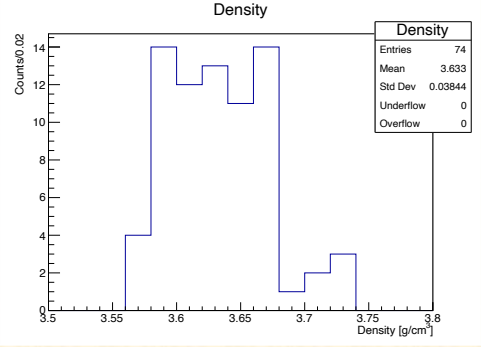
- $^{3}_{\Lambda}$H: 36
- $^{4}_{\Lambda}$H: 107 (Identified: 72 + Penetrated: 35)

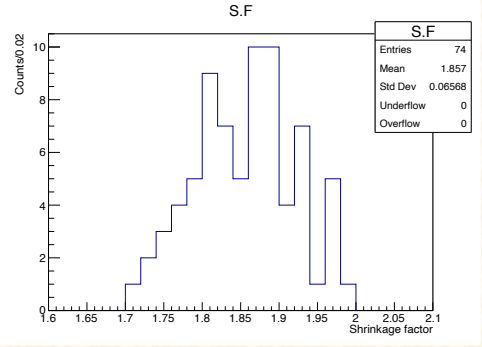
Calibration of nuclear emulsions

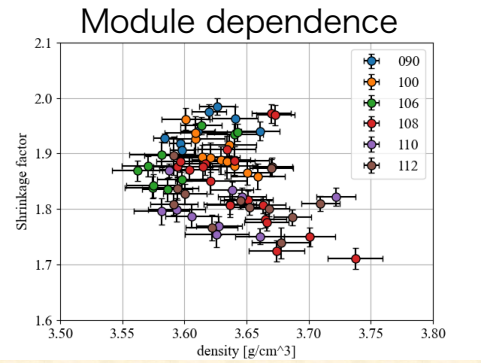


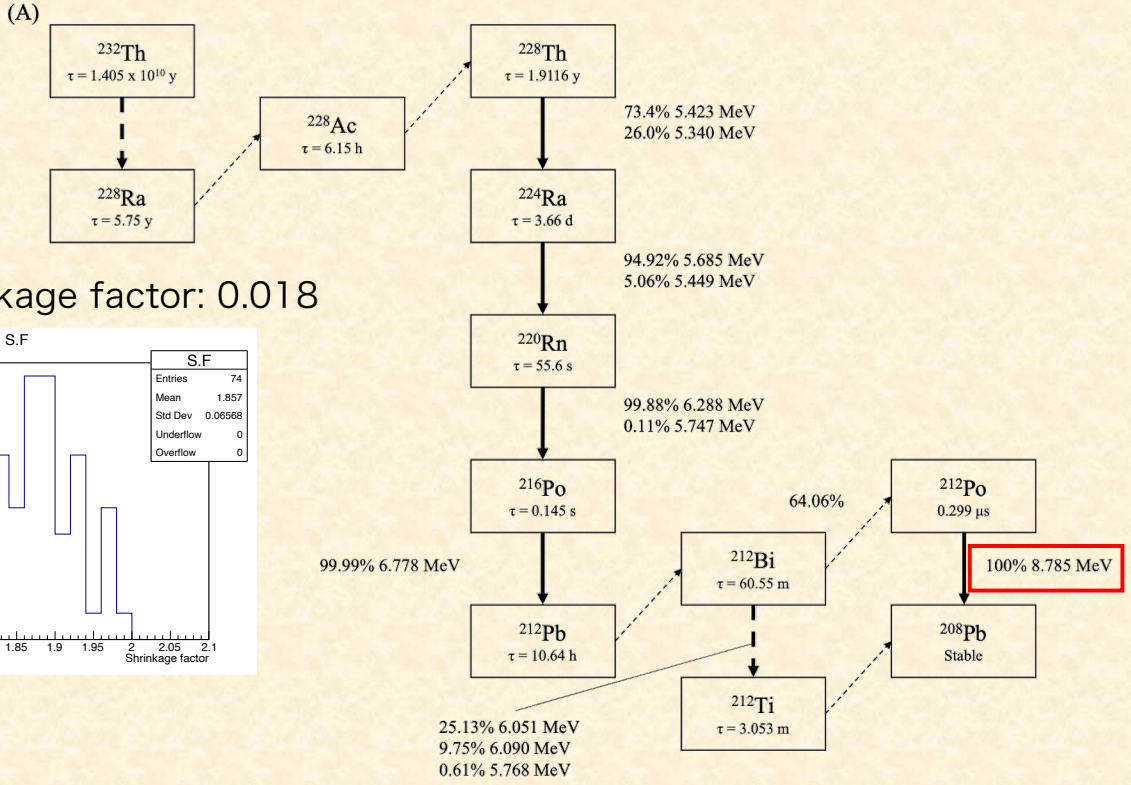
Calibration of nuclear emulsions

Tipical error: Density: 0.019 g/cm^3, Shrinkage factor: 0.018







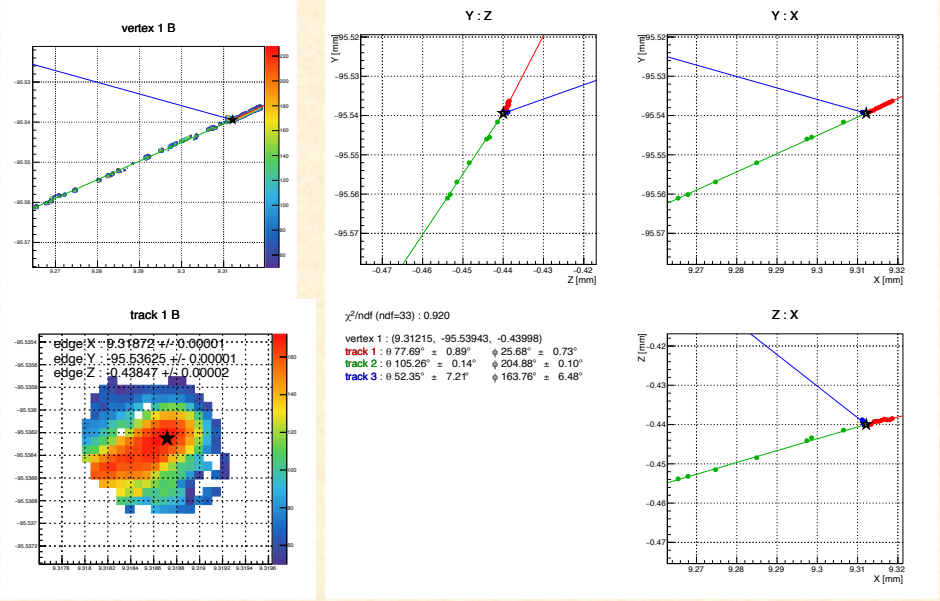


Ayumi Kasagi. Ph.D. thesis (2023)

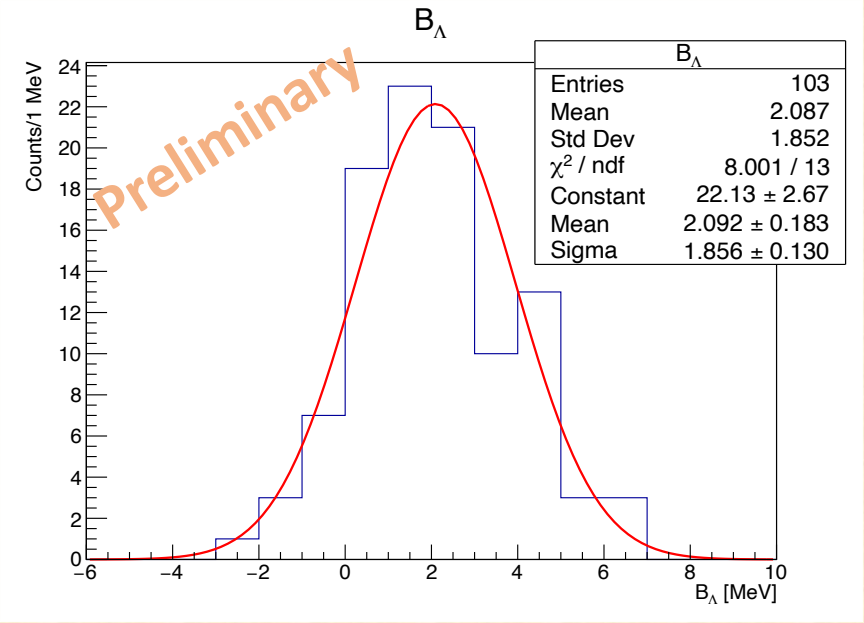
Analysis for $^{4}_{\Lambda}$H binding energy

- With measured Helium momentum (Back-to-back)
- Cut conditions: Inner product = -1 (±3σ)

Fitting results (can be checked one by one)



Binding energy on $^{4}_{\Lambda}$H



・Analyses for π- will be included
・Error analysis for each event
→Weighted avarage: To be obtained

Analysis for $^{4}_{\Lambda}$H binding energy

- With measured Helium momentum (Back-to-back)
- Cut conditions: Inner product = -1 (±3σ)

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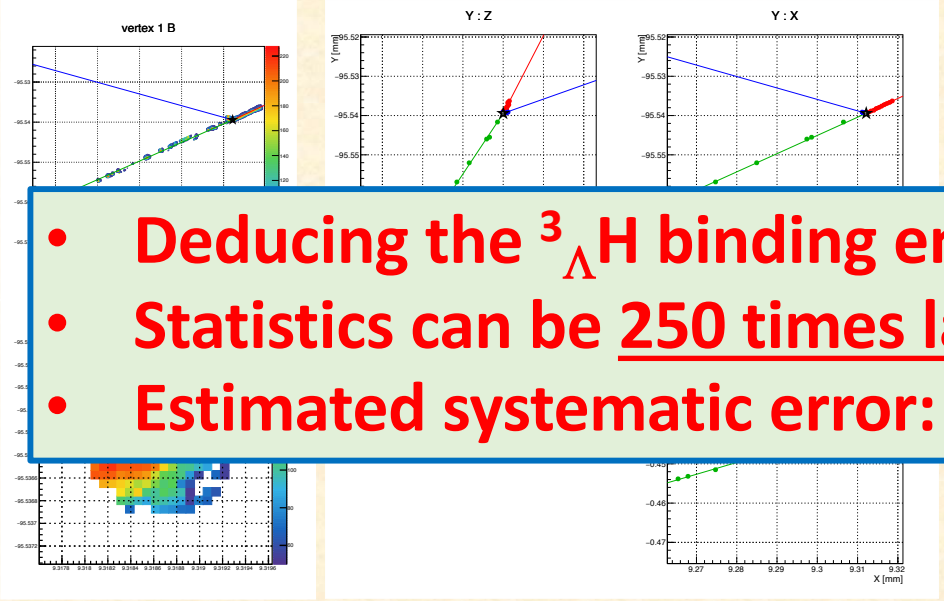
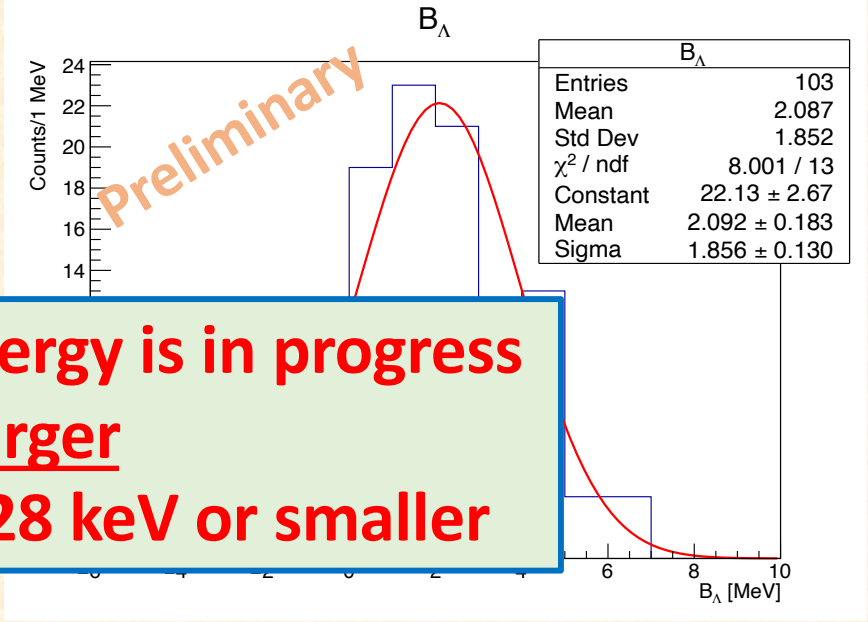


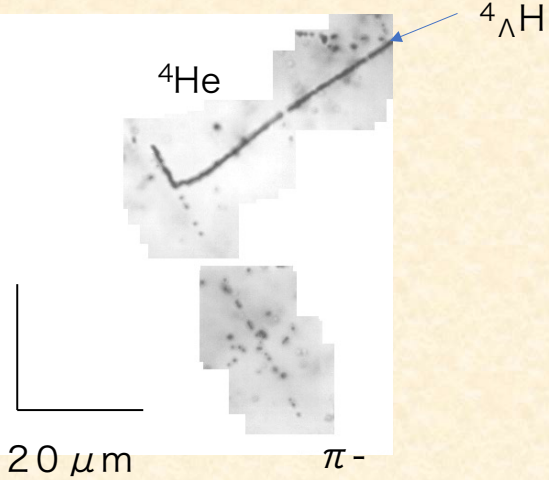
Binding energy on $^{4}_{\Lambda}$H



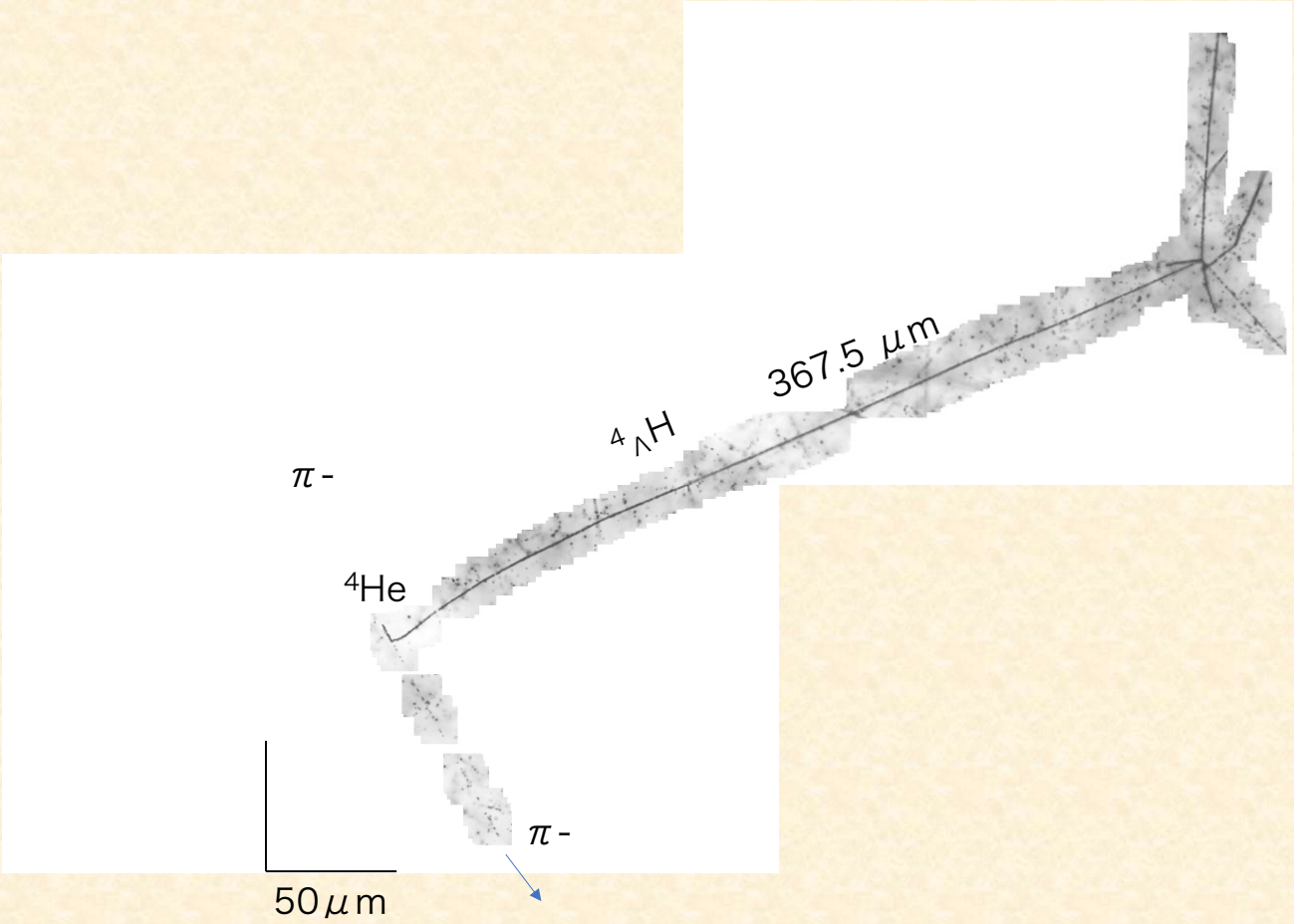
- **Deducing the $^{3}_{\Lambda}$H binding energy is in progress**
- **Statistics can be <u>250 times larger</u>**
- **Estimated systematic error: 28 keV or smaller**

・Analyses for π- will be included
・Error analysis for each event
→Weighted avarage: To be obtained

Byproduct 1:

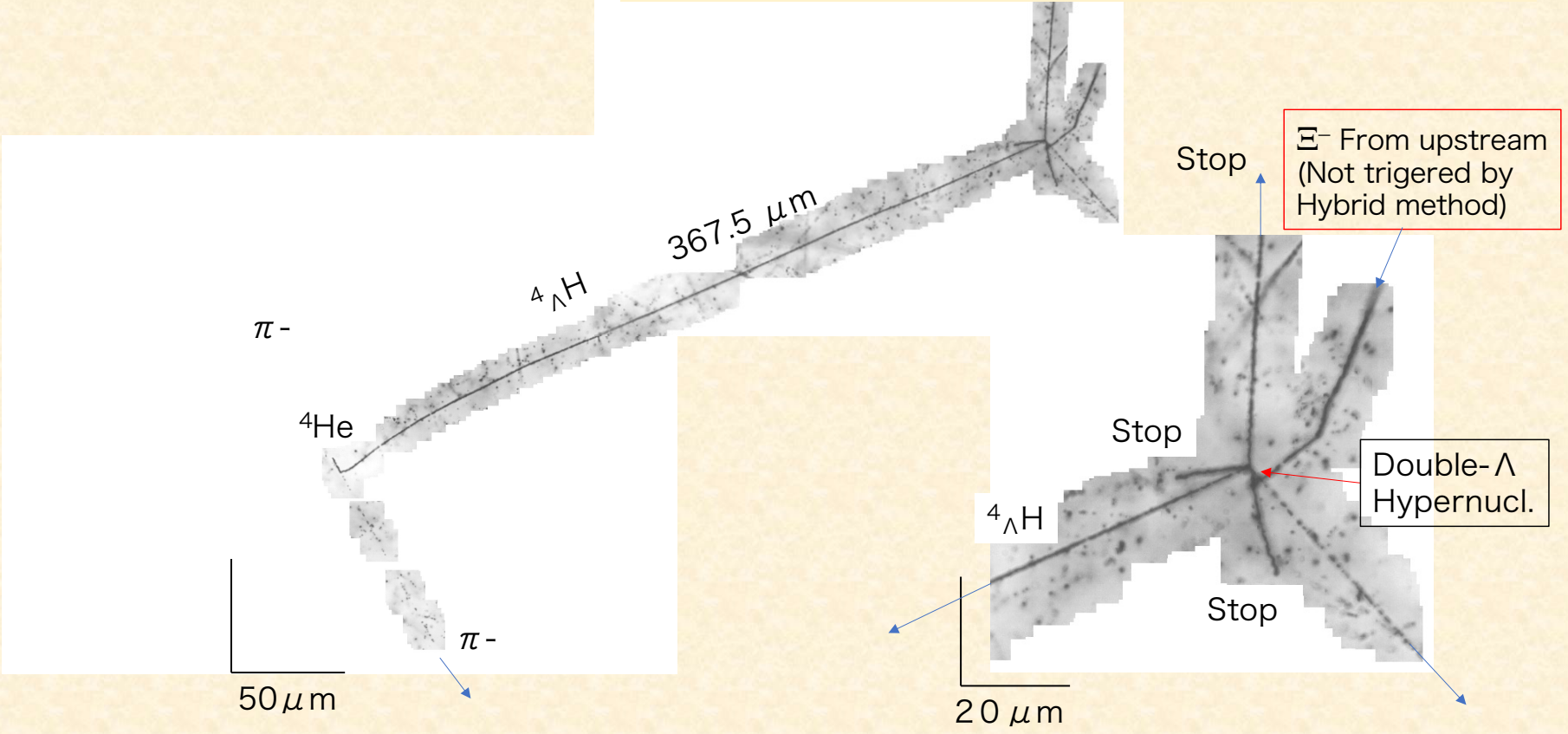


Byproduct 1:

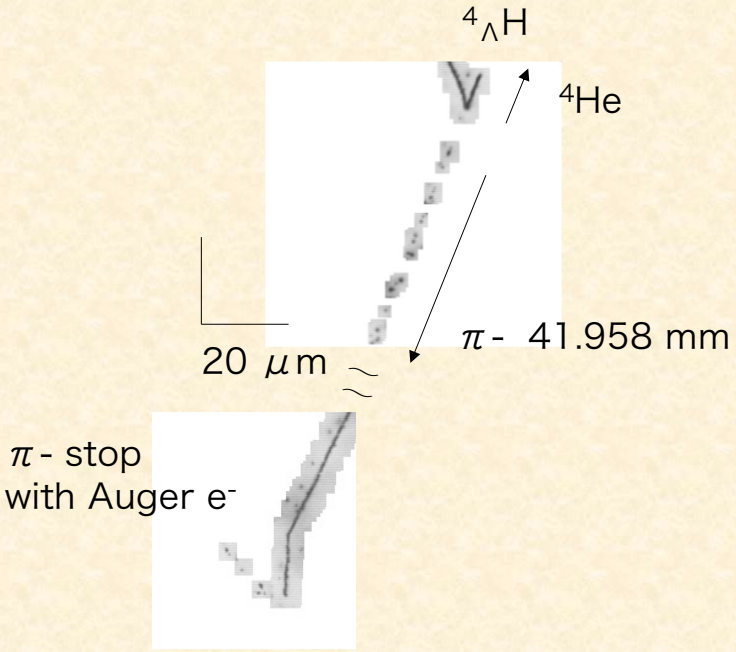


Byproduct 1:

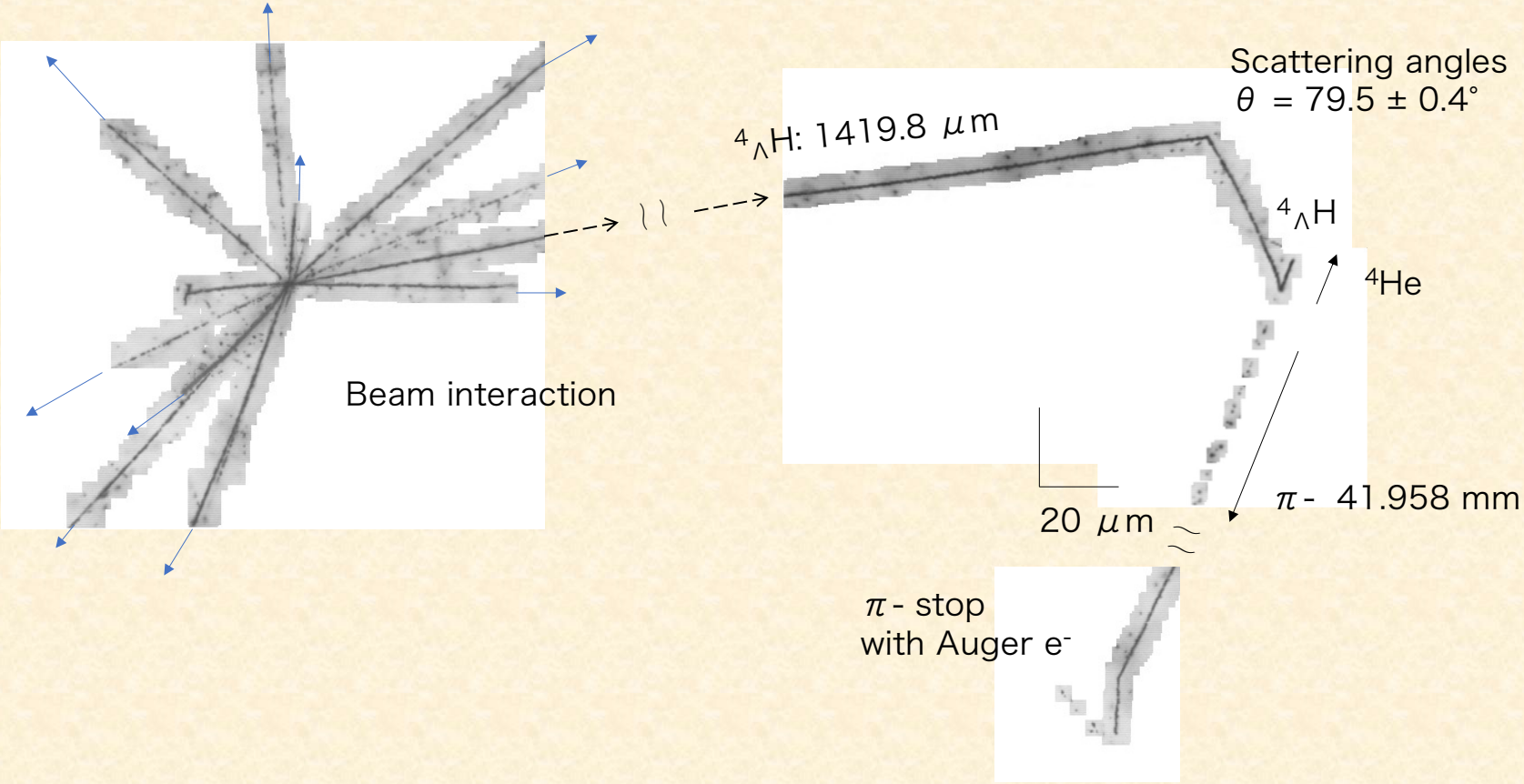
Discovery of double-Λ hypernucleus as a biproduct of $^{3}_{\Lambda}$H search



Byproduct 2:

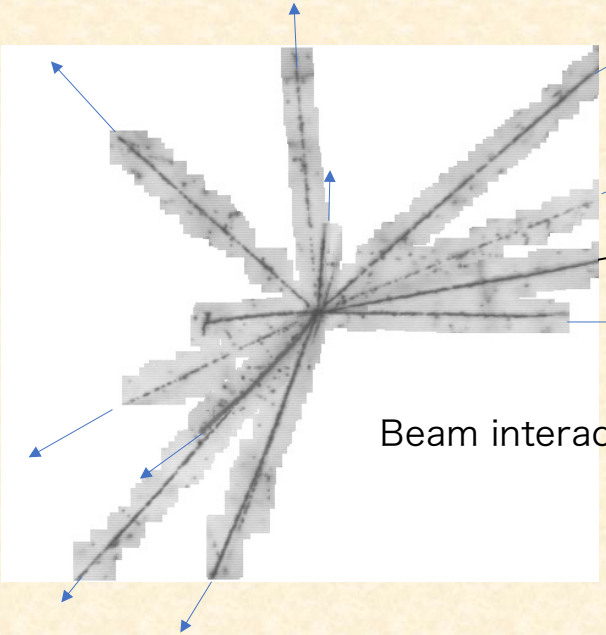


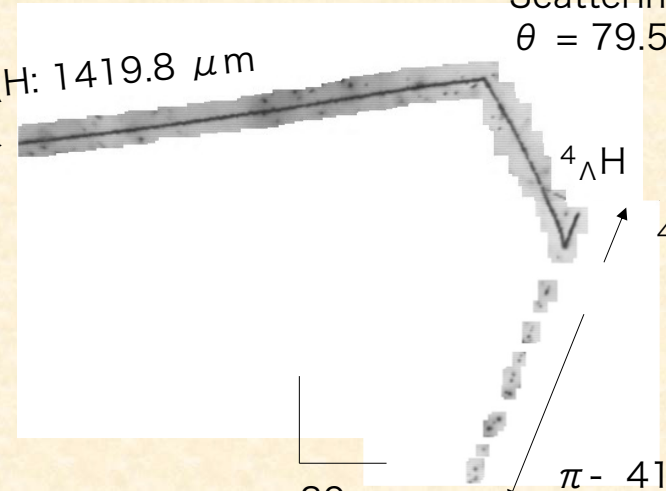
Byproduct 2:


Beam interaction
$^{4}_{\Lambda}$H: 1419.8 μm
Scattering angles
θ = 79.5 ± 0.4°
$^{4}_{\Lambda}$H
^{4}He
π- 41.958 mm
20 μm
π- stop
with Auger e-

Byproduct 2:

Hypernuclear scattering





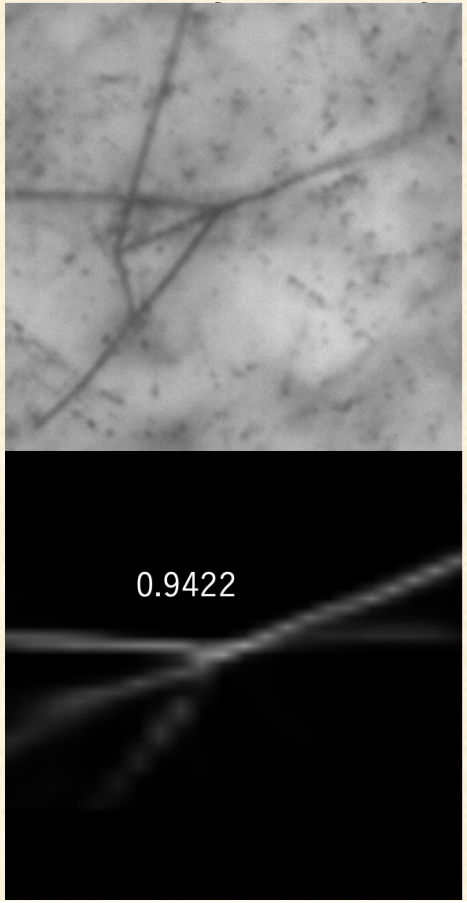
Current machine learning developments

Improvements for the hypertriton binding energy

- Automated pion tracking
- Automated emulsion calibration

Detection of three- and multi-body single-Λ hypernuclear decay (from May 2022)

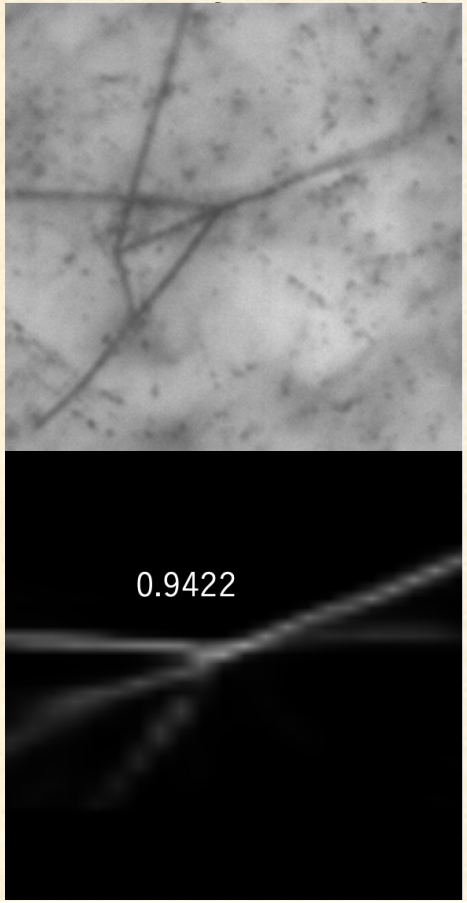
Three-body decay event

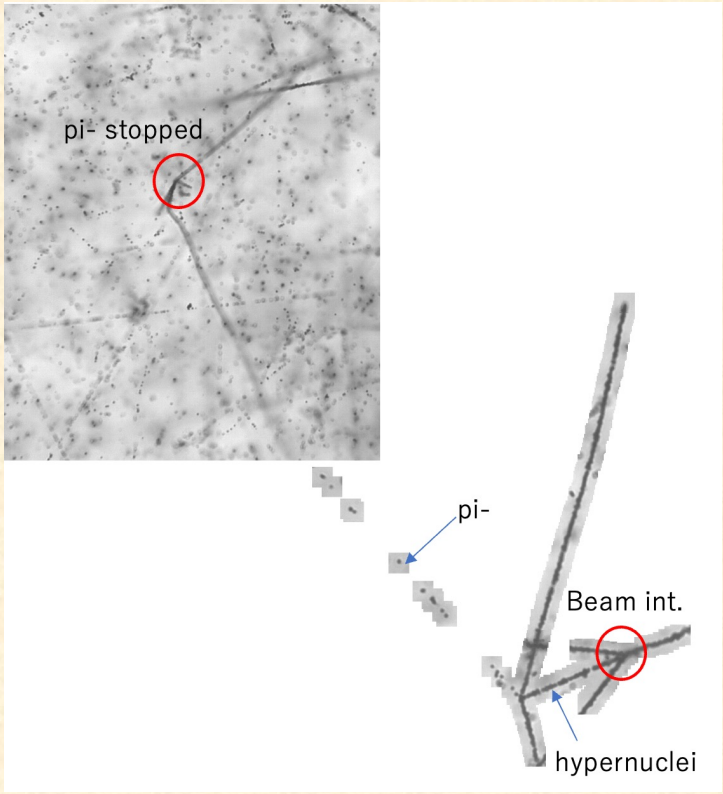


Courtesy of Shohei Sugimoto and Manami Nakagawa

Shohei Sugimoto, Master thesis

Three-body decay event





Courtesy of Shohei Sugimoto and Manami Nakagawa

Shohei Sugimoto, Master thesis

Current machine learning developments

Improvements for the hypertriton binding energy

- Automated pion tracking
- Automated emulsion calibration

Detection of three- and multi-body single-Λ hypernuclear decay (from May 2022)

Search for double-strangeness hypernuclei (from June 2022)

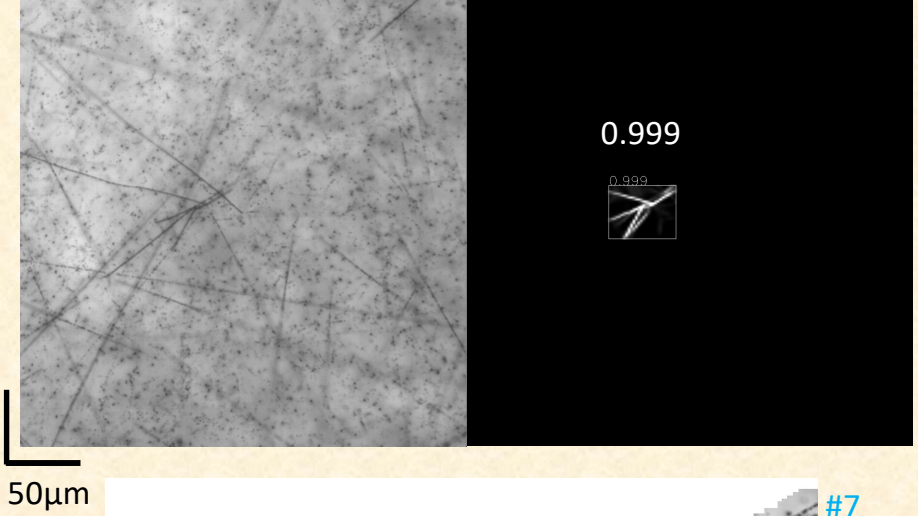
MOD100_PL02_AREA00

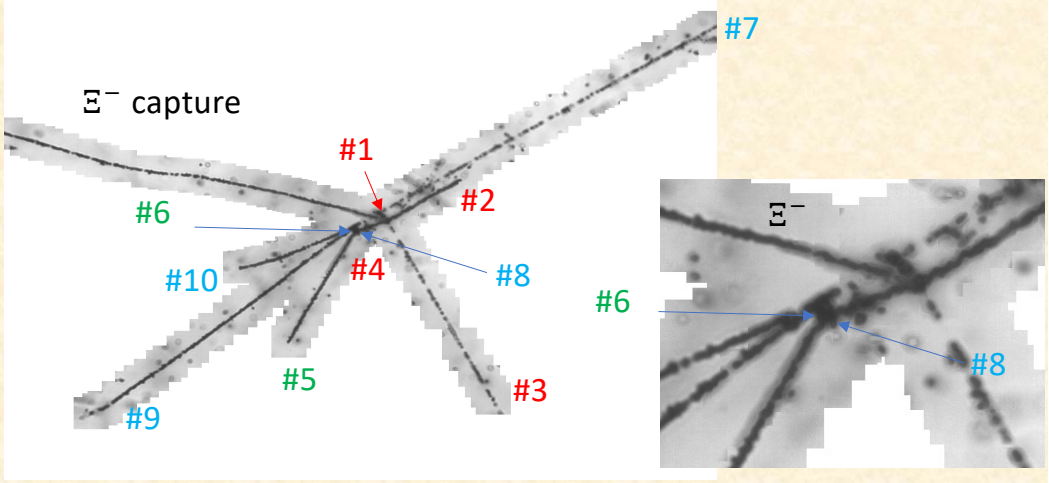
V3451

Ξ– capture:
#1: penetrate
#2: stop
#3: stop
#4: decay

second vertex:
#5: stop
#6: decay

third vertex:
#7: stop
#8: stop
#9: stop
#9: stop





Courtesy of Yan He and Manami Nakagawa

Only ~ 0.03 % of the entire data analyzed

Yan He, Ph.D. thesis

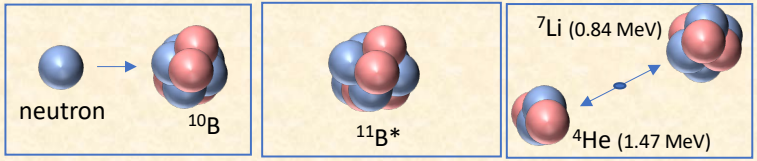
Nuclear Emulsion + Machine Learning Collaboration

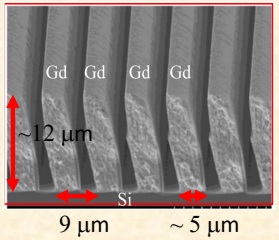
W. Dou[a,b], V. Drozd[a,c,d], H. Ekawa[a], S. Escrig[a,e], Y. Gao[a,f,g], Y. He[a,h], A. Kasagi[a,i,j], E. Liu[a,f,g], A. Muneem[a,k], M. Nakagawa[a], K. Nakazawa[a,i,l], C. Rappold[e], N. Saito[a], T.R. Saito[a,d,h], S. Sugimoto[a,b], M. Taki[j], Y.K. Tanaka[a], A. Yanai[a,b], J. Yoshida[a,m], M. Yoshimoto[n], and H. Wang[a]

[a] High Energy Nuclear Physics Laboratory, RIKEN, Japan
[b] Department of Physics, Saitama University, Japan
[c] Energy and Sustainability Research Institute Groningen, University of Groningen, Netherlands
[d] GSI Helmholtz Centre for Heavy Ion Research, Germany
[e] Instituto de Estructura de la Materia, Spain
[f] Institute of Modern Physics, Chinese Academy of Sciences, China
[g] University of Chinese Academy of Sciences, China
[h] School of Nuclear Science and Technology, Lanzhou University, China
[i] Graduate School of Engineering, Gifu University, Japan
[j] Graduate School of Artificial Intelligence and Science, Rikkyo University, Japan
[k] Faculty of Engineering Sciences, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan
[l] Faculty of Education, Gifu University, Japan
[m] Department of physics, Tohoku University, Japan
[n] RIKEN Nishina Center, RIKEN, Japan

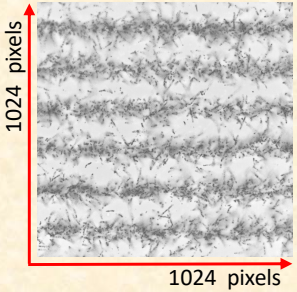
Neutron imaging with nuclear emulsions

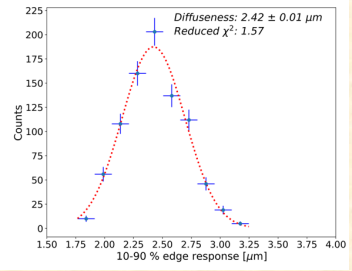
Physics process





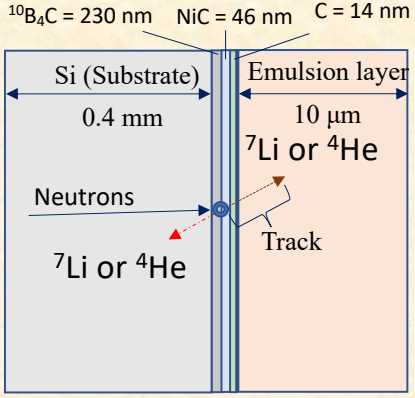
Tetsuo Samoto et al 2019
Jpn. J. Appl. Phys. 58 SDDF12

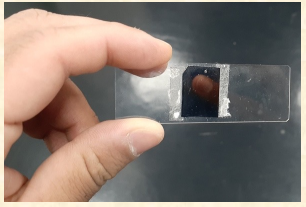




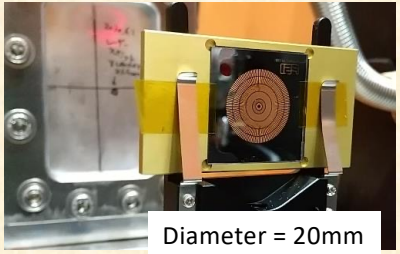
Spatial resolution:
0.945 ± 0.004 μm (1σ)

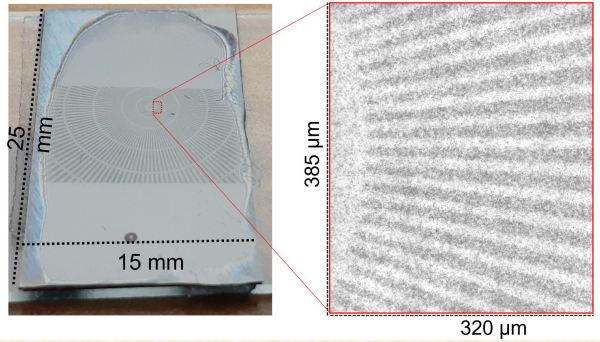
Neutron detector





Siemens star pattern





A. Muneem *et al.*, Journal of Applied Physics, 133, 054902 (2023)

Precise 2D imaging
Submicron resolution

→ Image reconstruction using beams with large angular dispersion and ML

→ **Neutron CT**

Summary

The WASA-FRS experiment at GSI (2022) with HI beams

- Hypertriton lifetime
- nnΛ state
- Proton-rich hypernuclei
- Development with **Machine Learning (GNN)**
- Data analyses in progress

Analyses of the J-PARC E07 nuclear emulsion with Machine Learning

- Binding energy of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H
- Single-Λ hypernuclei with multi-body decay channels
- Double-strangeness hypernuclei