Hypernuclear studies with the WASA-FRS experiment and nuclear emulsions + machine learning

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

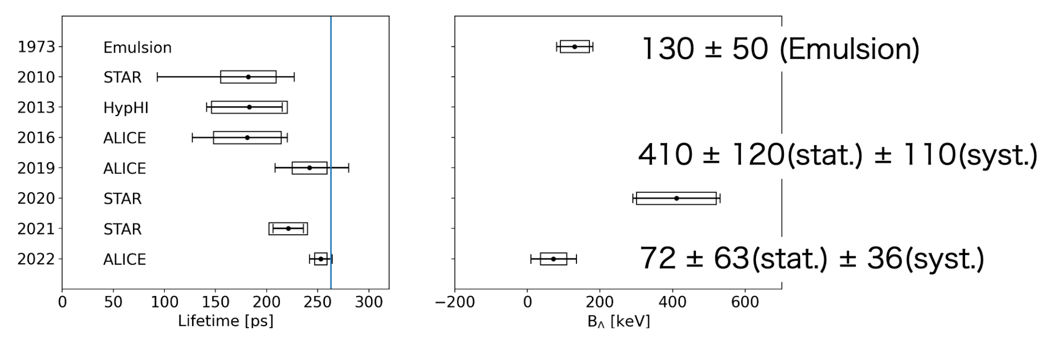
***GSI Helmholtz Center for Heavy Ion Research**,*

Germany

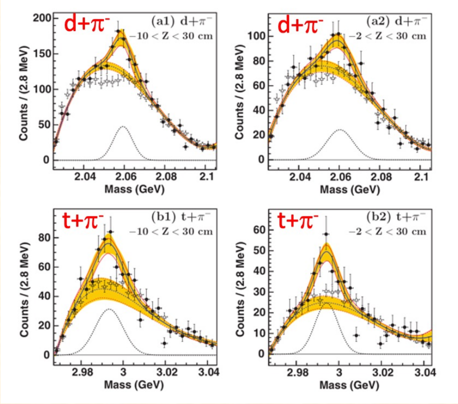
EMMI Workshop "4th Workshop on Anti-Matter, Hyper-Matter and Exotica Production at the LHC", 13-17 February 2023
Department of Physics and Astronomy "A. Righi", University of Bologna, Italy

Recent hot topics for few-body hypernuclei

On hypertriton



On Λnn



HypHI., PRC 88 (2013) 041001

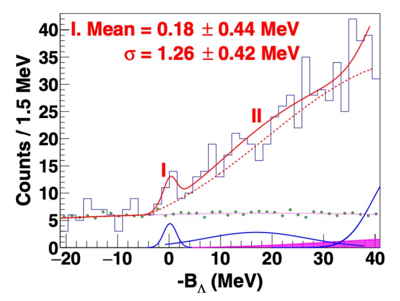


FIG. 5. The enlarged mass spectrum around the Λnn threshold. Two additional Gaussians were fitted together with the known contributions (the accidentals, the Λ quasifree, the free Λ, and the ^{3}He contamination). The one at the threshold is for the small peak, while the broad one is for the additional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

Talk by Sho Nagao

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

Recent hot topics for few-body hypernuclei

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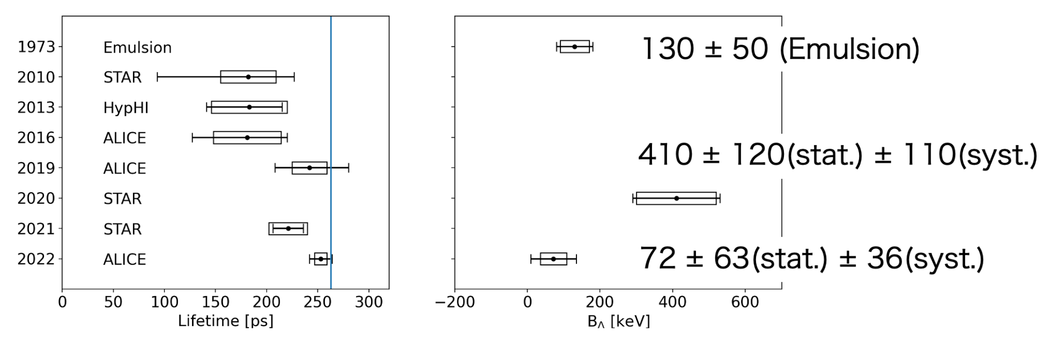

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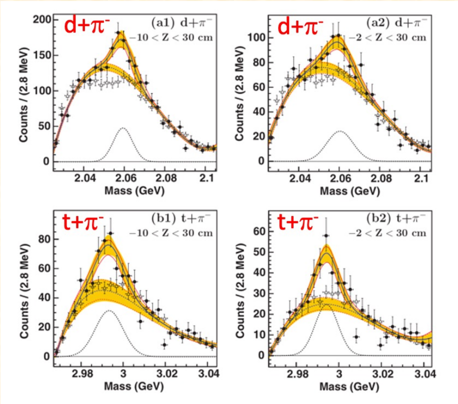
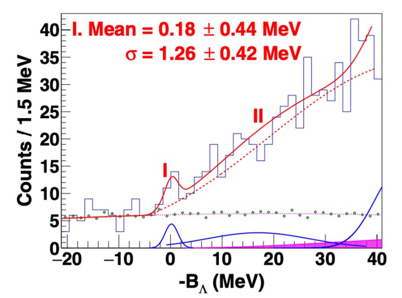


HypHI., PRC 88 (2013) 041001



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Talk by Sho Nagao

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

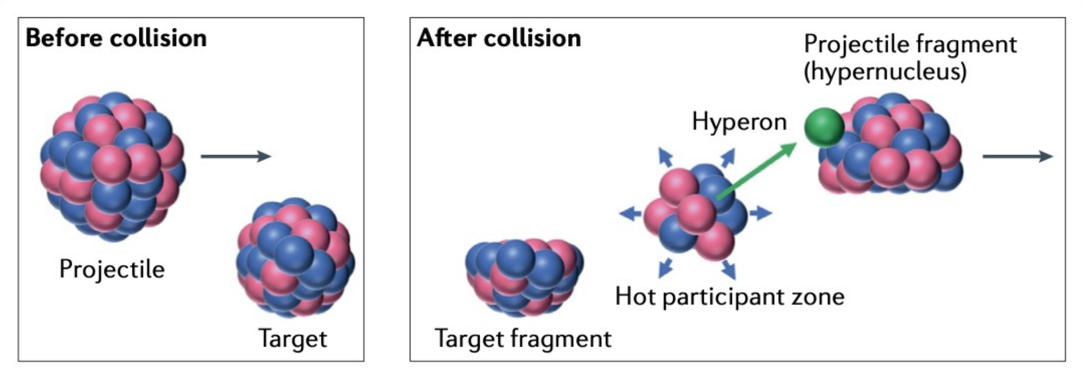
Our approaches:

Lifetime and Λnn: with heavy ion beams at FRS-GSI

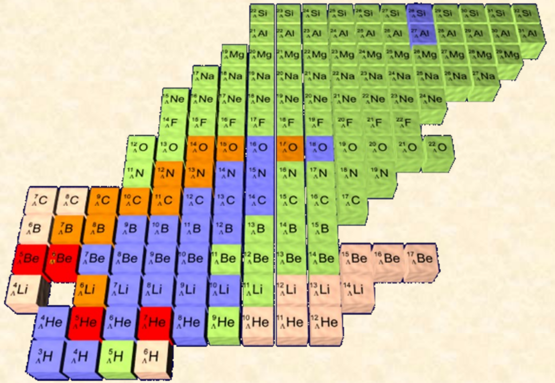
Binding energy: with nuclear emulsion and machine learning

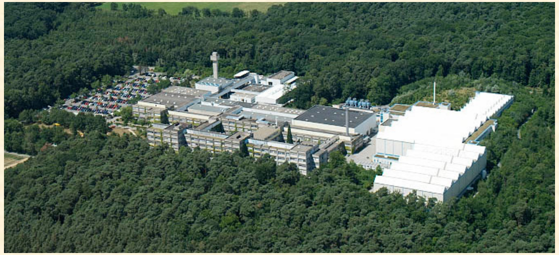
Our challenges on the hypertriton lifetime and Λnn

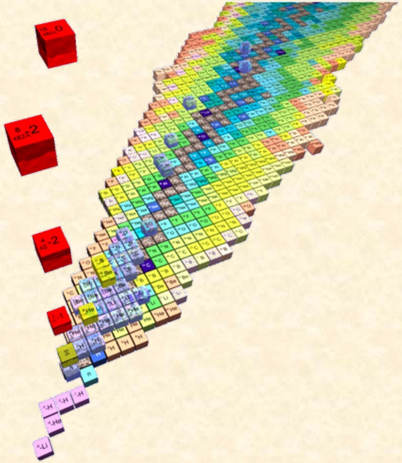
The HypHI Phase 0 at GSI (2006-2012)

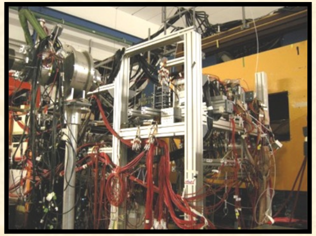


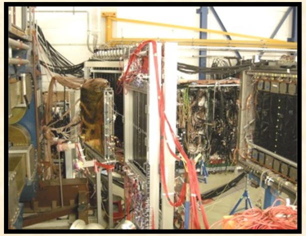
TRS et al., Nature Reviews Physics 3, 803-813 (2021)

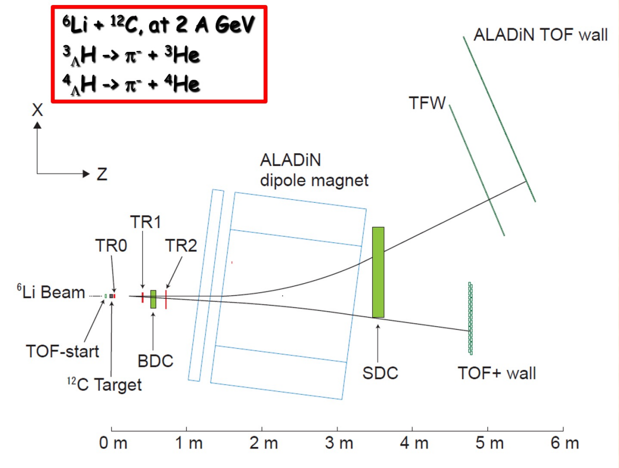




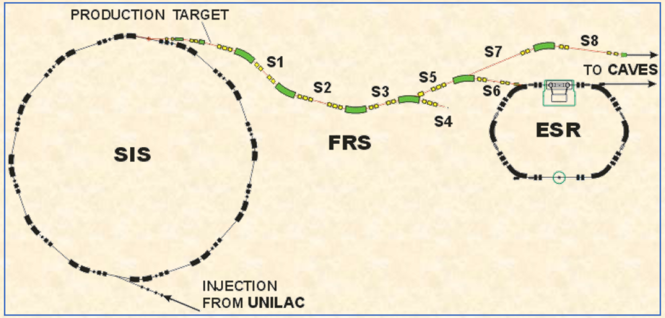


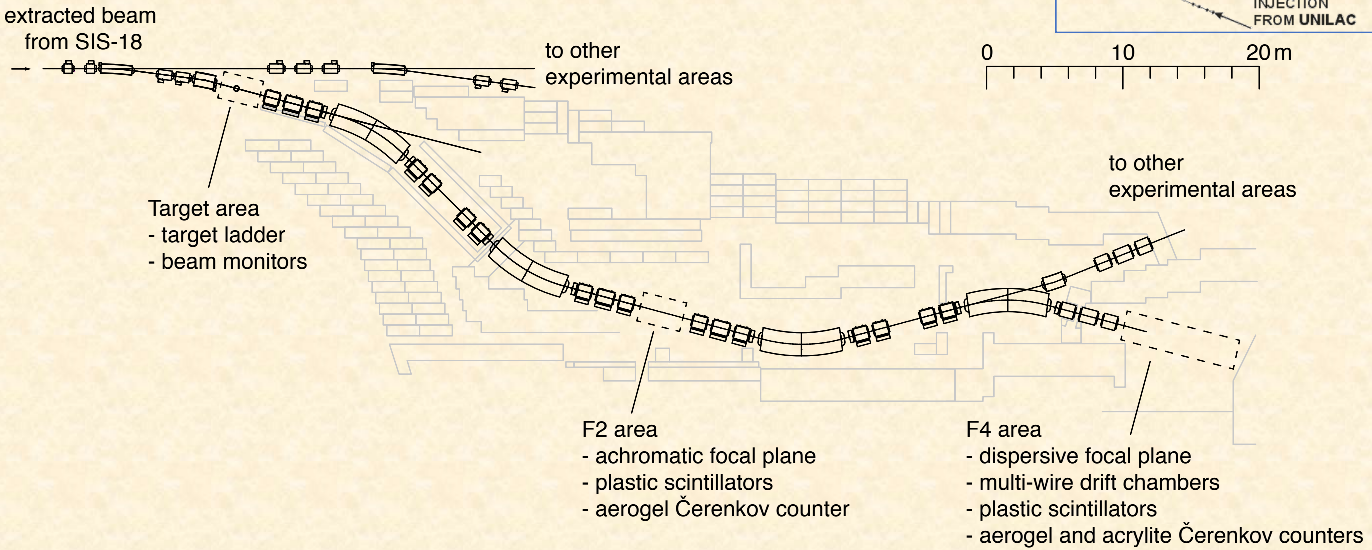






The novel technique with FRS at GSI





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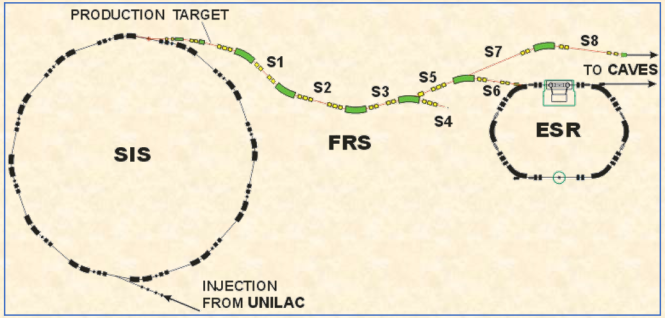
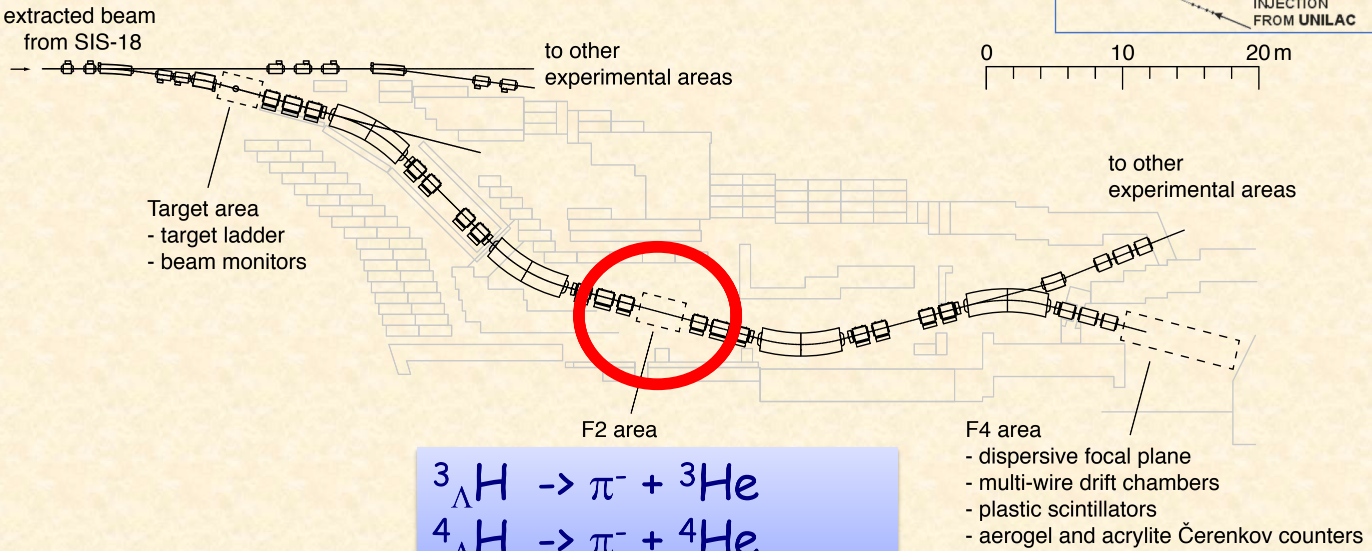




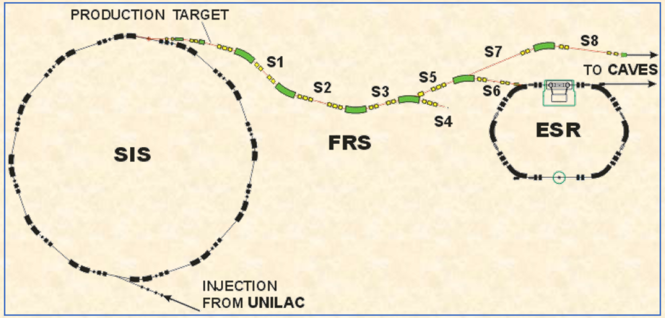
$^{3}_{\Lambda}H$ -> $\pi^- + {}^{3}He$

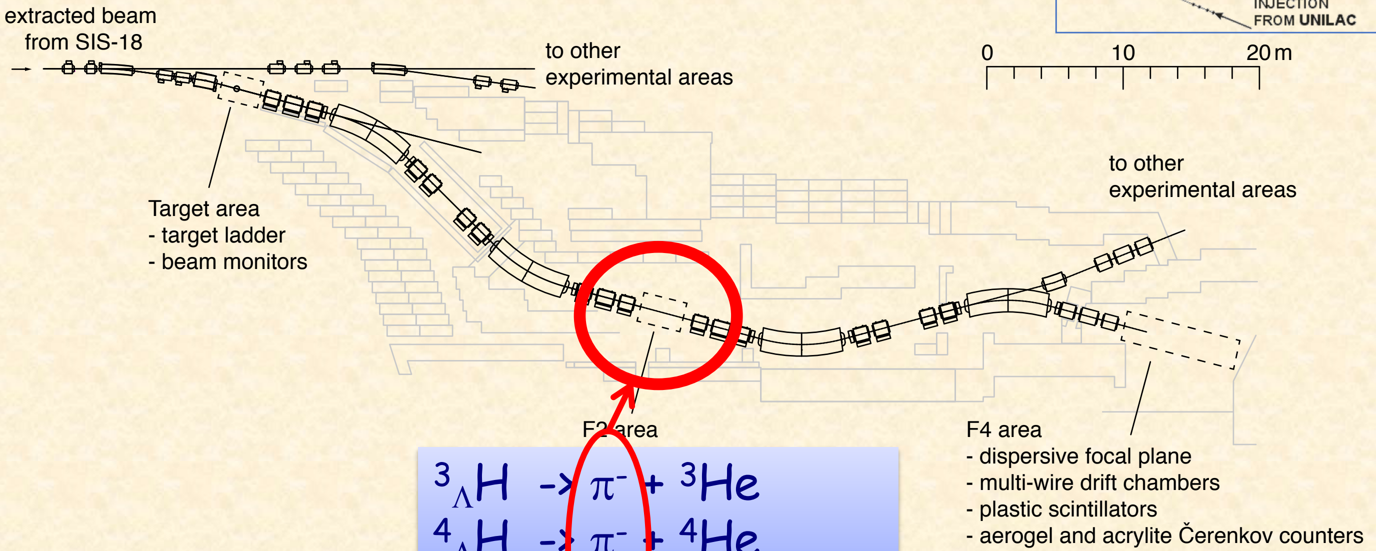
$^{4}_{\Lambda}H$ -> $\pi^- + {}^{4}He$

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

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

The novel technique with FRS at GSI





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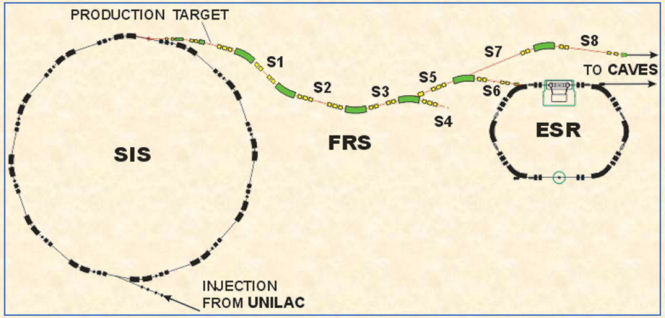

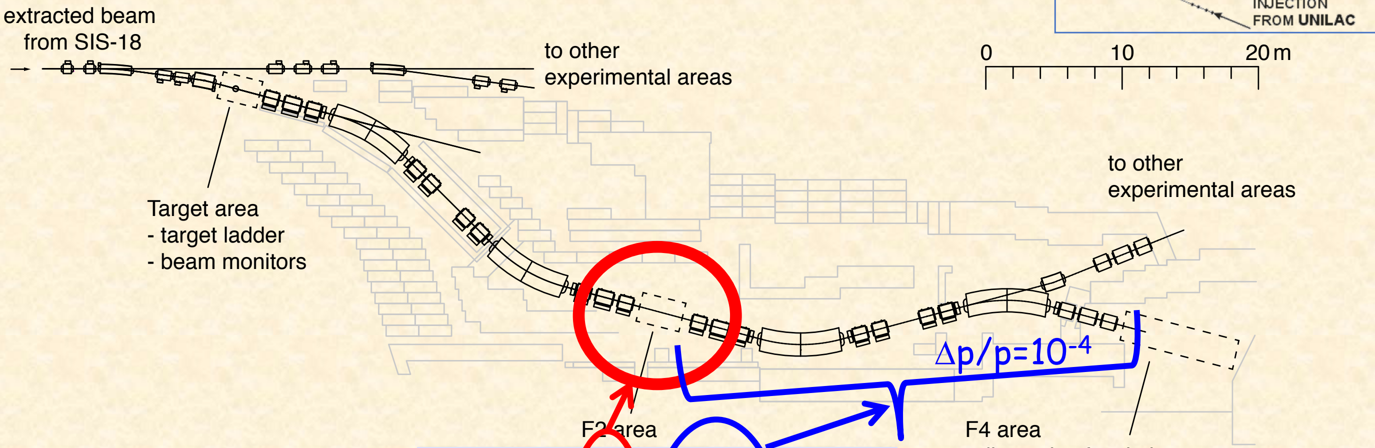

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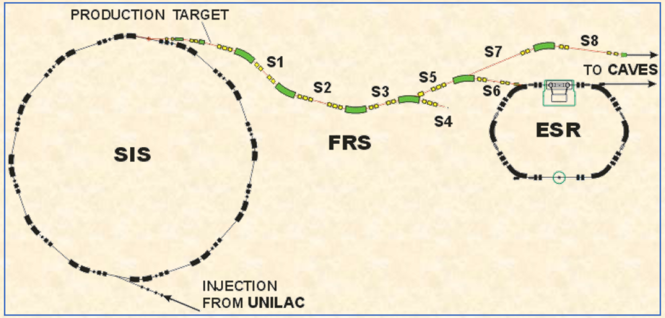

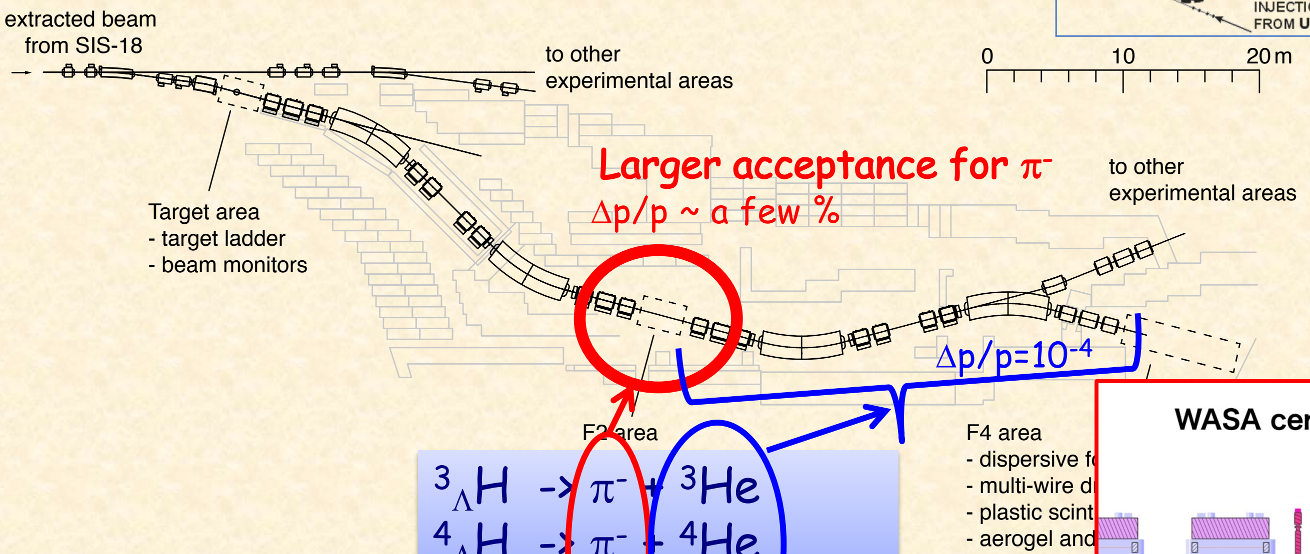

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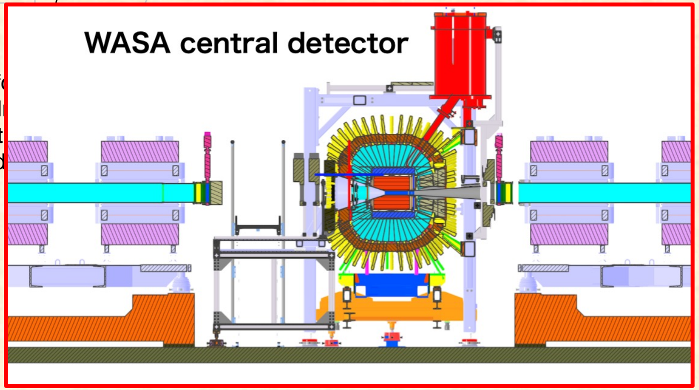
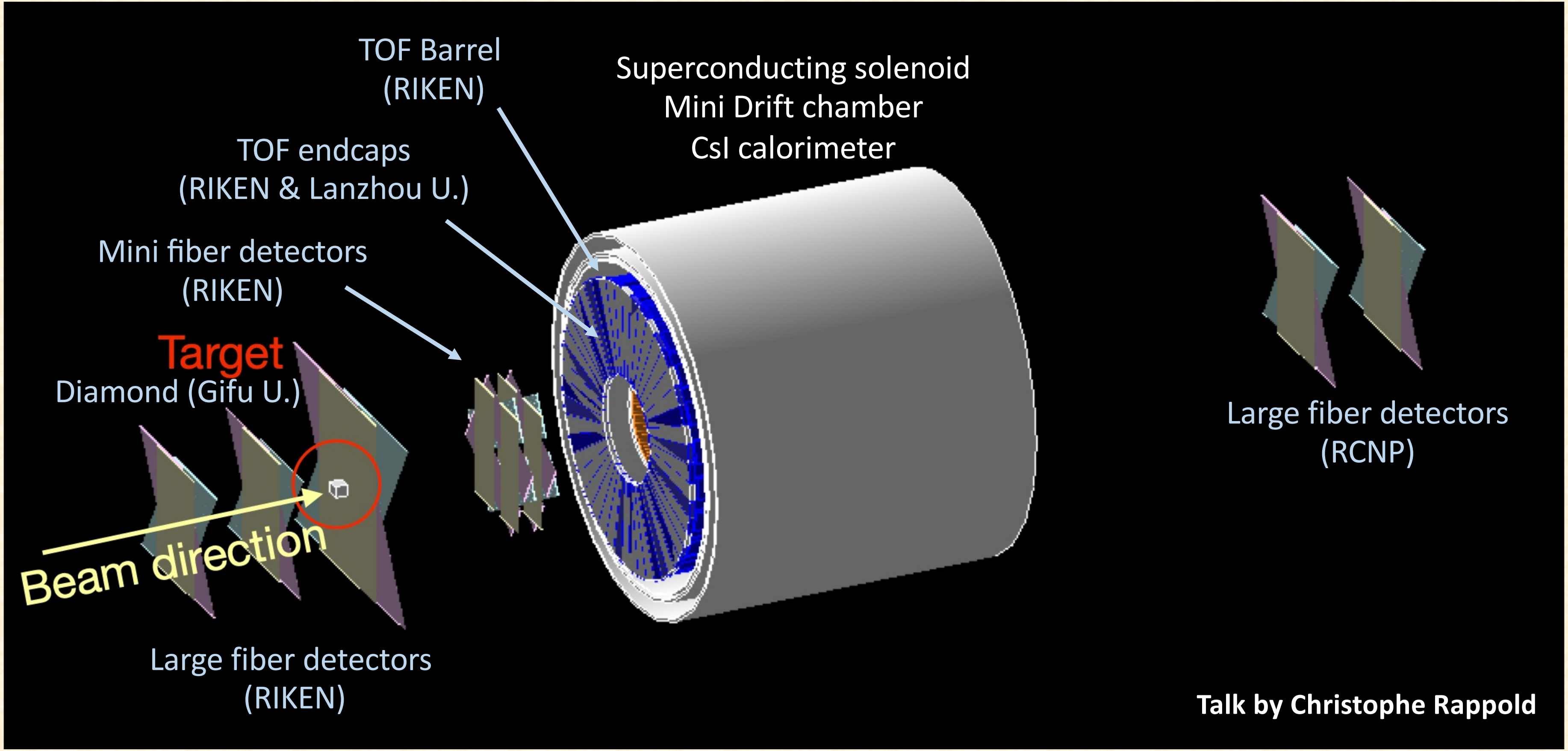
With $^{6}Li + ^{12}C$ at 2 A GeV



March 2019: WASA moved from Juelich to GSI

The WASA-FRS HypHI experiment at GSI



The WASA-FRS collaboration

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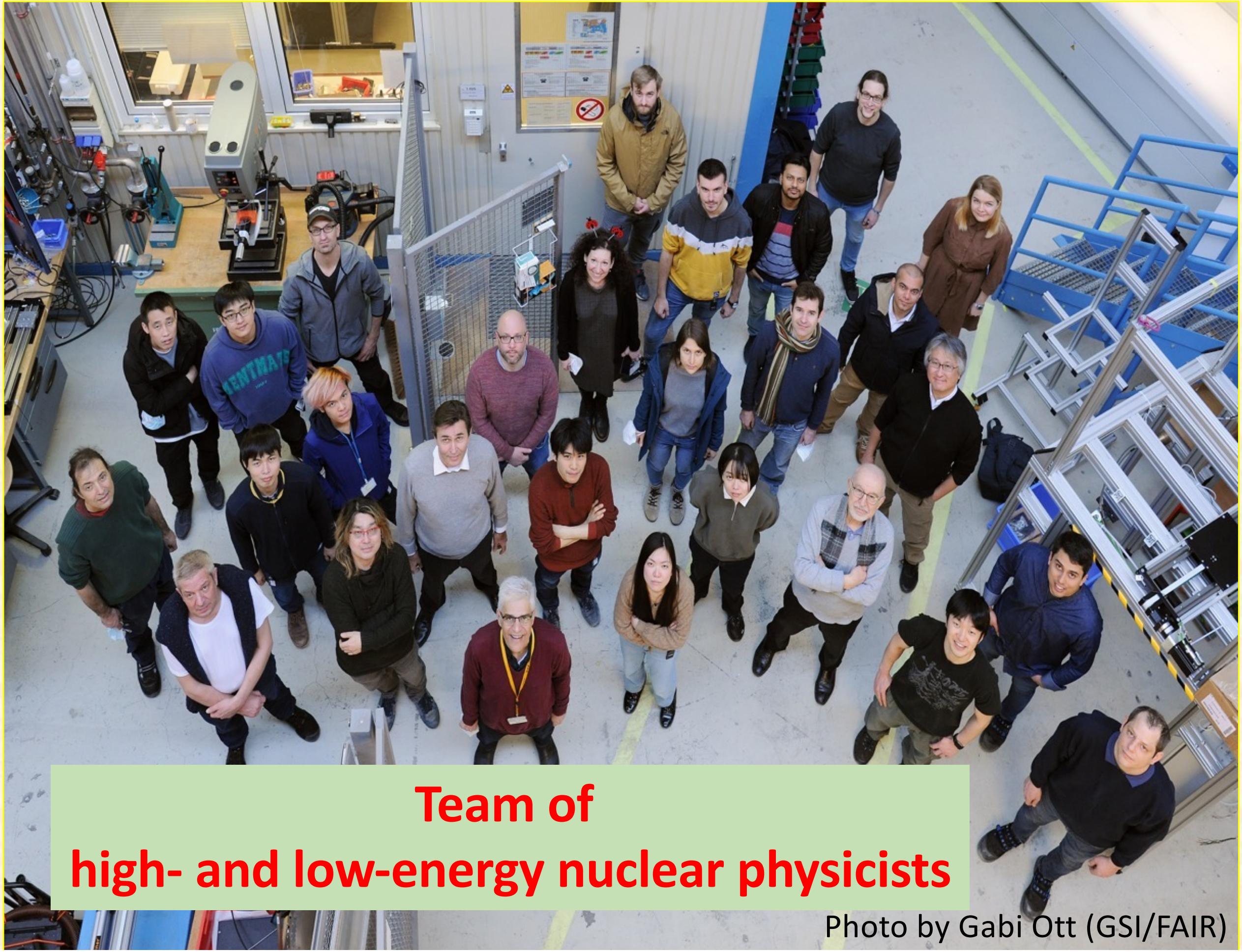
Part of the WASA-FRS collaboration

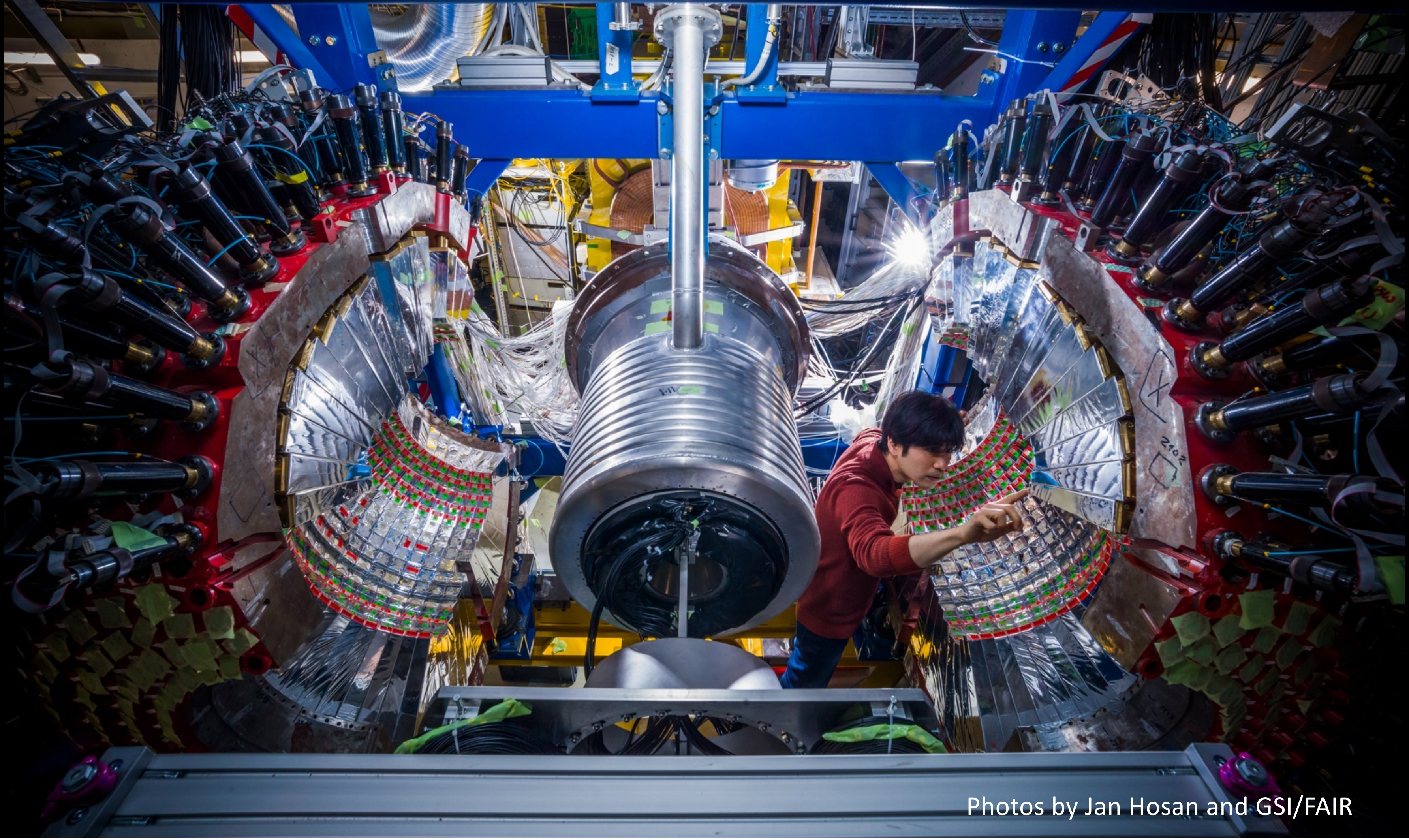


Team of high- and low-energy nuclear physicists

Photo by Gabi Ott (GSI/FAIR)

The entire setup of WASA at FRS

Photos by Jan Hosan and GSI/FAIR



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WASA-FRS and its perspective in Nature Reviews Physics

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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

Takehiko R. Saito et al., Nature Reviews Physics, 803-813 (2021)

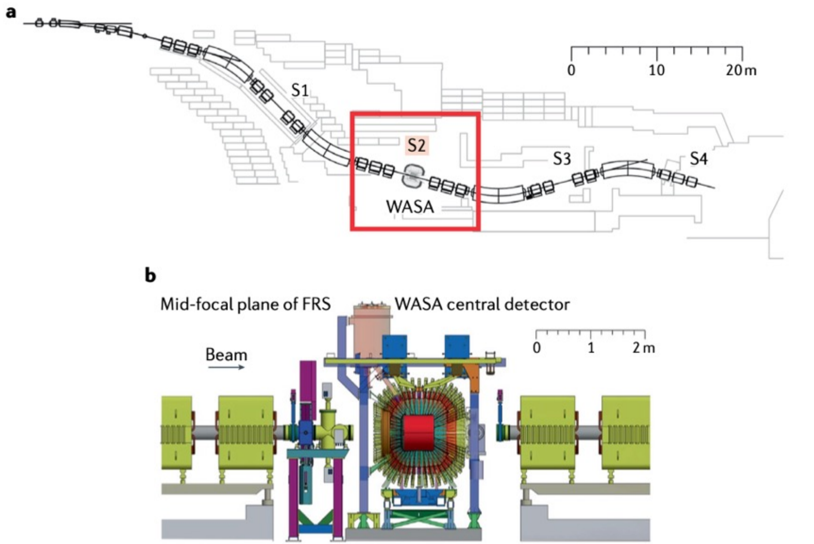


Fig. 1 | **The WASA-FRS hypernuclear experiment. a** | Schematic drawing of the fragment separator (FRS) at GSI. The ^{6}Li primary beams at 2 A GeV are delivered to the diamond target located at the mid-focal plane of the FRS, referred to as S2, to produce hypernuclei of interest. Residual nuclei of the π^- weak decays of hypernuclei are transported from S2 to S4 in the FRS, and measured precisely with a momentum-resolving power of 10^{-4}. The π^- mesons produced by the hypernuclear decays are measured at S2 by the Wide Angle Shower Apparatus (WASA) central detector. **b** | The WASA central detector. Panel **b** is adapted with permission from REF.[76].

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

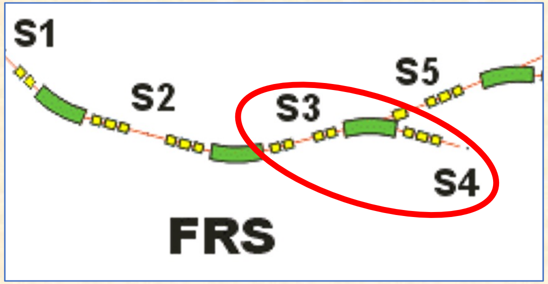
92 % of the prop.

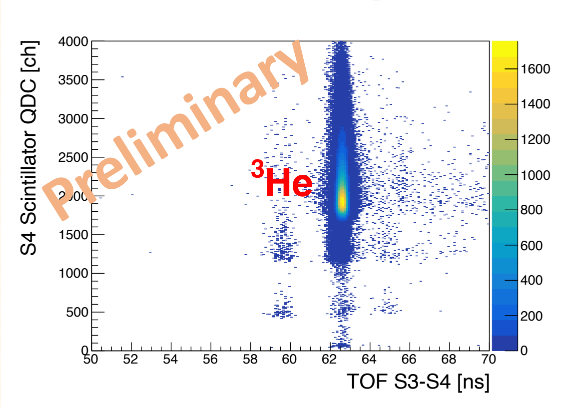
Acquired data for S447 (hypernuclei)

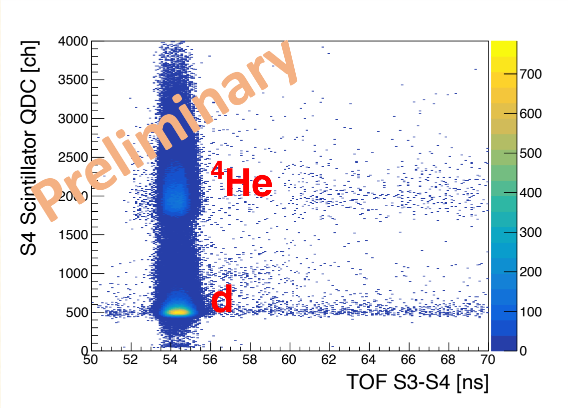
Beam	Fragment at S4	Amount	Time	Accepted trigger rate	
^{6}Li beam	^{3}He	3.3×10^{8}	40.9 hours	2600 Hz	**$^{3}_{\Lambda}$H**
	^{4}He	0.9×10^{8}	43.9 hours	1800 Hz	**$^{4}_{\Lambda}$H**
	deuteron	1.8×10^{8}			**nnΛ**
	proton (mid-rapidity)	5.3×10^{6}	3.2 hours	680 Hz	**Λ**
^{12}C beam	^{3}He	1.0×10^{8}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

Talk by Christophe Rappold

Data analyses in progress







Momentum resolution:

Preliminary:

$\Delta p/p \sim 5 \times 10^{-4}$

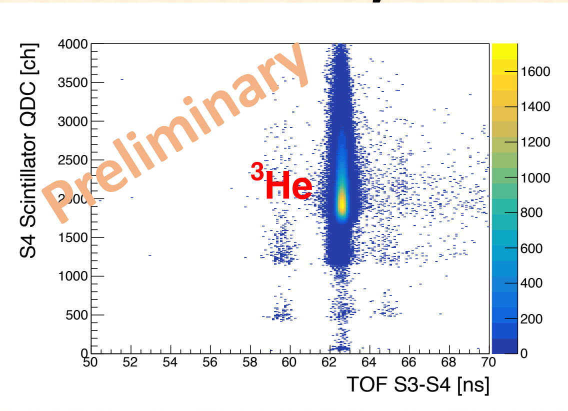
Ph.D. theses: Vasyl Drozd, Yiming Gao, Enqiang Liu, Samuel Escrig

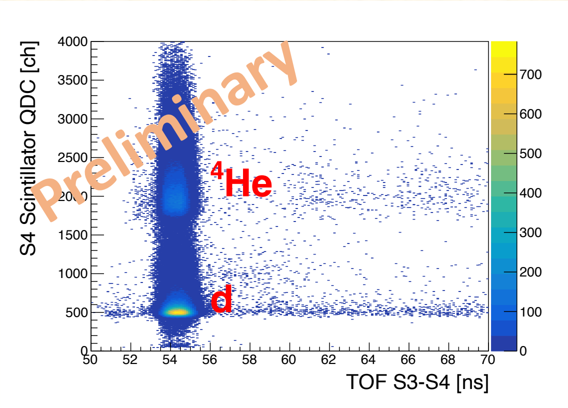
Master thesis: Ayari Yanai

Courtesy of Enqiang Liu

Talk by Christophe Rappold

Data analyses in progress





Courtesy of Enqiang Liu

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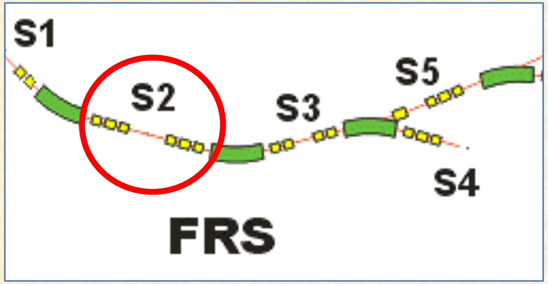
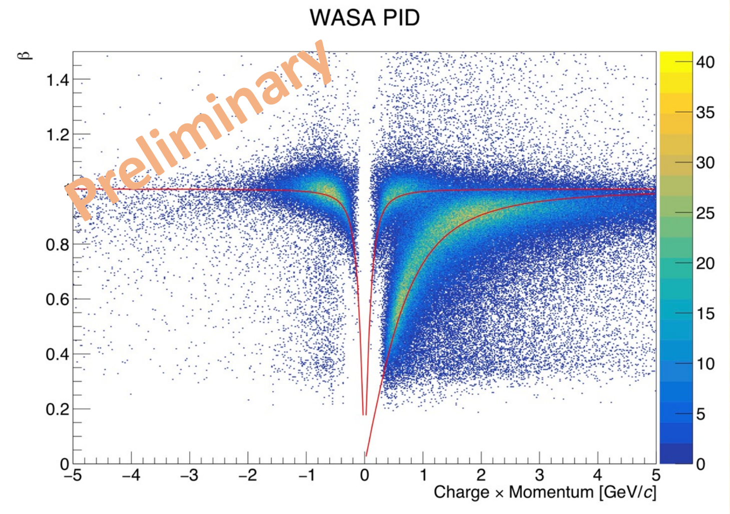




Courtesy of Hiroyuki Ekawa

Ph.D. theses: Vasyl Drozd, Yiming Gao, Enqiang Liu, Samuel Escrig

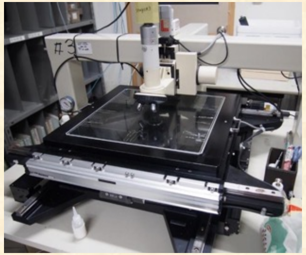
Master thesis: Ayari Yanai

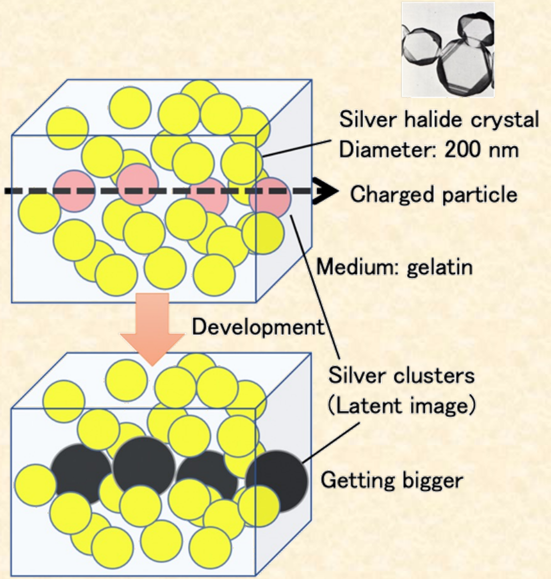
Talk by Christophe Rappold

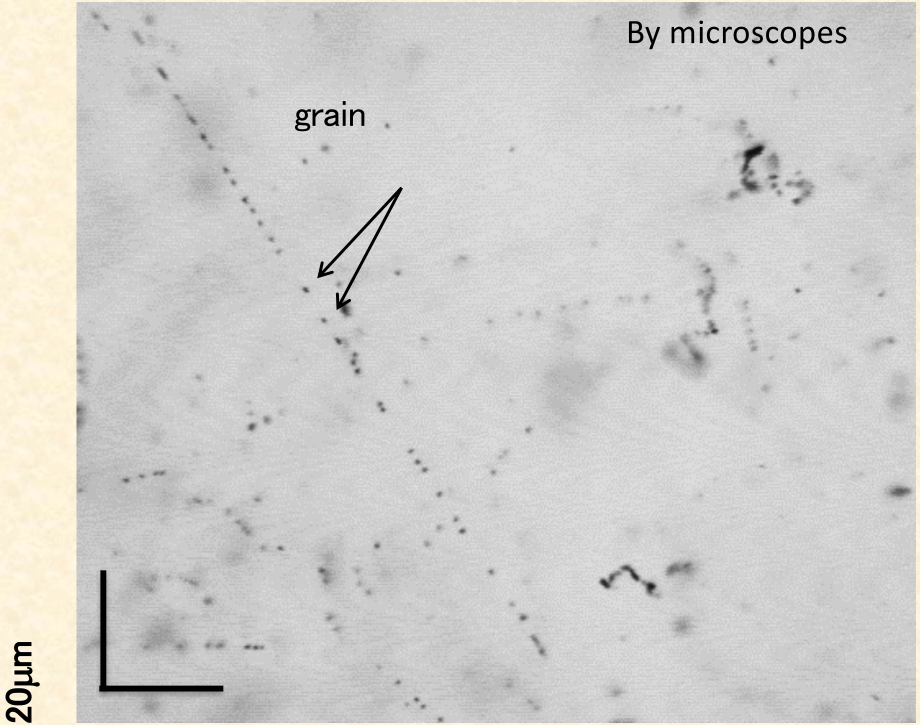
How about
the hypertriton binding energy?

Nuclear Emulsion:

Charged particle tracker with
the best spatial resolution
(easy to be < 1 μm, 11 nm at best)

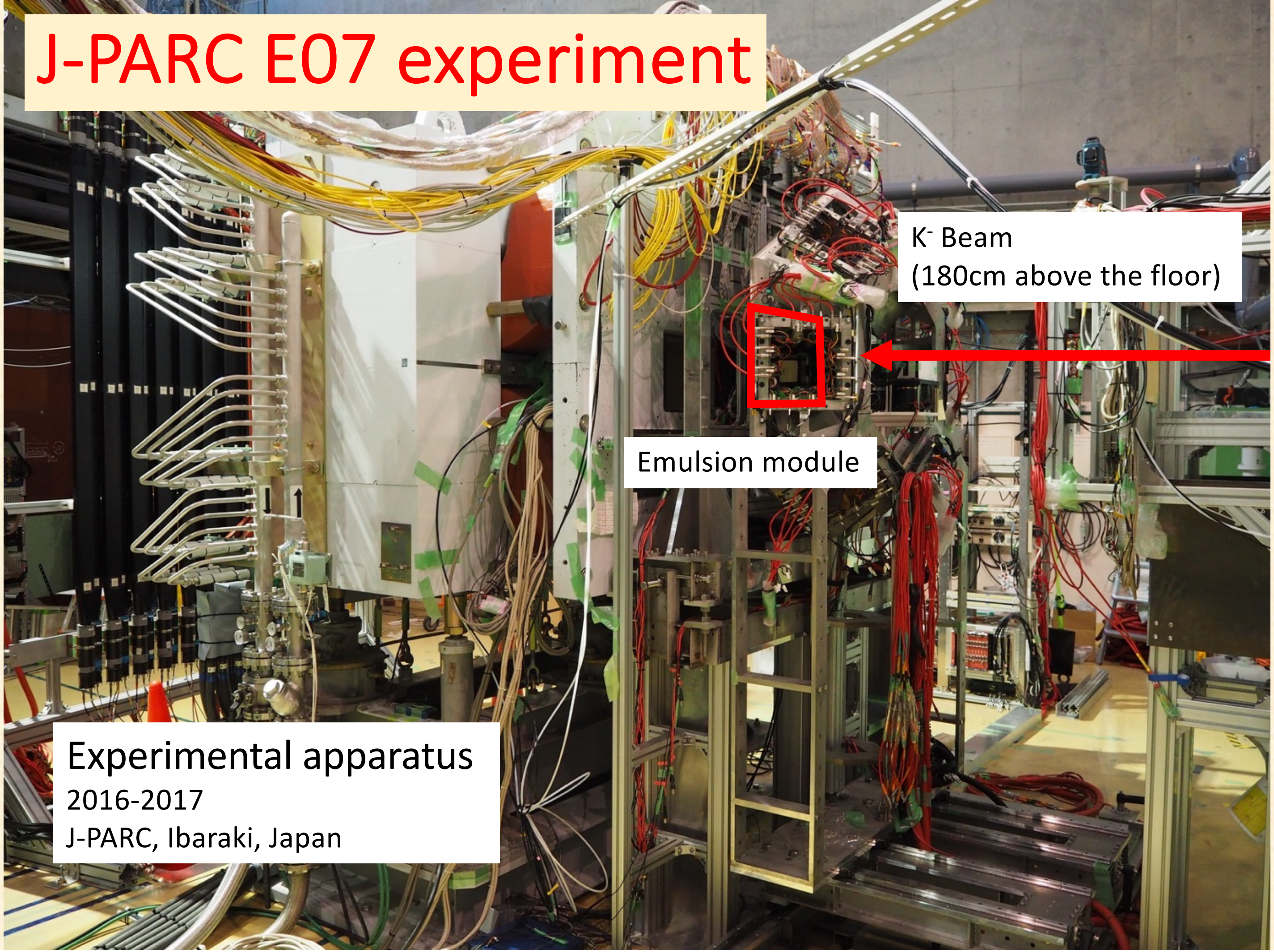




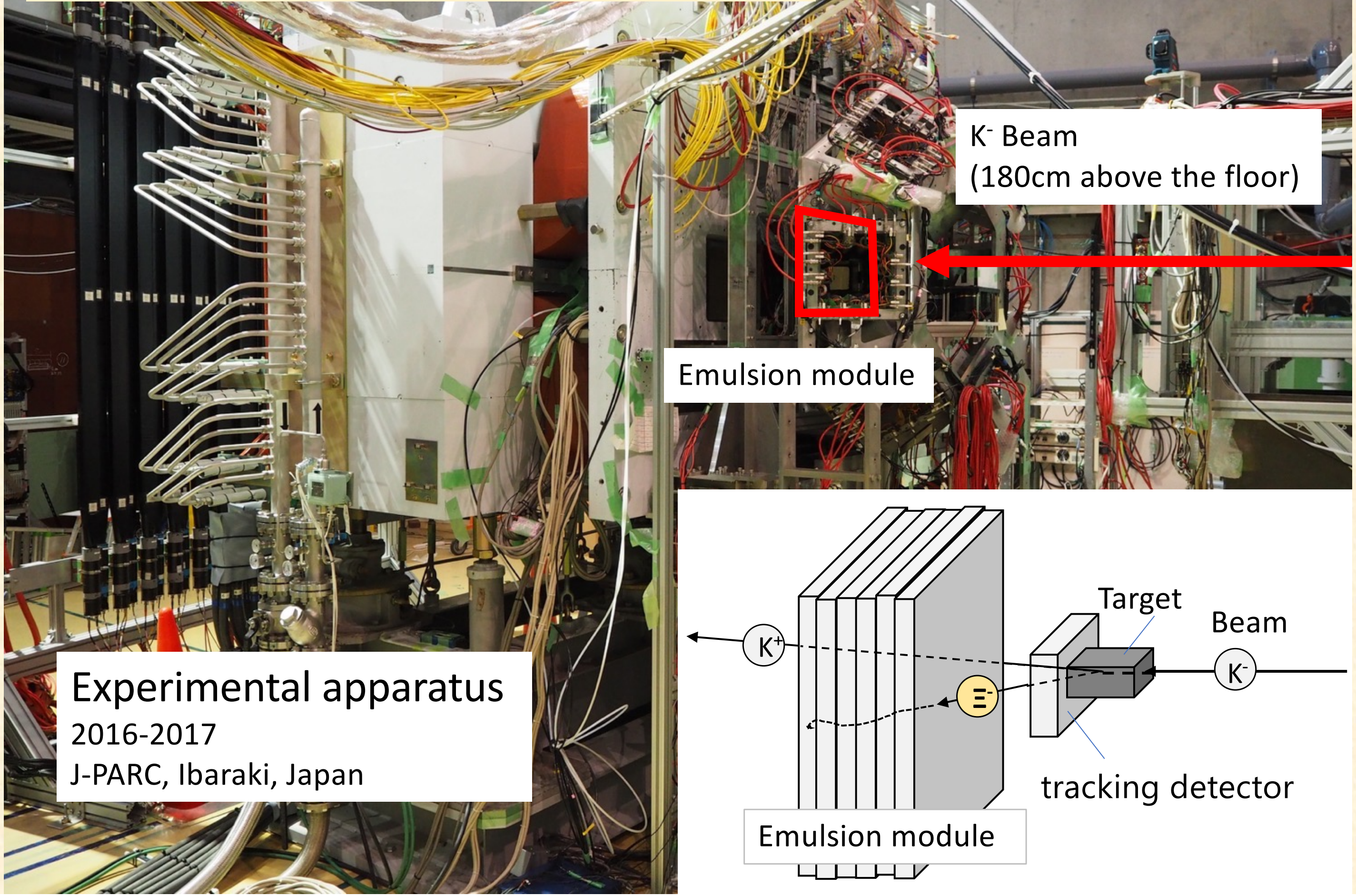


J-PARC accelerator facility

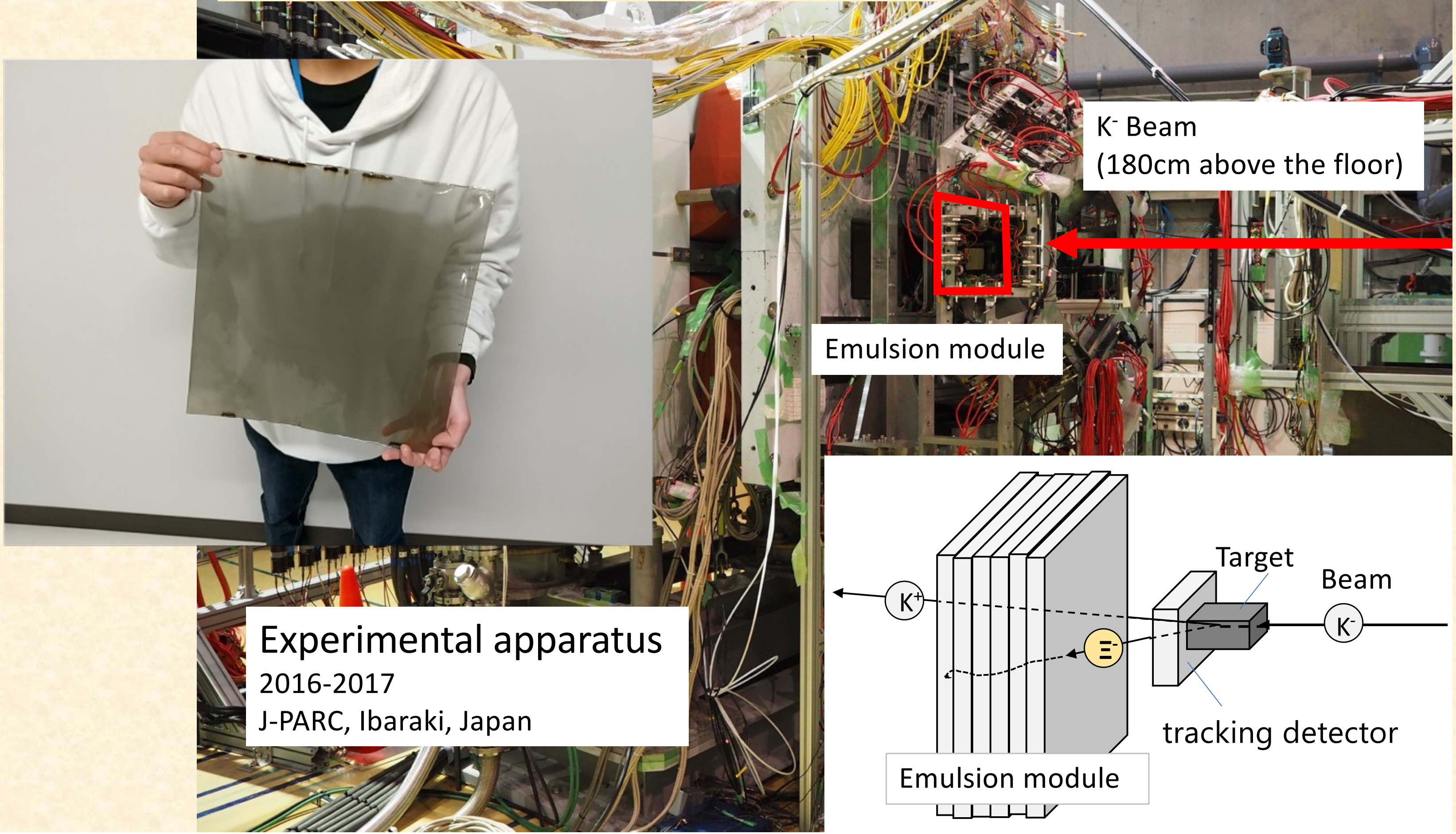
J-PARC E07 experiment



J-PARC E07 experiment



J-PARC E07 experiment



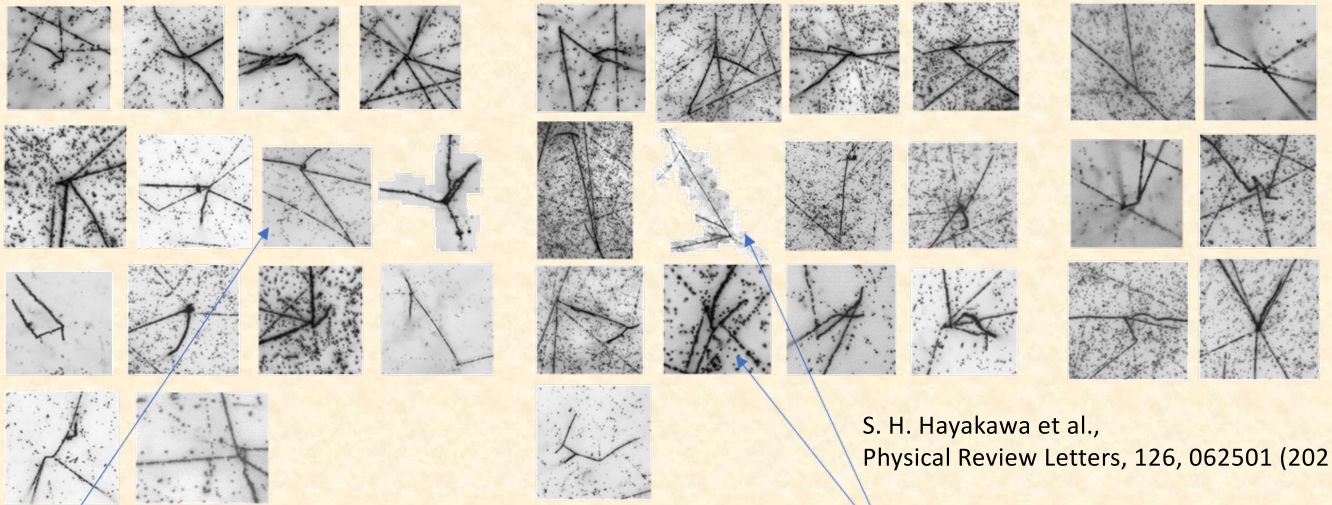
Experimental apparatus

2016-2017

J-PARC, Ibaraki, Japan

Results from J-PARC E07 (Hybrid method)

$\Lambda\Lambda$ candidates: 14 | Twin Λ events: 13 | Others: 6



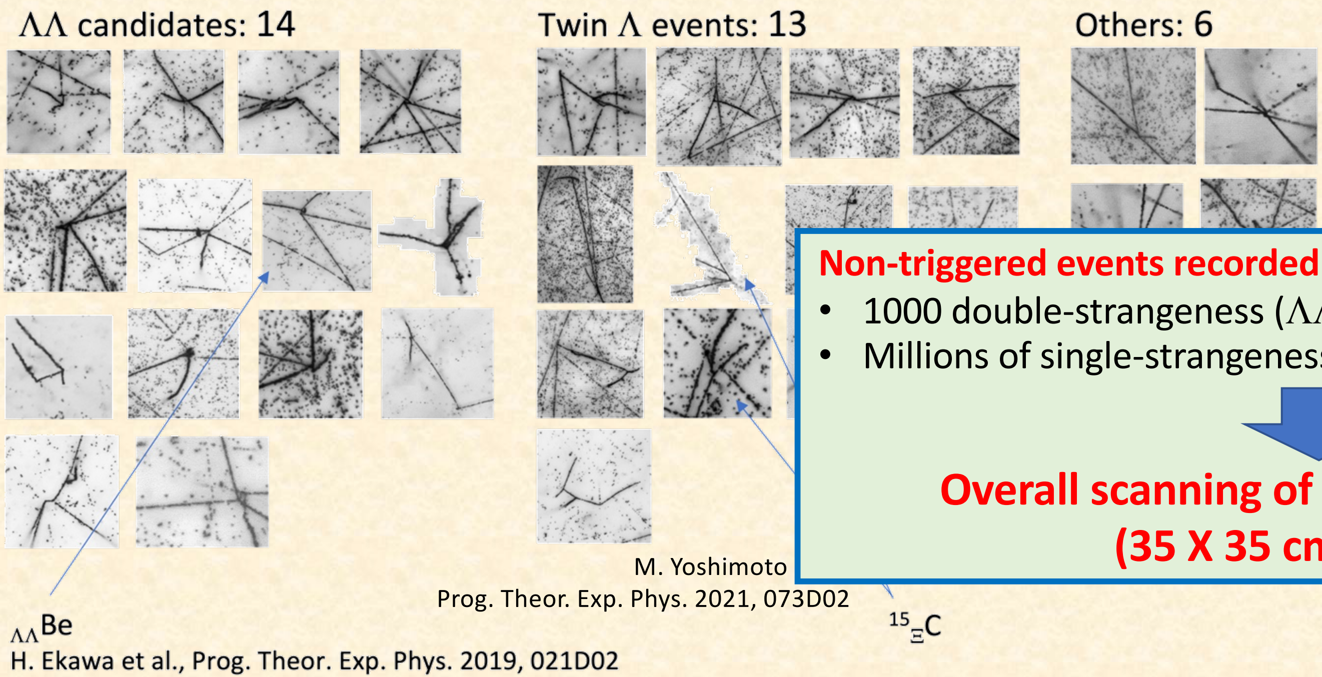
S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

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)



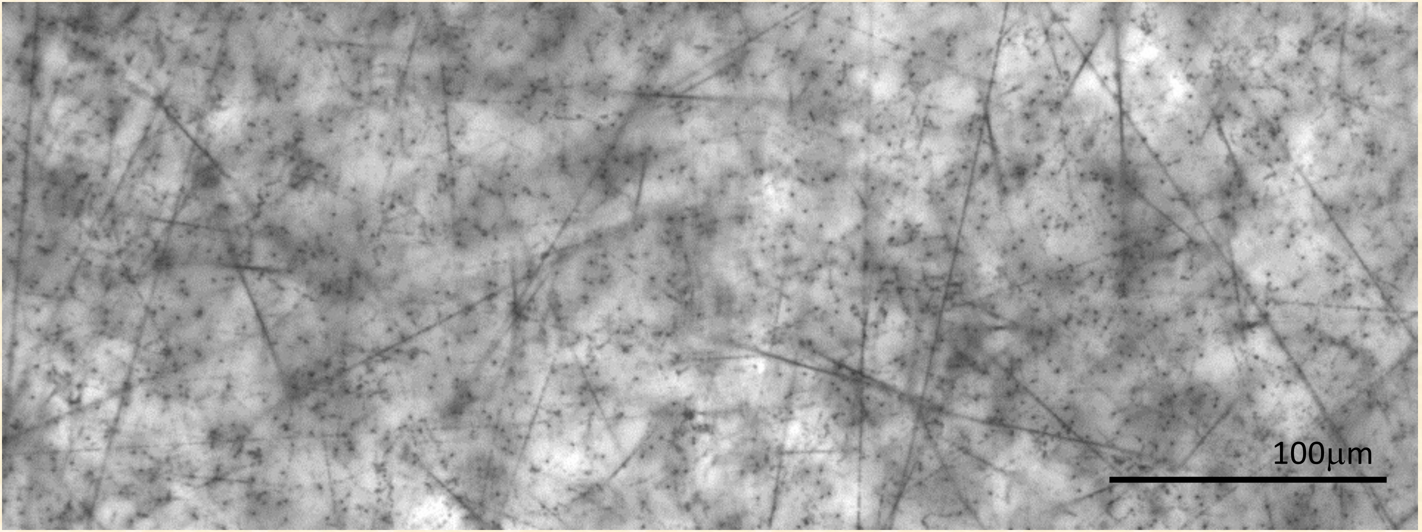
Non-triggered events recorded in 1000 emulsions sheets

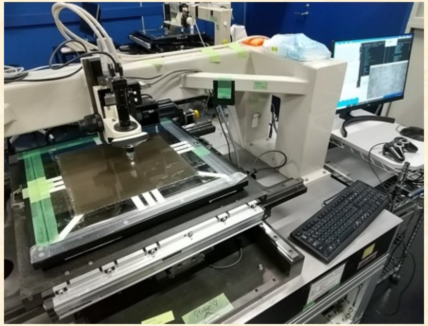
- 1000 double-strangeness (ΛΛ- and Ξ-) hypernuclear events
- Millions of single-strangeness hypernuclear events

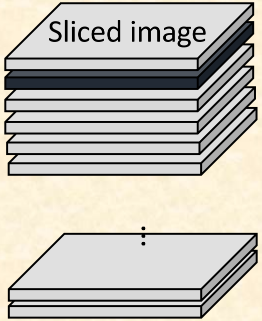
Overall scanning of all emulsion sheets

(35 X 35 cm^2 X 1000)

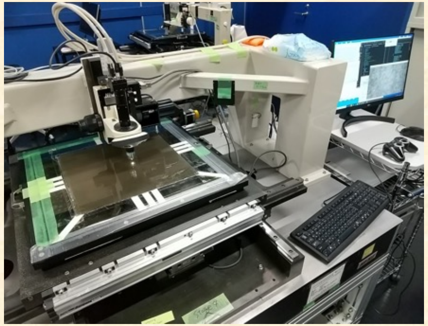
Overall scanning for E07 emulsions

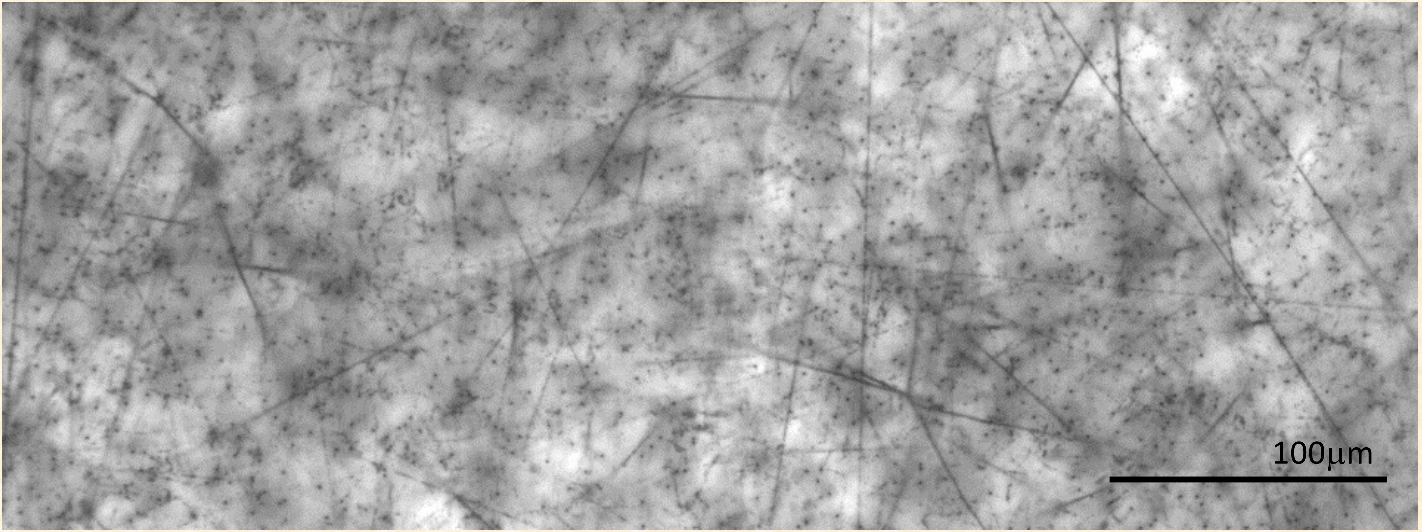


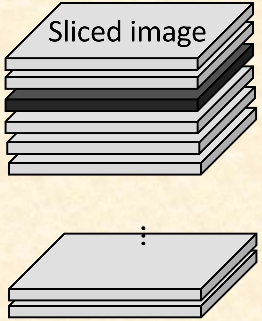




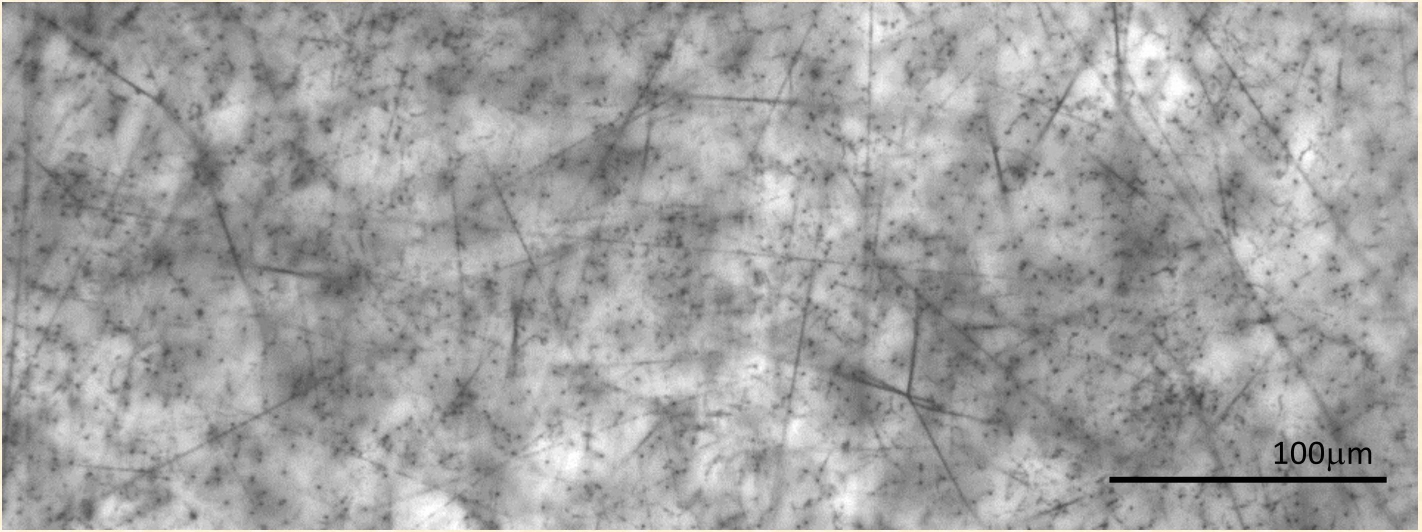
Overall scanning for E07 emulsions

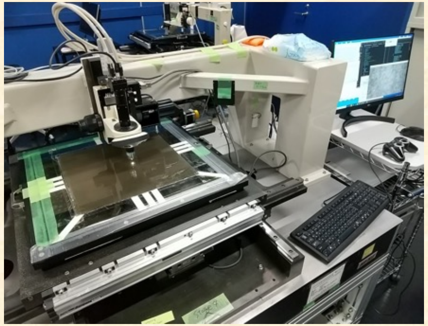


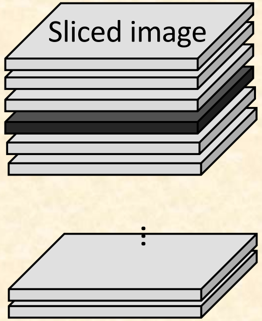




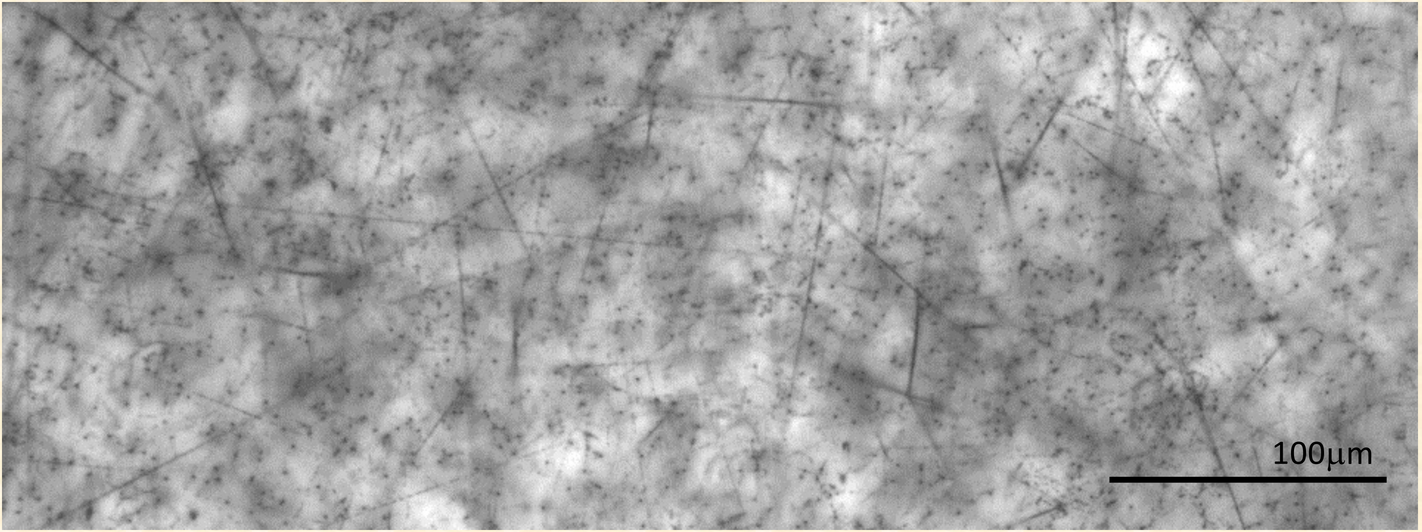
Overall scanning for E07 emulsions

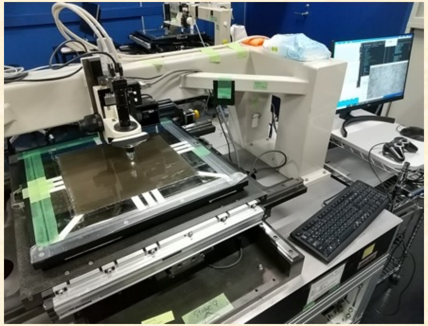


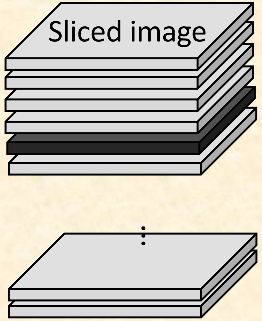




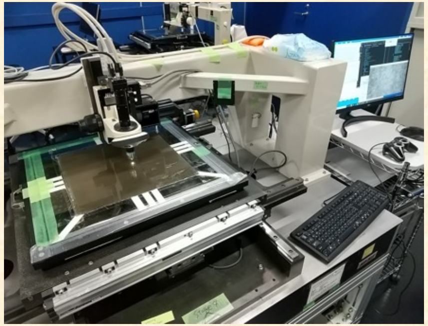
Overall scanning for E07 emulsions

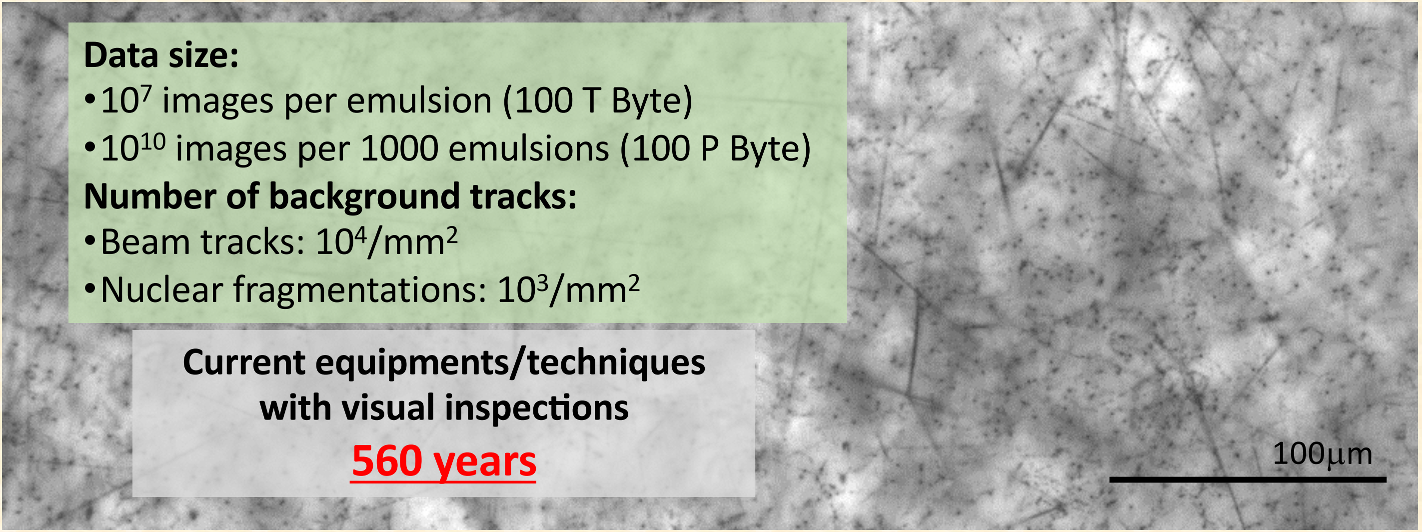






Overall scanning for E07 emulsions



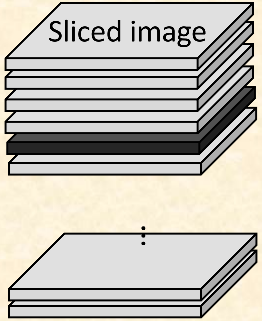


Data size:
- 10^7 images per emulsion (100 T Byte)
- 10^{10} images per 1000 emulsions (100 P Byte)

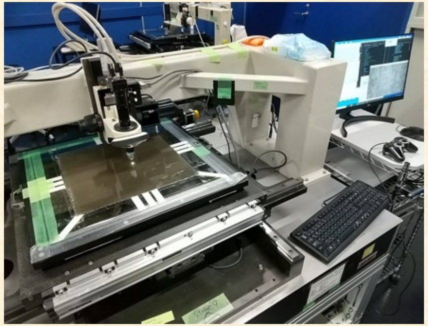
Number of background tracks:
- Beam tracks: $10^4/mm^2$
- Nuclear fragmentations: $10^3/mm^2$

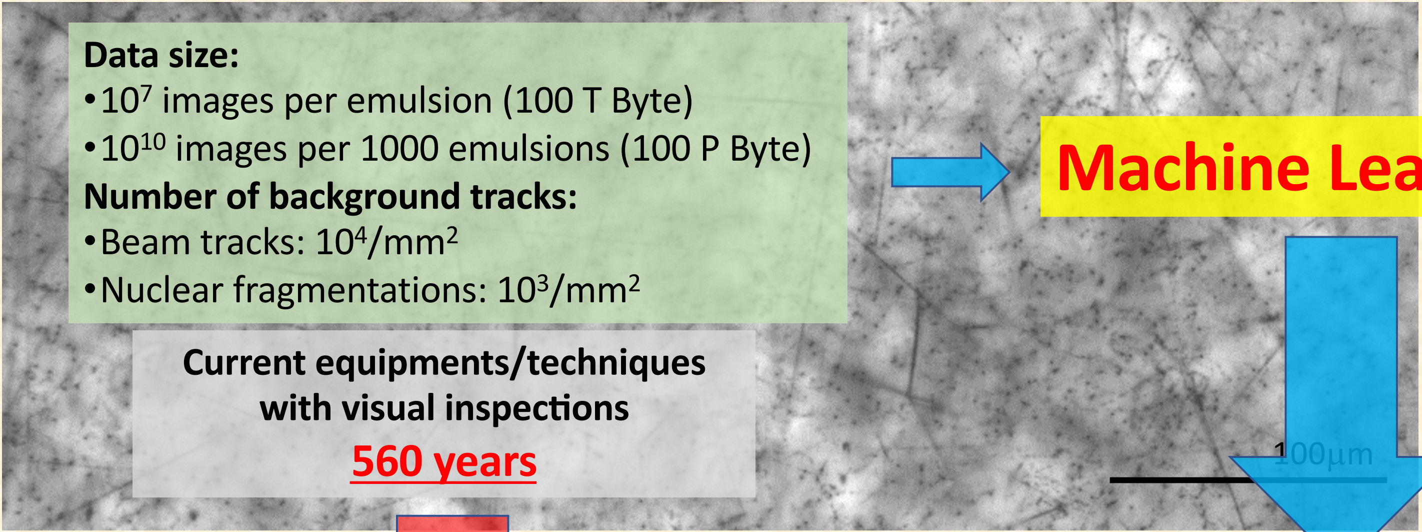
Current equipments/techniques with visual inspections

560 years



Overall scanning for E07 emulsions





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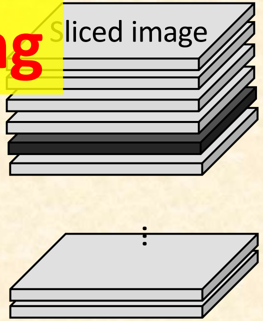
Number of background tracks:
- Beam tracks: $10^4/mm^2$
- Nuclear fragmentations: $10^3/mm^2$

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:

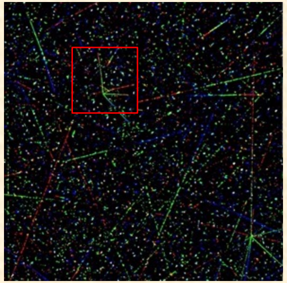
Producing training data with

- Monte Carlo simulations
- Image transfer techniques

Production of training data

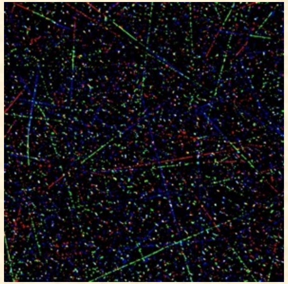
Monte Carlo simulations and GAN(Generative Adversarial Networks)

Binarized tracks from MC simulations
+ background from the real data

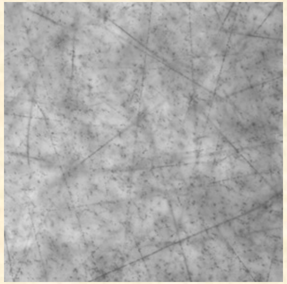


Imitated
emulsion image

GAN: pix2pix



Binarized (like for simulations)



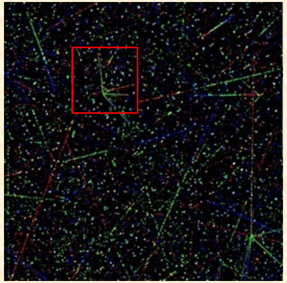
Real emulsion image

Ayumi Kasagi. Ph.D. thesis (2023)

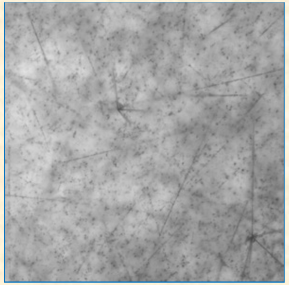
Production of training data

Monte Carlo simulations and GAN(Generative Adversarial Networks)

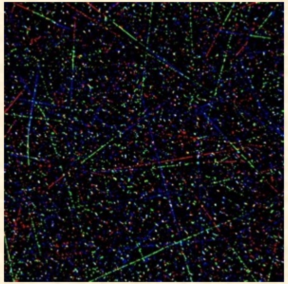
Binarized tracks from MC simulations
+ background from the real data



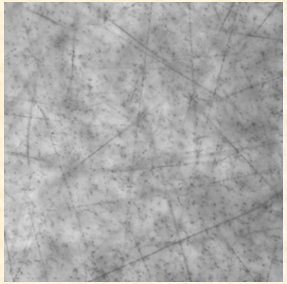
Produced training data



GAN: pix2pix



Binarized (like for simulations)

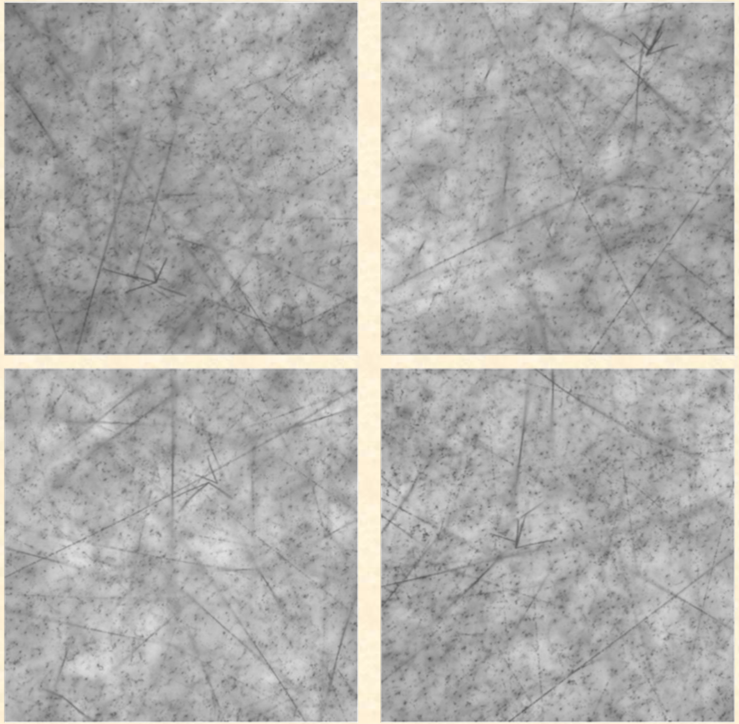


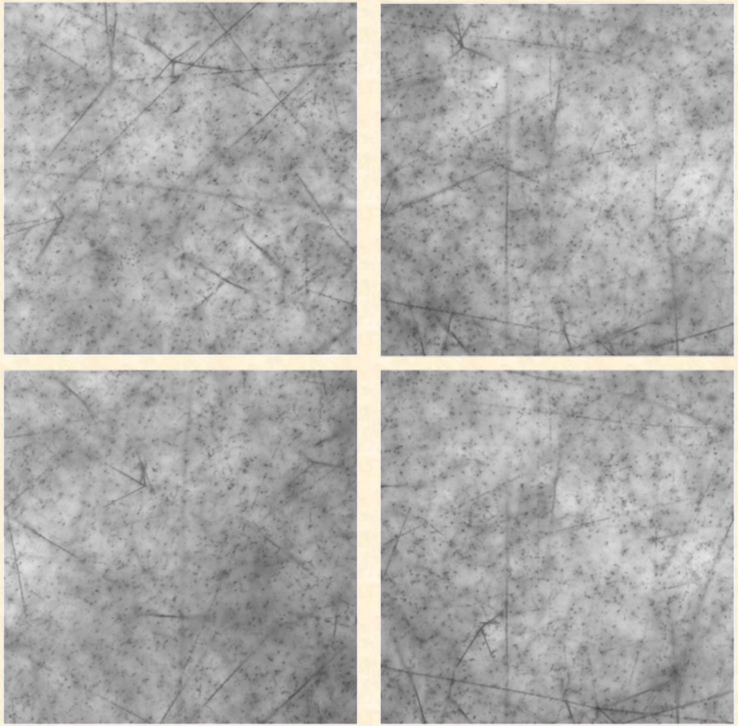
Real emulsion image

Ayumi Kasagi. Ph.D. thesis (2023)

Production of training data

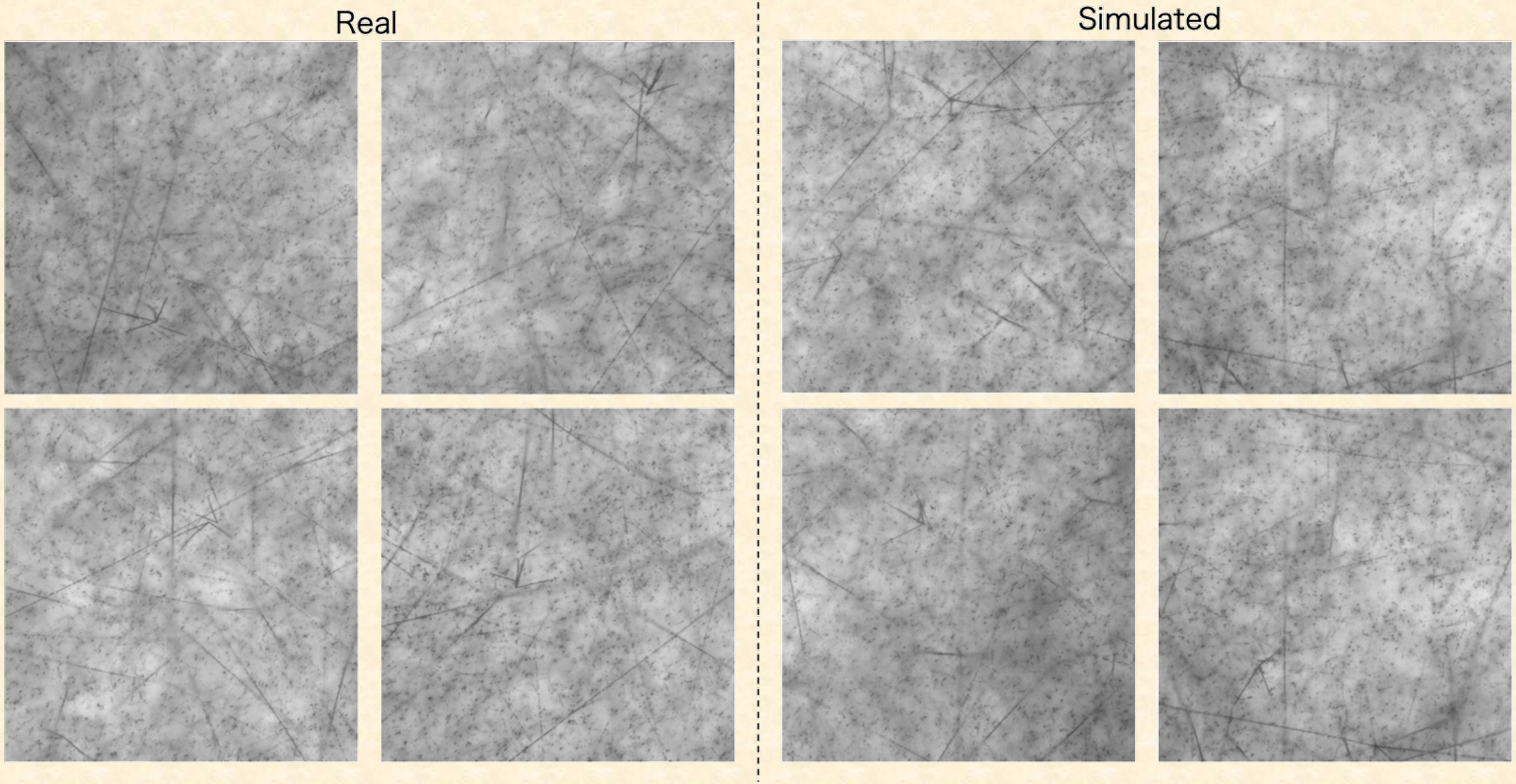
Monte Carlo simulations and GAN(Generative Adversarial Networks)





Production of training data

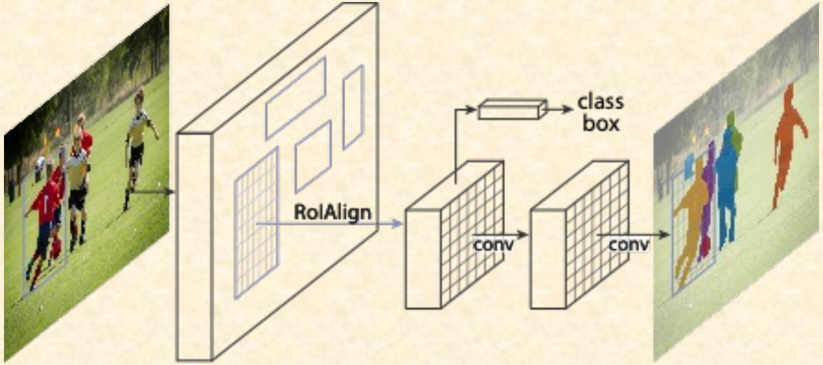
Monte Carlo simulations and GAN(Generative Adversarial Networks)

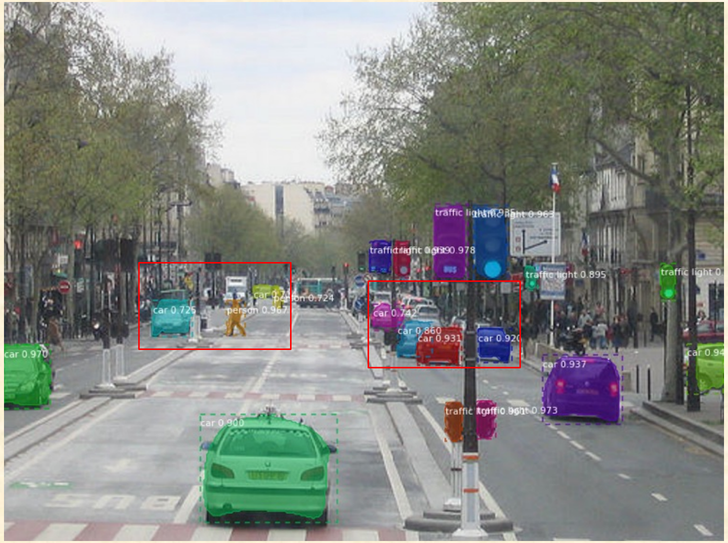


Detection of hypertriton events

With Mask R-CNN model

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





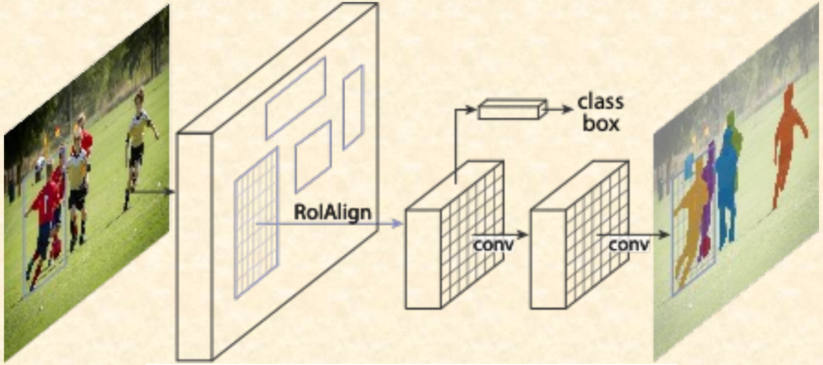
Detection of each object

At large object density

Detection of hypertriton events

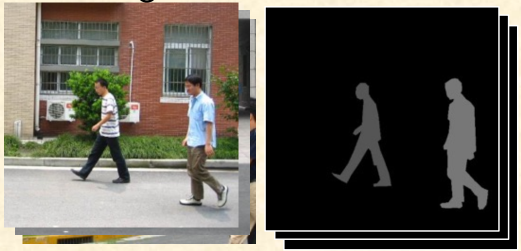
With Mask R-CNN model

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



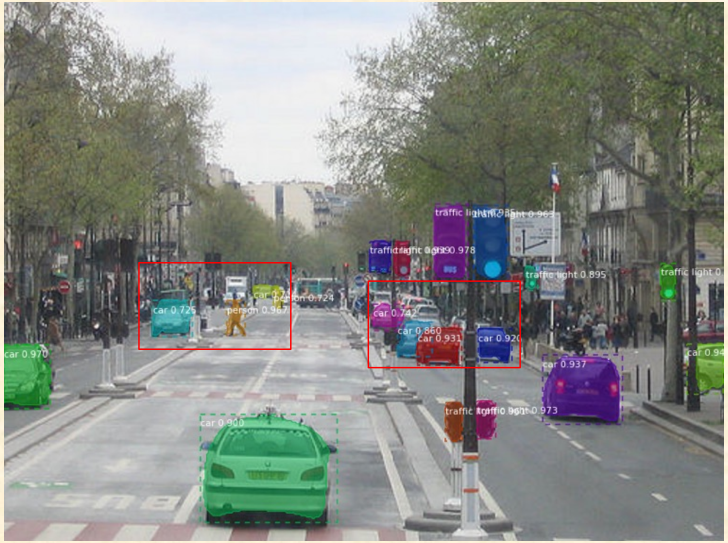
Example of training dataset

Image Mask



A Pedestrian dataset

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

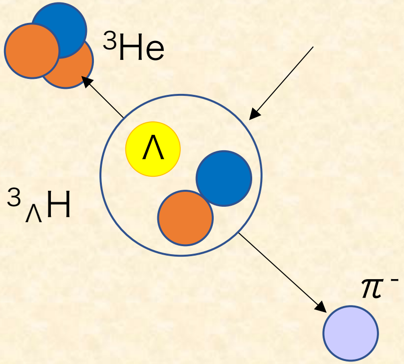


Detection of each object

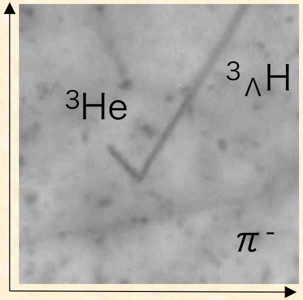
At large object density

Hypertriton search with Mask R-CNN

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



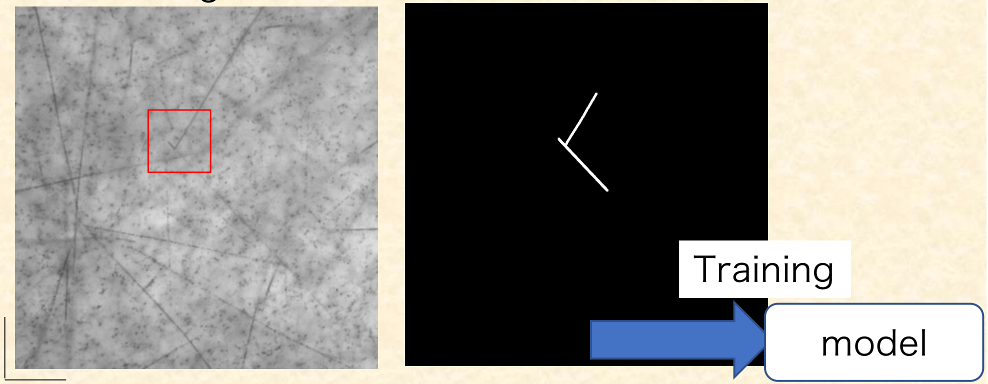
Simulated image



50 μm

Training dataset (Simulated images)

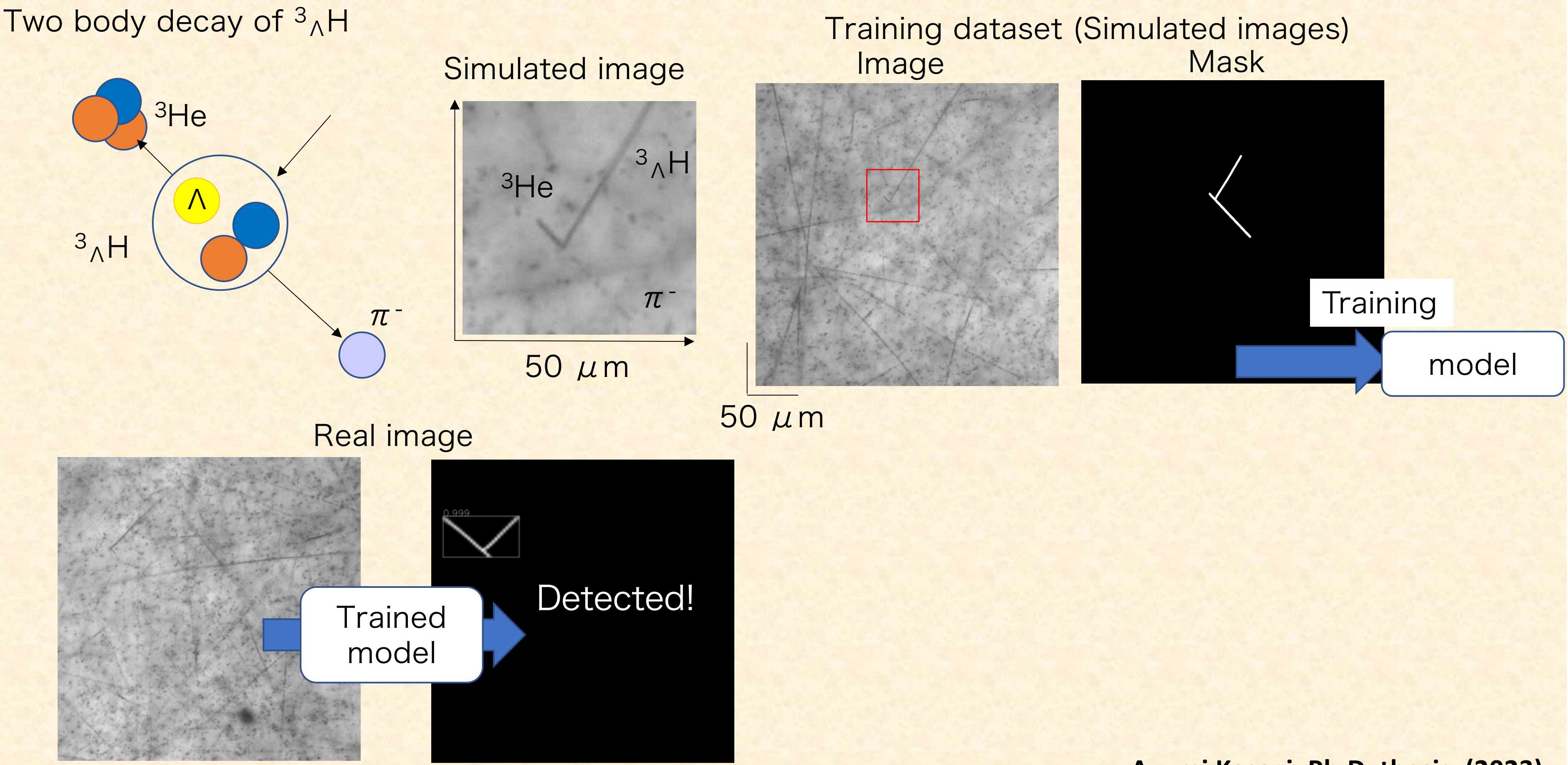
Image Mask



50 μm

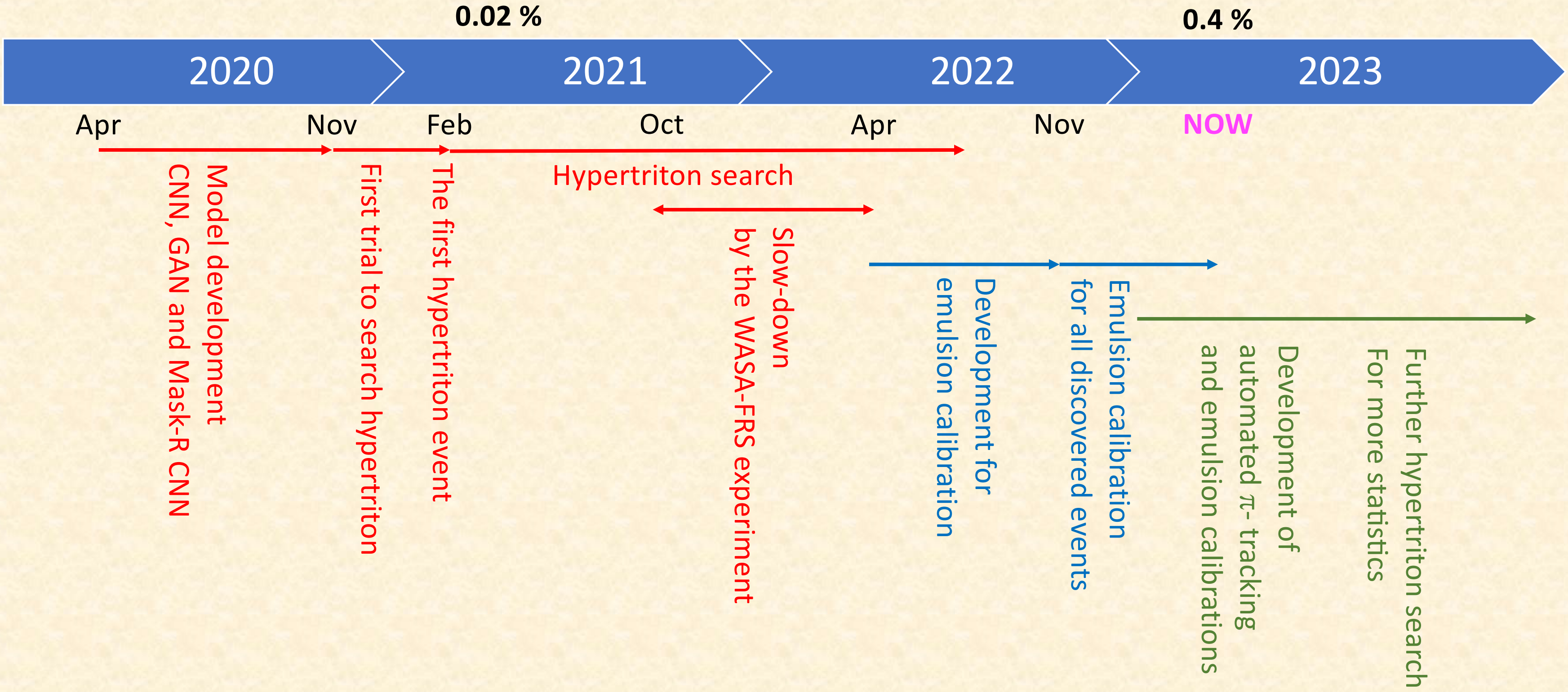
Ayumi Kasagi. Ph.D. thesis (2023)

Hypertriton search with Mask R-CNN



Ayumi Kasagi. Ph.D. thesis (2023)

Status of the project for hypertriton and $^{4}_{\Lambda}H$



Discovery of the first hypertriton event in E07 emulsions

nature reviews physics

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nature > nature reviews physics > perspectives > article

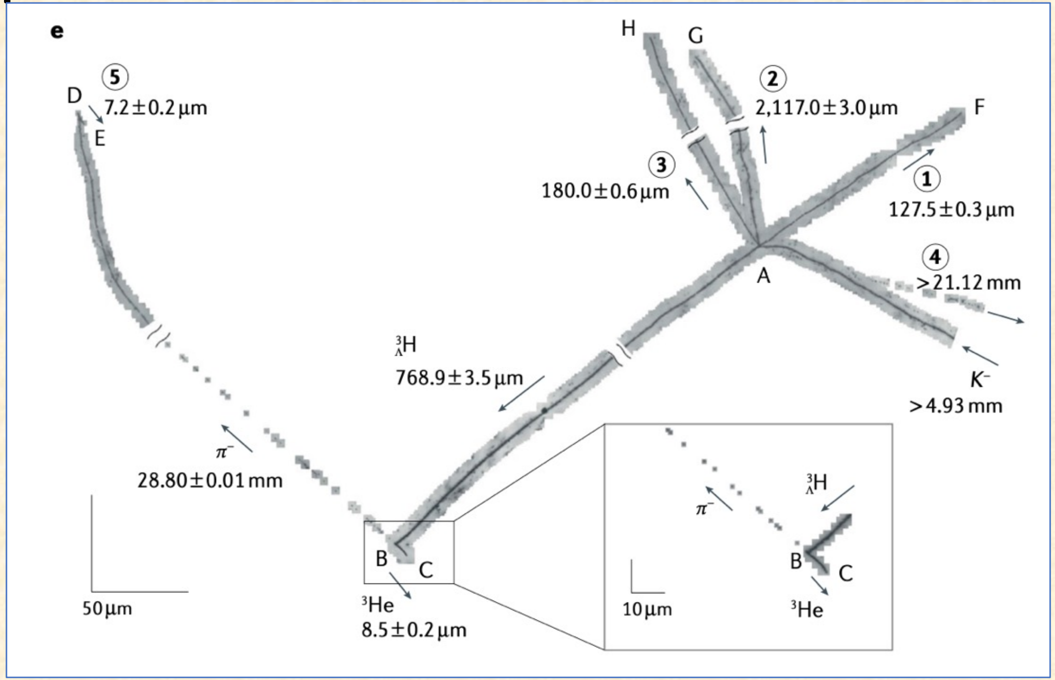
Perspective | Published: 14 September 2021

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



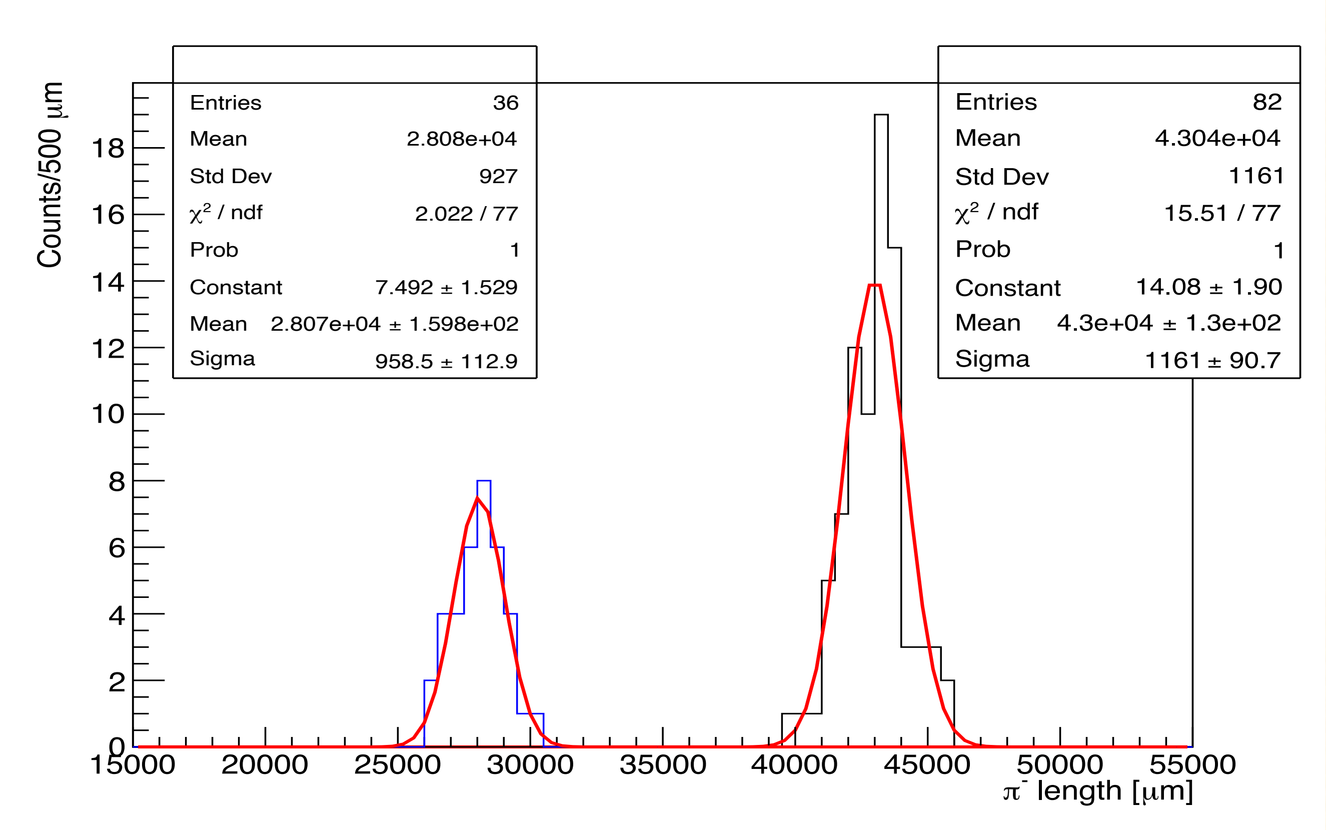
Ayumi Kasagi. Ph.D. thesis (2023)

Guaranteeing the determination of the hypertriton binding energy SOON

Precision: 28 keV

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

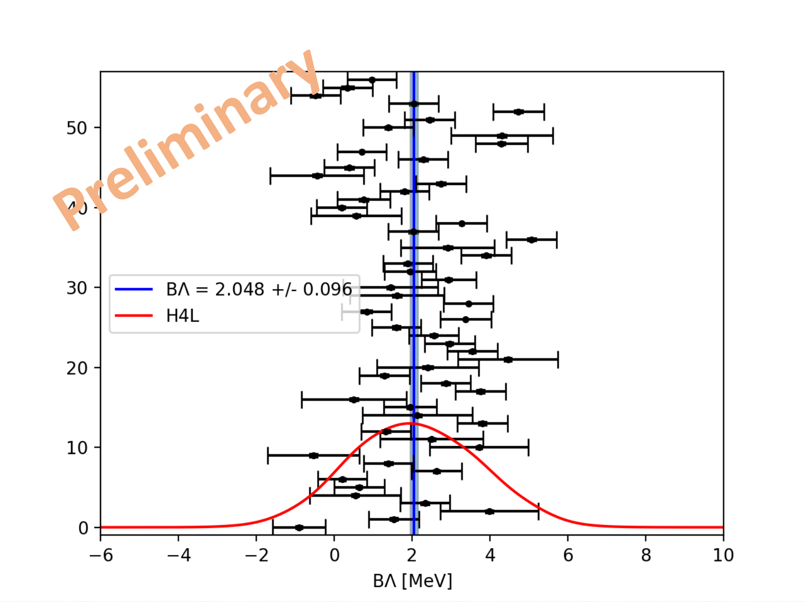
Identification of hypertriton and ${}^{4}_{\Lambda}H$ by π^- track length



Ayumi Kasagi. Ph.D. thesis (2023)

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

- Mass with range of ^{4}He
- **Emulsion calibration (density and shrinkage) for each event**
- Checking coplanarity and inner-product
- **Only 0.4 % of the entire data**



Ayumi Kasagi. Ph.D. thesis (2023)

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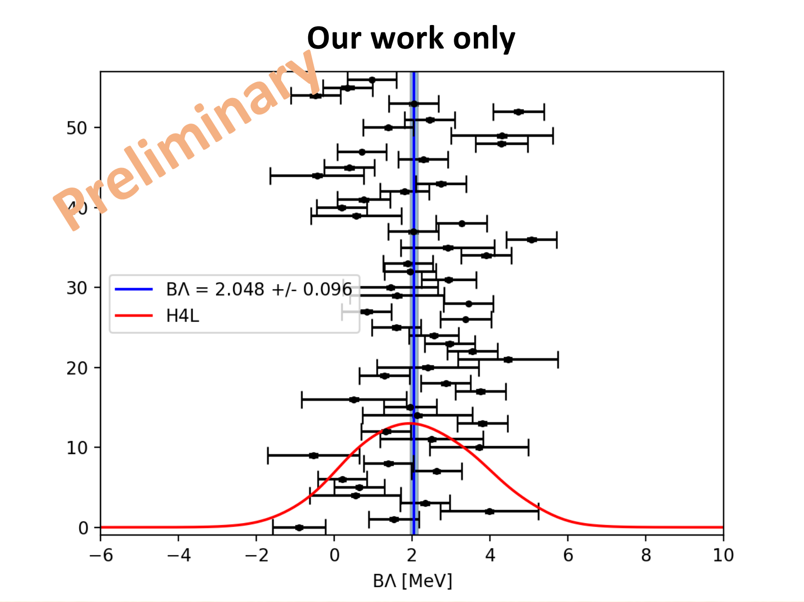
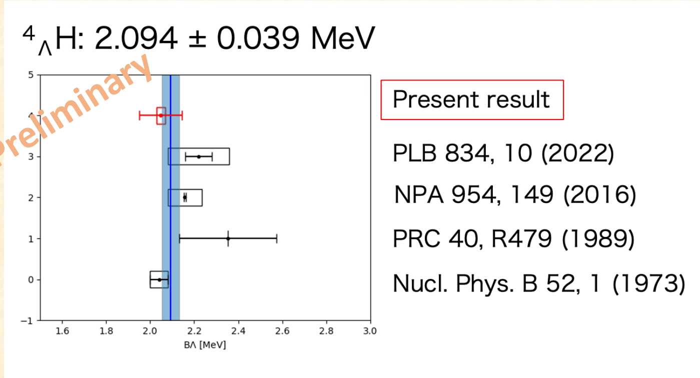
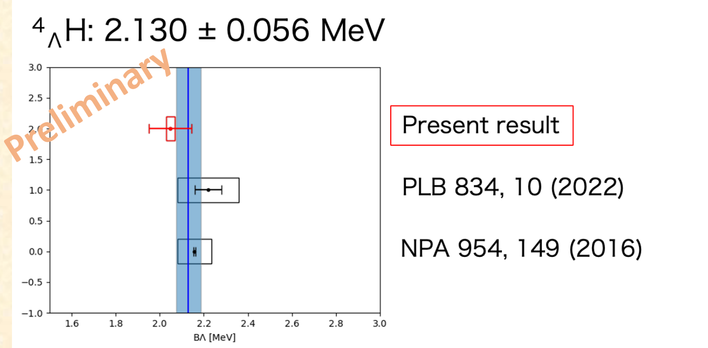


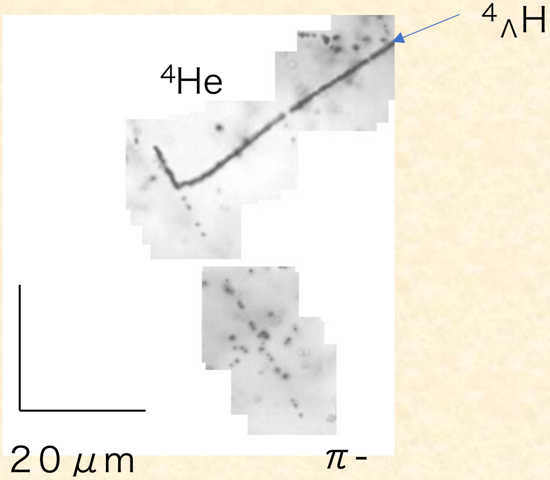




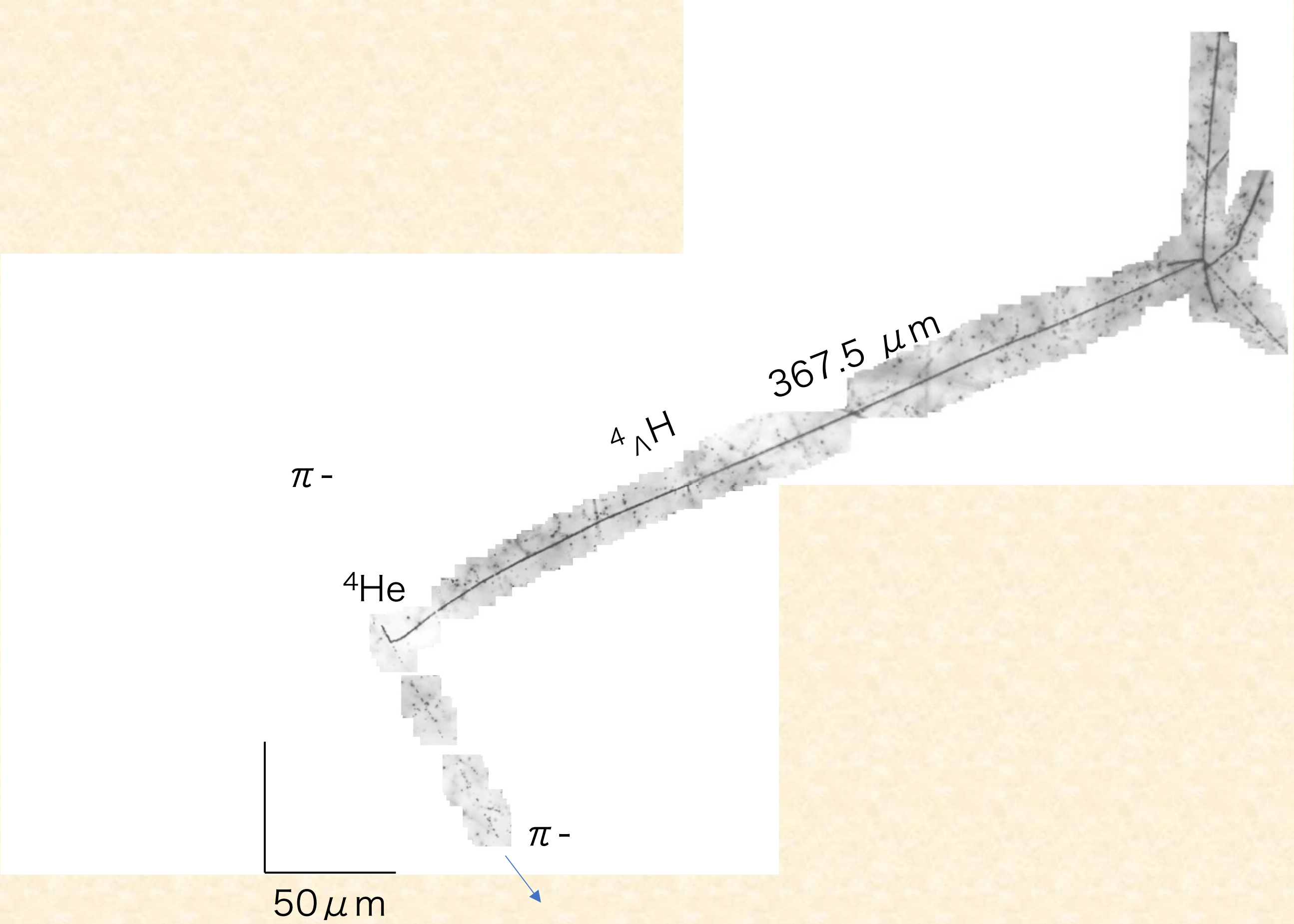
Similar analysis for hypertriton (to be published soon)

Ayumi Kasagi. Ph.D. thesis (2023)

Byproduct 1:

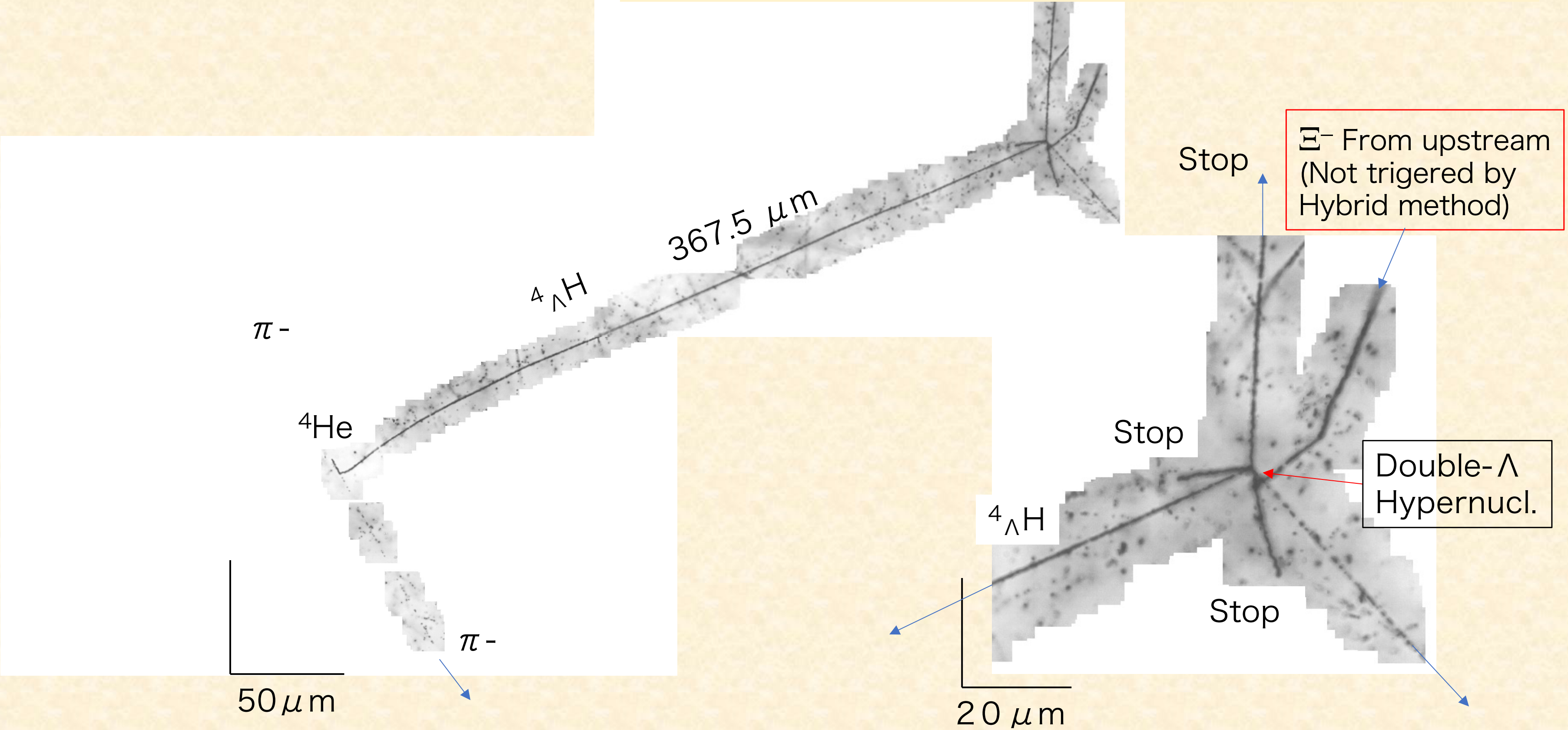


Byproduct 1:

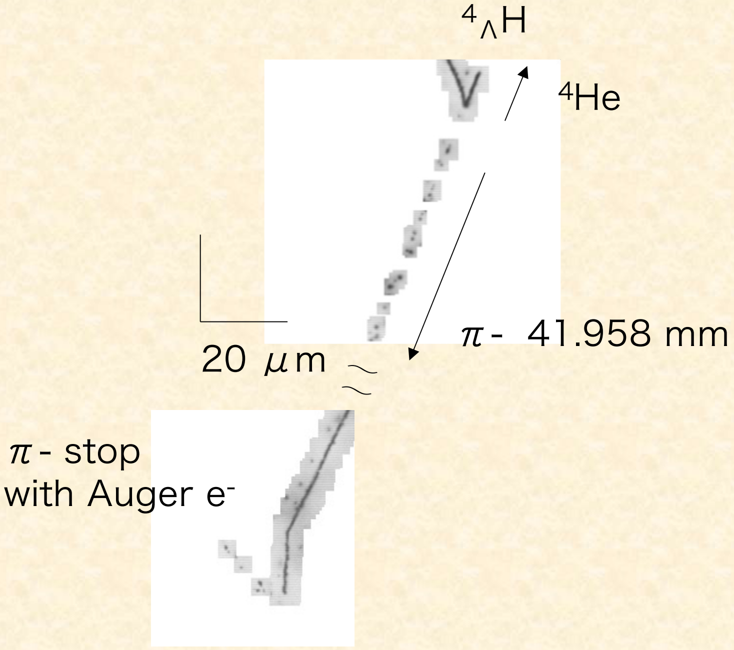


Byproduct 1:

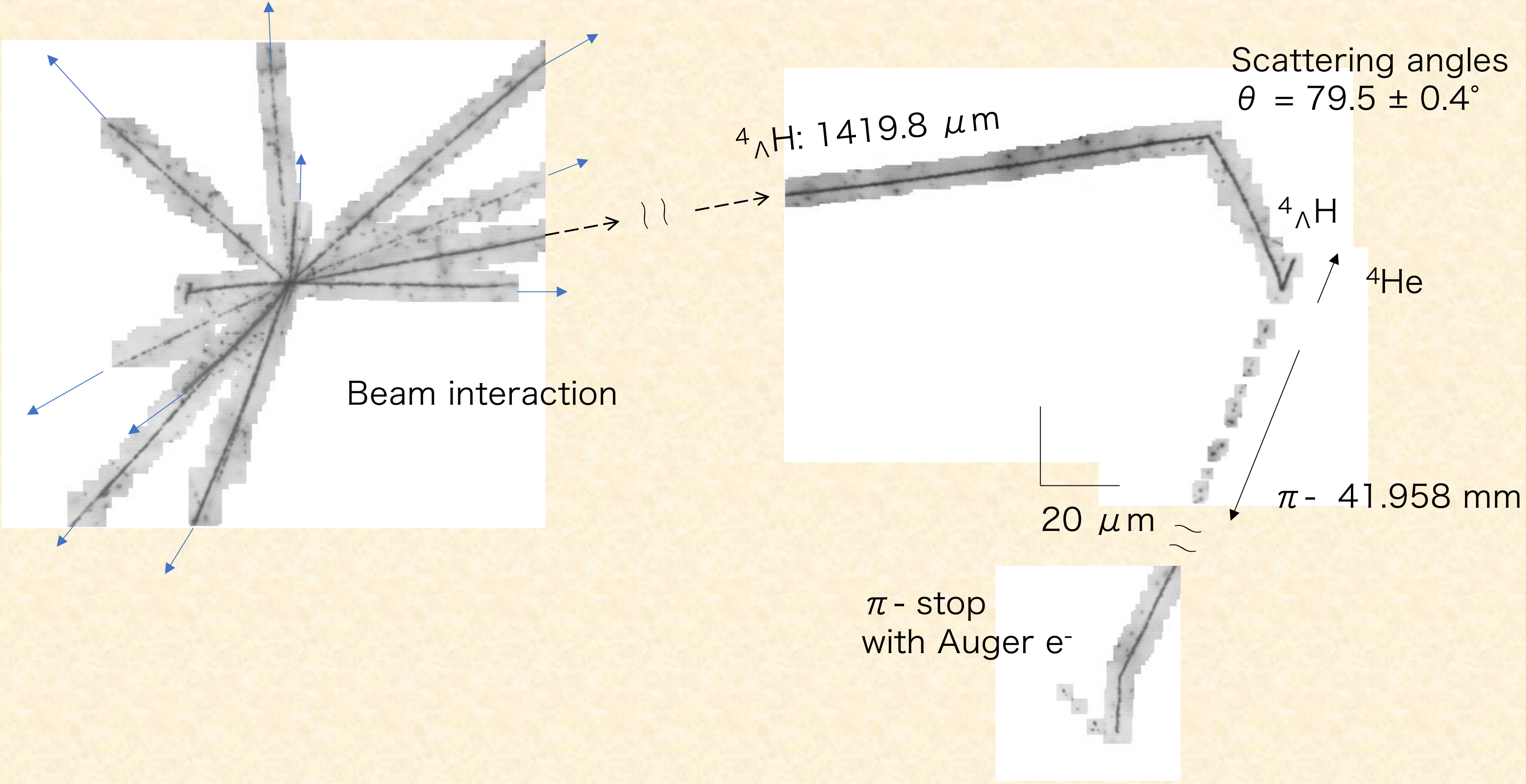
Discovery of double-Λ hypernucleus as a biproduct of $^{3}_{\Lambda}H$ search



Byproduct 2:



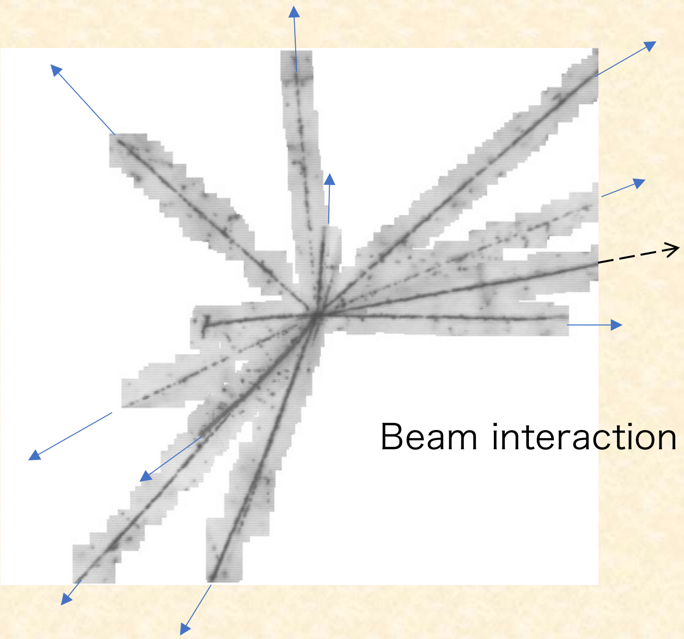
Byproduct 2:

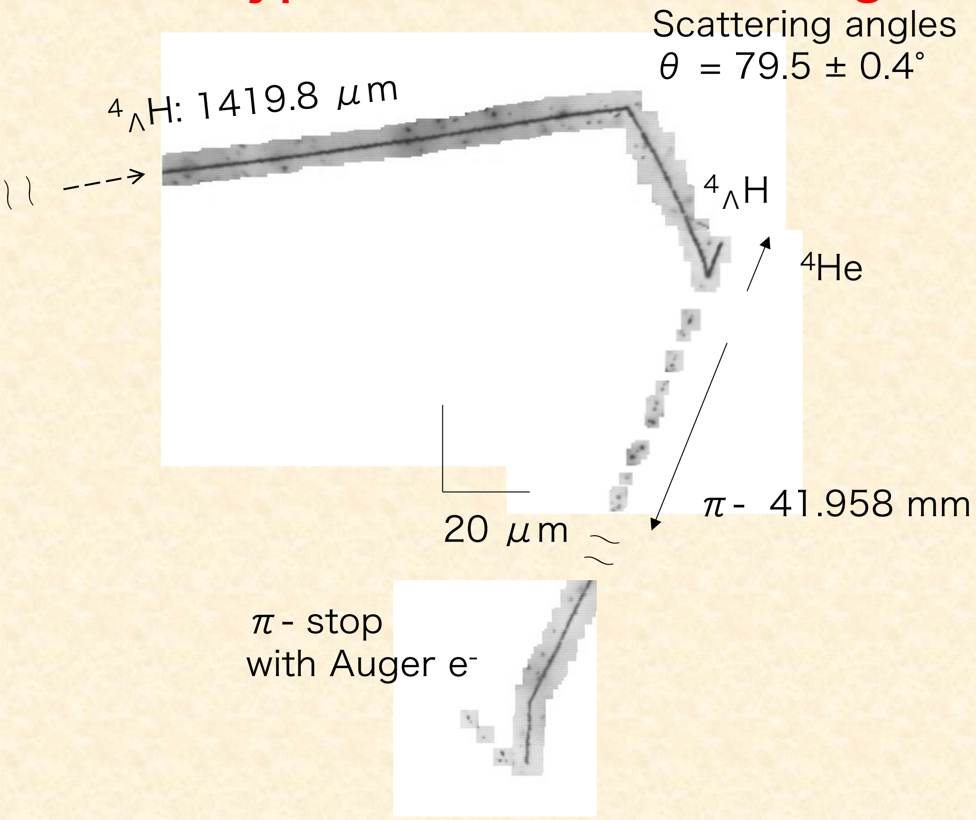


Beam interaction
$^{4}_{\Lambda}H$: 1419.8 μm
Scattering angles
θ = 79.5 ± 0.4°
$^{4}_{\Lambda}H$
^{4}He
π- 41.958 mm
20 μm
π- stop
with Auger e^{-}

Byproduct 2:

Hypernuclear scattering





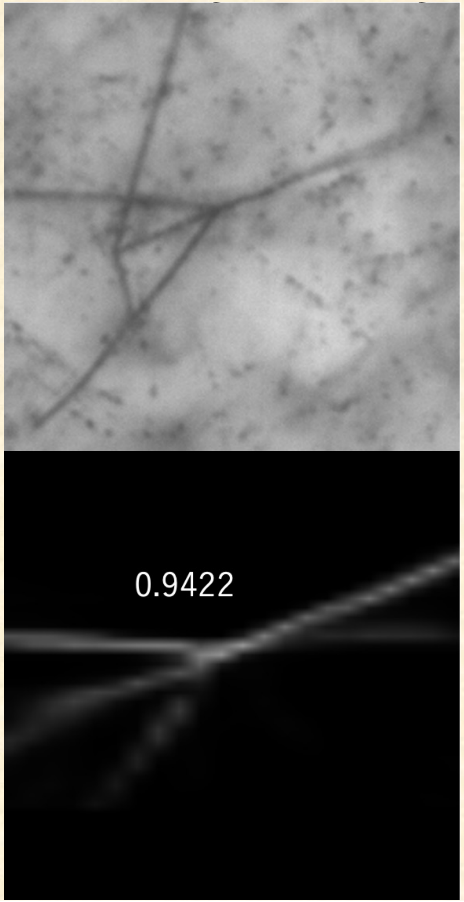
Current machine learning developments

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)

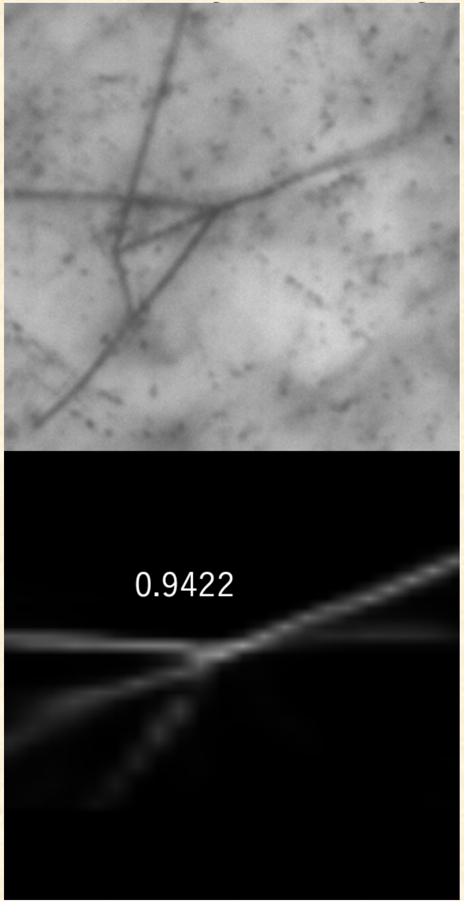
Three-body decay event

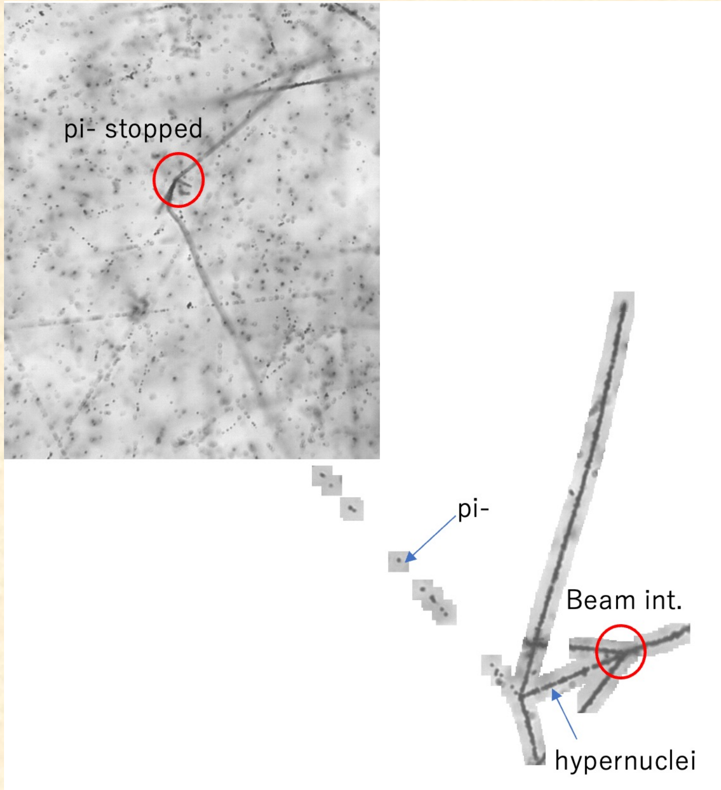


Courtesy of Shohei Sugimoto and Manami Nakagawa

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

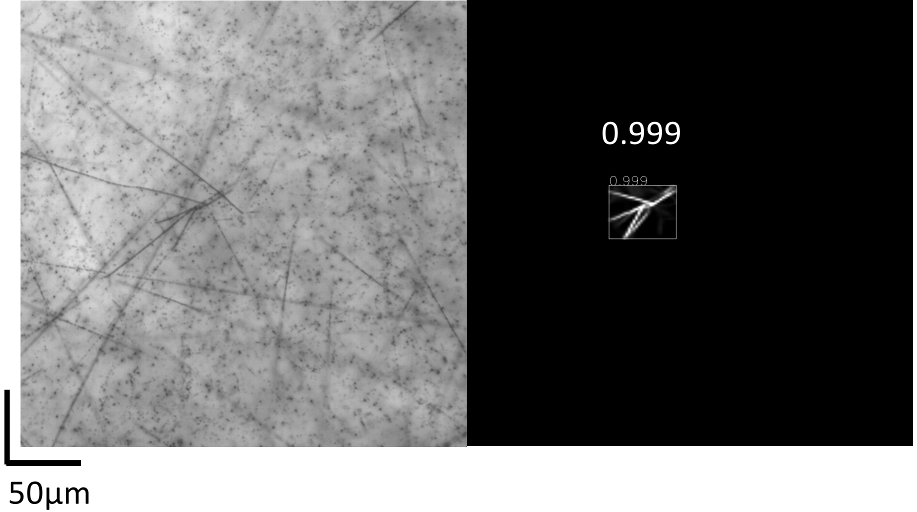
- Automated pion tracking
- Automated emulsion calibration

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

Search for double-strangeness hypernuclei (from June 2022)

MOD100_PL02_AREA00

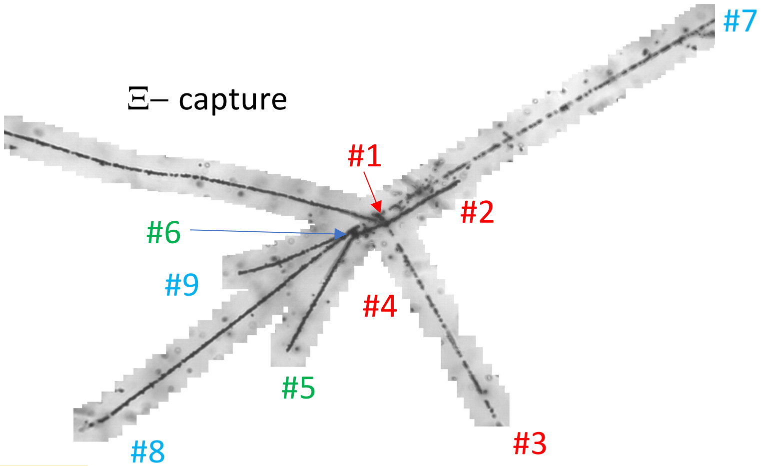
V3451



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

second vertex:
#5: stop
#6: decay

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



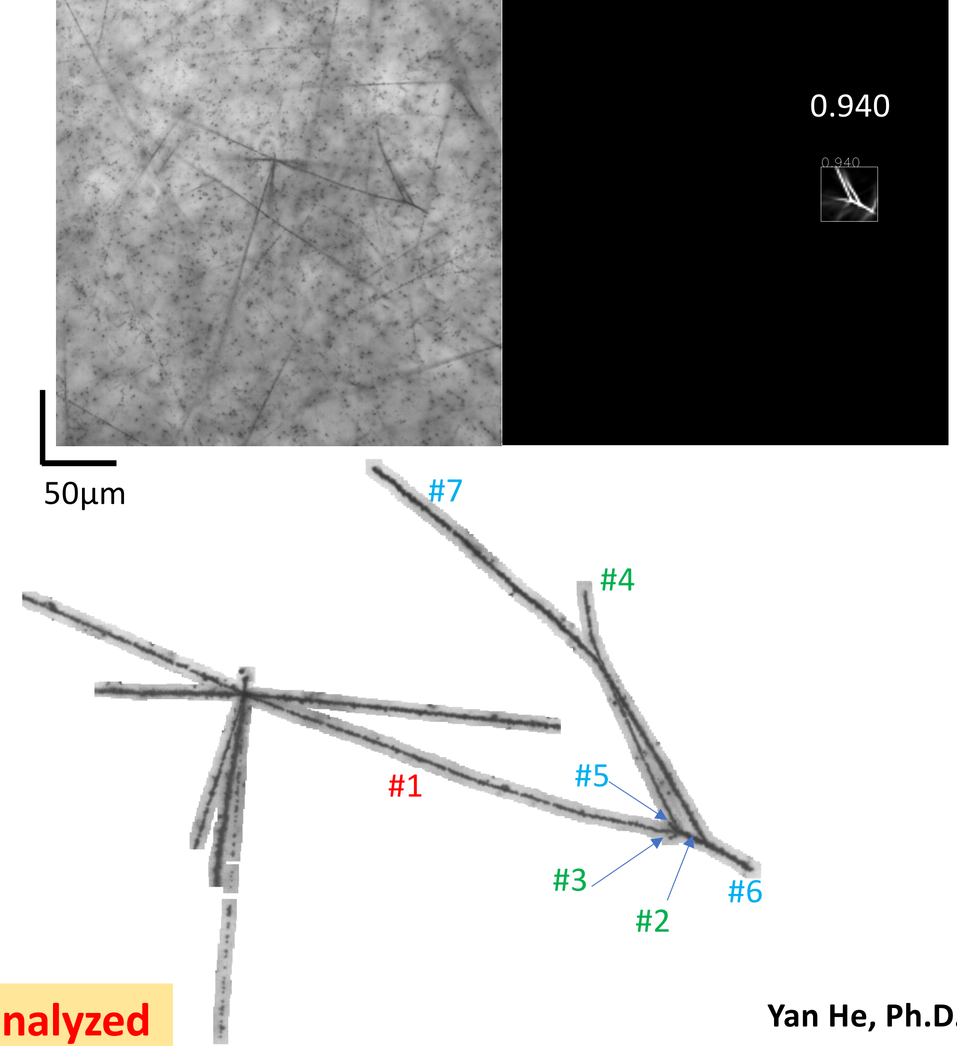
Courtesy of Yan He and Manami Nakagawa

Only ~ 0.03 % of the entire data analyzed

Yan He, Ph.D. thesis

MOD100_PL02_AREA10

V5171



Beam_int:
#1: decay

second vertex:
#2: decay
#3: stop
#4: stop

third vertex:
#5: stop
#6: stop
#7: stop

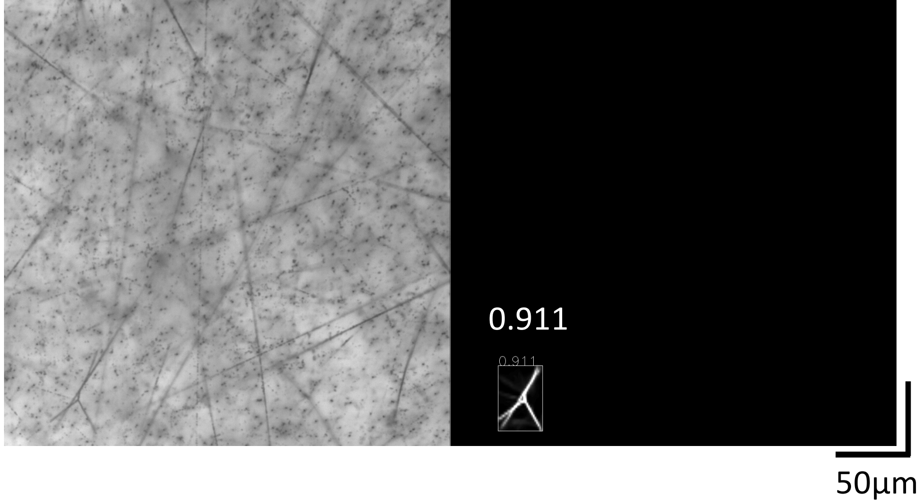
Courtesy of Yan He and Manami Nakagawa

Only ~ 0.03 % of the entire data analyzed

Yan He, Ph.D. thesis

MOD100_PL02_AREA11

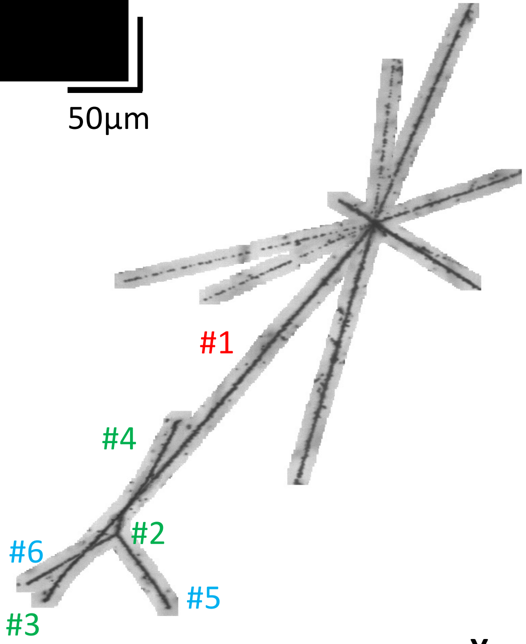
V1322



Beam_int:
#1: decay

second vertex:
#2: decay
#3: stop
#4: stop

third vertex:
#5: stop
#6: 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

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Summary

The WASA-FRS experiment at GSI

- Lifetime of hypertriton and ${}^{4}_{\Lambda}H$
- A state associated with Λnn state
- Proton rich hypernucleus ${}^{9}_{\Lambda}B$
- Further experiments at GSI/FAIR

Nuclear emulsion + Machine learning

- Binding energy of hypertriton and ${}^{4}_{\Lambda}H$
- Binding energy of single-strangeness hypernuclei with multi-body decays
- Binding energy of double-strangeness hypernuclei

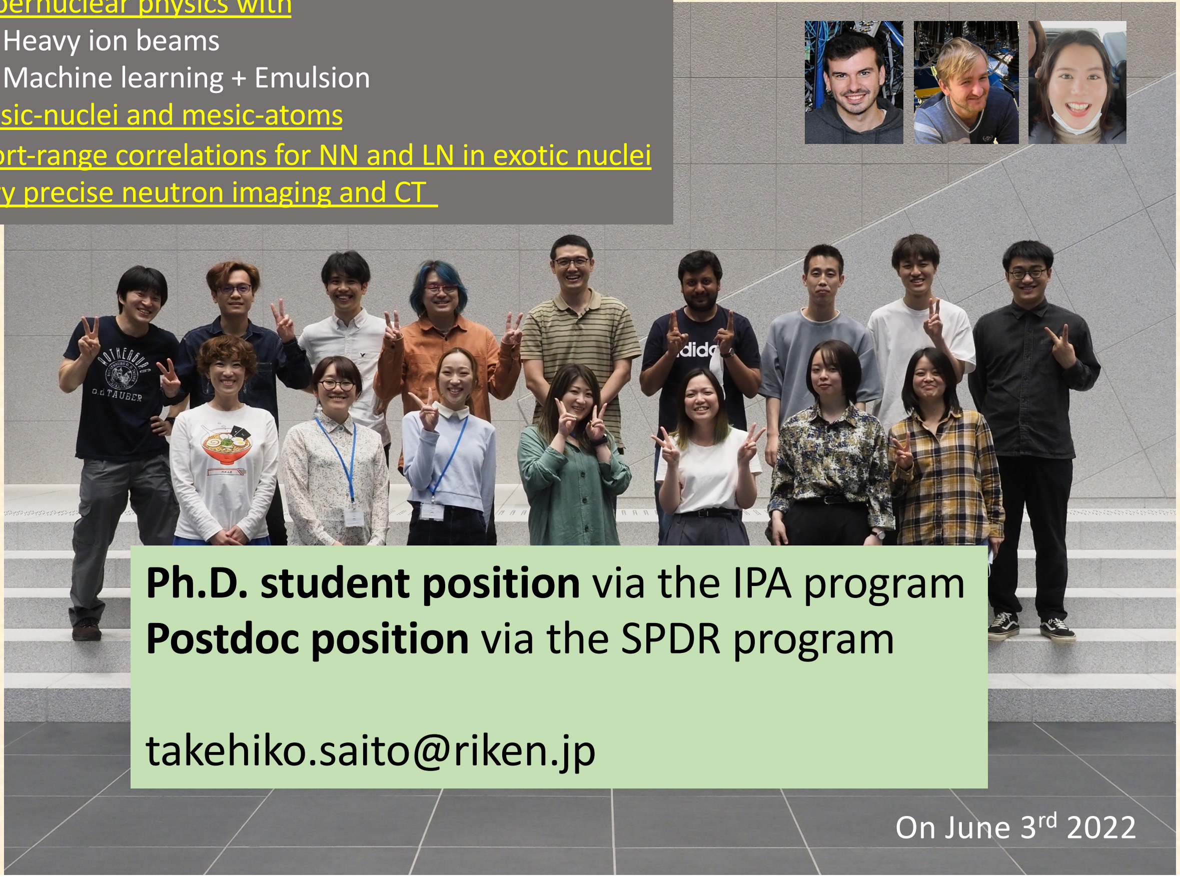
High Energy Nuclear Physics Lab. at RIKEN since 2019

Hypernuclear physics with
- Heavy ion beams
- Machine learning + Emulsion

Mesic-nuclei and mesic-atoms

Short-range correlations for NN and LN in exotic nuclei

Very precise neutron imaging and CT



Ph.D. student position via the IPA program

Postdoc position via the SPDR program

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On June 3rd 2022

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