Machine learning techniques applied to study light hypernuclei

Take R. Saito

High Energy Nuclear Physics Laboratory, RIKEN, Japan
and
HRS-HYS Research Group, GSI, Germany

for **the Nuclear Emulsion + ML Collaboration**

W. Dou, V. Drozd, H. Ekawa, S. Escrig, Y. Gao, **Y. He**, **A. Kasagi**, E. Liu, A. Muneem, **M. Nakagawa**, K. Nakazawa, C. Rappold, N. Saito, T.R. Saito, **S. Sugimoto**, M. Taki, Y.K. Tanaka, A. Yanai, J. Yoshida, M. Yoshimoto, and H. Wang

HADRON2023, Genova, Italy, June 5th – 9th, 2023

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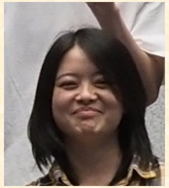
M. Nakagawa
Postdoc
RIKEN

A. Kasagi
Postdoc
RIKEN & Rikkyo U
Ph.D. thesis (Gifu U.)



Y. He
Ph.D. student
RIKEN & Lanzhou U.

S. Sugimoto
Master student
RIKEN & Saitama U.

HADRON2023, Genova, Italy, June 5th – 9th, 2023

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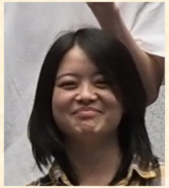

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S. Sugimoto
Master student
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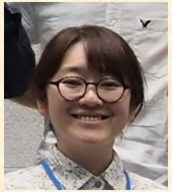
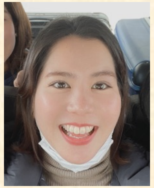
Technical staffs for nuclear emulsions



M. Ando
RIKEN

C. Harisaki
RIKEN

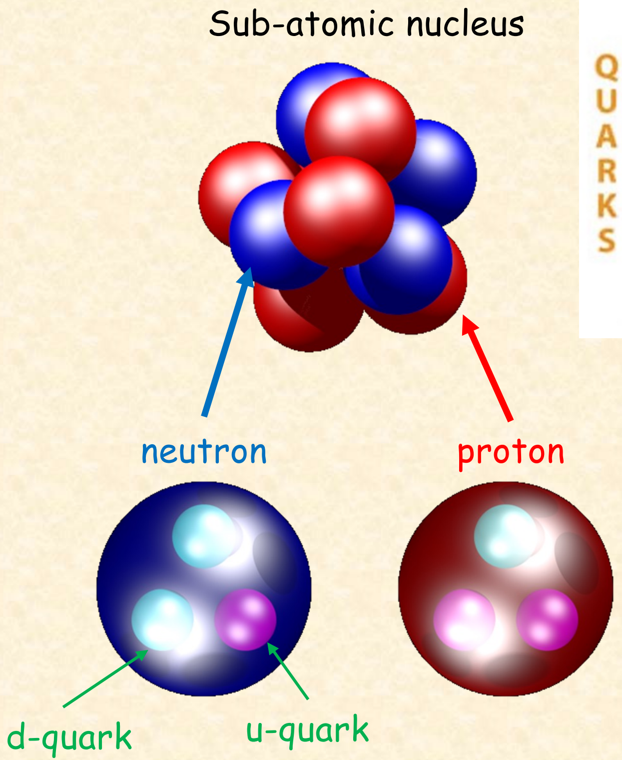
R. Kobayashi
RIKEN

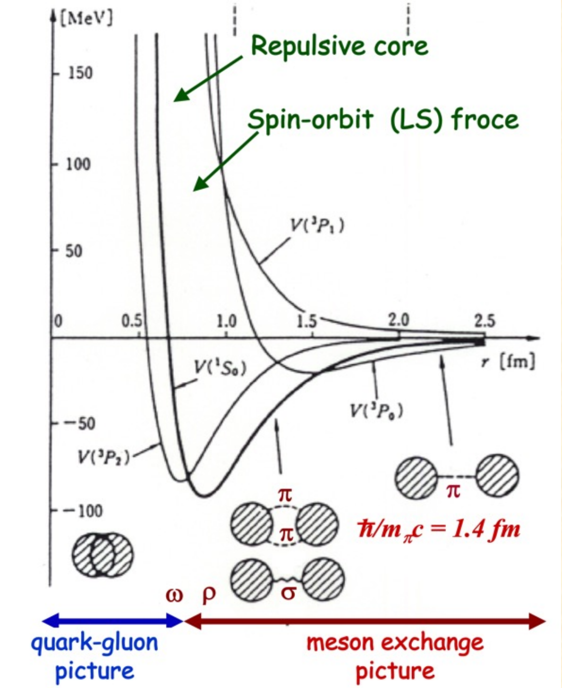


H. Kubota
RIKEN

HADRON2023, Genova, Italy, June 5th – 9th, 2023

Quarks and sub-atomic nuclei

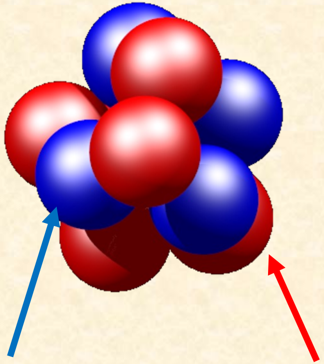




There are many identical quarks

Quarks and sub-atomic nuclei

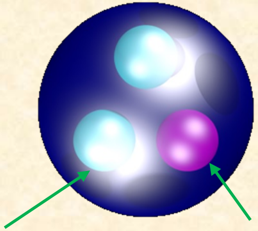
Sub-atomic nucleus



neutron

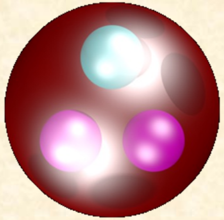
proton

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672



d-quark

u-quark

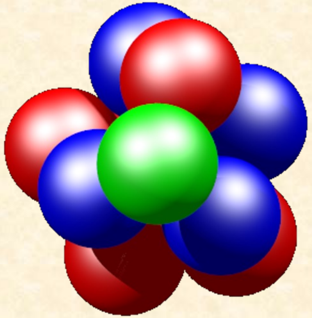


hyperon (Λ)

Lifetime: 10^{-10} s

s-quark: distinguishable from u- and d-quarks

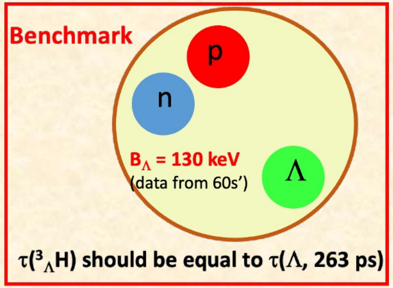
hypernucleus



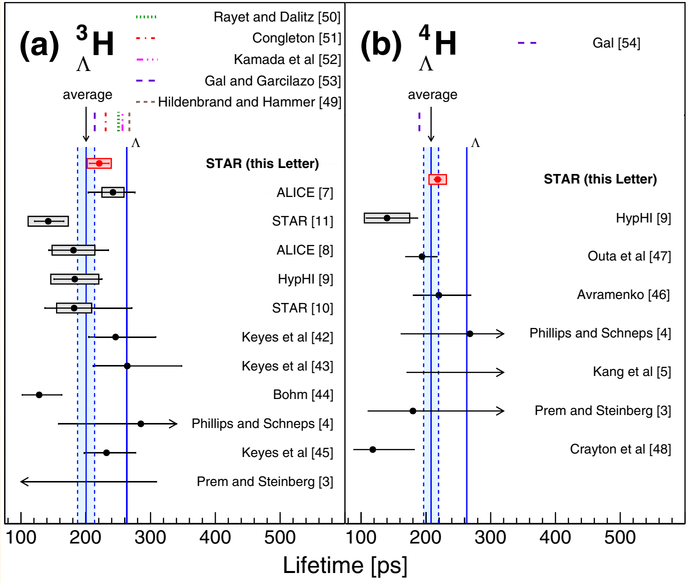
Micro-laboratory to study baryonic-interactions

Recent hot topics for few-body hypernuclei

On hypertriton



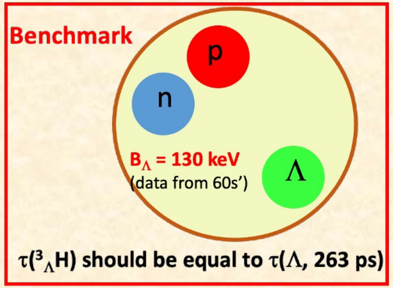
Average
200 ± 13 ps



STAR Collaboration, PRL **128** (2022) 202301

Recent hot topics for few-body hypernuclei

On hypertriton



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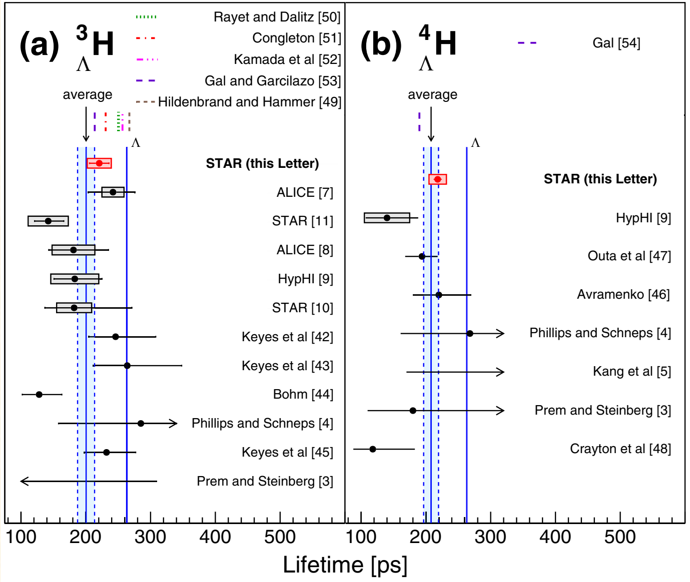

STAR Collaboration, PRL **128** (2022) 202301

${}^3_\Lambda$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

Recent hot topics for few-body hypernuclei

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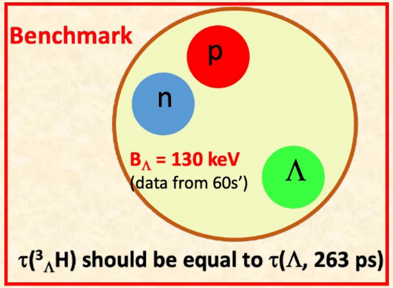

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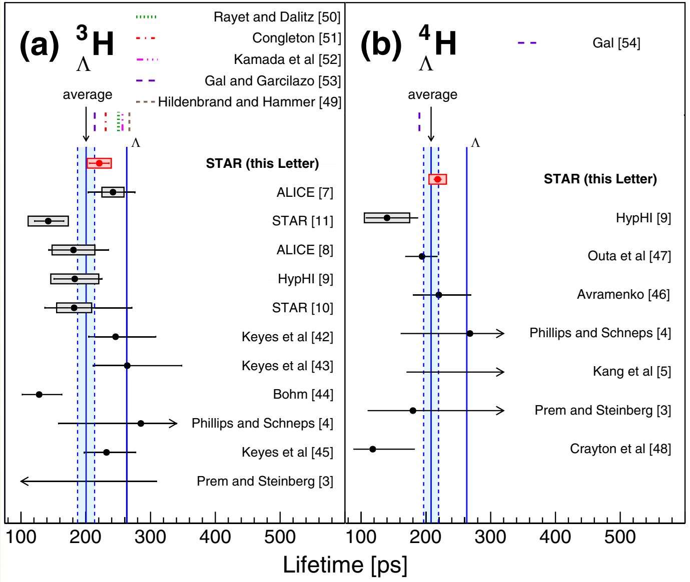

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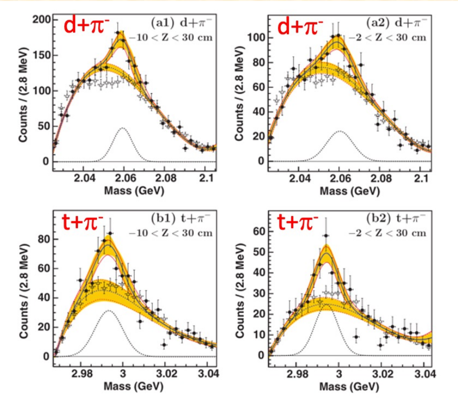
On Λnn



HypHI., PRC 88 (2013) 041001

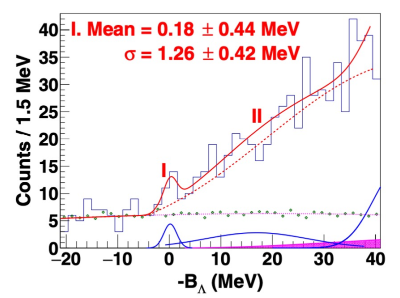
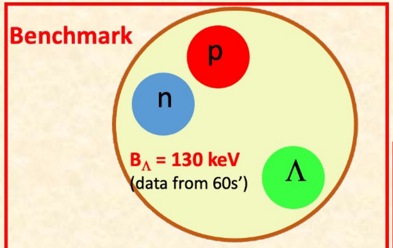


FIG. 5. The enlarged mass spectrum around the Λnn threshold. Two additional Gaussians were fitted together with the known contributions (the accidentals, the Λ quasifree, the free Λ, and the ^{3}He contamination). The one at the threshold is for the small peak, while the broad one is for the additional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

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

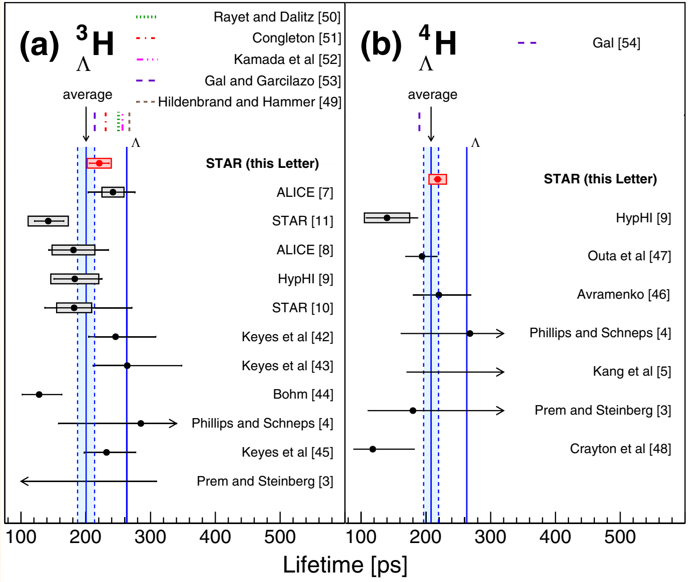
Recent hot topics for few-body hypernuclei

On hypertriton



$\tau(^3_\Lambda H)$ should be equal to $\tau(\Lambda$, 263 ps)

Average
200 ± 13 ps



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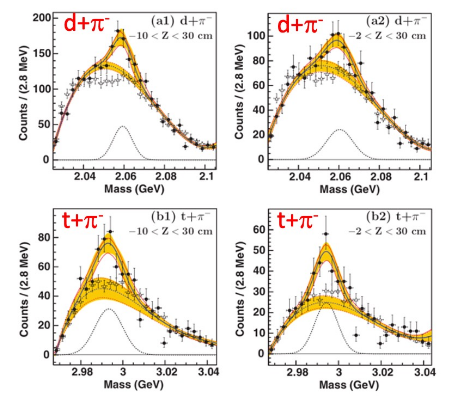
For the lifetime and Λnn
H. Ekawa's talk on June 7th
on the WASA-FRS HypHI

On Λnn



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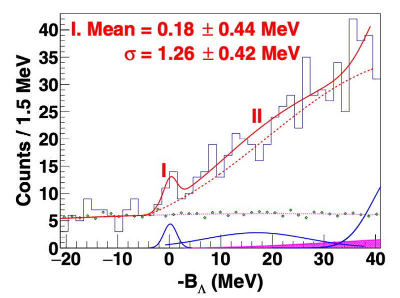

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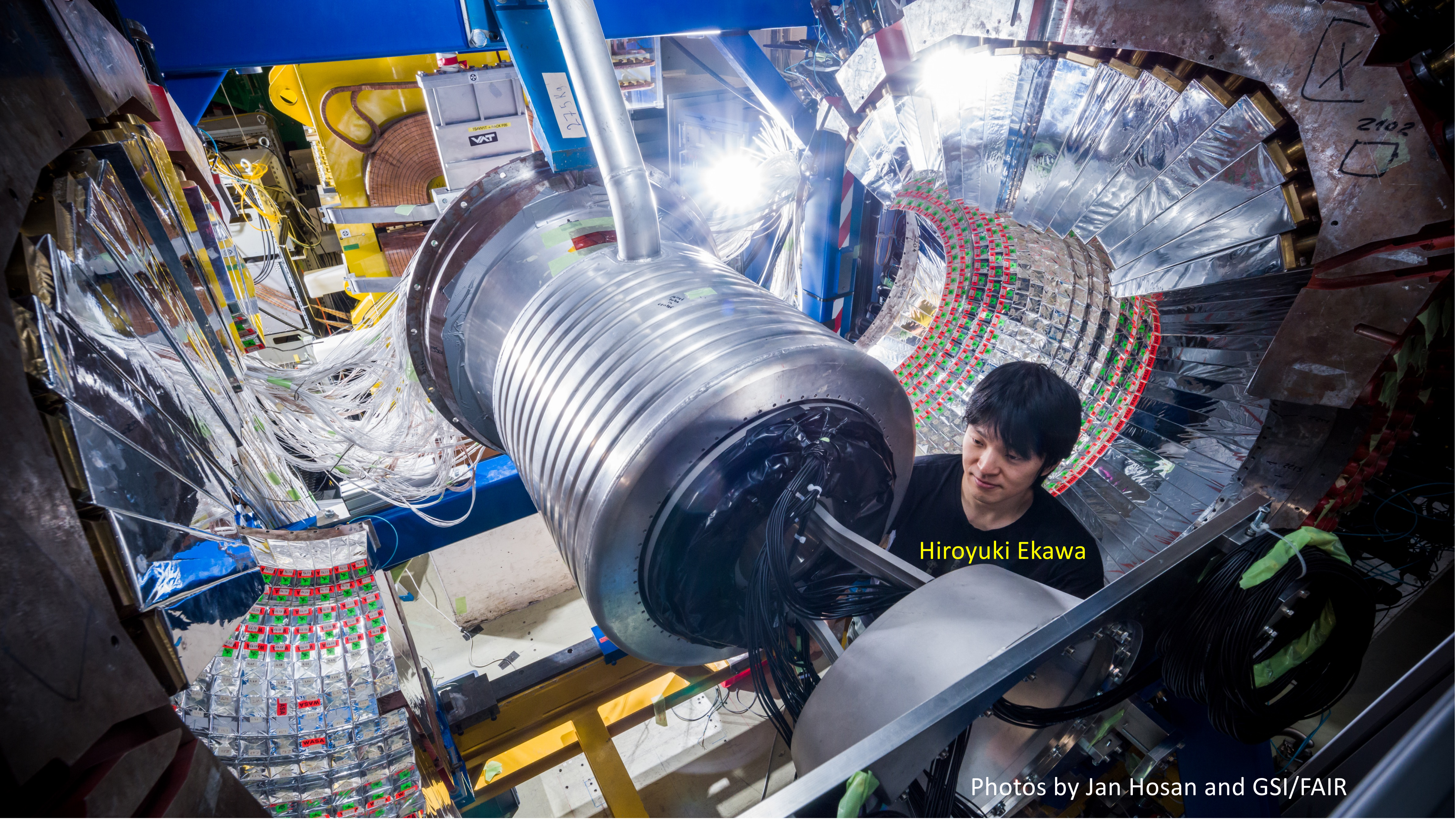
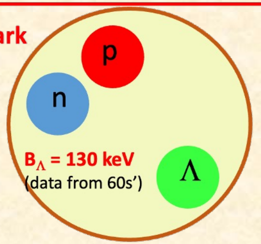
JLab E12-17-003., PRC 105 (2022) L051001


Hiroyuki Ekawa
Photos by Jan Hosan and GSI/FAIR

Recent hot topics for few-body hypernuclei

On hypertriton

Benchmark



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Average
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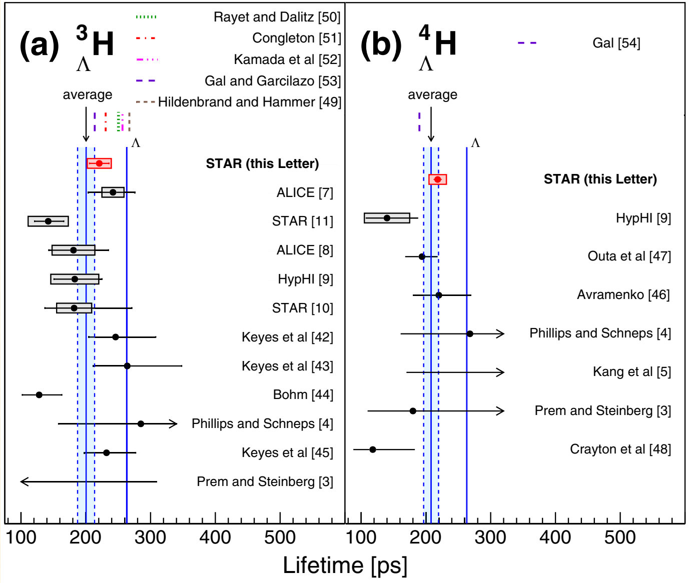

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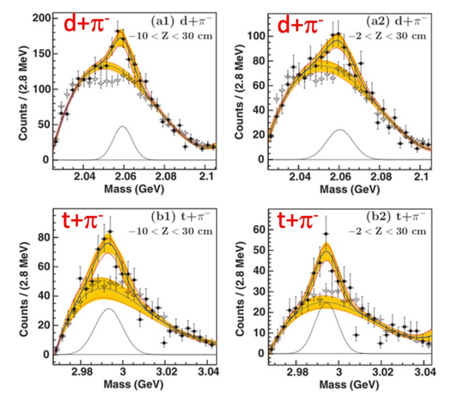

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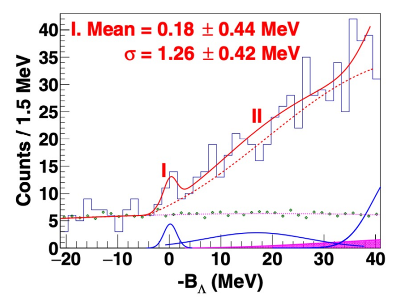

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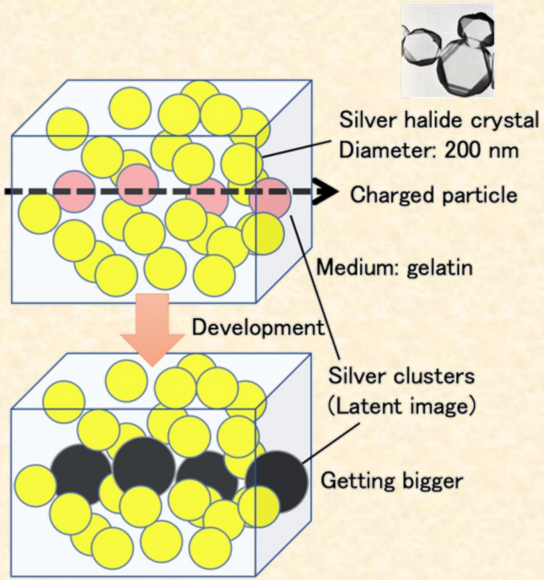
JLab E12-17-003., PRC 105 (2022) L051001

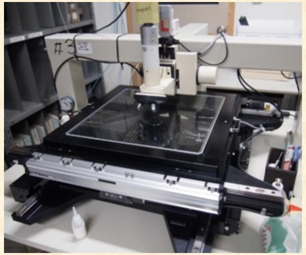
<u>Nuclear Emulsion</u>:

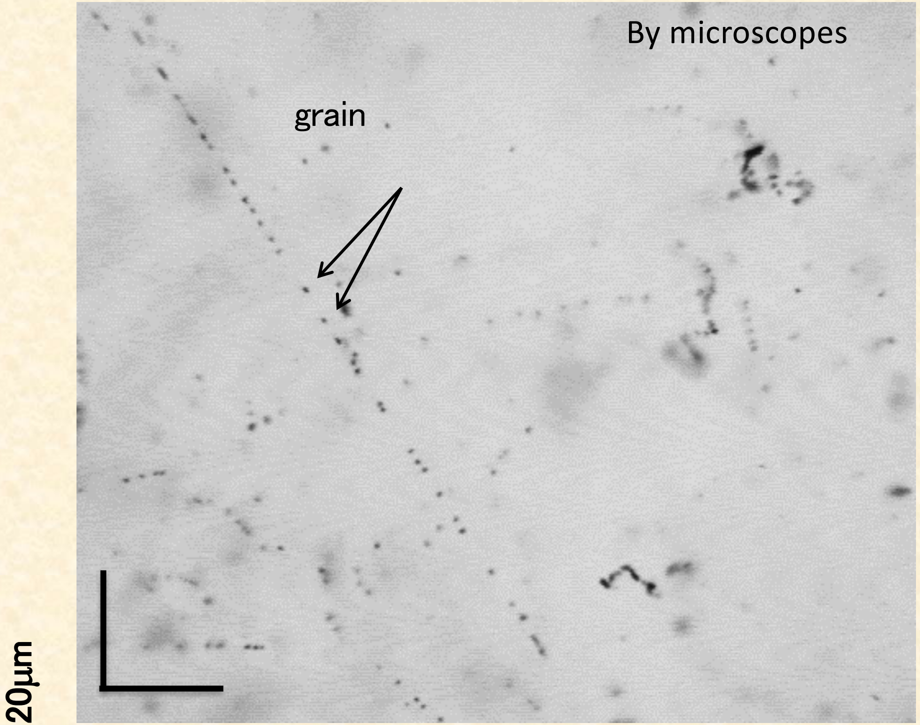
Charged particle tracker with

<u>the best spatial resolution</u>

<u>(easy to be < 1 μm, 11 nm at best)</u>

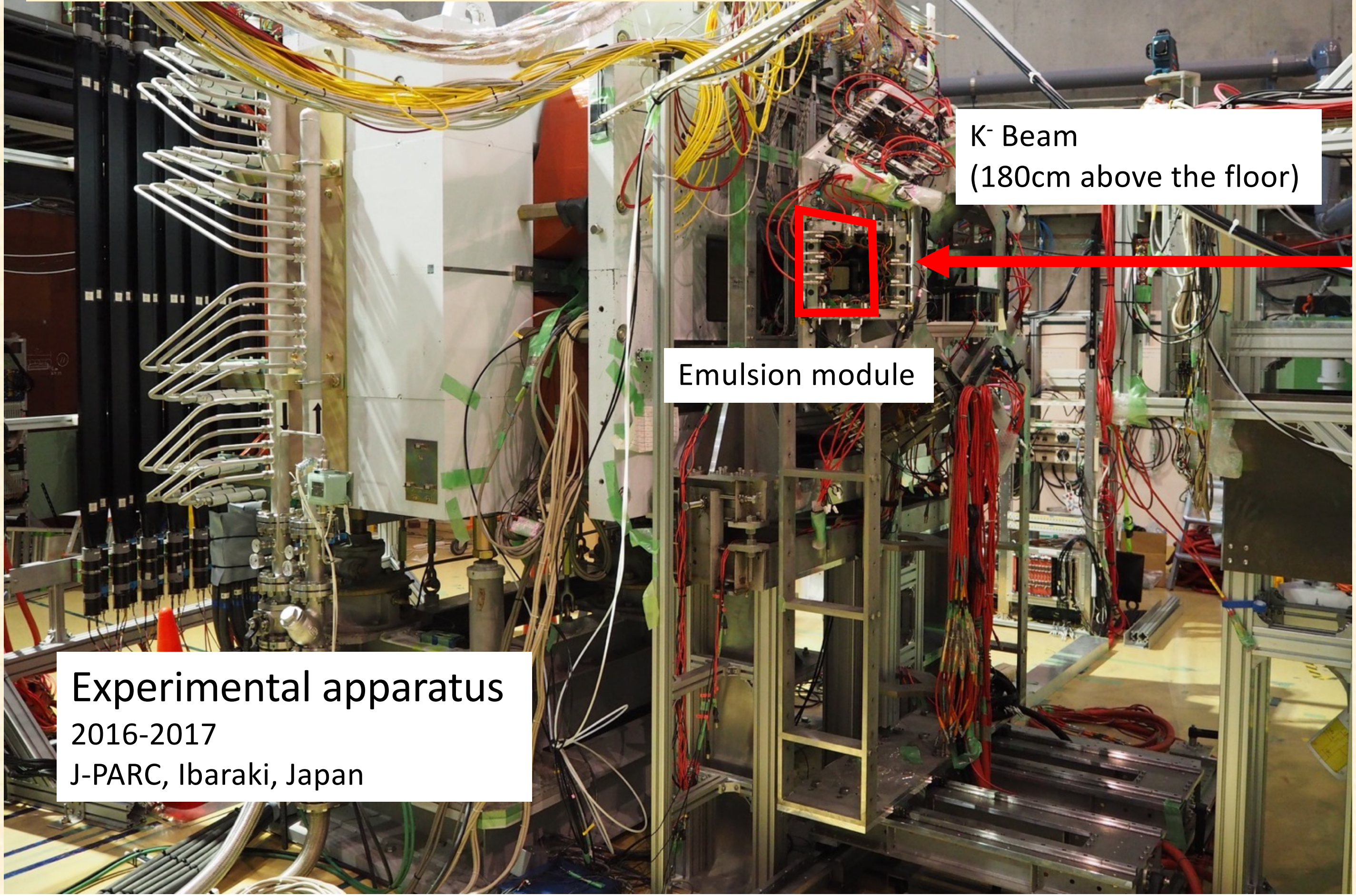




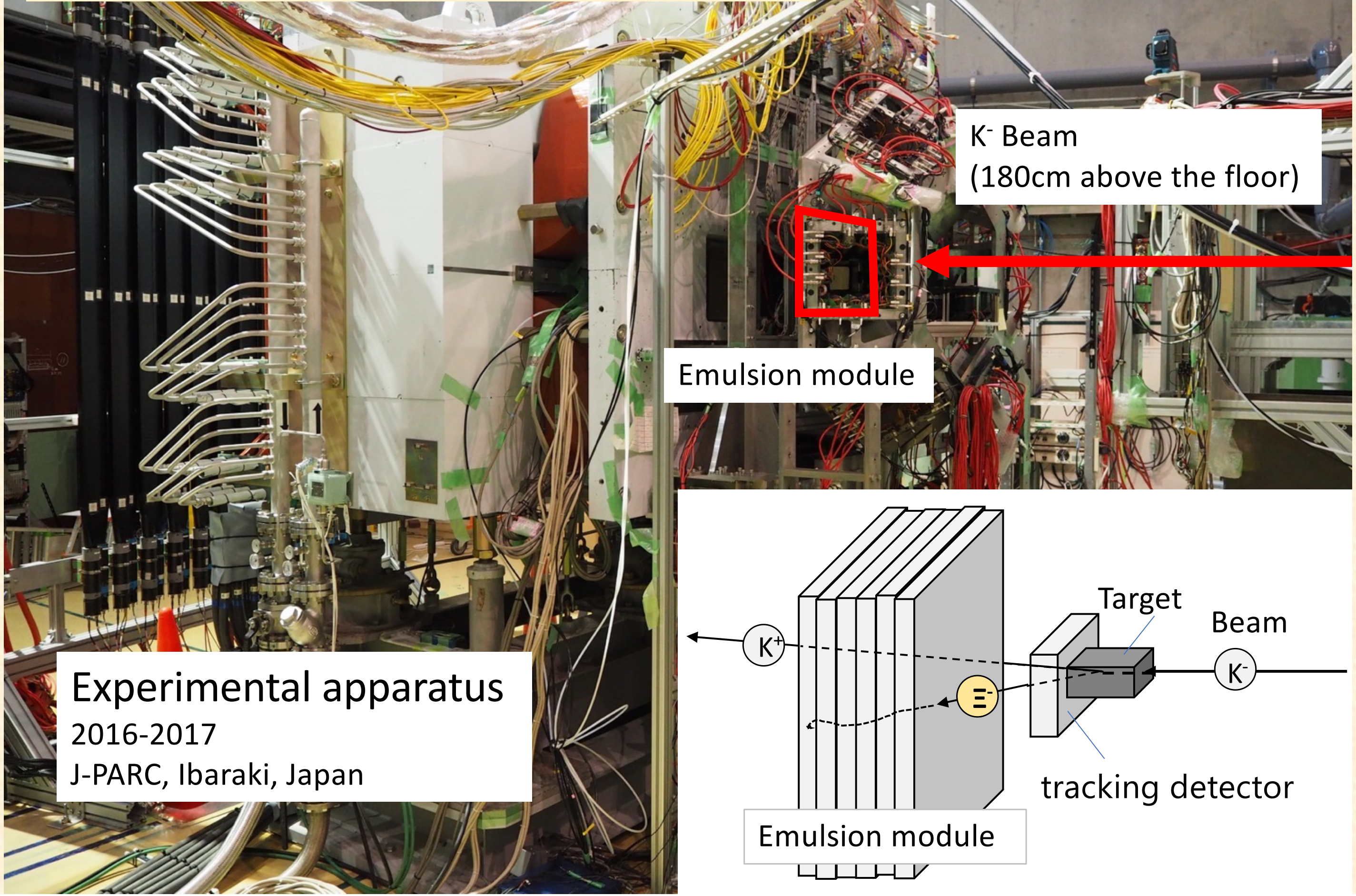


J-PARC accelerator facility

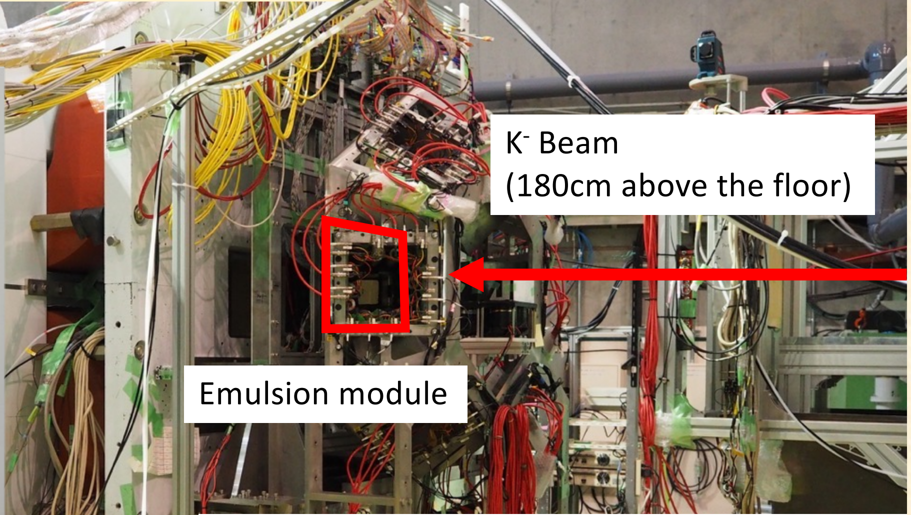
J-PARC E07 experiment

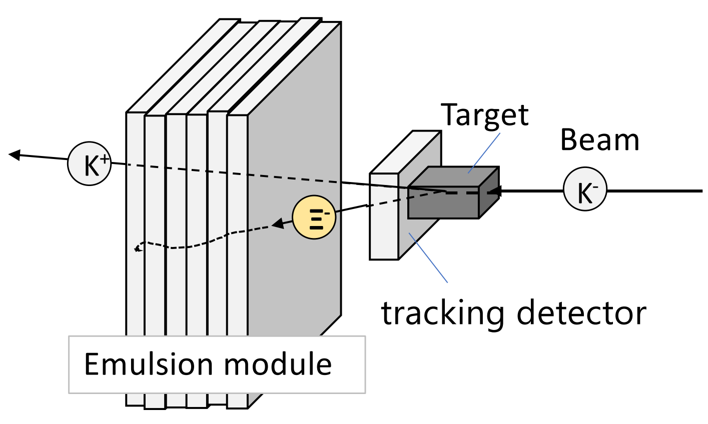


J-PARC E07 experiment



J-PARC E07 experiment





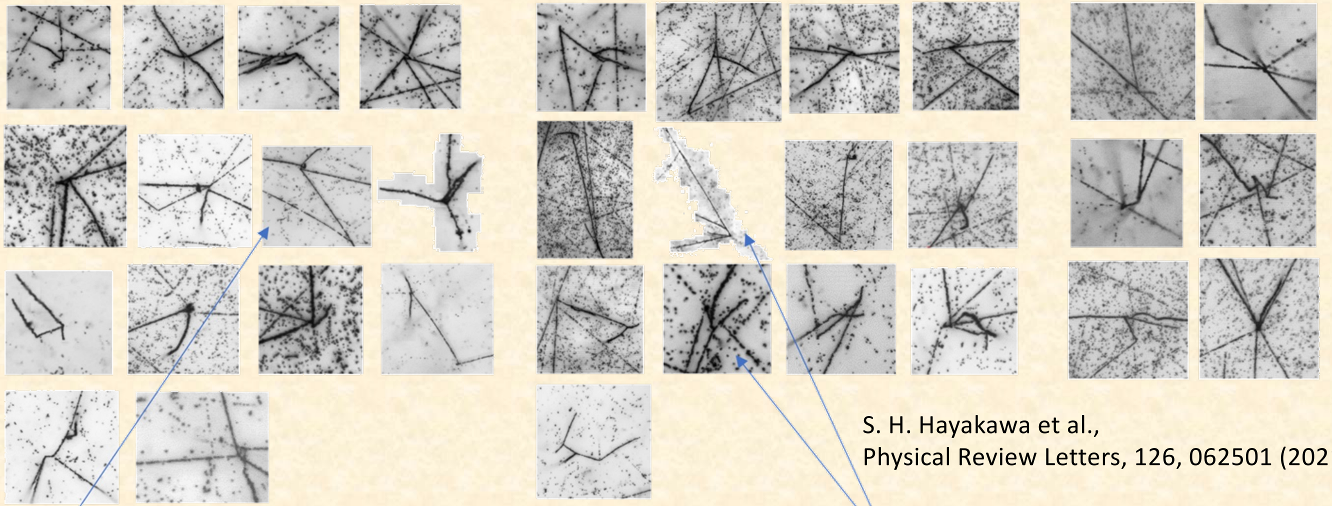
Experimental apparatus
2016-2017
J-PARC, Ibaraki, Japan

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

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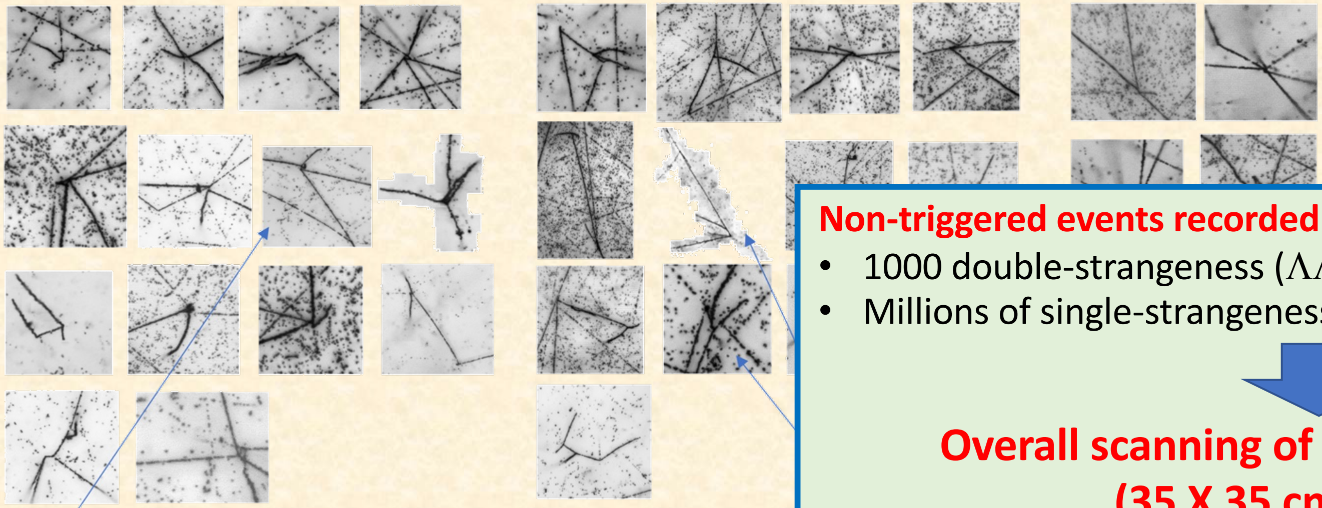


$_{\Lambda\Lambda}$Be
H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

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

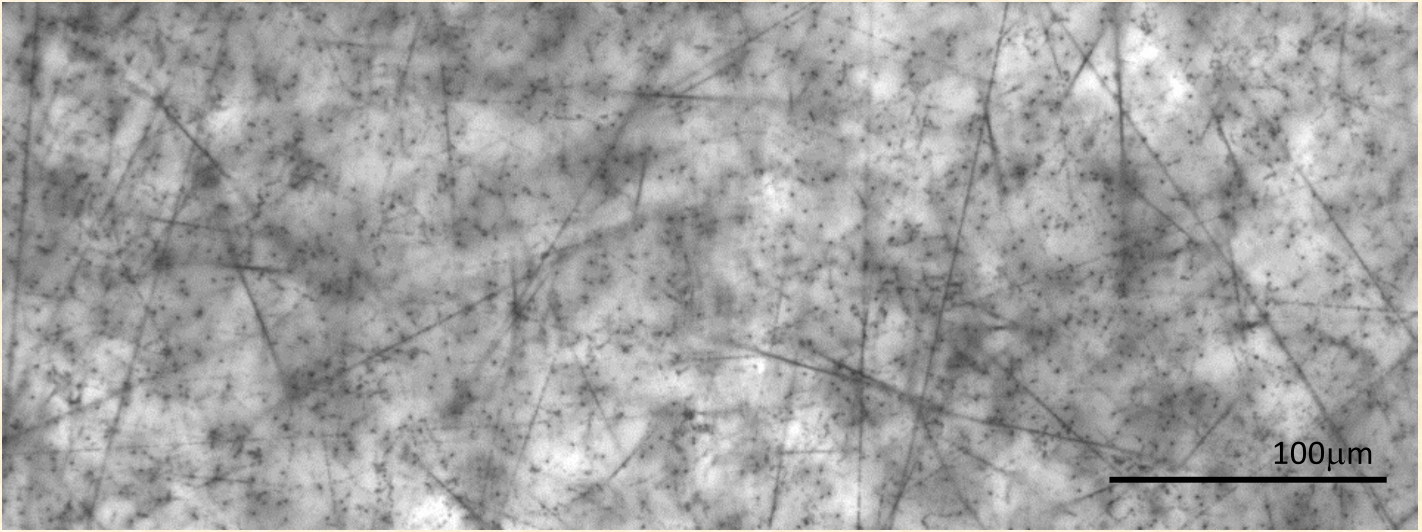
$^{15}{}_{\Xi}$C

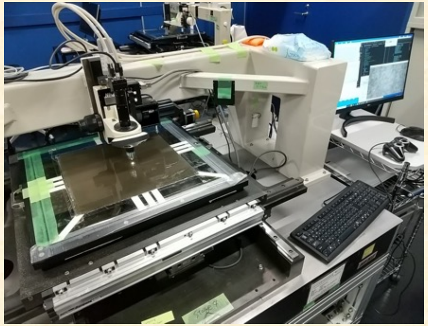
Non-triggered events recorded in 1000 emulsions sheets

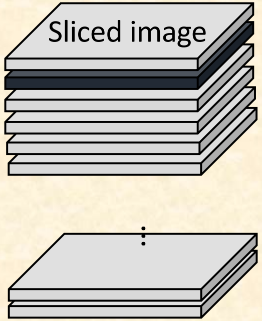
- 1000 double-strangeness ($\Lambda\Lambda$- and Ξ-) hypernuclear events
- Millions of single-strangeness hypernuclear events

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

Overall scanning for E07 emulsions







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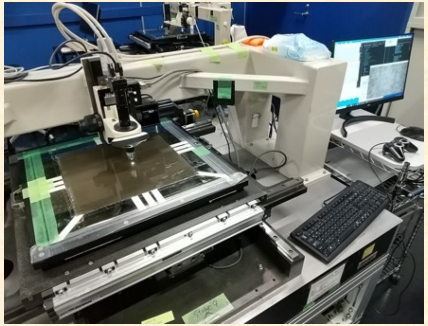

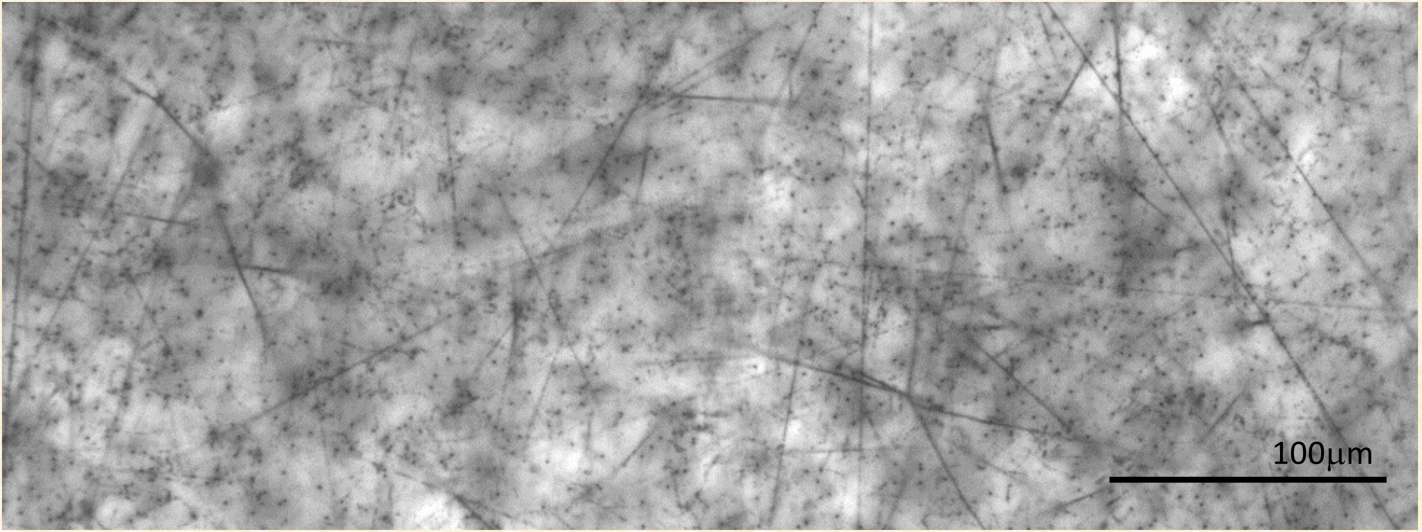

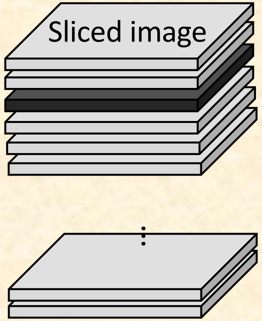

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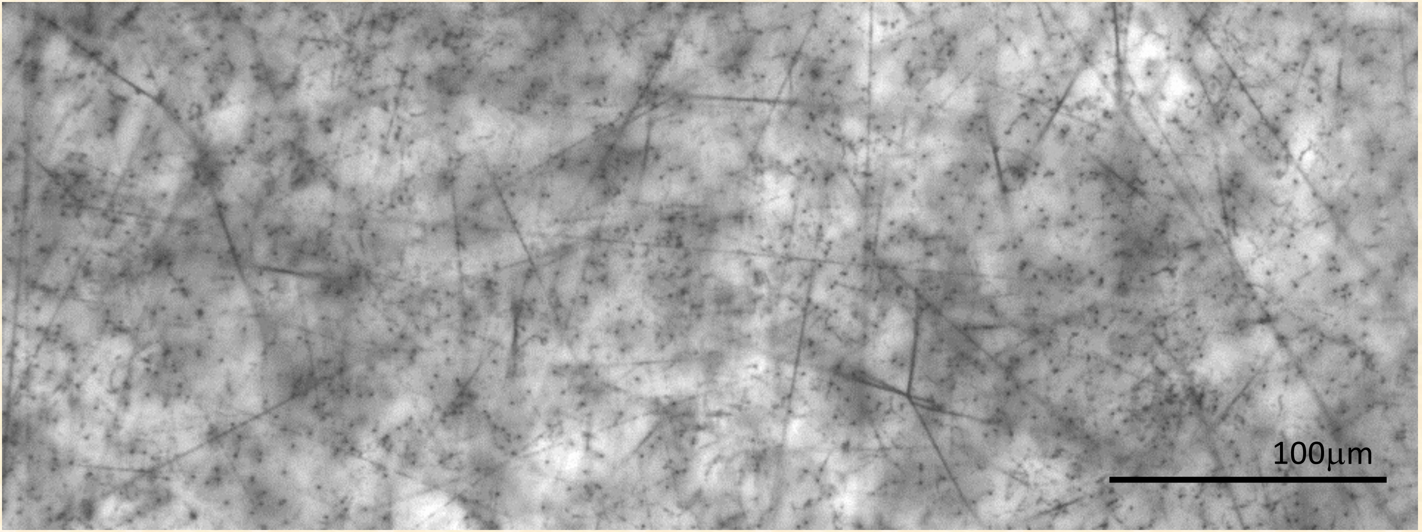

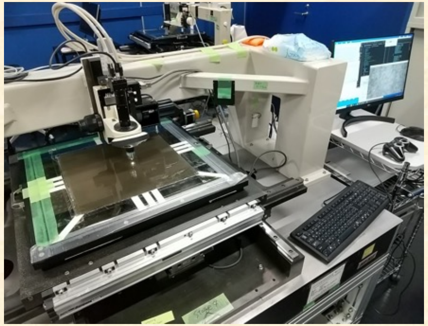

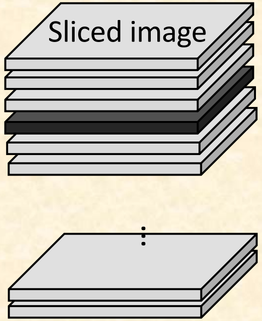

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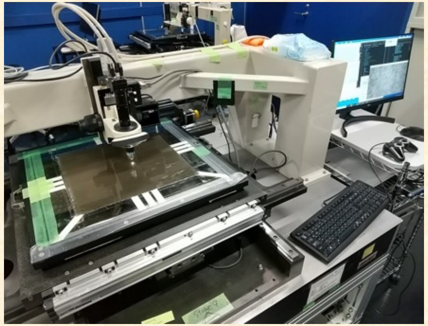

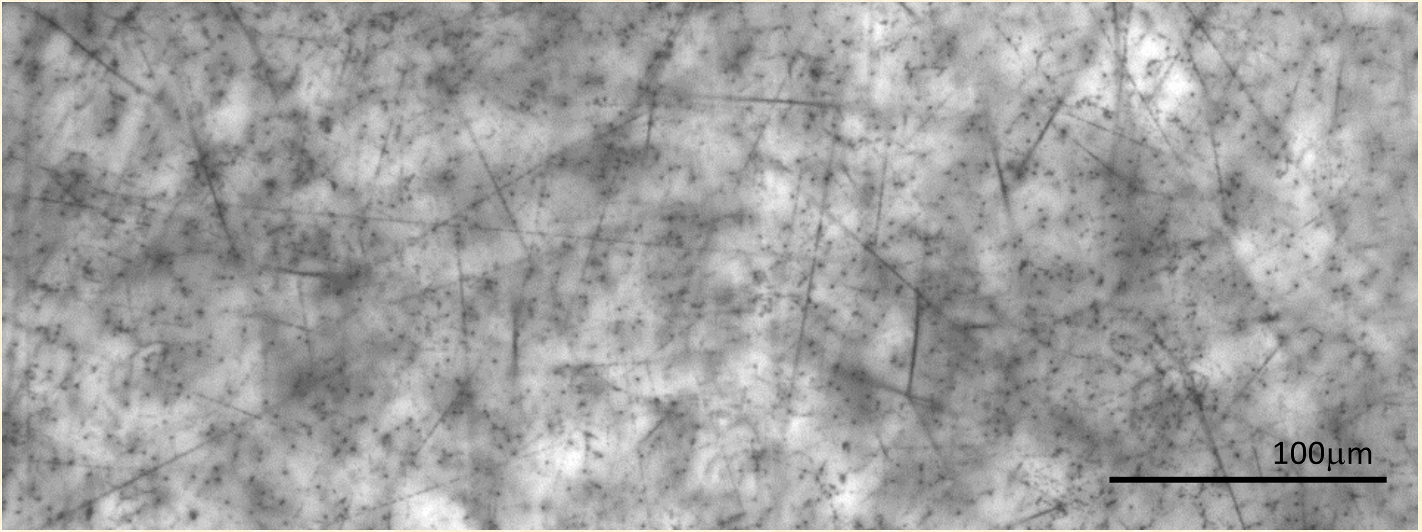

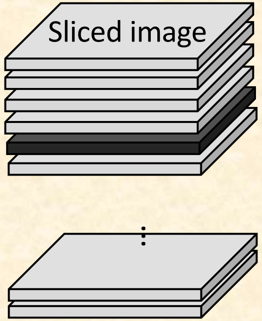

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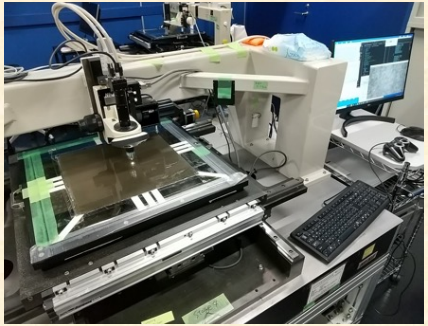
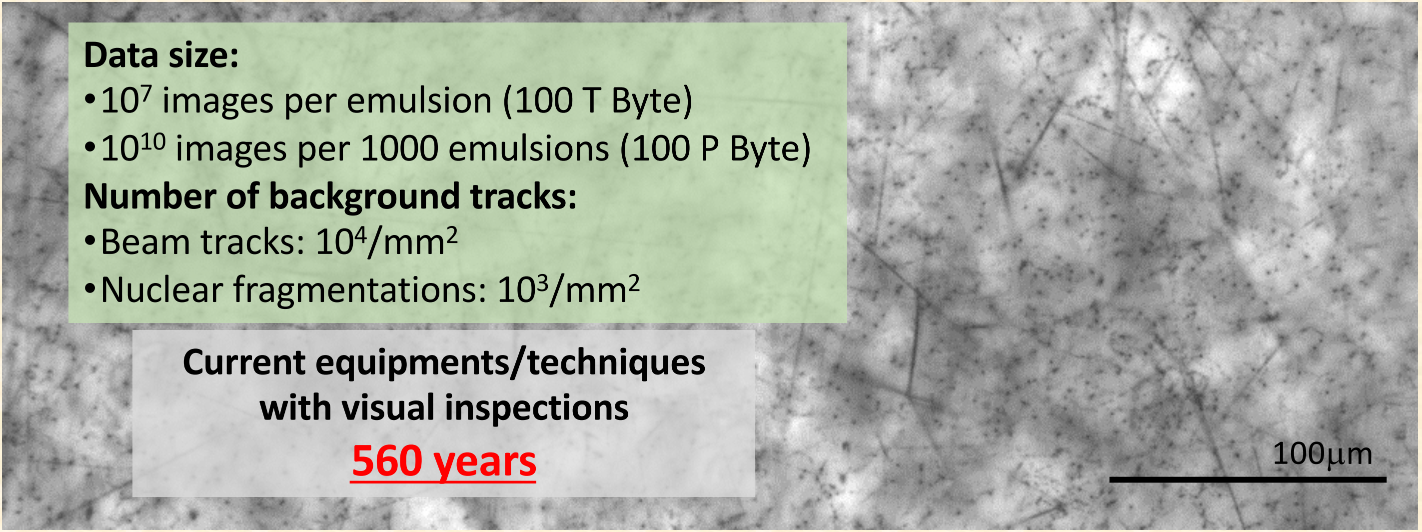


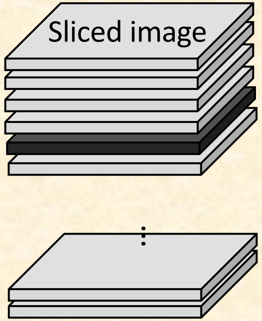


Data size:
- 10^7 images per emulsion (100 T Byte)
- 10^{10} images per 1000 emulsions (100 P Byte)

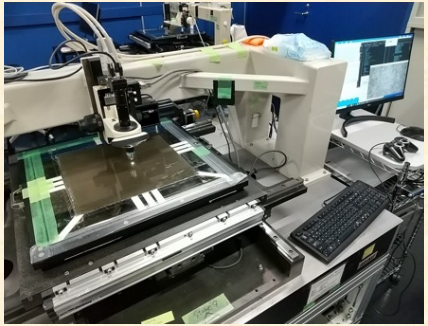
Number of background tracks:
- Beam tracks: $10^4/mm^2$
- Nuclear fragmentations: $10^3/mm^2$

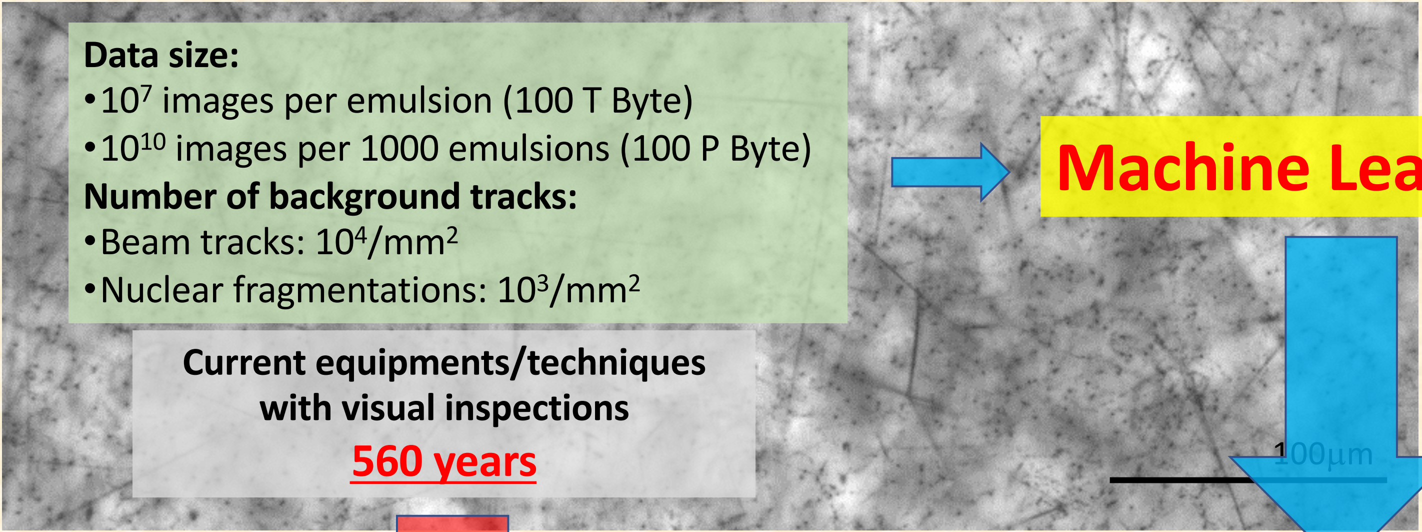
Current equipments/techniques with visual inspections

560 years



Overall scanning for E07 emulsions



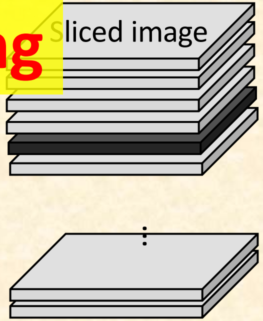


Data size:
- 10^7 images per emulsion (100 T Byte)
- 10^{10} images per 1000 emulsions (100 P Byte)

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

Current equipments/techniques with visual inspections
560 years

Machine Learning



3 years

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:

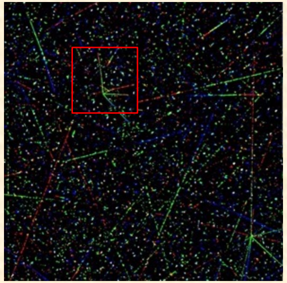
Producing training data with

- Monte Carlo simulations
- Image transfer techniques

Production of training data

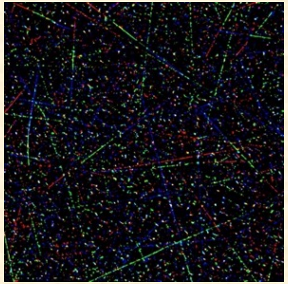
Monte Carlo simulations and GAN(Generative Adversarial Networks)

Binarized tracks from MC simulations
+ background from the real data

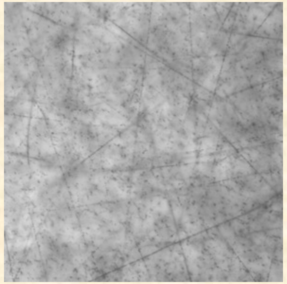


Imitated
emulsion image

GAN: pix2pix



Binarized (like for simulations)



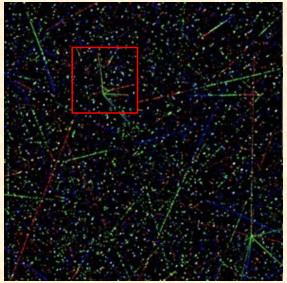
Real emulsion image

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

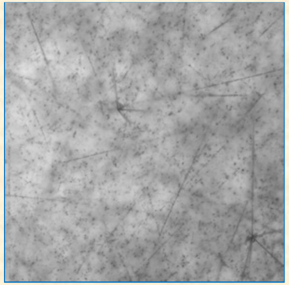
Production of training data

Monte Carlo simulations and GAN(Generative Adversarial Networks)

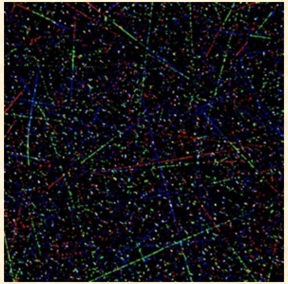
Binarized tracks from MC simulations
+ background from the real data



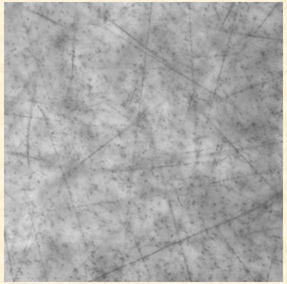
Produced training data



GAN: pix2pix



Binarized (like for simulations)

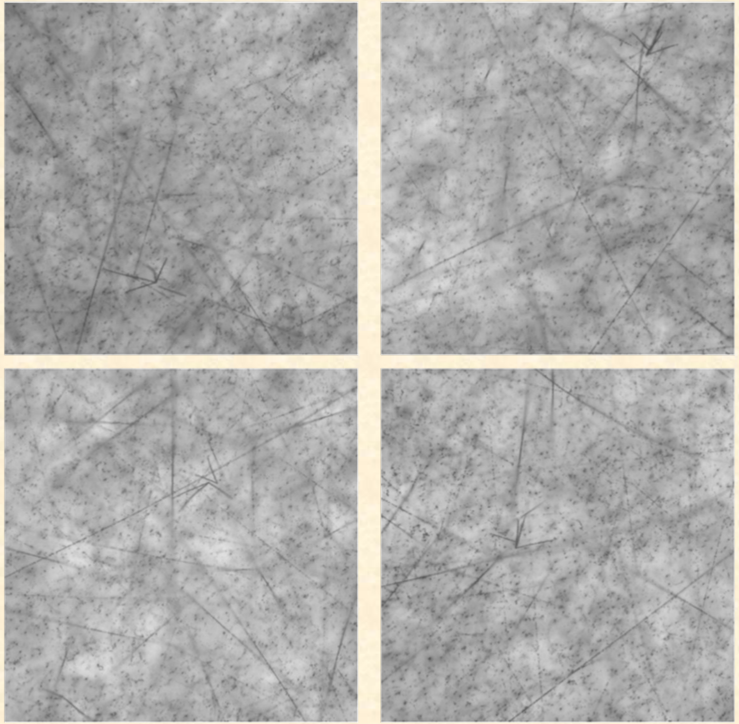


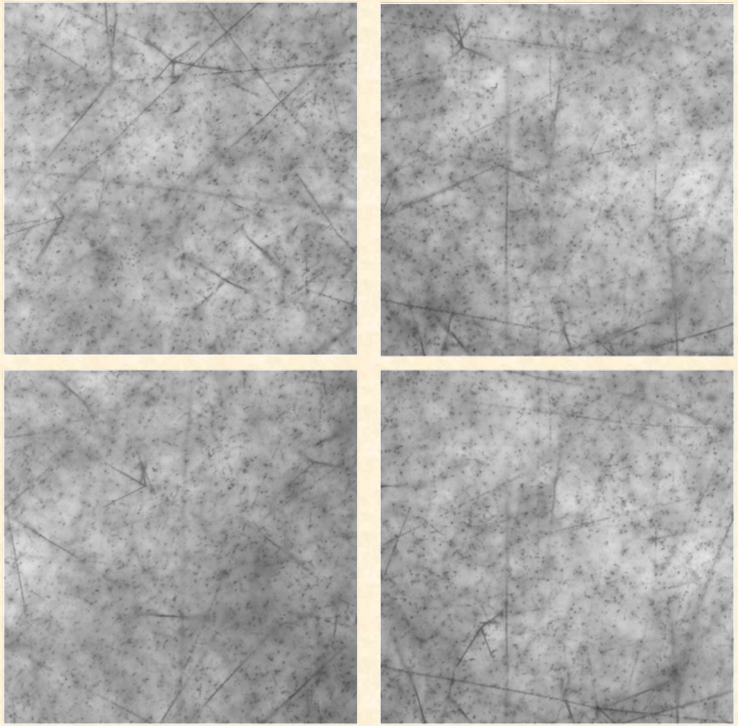
Real emulsion image

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

Production of training data

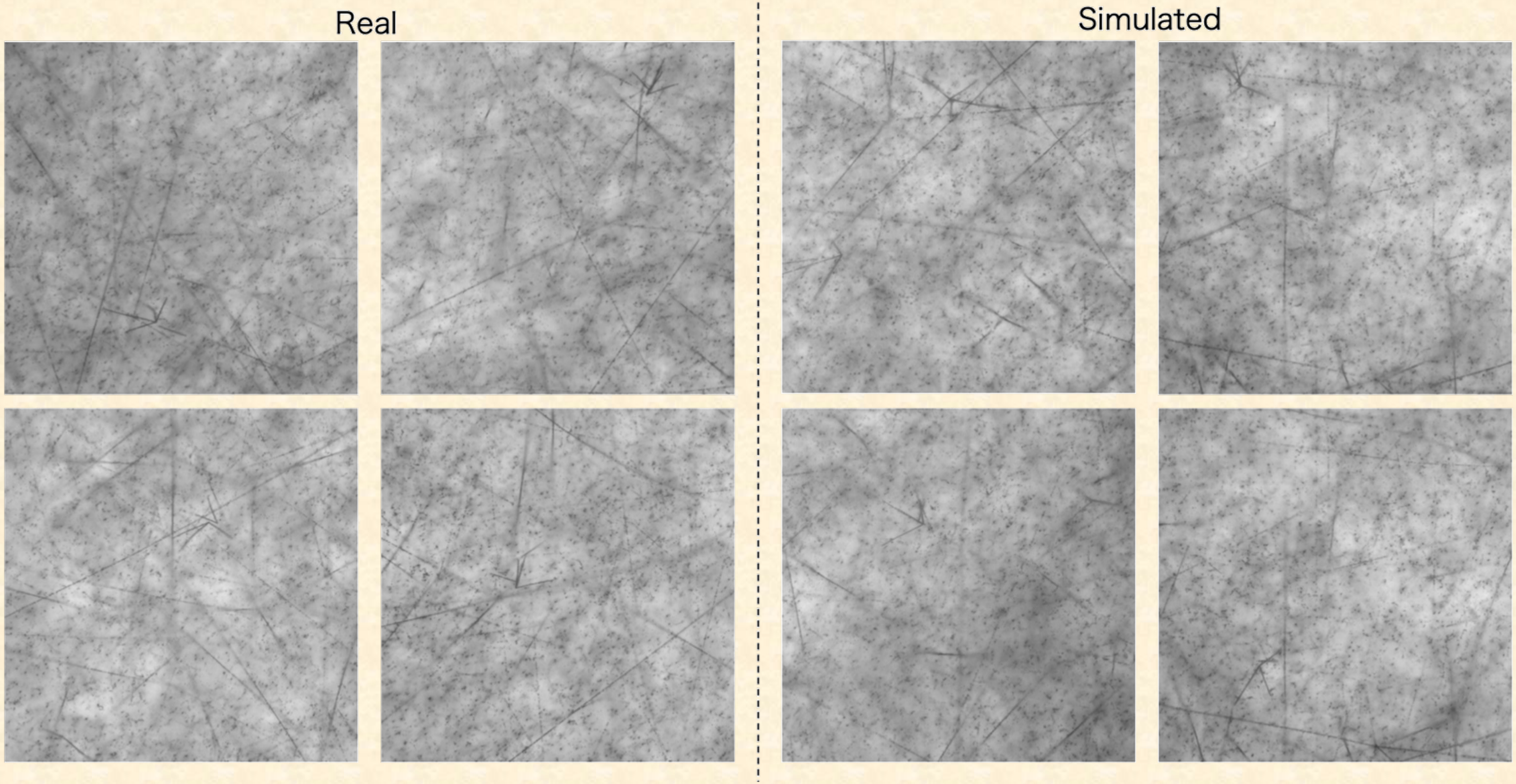
Monte Carlo simulations and GAN(Generative Adversarial Networks)





Production of training data

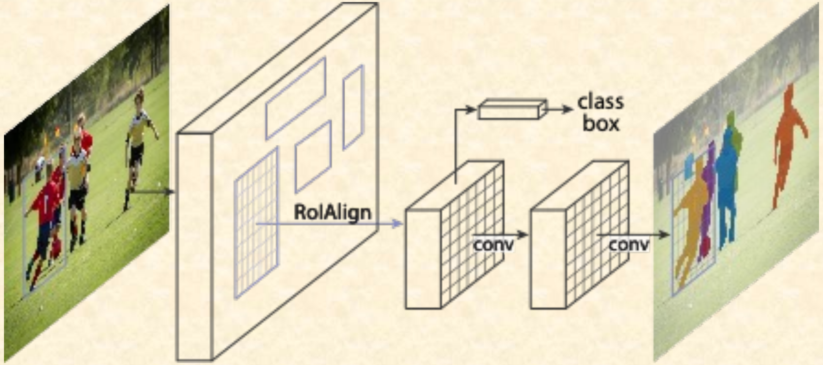
Monte Carlo simulations and GAN(Generative Adversarial Networks)

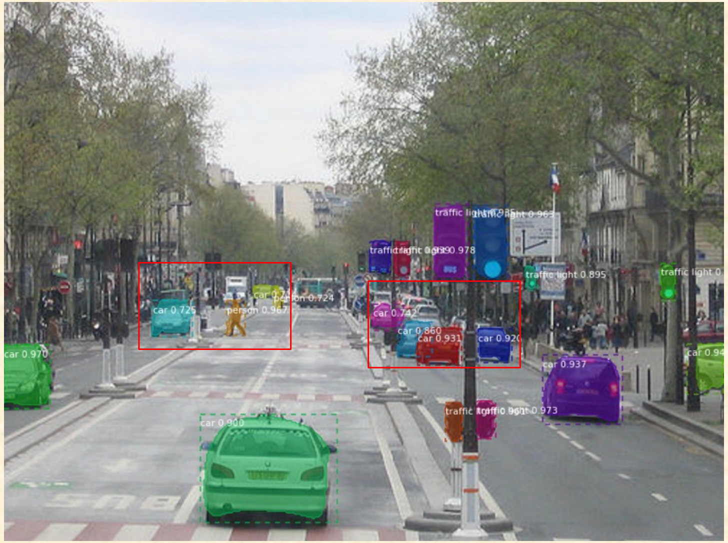


Detection of hypertriton events

With Mask R-CNN model

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





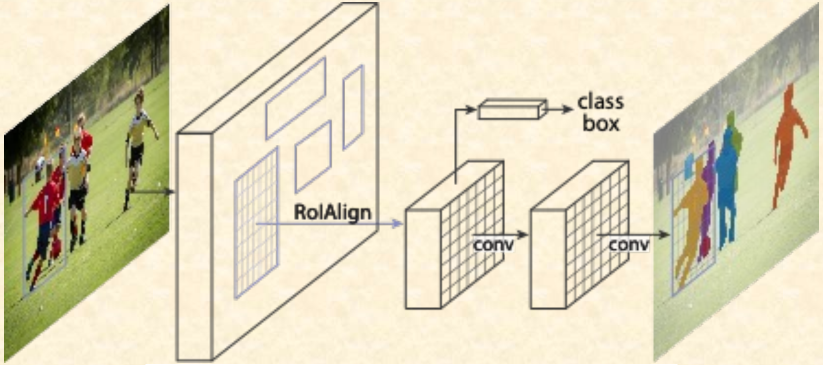
Detection of each object

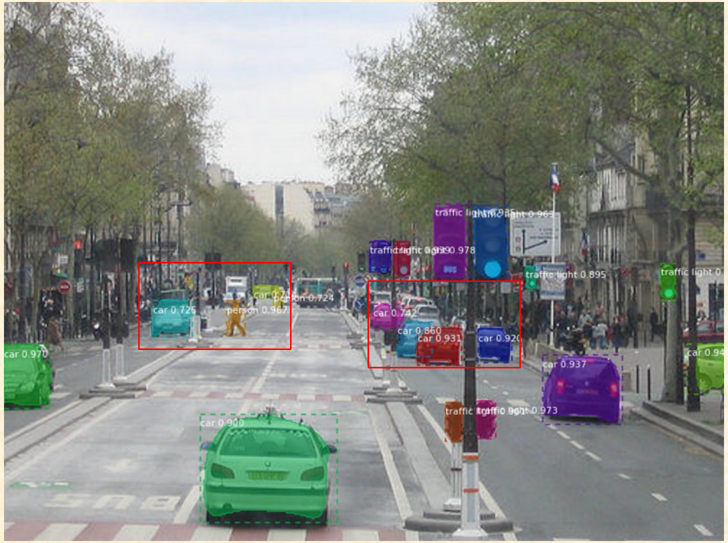
At large object density

Detection of hypertriton events

With Mask R-CNN model

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

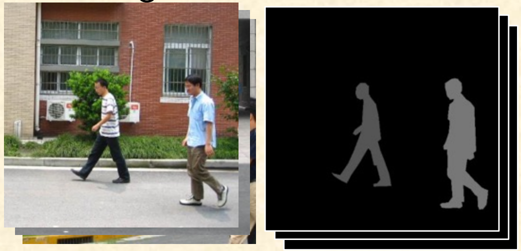




Example of training dataset

Image

Mask



A Pedestrian dataset

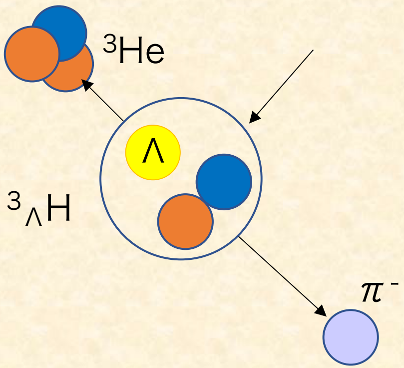
https://www.cis.upenn.edu/~jshi/ped_html/

Detection of each object

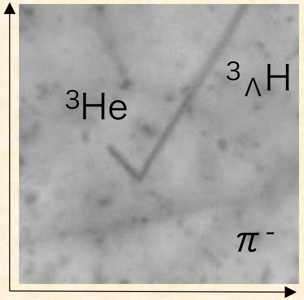
At large object density

Hypertriton search with Mask R-CNN

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



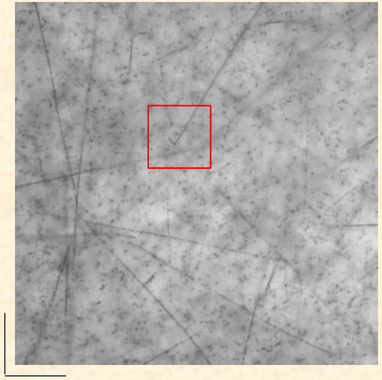
Simulated image



50 μm

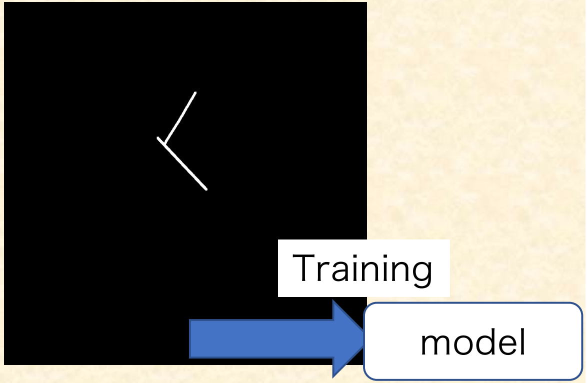
Training dataset (Simulated images)

Image



50 μm

Mask

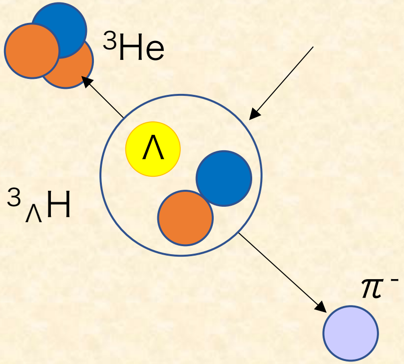


Ayumi Kasagi. Ph.D. thesis (2023)

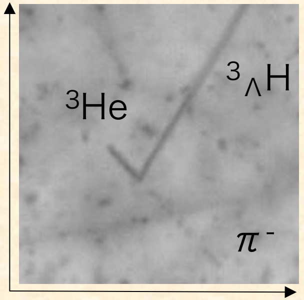
A. Kasagi et al., submitted to NIM A

Hypertriton search with Mask R-CNN

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



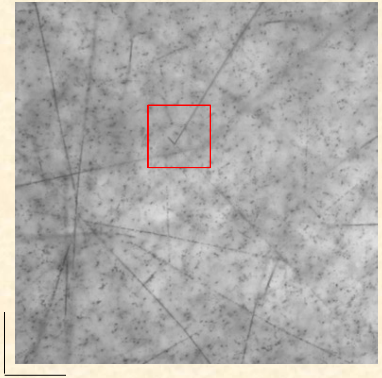
Simulated image



50 μm

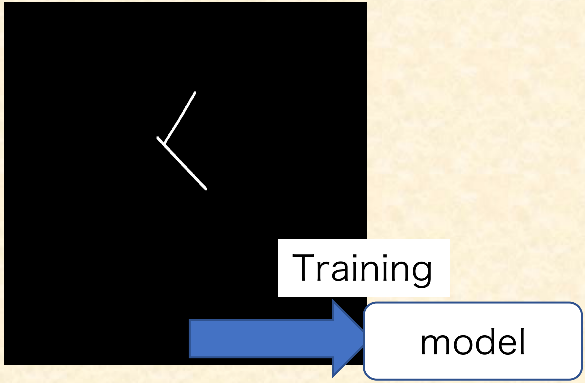
Training dataset (Simulated images)

Image

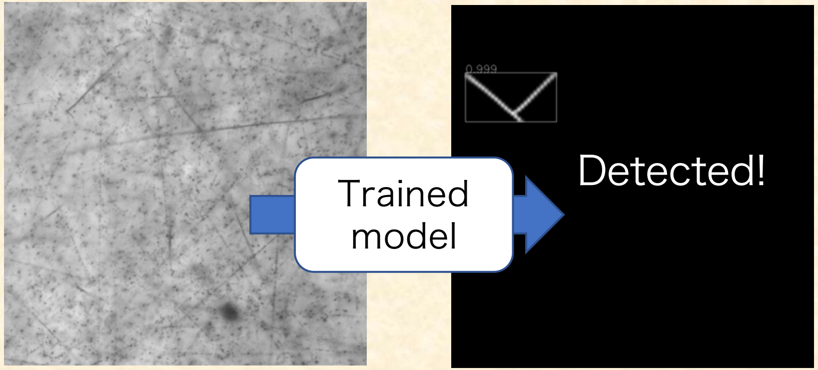


50 μm

Mask



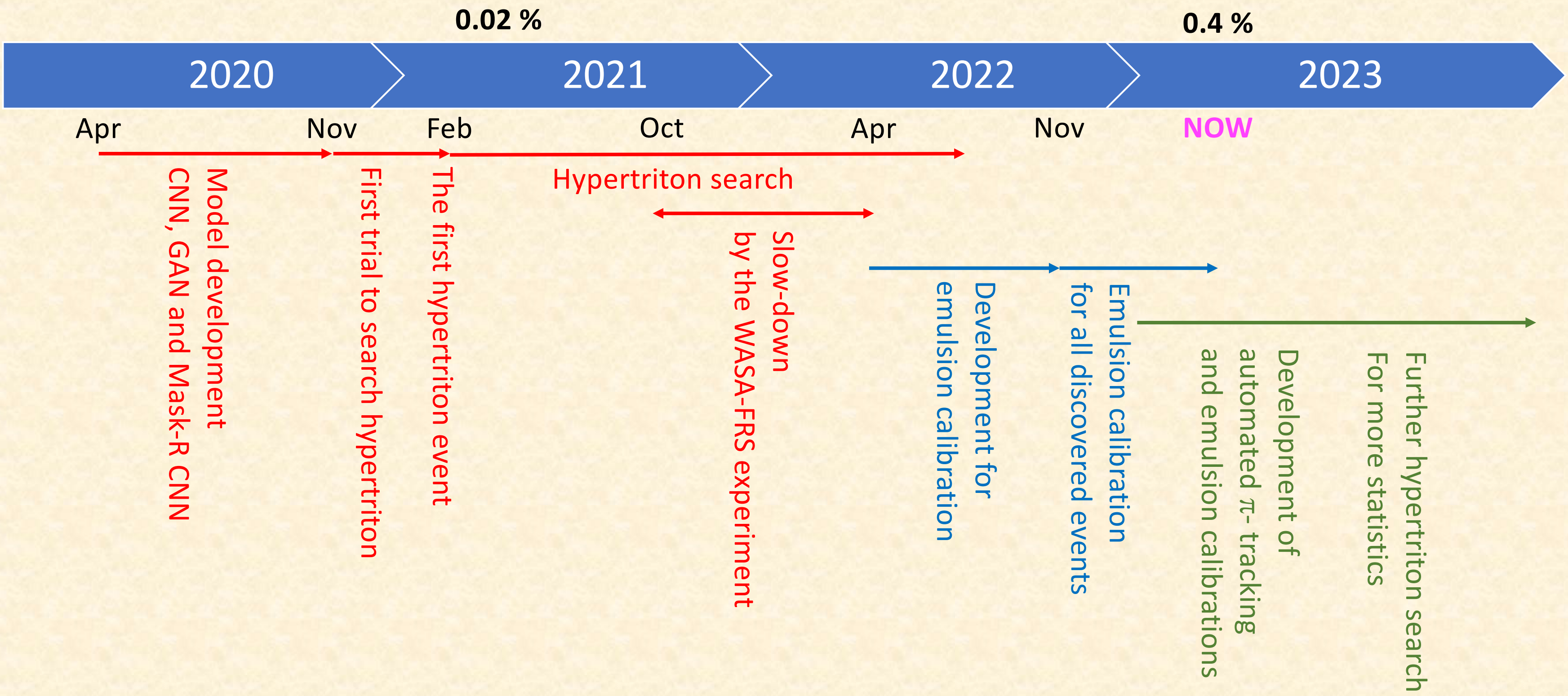
Real image



Ayumi Kasagi. Ph.D. thesis (2023)

A. Kasagi et al., submitted to NIM A

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



Discovery of the first hypertriton event in E07 emulsions

nature reviews physics

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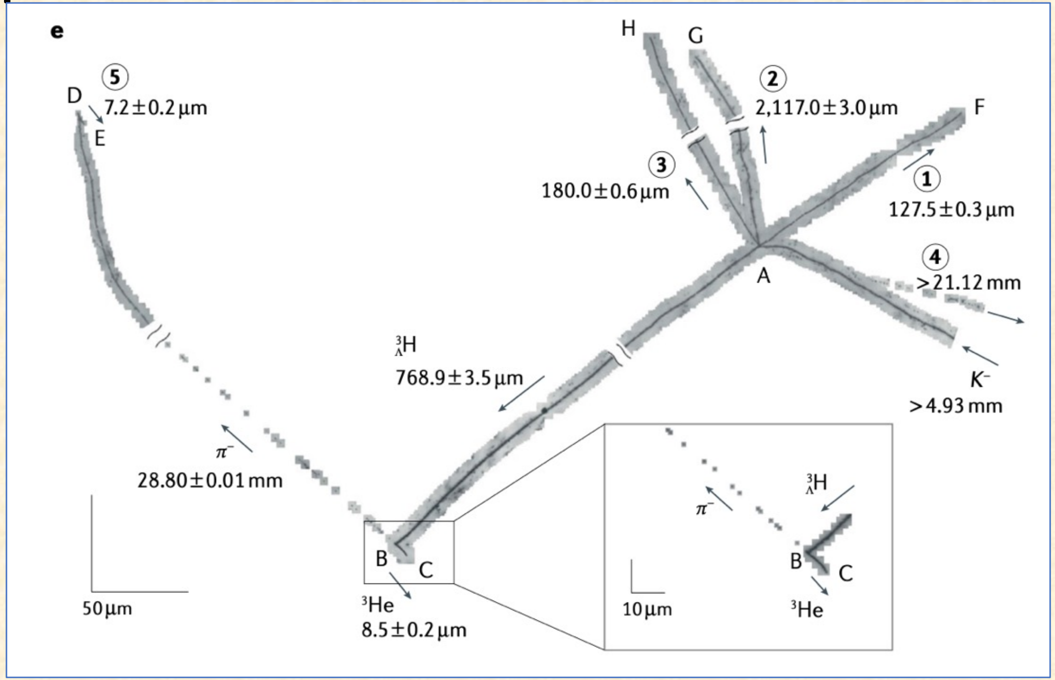
nature > nature reviews physics > perspectives > article

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

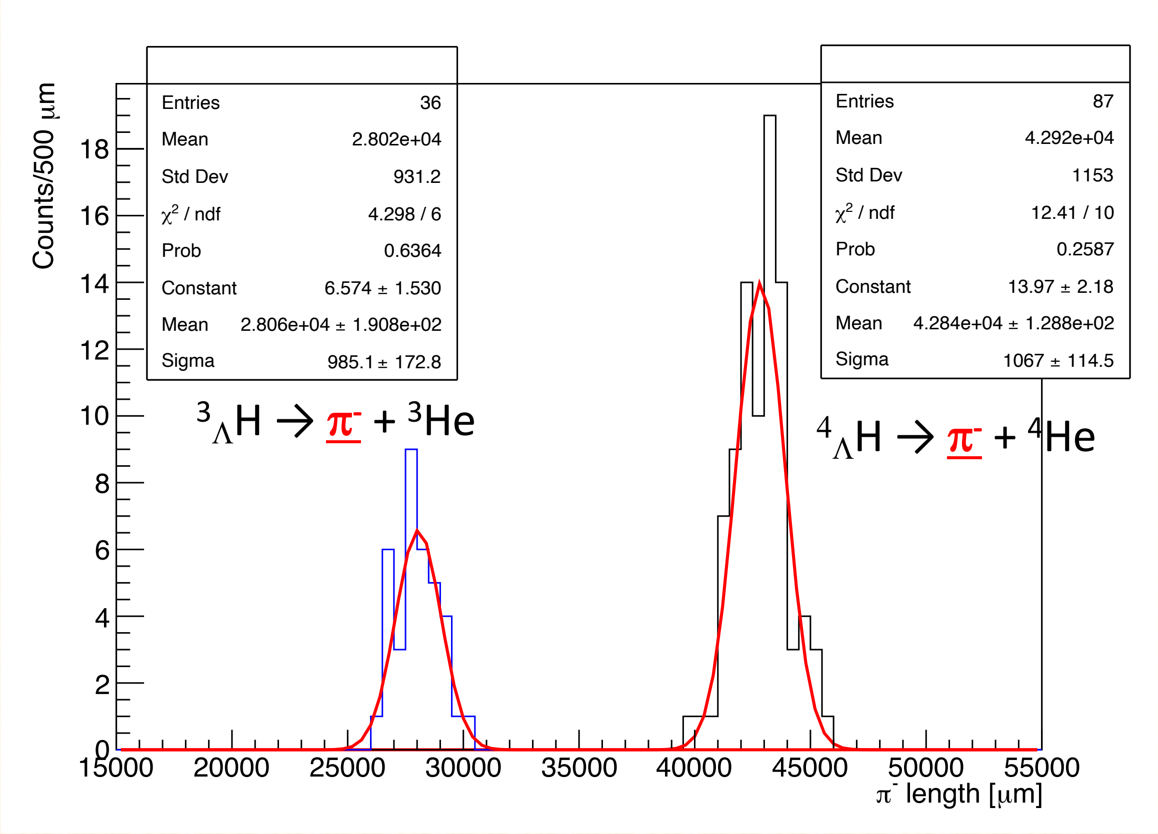
Guaranteeing the determination of the hypertriton binding energy SOON

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

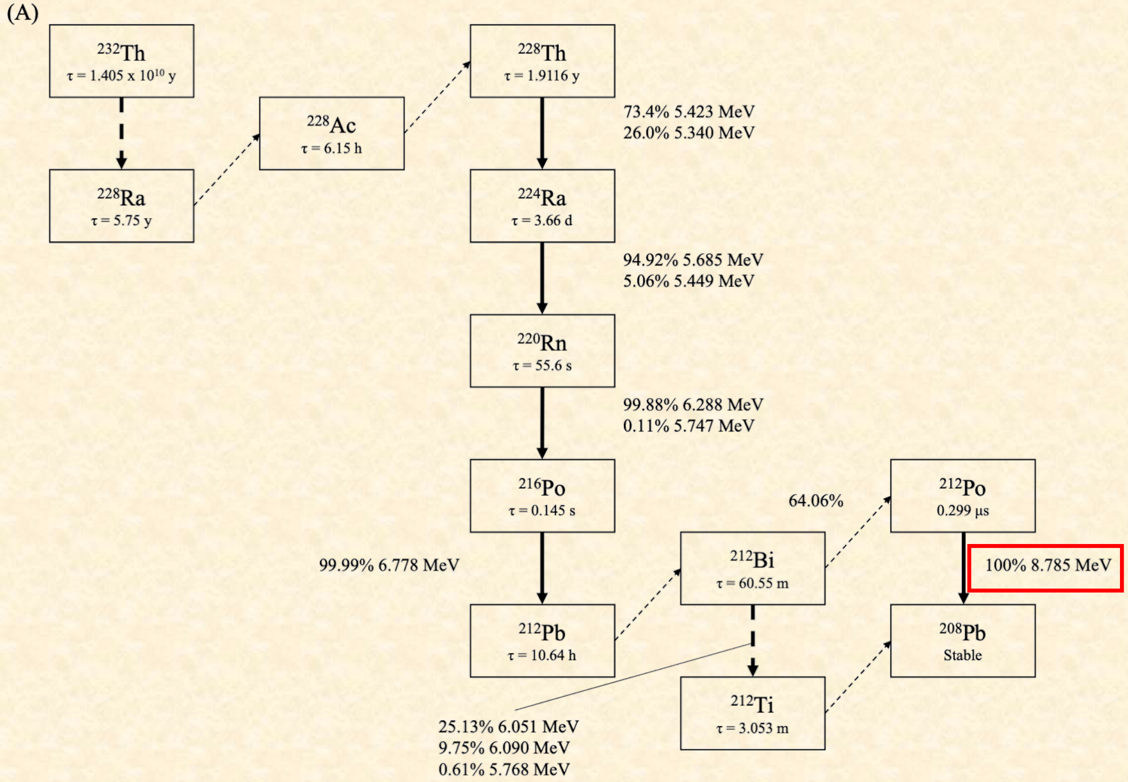
No. events: 174 (<u>0.4% of the entire E07 data</u>)

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

Calibrated events: 143

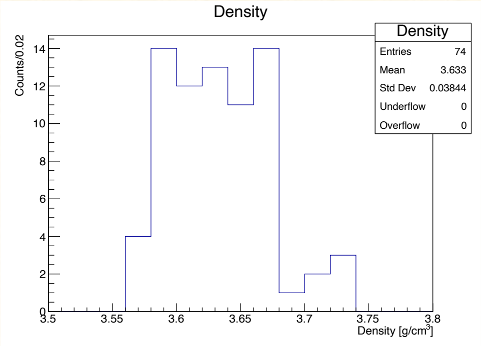
- ${}^{3}_{\Lambda}H$: 36
- ${}^{4}_{\Lambda}H$: 107 (Identified: 72 + Penetrated: 35)

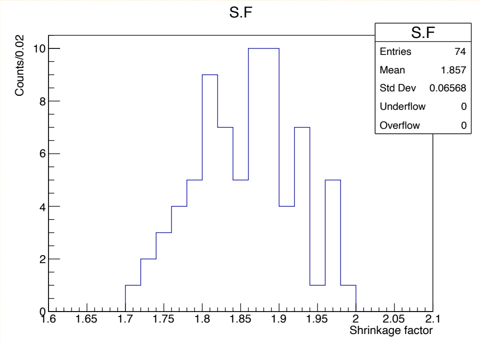
Calibration of nuclear emulsions

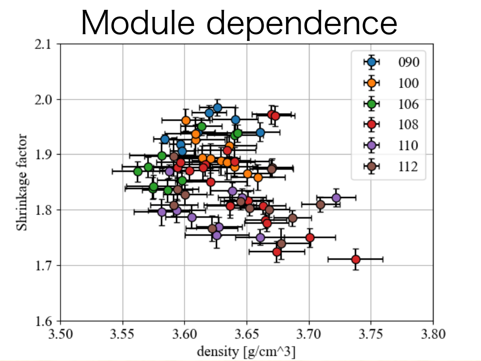


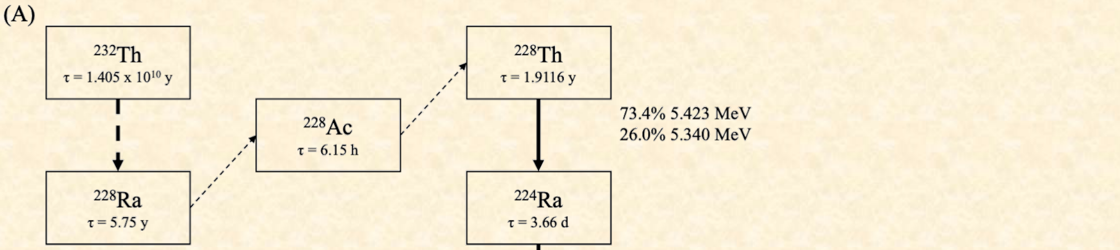
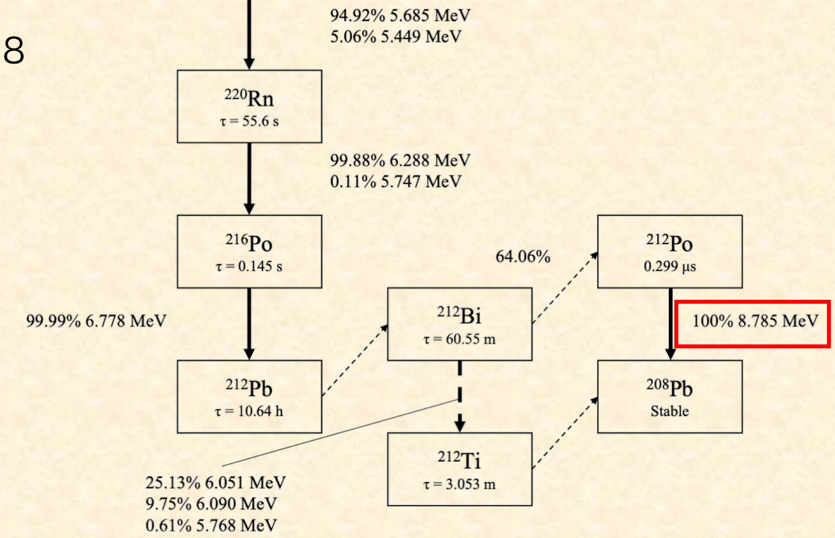
Calibration of nuclear emulsions

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







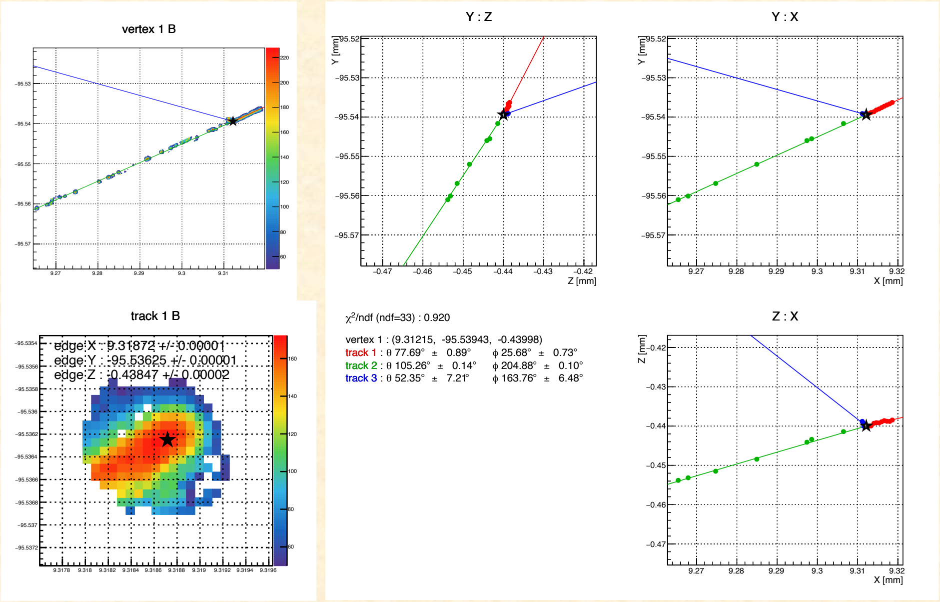



Ayumi Kasagi. Ph.D. thesis (2023)

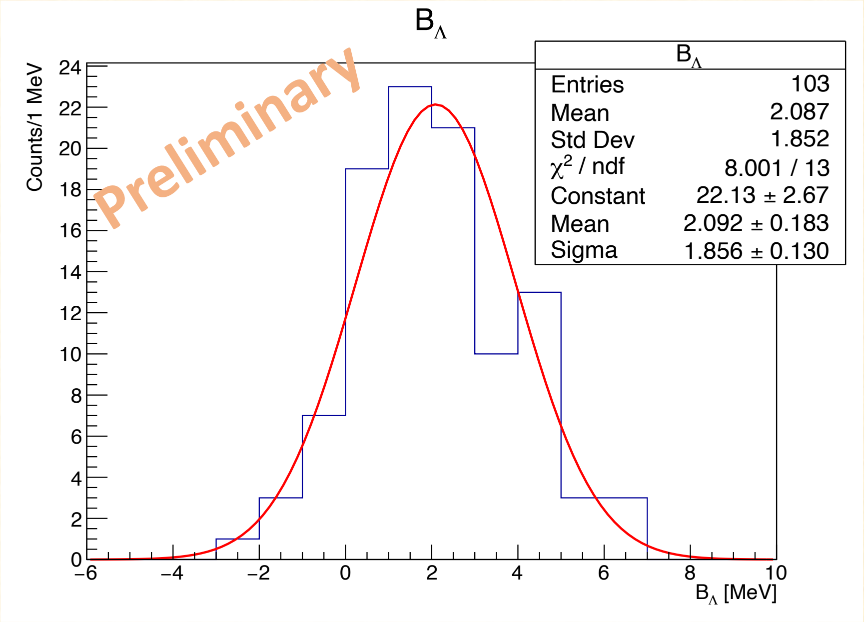
Analysis for ${}^{4}_{\Lambda}$H binding energy

- 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

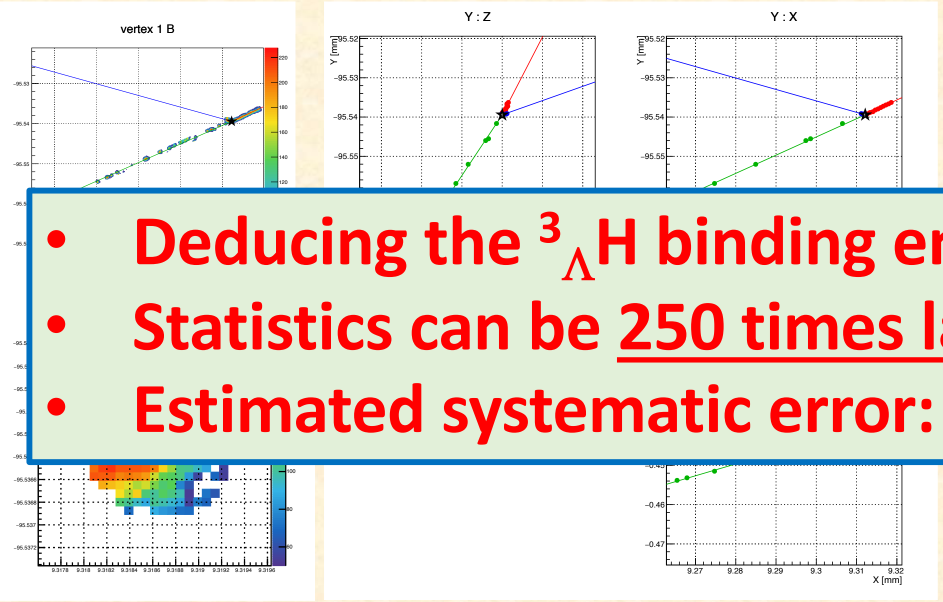


・Analyses for π- will be included
・Error analysis for each event
→Weighted avarage: To be obtained

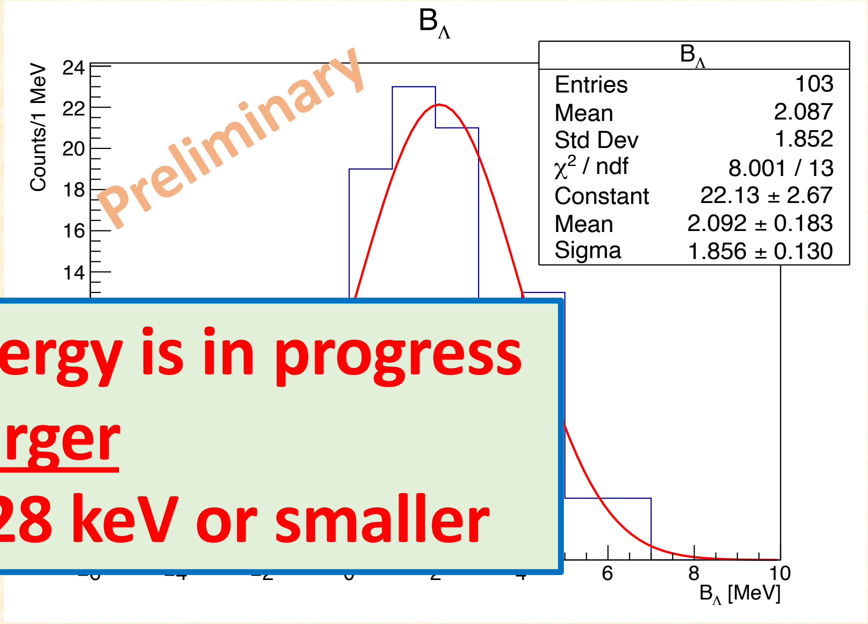
Analysis for $^4_\Lambda$H binding energy

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

Fitting results (can be checked one by one)



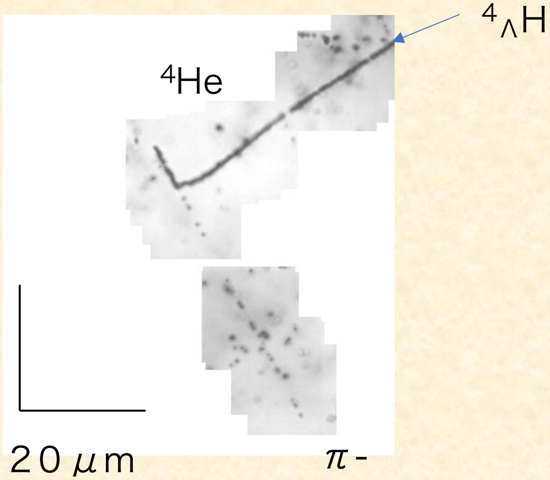
Binding energy on $^4_\Lambda$H



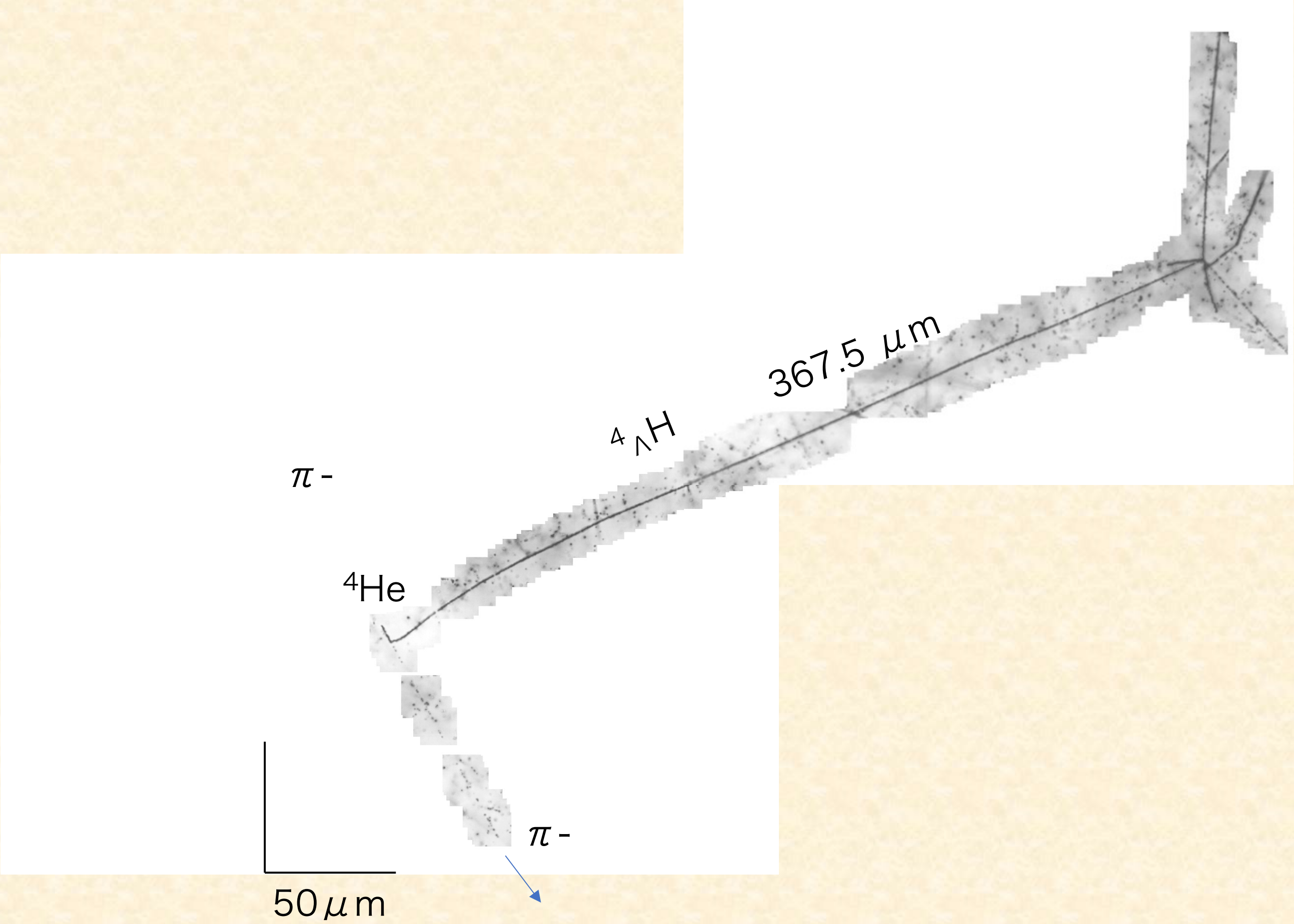
- **Deducing the $^3_\Lambda$H binding energy is in progress**
- **Statistics can be <u>250 times larger</u>**
- **Estimated systematic error: 28 keV or smaller**

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

Byproduct 1:

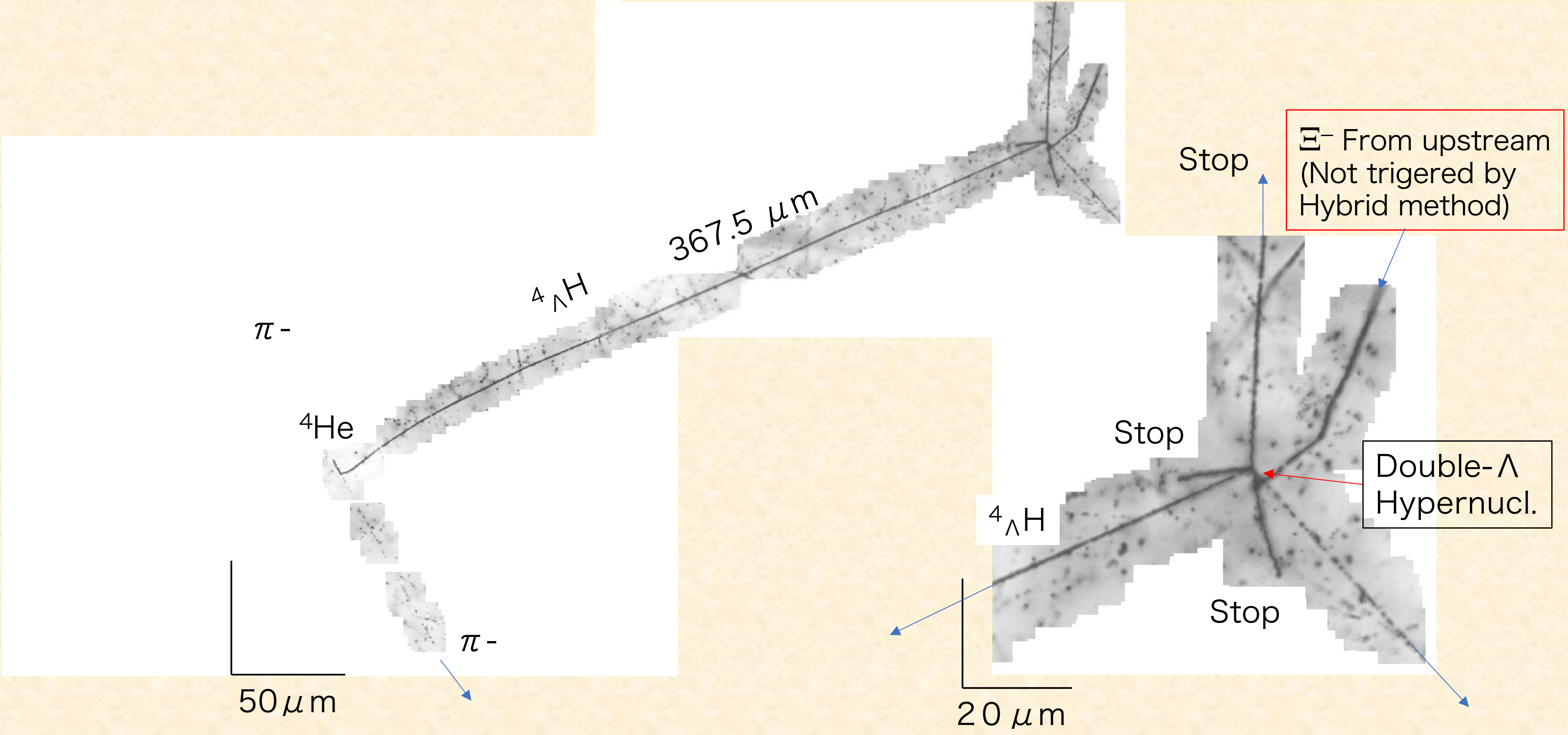


Byproduct 1:

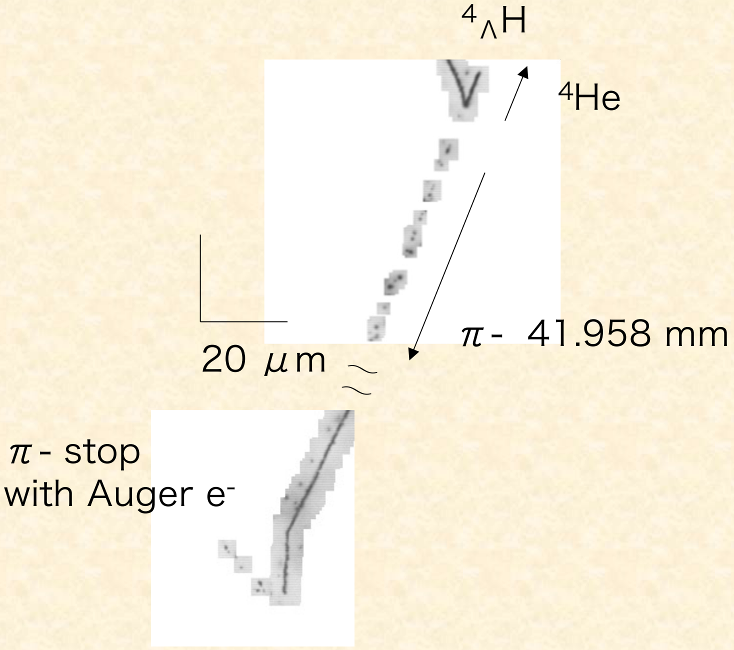


Byproduct 1:

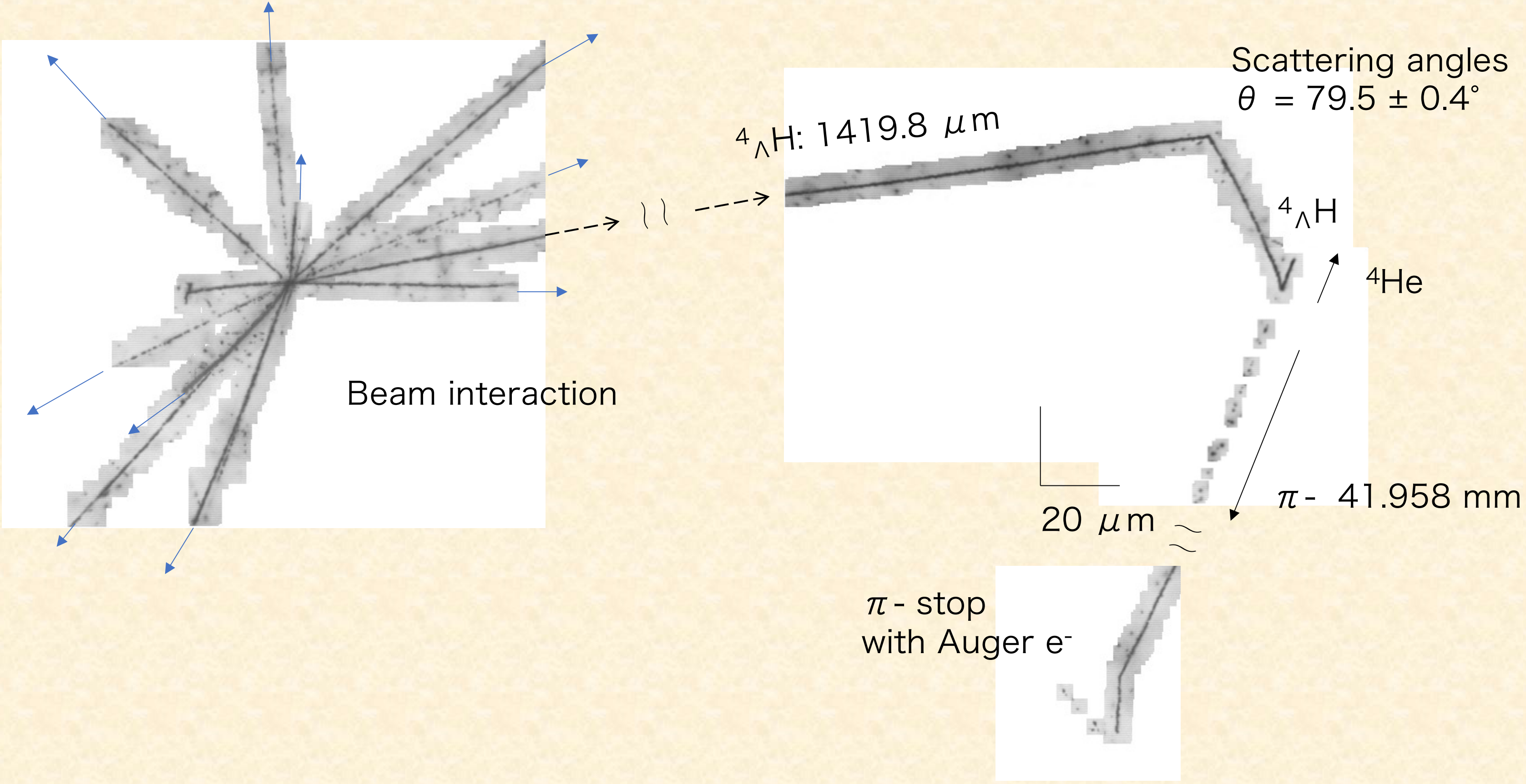
Discovery of double-Λ hypernucleus as a biproduct of $^{3}_{\Lambda}H$ search



Byproduct 2:



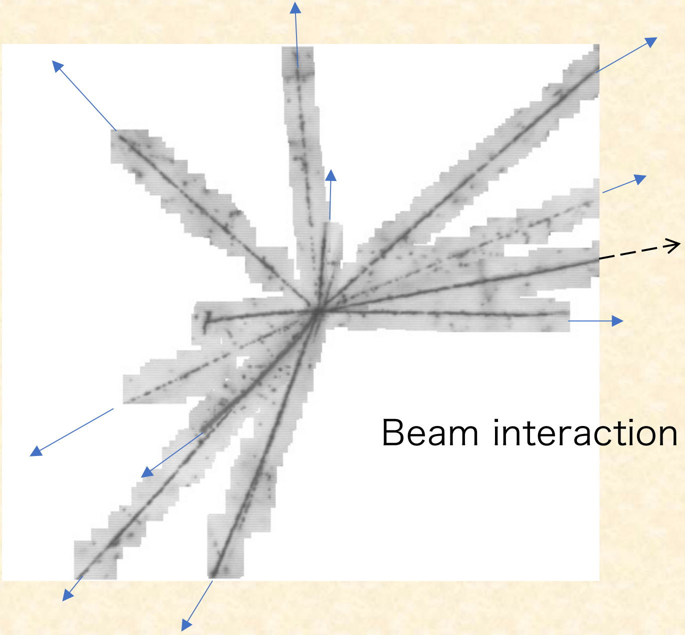
Byproduct 2:

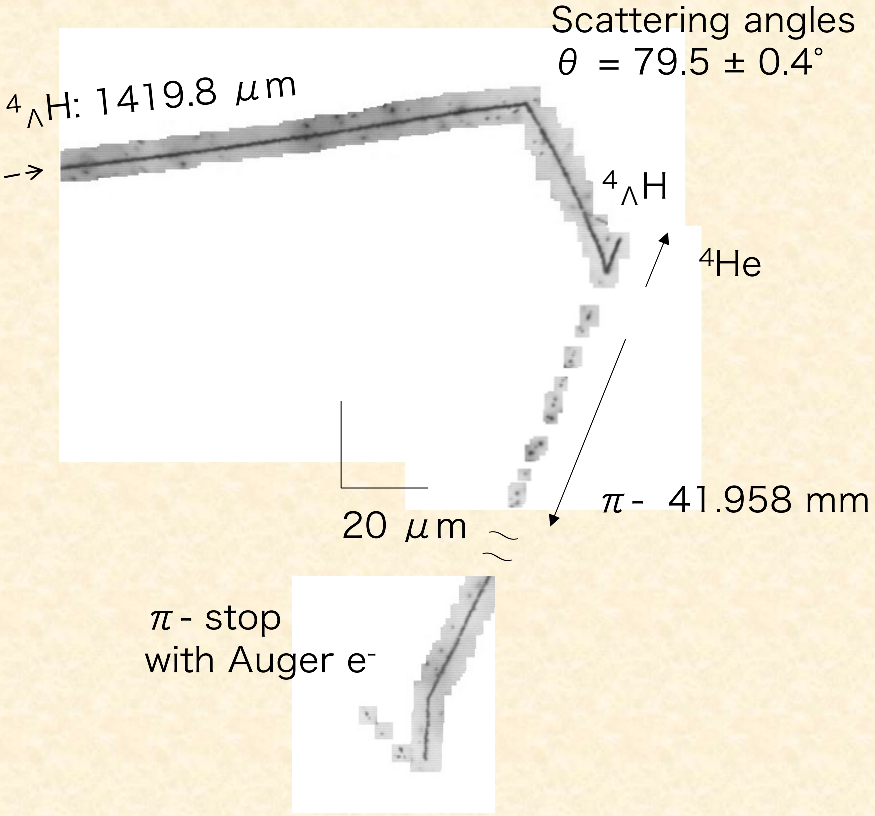


Beam interaction
⁴ΛH: 1419.8 μm
Scattering angles
θ = 79.5 ± 0.4°
⁴ΛH
⁴He
π- 41.958 mm
20 μm
π- stop
with Auger e⁻

Byproduct 2:

Hypernuclear scattering





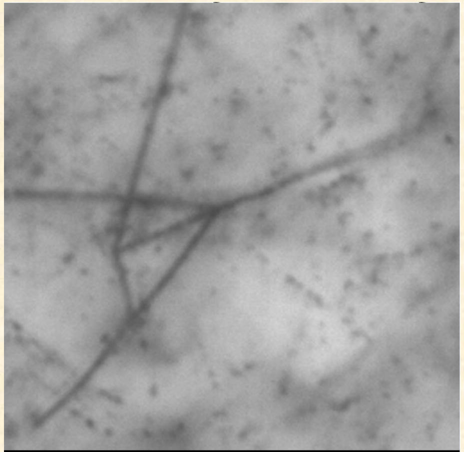
Current machine learning developments

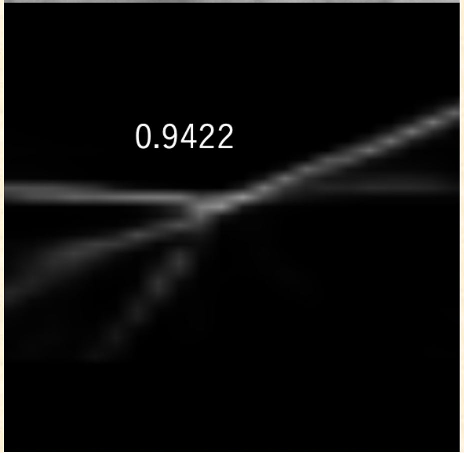
Improvements for the hypertriton binding energy

- Automated pion tracking
- Automated emulsion calibration

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

Three-body decay event

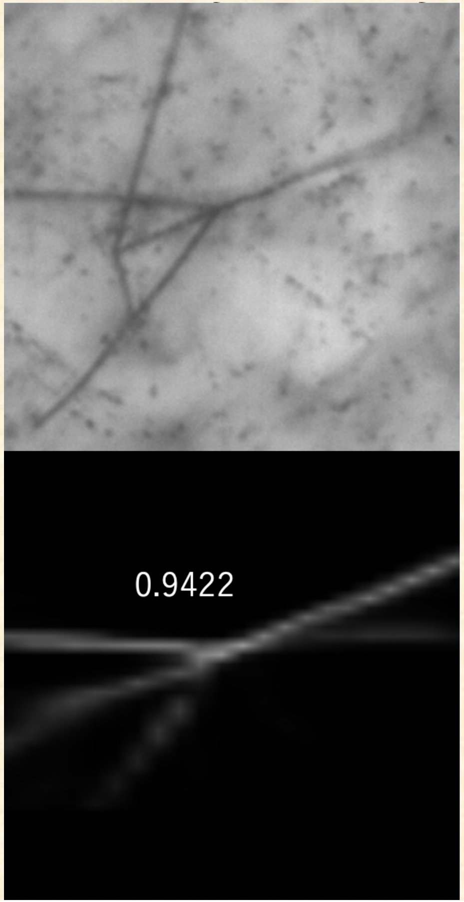


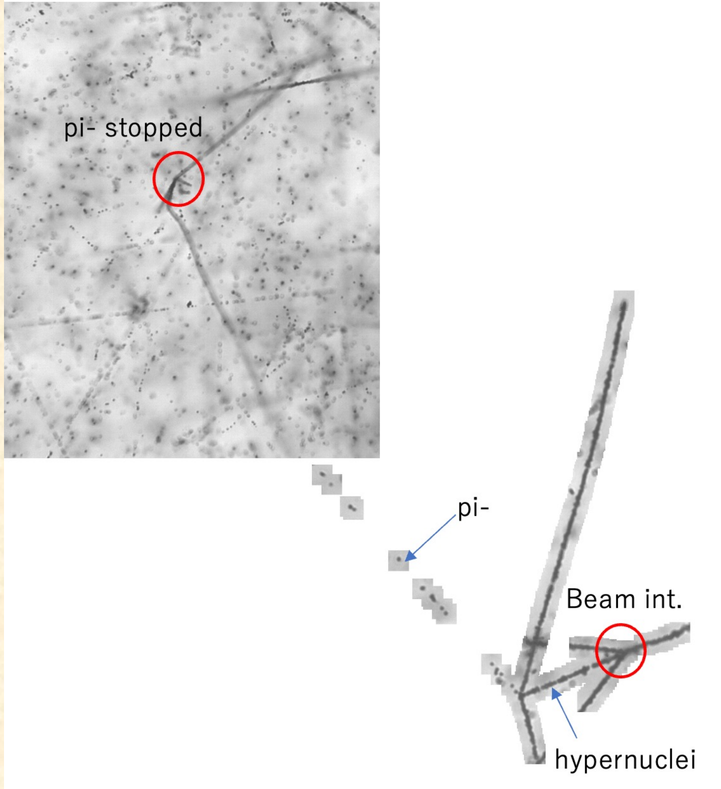


Courtesy of Shohei Sugimoto and Manami Nakagawa

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)

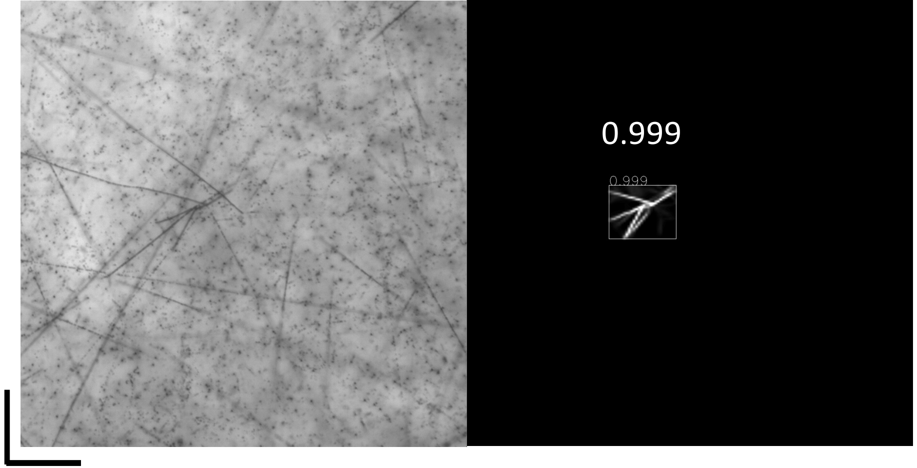
MOD100_PL02_AREA00

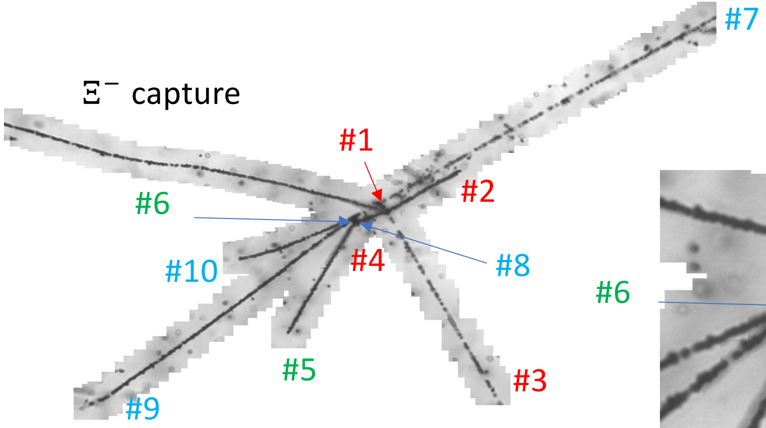
V3451

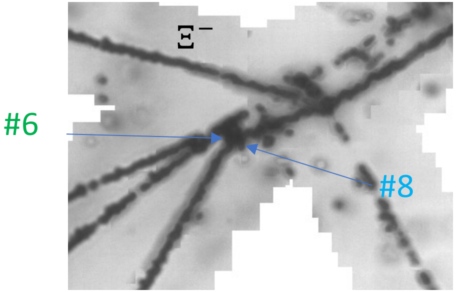
$\Xi-$ capture:
#1: penetrate
#2: stop
#3: stop
#4: decay

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

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Summary

Nuclear emulsion + Machine learning

- Binding energy of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$

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

  - ➢Currently 0.4 % of the entire data: $\Delta B_{\Lambda} \sim 180$ keV (only with He track length)
  - ➢With the entire data: $\Delta B_{\Lambda} \sim 10$ keV (but systematic uncertainty will be 20 keV)
  - ➢Analyzing 25 % data will be sufficient

- Single-strangeness hypernuclei with multi-body decays
  - ➢Heavier hypernuclei
  - ➢Increasing statistics for ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$

- Double-strangeness hypernuclei