J-PARC E07原子核乾板を用いたS=-1,-2ハイパー核の束縛エネルギー精密測定

Manami Nakagawa

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[5]University of Groningen, [6]Instituto de Estructura de la Materia, CSIC-Madrid,
[7]Institute of Modern Physics, CAS, [8]University of Chinese Academy of Sciences,
[9]Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, [10]GSI,
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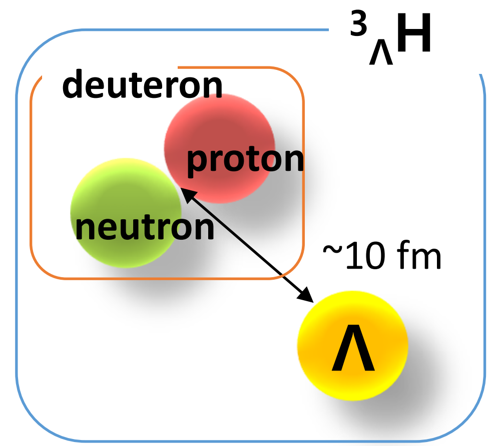
Contents

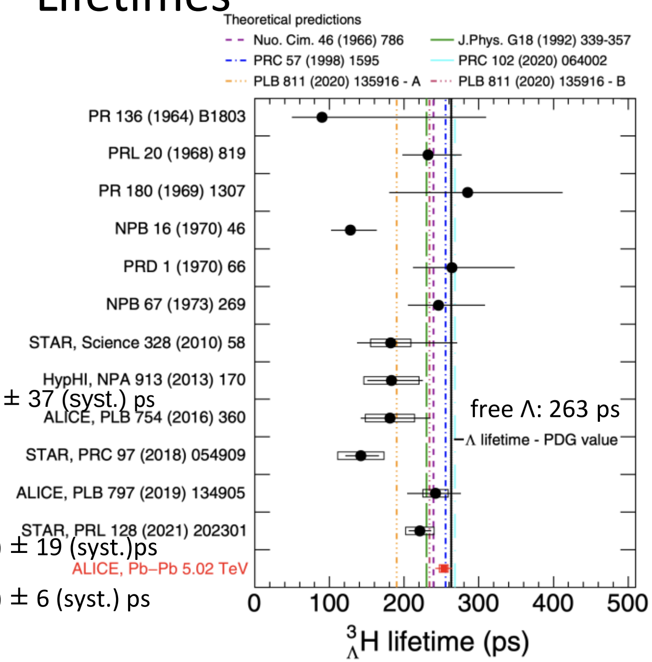
- Introduction
- Nuclear emulsion & Machine learning
- Hypernuclear search
- Summary

Hypertriton puzzle



- The simplest hypernuclear system, $^3_\Lambda$H
  - a benchmark in hypernuclear physics

Lifetimes



$183\ ^{+42}_{-32}$ (stat.) ± 37 (syst.) ps

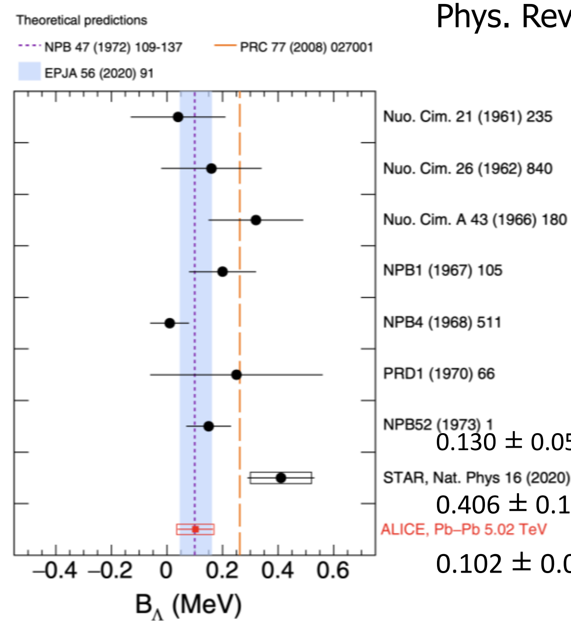
free Λ: 263 ps

221 ± 15 (stat.) ± 19 (syst.) ps

253 ± 11 (stat.) ± 6 (syst.) ps

Binding energy

Phys. Rev. Lett. 131, 102302



0.130 ± 0.050 (stat.) MeV

0.406 ± 0.120 (stat.) ± 0.110 (syst.) MeV

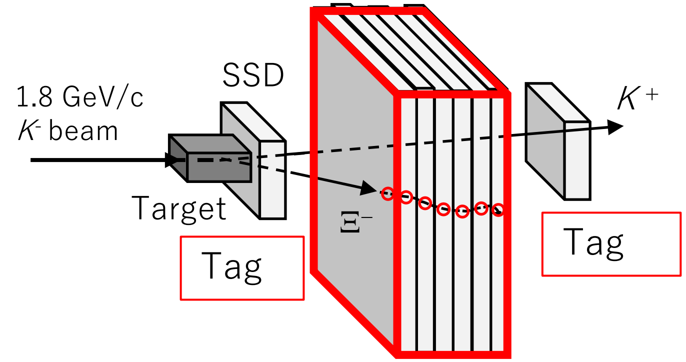
0.102 ± 0.063 (stat.) ± 0.067 (syst.) MeV

Can be different from conventional interpretation

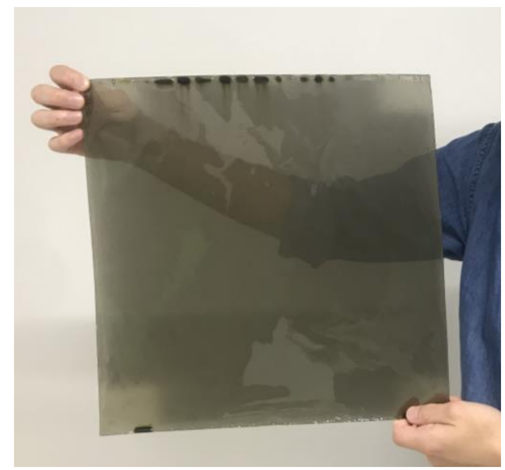
→ Precise measurement is necessary

Our approach : Nuclear emulsion & State-of-the-art technology

Nuclear emulsion

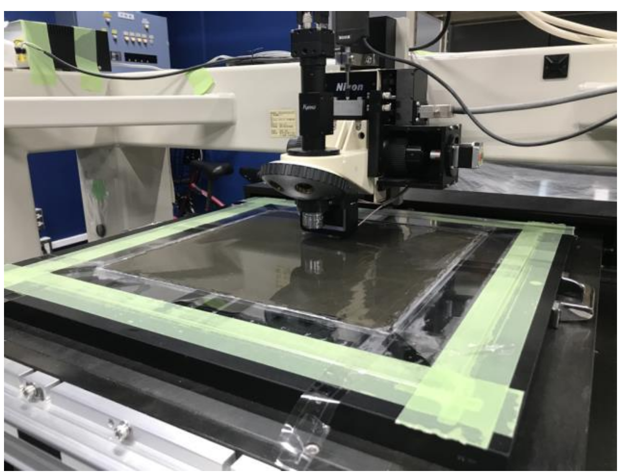


- J-PARC E07 Experiment
  - To search for double hypernuclei
  - Already 33 events observed by (K-,K+) trigger
  - Non-triggered events
    - Thousands of double hypernuclei
    - Millions of single hypernuclei
- Overall scanning

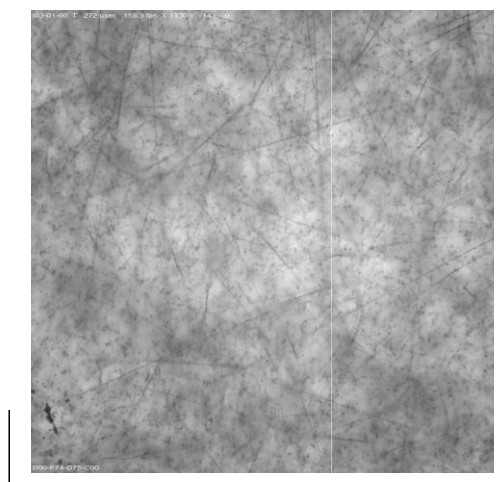


～1300 emulsion sheets
Data size: 140 PB
Background: 10^{10} events
Eye check : ～560 years

→ Machine learning



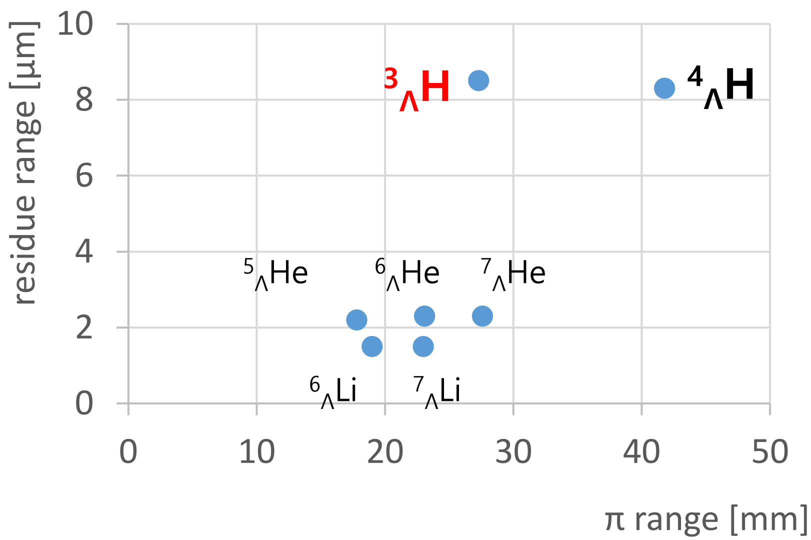
microscope

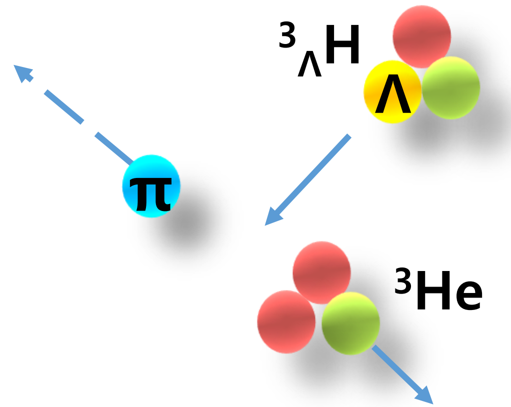


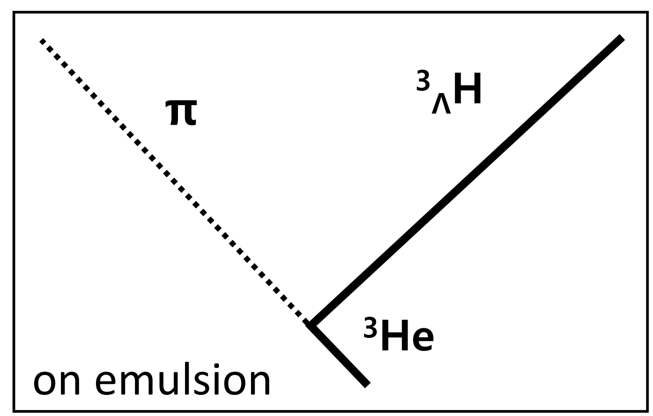
100 μm

Hypertriton detection

- Two-body (mesonic) decay at rest
  - unique identification





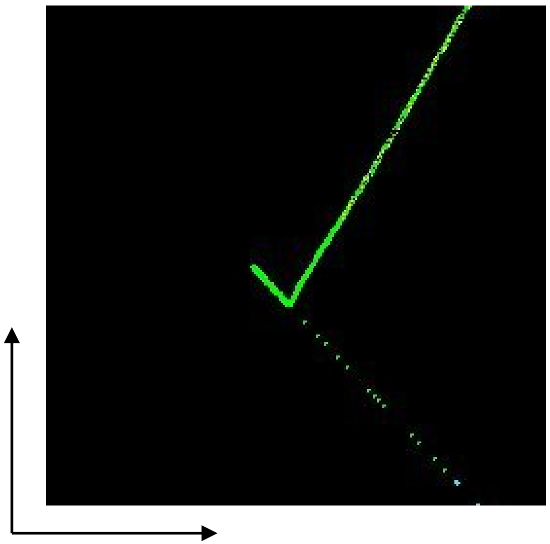


Detection is suitable for machine learning, but no training data
→ Create images from physics simulations

Production of Simulated Image
①Simulate events by Geant4

Color = depth to reproduce defocusing

Simulated hypertriton

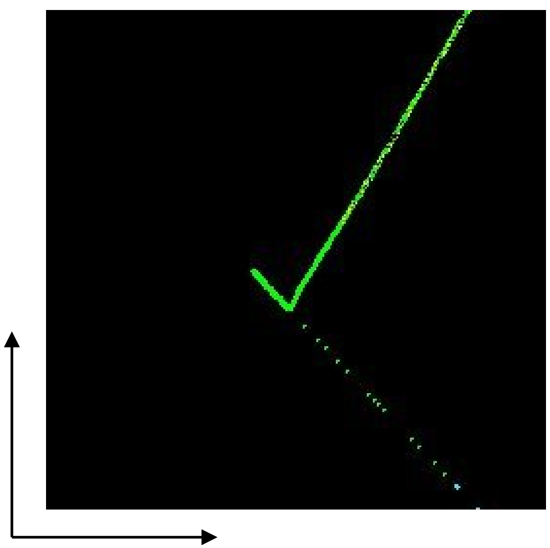


50 μm

Production of Simulated Image
②Convert real image to line image as BG

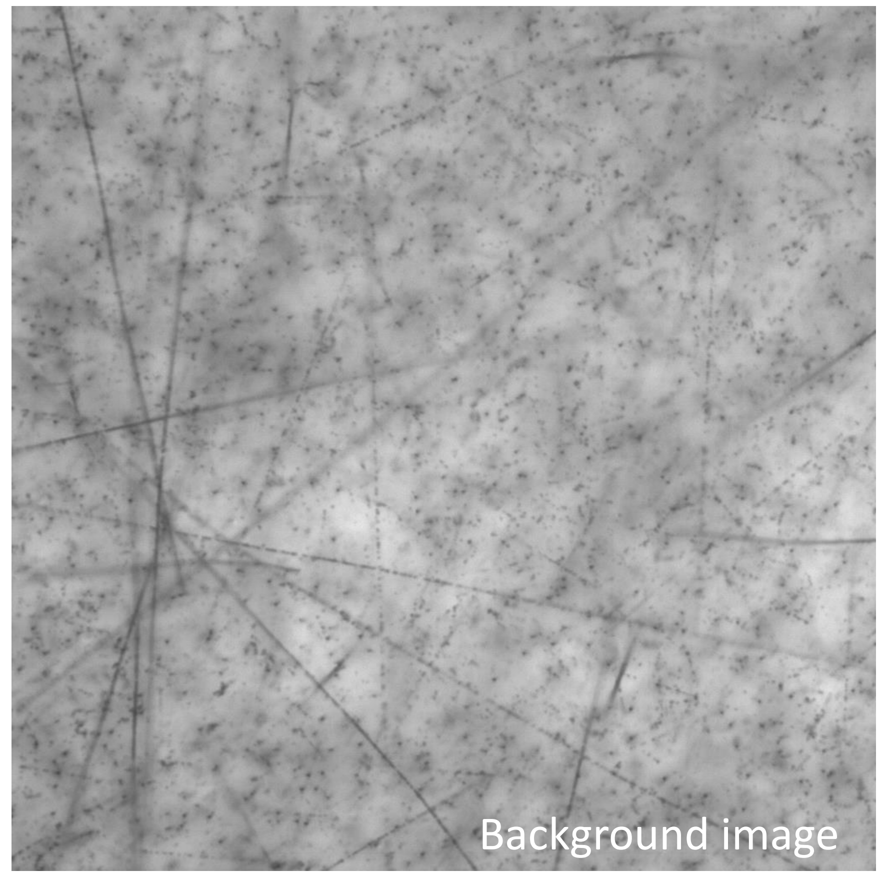
Color = depth to reproduce defocusing

Simulated hypertriton



50 μm

Real background image



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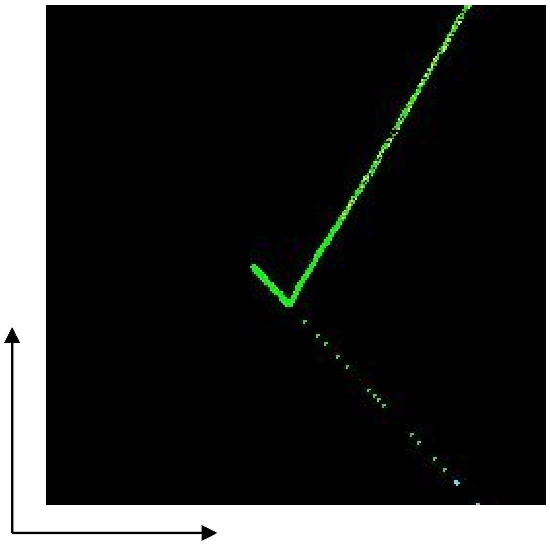
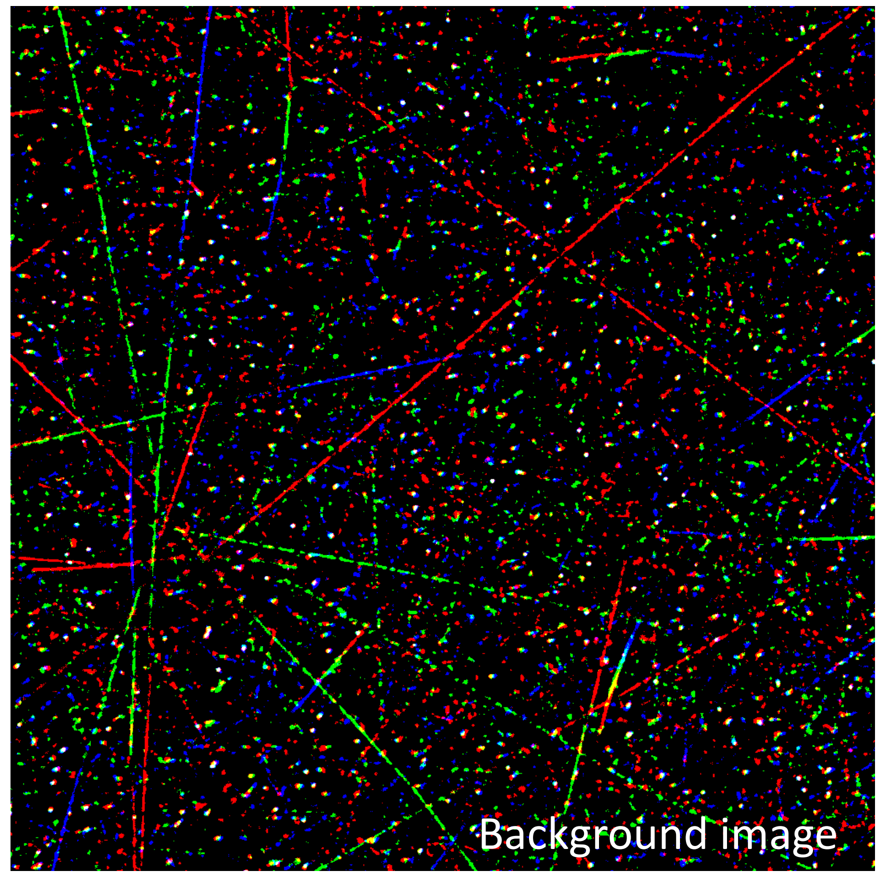


50 μm

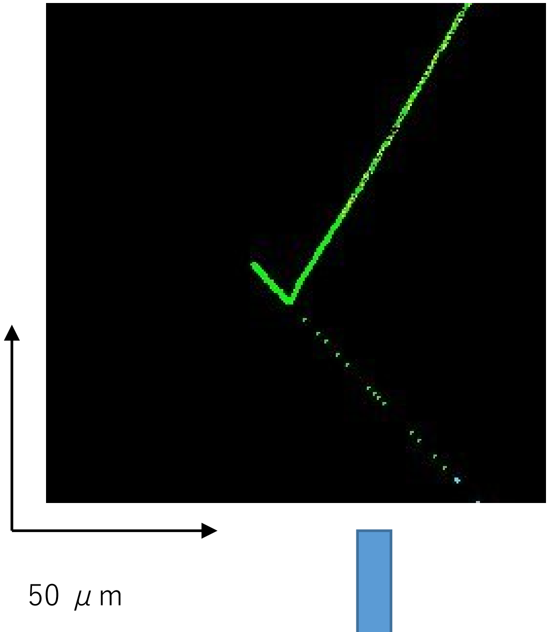
Line image from real image



Production of Simulated Image ③Synthesize

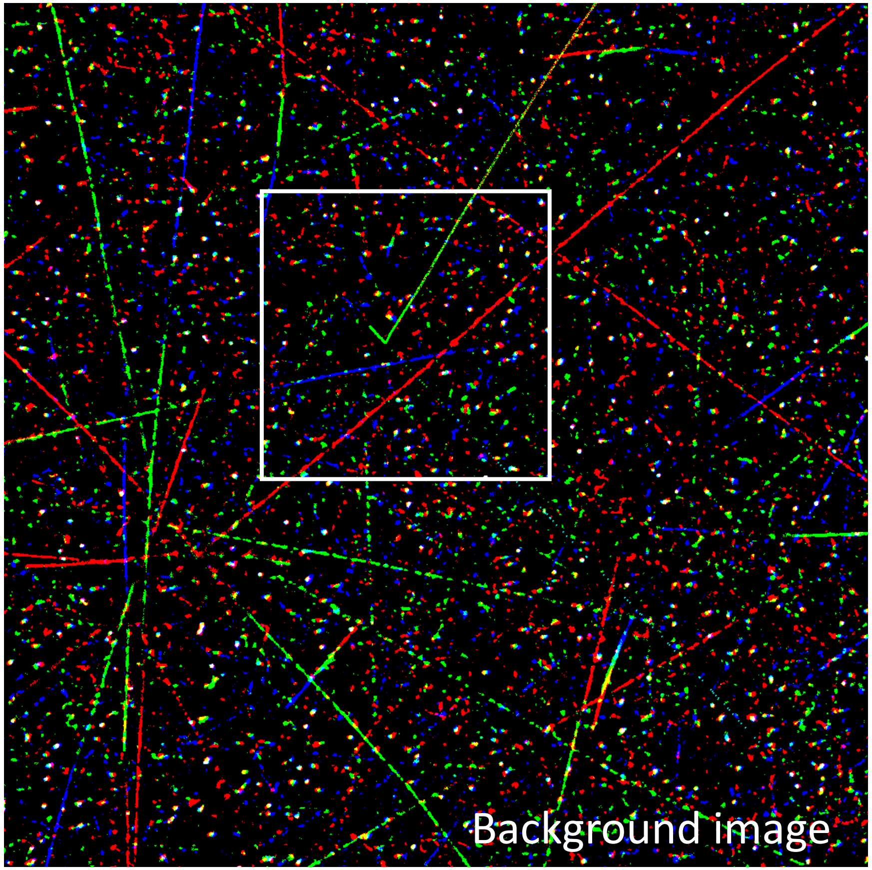
Color = depth to reproduce defocusing

Simulated hypertriton



Synthesize

Synthesized line image

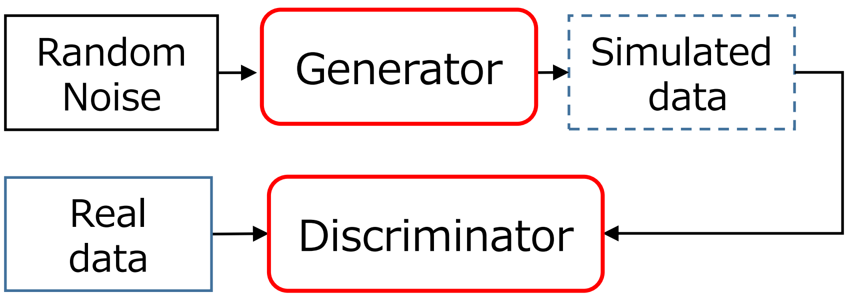


Should convert to microscopic image

Production of Simulated Image ④Convert image by GAN

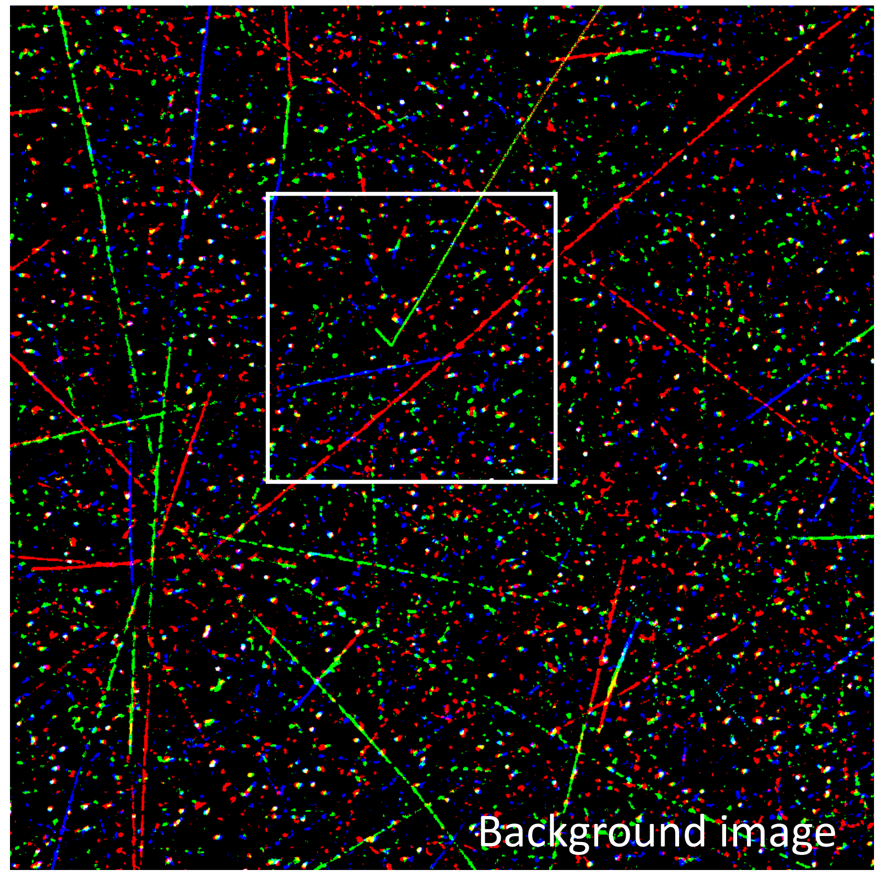
Color = depth to reproduce defocusing

- Generative Adversarial Networks (GAN)
  - Train Generator and Discriminator simultaneously
    arXiv:1406.2661



  - pix2pix Model is applied
    - Image style transformation
    arXiv:1611.07004

Synthesized line image



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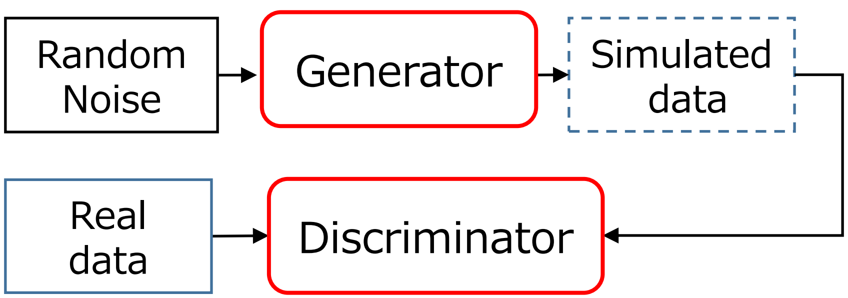

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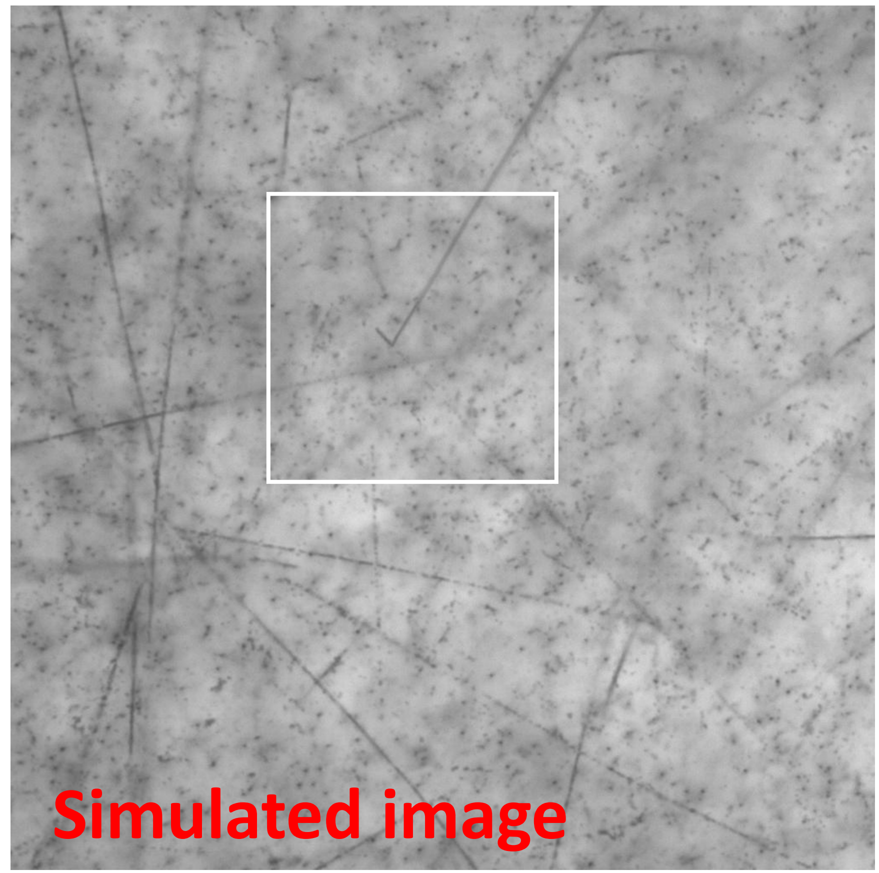
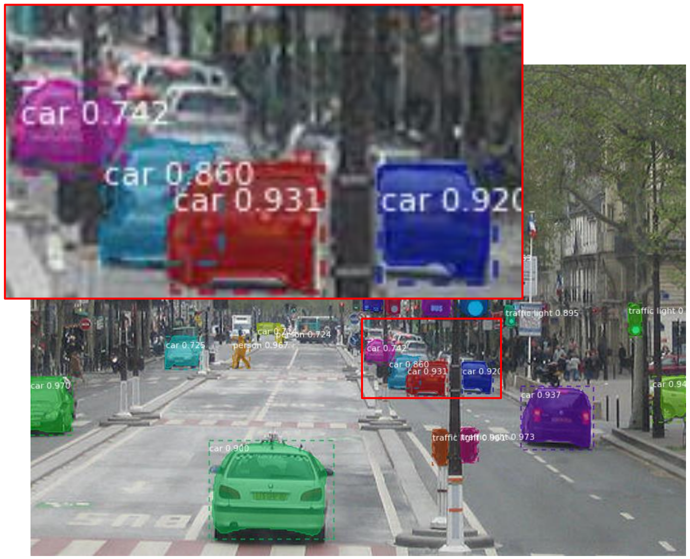


Input image of training data is obtained

$^{3}_{\Lambda}$H event detection using object detection

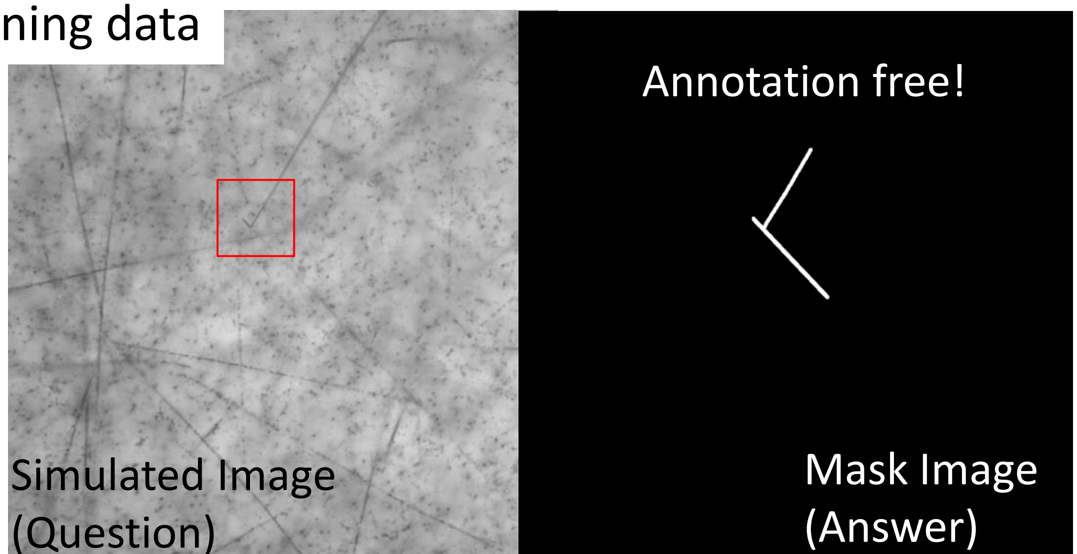


Mask R-CNN
Object detection model
arXiv:1703.06870

example of training data
https://www.cis.upenn.edu/~jshi/ped_html/

Image
Mask

Training data



* Track length resolution is too low to make bias of binding energy

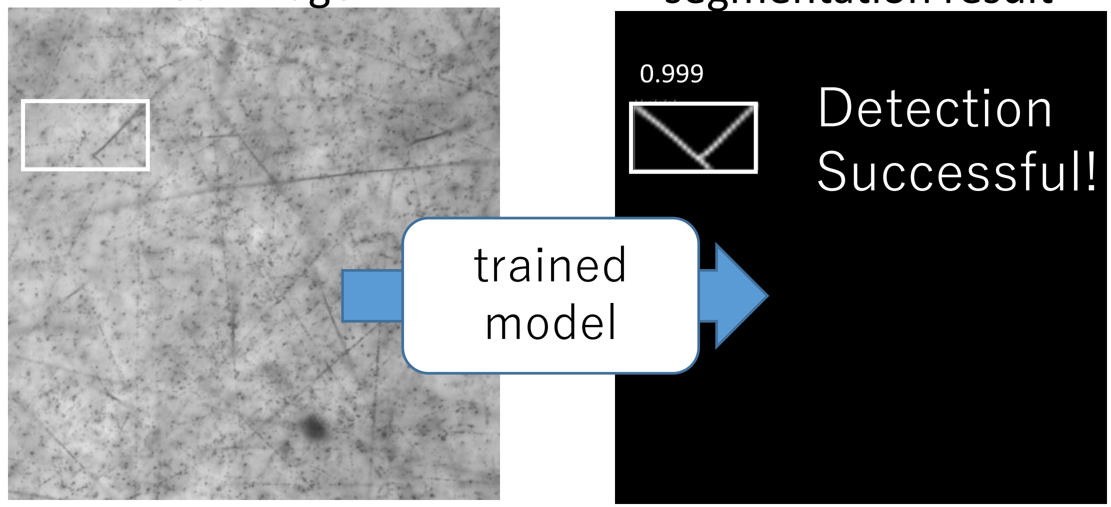
Detection

- Detection with trained model

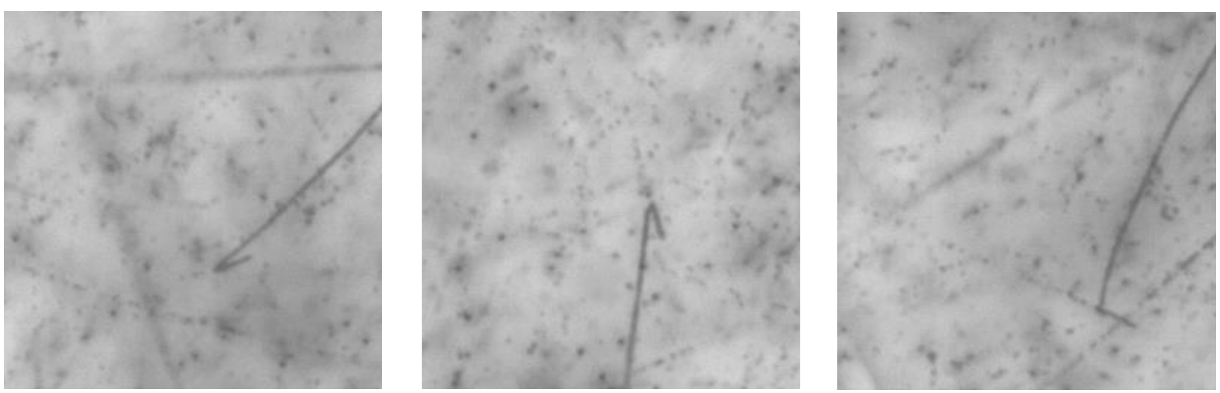
Published
A. Kasagi, et al.,
NIM A, 1056 (2023) 168663

real image

segmentation result



- Examples of detected hypernuclear events

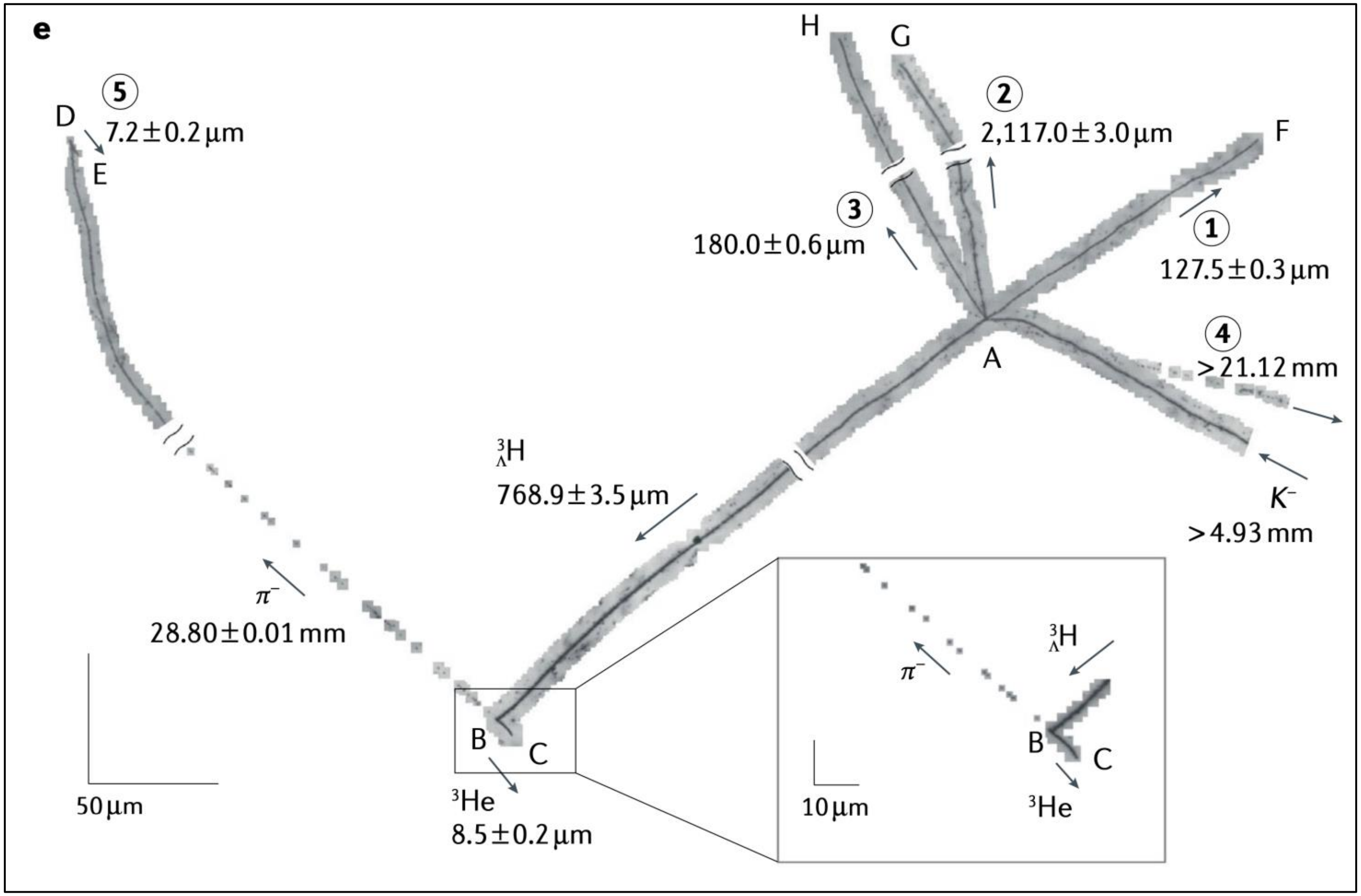


Detected 1075 events
Identified 183 events
in 0.55% of entire data

2023. Aug.

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

T.R. Saito, *et al.,* Nat Rev Phys **3,** 803–813 (2021).



Current observations
${}^{3}_{\Lambda}H$: 37, ${}^{4}_{\Lambda}H$: 146

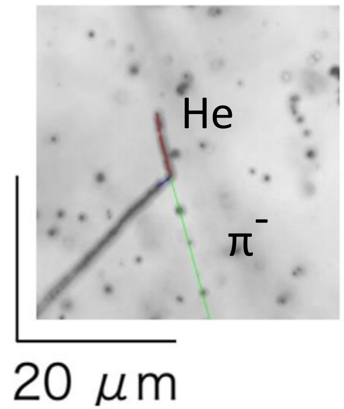
2023. Aug.

400 events → 30keV(stat.), 30keV(sys.)

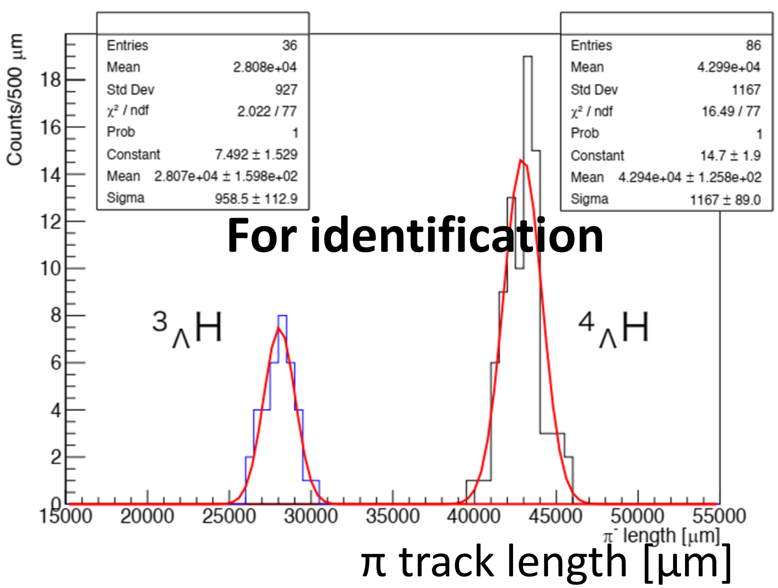
E. Liu, et al., Eur. Phys. J. A (2021) 57:327

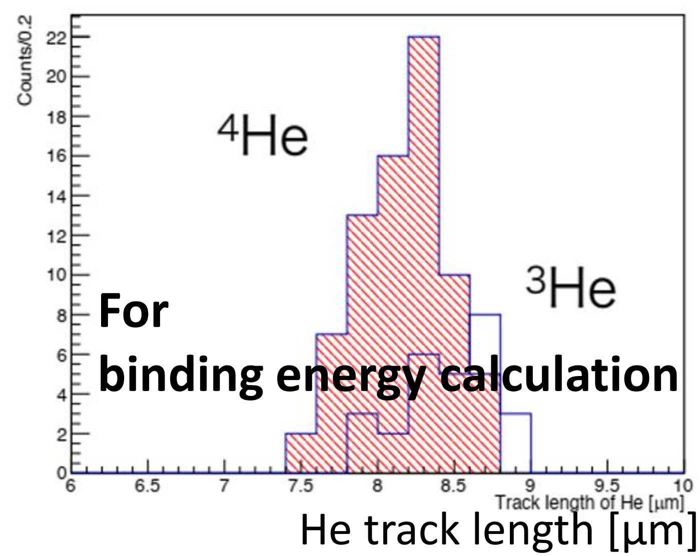
Analysis of ${}^{3}_{\Lambda}\mathrm{H}$ & ${}^{4}_{\Lambda}\mathrm{H}$

- Fitting tracks
  to determine range (& vertex)
  - images were taken
    under high magnified lens



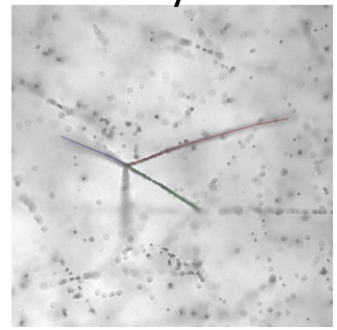
- Track length measurements



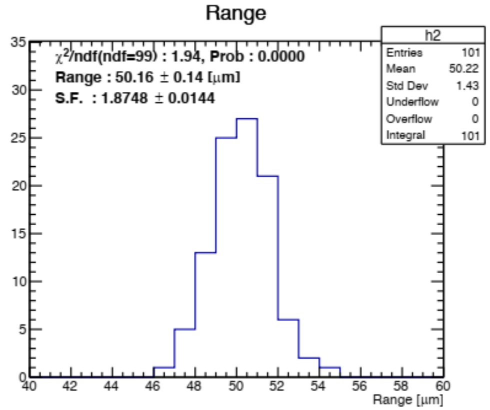


Analysis of $^{3}_{\Lambda}$H & $^{4}_{\Lambda}$H

α decay event



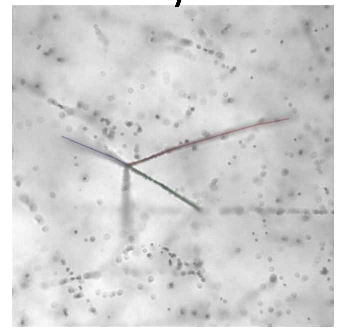
track length of α
to calibrate momentum



- Binding energy calculation
  - invariant mass: $$M_{hyp} = \sqrt{M_{He}^2 + P_{\mathrm{He}}^2} + \sqrt{M_{\pi}^2 + P_{\mathrm{He}}^2}$$
  - Binding energy: $$B_{\Lambda} = (M_{He} + M_{\Lambda}) - M_{hyp}$$

Analysis of ${}^{3}_{\Lambda}$H & ${}^{4}_{\Lambda}$H

α decay event



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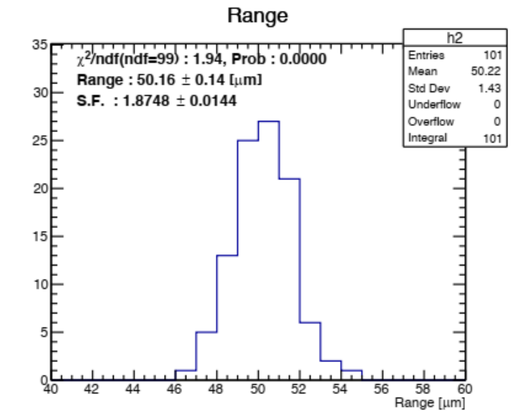

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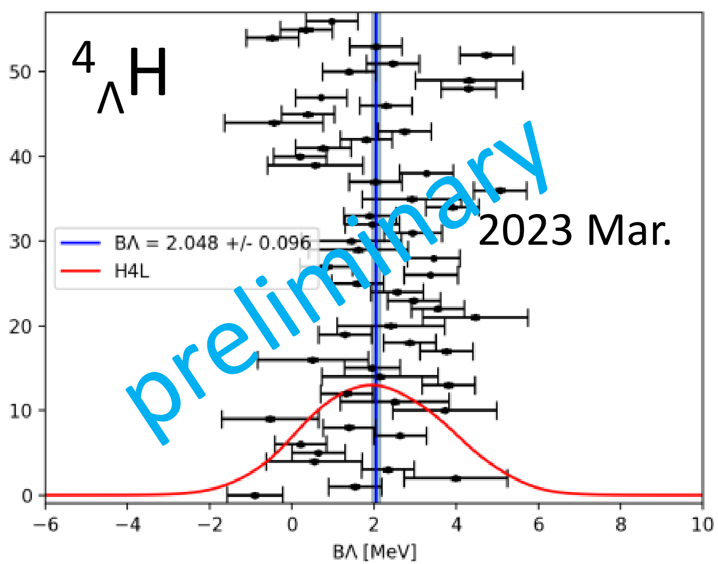
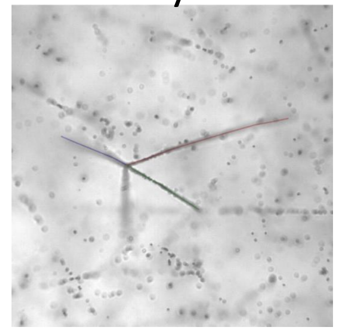
$$B_{\Lambda} = (M_{He} + M_{\Lambda}) - M_{hyp}$$



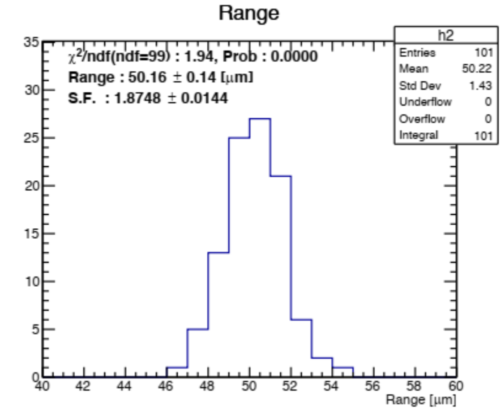
85 events calibrated (144 events now) → 57 events required at-rest decay

Analysis of $^{3}_{\Lambda}H$ & $^{4}_{\Lambda}H$

α decay event



track length of α
to calibrate momentum



- Binding energy calculation
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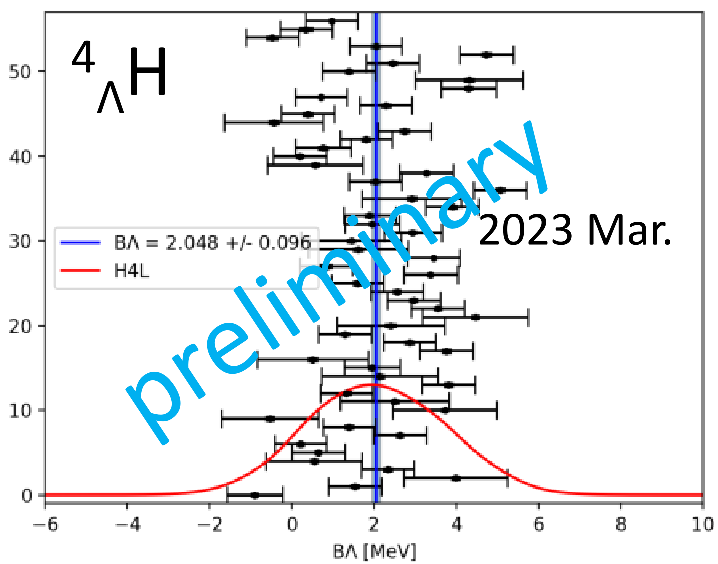


85 events calibrated
(144 events now)
→
57 events
required at-rest decay

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

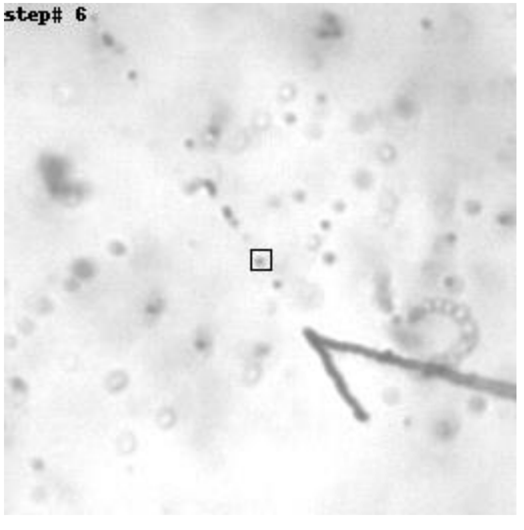
?

will be published

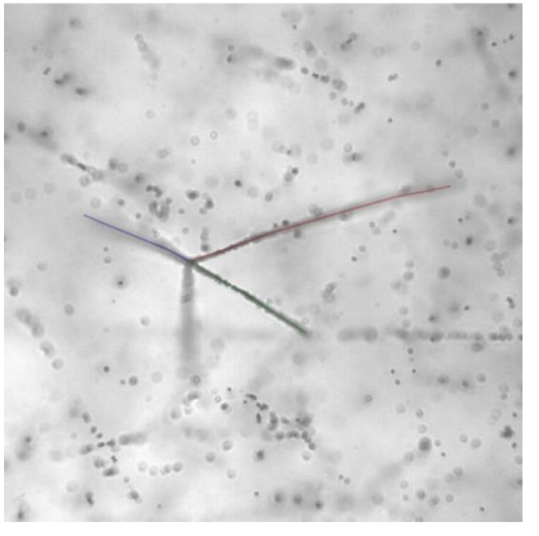
Ph.D thesis by Ayumi Kasagi
Gifu Univ., RIKEN

Automation by Reinforcement Learning

- Automatic tracking of π track
  - π track is too thin to tack by image analysis
  - ~ 6 hours / π track by human eyes

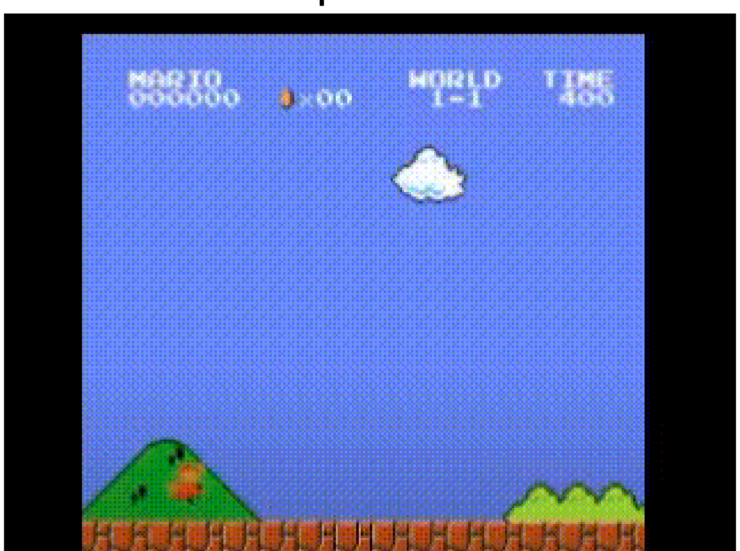


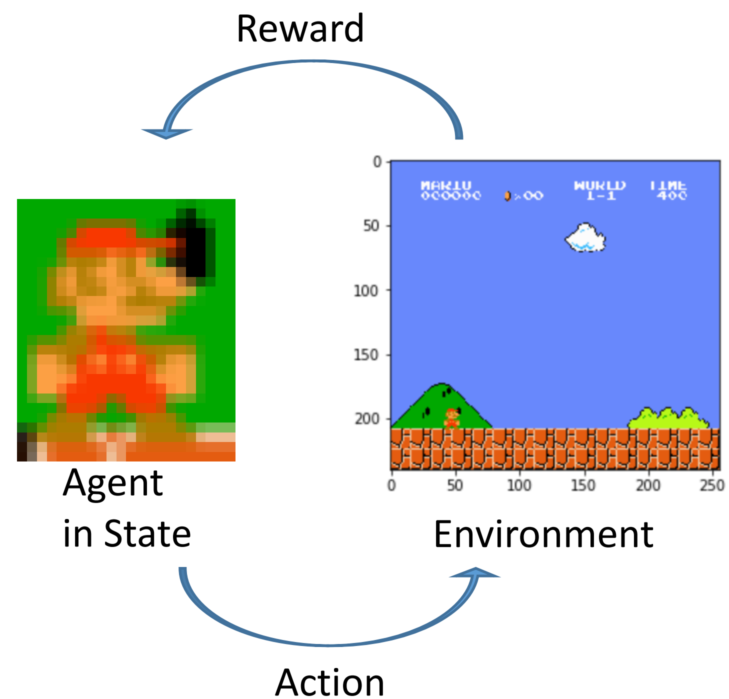
- Automatic tracking of α track
  - For momentum calibration
  - ~400 α/ 1 day / hypernuclear event by human hands



Reinforcement learning

- Overview
  - One of three categories of machine leaning technique
  - Learn to Maximize total reward
    - like how a baby learns
  - Game playing is applied mainly
  - Suitable to optimize a route





Cleaning robot plans a route

Automation by Reinforcement Learning

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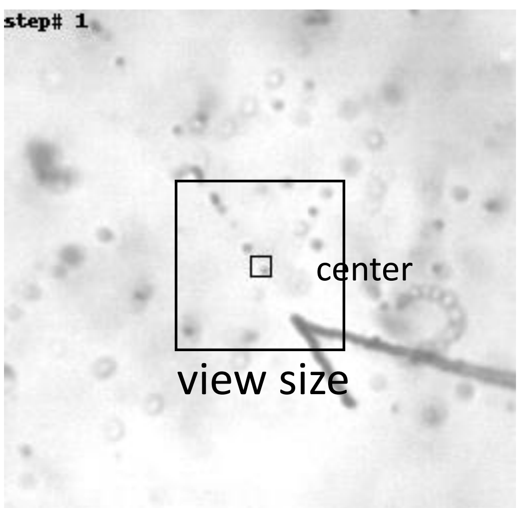

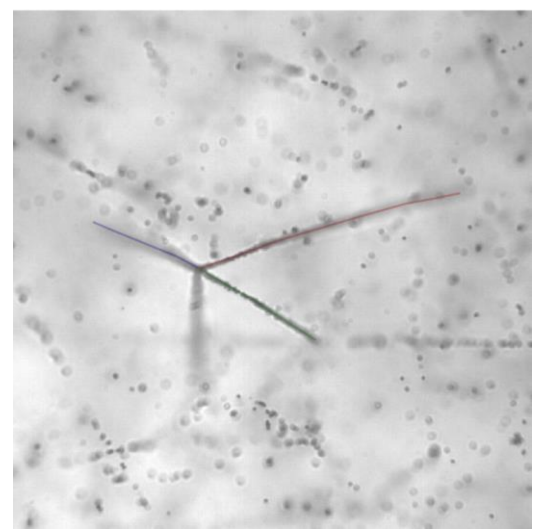

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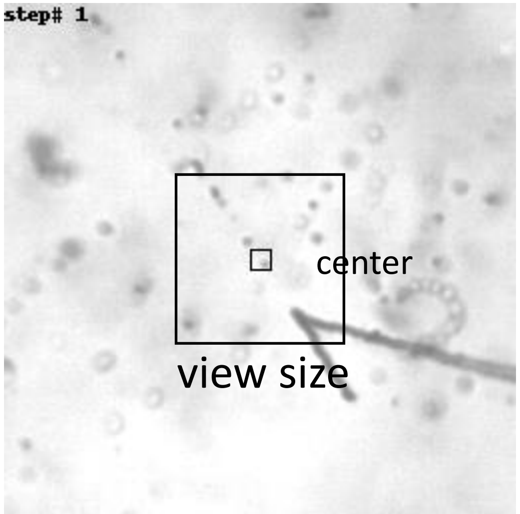

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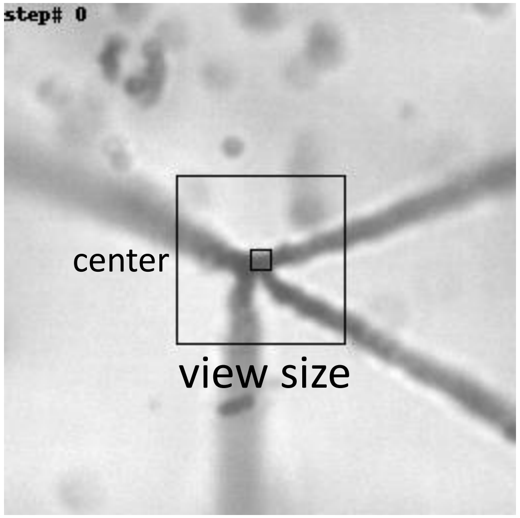
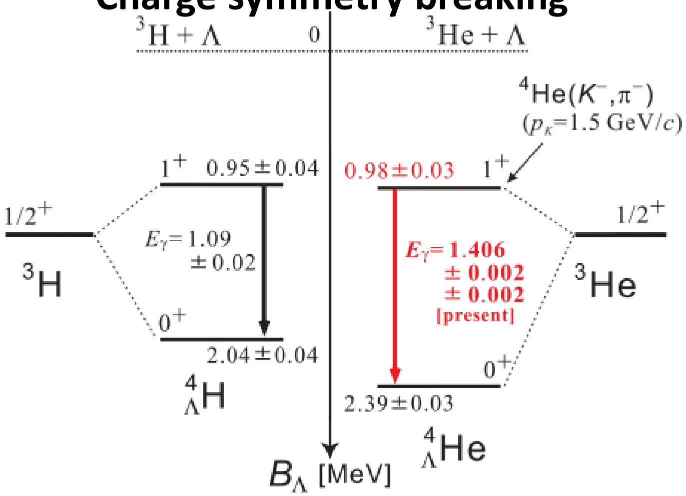


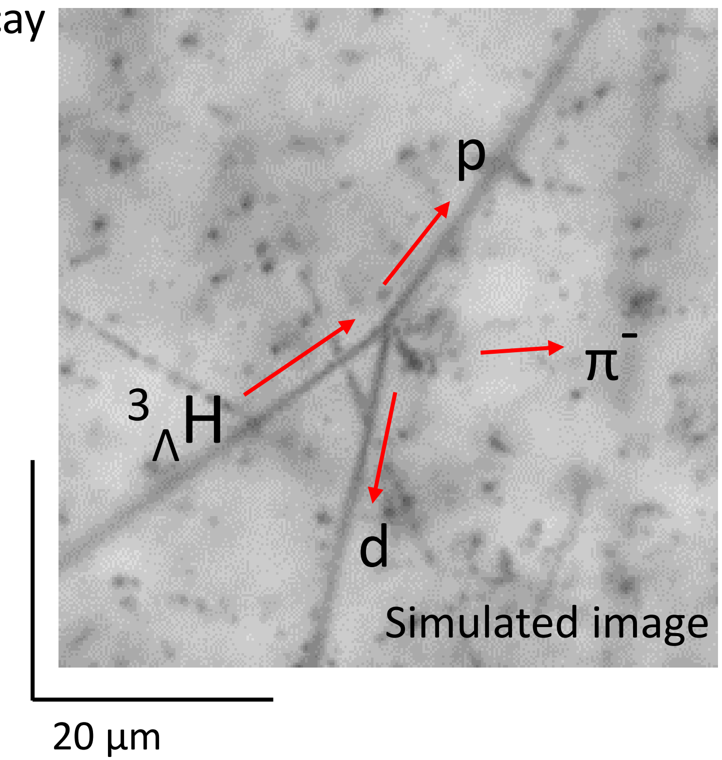
Single hypernuclear search

- Three-body (mesonic) decay as a first step
  - Many hypernuclei decay with many-body final states
  - Especially ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ & ${}^{4}_{\Lambda}He$
    - ${}^{3}_{\Lambda}H$: Comparison with 2-body decay
    - ${}^{4}_{\Lambda}H$: Comparison with 2-body decay
    - ${}^{4}_{\Lambda}He$: Only old emulsion data

Charge symmetry breaking



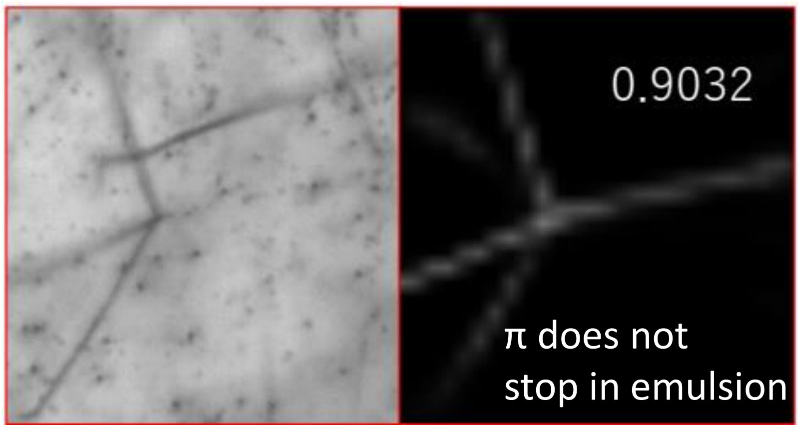
T. O. Yamamoto, et al.,
Phys. Rev. Lett. **115**, 222501 (2015)

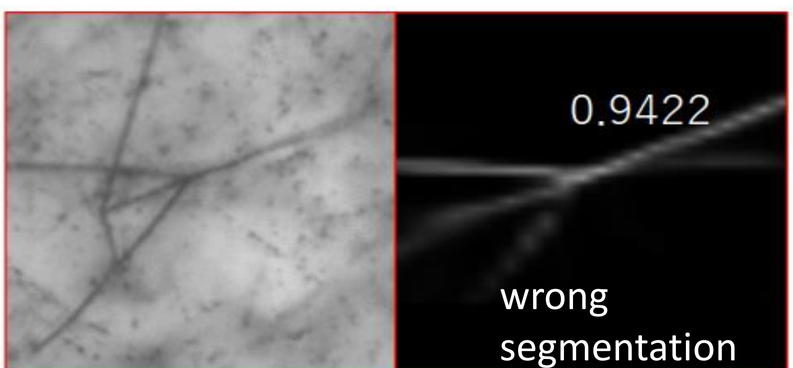


Single hypernuclear search

Searched region:
0.01% of entire data in 2023 Mar.

- Detected candidates of three-body decay event
  - Unfortunately, unique solution cannot be found



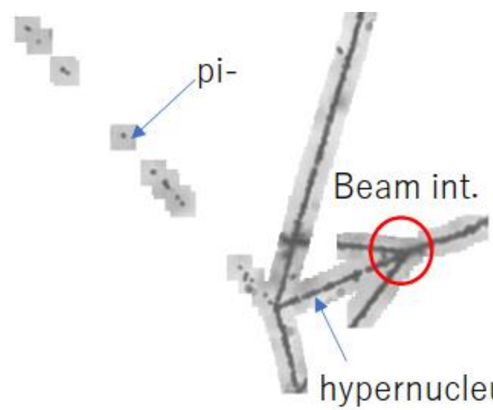


12 solutions remain...

1 . ${}^{8}_{\Lambda}\mathrm{He} \to {}^{6}\mathrm{He} + d + \pi^{-}$

2 . ${}^{5}_{\Lambda}\mathrm{H} \to p + p + \pi^{-} + 3n$

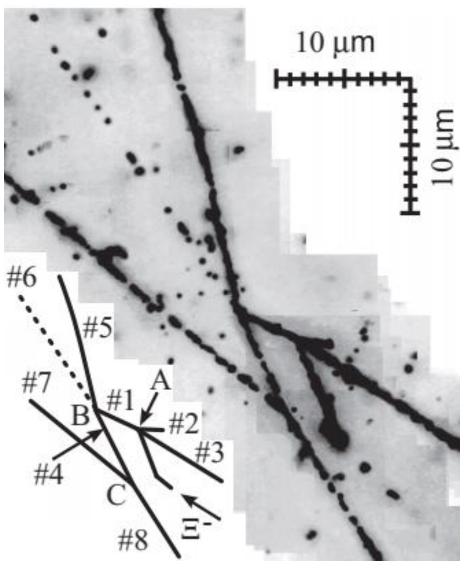
.
.
.



To be summarized in Master thesis by Shohei Sugimoto
Saitama Univ., RIKEN

Double hypernuclear search

- Double hypernuclear event
  - Observe new double hypernuclei
  - Increase statistics of known double hypernuclei
- ${}^{6}_{\Lambda\Lambda}$He detection as a first step



H. Takahashi *et al.*
Phys. Rev. Lett. **87**, 212502 (2001)

NAGARA

$\Xi^- {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He\ \alpha\ t$

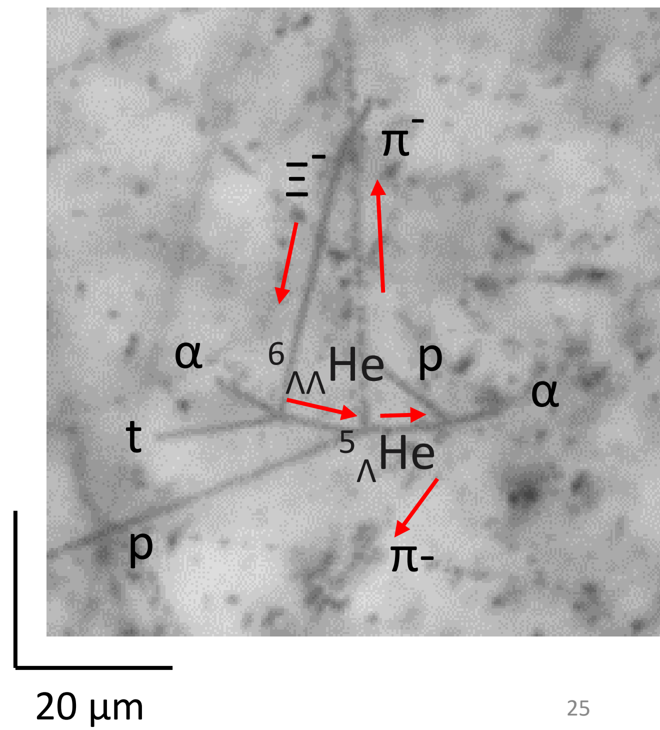
${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He\ p\ \pi^-$

${}^{5}_{\Lambda}He \rightarrow p\ p\ n(s)$

$\Xi^- {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He\ \alpha\ t$

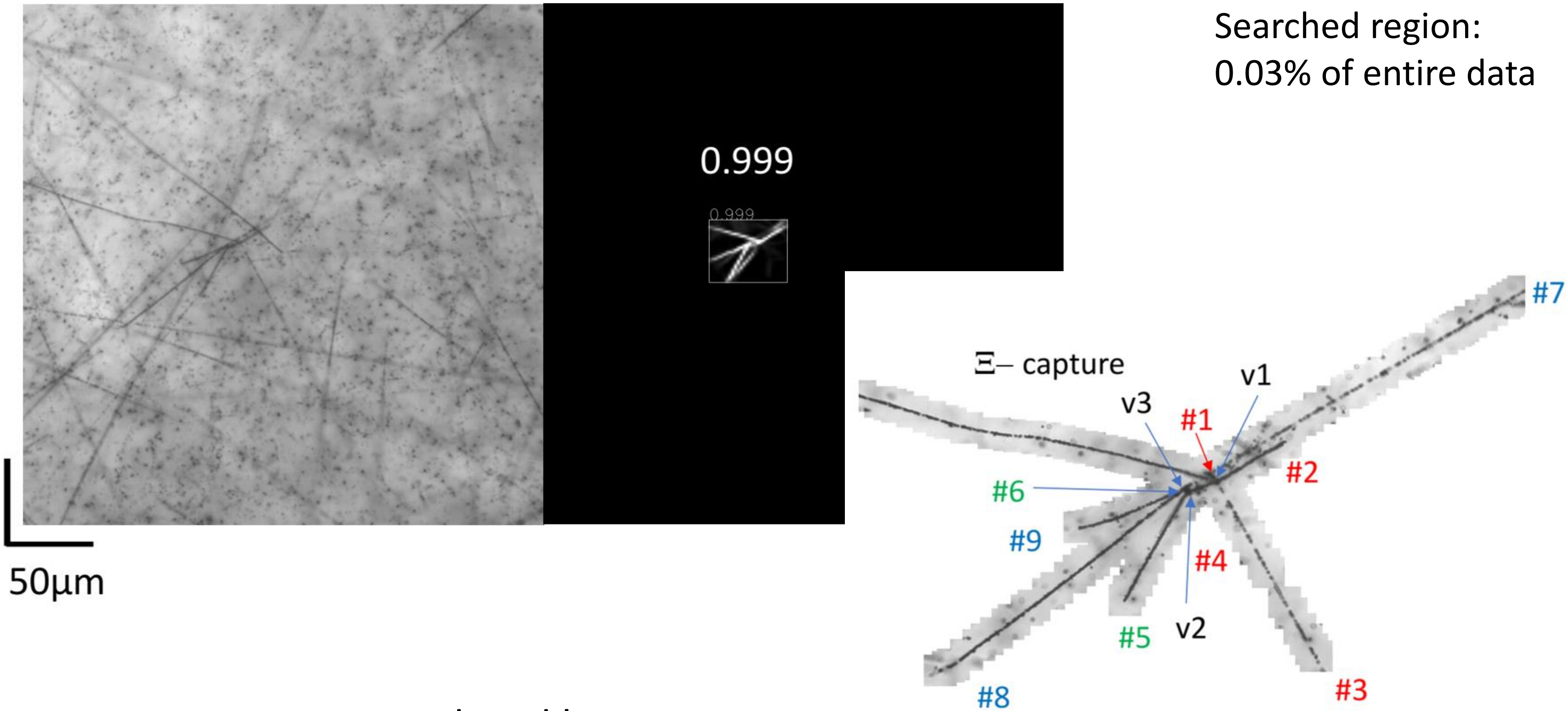
${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He\ p\ \pi^-$

${}^{5}_{\Lambda}He \rightarrow \alpha\ p\ \pi^-$



Double hypernuclear search

- Detected candidates of double-hypernuclear events



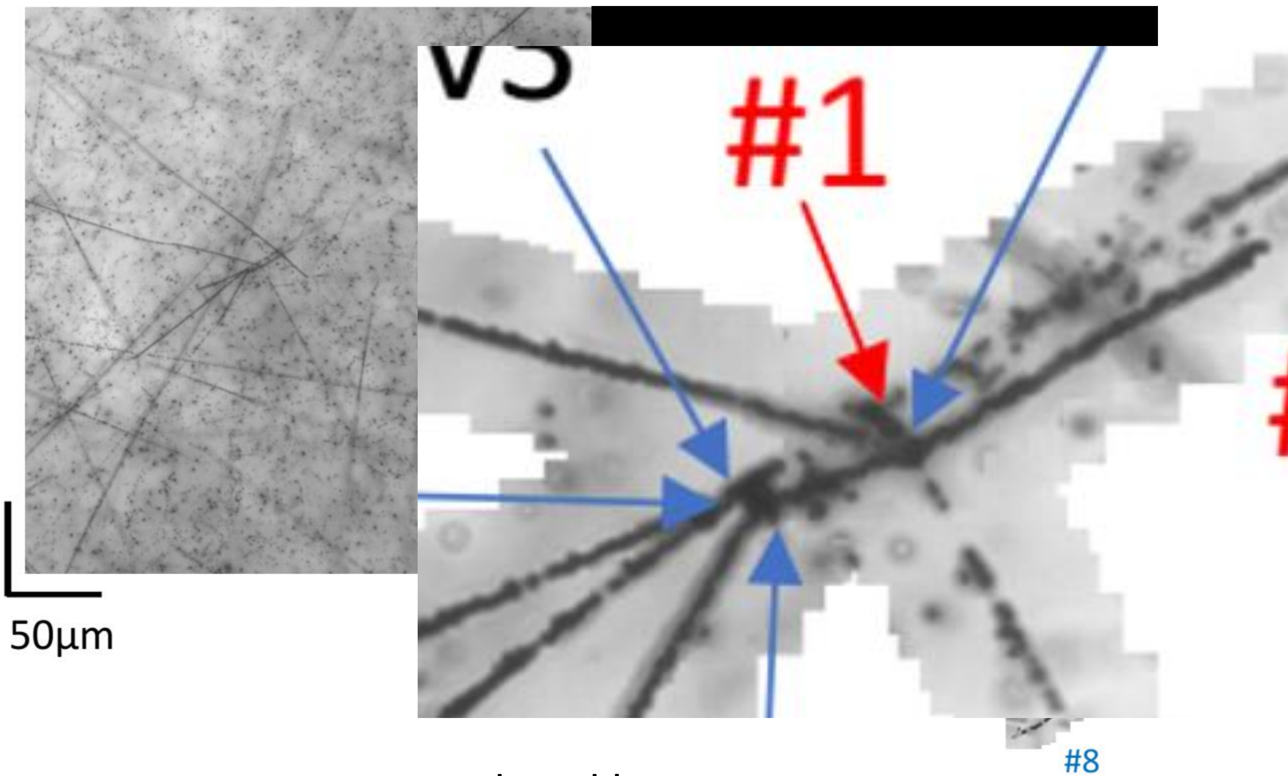
Searched region:
0.03% of entire data

produced by Ξ- capture

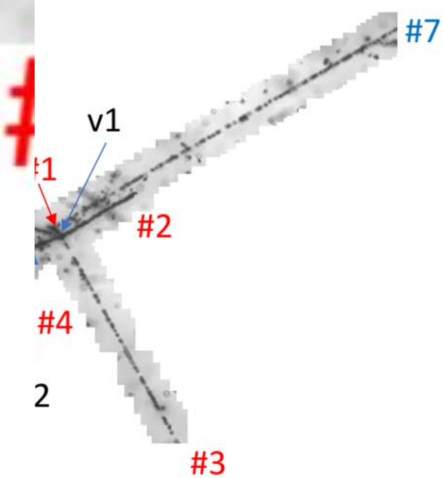
Double hypernuclear search

- Detected candidates of double-hypernuclear events
  - Non mesonic decay is hard to identify

[redacted]



Searched region:
0.03% of entire data in 2023 Mar.
→ 0.2% currently searched in 2023 Aug.
but no other clear event
observed yet



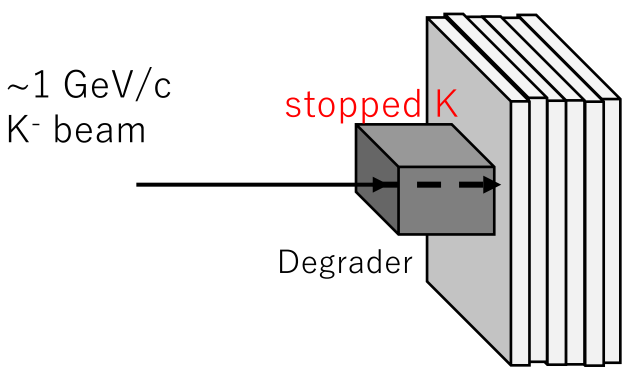
produced by Ξ- capture

Future experiments

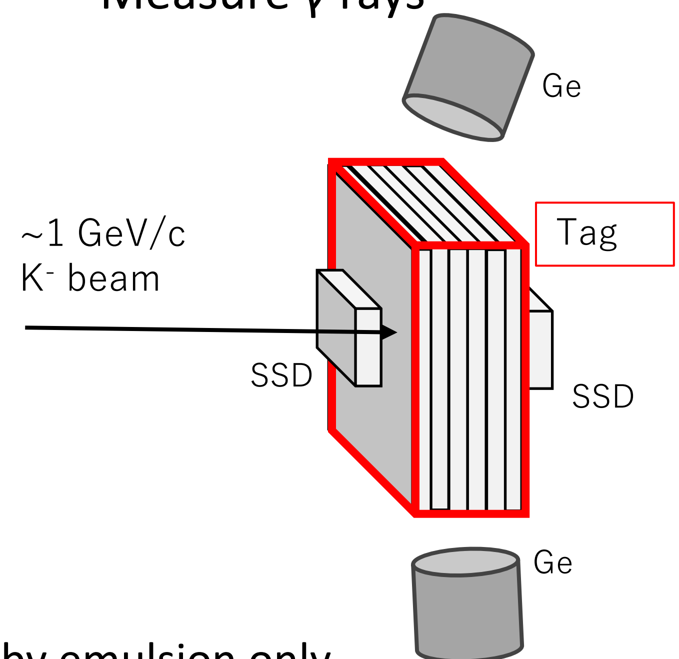
Making emulsion with Nagoya U.

Thanks to Tamura san

- Binding energy of $^{12}_{\Lambda}C$ @ stopped K^-
  - Remeasure binding energy of $^{12}_{\Lambda}C$ by emulsion



- Binding energy & Level structure of Λ hypernuclei
  - Tag by emulsion
  - Coincidence with SSD
  - Measure γ rays



Machine learning allows us to find events by emulsion only

Summary & Perspective

- Precise binding energy measurement of hypernuclei
  - To solve hypertriton puzzle
- Nuclear emulsion
  - For J-PARC E07 experiment
  - Overall scan of whole data
- Machine learning
  - Simulated image production by Geant4 + GAN
  - Object detection as event detection
- On-going search
  - Two-body decay (at rest) of ${}^{3}_{\Lambda}H$ & ${}^{4}_{\Lambda}H$
  - Single hypernuclear search
  - Double hypernuclear search

→We will provide precise binding energies of various hypernuclei