RIKEN's Programs for Junior Scientists

HENP High Energy Nuclear Physics

Precise measurement of binding energies of hypernuclei on nuclear emulsion with machine learning

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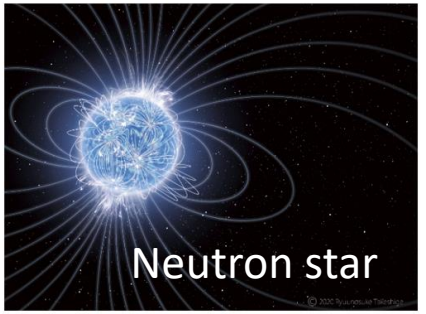
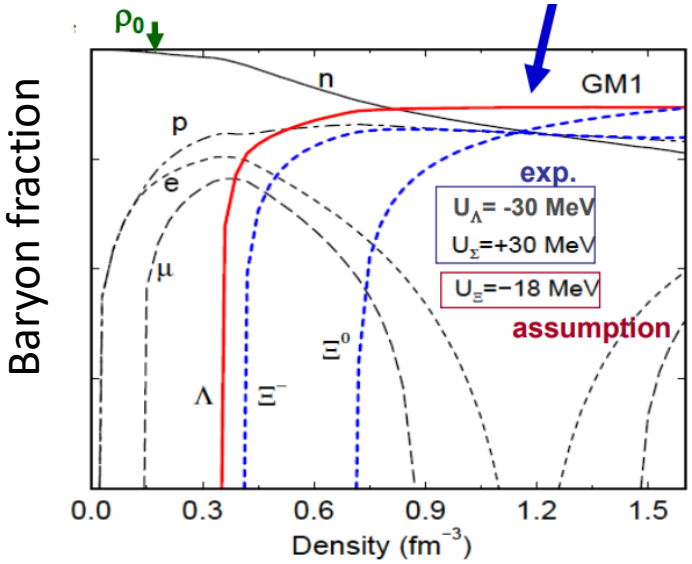
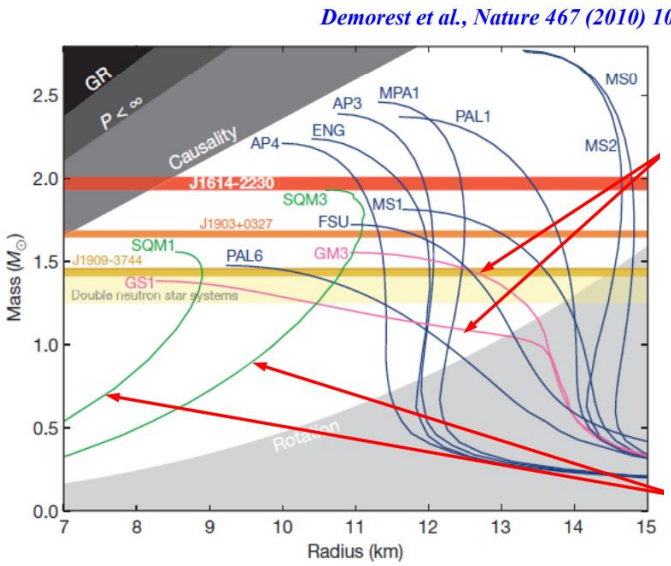
Introduction



- Origin of heavier elements than iron
  - Heavy element production by Neutron star merger
  - Necessary to understand the interior structure of neutron stars





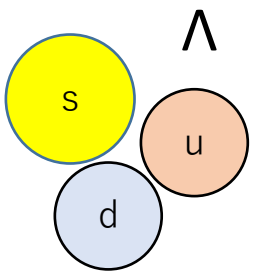
With hyperons

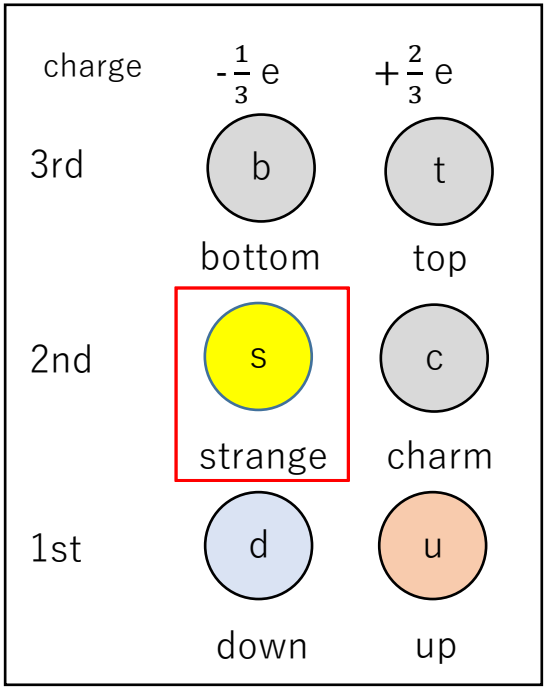
Only quark matter

  - It is expected that hyperons exist in neutron stars

→ Important to study **hypernuclei**, which are nuclei with hyperons

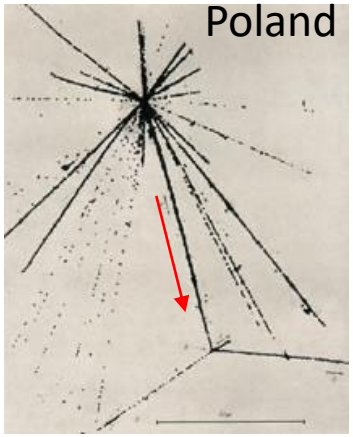
Hypernuclear physics



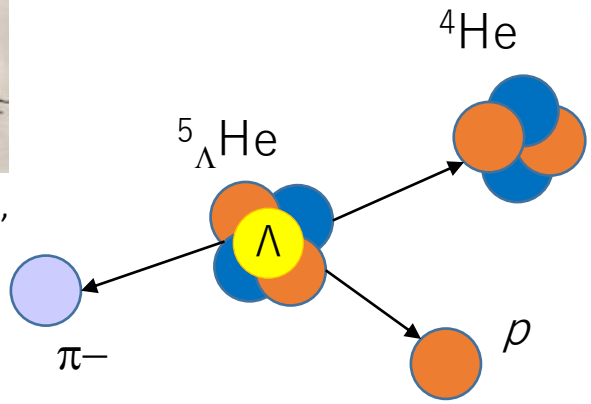


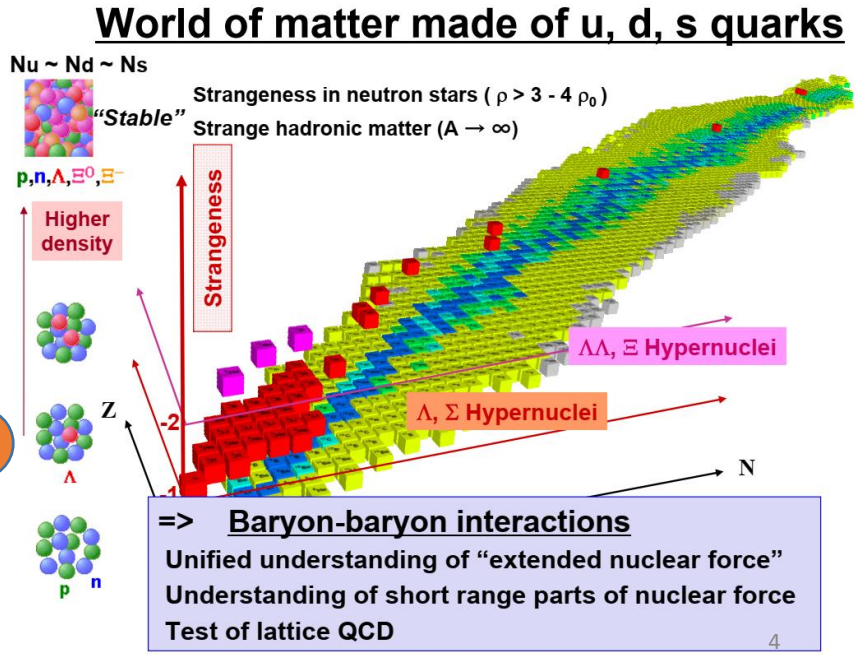
- Hypernucleus
  - Hyperon
    - nucleon with strange quark
  - Nucleus with hyperon

Discovery of hypernuclei

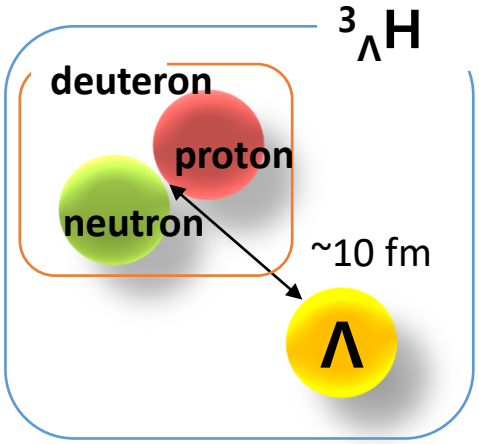


M. Danysz and J. Pniewki,
Phil. Mag. 44, 348(1953)



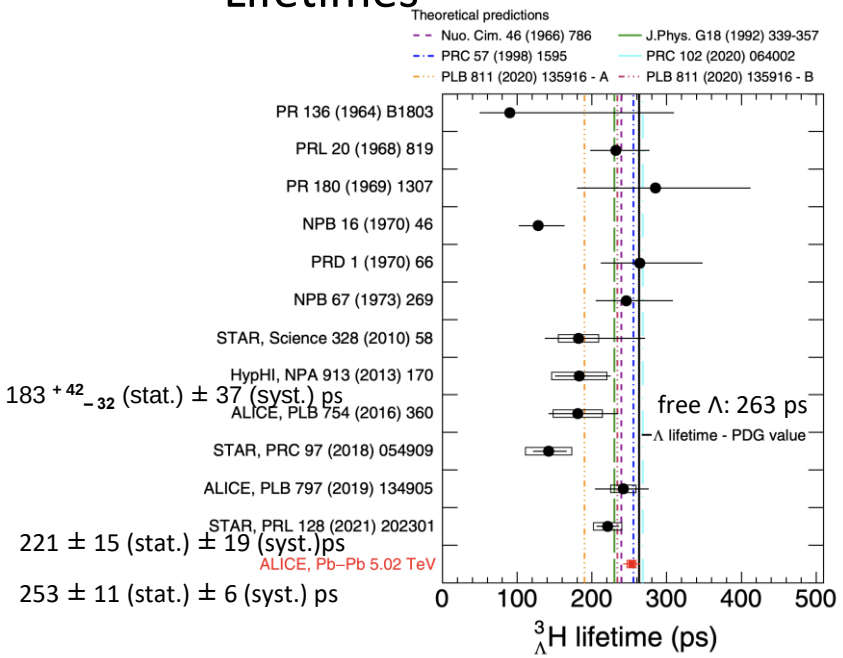


Hypertriton puzzle



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

Lifetimes

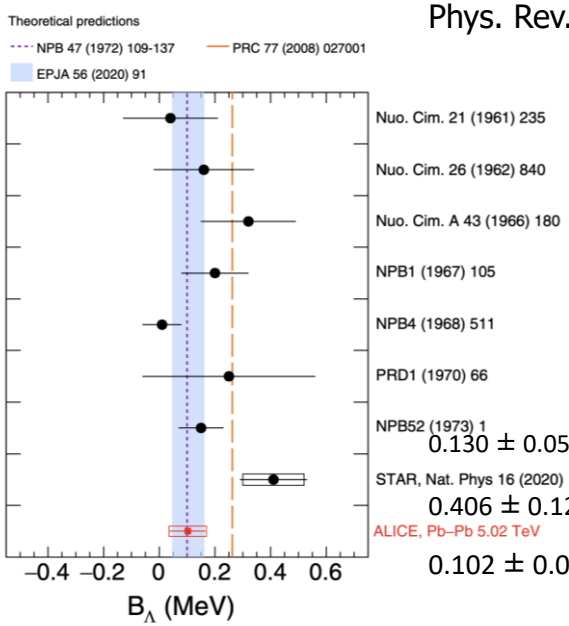


$183\ ^{+42}_{-32}$ (stat.) ± 37 (syst.) ps

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

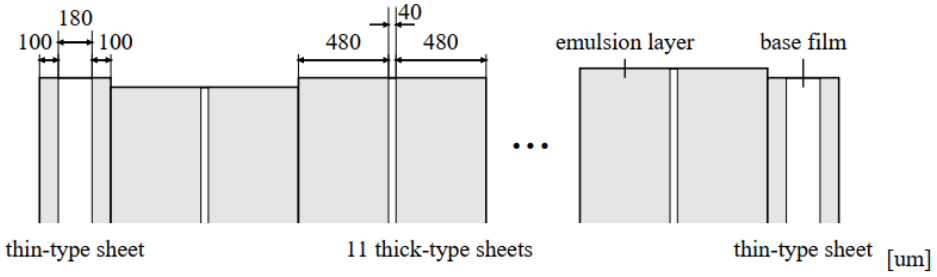
0.102 ± 0.063 (stat.) ± 0.067 (syst.) MeV

Can be different from conventional interpretation

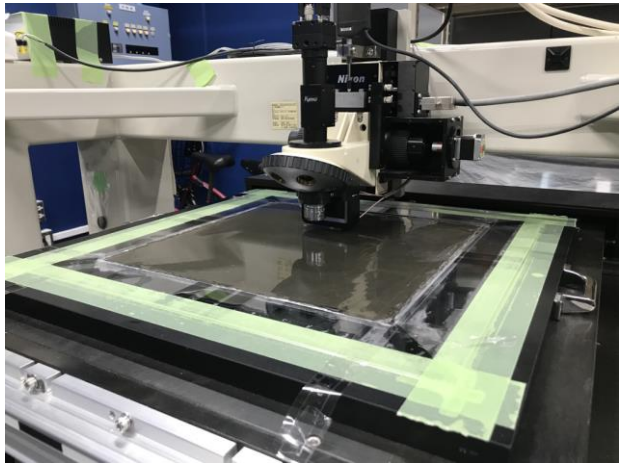
→ Precise measurement is necessary

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

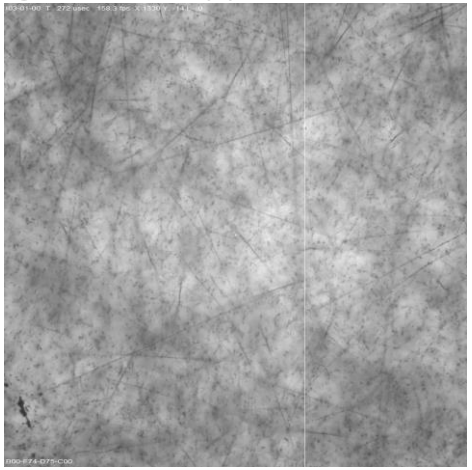
J-PARC E07
Nuclear emulsion



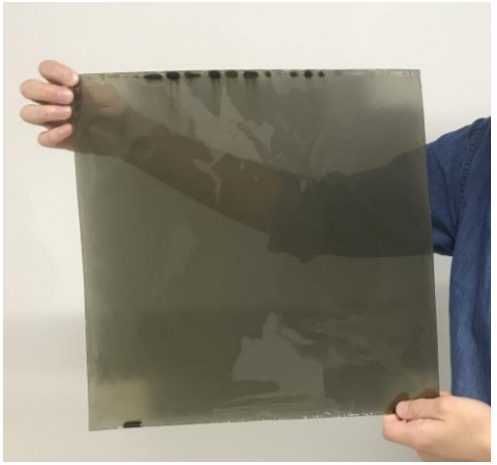
- Feature
  - size of AgBr crystal: 0.2μm
  - weight ratio of Ag to gelatin: 3.16
  - density: 3.53 g/cm^3
  - track density: 10^6 tracks/cm^2
- Hypernuclei recorded
  - millions of single strangess hypernuclei
  - thousand double strangeness hypercnulei



microscope



100 μm



～1300 emulsion sheets

Data size: 140 PB

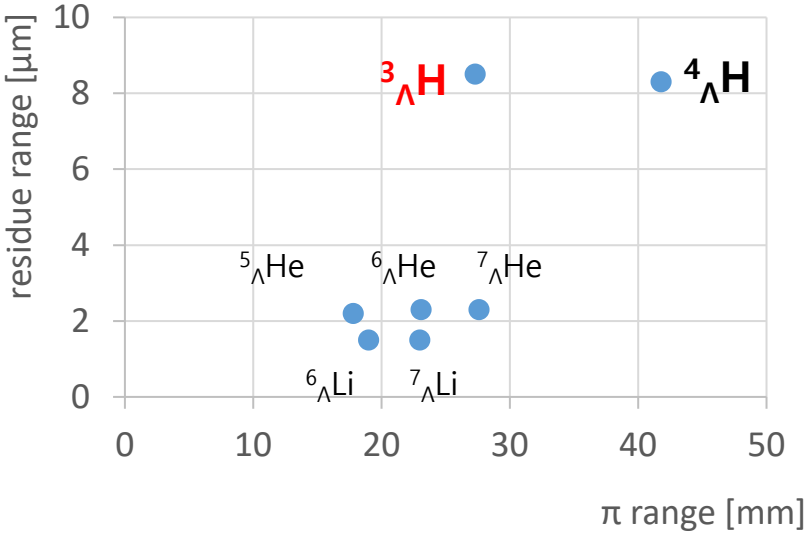
Background: 10^{10} events

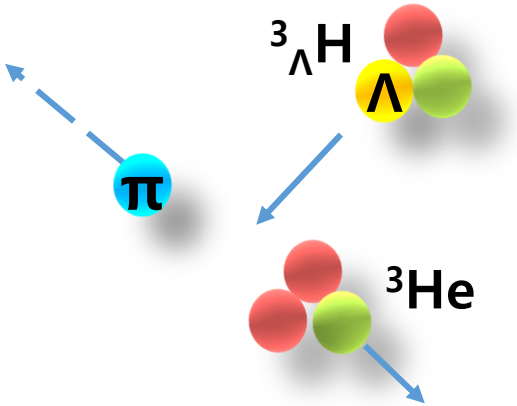
Eye check : ～560 years

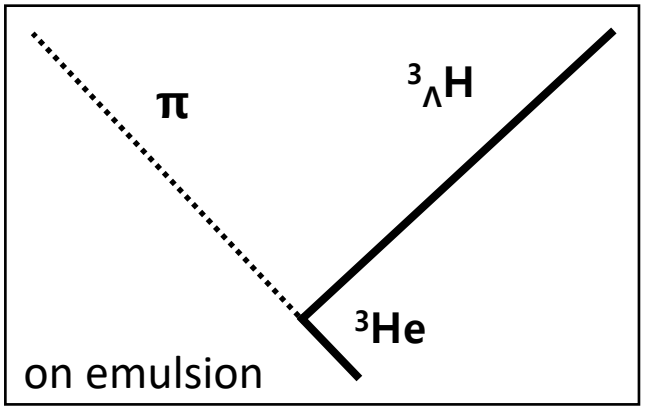
⇒ Machine learning

Hypertriton detection

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





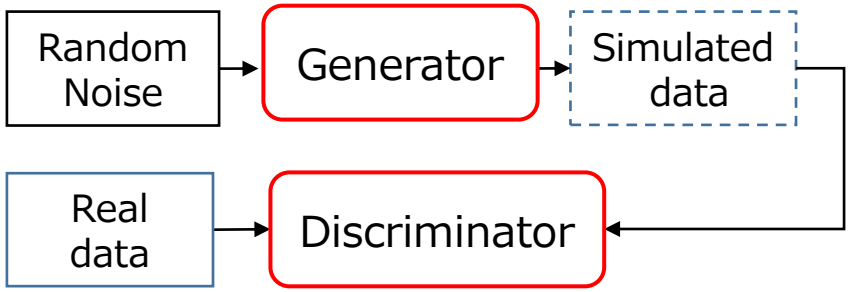


Detection is suitable for machine learning, but no training data
→ Create images from physics simulations

Production of Simulated Image Convert image by GAN

Color = depth to reproduce defocusing

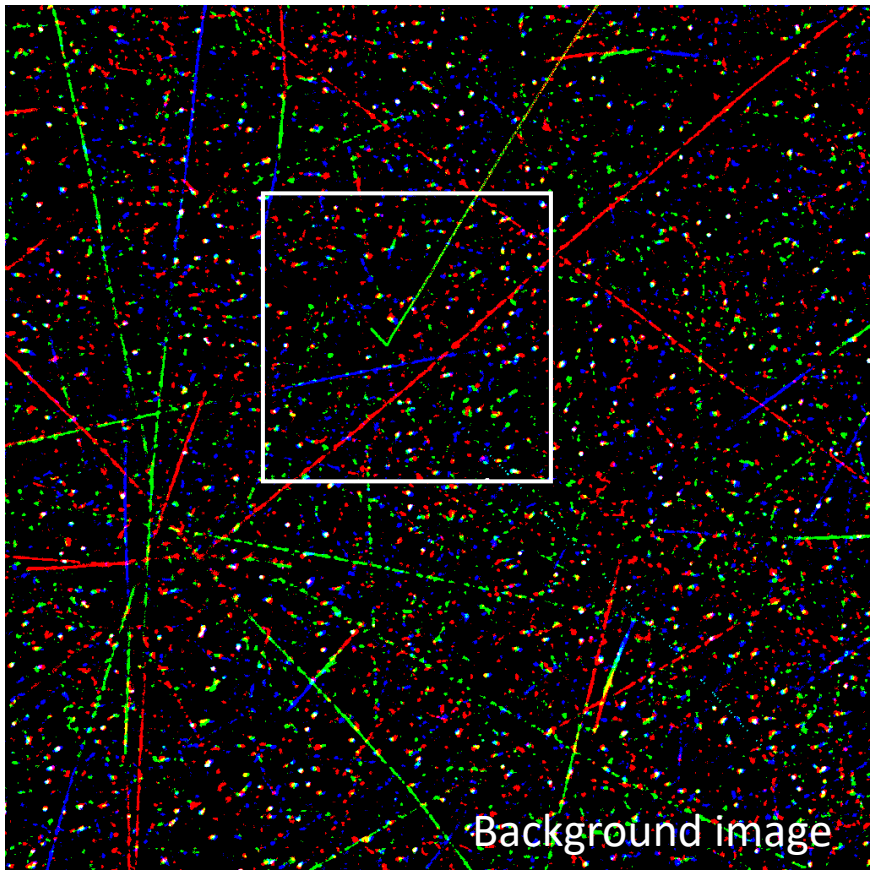
- Generative Adversarial Networks (GAN)
  - Train Generator and Discriminator simultaneously
    arXiv:1406.2661



  - pix2pix Model is applied
    - Image style transformation

    arXiv:1611.07004

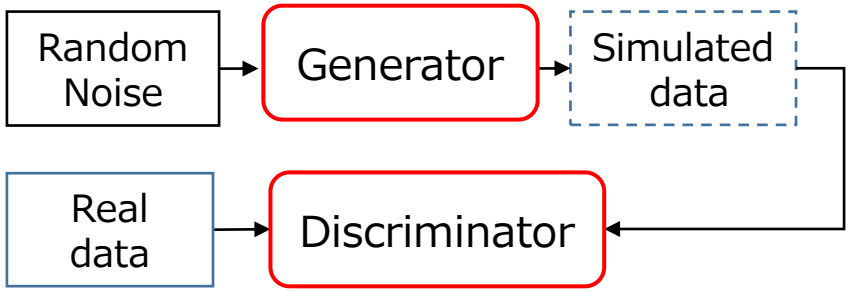
Synthesized line image



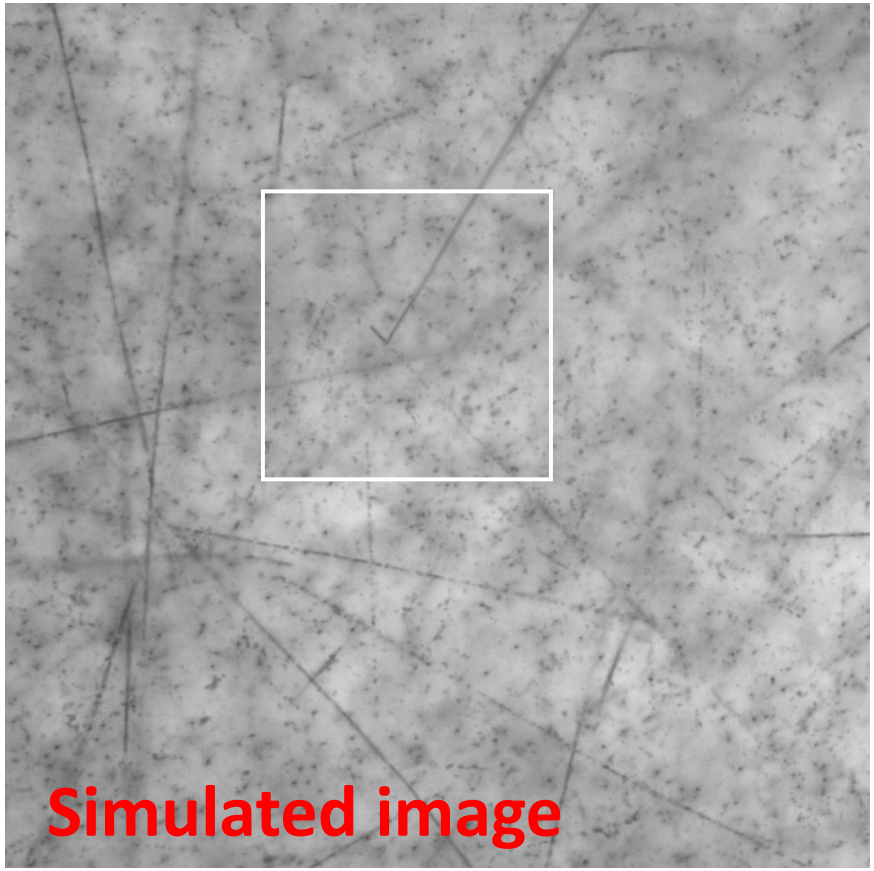
Should convert to microscopic image

Production of Simulated Image Convert image by GAN

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

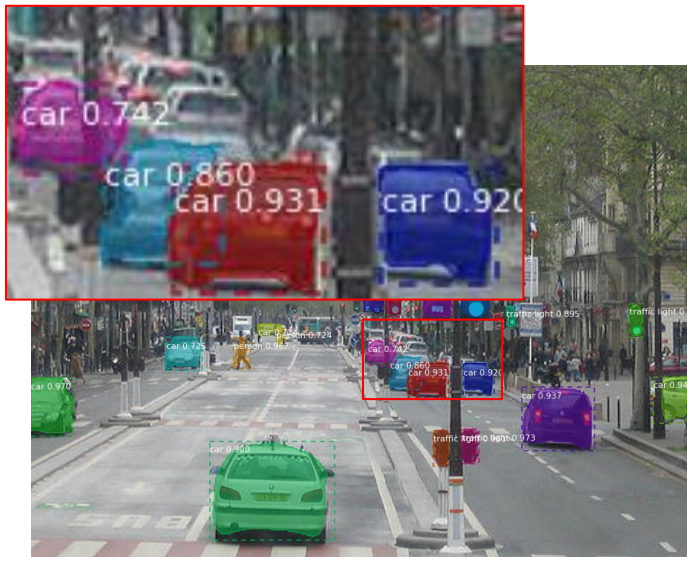


  - pix2pix Model is applied
    - Image style transformation
      arXiv:1611.07004



Input image of training data is obtained

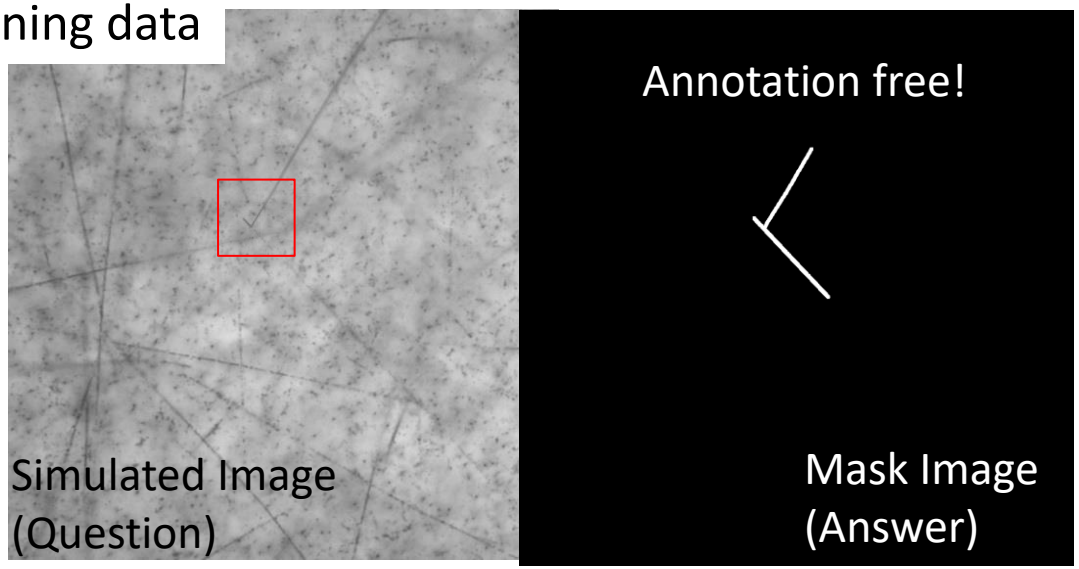
$^{3}_{\Lambda}$H event detection using object detection



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

Mask R-CNN
Object detection model
arXiv:1703.06870

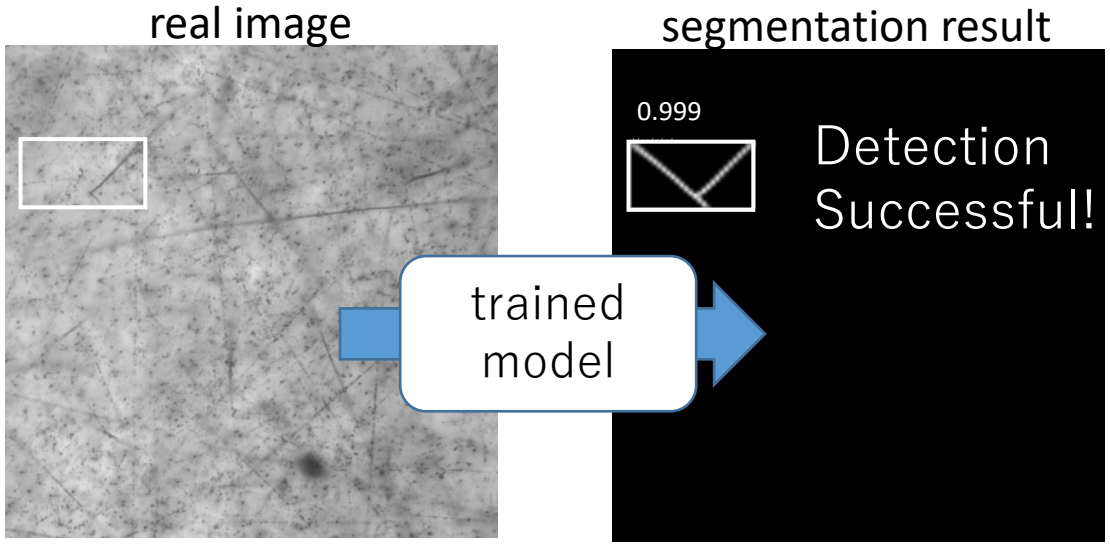
Training data



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

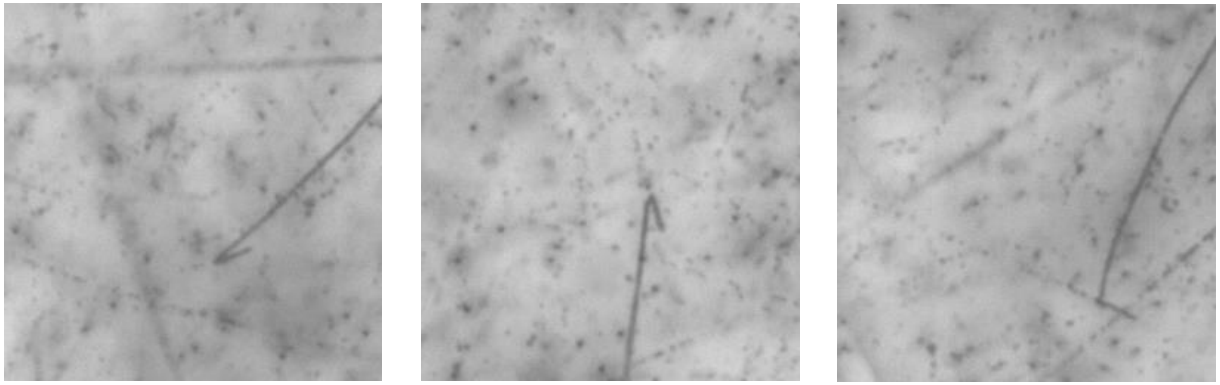
Detection

- Detection with trained model



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

- Examples of detected hypernuclear events

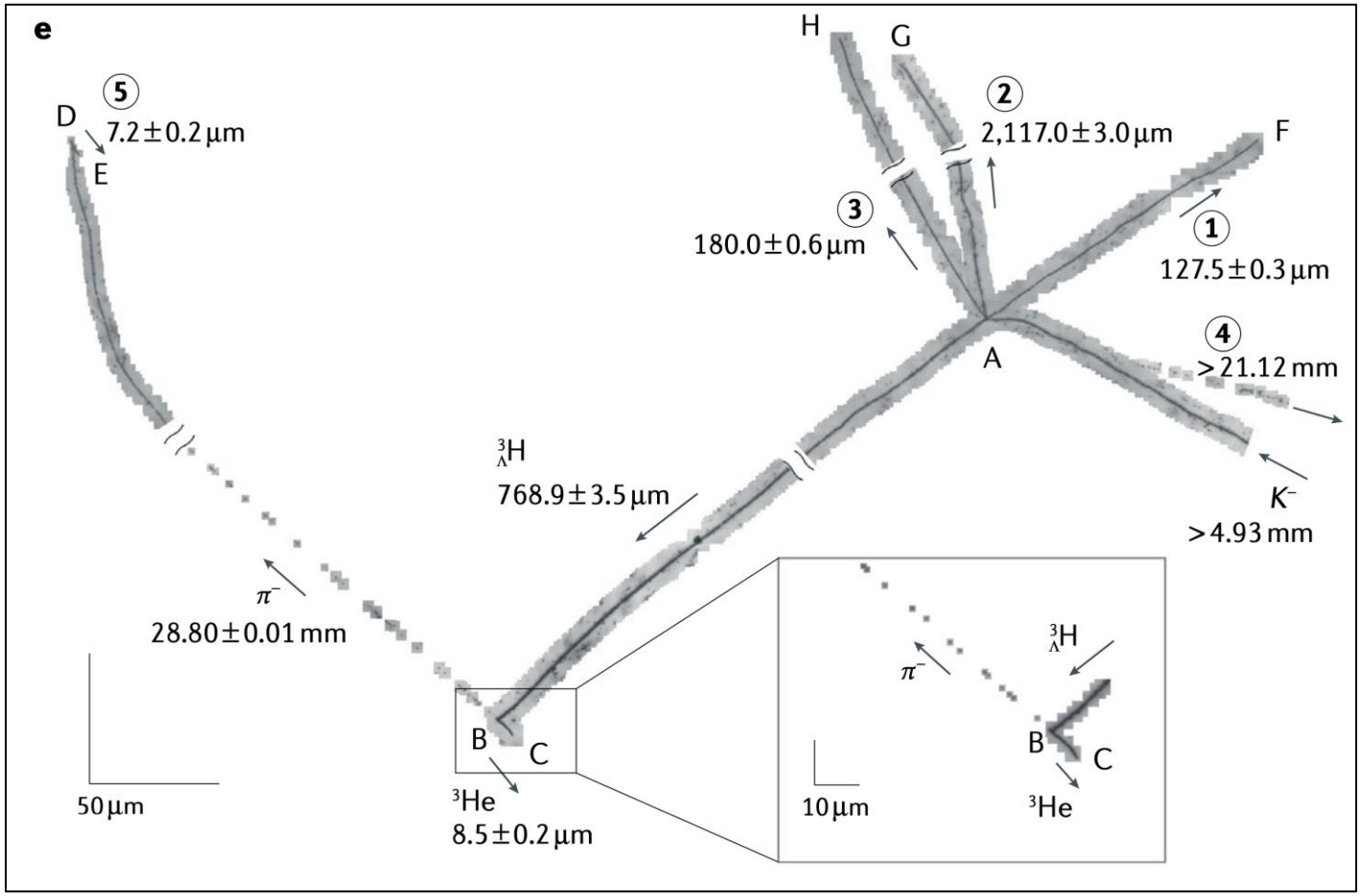


Detected 1075 events
Identified 183 events
in 0.55% of entire data

2023. Aug.

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

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



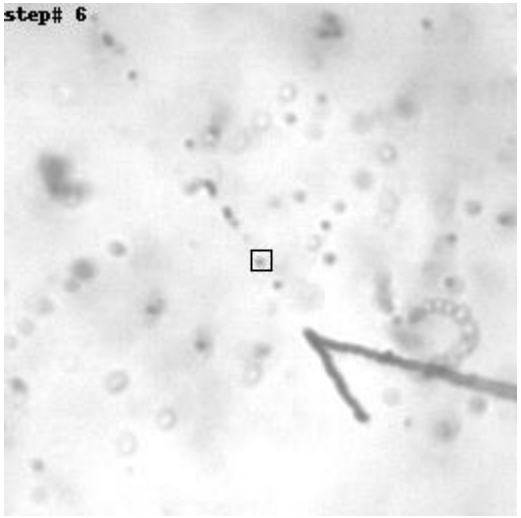
Current observations
$^{3}_{\Lambda}$H : 37, $^{4}_{\Lambda}$H : 146

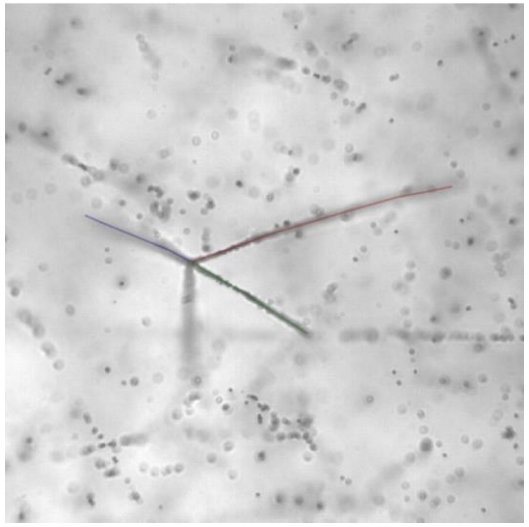
400 events → 30keV(stat.), 30keV(sys.)

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

Automation by Reinforcement Learning

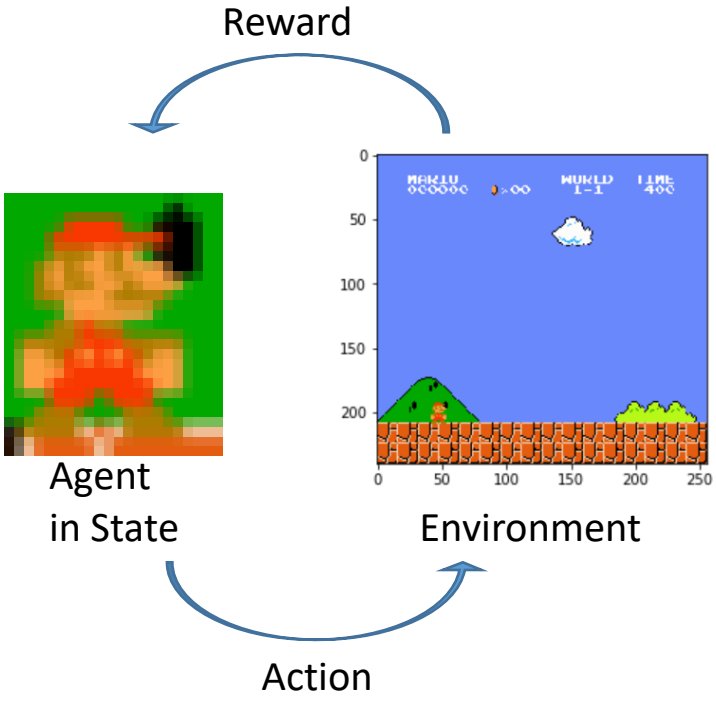
- Automatic tracking of π track
  - π track is too thin to tack by image analysis
  - ~ 6 hours / π track by human eyes
- Automatic tracking of α track
  - For momentum calibration
  - ~400 α/ 1 day / hypernuclear event by human hands





Reinforcement learning

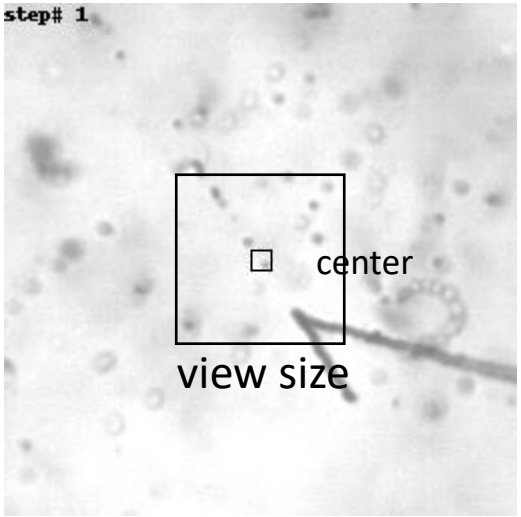
- Overview
  - One of three categories of machine leaning technique
  - Learn to Maximize total reward
    - like how a baby learns
  - Game playing is applied mainly
  - Suitable to optimize a route

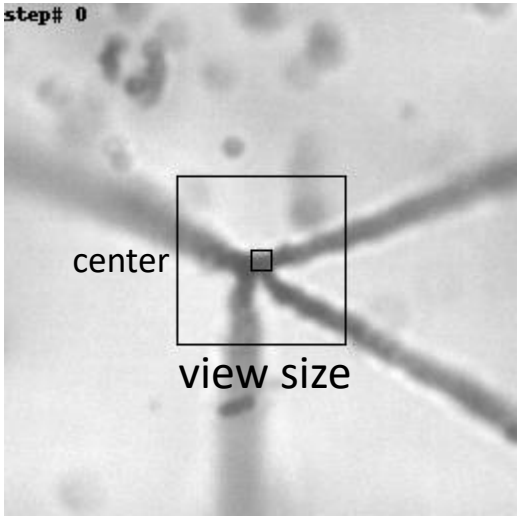


Cleaning robot plans a route

Automation by Reinforcement Learning

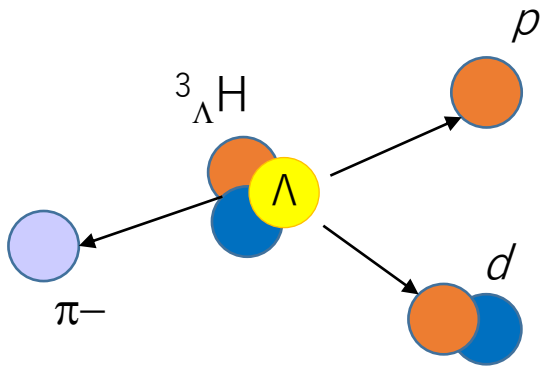
- Automatic tracking of π track
  - π track is too thin to tack by image analysis
  - ~ 6 hours / π track by human eyes
- Automatic tracking of α track
  - For momentum calibration
  - ~400 α/ 1 day / hypernuclear event by human hands

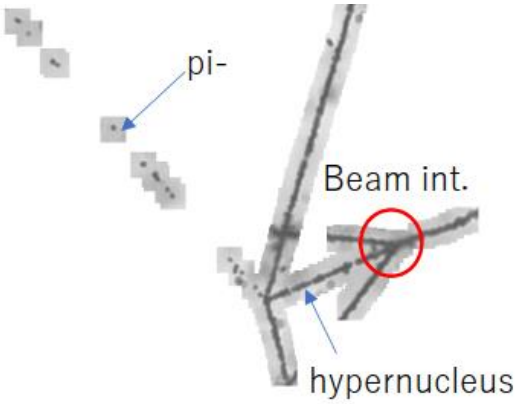




Single hypernuclear search

- 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





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

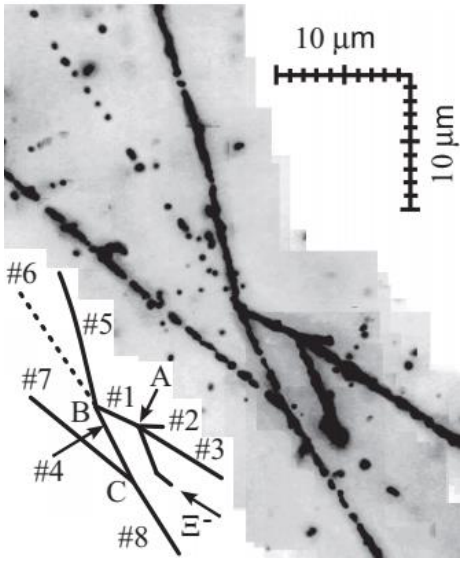
12 solutions remain...

1. ${}^{8}_{\Lambda}\mathrm{He} \rightarrow {}^{6}\mathrm{He} + d + \pi^{-}$
2. ${}^{5}_{\Lambda}\mathrm{H} \rightarrow p + p + \pi^{-} + 3n$

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

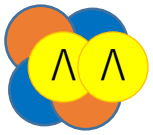
Double hypernuclear search

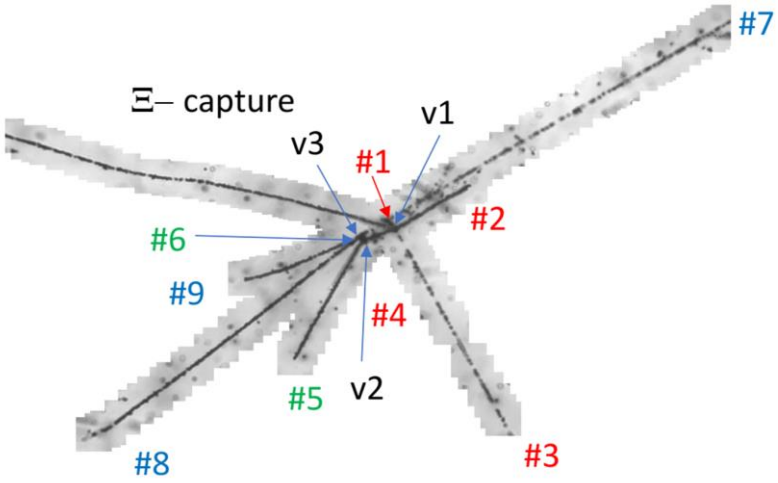
- Double hypernuclear event
  - Observe new double hypernuclei
  - Increase statistics of known double hypernuclei
- ${}^{6}_{\Lambda\Lambda}$He detection as a first step



KEK E373 experiment
H. Takahashi *et al.*
Phys. Rev. Lett. **87**, 212502 (2001)

${}^{6}_{\Lambda\Lambda}$He



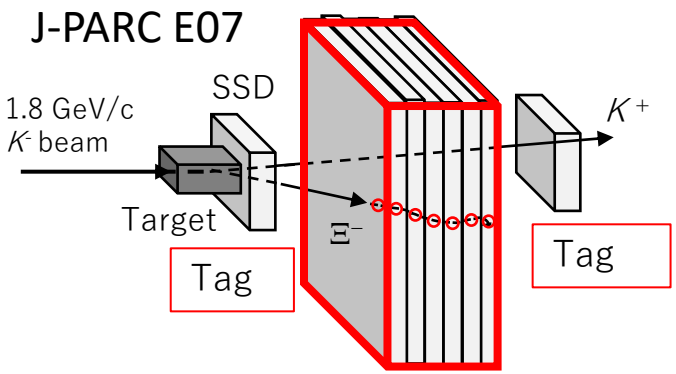


produced by Ξ- capture

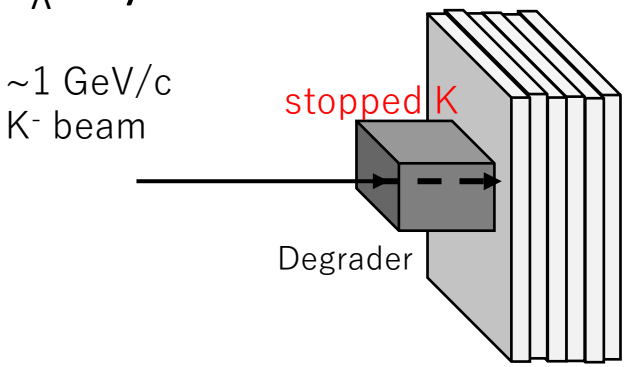
Searched region:
0.03% of entire data in 2023 Mar.
→ 0.2% currently searched in 2023 Aug.
but no other clear event observed yet

To be summarized in Ph.D thesis by Yan He
Lanzhou Univ., RIKEN

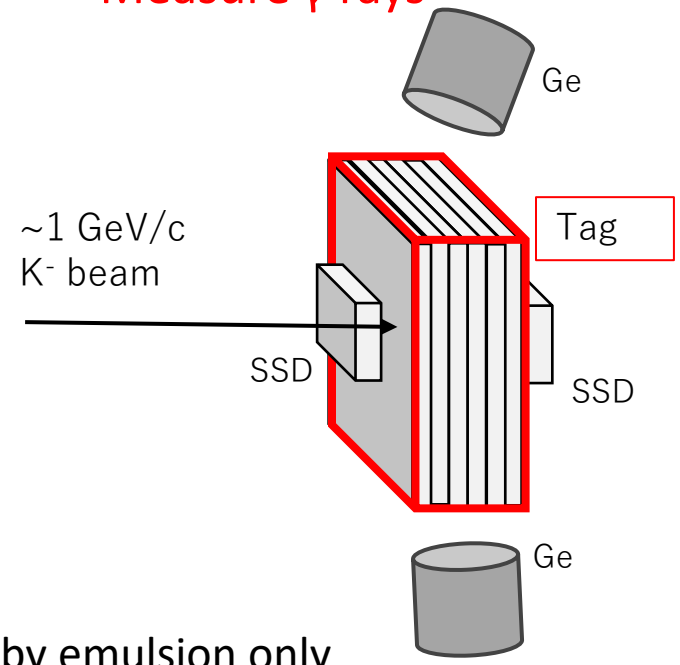
Future experiments at J-PARC



- Binding energy of ${}^{12}_{\Lambda}$C @ stopped K^-
  - Shifted binding energy was used for calibrations in a long time
    - Accuracy was poor in old emulsion exp.
  - 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 ${}^{3}_{\Lambda}\mathrm{H}$ & ${}^{4}_{\Lambda}\mathrm{H}$
  - Single hypernuclear search
  - Double hypernuclear search

→We will provide precise binding energies of various hypernuclei