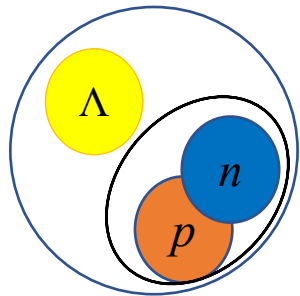# Precise studies of light hypernuclei: with nuclear emulsion and machine learning

Rikkyo University, HENP RIKEN
Ayumi Kasagi

SPICE: Strange hadrons as a Precision tool for strongly InteraCting systEms
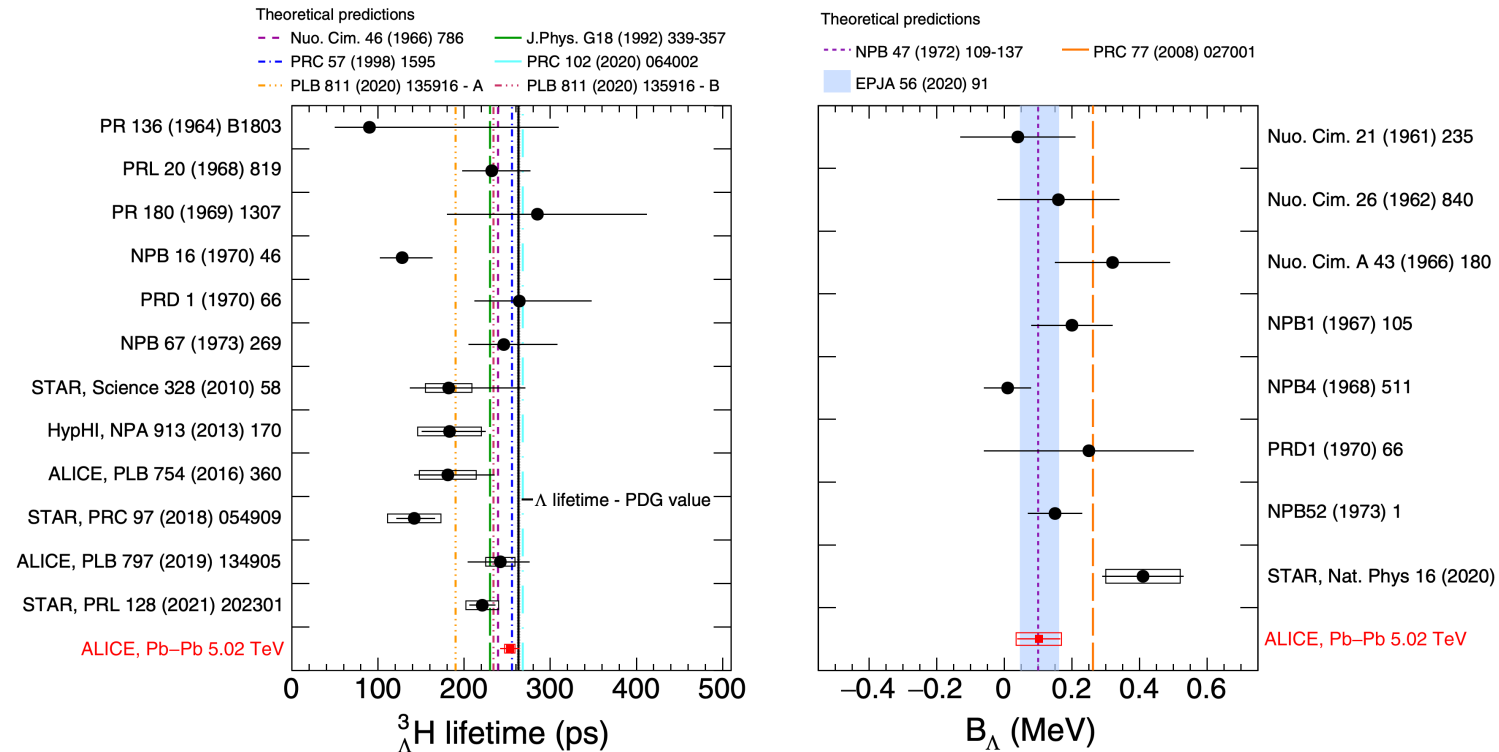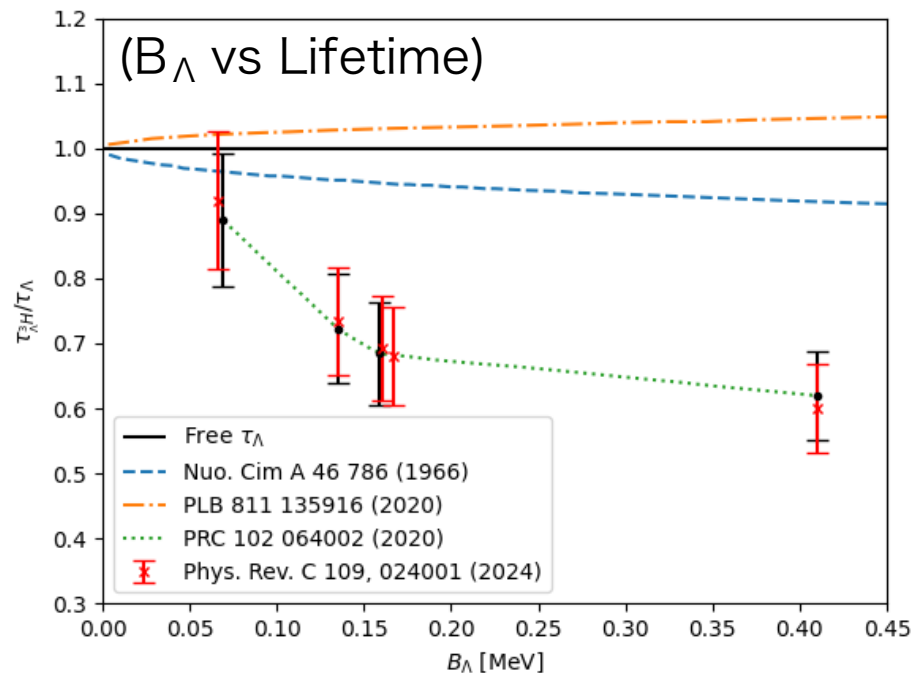
Hypertriton puzzle

$^3_\Lambda$H: Hypertriton (Λpn)

Λ-d : Binding energy
130 ± 50 keV (1973)

τ ($^3_\Lambda$H) $\sim$ 263 ps?

Theoretical calculations

(B$_\Lambda$ vs Lifetime)

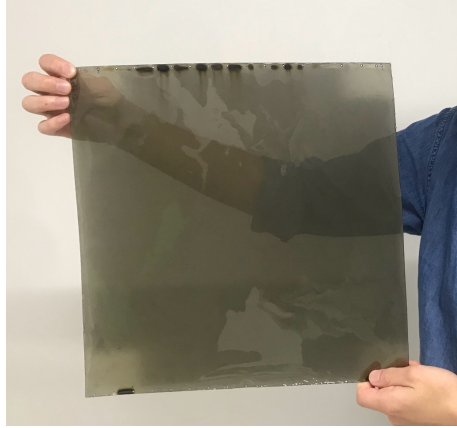

Hypertriton lifetime puzzle → Hypertriton puzzle
・Benchmark on Hypernuclear physics and *YNN* int.

・Large statistics + Background free
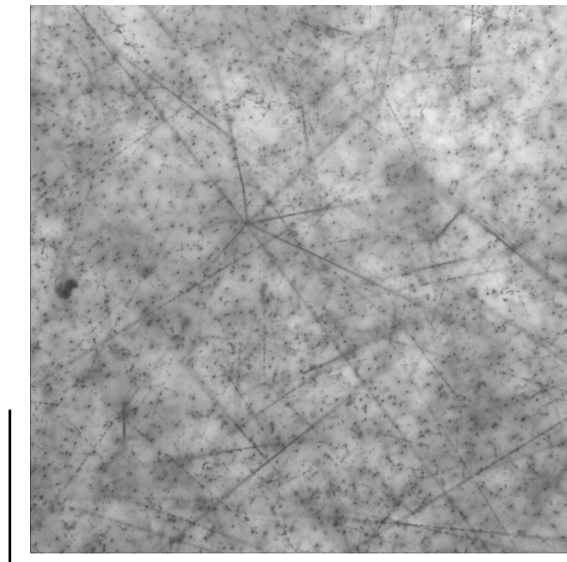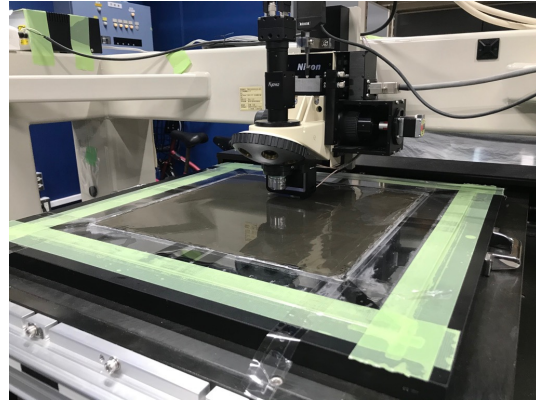・Verification of past emulsion experiments
→ Analysis of J-PARC E07 emulsion

Nuclear emulsion

E07 nuclear emulsion

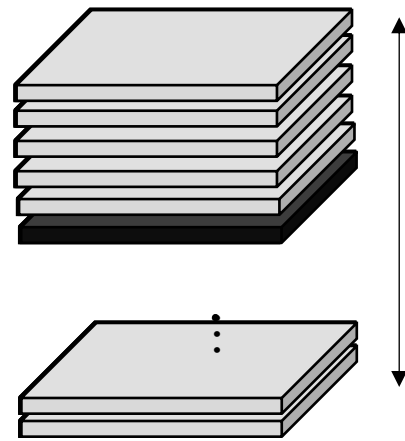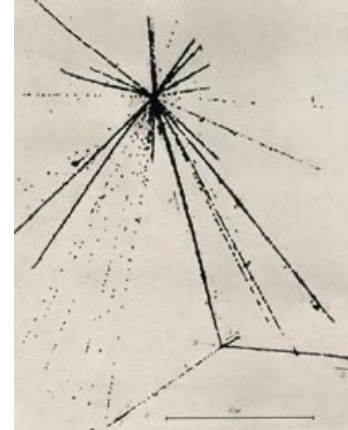(35 cm × 35 cm × 0.6 mm)

100 μm

Microscope system

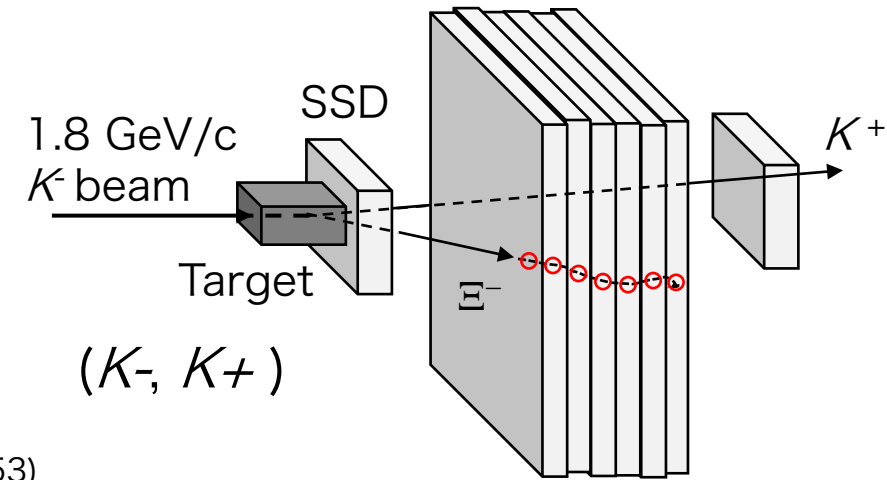

Spatial resolution
sub-μm

Discovery (1953)

Phil. Mag. 44, 348 (1953)

J-PARC E07 (2016-2017) Emulsion-Counter hybrid method

1.8 GeV/c
K^- beam

SSD

Target

Ξ^-

K^+

($K-$, $K+$)

Double-strangeness candidates: 33

$_{\Lambda\Lambda}$Be

$\Xi^- - {}^{14}$N

10 μm

10 μm

10 μm
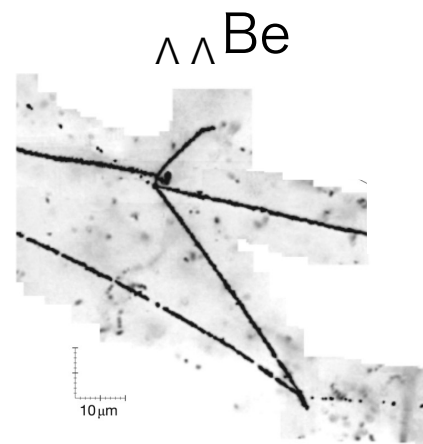
H. Ekawa et al., PTEP, (2019)
A.N.L. Nyaw et al., BSPIJ, (2020)
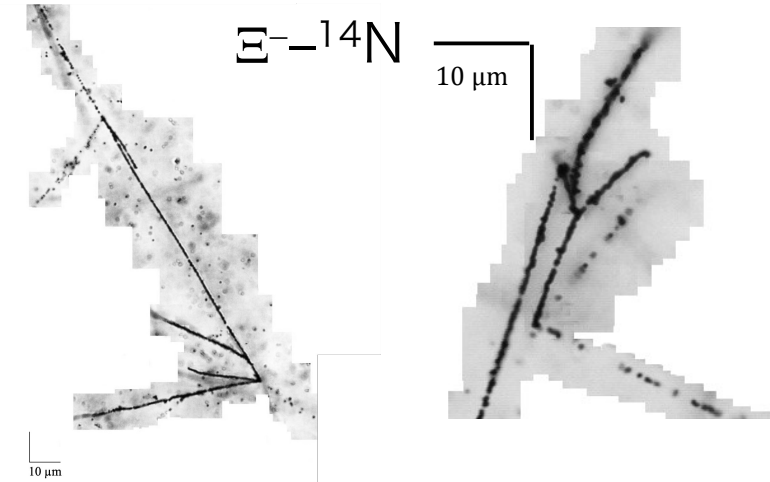
S. H. Hayakawa et al., PRL, (2021)
M. Yoshimoto et al., PTEP, (2021)

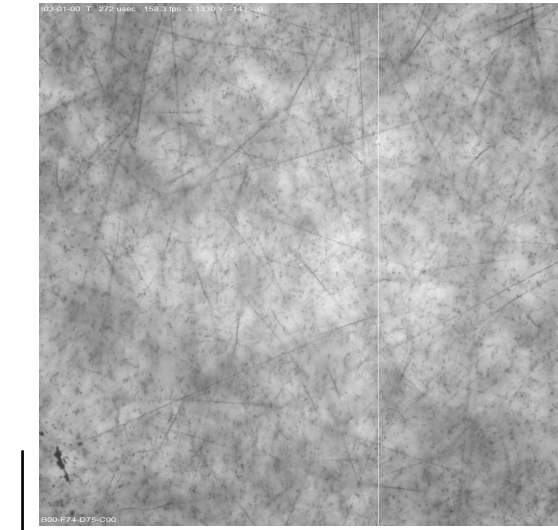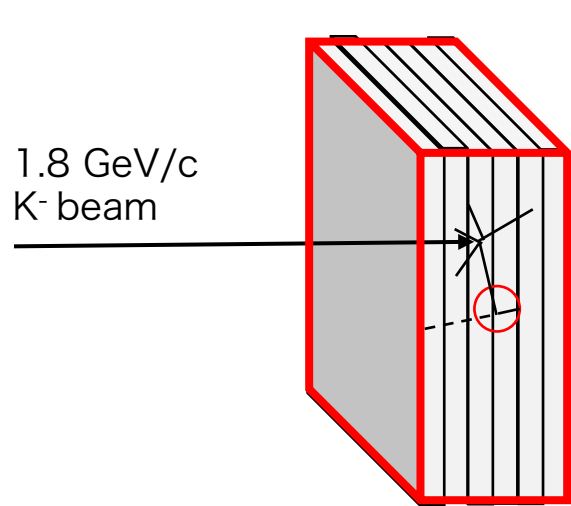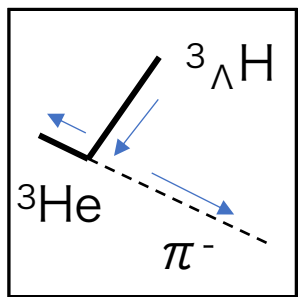$S = -1$: 10^6 events (3 <= A <= 15)
$S = -2$: 10^3 events

1.8 GeV/c
K⁻ beam

100 μm

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

$^3_\Lambda H$

^3He

π^-

Store images
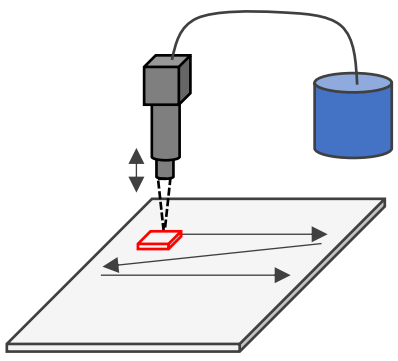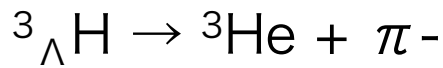
Event search

Vertex picker: Image processing

J. Yoshida, et al., N.I.M A, 847 (2017) 86-92

Background events

Cross   Fragmentation α decay
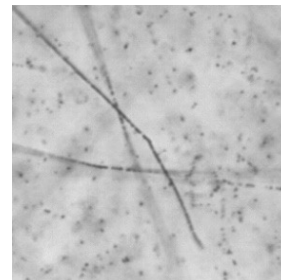
Data size: 140 PB
Detected: 10^9
Classification: ~560 years

→ Appling Machine-Learning techniques

Generating training data with ML
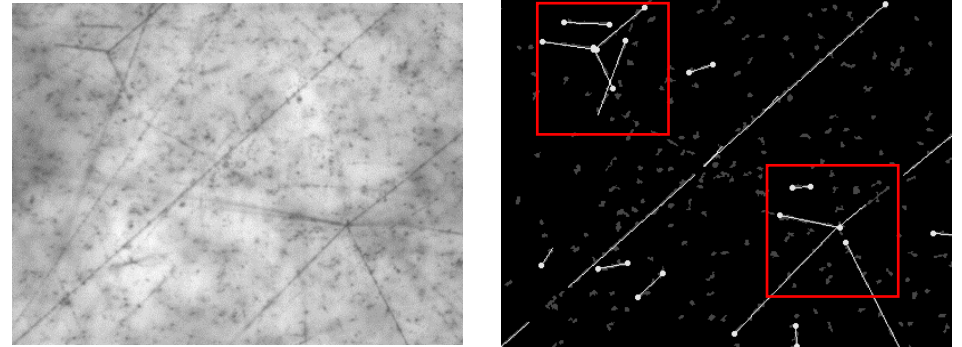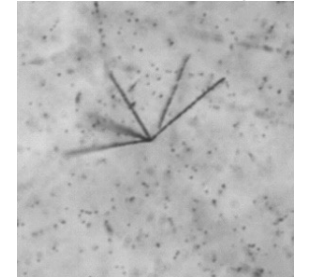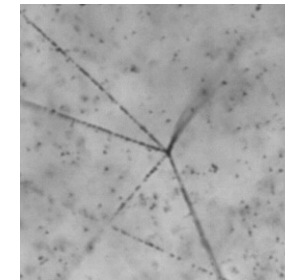
Training data for Rare-event

$^3_\Lambda H$

^3He

Λ

n

p

At-rest decay

π^-

(Color = depth)

50 μm
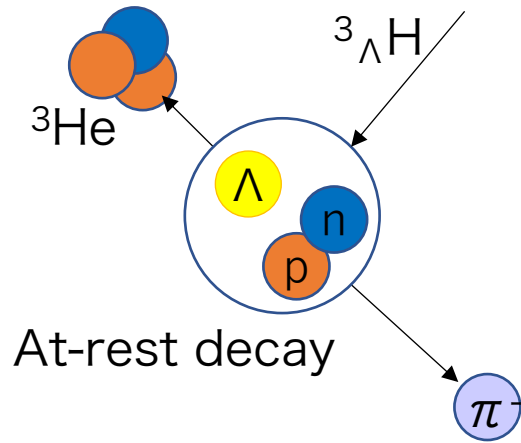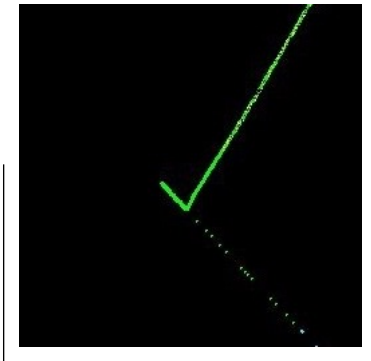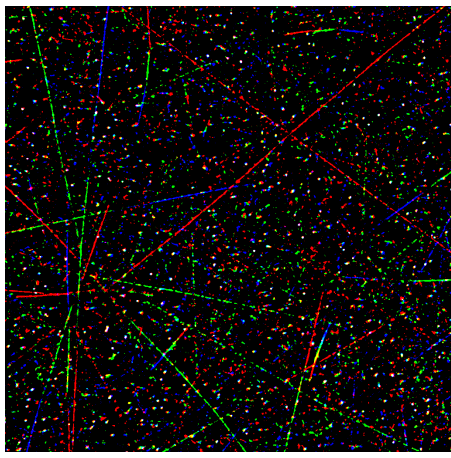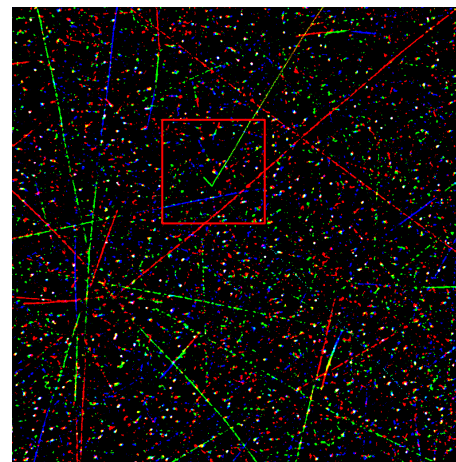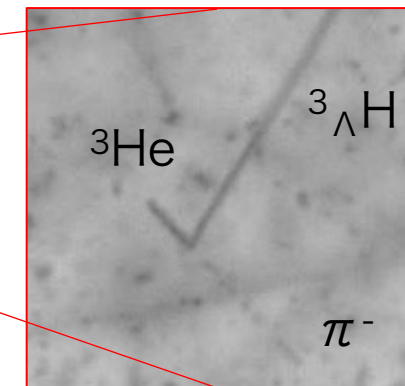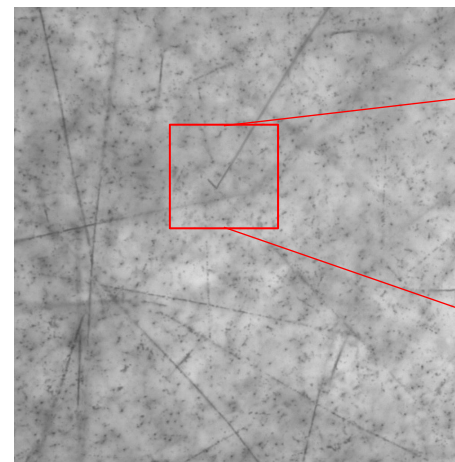
Generative Adversarial Networks (GAN)
Pix2pix: Image-style transform https://phillipi.github.io/pix2pix/

INPUT

OUTPUT

pix2pix

process

Background

Mix

50 μm

Simulated image

^3He

$^3_\Lambda H$

π^-
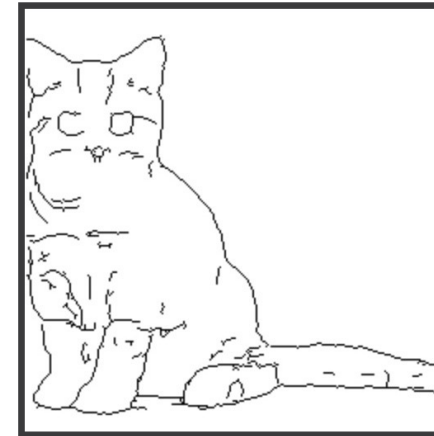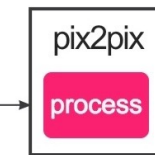
Object detection model for $^3_\Lambda$H events

Object detection (Mask R-CNN)

Training data

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

Real image

Trained model

Detected

T.R Saito et.al, Nature Rev. Phys. **3** 12, 803-813 (2021)
A. Kasagi et.al, Nucl. Instrum. Meth. A 1056 (2023)

Our training data (Simulation + pix2pix)

Without annotation

50 μm

C

π^- $^3_\Lambda$H

10 μm ^{3}He

$^3_\Lambda$H   A
                K$^-$

π^- ^{3}He

B

50 μm

Automatic detection
Human load: 1/10^4

Event analysis

Following

Detection (Auto)

50 μm

Calibration: α-particle: 8.785 MeV

Range

h2	
Entries	101
Mean	50.22
Std Dev	1.43
Underflow	0
Overflow	0
Integral	101

χ^2/ndf(ndf=99) : 1.94, Prob : 0.0000
Range : 50.16 ± 0.14 [μm]
S.F. : 1.8748 ± 0.0144

Range [μm]

Entries	49
Mean	2.8e+04
Std Dev	931.2
χ^2 / ndf	0.882 / 3
Prob	0.8298
Constant	15.52 ± 2.92
Mean	2.786e+04 ± 1.984e+02
Sigma	1044 ± 170.9

Entries	101
Mean	4.299e+04
Std Dev	1151
χ^2 / ndf	6.083 / 6
Prob	0.4139
Constant	26.4 ± 3.5
Mean	4.3e+04 ± 1.2e+02
Sigma	1150 ± 101.7

$^3_\Lambda$H

$^4_\Lambda$H

π^- length [μm]

Line fitting

He4

Calibration

Range : 49.82 ± 0.09 [μm]
S.F. : 1.8748 ± 0.0099

Kinetic energy [MeV]

Analyzed

Range [μm]

dX^2+dY^2

^{212}Po
^{214}Po
^{228}Th
^{226}Ra
HT

KE [MeV]

Range[μm]

From 0.6% of E07 emulsion data
$^3_\Lambda$H: 49, $^4_\Lambda$H: 101

ΔK.E < ±10 keV

$^4_\Lambda H \rightarrow\ ^4He + \pi$-
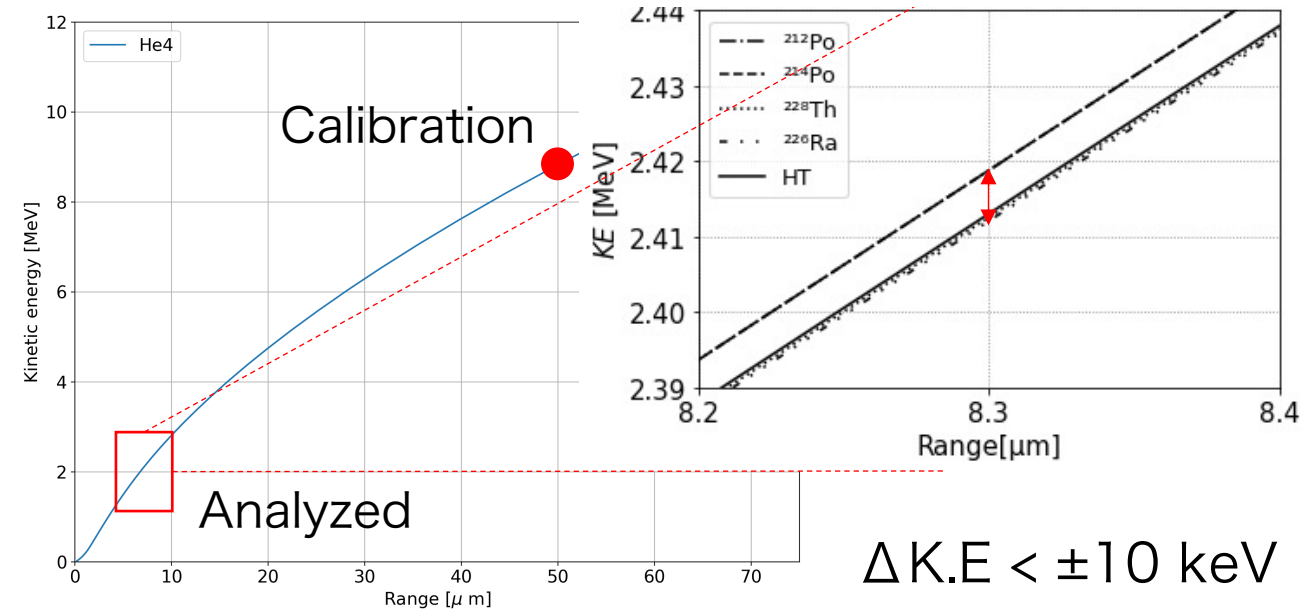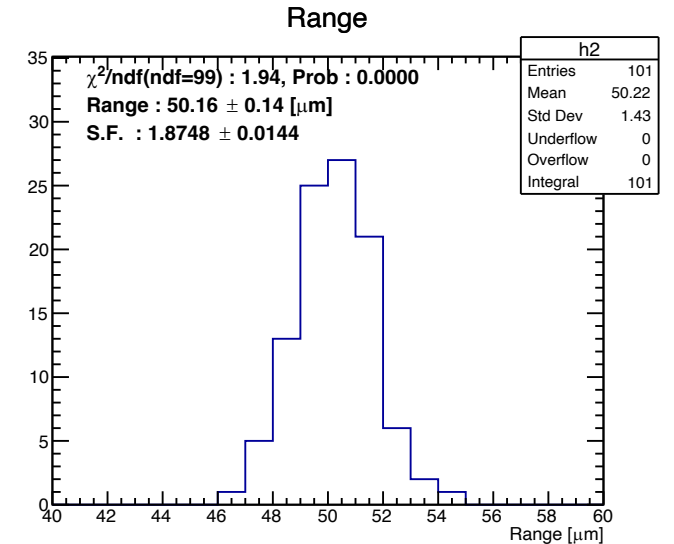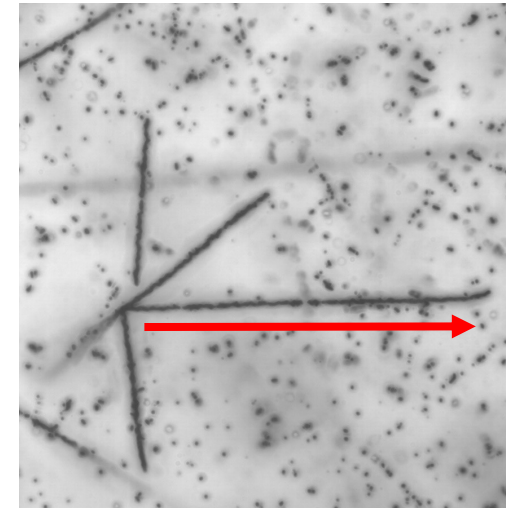
132.650 ± 0.345 MeV/c
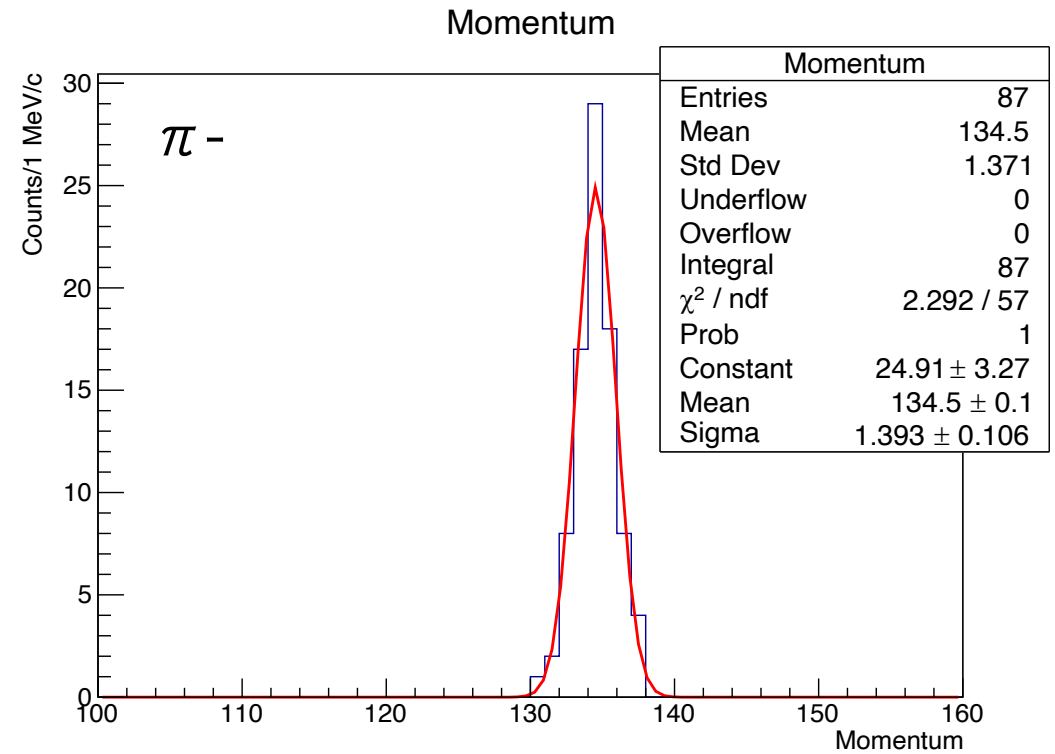
134.453 ± 0.149 MeV/c

Experiment in 1960s:
· Calibrated with proton ($\Sigma \rightarrow p + \pi^0$)
· Λ-hyperon was analyzed in the same system

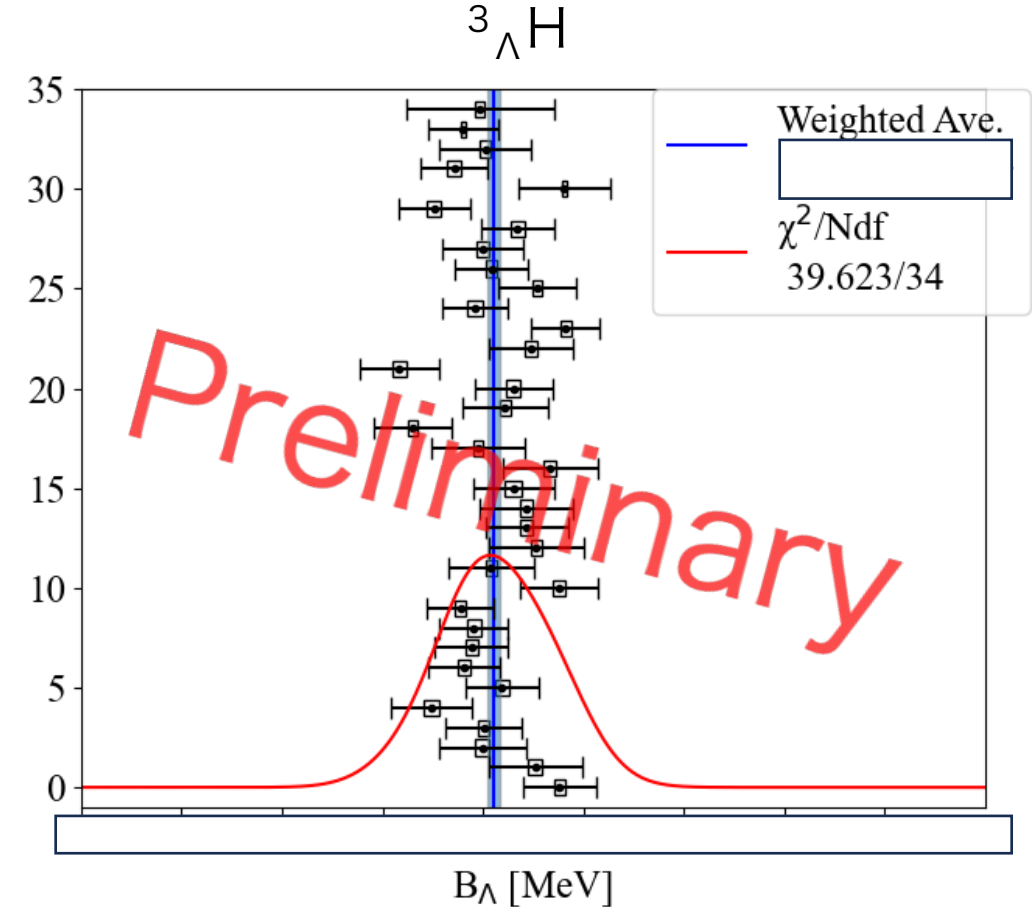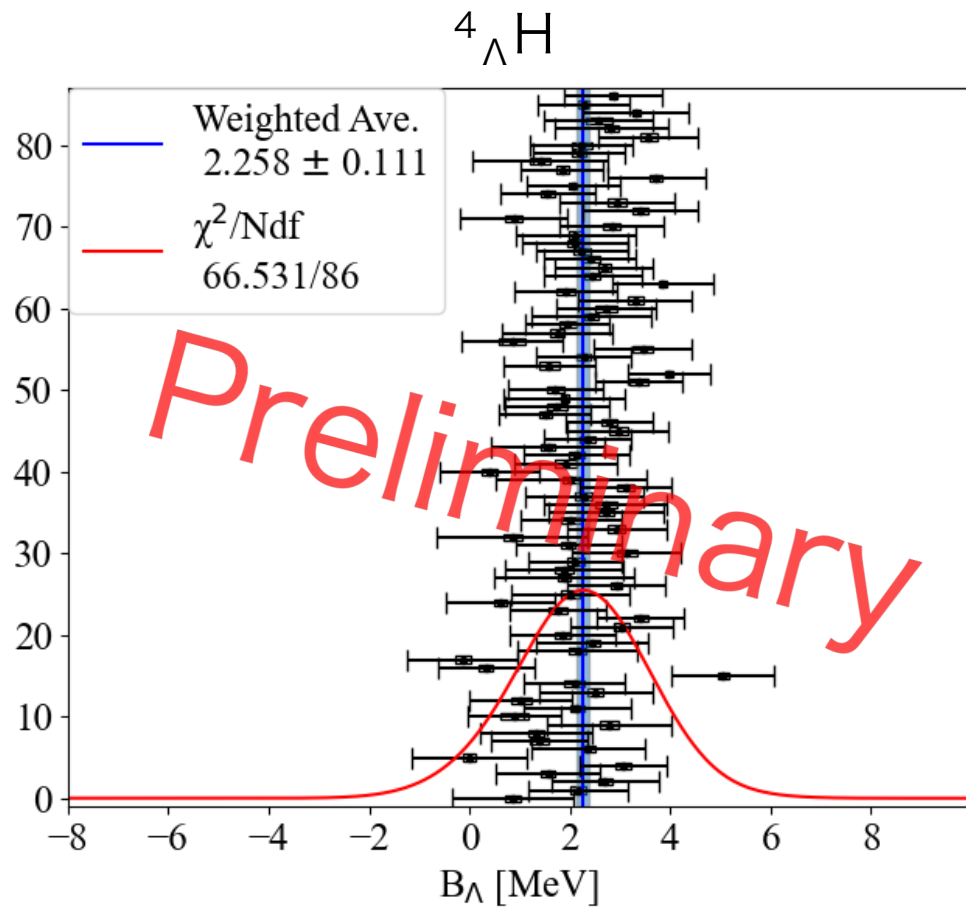Investigation: Ongoing
Result of NAGARA: to be revised
($^6_{\Lambda\Lambda}He \rightarrow\ ^5_\Lambda He + p + \pi$-)

Factor on momentum: Ref. from MAMI-C ($^4_\Lambda$H $\rightarrow$ π- + ^{4}He)
P_{π^-} = 132.851 ± 0.011 (stat.) ± 0.101 (syst.) MeV/c https://doi.org/10.1016/j.nuclphysa.2016.03.015

$^4_\Lambda$H $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $^3_\Lambda$H

With new techniques and the investigation of R.E
・Statistical errors:$\quad\quad\quad\quad$ 100 keV $\rightarrow$ 30 keV (from 2% data of E07)
・Systematical errors:$\quad\quad\quad\quad$ 100 keV $\rightarrow$ 30 keV

Need for new analysis

Measurements of decay particles

Following (Manual)

Detection (Auto)

50 μm

Expert work and Time consuming

Limitation of object detection model

Double-Λ search (by Yan He)
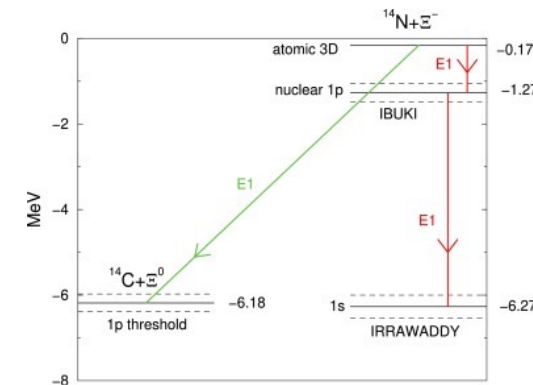

More complicated shapes

S = -1
- *ΛNN*: Hypertriton puzzle: $^{3}_{\Lambda}$H
- Charge symmetry braking(A = 4): $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He
- A = 6 Hypernuclei as $\Lambda\alpha$N : $^{6}_{\Lambda}$He
- Caribration for HIHR in J-PARC: $^{12}_{\Lambda}$C

S = -2
- $\Lambda\Lambda$-ΞN mixing $^{5}_{\Lambda\Lambda}$H, $^{5}_{\Lambda\Lambda}$He, $^{6}_{\Lambda\Lambda}$He
- Ξ_{1s} nuclear state: $^{13}_{\Xi}$B, $^{15}_{\Xi}$C, $^{17}_{\Xi}$N
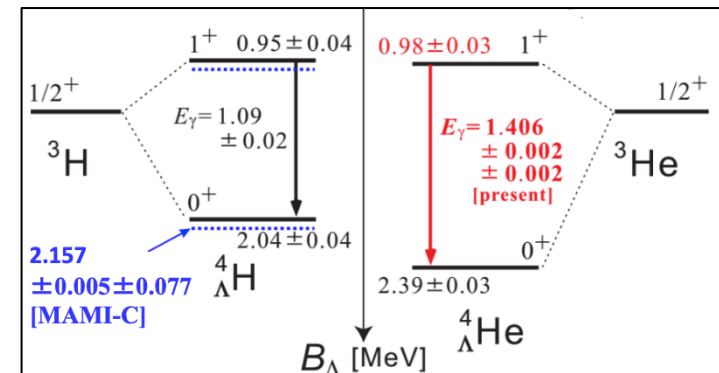
From T.O. Yamamoto-san's slide https://x.gd/YfBTZ

E. Friedeman, A. Gal
PLB **837** 10 (2023)

New developments (ML + Image analysis)

Faster, Efficient and Robust analysis for various type of events
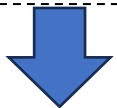
Obtaining raw microscopic image
· High-speed scanning with piezo actuator ✔
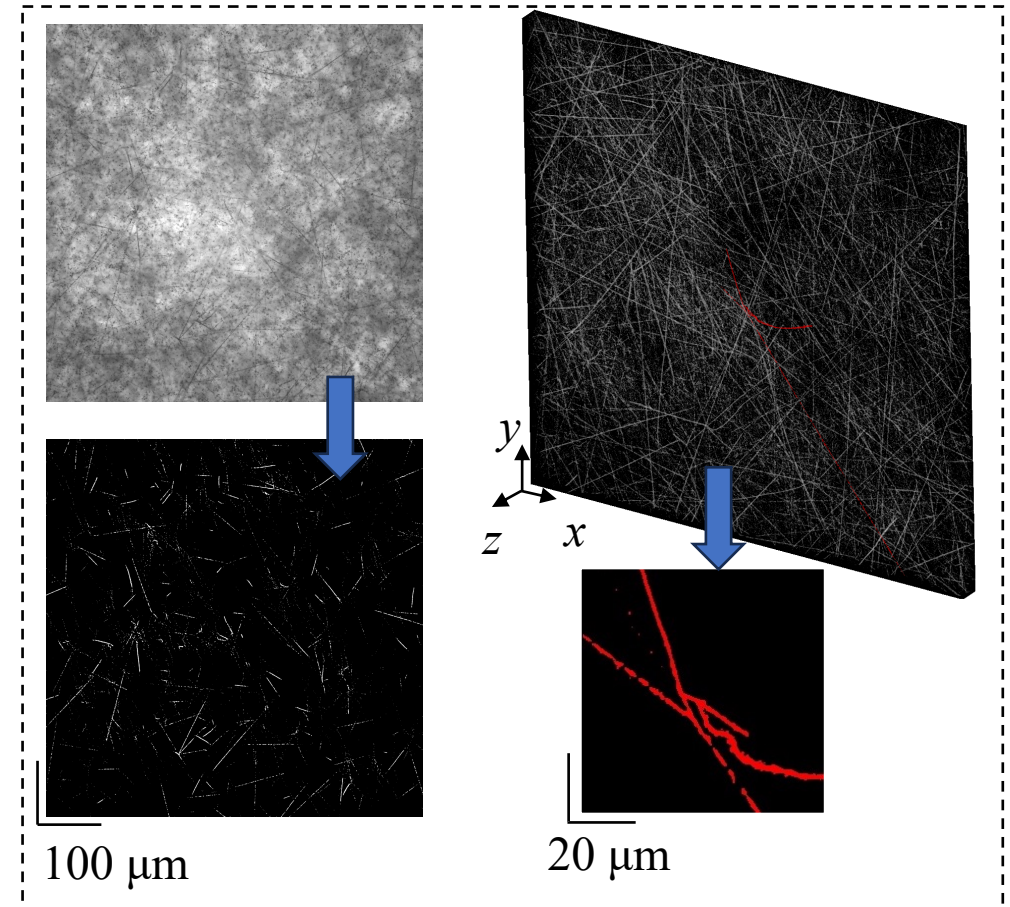
An acknowledgment to Dr. Yoshimoto

Extract Hit pixels
· Machine Learning techniques
  - Creation of training data using simulation ✔
  - Development of Specialized Segmentation model

Reconstruction of tracks
· Image analysis for line segment detection
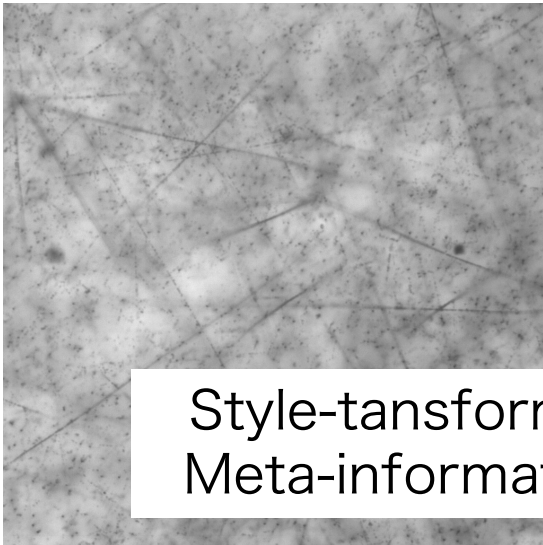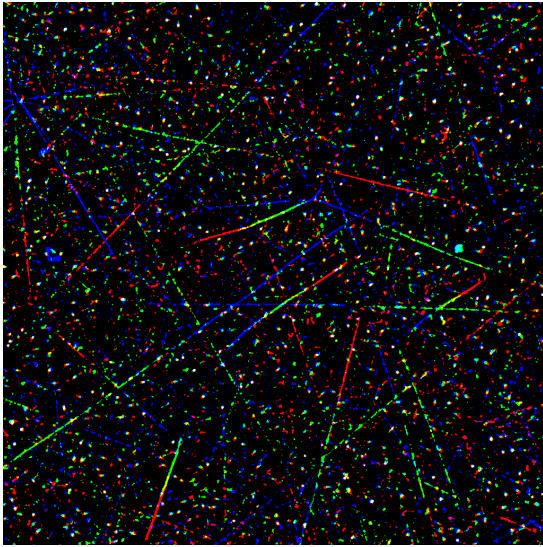 - 2D Gabor filter
  - Connected Component
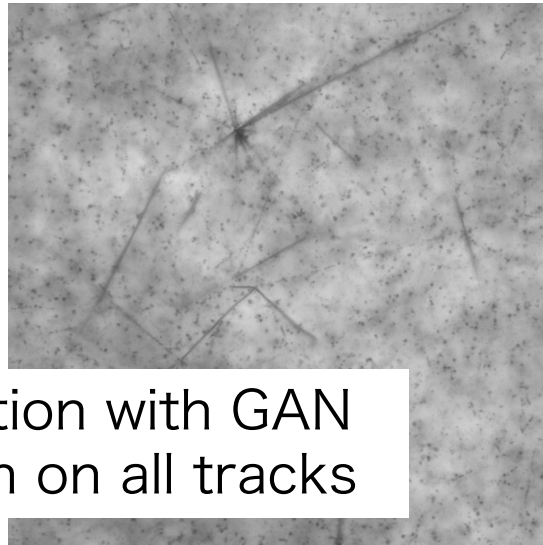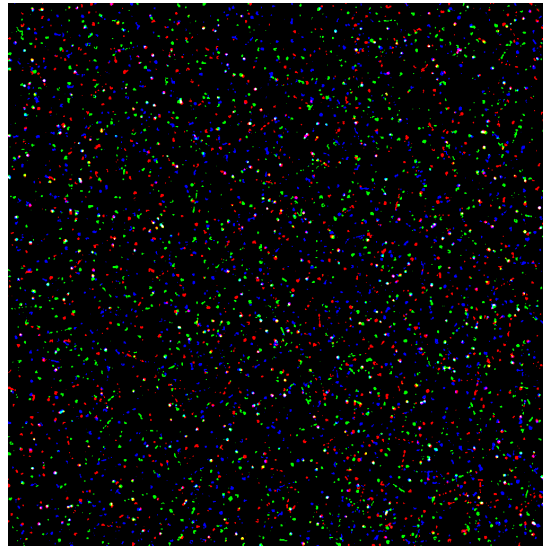
Prof. Yokota, Dr. Shimizu (Gifu University)

100 μm

20 μm

New training data (Geant4 simulation + GAN)

Background(Real)

fog & beam(toy MC)

Unrelated tracks(Geant4)

Phyics process(Geant4)

K- Beam interaction

Hypernuclear decay
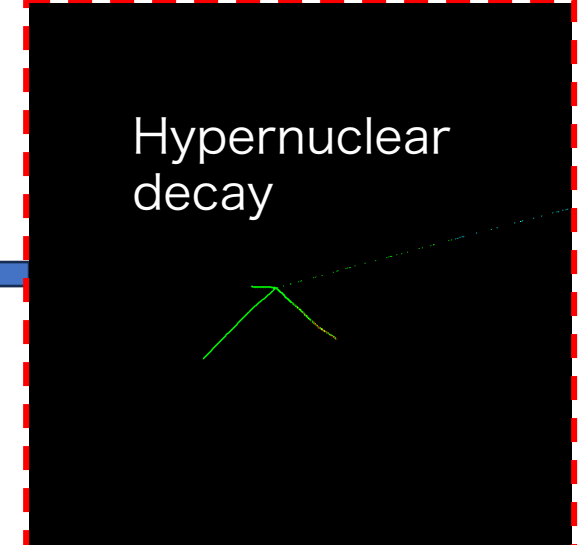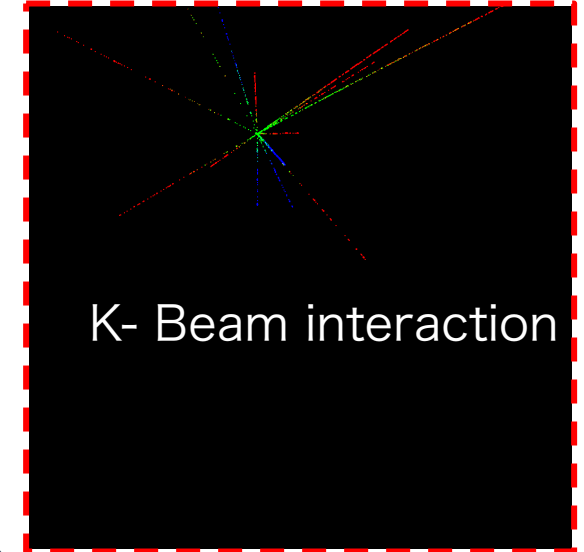
Style-tansformation with GAN
Meta-information on all tracks
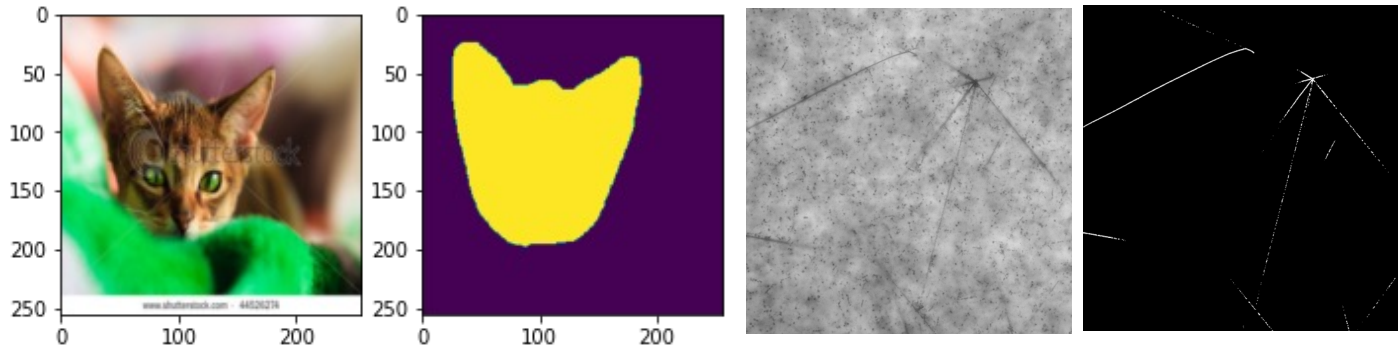
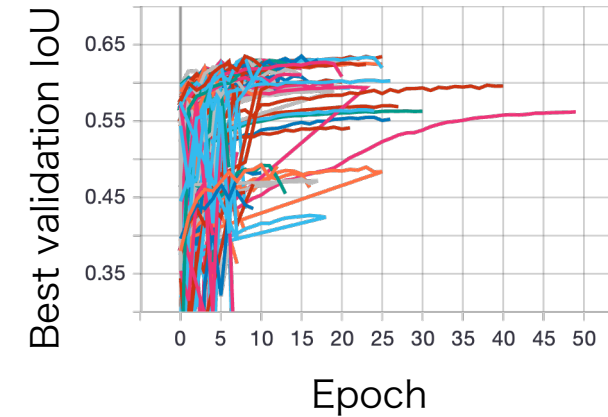# Segmentation task to detect hit infomation

・Binary segmentation (background or track)
・Training from scratch (with 40k surrogate images)

Hyperparameter search with Optuna

IoU	0.659
F1_score	0.795
Accuracy	0.998
Precision	0.748
Recall	0.805

Raw data | Conventional processing | Present work
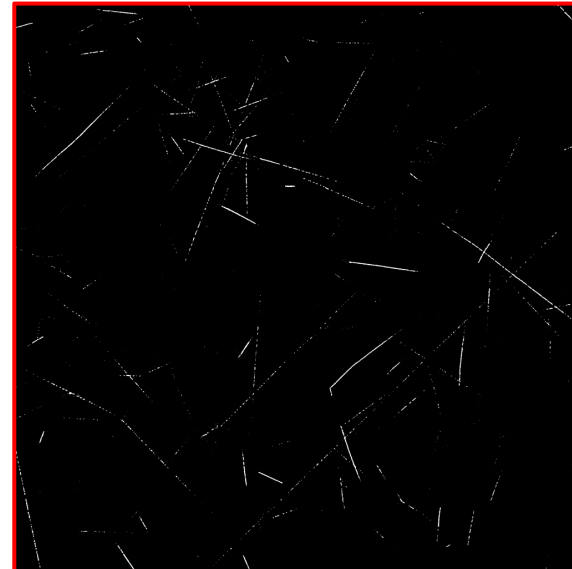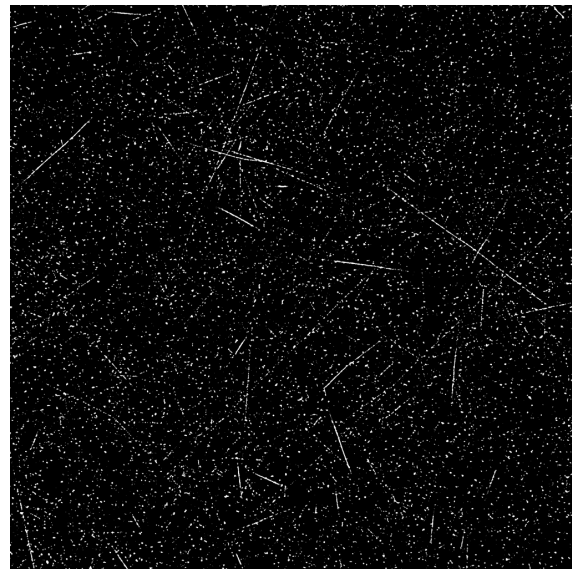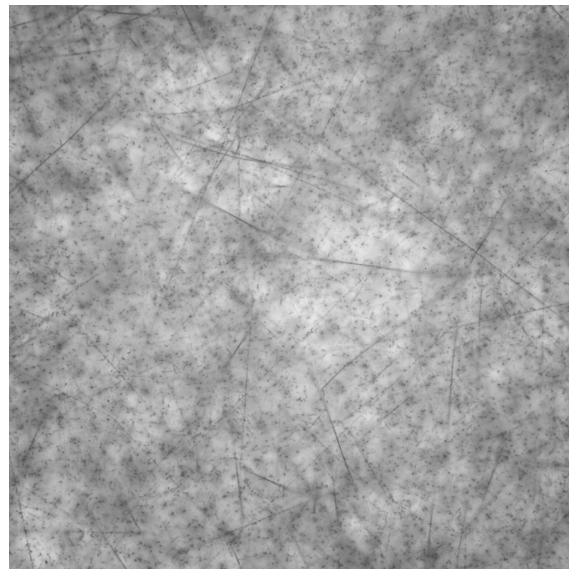
・Noise reduction
・Datasize: 1/200

→ E07 image data
　140 PB -> 750 TB

Segmentation task to detect hit infomation
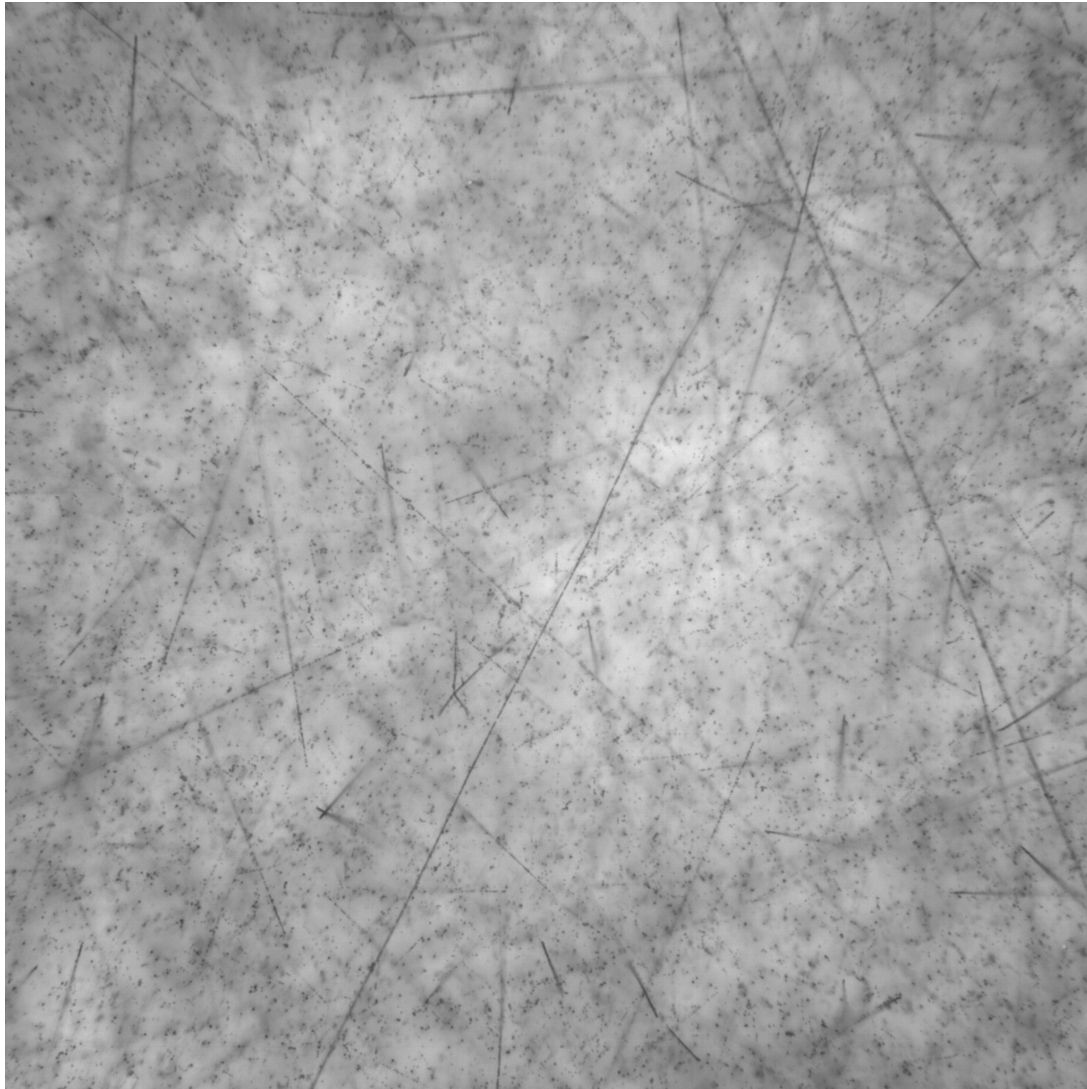
Raw data: 200 MB

Segmentation: 1MB

Results for Double-Λ

100 μm

Kasagi, Nakazawa, Rappold, Shimizu, Yokota
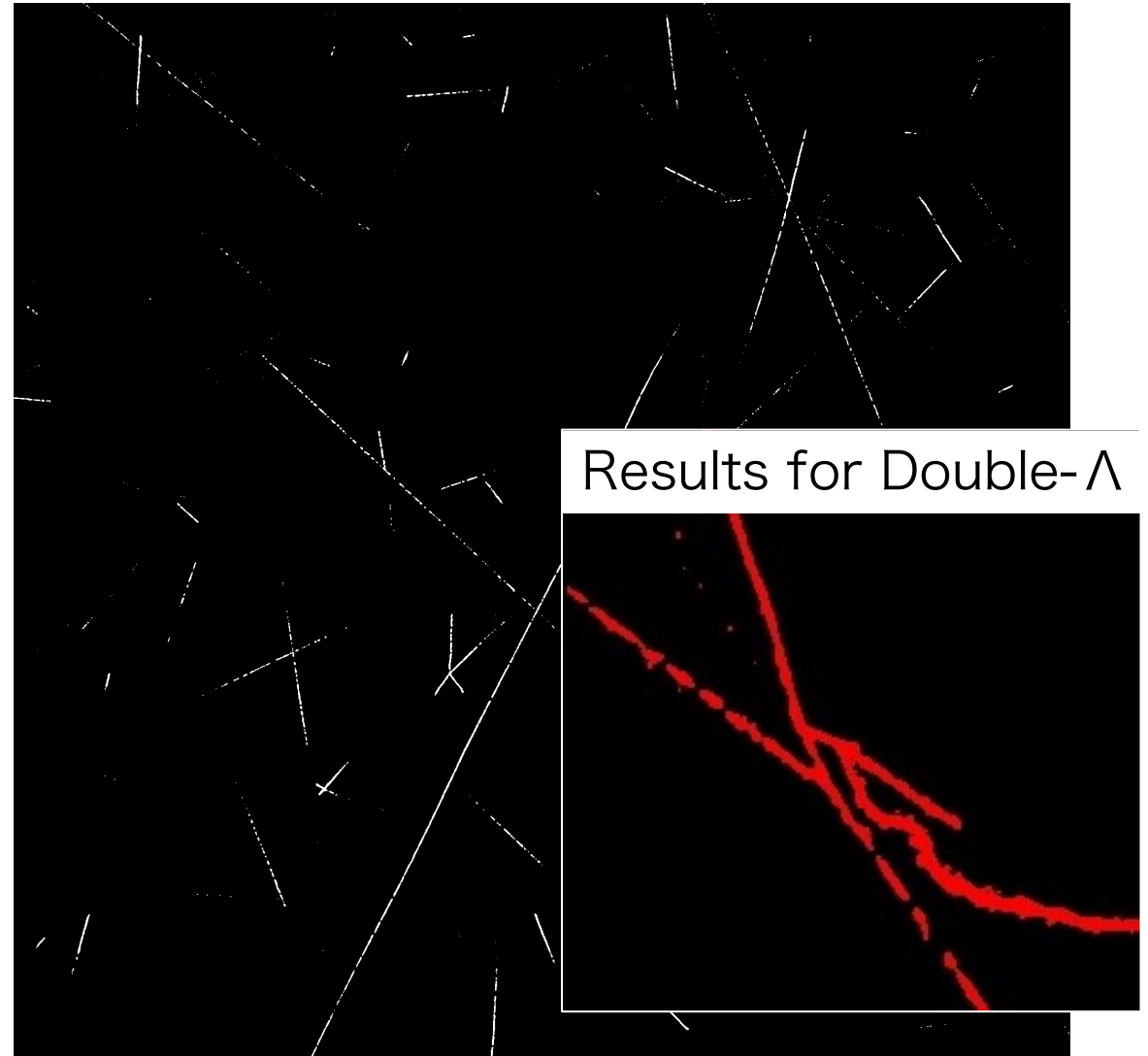
Reconstruction of track

Gabor filter & Connected Components

3D track reconstruction
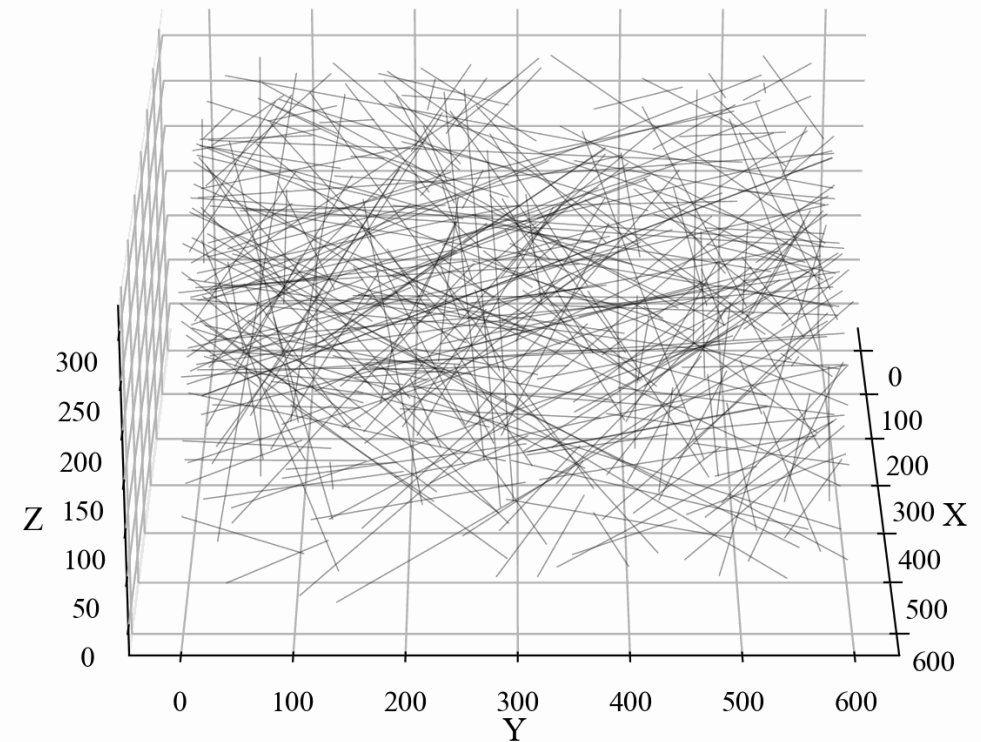
・Image -> meta information of tracks:　　Data size will be negligible
・Reconstruction of dizzy track & vertex:　Ongoing

Kasagi, Nakazawa, Rappold, Shimizu, Yokota

Summary

Tackling the challenges of Hypernuclear physics with the emulsion detector
  ・ Hypertriton puzzle
  ・ Event detection techniques with Machine-Learning

New Developments for various hypernuclei detection
  ・ Segmentation for extracting tracks
  ・ Gabor filter & Connected Components
  ・ Data size will be negligible

Analysis of various events from track information
  ・ Λ, $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He, $^{6}_{\Lambda}$He, $^{12}_{\Lambda}$C, Double-Λ, Σ, Ξ-hypernuclei
  ・ Hypernuclear Scattering, $^{3}_{\Lambda}$n ?, $^{4}_{\Lambda\Lambda}$n ?, H-dibaryon?

A. Kasagi[A,B], V. Drozd[C] , H. Ekawa[B], S. Escrig[D], Y. Gao[B,E,F] , Y. He[B,G], E. Liu[E,F], A. Muneem[H], M. Nakagawa[B], K. Nakazawa[B,I], C. Rappold[D], N. Saito[B], T. R. Saito[B,K], M. Taki[A], Y. K. Tanaka[B], H. Wang[B], A. Yanai[B,L], J. Yoshida[N]

Rikkyo AI[A], HENP RIKEN[B], Groningen Univ.[C], IEM-CSIC[D], IMP[E], UCAS[F], Lauzhou Univ.[G], GIK[H], Gifu Univ. Edu[I], GSI[K], Saitama Univ.[L], Tohoku Univ. SRIS[N]

backup