Precise measurement of the binding energy of hypertriton
- from the nuclear emulsion data using analysis with machine learning -

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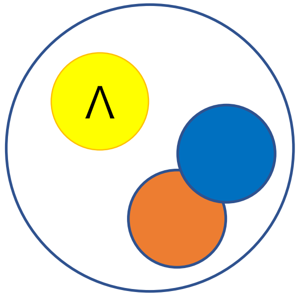
HADRON 2021

Hypertriton puzzle



Hypertriton: ${}^{3}_{\Lambda}H$
Benchmark for hypernuclear physics

τ ≒ 263 ps?? (Free Λ: 263 ± 2 ps)

Binding energy measurements

B_Λ = 130 ± 50(stat.) ± ???(syst.) keV
Nuclear emulsion (～1973)

Lifetime measurement with Heavy Ion beams

HypHI (GSI): 183^{+42}_{-32} ps
STAR (RHIC): 142^{+24}_{-21} ps
ALICE (LHC): 237^{+33}_{-36} ps

C. Rappold et al., Nucl. Phys. A 913 (2013) 170
STAR Collaboration, Phys. Rev. C 97 (2018) 054909
ALICE Collaboration, Phys. Lett. B 797 (2019) 134905

GSI, J-PARC, ELPH, RHIC, LHC, FAIR and HIAF…

Will be presentated in this session

nature physics LETTERS
https://doi.org/10.1038/s41567-020-0799-7
Check for updates

Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton

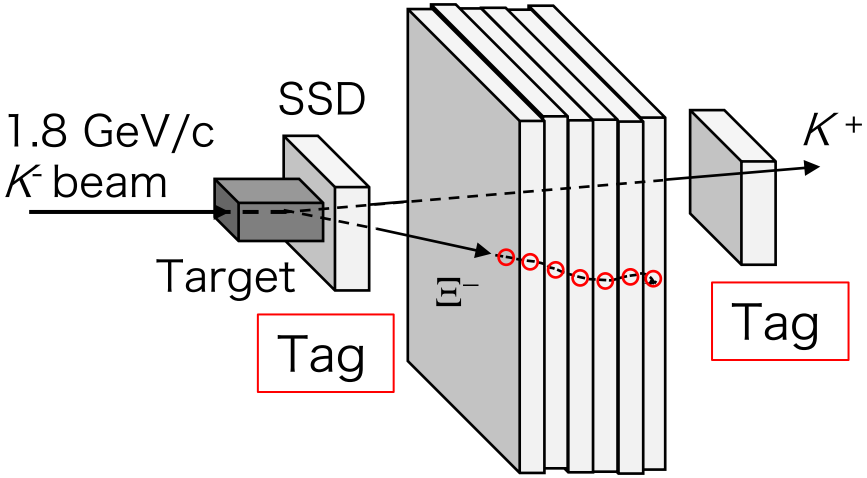
The STAR Collaboration*

B_Λ = 410 ± 120(stat.) ± 110(syst.) keV

The nature of Hypertriton is not clear…
→ New measurement of B_Λ with Nuclear Emulsion + modern technique

Nuclear Emulsion data from J-PARC E07 experiment

Emulsion-Counter hybrid method for double-strangeness hypernuclear seach

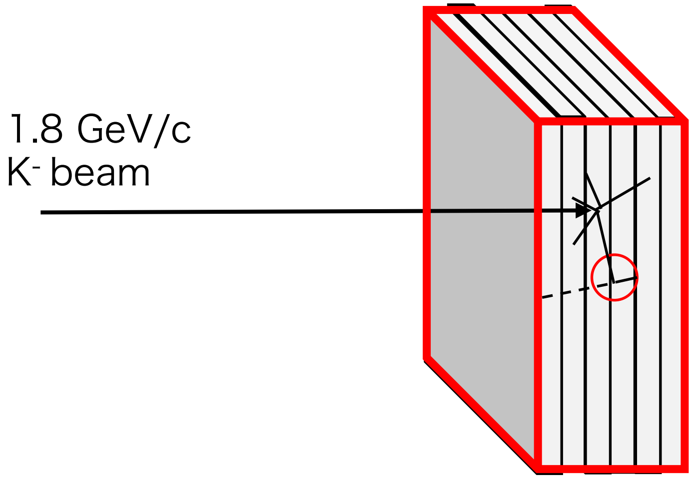


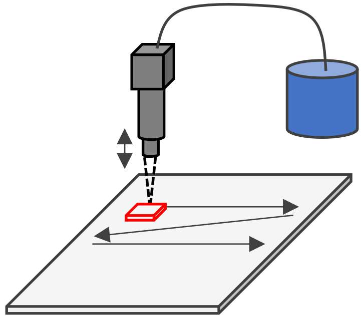
- Reduce the scanning volume and human load

H. Ekawa et al., PTEP, (2019)
S. H. Hayakawa et al., PRL, (2021)
M. Yoshimoto et al., PTEP, (2021)

Will be presentated in this session

Overall scaning method



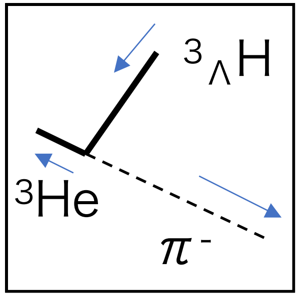


- 1000 double-strangeness hypernuclei
- Millions of Single-hypernuclei

- Requres a huge amount of visial inspections

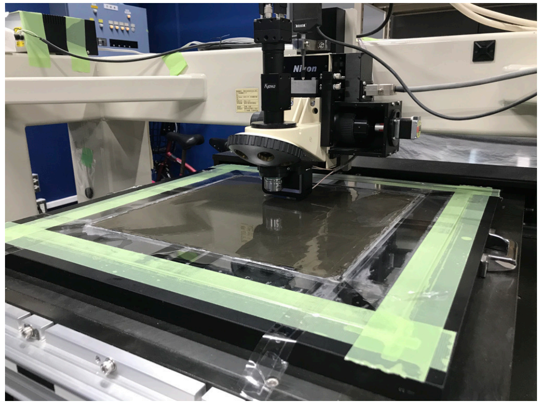
Hypertriton search from dataset

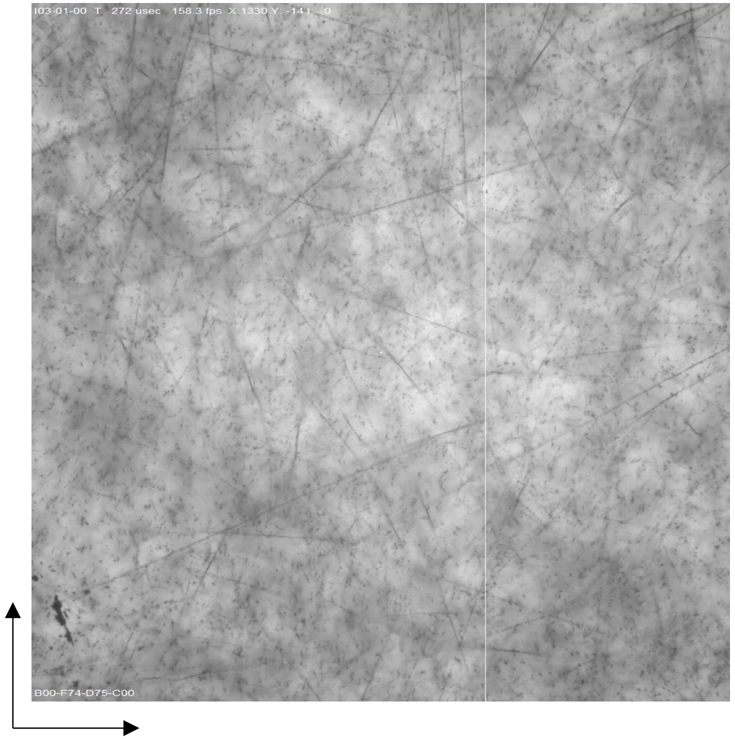
- Hypertriton can be visually observed.
  $^{3}_{\Lambda}H$(At rest) → ^{3}He + π^{-}



- Measurement with sub-μm spatial resolution
- Invariant mass measurement(event by event)

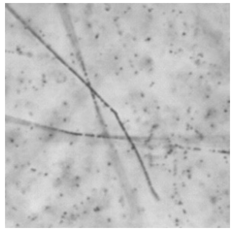
Scanning stage



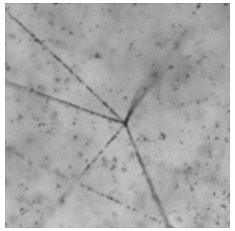


100 μm

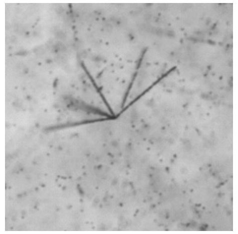
Cross tracks



K^{-} Beam interaction



*α decay



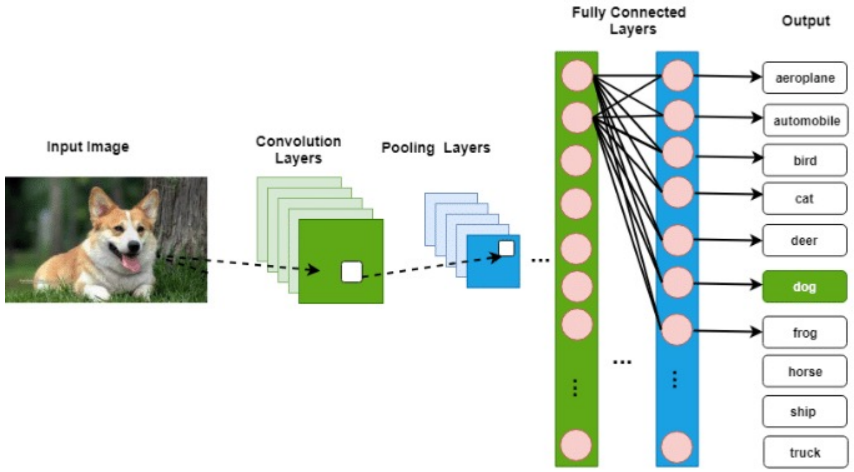
* Th chain α decay with 5 tracks
Radio isotope in emulsion

Data size : 140 PB (110 TB/sheet x 1300)
10^{9} vertex like events
Eye check : 560 years…

We need a Breakthrough!!

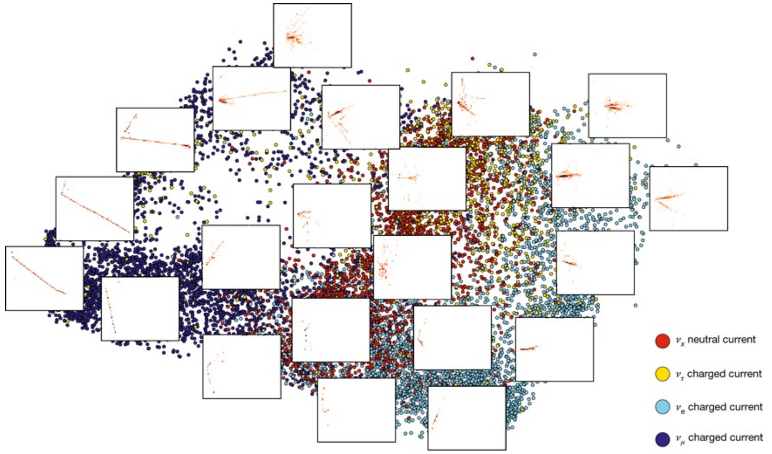
Machine Learning(ML)

Image classification



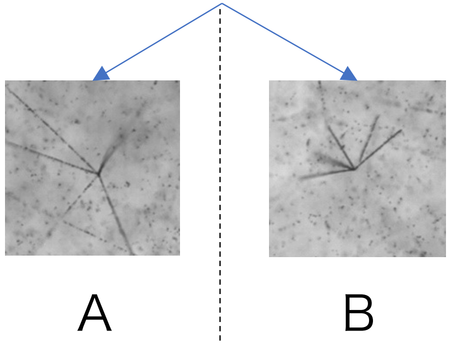
Object detection

Event-selection for neutrino interactions



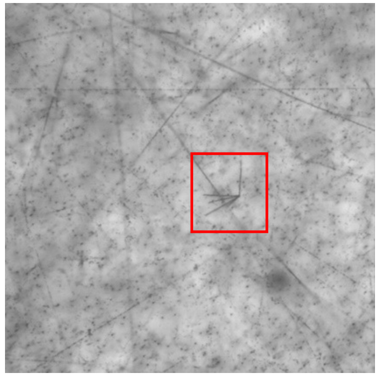
What is good for us?

Classification



A B

Detection



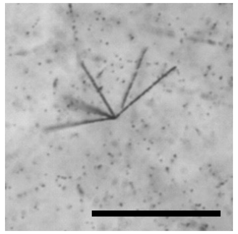
https://transcranial.github.io/keras-js/#/mnist-cnn, http://bdm.change-jp.com/
Nature 560, 41–48 (2018). https://doi.org/10.1038/s41586-018-0361-2

- Training dataset:
  At least a few thousand images is necessary.
  "How to train the model for rare events?"

Physics simulation + ML

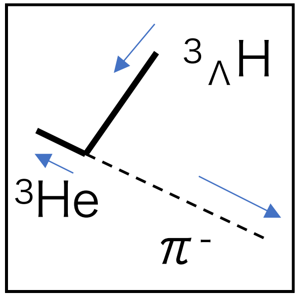
Strategy of ML + Nuclear Emulsion

	Training data	Target event
1st step ✓ CNN image classifier: Published as "J. Yoshida, et al., NIM A 989 (2021)164930"	Real images	
2nd step ✓ Physics simulation + Object detection(ML)	Simulated images	
	Evaluation of performance	
3rd step ✓ Detection of hypertriton	Simulated images	



α decay

50 μm

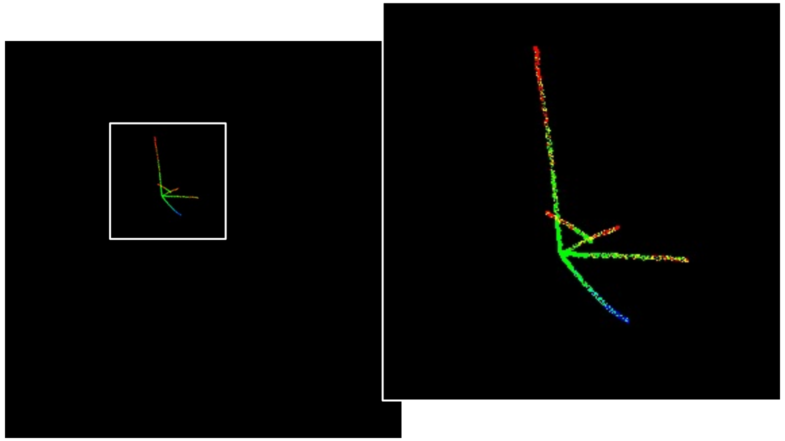


↓

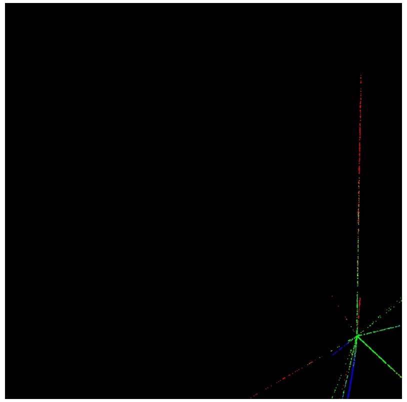
Precice measurement of the binding energy

Training data with Geant4 simulation + ML

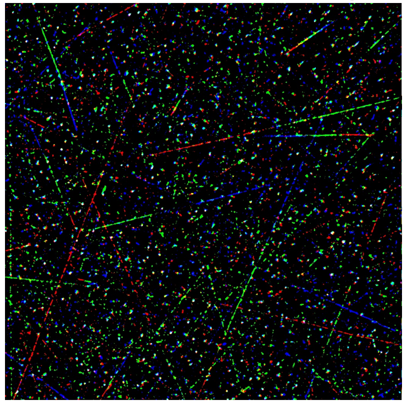
α decay event



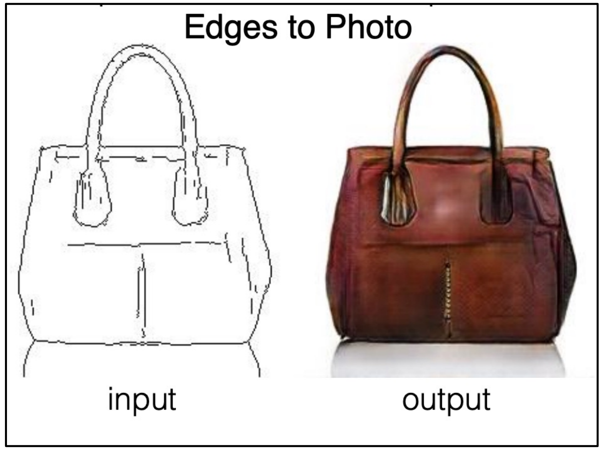
Other vertex event
(Negative sample)



Back ground
From real image

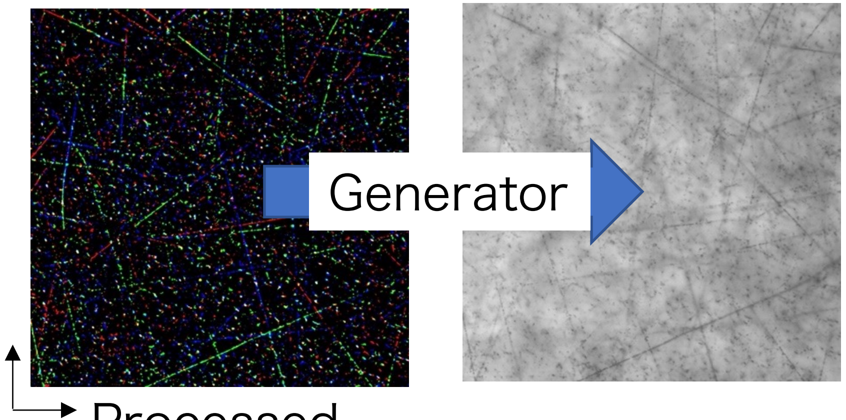


Generative Adversarial Networks (GAN)
Image transformation by ML.

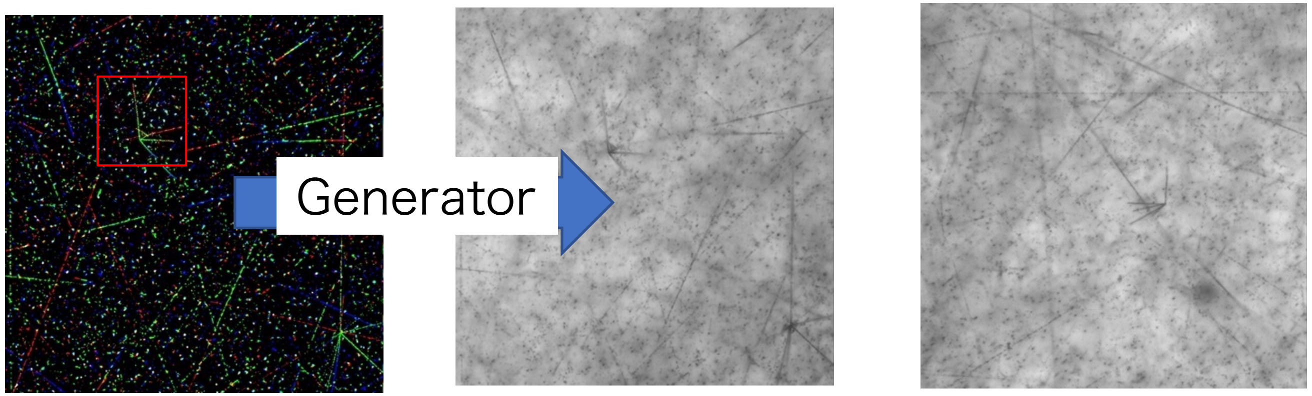


https://arxiv.org/abs/1611.07004

Training data (Real images)



Processed



Simulated images

Real image

Training of Mask R-CNN with Simulated image

Mask R-CNN

Example of training dataset

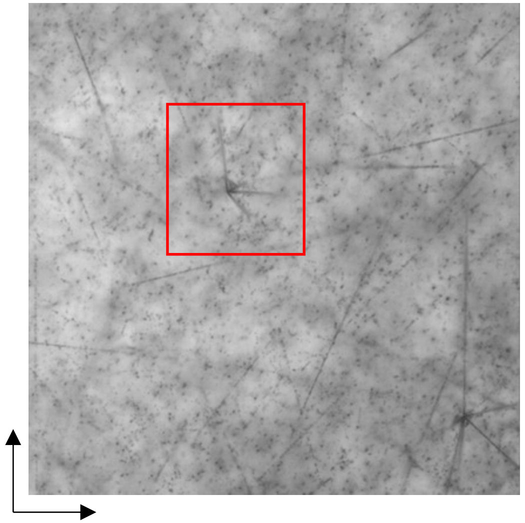
Image

Mask

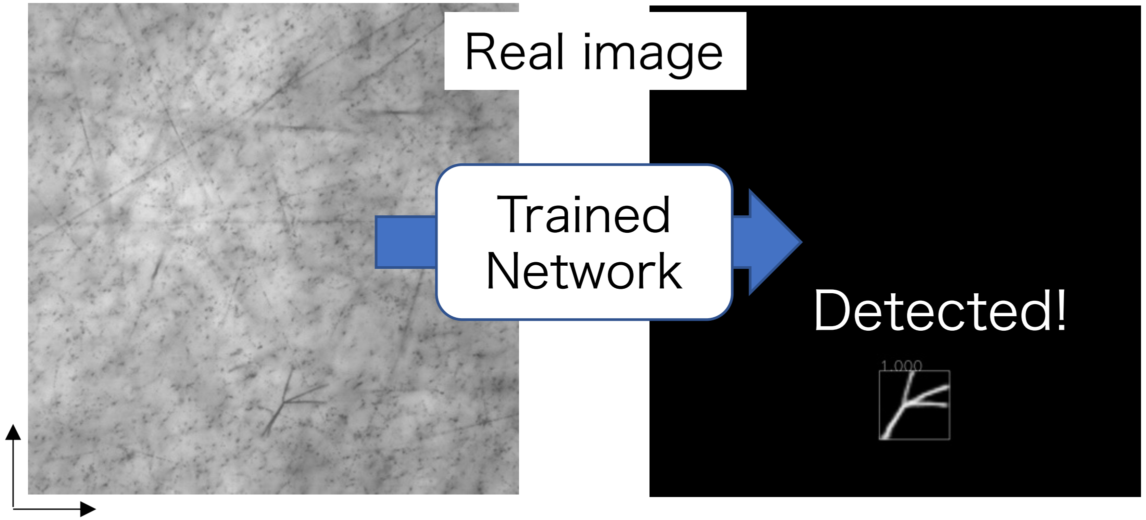
A Pedestrian dataset

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

Training data (Simulated image)



50 μm



50 μm

- Training dataset: Simulated images.
- Network can detect events in real images.

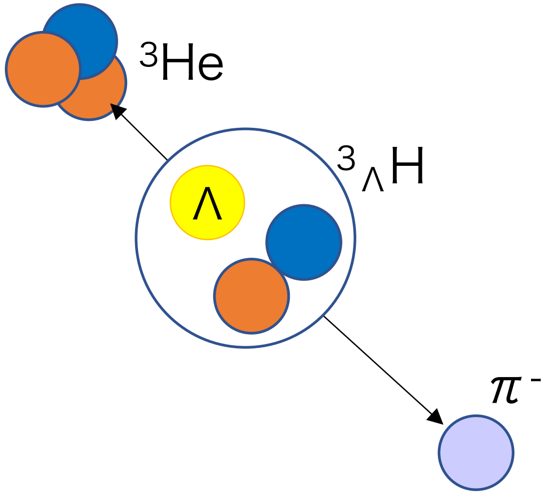
- High detection efficiency(80%～90%)

A.Kasagi et.al,
To be submitted to Computer Physics Communications

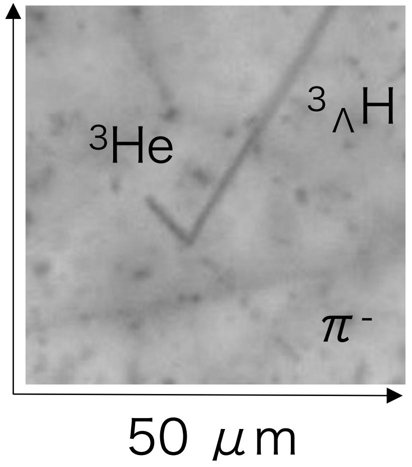
Hypertriton search by Mask R-CNN

Rare event detection

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

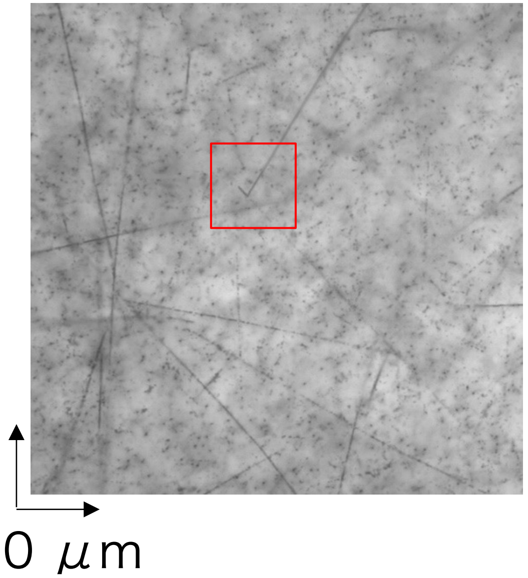


Simulated image

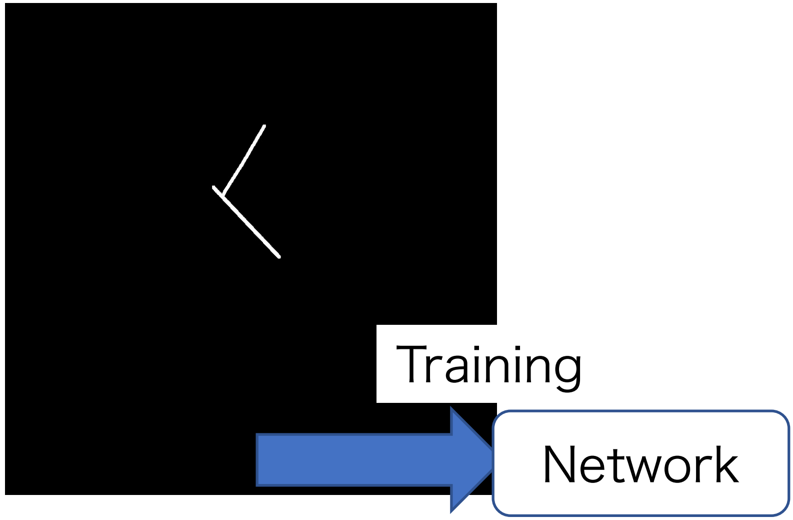


Training dataset (Simulated images)

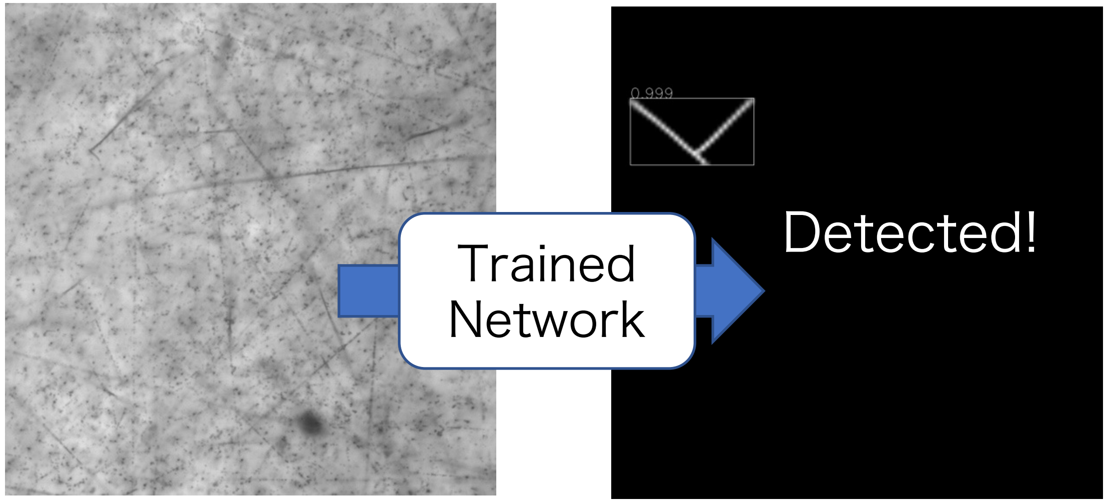
Image



Mask



Real image

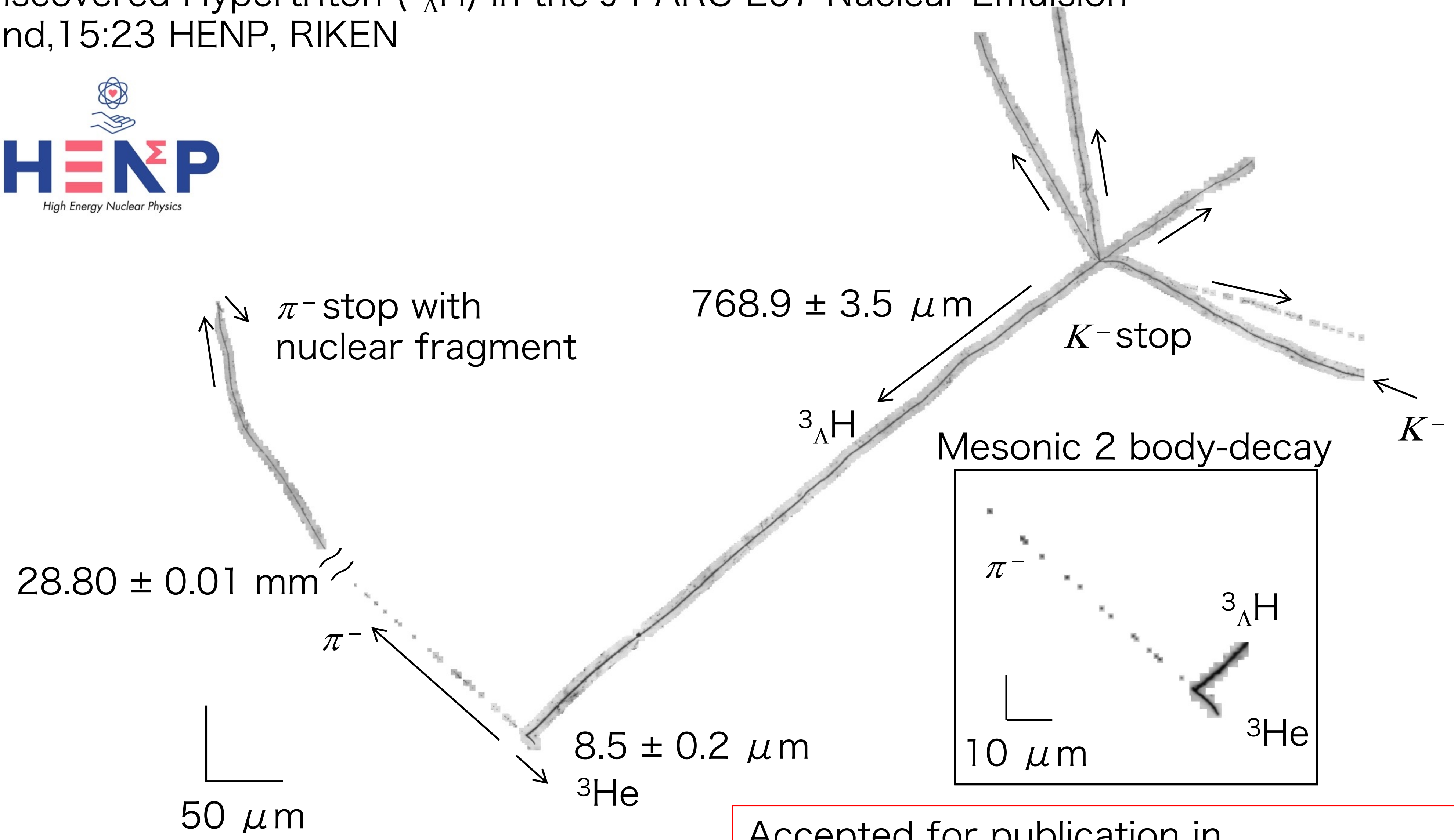


- Training dataset: 10^4 simulated $^{3}_{\Lambda}H$
- Rare events are detected!

The First Discovered Hypertriton

The First Discovered Hypertriton ($^{3}_{\Lambda}H$) in the J-PARC E07 Nuclear Emulsion
February 2nd,15:23 HENP, RIKEN

High Energy Nuclear Physics



Accepted for publication in
Nature Reviews Physics as a Perspective article

Summary and prospect

・Hypertriton puzzle on
- Lifetime
- Binding energy

・Measurement of Hypertriton binding energy very precisely
- J-PARC E07 nuclear emulsion
- Machine learning
  → Result of binding energy will come soon.

・Precise measurement of binding energy of various hypernuclei
  ${}^{4}_{\Lambda}He$, ${}^{5}_{\Lambda}He$,(3 body decay)⋯ ${}^{4}_{\Lambda\Lambda}H$, ${}^{5}_{\Lambda\Lambda}H$⋯(Double-strangeness hypernuclei)

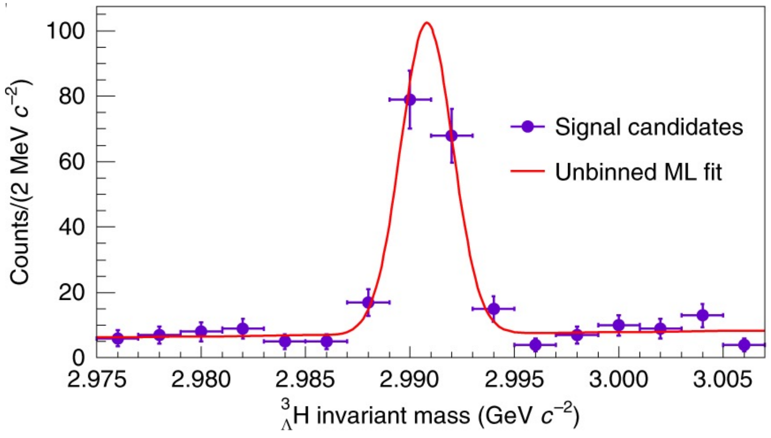
*A. Kasagi[1,2], E. Liu[1,3,4], M. Nakagawa[1], H. Ekawa[1], J. Yoshida[1,5], W. Dou[1,6],A. Muneem[1,7],K. Nakazawa[2], C. Rappold[8], N. Saito[1], T R. Saito[1,9,10], M. Taki[11], Y K. Tanaka[1], H. Wang[1], M. Yoshimoto[12]

1. High Energy Nuclear Physics Laboratory,, RIKEN, 2. Gifu University
3. Institute of Modern Physics, CAS, 4. University of Chinese Academy of Sciences,
5. Tohoku University, 6. Saitama University,
7. Ghulam Ishaq Khan Institute of Engineering Sciences and Technology,
8. Instituto de Estructura de la Materia, CSIC-Madrid, 9. GSI, 10. Lanzhou University,
11. Rikkyo University 12. Nishina Center, RIKEN

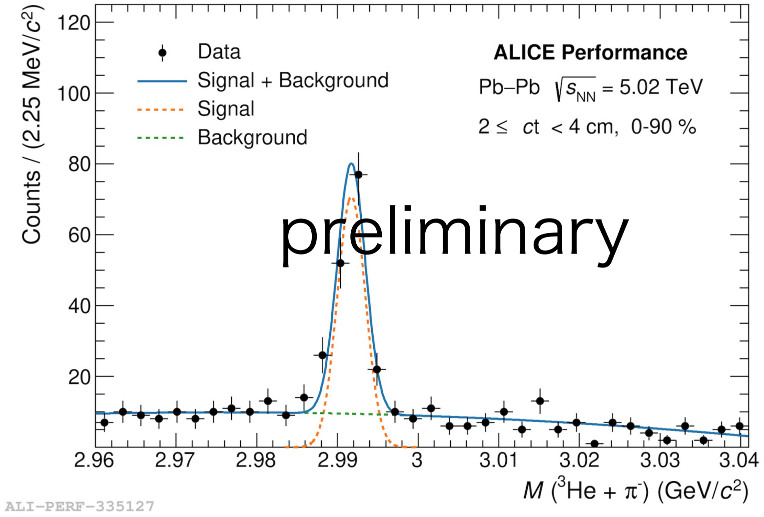
backup

Binding energy of Hypertriton

STAR (2020): 410 ± 120(stat.) ± 110(syst.) keV

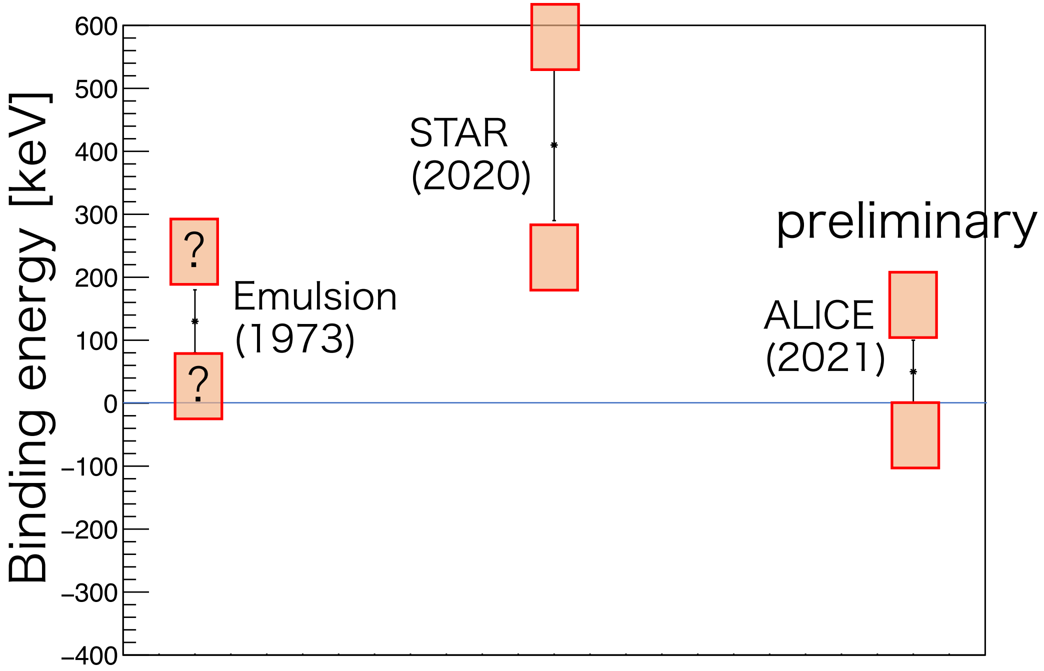


ALICE (2021): ~ 50 ± 50(stat.) ± 90(syst.) keV



STAR collaboration Nature Physics volume 16, 409-412(2020)
Pietro Fecchio on behalf of the ALICE Collaboration(SQM2021)

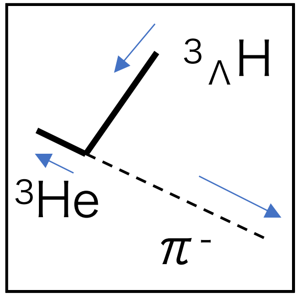
Nuclear emulsion (~1973)
130 ± 50(stat.) ± ???(syst.) keV



- New results on hypertriton binding energy
  → Importance of evaluating systematic errors
- To understand hypertriton nature
  → Precise measurement of lifetime and binding energy
  → New measurement with nuclear emulsion

Precise measurement with Nuclear Emulsion

- Background-free measurement
  Hypertriton decay can be visually observed.
  Unique topology in two-body decay
  ($^{3}_{\Lambda}$H: ~28 mm, $^{4}_{\Lambda}$H: ~42 mm)



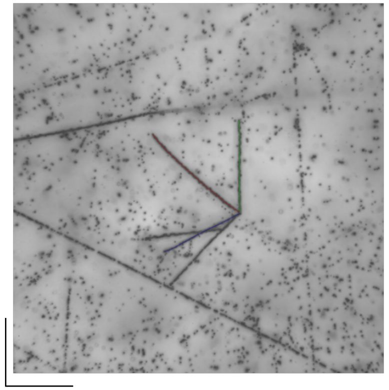
	$^{3}_{\Lambda}$H	$^{4}_{\Lambda}$H	$^{6}_{\Lambda}$He	$^{7}_{\Lambda}$He
He, Li etc… [μm]	~8	~8	~2	~2
π^- [mm]	~28	~42	~24	~28

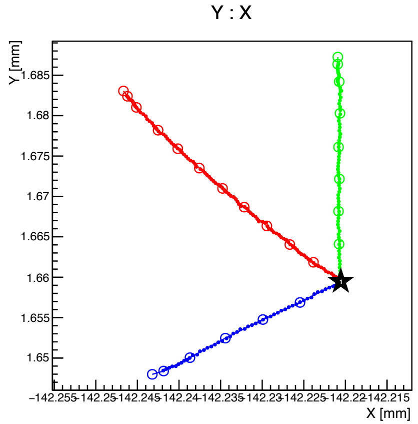
- Calibration

	~1970s	In our analysis
Calibration source	Proton ($\Sigma^+ \rightarrow p + \pi^0$)	^{4}He (RI in emulsion)
Volume	6.5×10^3 cm^3	5 cm^3

K.E of proton depends on Mass of Σ^+.
(K^- + p → Σ^+ + π^-, $\Sigma^+ \rightarrow p + \pi^0$)

Range measurement for α tracks by fitting





- Kinematical analysis
  $^{3}_{\Lambda}$H → ^{3}He(~8 μm) + π^-(~28 mm)

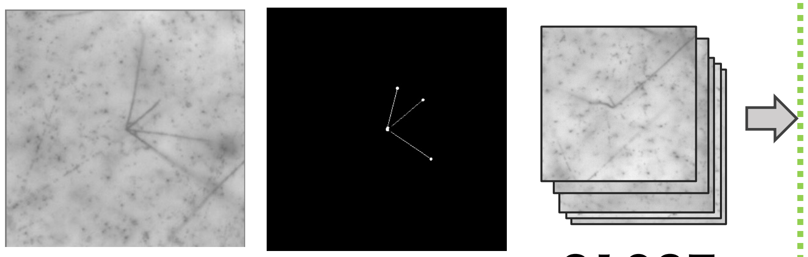
  ~1970s: Measurement of Mass of Λ
  ($\Lambda \rightarrow p + \pi^-$) π^-: 10~20 mm

- ^{3}He, ^{4}He calibrated by ^{4}He
- Calibration in each small volume
  → We can achieve ~30 keV syst. error.
- Analysis of $^{4}_{\Lambda}$H at the same systematic

Image classification by CNN filter

Feasibility study of machine learning training with real images

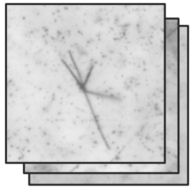
Detected by vertex picker



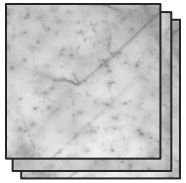
21037

・Training with real images

Training data (real images)



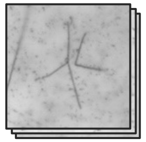
alpha
1124



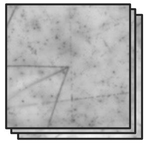
others
19913

Training

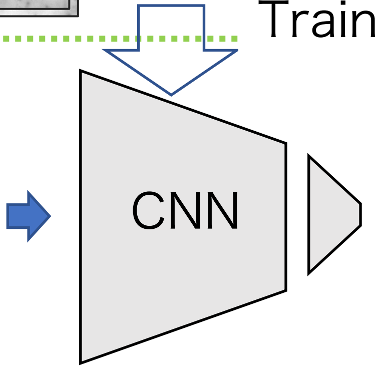
Test data(not used in training)



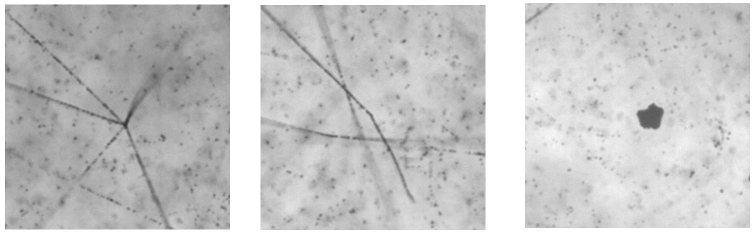
alpha
255



others
46693



Noise: others

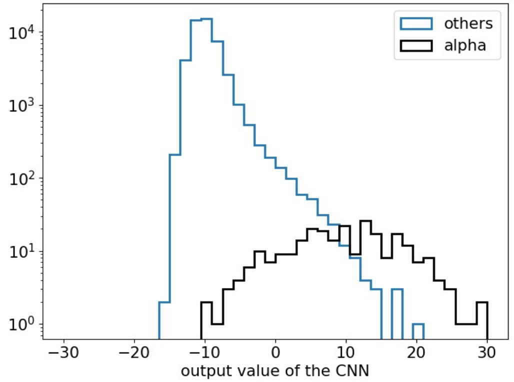


Other interaction

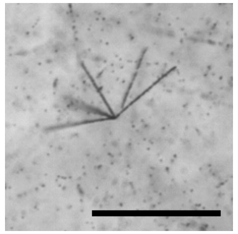
Cross

Dust

Scalar value



Target



50 μm

α decay

	Purity	Efficiency	No. images
Image processing	0.081 ± 0.006	0.788 ± 0.056	2489
CNN filter	**0.547 ± 0.025**	0.788	**366 ± 18**

Classification performance was improved by 7 times.

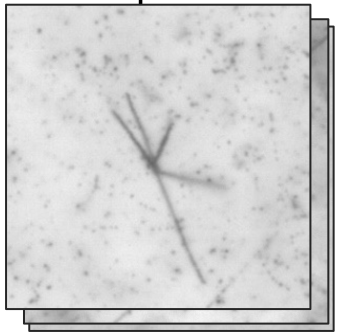
Published as "J. Yoshida, et al., Nuclear Instrument and Method A, 989 (2021) 164930"

New method for detecting rare events

2 issues

- Images for training
  (At least a few thousand〜)

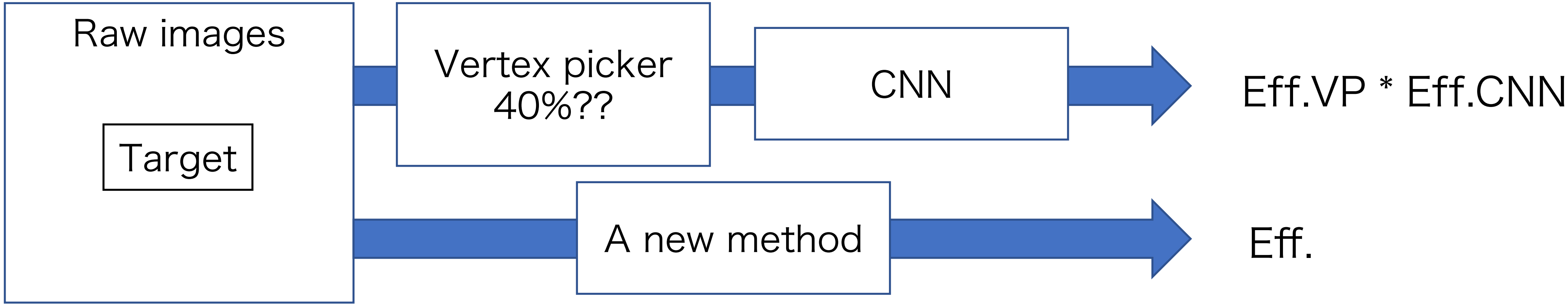
alpha



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

Generating training data : Physics simulation + Image conversion

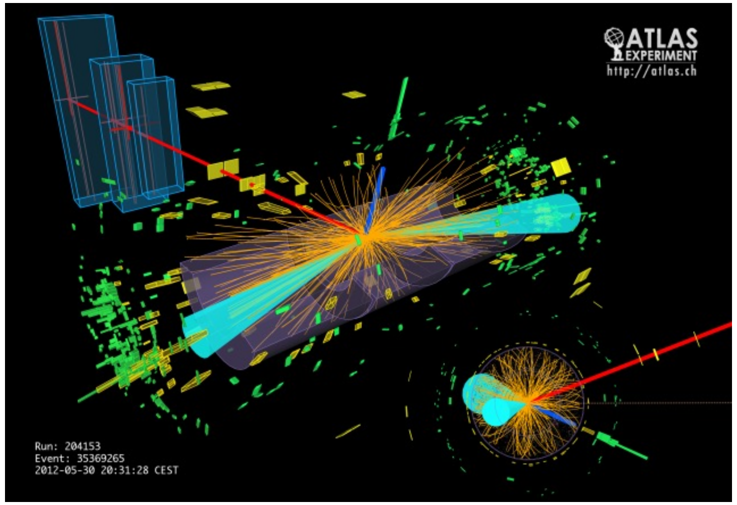
- Development of a direct detection method
  ex) Vertex picker: Efficiency for alpha decay: 〜40%



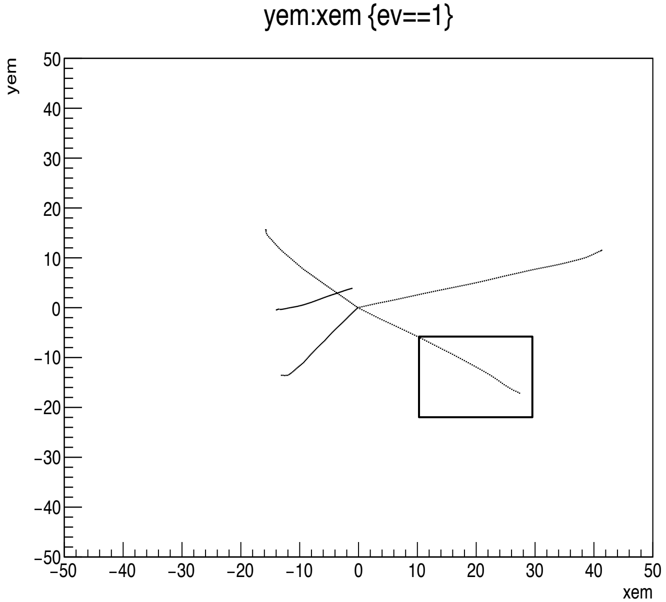
Direct detection method : Object detection by ML

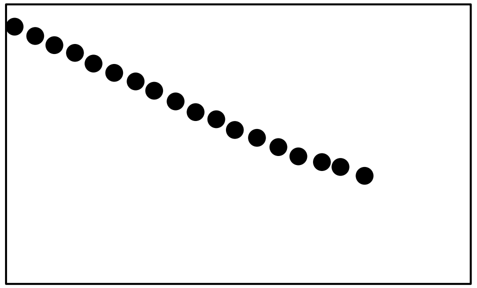
Training data with Simulation + ML

Geant4 simulation



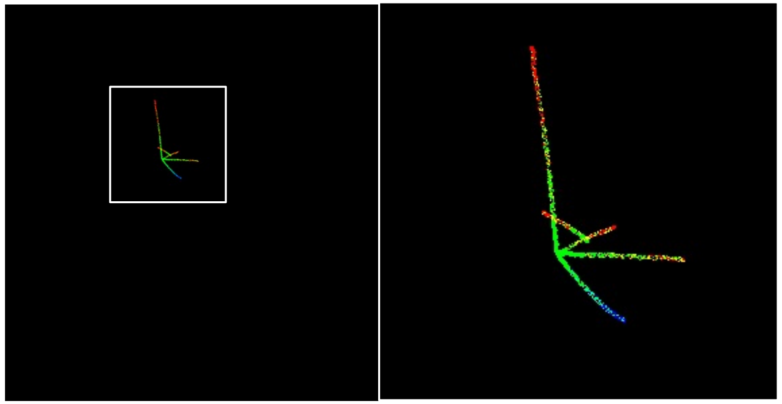
http://cds.cern.ch/record/1631395



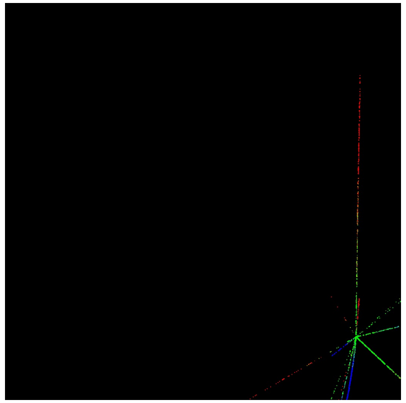


Step information of particles

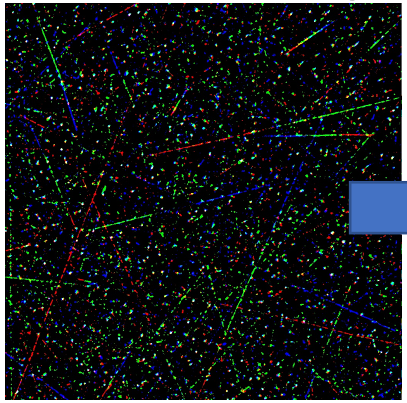
α decay generated by Geant4

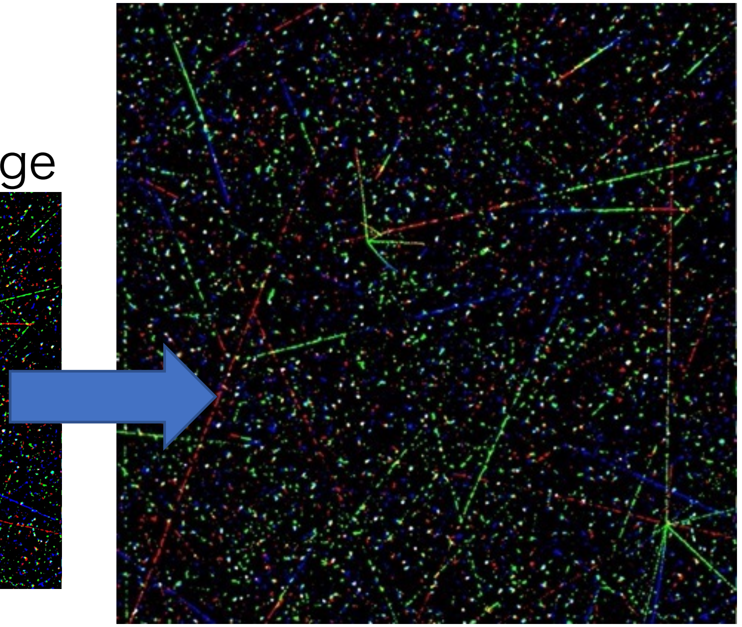


Other vertex event
(Negative sample)



Back ground
From real image





Generating training data with GAN

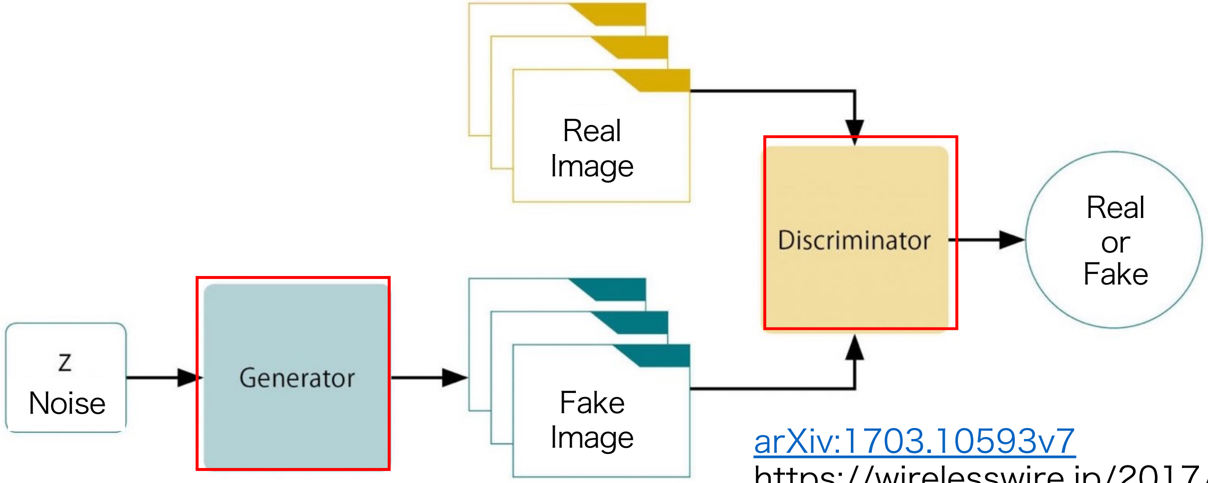
pix2pix: Image transformation by ML.

example

Zebra -> Horse

Horse -> Zebra

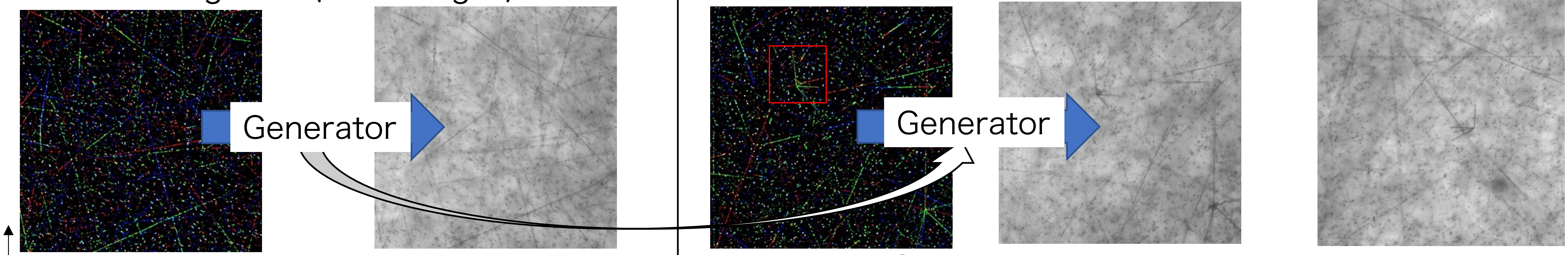
GAN(Generative Adversarial Networks)



arXiv:1703.10593v7

https://wirelesswire.jp/2017/01/58467/

Training data (Real images)



Processed

50 μm

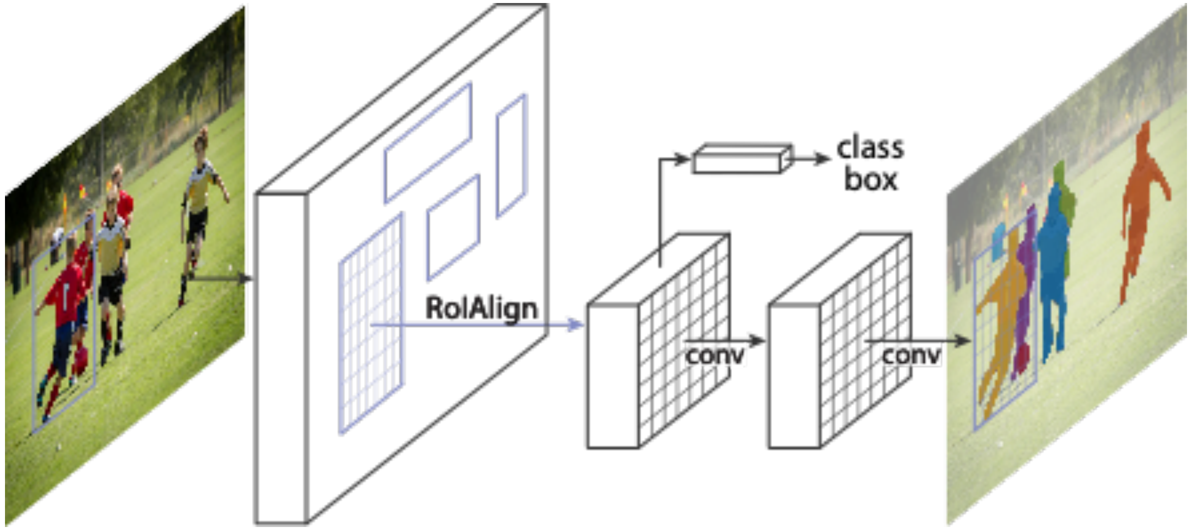
Original

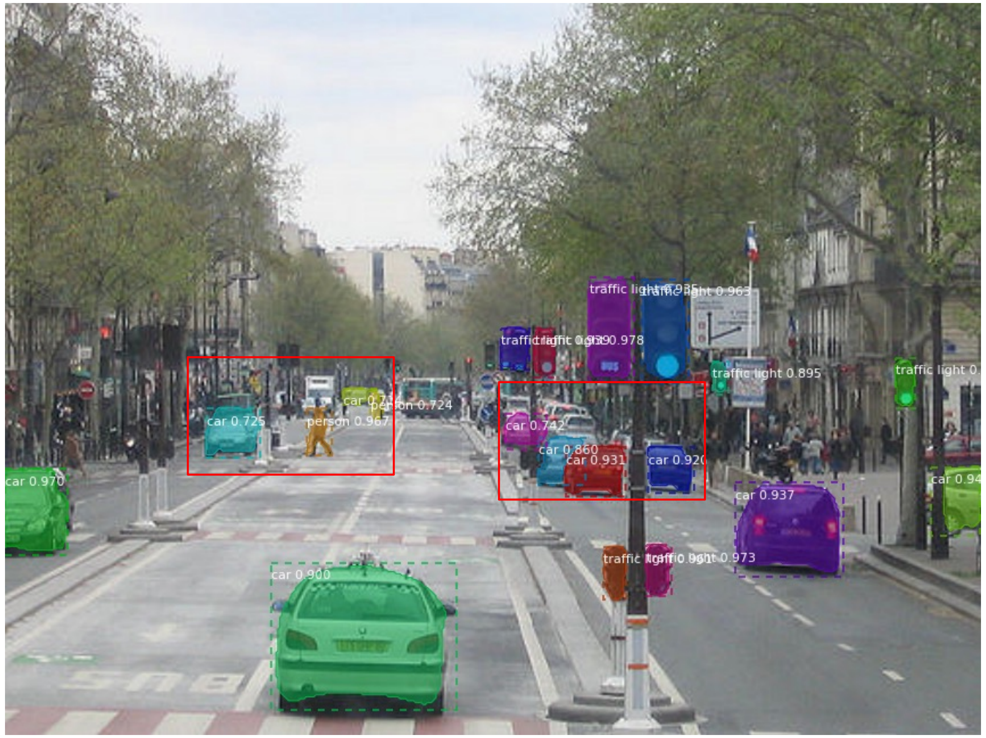
Simulated

Real

Object detection (Mask R-CNN)

- Convolutional operation on the region of interest (ROI)
- Determine the category and banding box for each object





https://arxiv.org/abs/1703.06870
https://github.com/matterport/Mask_RCNN

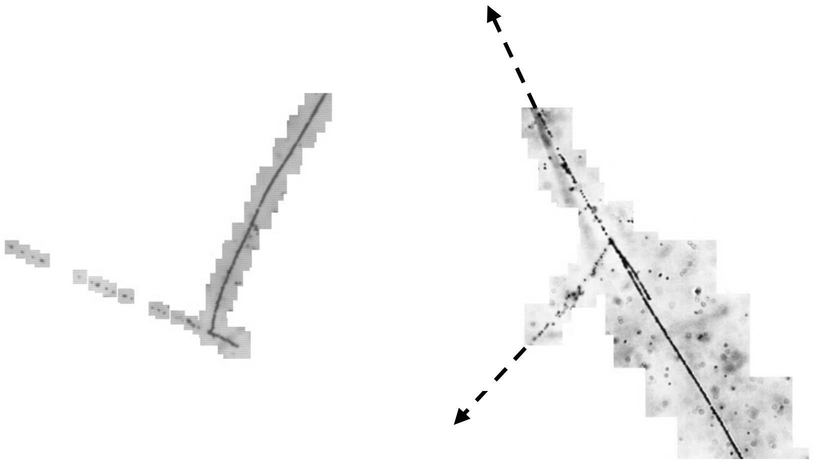
- Detecting objects directly in images

Classification of each object

For crowded region.

Precise measurement of Hypernuclei

- $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H $^{4}_{\Lambda}$He, $^{5}_{\Lambda}$He… (2body & 3 body decay)



Precise measurement B_{Λ}

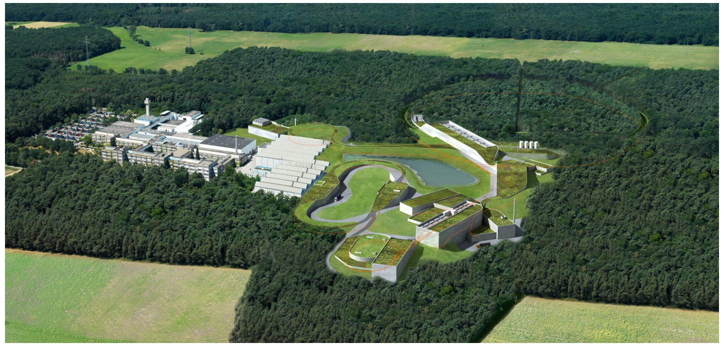
A lot of Single hypernuclei

$^{3}_{\Lambda}$H:	± 50 keV (100 events)
$^{4}_{\Lambda}$H:	± 40 keV (150 events)
$^{4}_{\Lambda}$He:	± 30 keV (200 events)
$^{5}_{\Lambda}$He:	± 20 keV (～800 events)

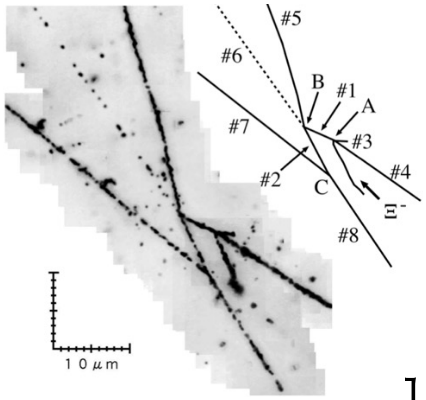
・
・
・

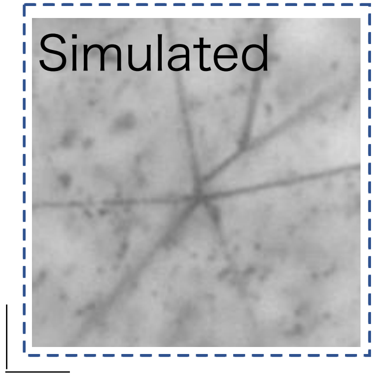
Lifetime measurements

at FAIR ～ a few ps accuracy



- $^{5}_{\Lambda\Lambda}$H, $^{6}_{\Lambda\Lambda}$He, $^{15}_{\Xi}$C



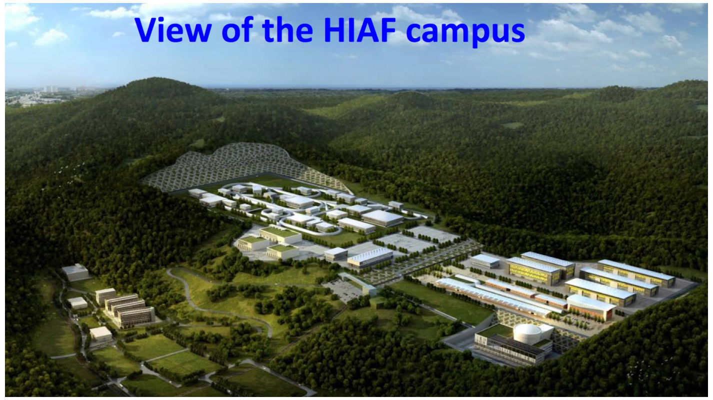


10 μm

Precise measurement $B_{\Lambda\Lambda}$ and B_{Ξ^-}

$^{6}_{\Lambda\Lambda}$He:	± 20 keV (10～ events)
$^{15}_{\Xi}$C:	± 30 keV (10～ events)

at HIAF ～ 10 ps accuracy



Precise measurements of Binding energy & Lifetime

Vertex picker

Vertex picker: Line segment analysis by image processing

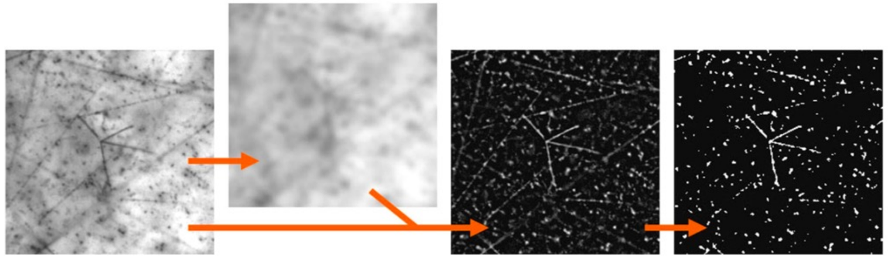


Fig. 4. The first step of the image processing for vertex detection, i.e., raw image, Gaussian-blur, difference of Gaussians and binary thresholding from left to right. The area of the FOV is 120 × 120 μm², which are cropped from the original FOV having 1140 × 200 μm².

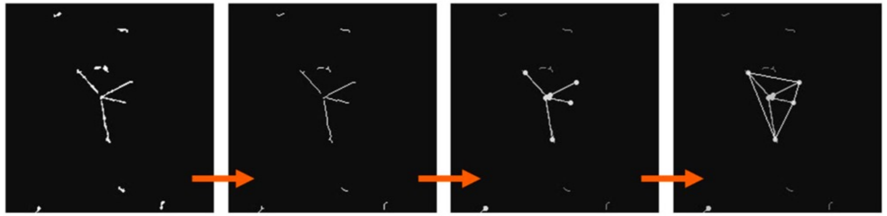


Fig. 5. The second and third step of the image processing: noise reduction, thinning, line detection and vertex detection.

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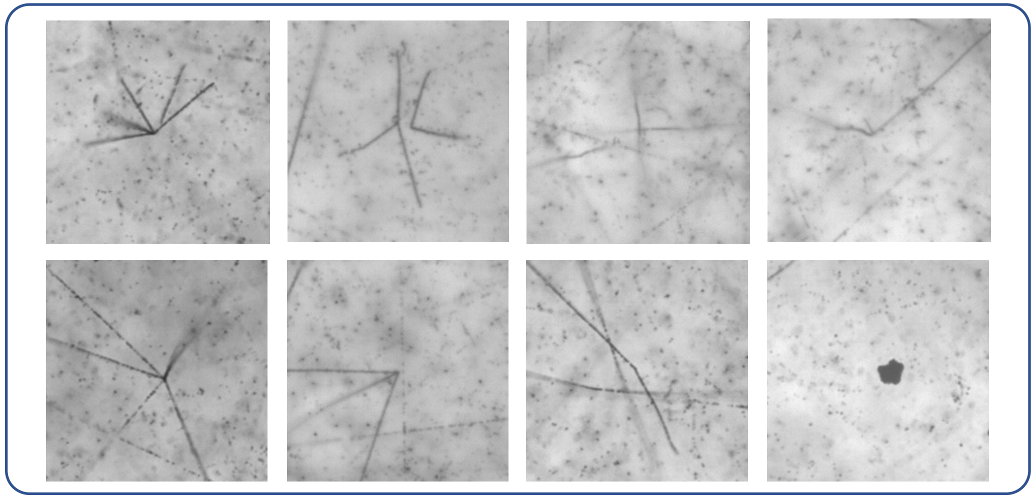
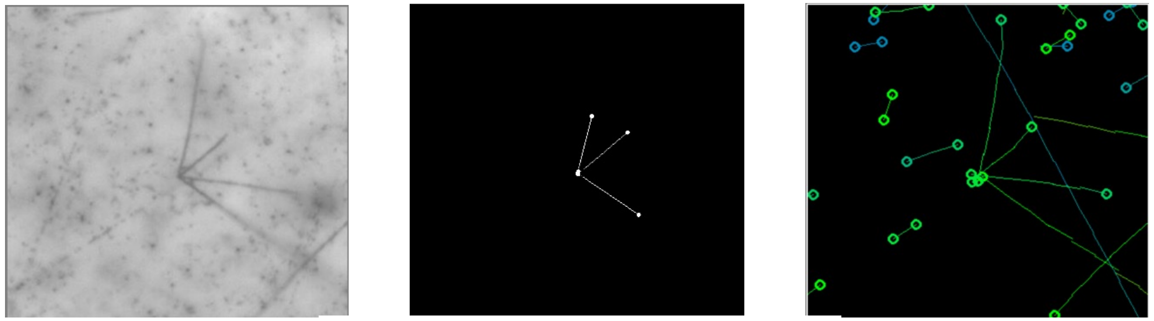
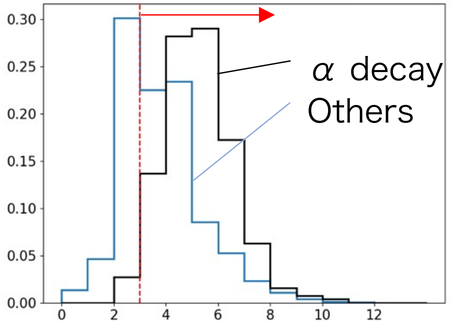
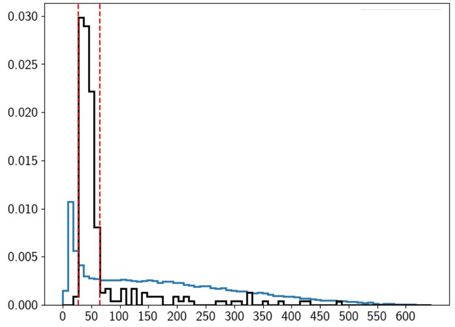
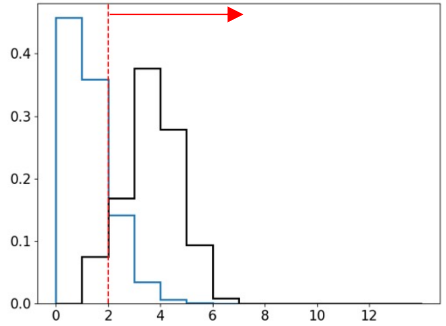




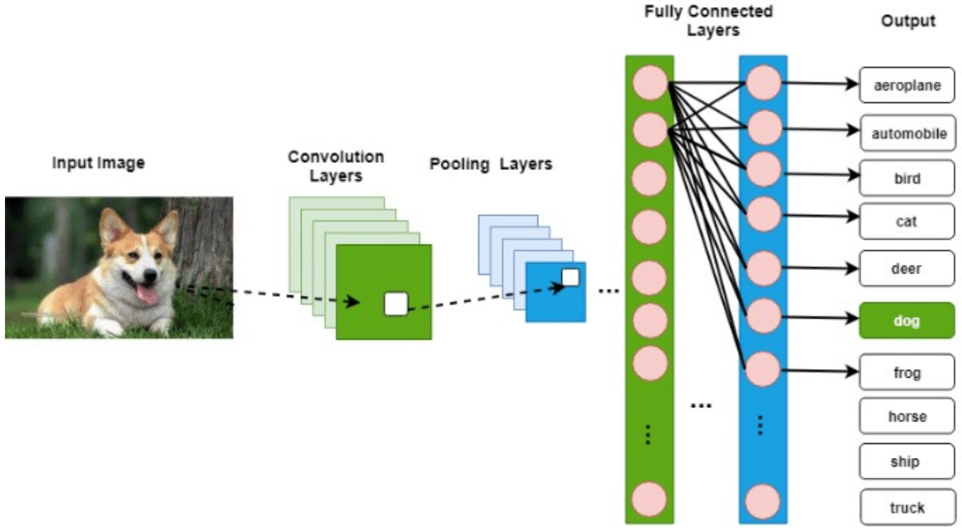






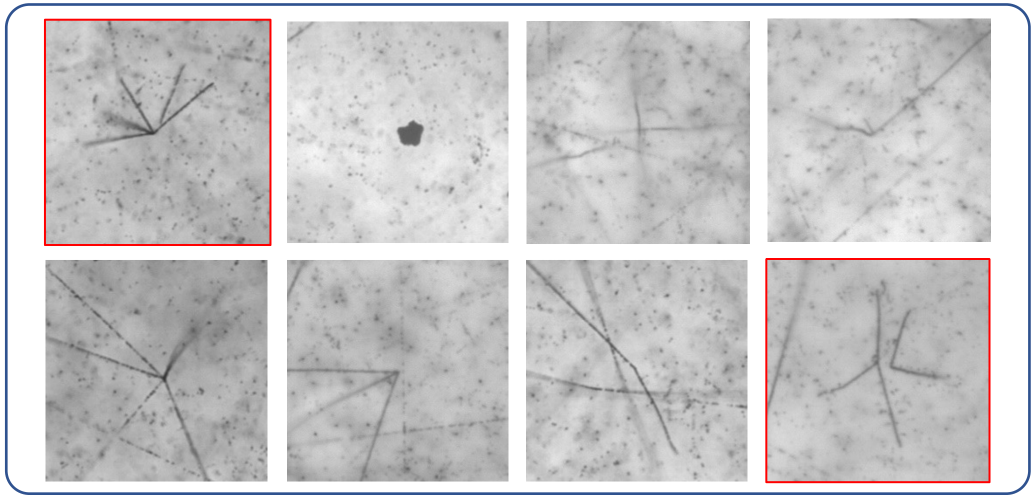
CNN filter

Convolutional Neural Network

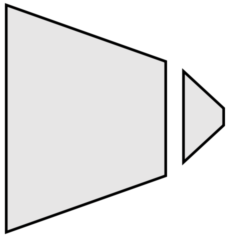


- images and correct answer labels (training data)
- Quantify features by convolutional operations
- Iteratively updating the calculation weights (parameters) in each layer

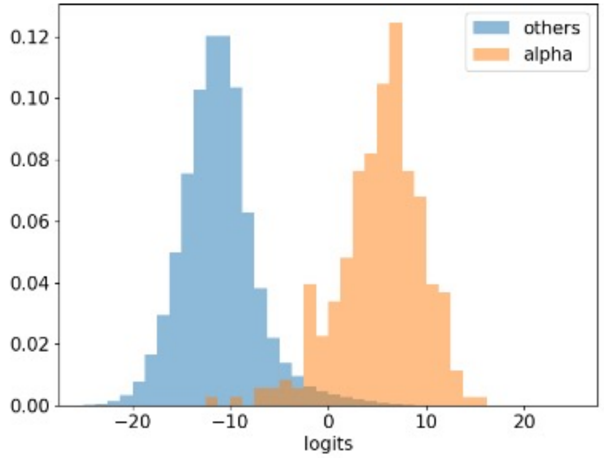
→Making the best model



Model



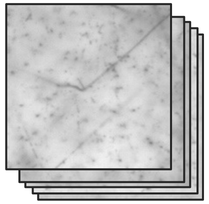
Noise



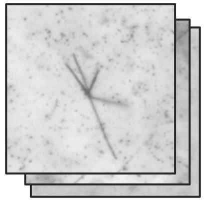
Signal

Training of CNN model

We classfied 20k images to make train

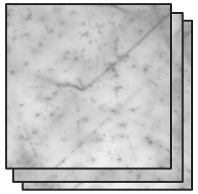


19913 images



alpha

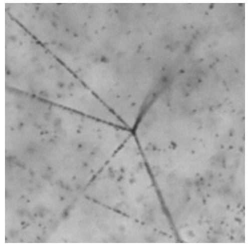
1124



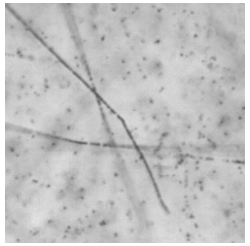
others

19913

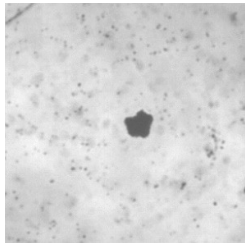
Noise: others



Other interaction

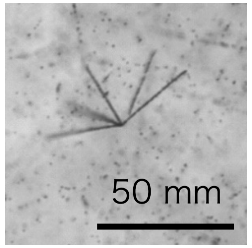


Cross

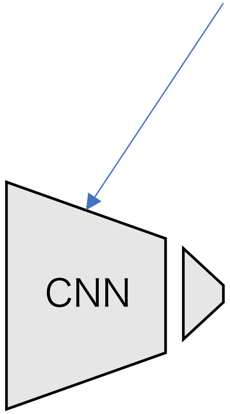


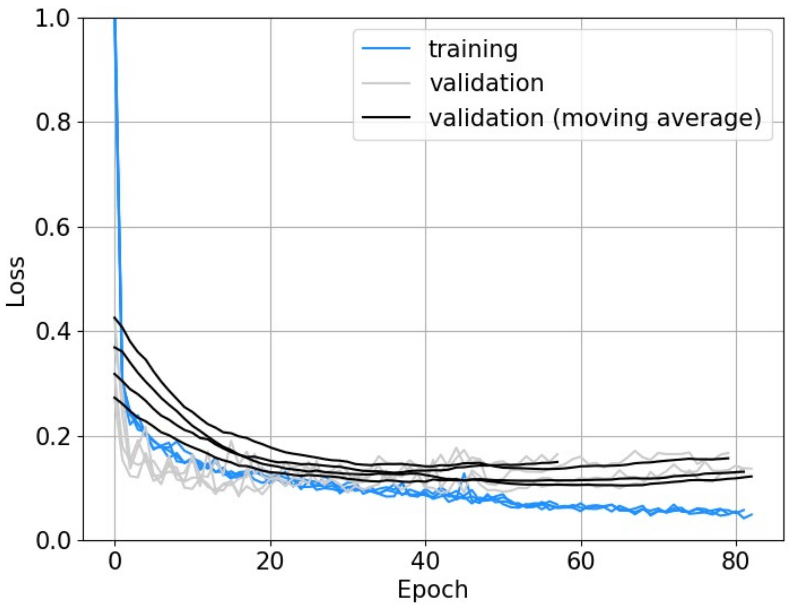
Dust

Target

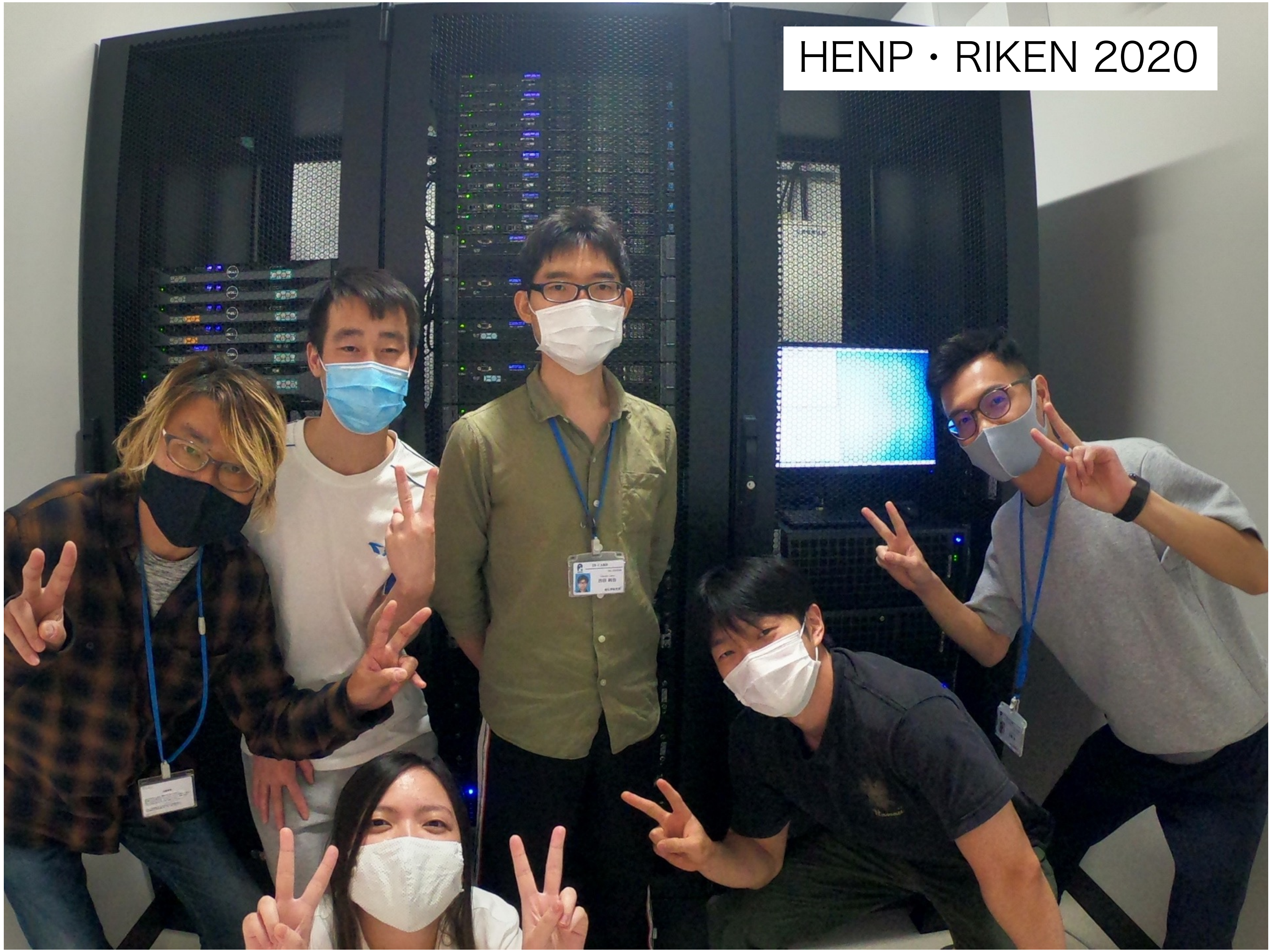


α decay





CPU・GPU server @HENP RIKEN



CPU: 1400 cores
GPU: 36 GPU boards
Storage: 1000 TB