Recent results on double-Lambda and Xi hypernuclei from the J-PARC E07 experiment.

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J-PARC E07 collaboration
High Energy Nuclear Physics Lab at RIKEN

Double hypernuclei

ΛΛ hypernucleus

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

ΛΛ interaction

Ξ hypernucleus

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

Ξ*N* interaction

information source of baryon-baryon interaction with u,d,s quarks

Nucleon

Proton

(u, u, d)

Neutron

(u, d, d)

Hyperon

Lambda

(u, d, s)

Xi minus

(d, s, s)

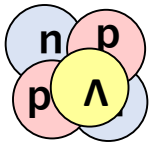
Baryon-baryon interaction

- Generalization of nuclear force
- Neutron star

Nuclear force

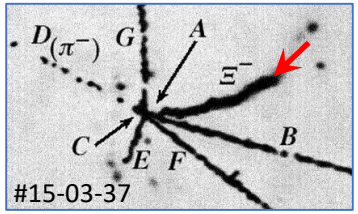
Λ*N* interaction

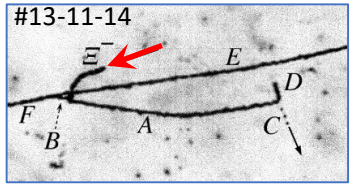
Single Λ hypernucleus

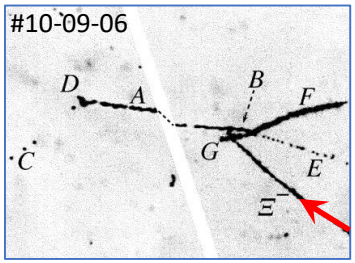


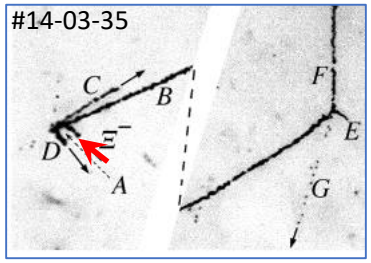
Nuclear Physics A 828 (2009) 191–232

KEK-PS E176 (1988-89)







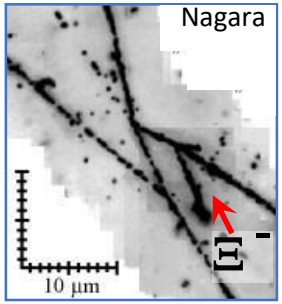


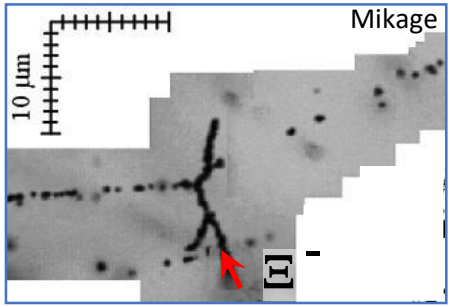
* ~80 Ξ^- stop events
* Existence of double Lambda hypernucleus has been confirmed

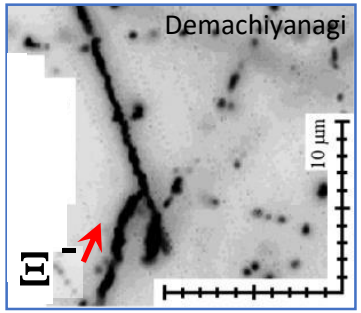
X10 statistics

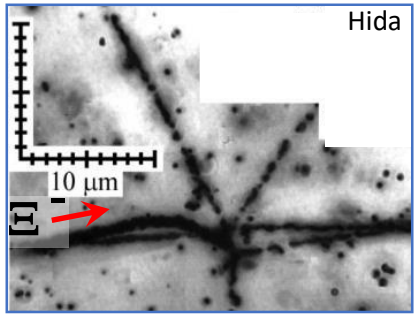
KEK-PS E373 (1998-2000)

PHYSICAL REVIEW C 88, 014003 (2013)









* At least ~650 Ξ^- stop events; Prog. Theor. Exp. Phys. 2019, 021D01
* NAGARA, KISO

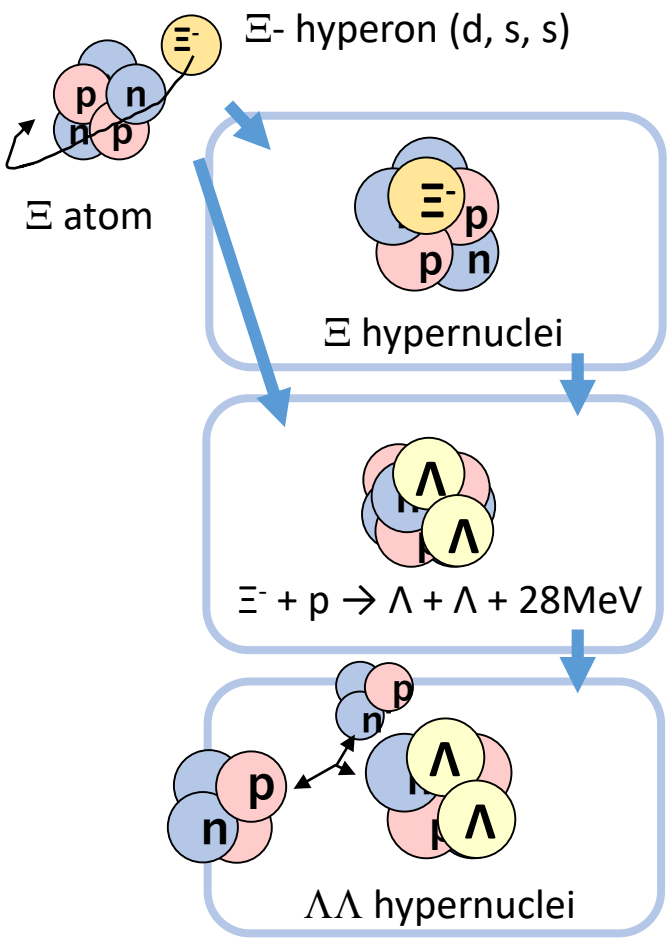
X10 statistics

J-PARC E07 (2016-17)

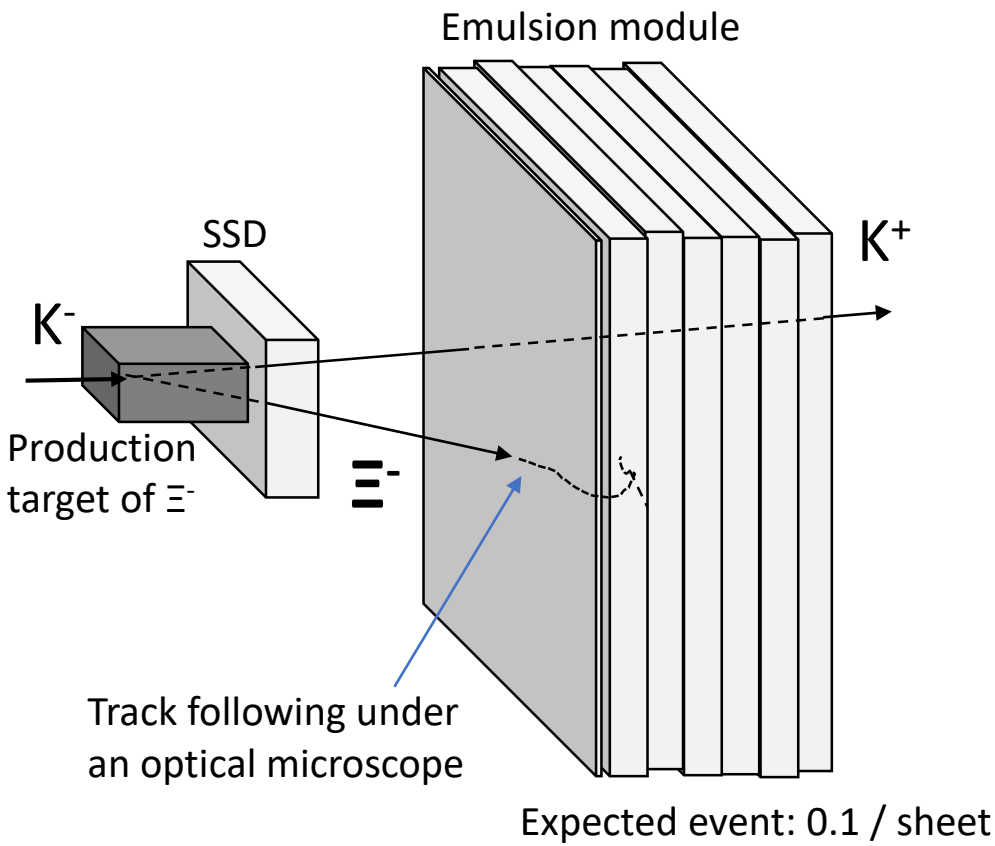
* ~10k Ξ^- stop events
* Systematic study of S=-2 system

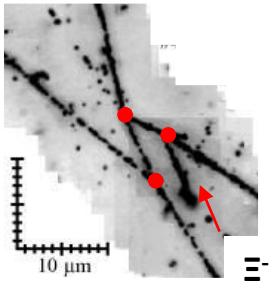
	Emulsion gel	K^- purity	Beam intensity
KEK-PS E373	0.8 tons	25%	$1*10^4$/spill
J-PARC E07	2.1 tons	~85%	$3*10^5$/spill

Principle of "Hybrid emulsion method"



The (K^-, K^+) reaction



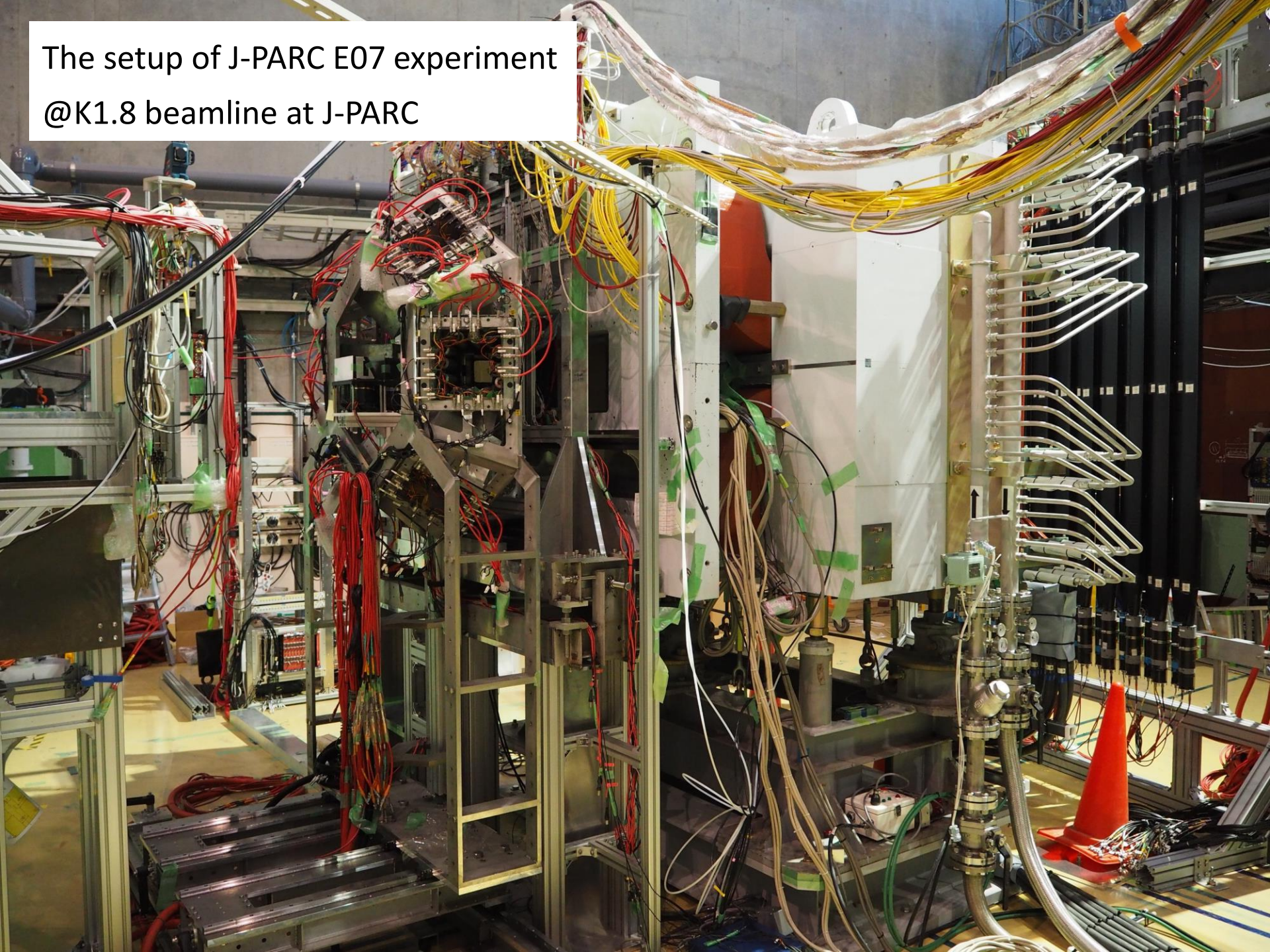


Visible as 3-vertex event

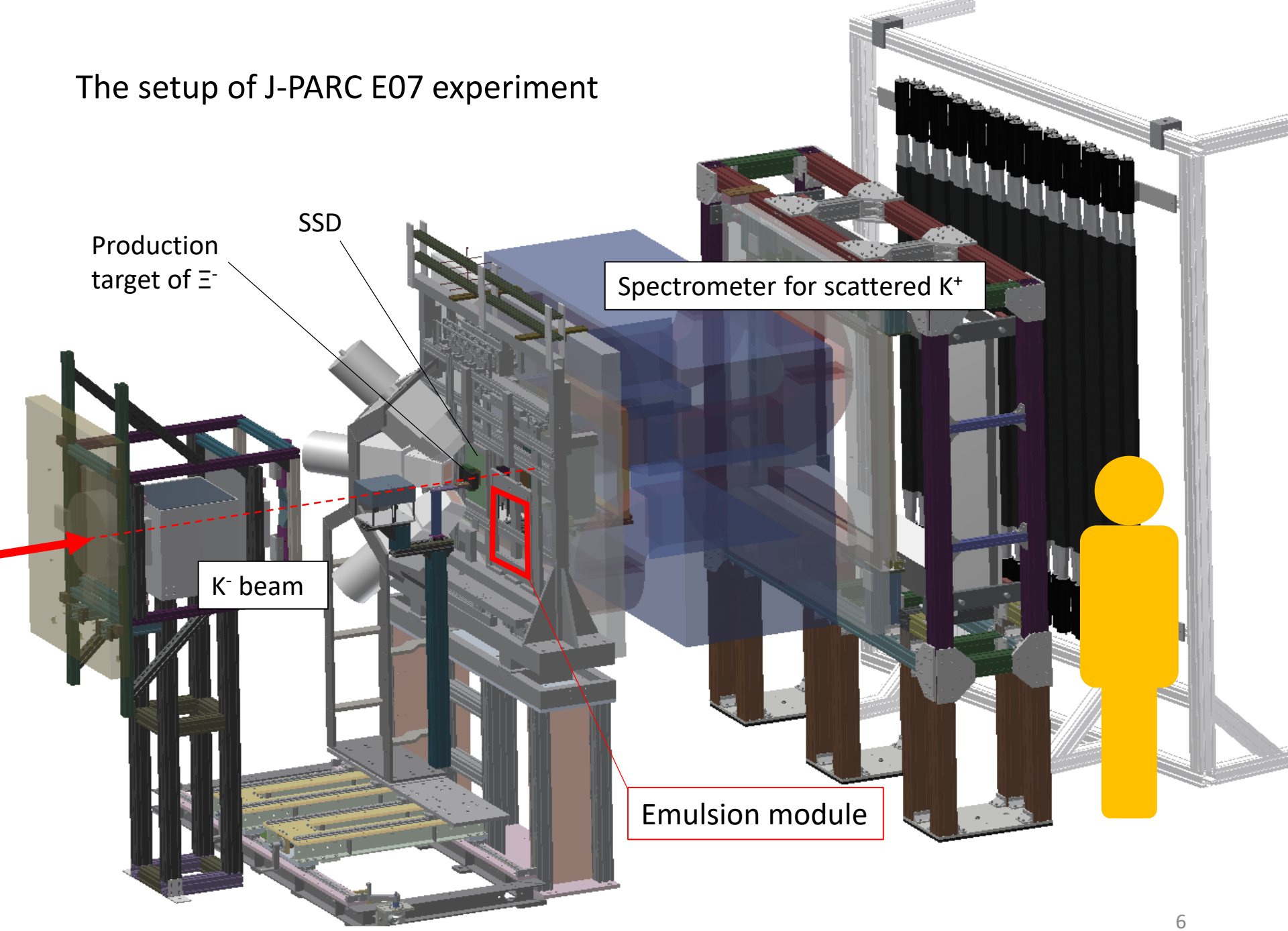
1. The capture point of Ξ^-
2. The weak decay point of the 1st Λ
3. The weak decay point of the 2nd Λ

The setup of J-PARC E07 experiment

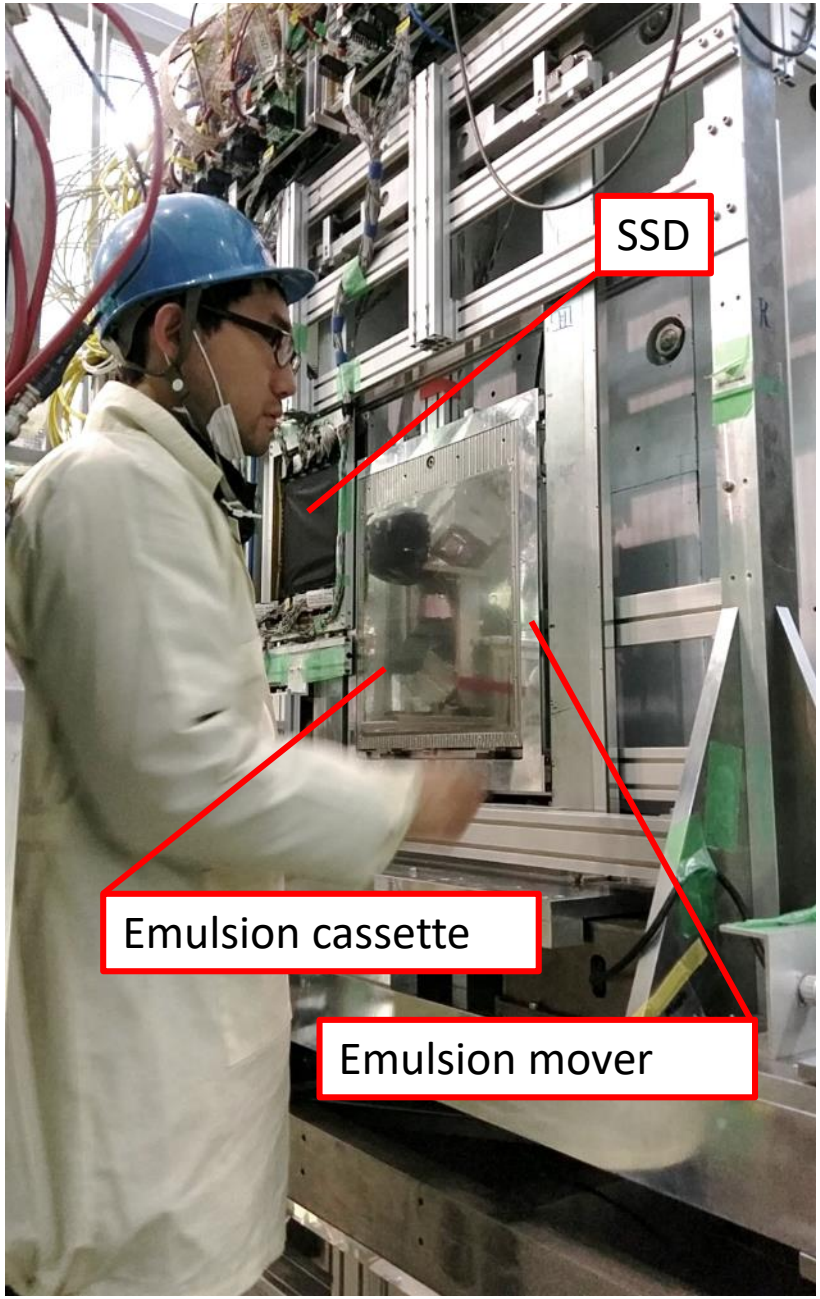
@K1.8 beamline at J-PARC

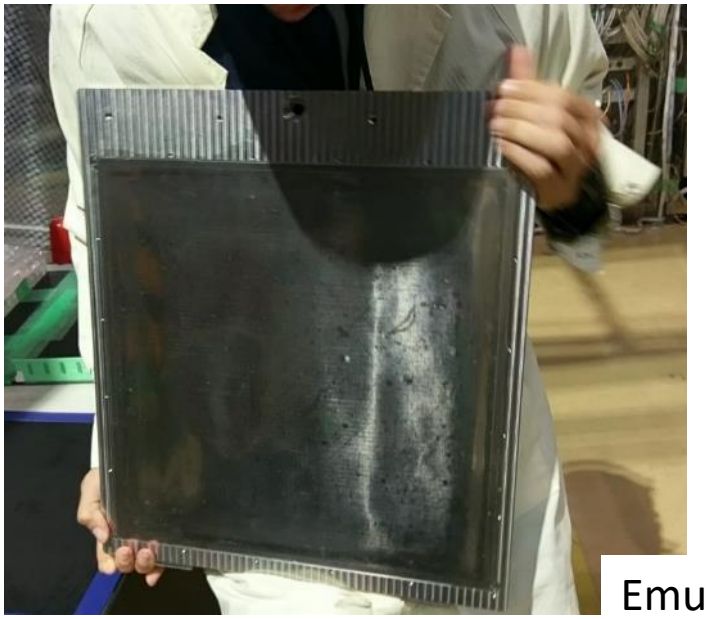


The setup of J-PARC E07 experiment

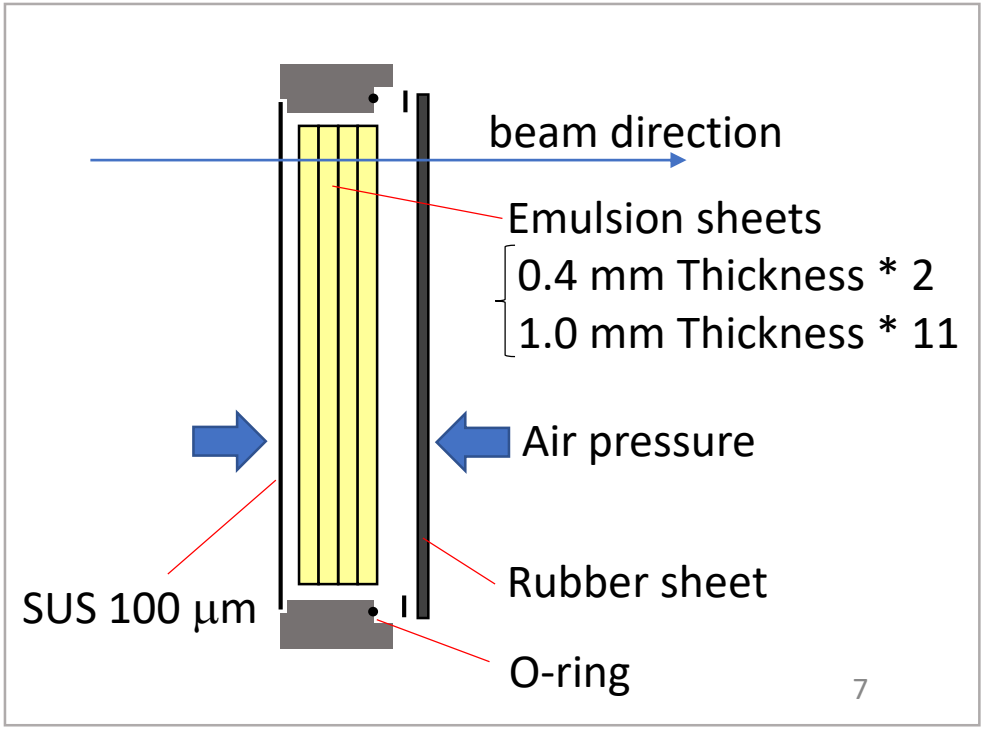


Near the emulsion module

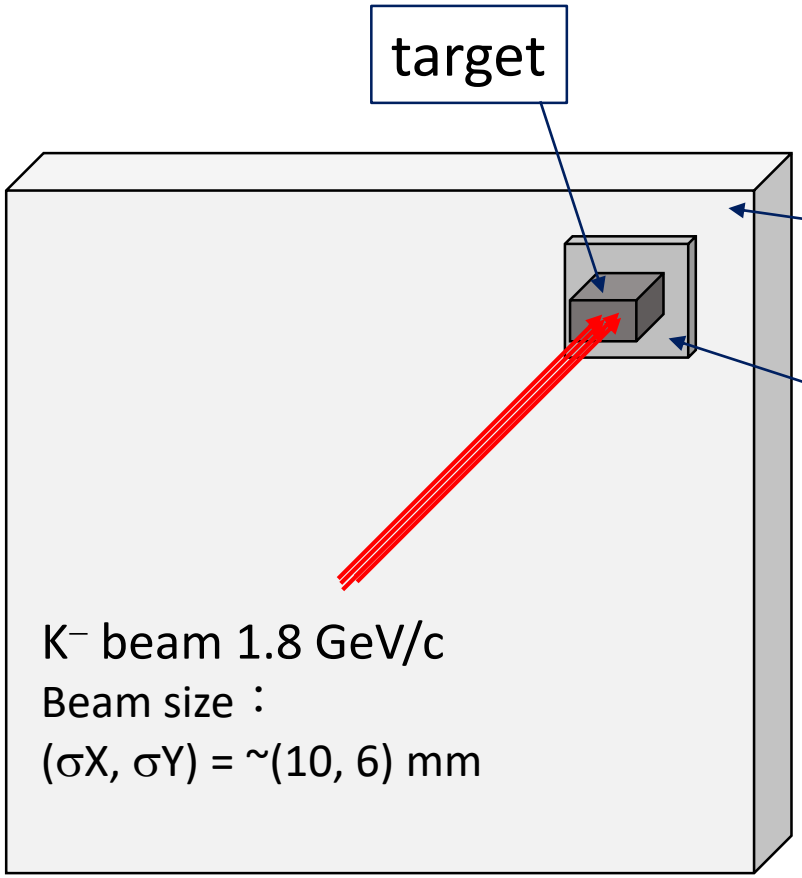


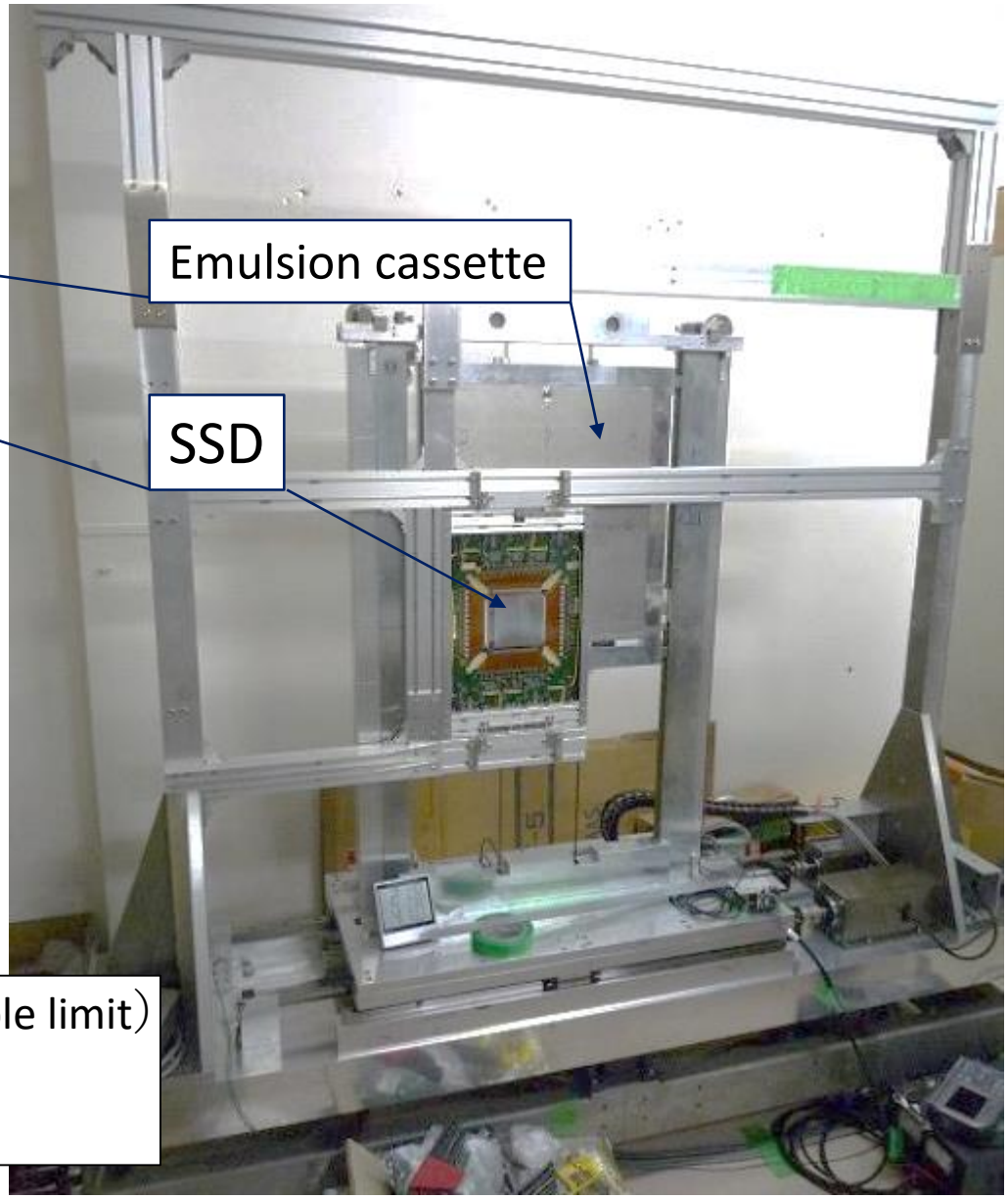


Emulsion cassette



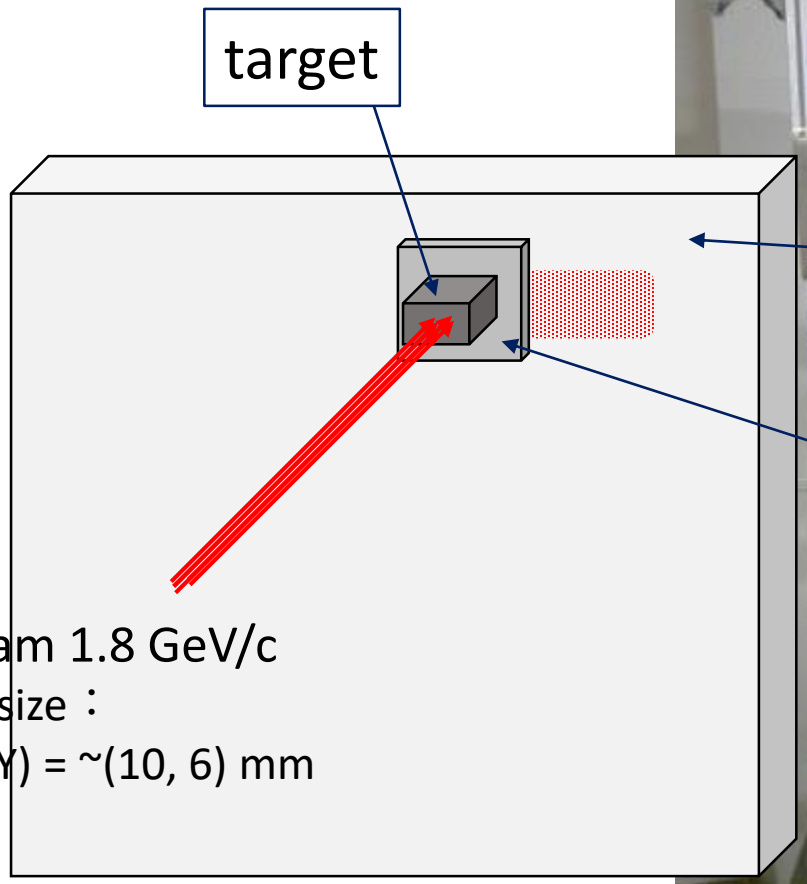
“Emulsion mover” for J-PARC E07

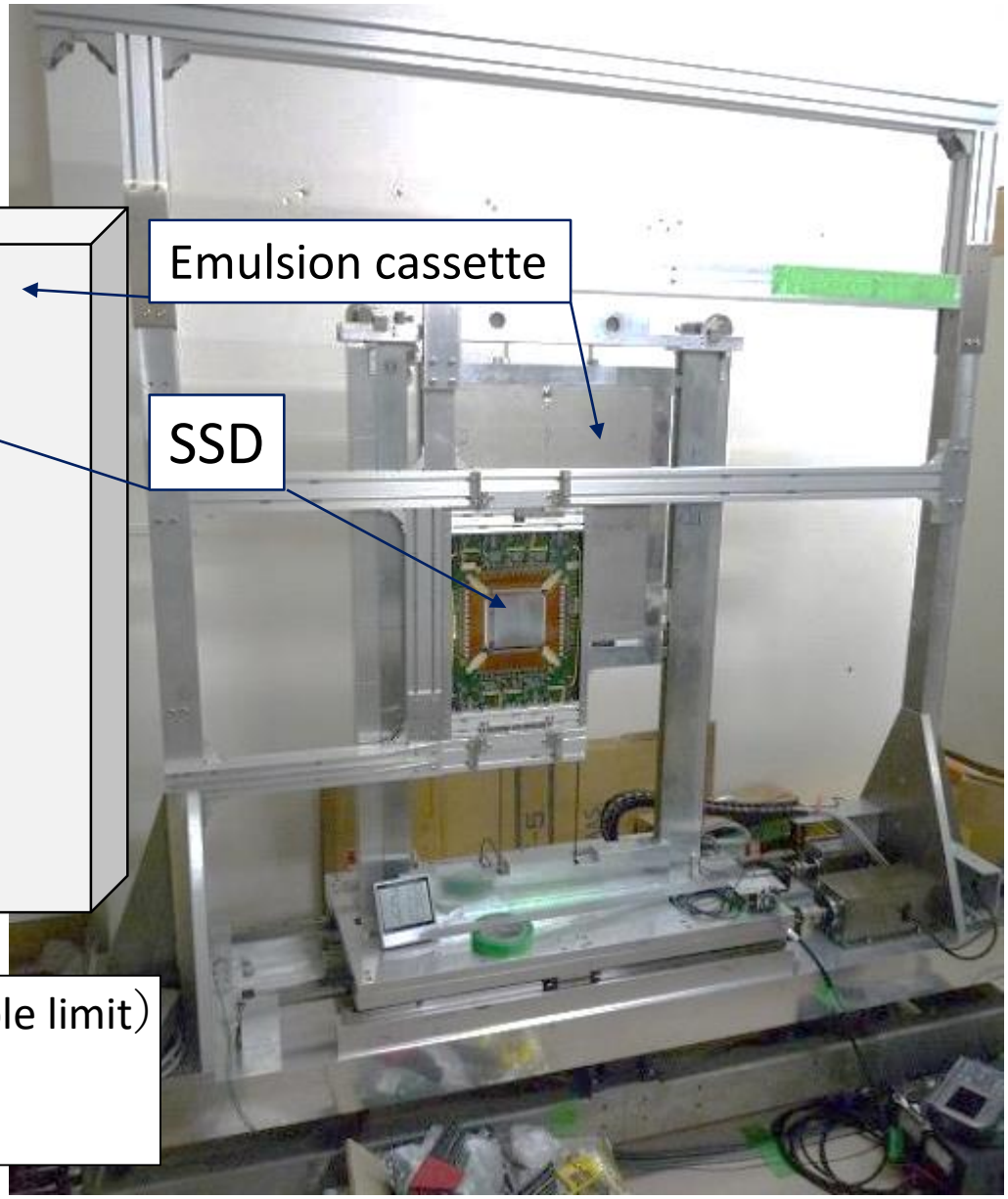




* Track density < 10^6/cm^2 （Observable limit）
* Sliding emulsion module spill by spill
* 6 hours / module

“Emulsion mover” for J-PARC E07





K^- beam 1.8 GeV/c
Beam size：
(σX, σY) = ~(10, 6) mm

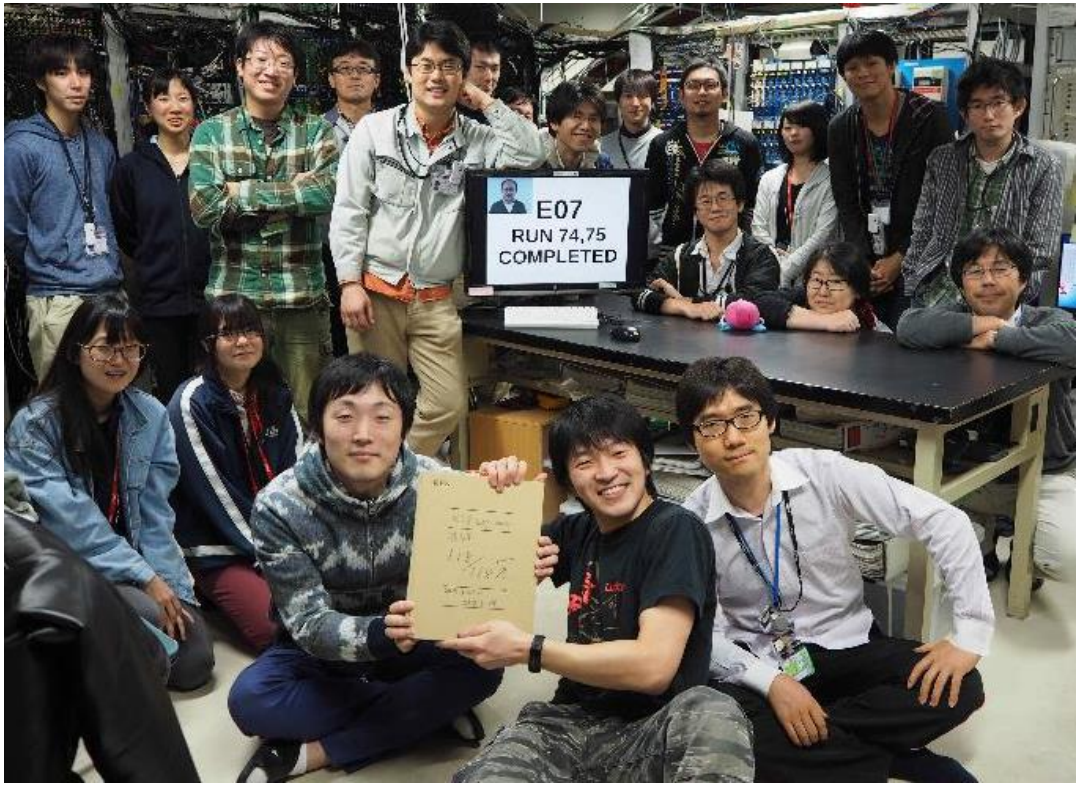
* Track density < $10^6/cm^2$ （Observable limit）
* Sliding emulsion module spill by spill
* 6 hours / module

Beam exposure

2016 May-Jun.
KURAMA Commissioning : 5.0 days
Physics run : 4.9 days

2017 4/15 - 4/19 (44 kW)
Emulsion exposure : 50 h
calibration : 19 h

2017 5/25 - 6/29 (10 - 37.5 kW)
Emulsion exposure : 23.4 days
calibration : 8.5 h



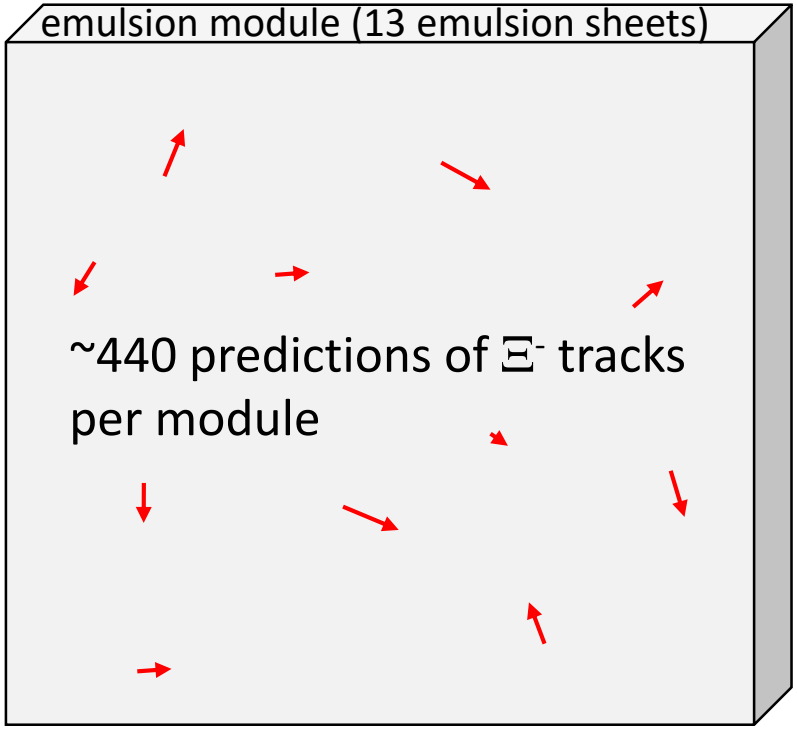
Jul. 1st 2017, Run end photo @K1.8 counting room

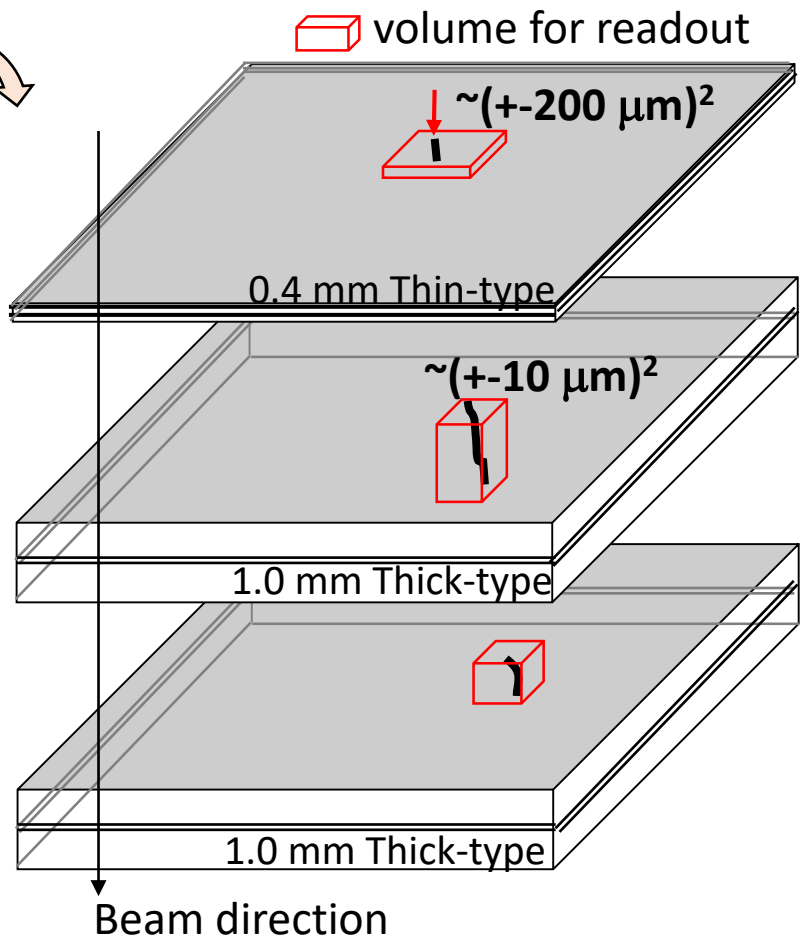
Year	Beam power [kW]	K^- intensity [/spill]	K^- purity	Time [h/mod.]	Integrated K^- [G/mod.]	DAQ Eff.	Emulsion modules
2016	42	260	81%	6.5	0.92	83%	18
2017	44	310	83%	5.6	1.0	84%	8
2017	37.5	280	82%	6.0	1.0	89%	78
2017	10 - 35	120 - 270	50% - 82%	6.5 – 9.0	0.52 – 1.0	89-92%	14

118 emulsion modules * 13 emulsion sheets

Track following for Ξ⁻ stop event
with dedicated image processing

* Disassembling
* Photographic developing





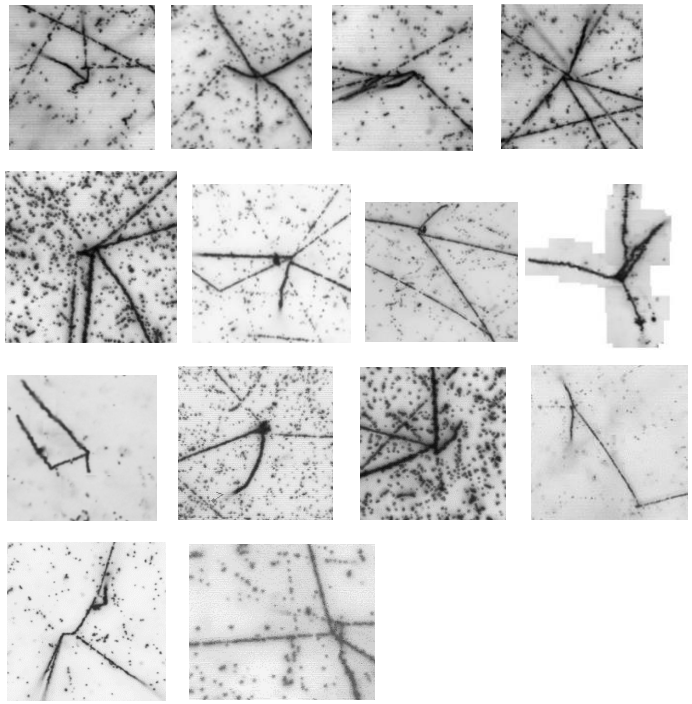
Automated Track Following (Sample Movie)
https://youtu.be/3fiWI5tDx2U

Detected 3-vertex events (33 events)

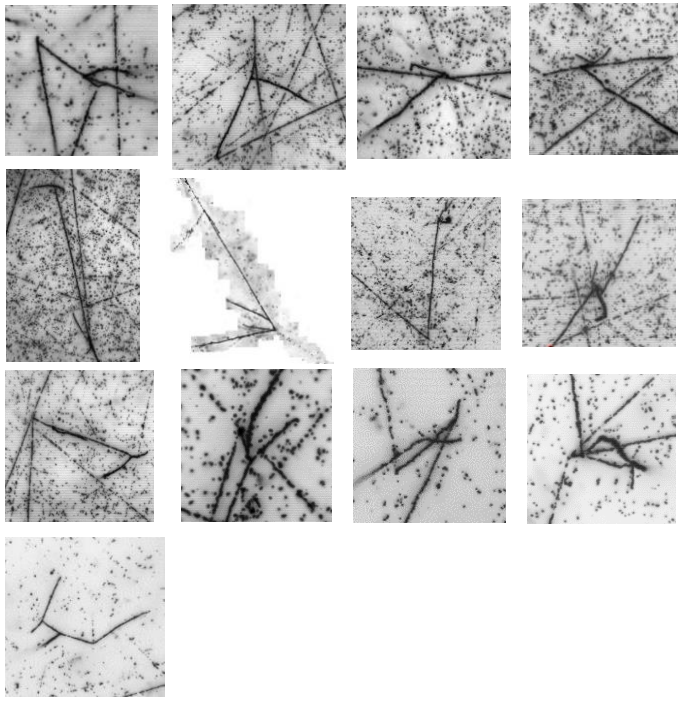
1. The capture point of Ξ^-
2. The weak decay point of the 1st Λ
3. The weak decay point of the 2nd Λ

- $3*10^3$ Ξ^- stop events
- The number of detected events has nearly tripled in the past.

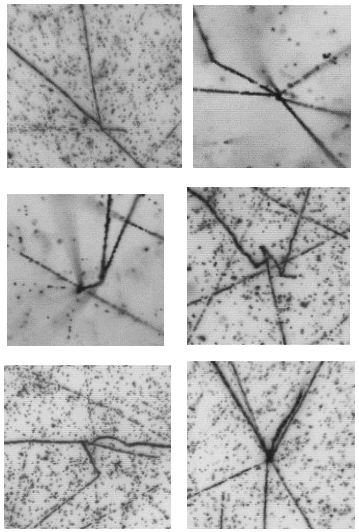
$\Lambda\Lambda$ candidates: 14

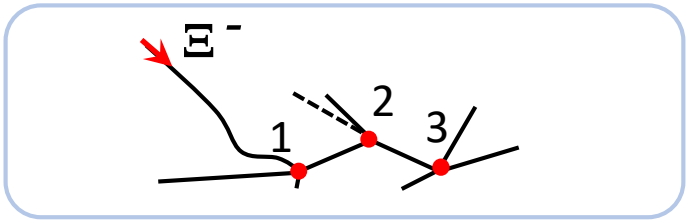


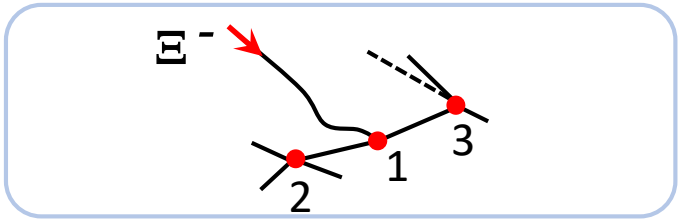
Twin Λ events: 13



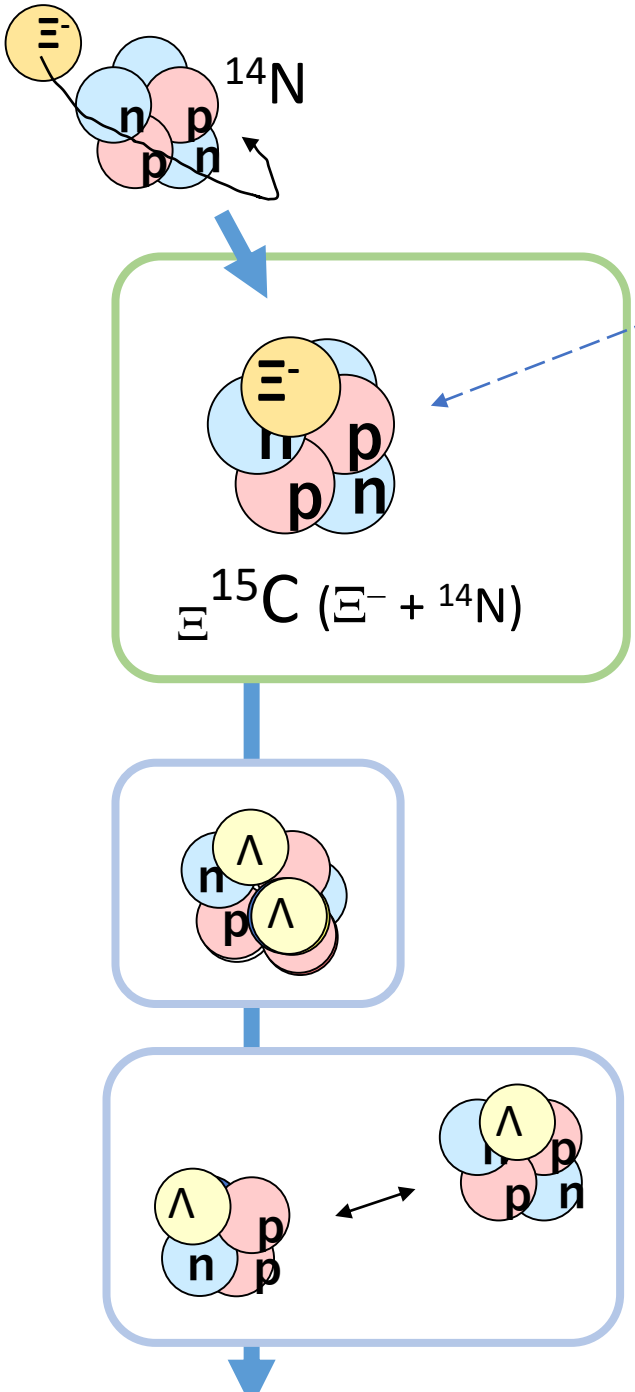
Others: 6



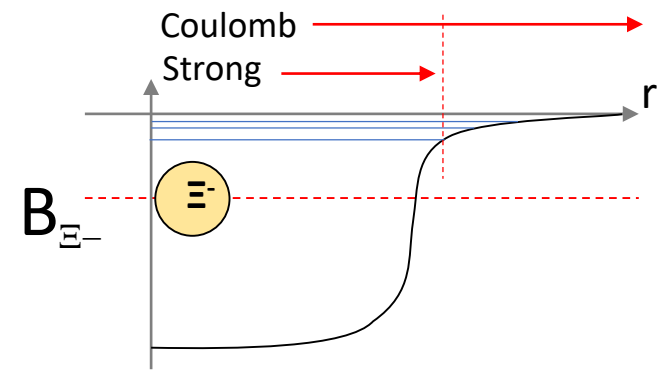




Ξ hypernuclei detection via "twin Λ hypernuclear event"



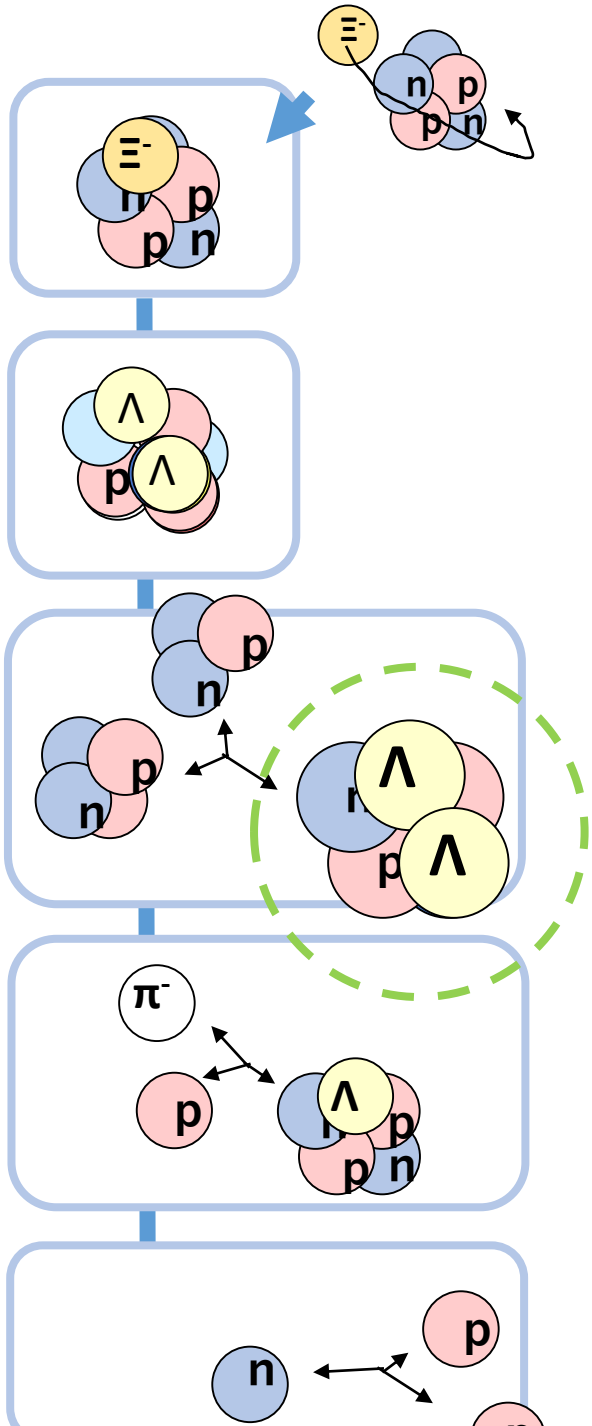
Ξ Hypernucleus formation



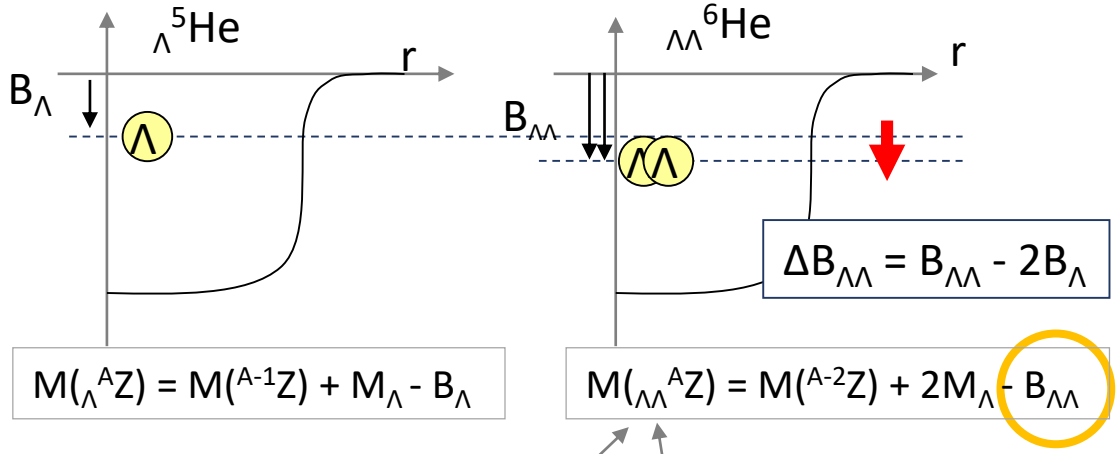
$E_{initial\_state}$ = Mass (^{14}N) + Mass (Ξ^-) − $B_{\Xi-}$

Energy conservation

E_{final_state} = SUM (Mass + kinetic energy) for all fragments



ΛΛ hypernuclei detection



Energy conservation

Production:

$$\text{Mass}(Z) + \text{Mass}(\Xi^{-}) - B_{\Xi^{-}} = \text{Mass}(_{\Lambda\Lambda}{}^{A}Z) + \text{kinetic energy}(_{\Lambda\Lambda}{}^{A}Z) + \text{SUM}(\text{Mass} + \text{kinetic energy})$$

for other fragments

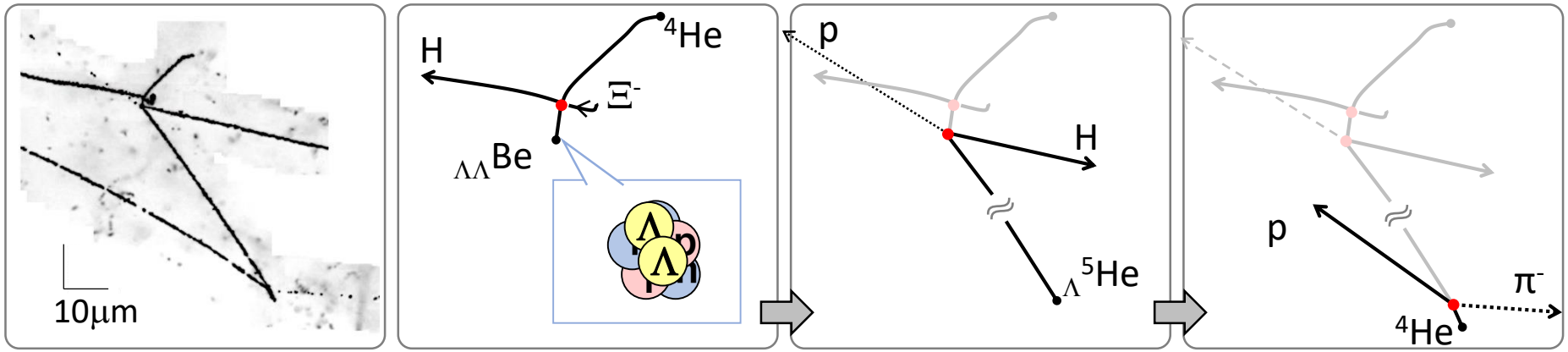
Decay:

$$\text{Mass}(_{\Lambda\Lambda}{}^{A}Z) = \text{SUM}(\text{Mass} + \text{kinetic energy})$$

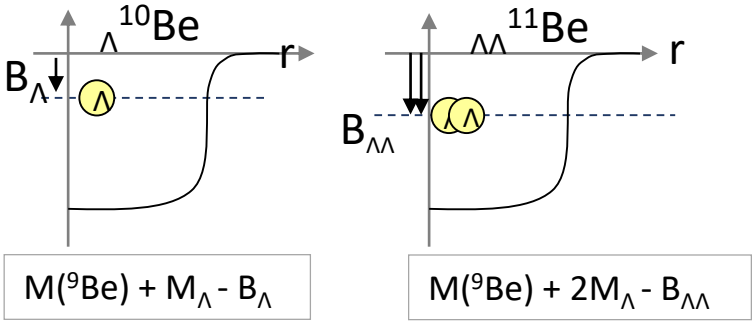
for all fragments

MINO event

H. Ekawa et al.,
Prog. Theor. Exp. Phys. 2019, 021D02



$$^{16}\mathrm{O} + \Xi^- \rightarrow ({}^{10}_{\Lambda\Lambda}\mathrm{Be},\ {}^{11}_{\Lambda\Lambda}\mathrm{Be},\ {}^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_\Lambda\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$

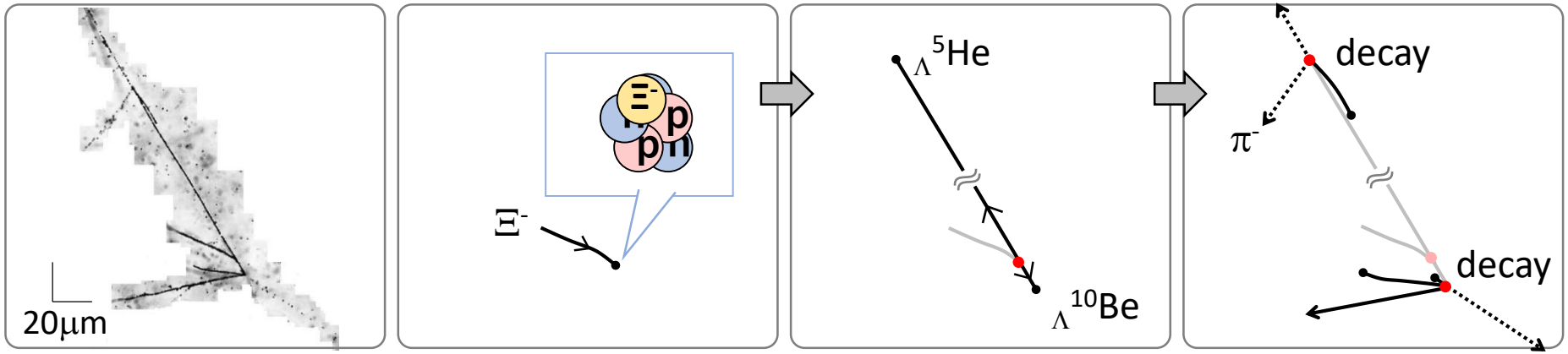


	Possible interpretations	$B_{\Lambda\Lambda}$ [MeV]	Kinematic fitting χ^2 (DOF=3)
Most probable	$\Xi^- + {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{10}Be + {}^4He + t$	15.05 +- 0.11	11.5
➡	$\Xi^- + {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{11}Be + {}^4He + d$	19.07 +- 0.11	7.3
	$\Xi^- + {}^{16}O \rightarrow {}_{\Lambda\Lambda}{}^{12}Be^* + {}^4He + p$	13.68 +- 0.11 + E_{ex}	11.3

Where, B_{Ξ^-} = 0.23 MeV (3D state)

IBUKI event

S. H. Hayakawa, Ph.D. Thesis, Osaka Univ. (2019)



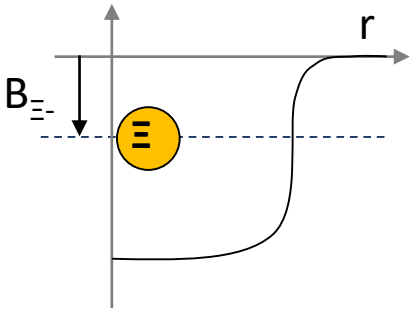
$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$

${}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{10}Be + {}_{\Lambda}{}^{5}He$

${}_{\Lambda}{}^{5}He$ -> 3-prong with π^-

${}_{\Lambda}{}^{10}Be$ -> 4-prong

- The 1st candidate of Ξ hypernucleus in E07.
- The B_{Ξ^-} are measured precisely.

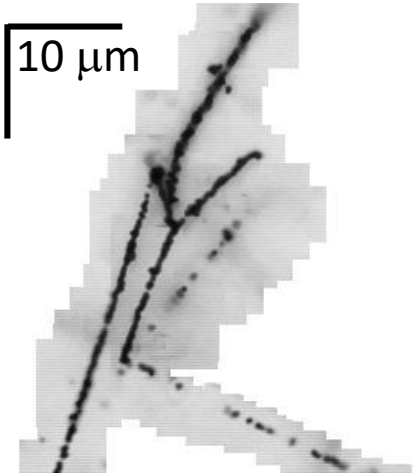


Possible interpretation	B_{Ξ^-} [MeV]	Uncertainty of B_{Ξ^-} [MeV]
$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{10}Be + {}_{\Lambda}{}^{5}He$	1.27	0.21

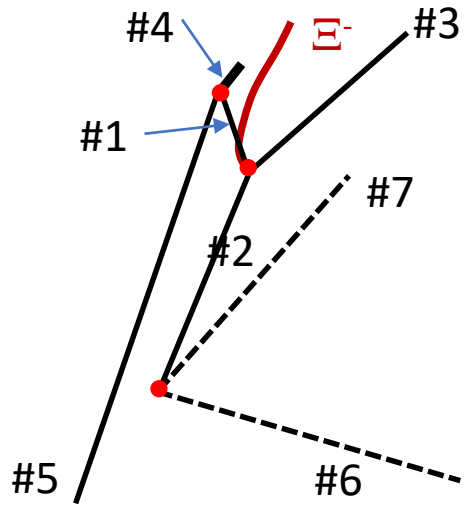
- Decay without neutron -> Kinematic fit

Event –Twin#010 (Irrawaddy event)

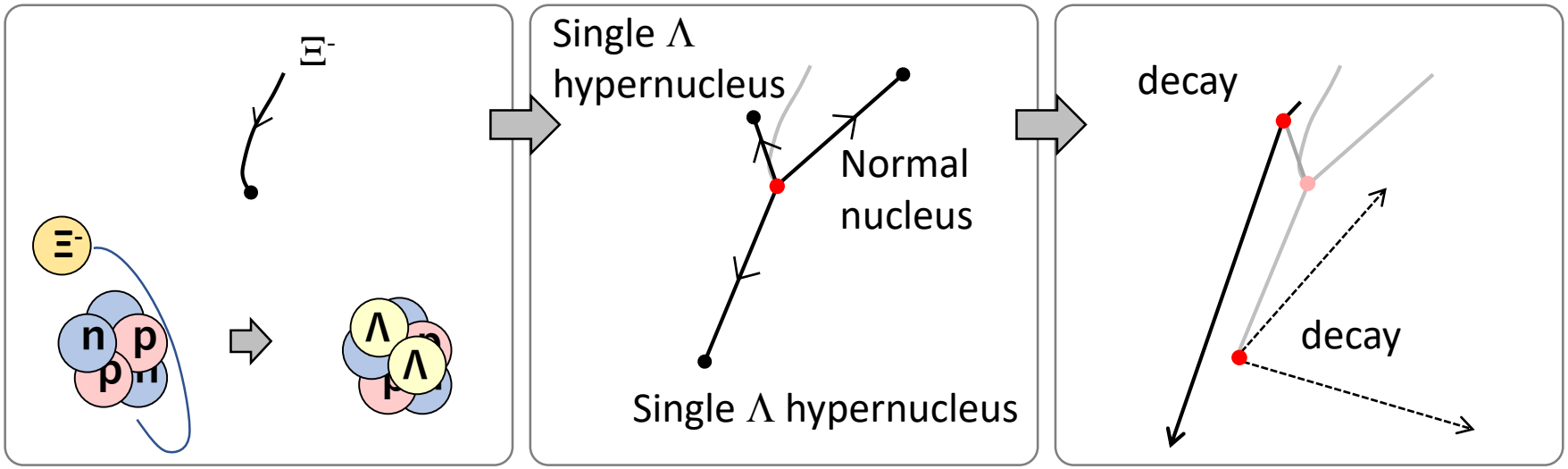
Microscopic image



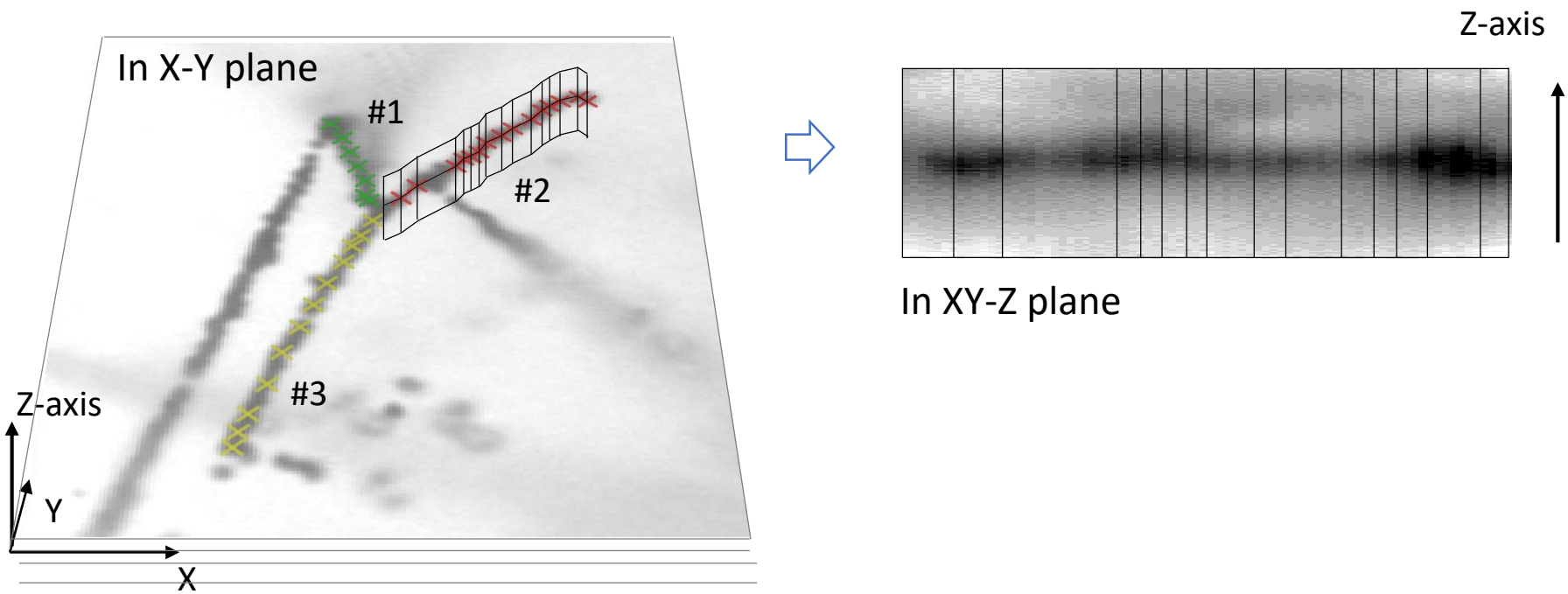
Event Topology



- 3-prong from a Ξ^- stop
- 2 hyperfragments
- 2 non-mesonic decay

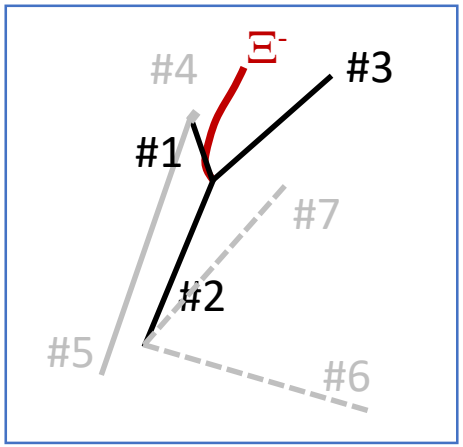


Precise track measurement using image processing



Track	Range [μm]	θ [deg]	ϕ [deg]
#1	4.99 ± 0.22	97.68 ± 2.8	288.17 ± 2.6
#2	12.31 ± 0.22	88.21 ± 1.0	68.91 ± 0.95
#3	10.12 ± 0.24	92.67 ± 1.5	222.20 ± 1.2
#4	2.9 ± 0.2	170 ± 4	214 ± 4
#5	189.7 ± 0.6	84 ± 1	69 ± 1
#6	2770.5 ± 1.3	116.7 ± 1.4	154.0 ± 0.4
#7	8404.2 ± 8.5	27.4 ± 0.8	229.3 ± 1.3

Identification of nuclides



	Target		#1		#2		#3		Invisible
Ξ^- +	^{12}C ^{13}C ^{14}N ^{15}N ^{16}O ^{18}O	→	$^{3}_{\Lambda}H$ $^{4}_{\Lambda}H$ $^{4}_{\Lambda}He$ …	+	$^{3}_{\Lambda}H$ $^{4}_{\Lambda}H$ $^{4}_{\Lambda}He$ …	+	p d t ^{3}He …	+	None n 2n 3n
# of case:	6		41		41		57		4

All combination:

2299608

= 6*41*41*57*4

>>

Mass number and charge conservation:

1700

>>

Initial mass > Final mass:

104

↓

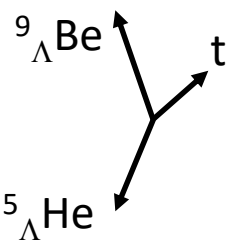
kinematical consistency check

Identification of nuclides

Example:1

$\Xi^- + {}^{16}O \rightarrow {}^{9}_{\Lambda}Be + {}^{5}_{\Lambda}He + t$

K.E. = 3.7 +- 0.2 MeV
|p| = 251.3 +- 6.2 MeV/c



K.E. = 1.06 +- 0.02 MeV
|p| = 77.0 +- 0.9 MeV/c

K.E. = 3.5 +- 0.1 MeV
|p| = 184.9 +- 1.5 MeV/c

$|p_{invisible}|$ = 148.4 +- 9.8 MeV/c

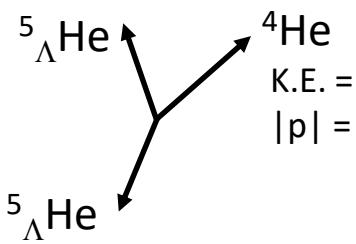
Inbalancement of momentum:

Rejected

Example:2

$\Xi^- + {}^{14}N \rightarrow {}^{5}_{\Lambda}He + {}^{5}_{\Lambda}He + {}^{4}He + n$

K.E. = 1.5 +- 0.1 MeV
|p| = 119.6 +- 3.0 MeV/c



K.E. = 2.8 +- 0.1 MeV
|p| = 146.3 +- 1.5 MeV/c

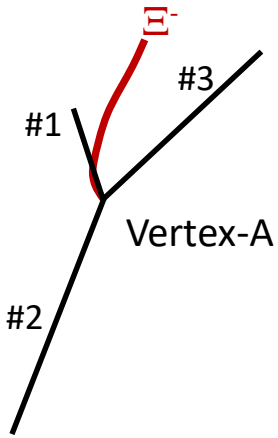
K.E. = 3.5 +- 0.1 MeV
|p| = 184.9 +- 1.5 MeV/c

$|p_{Missing}| = |p_{neutron}|$ = 42.1 +- 5.3 MeV/c
K.E. of neutron = 0.9 +- 0.2 MeV

Q-value > 0:

Accepted

Identification of Nucleus



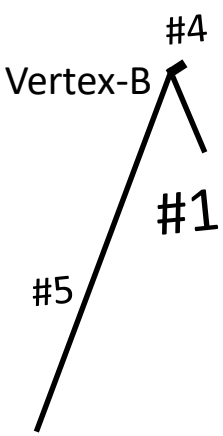
Possible reactions at vertex-A :

$$\Xi^- + {}^{14}N \rightarrow {}^{5}_{\Lambda}He + {}^{5}_{\Lambda}He + {}^{4}He + n$$

Mass (Ξ^-) + Mass (^{14}N) - B_{Ξ^-} = Mass (All_fragmemts) + K.E. (All_fragmemts)

B_{Ξ^-} = 6.3 ± 0.3 MeV (preliminary result)

(Rounded to two significant figures.)



Possible reactions at vertex-B :

${}^{5}_{\Lambda}He \rightarrow p + p + 3n$

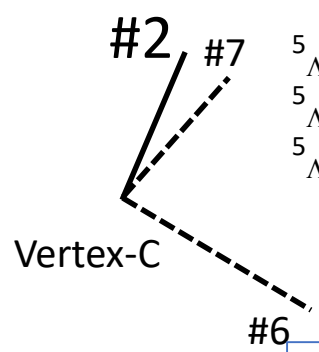
${}^{5}_{\Lambda}He \rightarrow p + d + 2n$

${}^{5}_{\Lambda}He \rightarrow d + p + 2n$

${}^{5}_{\Lambda}He \rightarrow d + p + \pi^0 + 2n$

${}^{5}_{\Lambda}He \rightarrow d + p + \pi^0 + 2n$

${}^{5}_{\Lambda}He$ is Possible



Possible reactions at vertex-C:

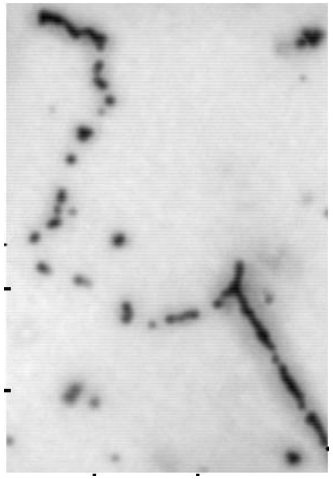
${}^{5}_{\Lambda}He \rightarrow p + p + 3n$

${}^{5}_{\Lambda}He \rightarrow p + d + 2n$

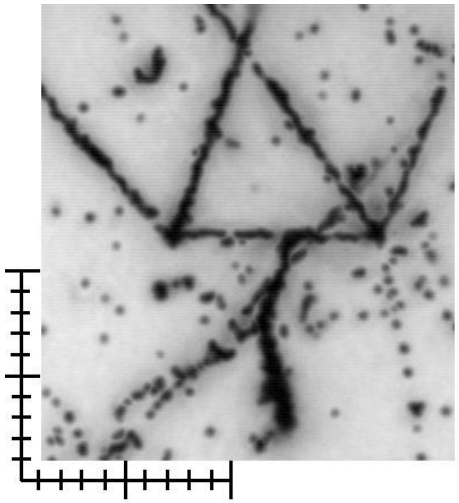
${}^{5}_{\Lambda}He \rightarrow d + p + 2n$

${}^{5}_{\Lambda}He$ is Possible

E373 Kinka event



X-Y view



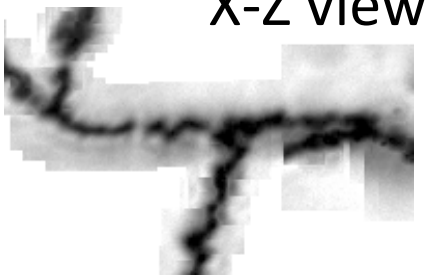
Uniquely identified
via a new charge identification method

An experiment at RIKEN : NP1406-RRC32

S. Kinbara, et al., PTEP 2019, 011H01
https://doi.org/10.1093/ptep/pty137.

3D measurement
as X-Z plane

X-Z view



Possible B_{Ξ^-}

$\Xi^- + {}^{14}N \rightarrow {}^{9}_{\Lambda}Be + {}^{5}_{\Lambda}He + n$

$B_{\Xi^-} = 8.0 \pm 1.1$ MeV (preliminary result)

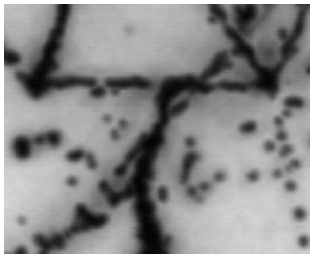
$\Xi^- + {}^{14}N \rightarrow {}^{9}_{\Lambda}Be^* + {}^{5}_{\Lambda}He + n$

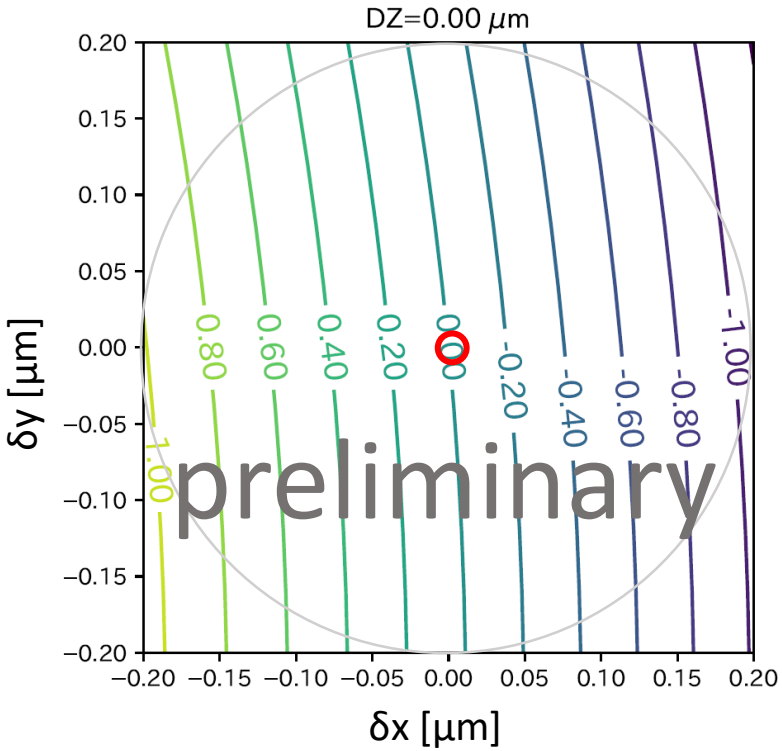
$B_{\Xi^-} = 5.1 \pm 1.1$ MeV (preliminary result)

B_{Ξ^-} Uncertainty

Spatial resolution of AgBr crystal in emulsion ~= 0.2 μm.

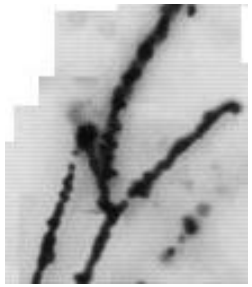
Kinka

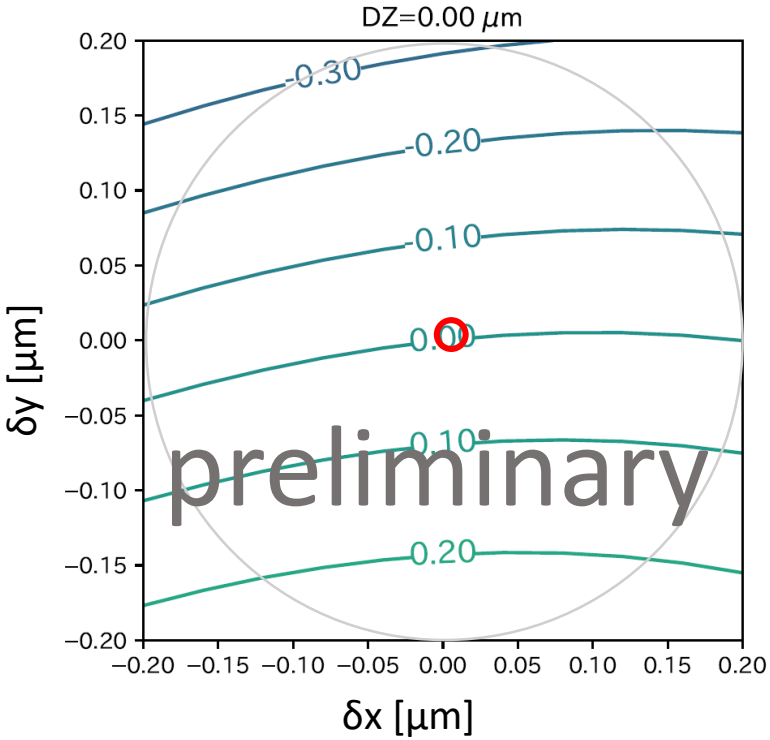




B_{Ξ^-} = 8.0 or 5.1 ± 1.1 MeV (preliminary result)

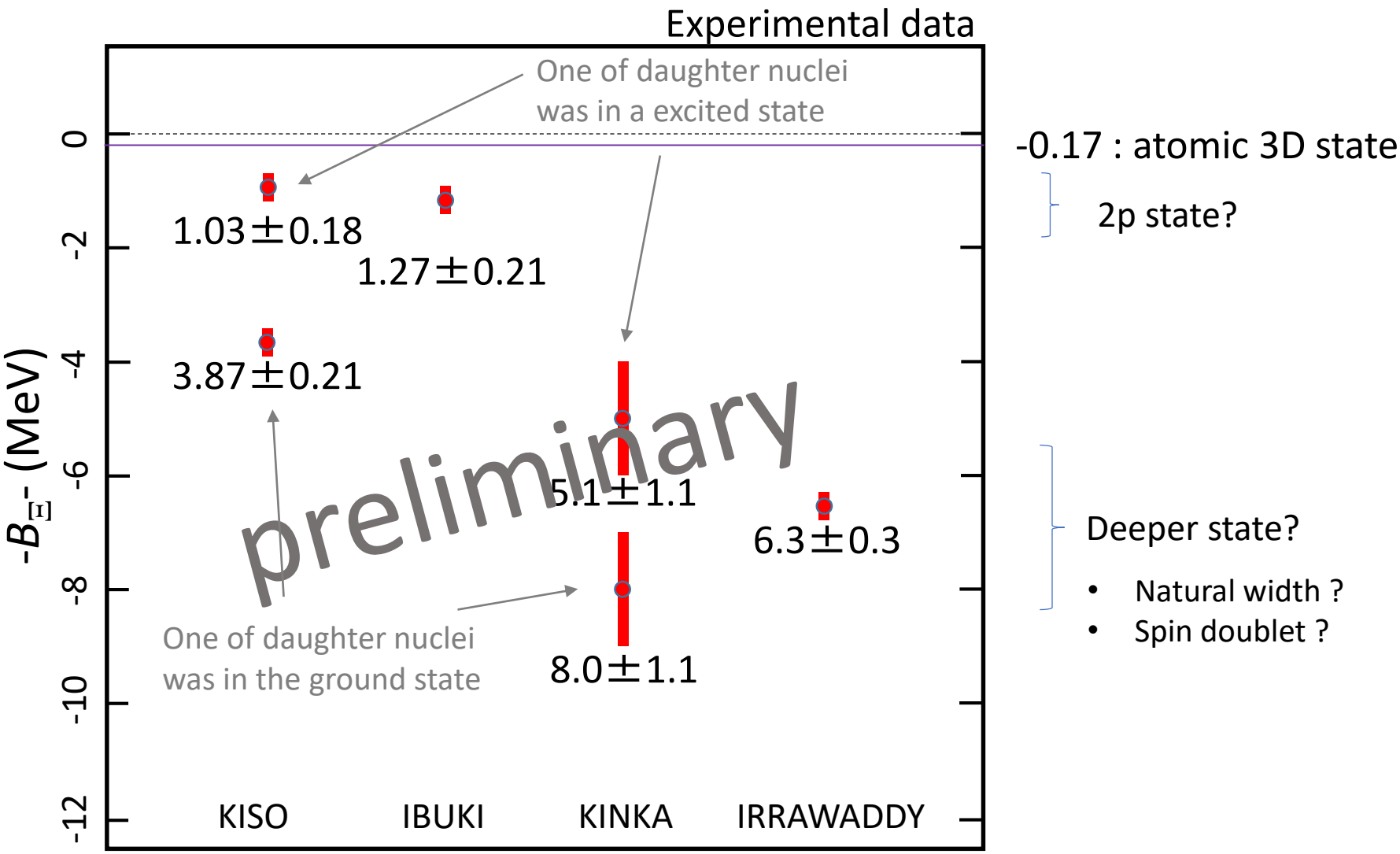
Irrawaddy





B_{Ξ^-} = 6.3 ± 0.3 MeV (preliminary result)

Level scheme of Ξ^--^{14}N system



List of twin Λ hypernuclear events

		Ξ^- captured by…			daughter hypernuclei						
		^{12}C	^{14}N	^{16}O	H	He	Li	Be	B	C	n
Atomic state	E176 #10-9-6 (2*p*?)	●			^{4}H			^{9}Be			
	E176 #13-11-14 (2*p*?)	●			^{4}H			^{9}Be			
	T008, atomic	●			*t*	2^{5}He					
	T009, atomic	●				^{5}He	^{8}Li				
	T004, atomic			●		^{5}He			^{12}B		
	E373 - 1		●			2^{5}He,α					1
	E176 #14-03-35(2*p*?)		○	○							
	T002 (2*p*?)		●			^{5}He		^{9}Be			1
	T013 (2*p*?)	○	○		(*t*)	2^{5}He, (α)					(1)
Ξ hypernuclei	E373 : **KISO**		●			^{5}He		^{10}Be			
	T006 : **IBUKI**		●			^{5}He		^{10}Be			
	T003	?	●	?		^{5}He		^{9}Be			1
	E373 : **KINKA**		●			He		^{9}Be			1
	T007		●			^{5}He		^{9}Be			1
	T010 : **IRRAWADDY**		●			2^{5}He, α					1
	T011 (under analysis)		●			2^{5}He, α					1

preliminary result

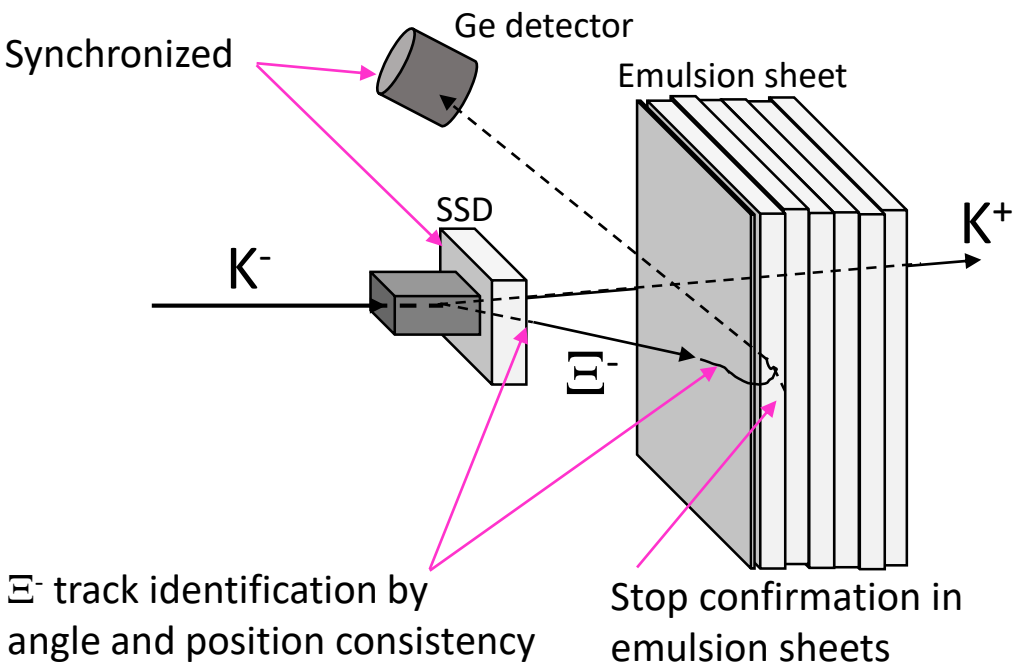
Excess?

alpha cluster structure?

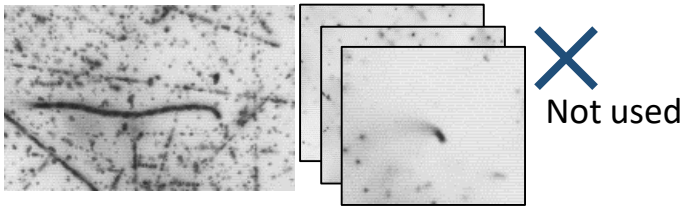
●: Uniquely identified
○: Multiple interpretations

X-ray measurement from Ξ⁻ atom

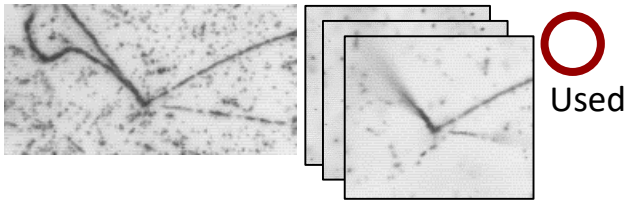
with Hybrid method combined Ge detector and emulsion

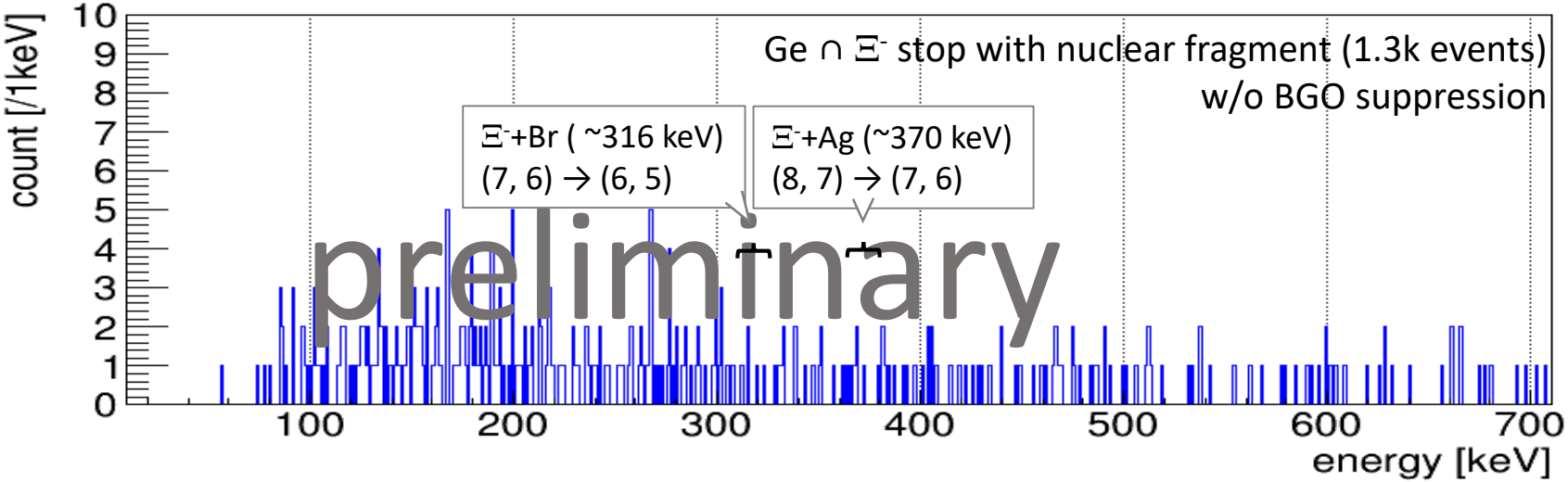


Stop without nuclear fragment (Ξ- or proton)



Stop with nuclear fragment (almost Ξ-)





Short summary

- Number of Ξ^- stop events is approximately $4*10^3$
  KEK-PS E176: ~80
  KEK-PS E373: At least ~650
  J-PARC E07: $3*10^3$

- The number of detected double strangeness events has nearly tripled in the past.

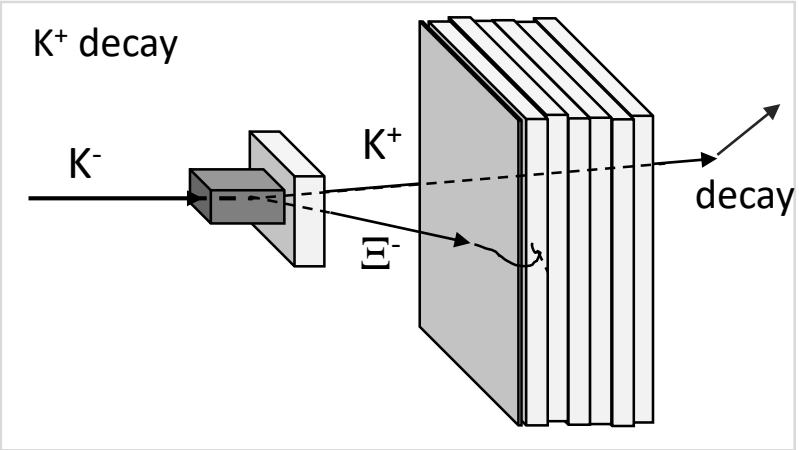
- Analyses of twin Λ hypernuclear events
  Irrawaddy event
  Kinka event
  They suggest existence of a very deep bound state of Ξ^--^{14}N system.

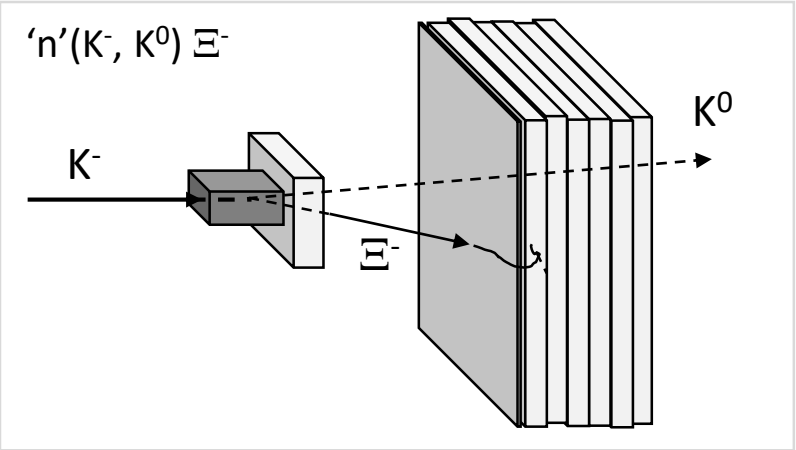
- Several events are identified as ($\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}Be + {}_{\Lambda}He$)

- X-ray measurement from Ξ^- atom is ongoing

Overall scanning method

Untriggerable reactions

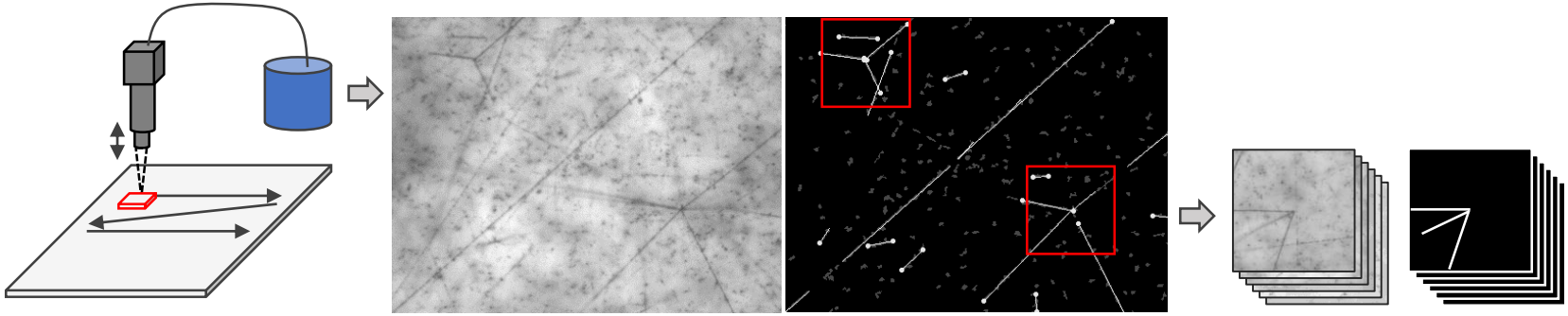




Trigger efficiency is approximately 0.3

Double cross section to (K^-,K^+)

Expected event number: ~1 / sheet. Totally 10^3 events in emulsion sheet of J-PARC E07

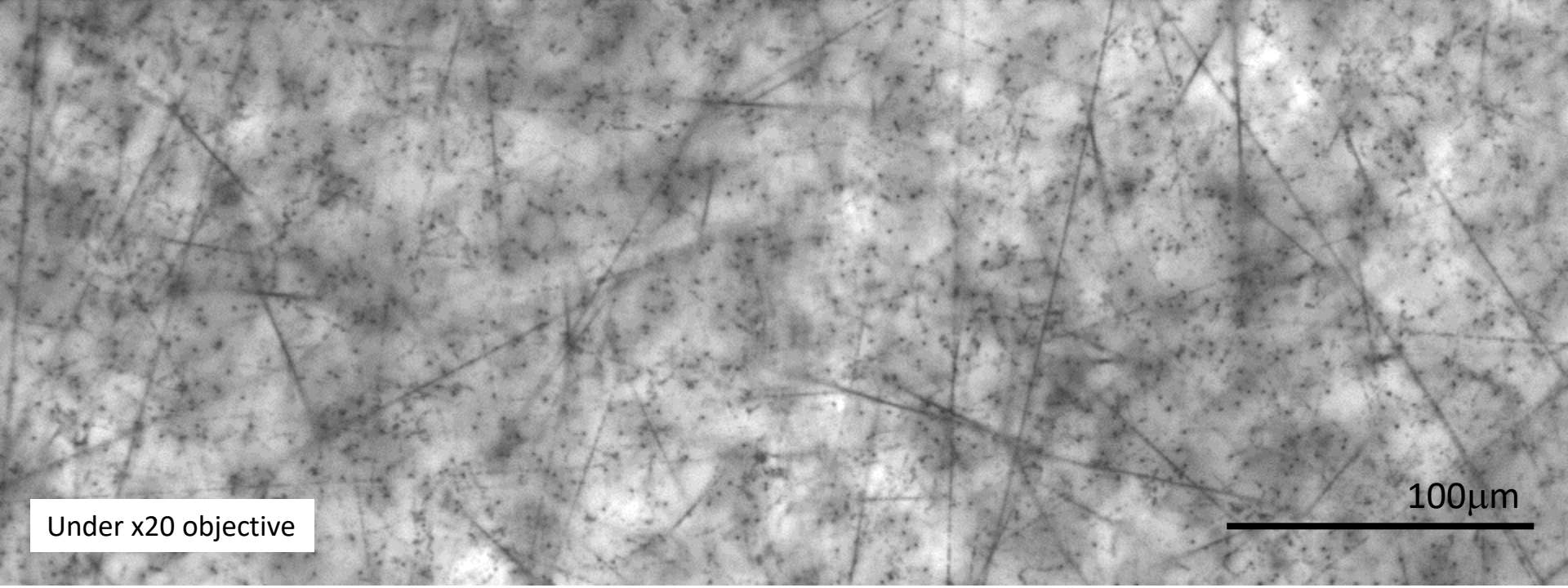


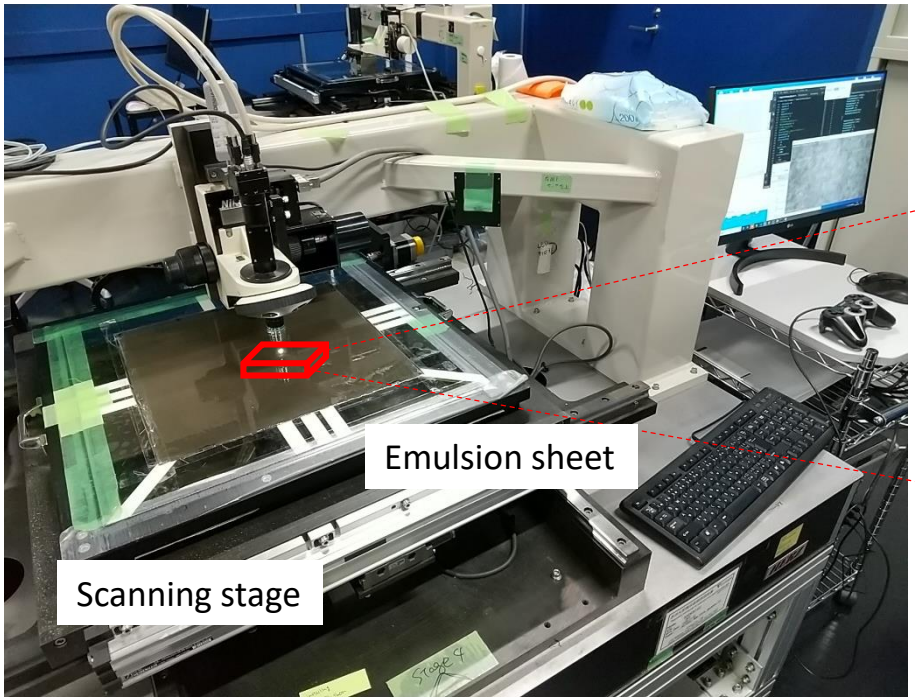
Scanning

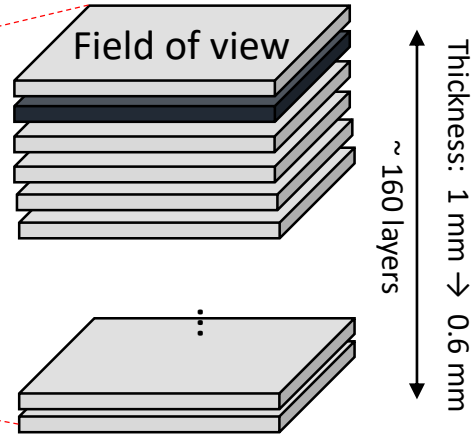
Vertex detection using image processing

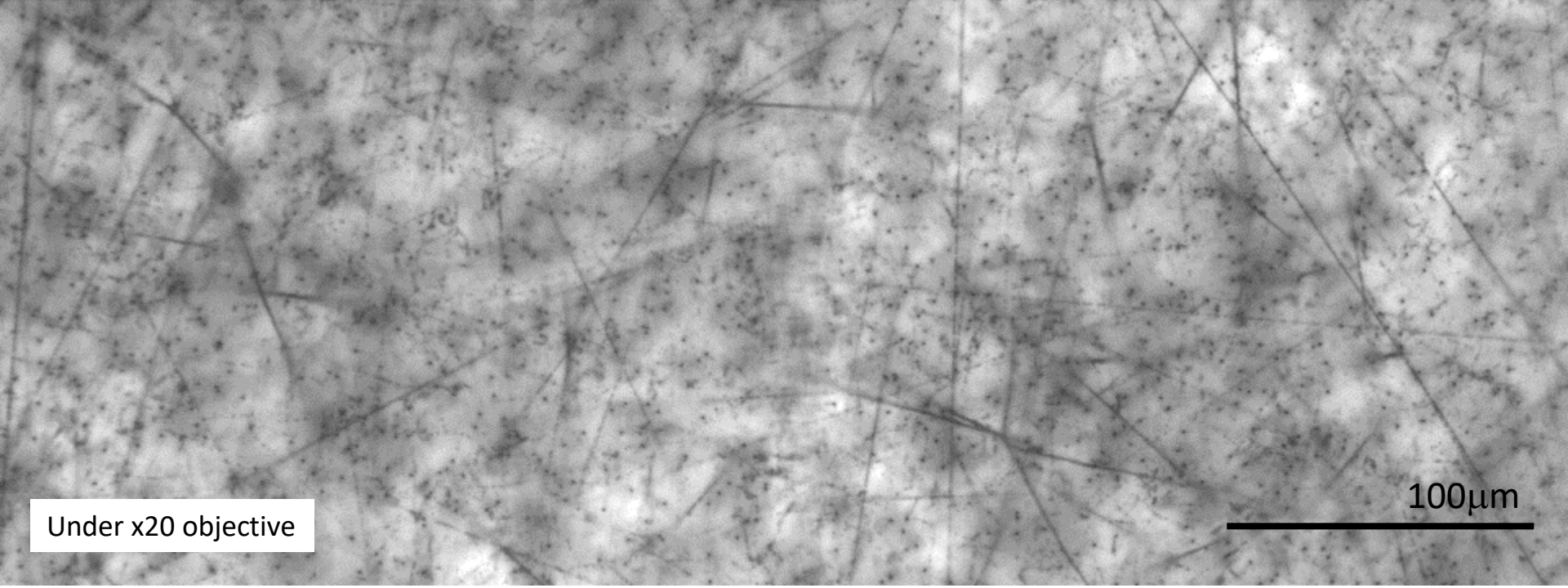
Image and line information

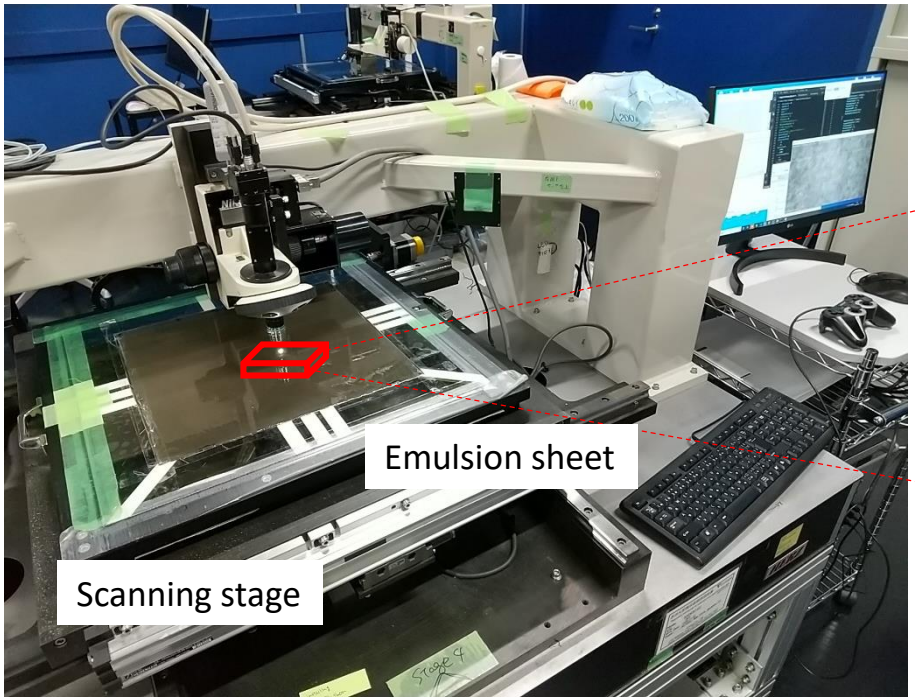
J. Yoshida, et al., N.I.M A, 847 (2017) 86-92

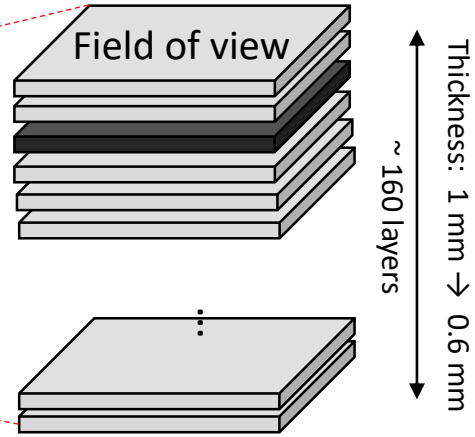

Under x20 objective
100μm

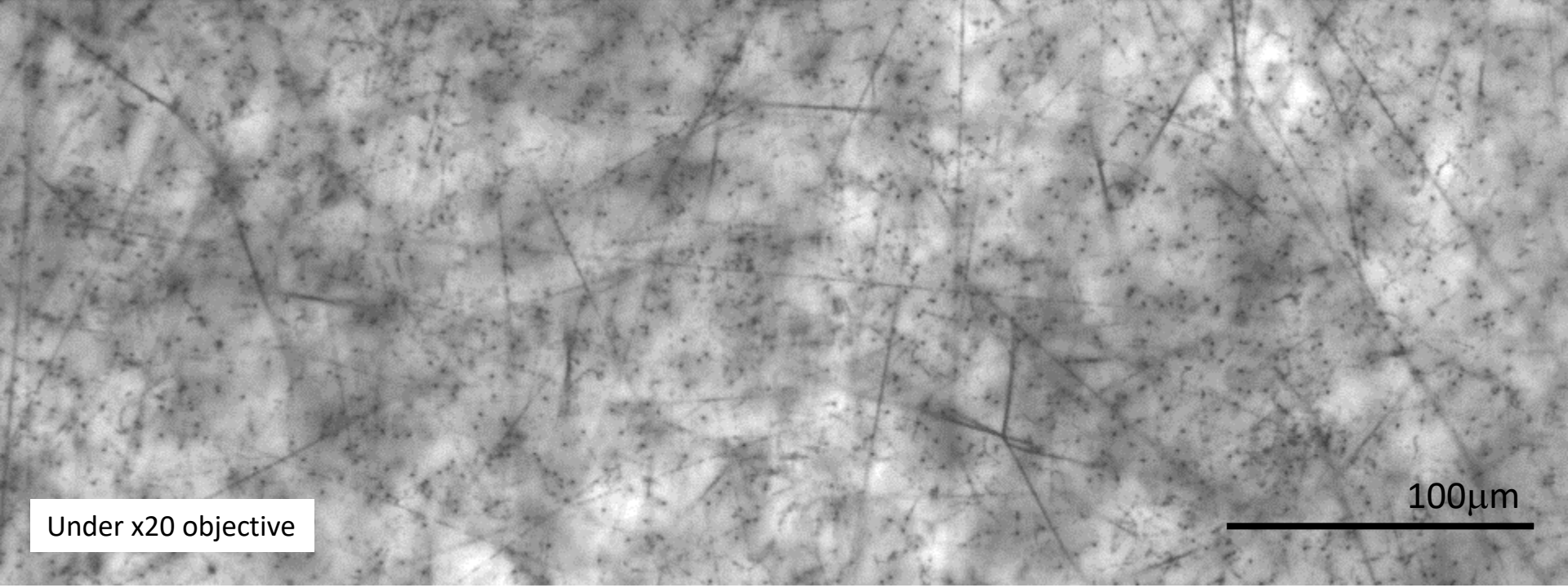

Emulsion sheet
Scanning stage

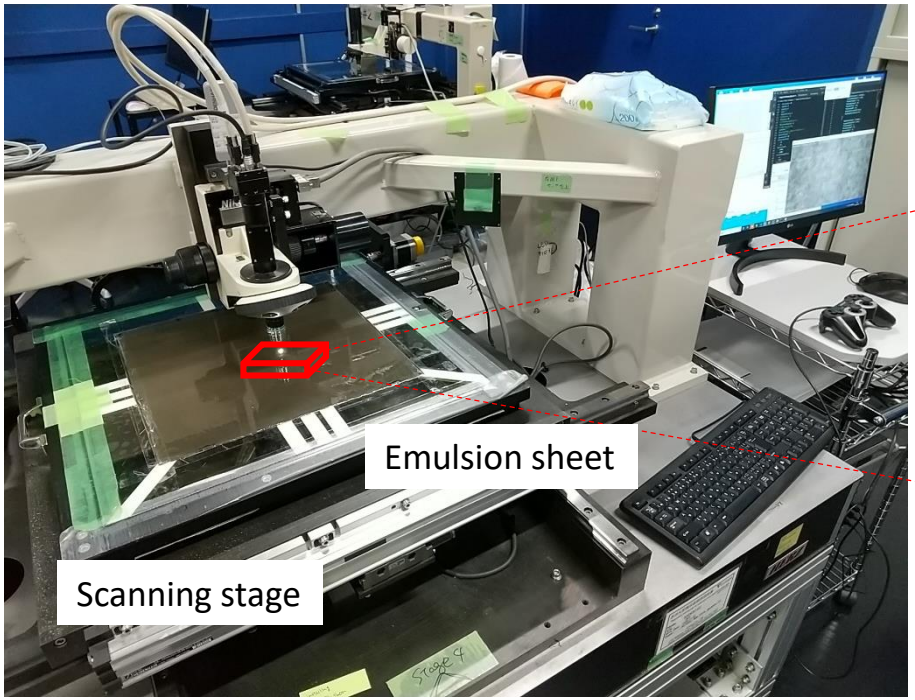

Field of view
~ 160 layers
Thickness: 1 mm → 0.6 mm

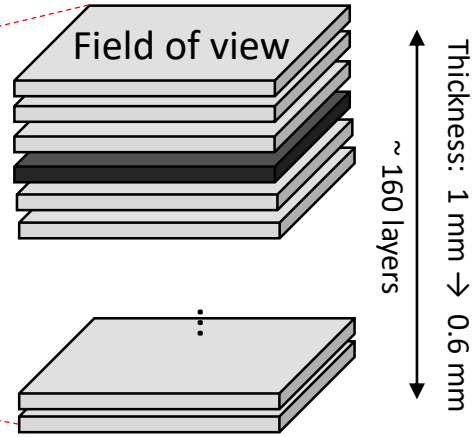

Under x20 objective
100μm

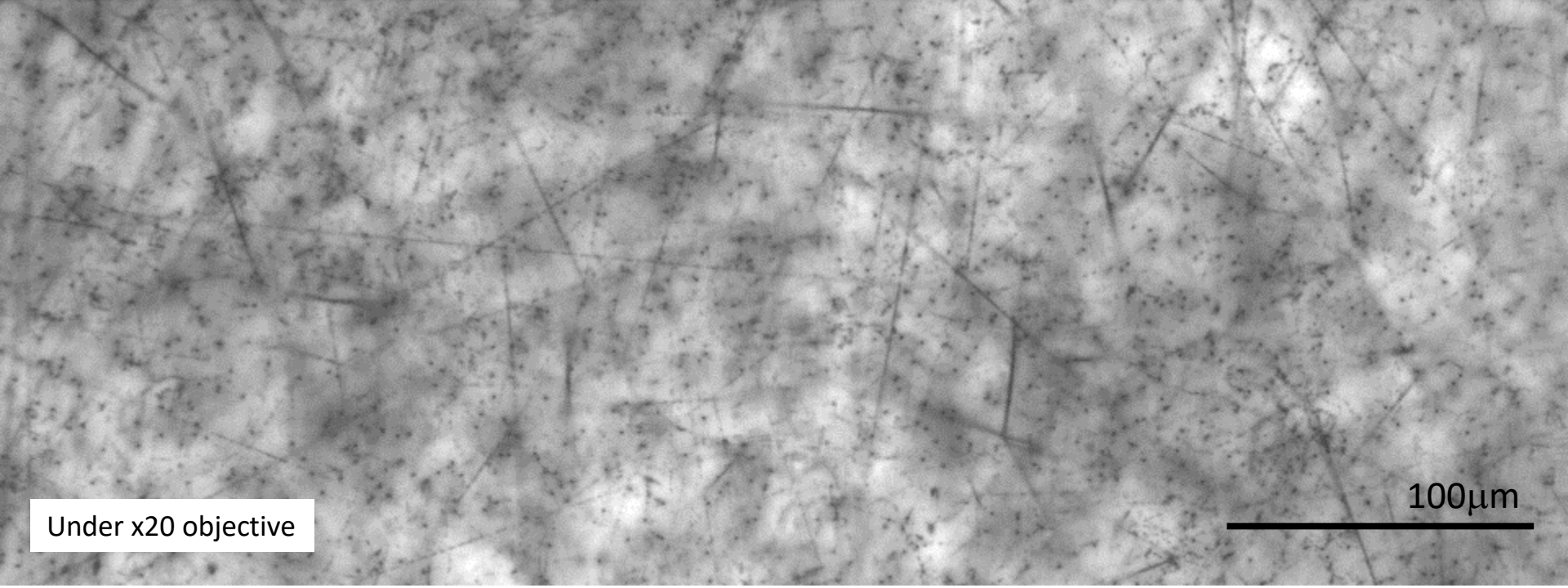

Emulsion sheet
Scanning stage

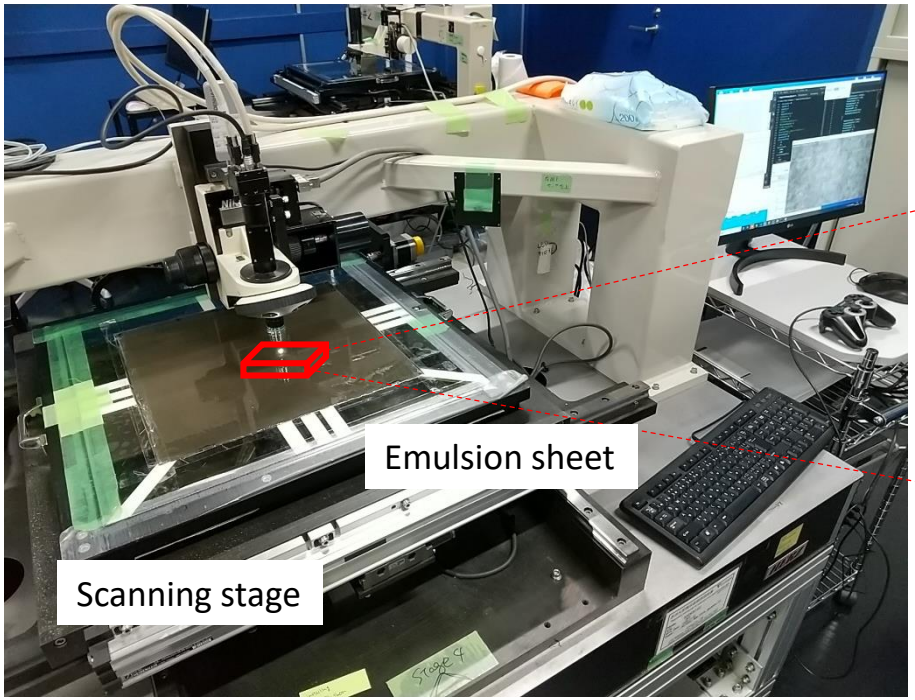

Field of view
~ 160 layers
Thickness: 1 mm → 0.6 mm

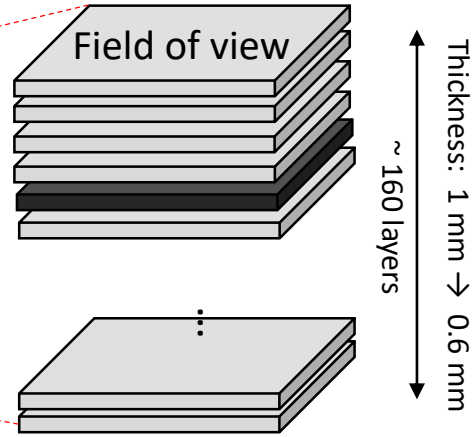

Under x20 objective
100μm


Emulsion sheet
Scanning stage


Field of view
~ 160 layers
Thickness: 1 mm → 0.6 mm


Under x20 objective
100μm


Emulsion sheet
Scanning stage


Field of view
~ 160 layers
Thickness: 1 mm → 0.6 mm

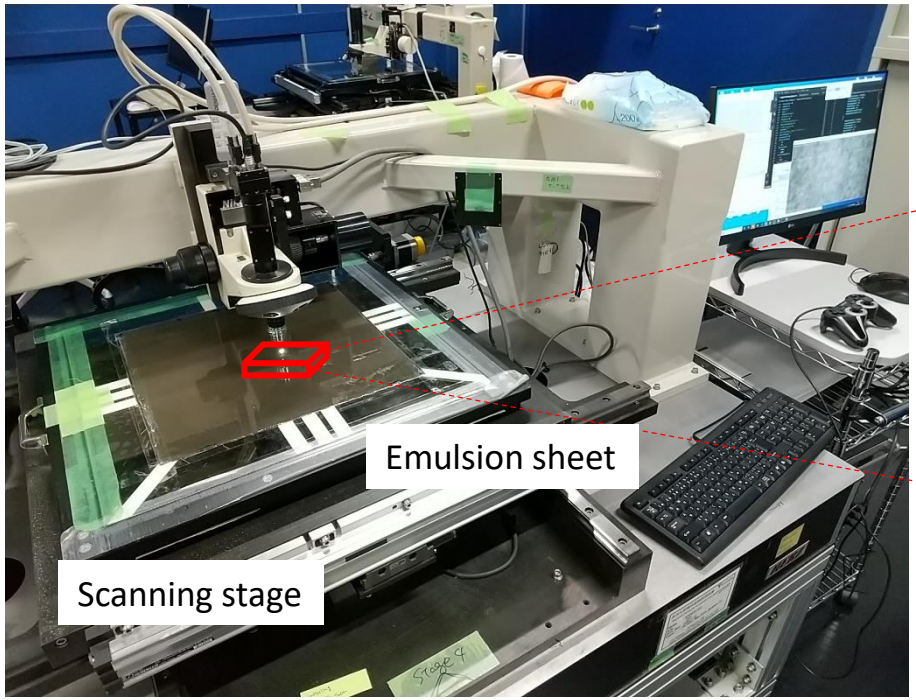
* Data size
  1 sheet = 10^7 images (~100 TB)
  10^3 sheets = 10^{10} images (~100 PB)

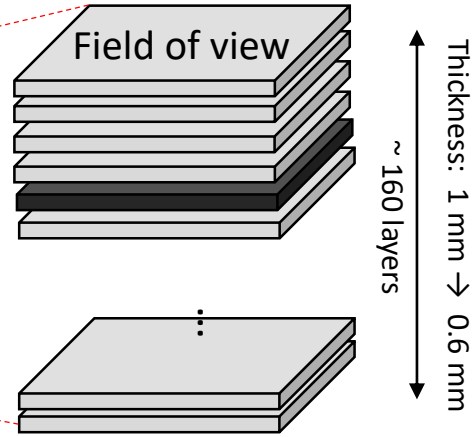
* Track density
  Hadron beam (~10^4/mm^2)
  Nuclear fragments (~10^3/mm^2)

→ Machine Learning

Under x20 objective

100μm





Roadmap

Detection of Double hypernuclear events using machine learning

* Enough training data are necessary but double hypernucler events are rare.

Training using double hypernuclear events generated by simulation

* Statistical performance evaluation is not possible.

Training and validation using alpha decay events generated by simulation

alpha decay events

~10 events / 1cm*1cm*0.5mm

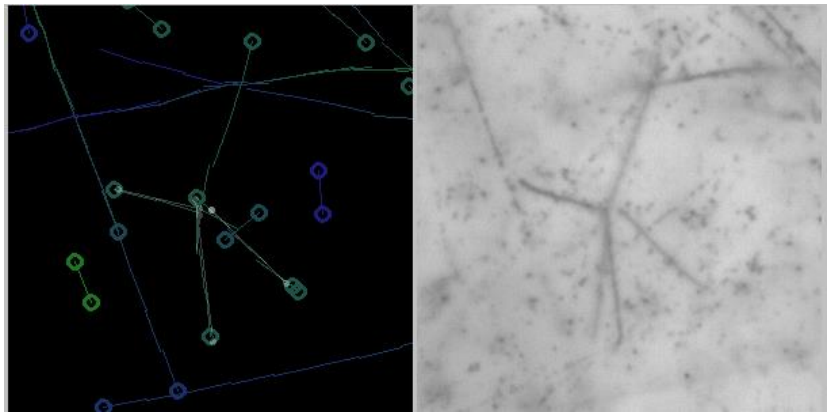
* As a first step,

Training and validation using real alpha decay

* Implementing machine learning
* Comparison with existing method

J. Yoshida, et al., arXiv:2009.05770 [nucl-ex]
In the revision process with N.I.M.-A

Conventional method using geometrical feature



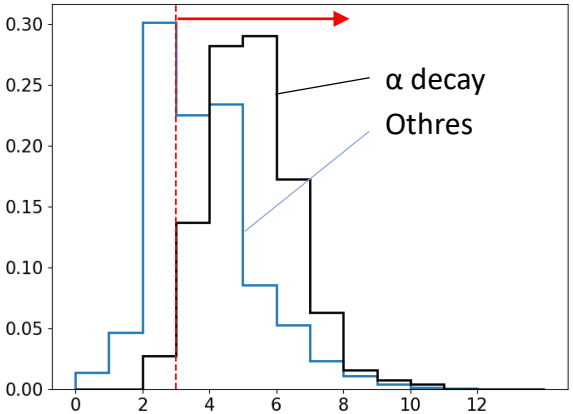
Process:

- Line segment detection
- Connecting the lines in a picture
- Connecting the lines across layers

Output files of Vertex Picker:

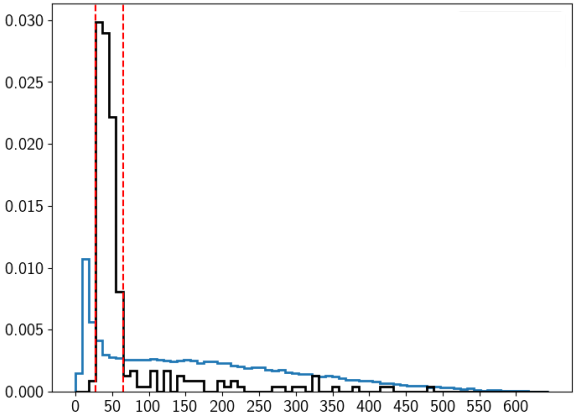
- Cropped micrographs for each vertex-cand.
- Information of line segments

Three or more



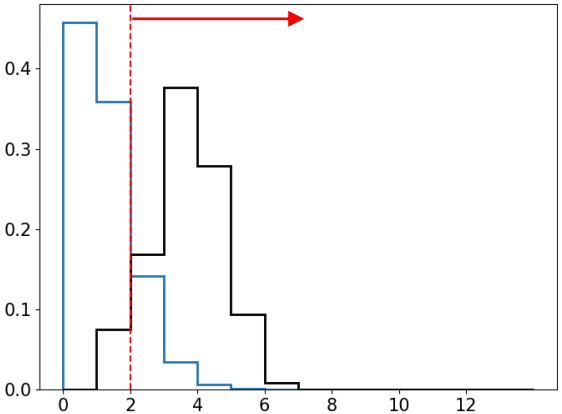
Number of tracks that make up a vertex.

27.6 ~ 64.4 μm



Length of the longest track [μm]

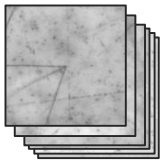
Two or more



Number of tracks having typical length of α-tracks (from 18.4 to 46.0 μm)

Conventional method using line detection

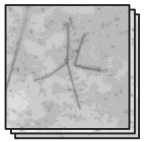
46948 images



16.1cm^2

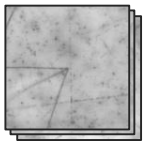
0.5mmThickness

Eye check



alpha

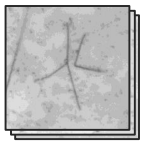
255



others

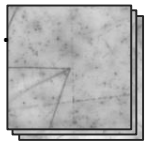
46693

Conventional method



alpha cands.

2489

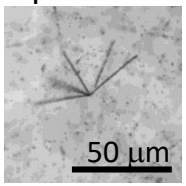


others

44459

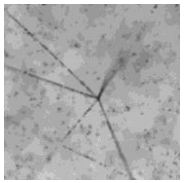
201 alphas

Alphas

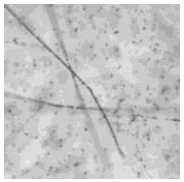


Th or U seriese

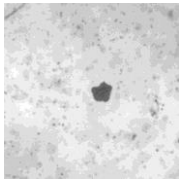
Others



Beam interaction



Cross



Dust like object

Precision (Purity): 0.081 +- 0.006 = 201 +- √201 / 2498

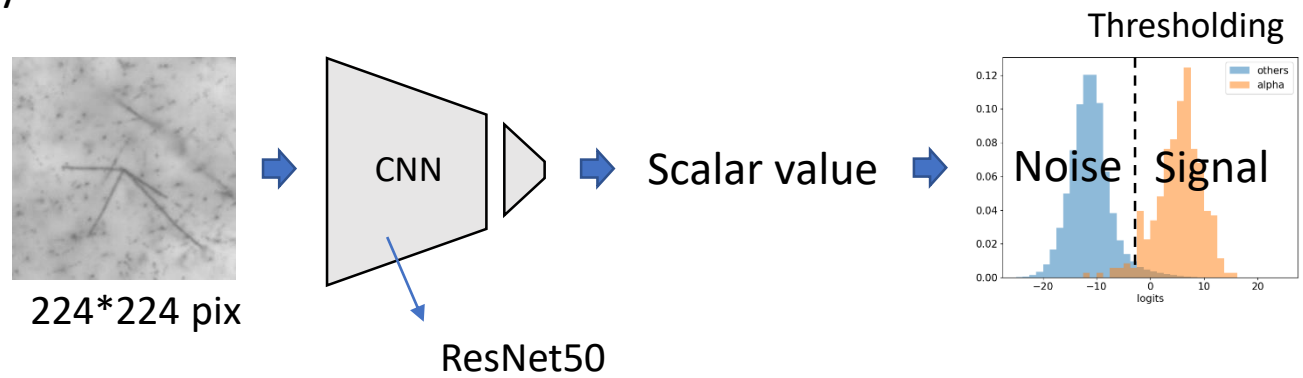
Recall (Efficiency): 0.788 +- 0.056 = 201 +- √201 / 255

For Comparison

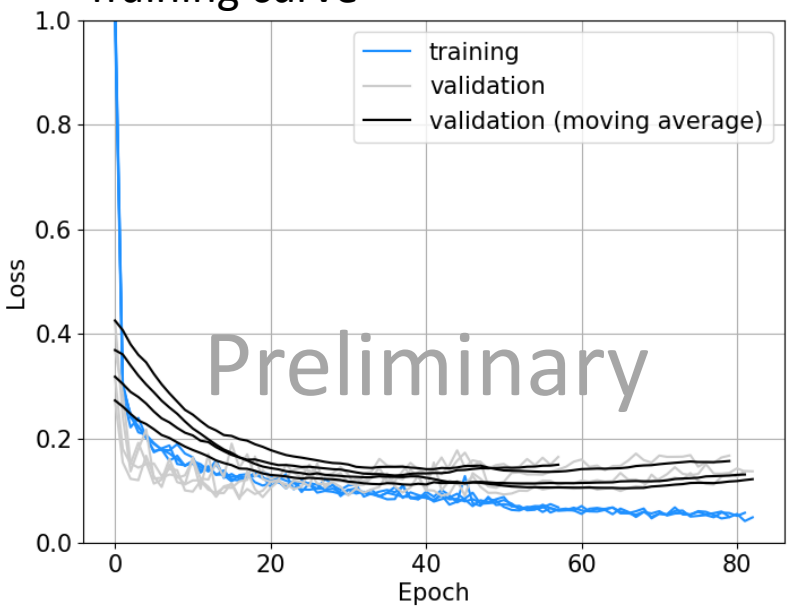
	# of candidates	Precision	Recall
Conventional (line information)	2489	0.081 +- 0.006	0.788 +- 0.056
Machine learning	???	???	???

Model (Convolutional Neural Network: CNN) and training

Binary classifier



Training curve



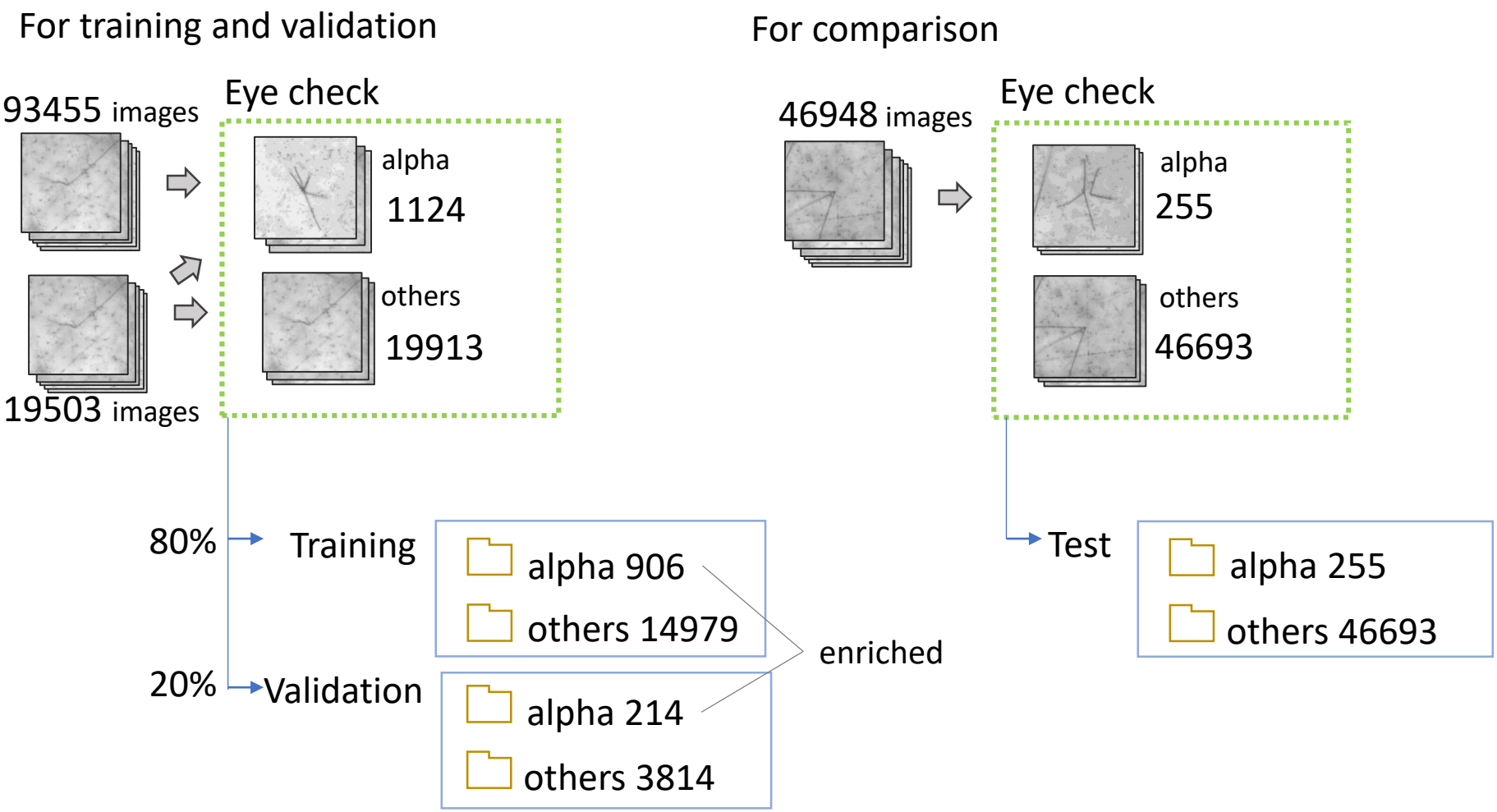
Loss: The value to minimize during the training (cross entropy)

Epoch: Iteration number of optimization

Best: at the epoch providing the minimum validation loss

The performance is depend on random number
→ Averaged performance of four trials

Datasets



Challenges:
How to conduct training with small imbalanced dataset?

Techniques to conduct training with a small imbalanced dataset

- Using a pre-trained model with large scale image dataset
- Oversampling
- Data Augmentation

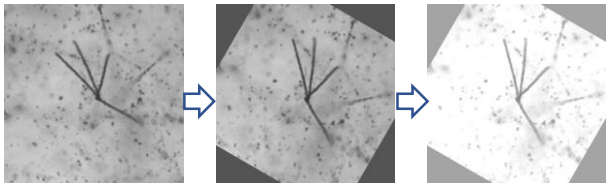
An Important technique

Data Augmentation by RandAugment https://arxiv.org/abs/1909.13719

- N (1 ~ 8), how many image transformations are executed randomly in defined 8 ones.
- M (0 ~ 30), the magnitude of image transformation
- Only 2 parameters

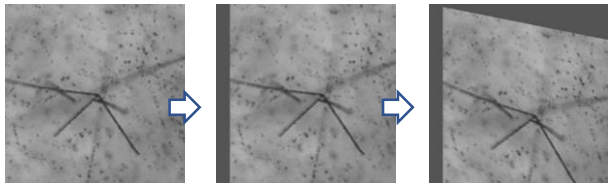
Example (N = 2, M = 30)

Image 1



1. Rotation 2. change in brightness

Image 2

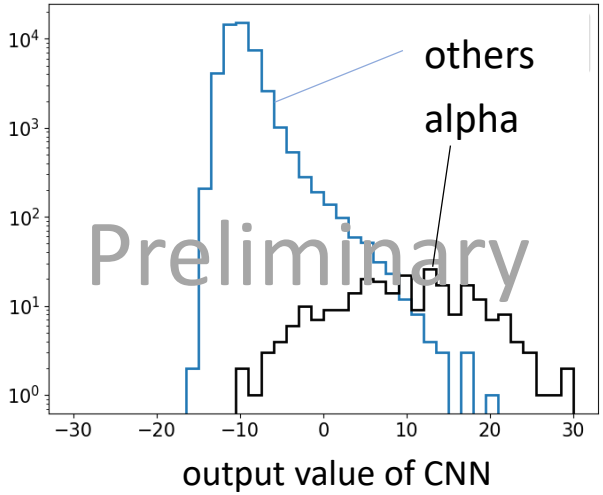


1. Shift X 2. Shear Y

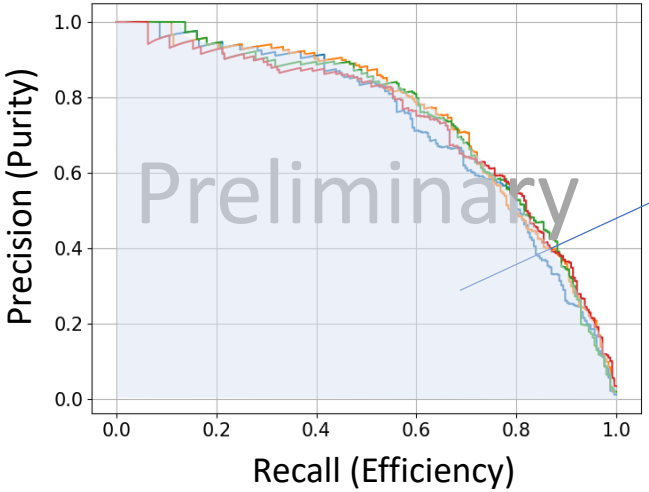
→ We conduct a (N, M) search

Hyperparameter search

Output value of the CNN

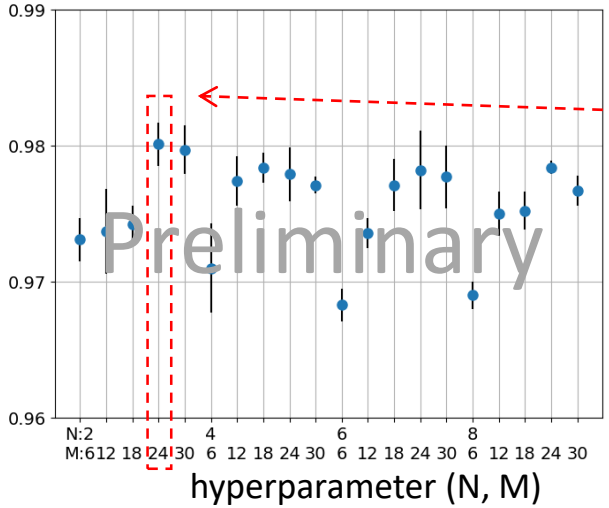


Precision – Recall curve (4 trials)



Metric:
Area under the curve

Area under the Precision – Recall curve for the Validation dataset



the best combination (N = 2, M = 24)

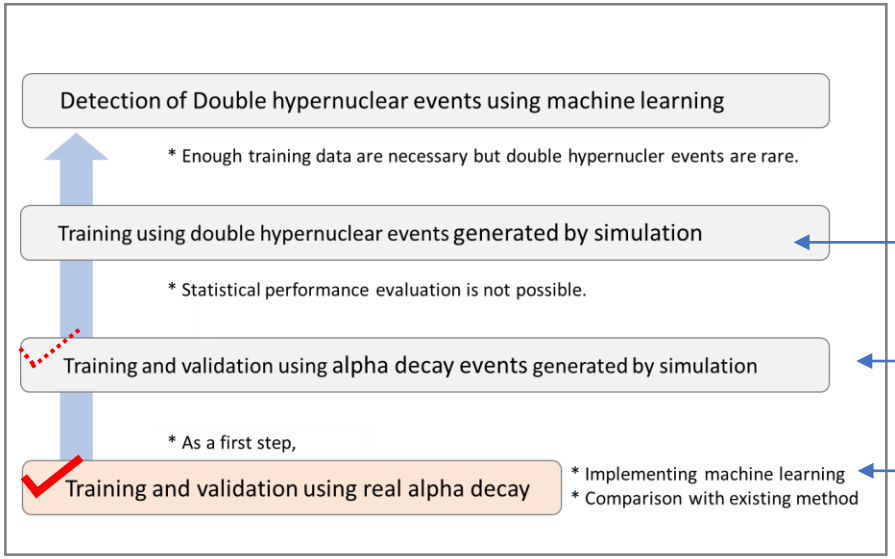
J. Yoshida, et al., arXiv:2009.05770 [nucl-ex]

Result

Performance with dataset for comparison

	Precision (Purity)	Recall (Efficiency)	# of Candidates
Conventional (line information)	0.081 +- 0.006	0.788 +- 0.056	2489
Machine learning 4 trials	0.547 +- 0.025	0.788	366 +- 18
	6.8 +- 0.6 times larger		**1 / 6.8 +- 0.6**

A foundation for the further development to discover a number of double hypernuclei



Current Achievements

On going

Done

Done

J. Yoshida, et al., arXiv:2009.05770 [nucl-ex]

Scanning stage for Overall scanning

In 2020 Dec.,

1 scanning system for test operation.

In 2021 Mar.,

3 scanning systems will be in operation.

- Development of piezo actuator at Gifu-U
- Scanning at HENP, RIKEN
- Online process

	New scanning system (2020)
Objective lense	x20
N pictures	80 (Focal depth: 6 μm)
Area of Field of view [μm^2]	530*530 → 4Mpix CMOS sensor
Frame rate [fps]	160 → 4Mpix CMOS sensor
Dead time ratio	0.2 → by a piezo actuator
scanning speed/day	540 cm^2
To scan the all E07 sheets	15 years → 3 years using 5 stages

1000cm^2 × both_side × 1000 sheets, 250 days operation per year

Summary

- Overall scanning method
- Image recognition for vertex detection

  Basic development using CNN (image classification) is established

  Precision is 0.547 +- 0.025 when recall is 0.788

  Eye-check load: 1 / (6.8 +- 0.6)

- Upgrade of scanning stage
- We aim to detect 10^3 events of double hypernuclei within a few years.

J-PARC E07 Collaboration

Japan

Gifu University
JAEA
KEK
Kyoto University
Nagoya University
Osaka University
RIKEN
Tohoku University

Korea

Gyeongsang National University
Korea Research Institute of Standards and Science
Korea University
Seoul National University

China

Chinese Academy of Sciences
Institute of High Energy Physics China
Shanxi Normal University

Germany

Helmholtz Institute Mainz
Johannes Gutenberg-Universität

Myanmar

Lashio University
University of Yangon

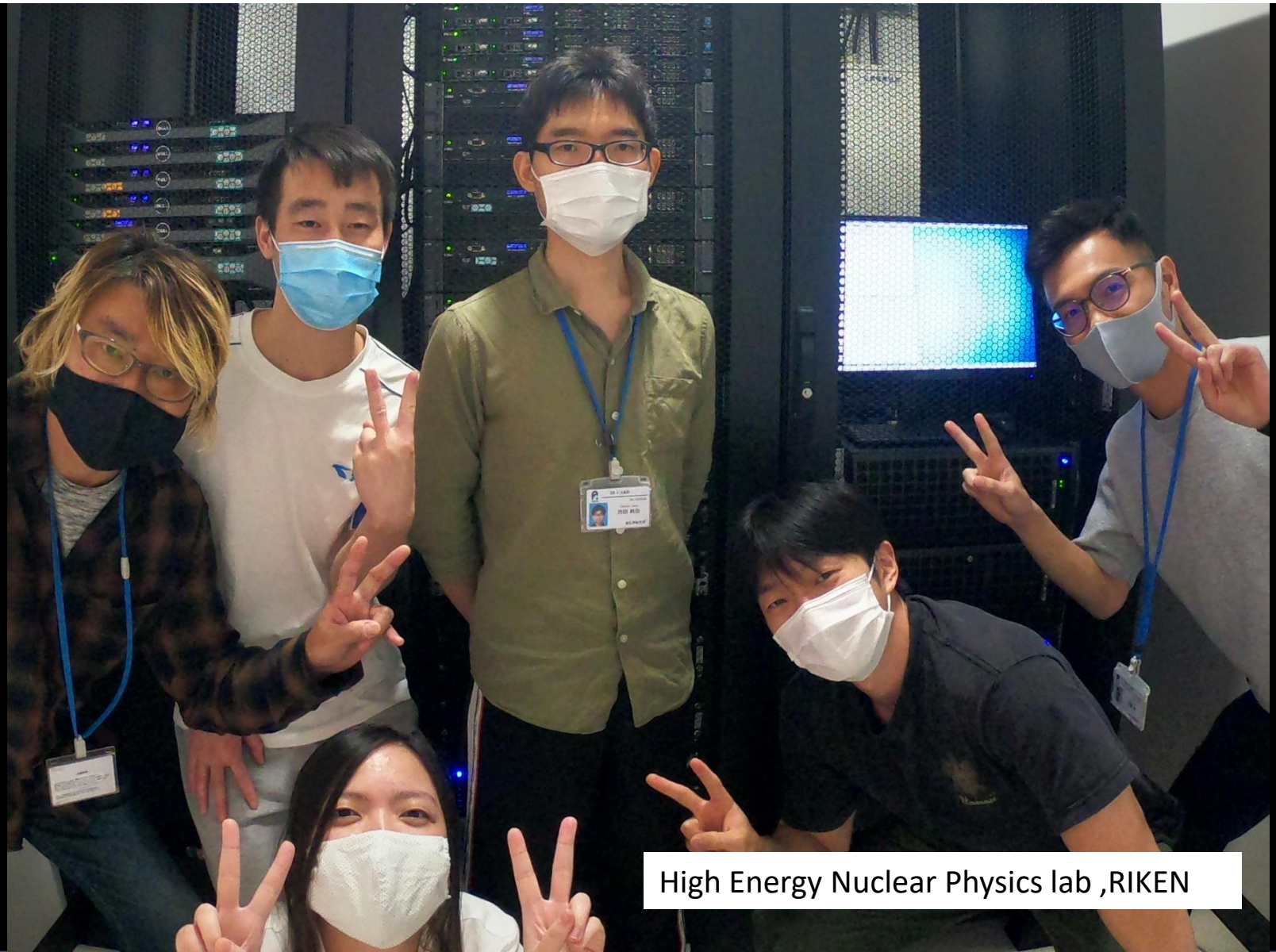
USA

Ohio University
University of New Mexico

6 Countries
24 Institutes
~100 Members

Emulsion × Machine learning collaboration

J. Yoshida, H. Ekawa, A. Kasagi, E. Liu, A. Muneem, W. Dou
M. Nakagawa, K. Nakazawa, N. Saito, T. R. Saito, M. Taki, Y. Tanaka, M. Yoshimoto



High Energy Nuclear Physics lab ,RIKEN