International Symposium on
Clustering as a Window on the Hierarchical Structure of Quantum Systems
(CLUSHIQ2022)

Experimental studies of nuclear systems with double strangeness using nuclear emulsion

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Tohoku University

Hypernuclei: nuclear systems with strangeness

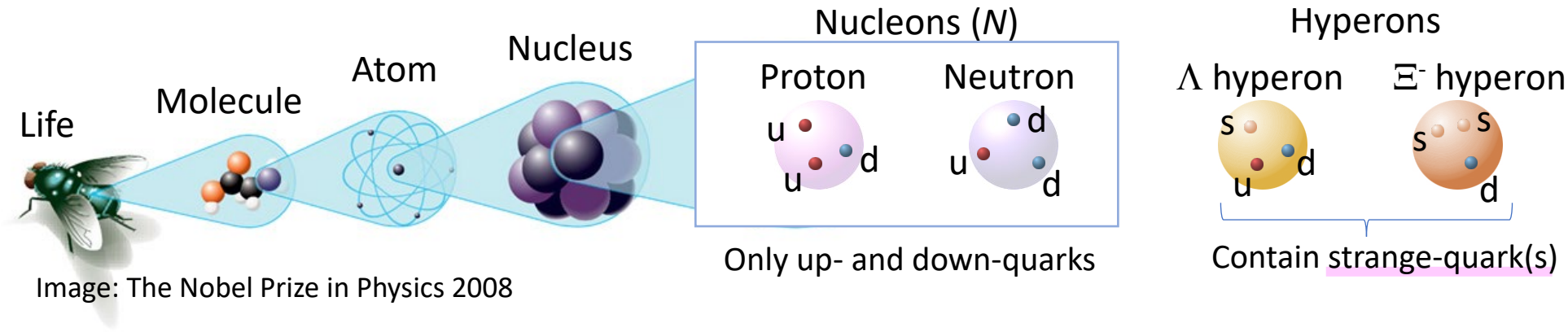
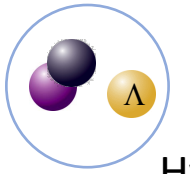


Image: The Nobel Prize in Physics 2008

- Baryon-baryon interaction as an extension of the nuclear force
  - Contributions of quark for nuclear force at short range
  - Introducing the 3rd quark, strange, is an effective way

Single Λ hypernucleus



Hypertriton ($^{3}_{\Lambda}$H)

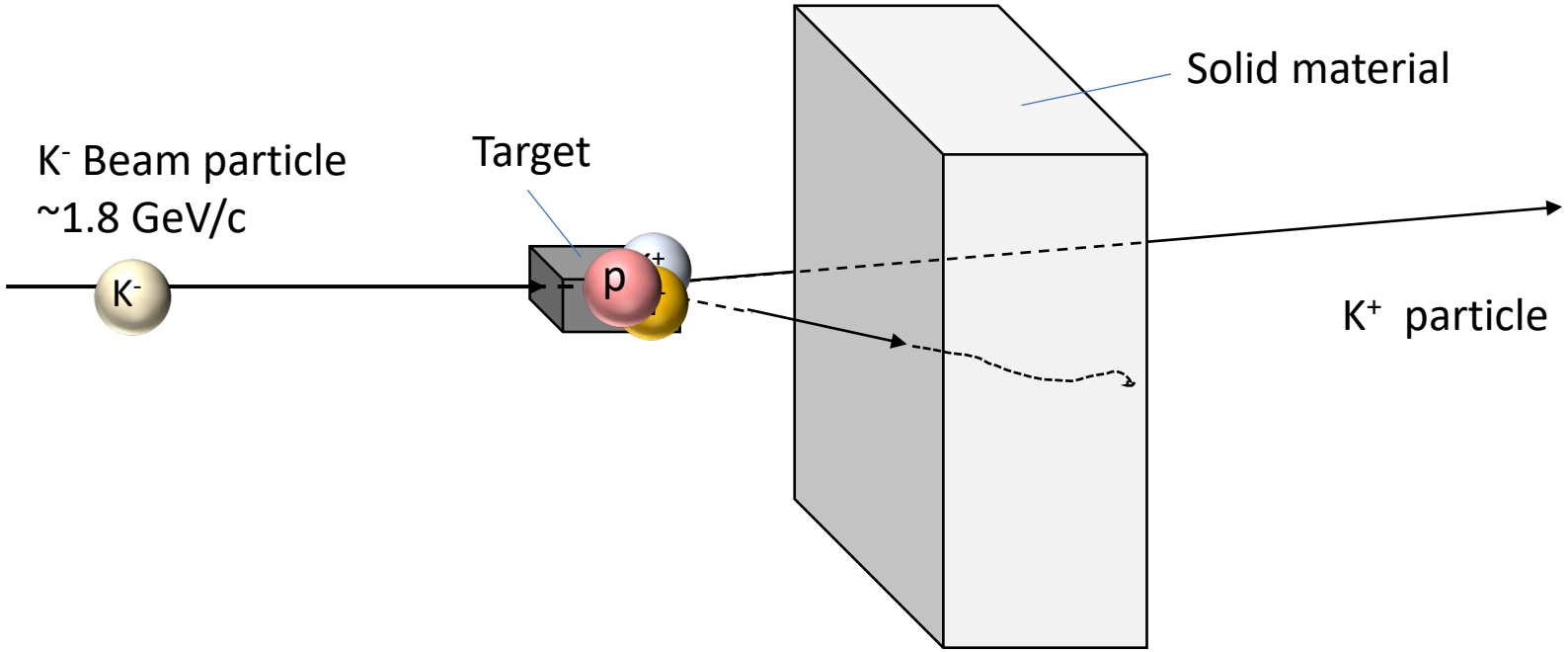
Double strangeness nuclei

Double Λ hypernucleus

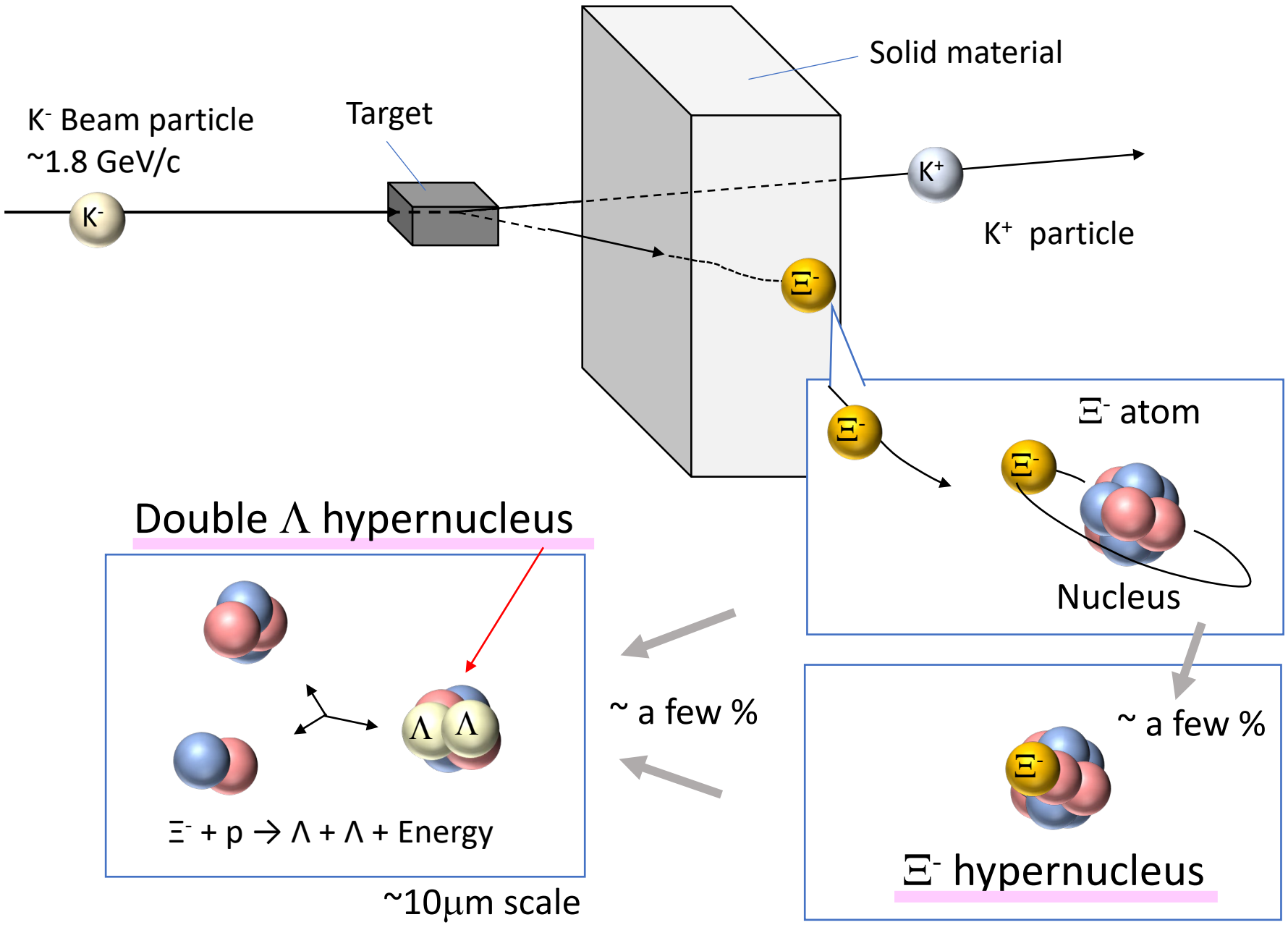
Ξ hypernucleus

- Precise measurement of hyperon in the core nucleus
- Information source of Λ*N*, ΛΛ and Ξ*N* interactions

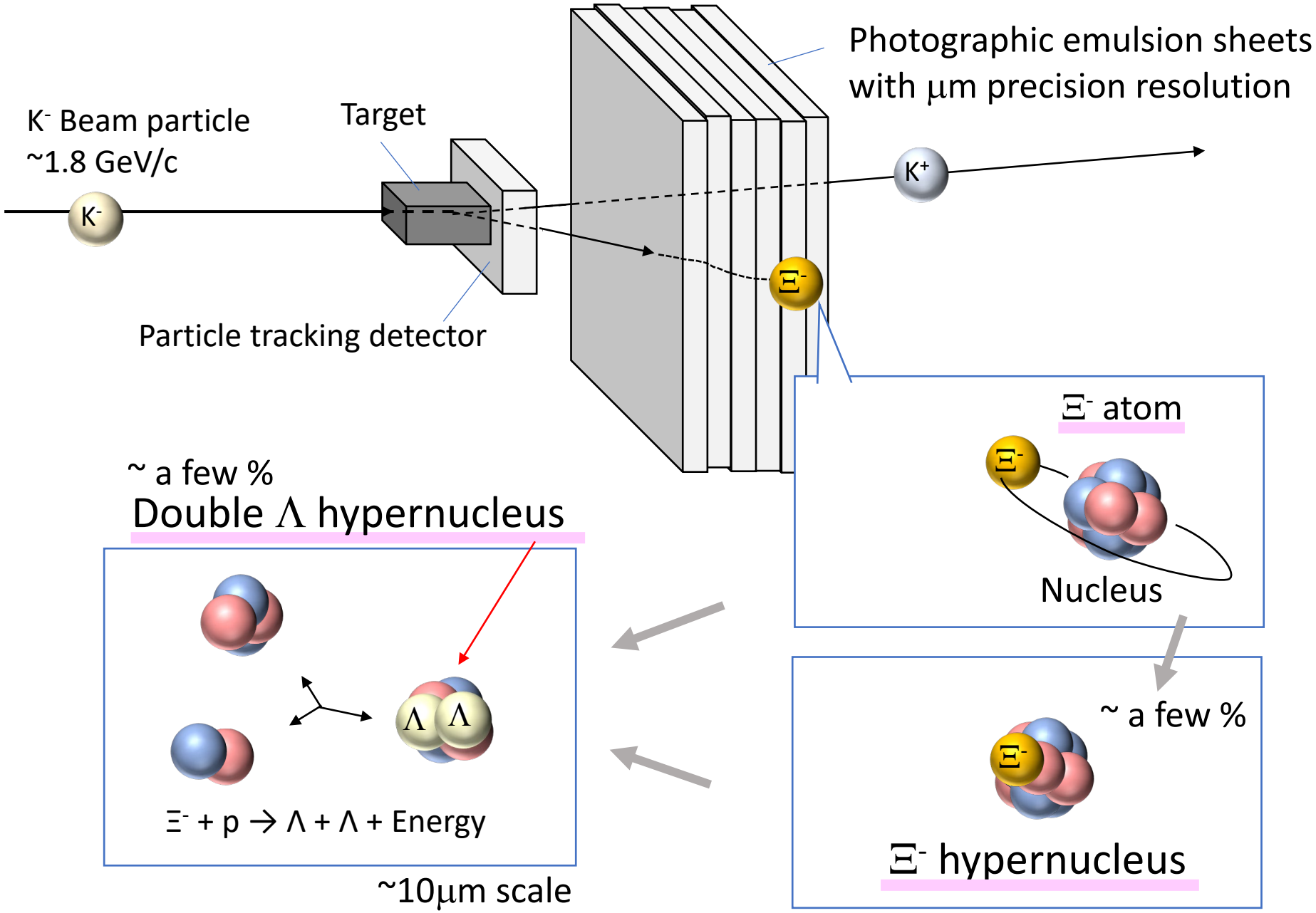
Production and decay of a double strangeness nuclei



Production and decay of a double strangeness nuclei



Production and decay of a double strangeness nuclei



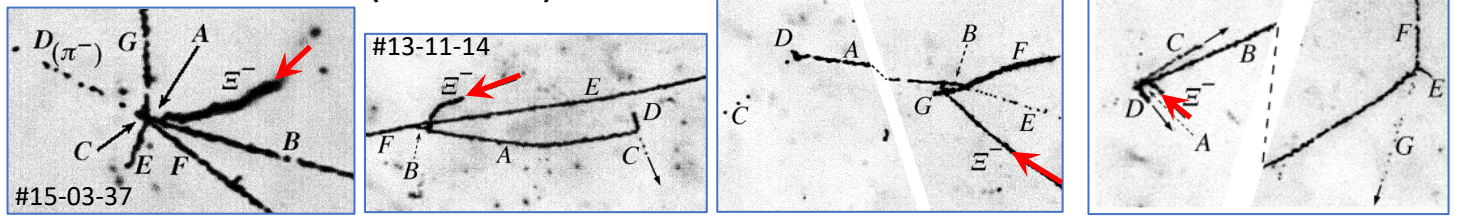
Evolution of experiments with hybrid emulsion method for double strangeness

Number of Ξ^- stop events

~80

KEK-PS E176 (1988-89)

Nuclear Physics A 828 (2009) 191–232



* Existence of double Λ hypernucleus

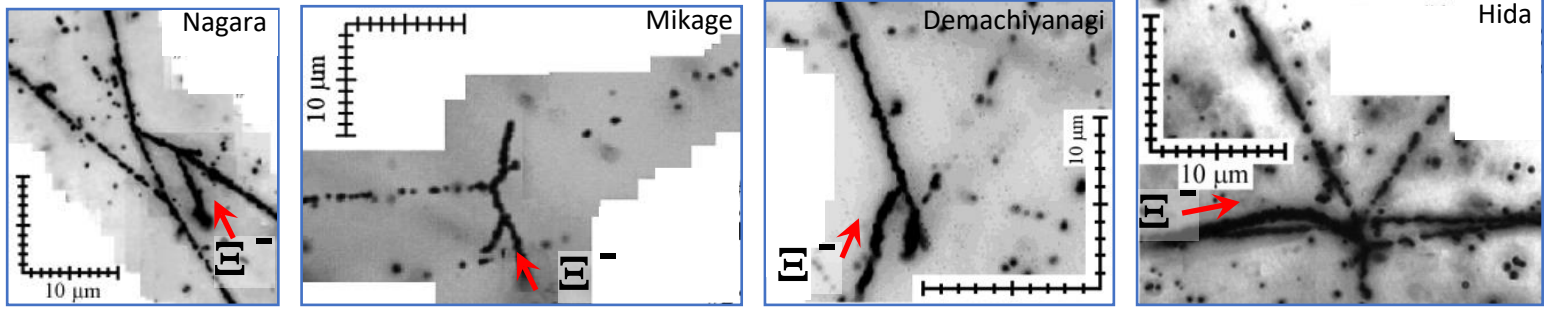
X10 scale

~650

PTEP 2019, 021D01

KEK-PS E373 (1998-2000)

PHYSICAL REVIEW C 88, 014003 (2013)



* Identification of ${}^{6}_{\Lambda\Lambda}$He and Ξ hypernucleus

X10 scale

~10^4

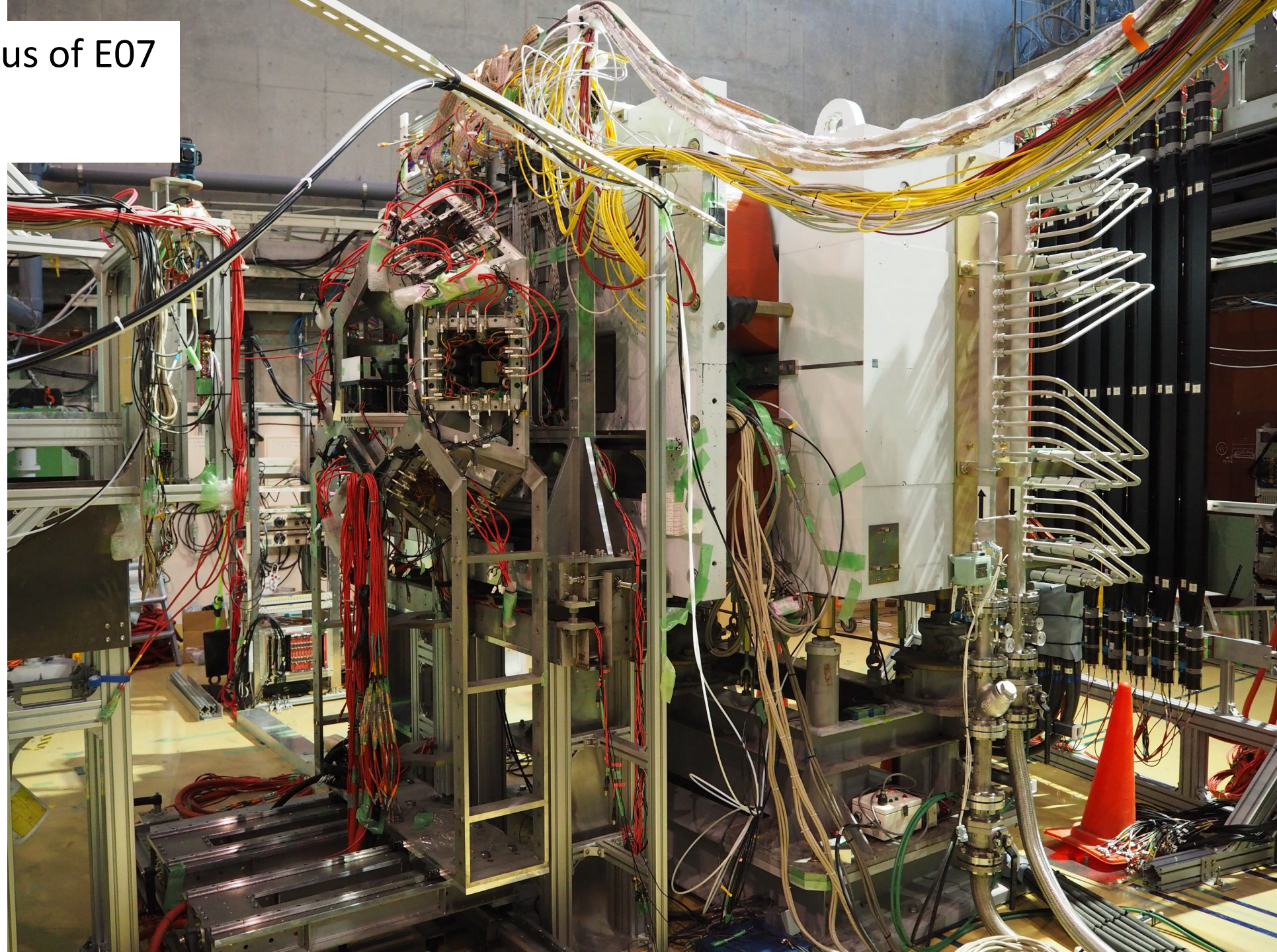
J-PARC E07 (2016-17)

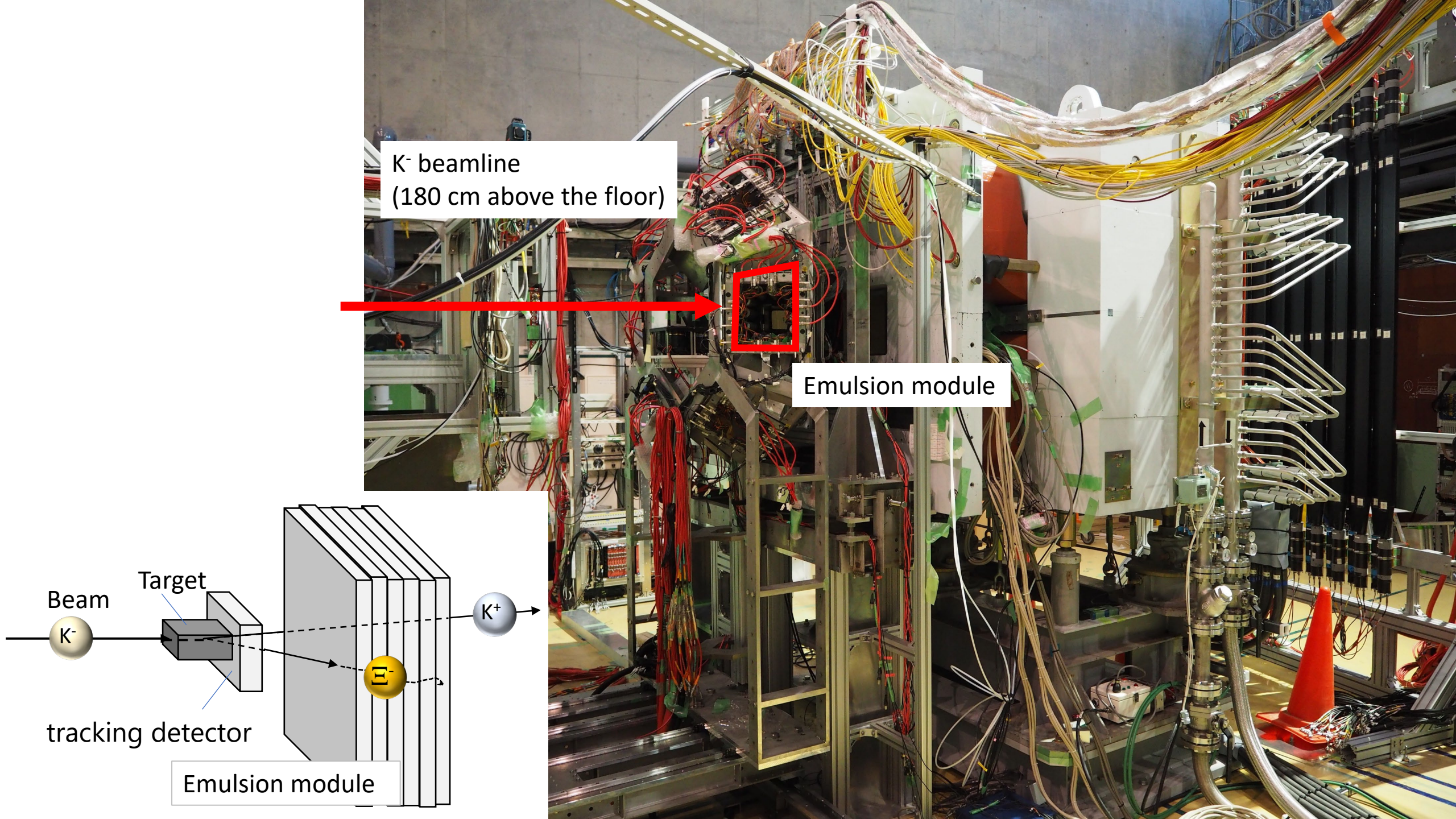
	Emulsion gel	K^- purity	Beam intensity
KEK-PS E373	0.8 tons	25%	$1*10^4$/spill
↓	↓	↓	↓
J-PARC E07	2.1 tons	~82%	$3*10^5$/spill

Experimental apparatus of E07

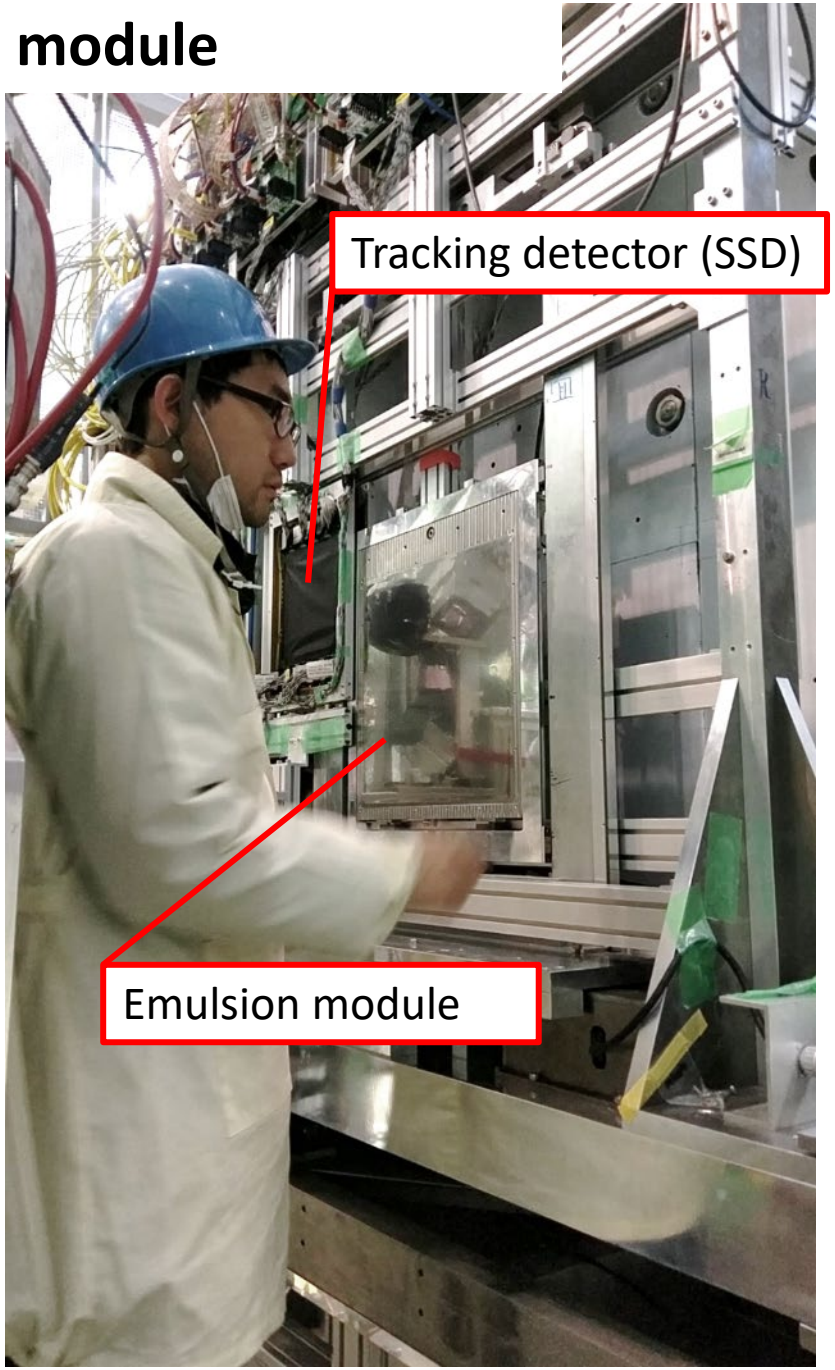
2016-2017

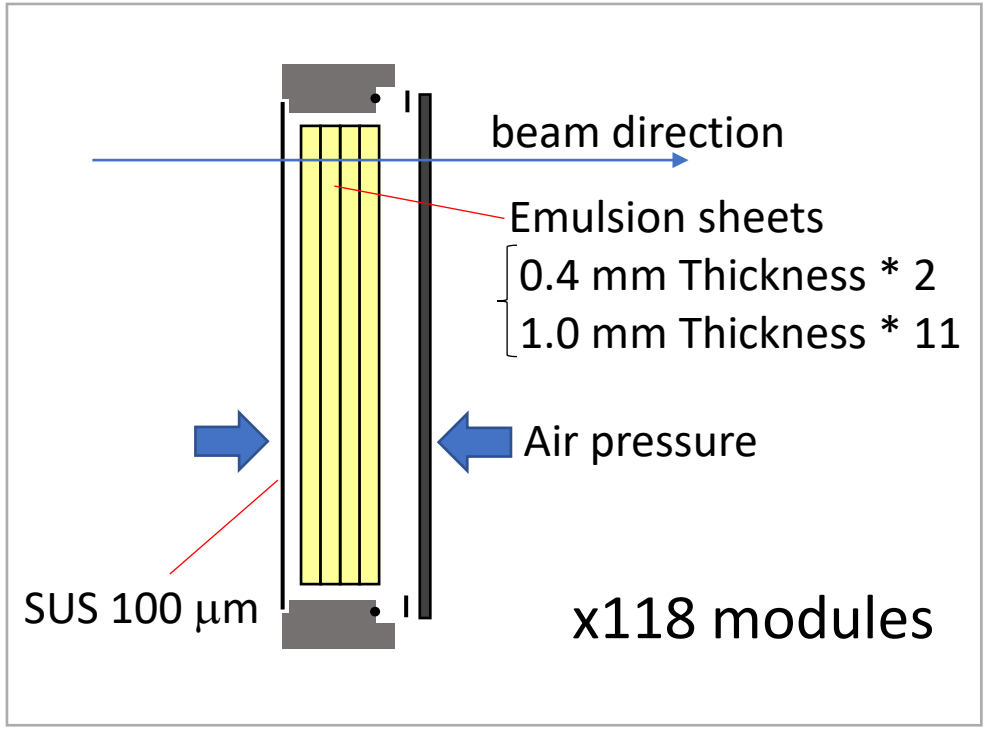
K1.8 beamline, J-PARC




K- beamline
(180 cm above the floor)
Emulsion module
Beam
K-
Target
tracking detector
Ξ-
K+
Emulsion module

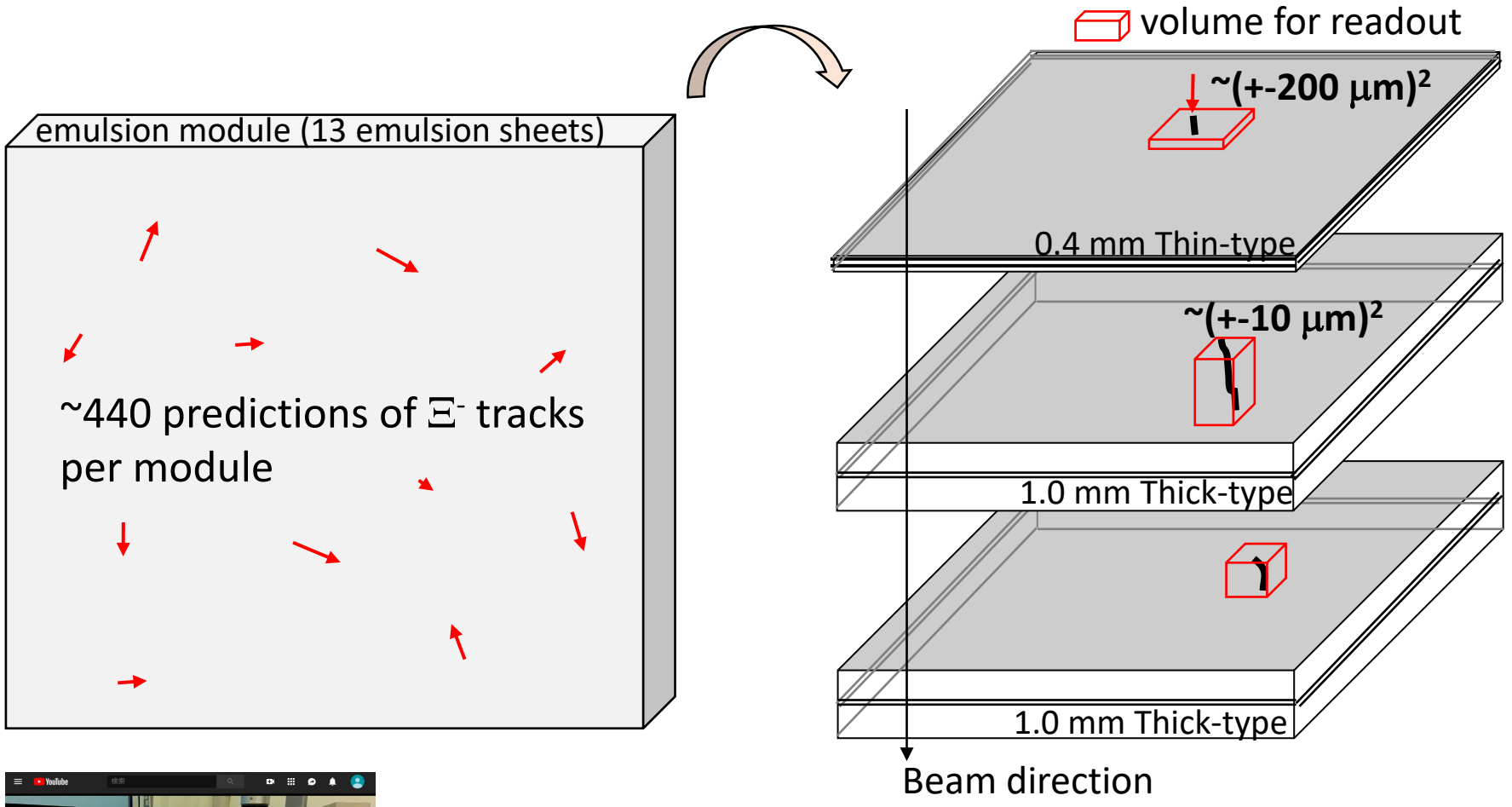
Emulsion module

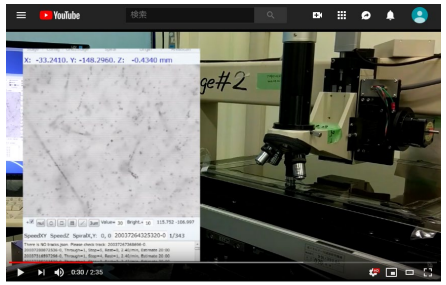




Track following for Ξ^- stop event search

with dedicated image processing

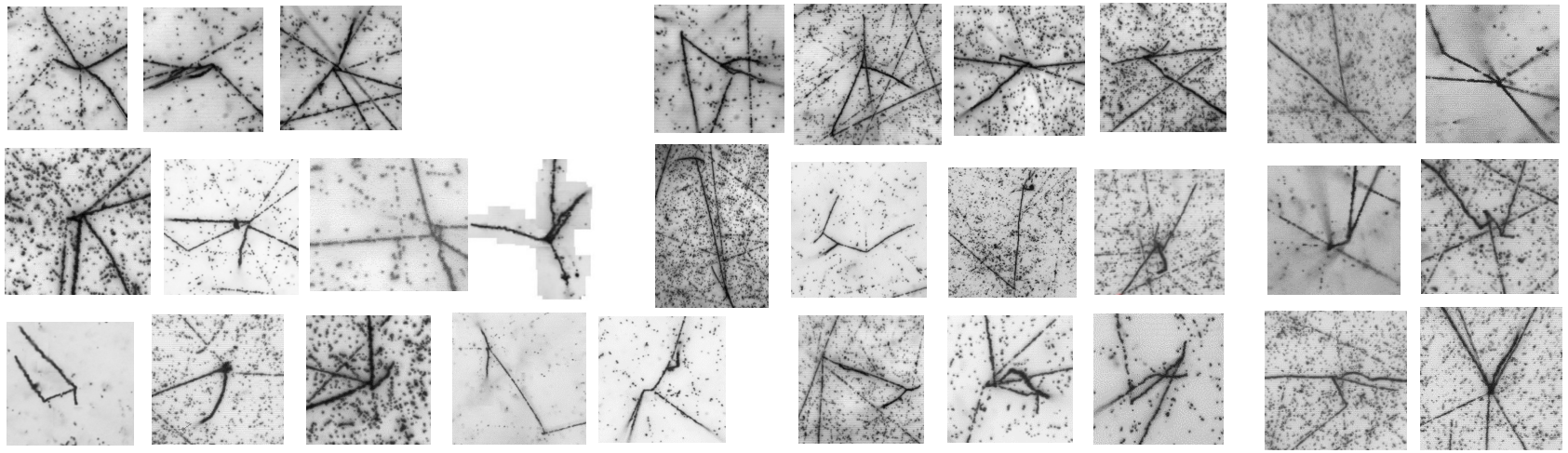




Automated Track Following
https://youtu.be/3fiWI5tDx2U

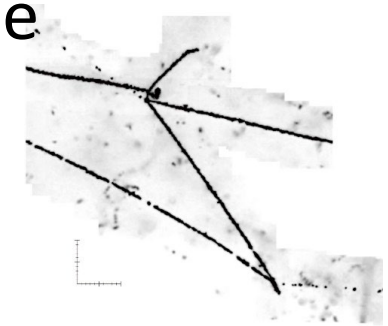
Detected double strangeness events:

14 events in the former experiments
33 events in J-PARC E07



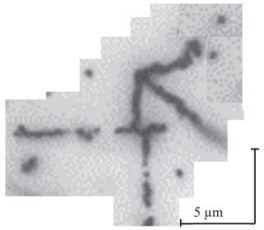
Double Λ hypernuclear events

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



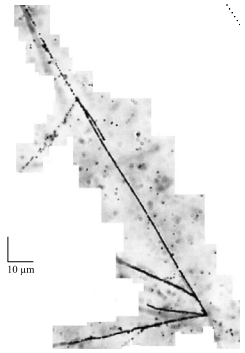
H. Ekawa, et al.,
Prog. Theor. Exp. Phys.
2019, 021D02 (2019)

$_{\Lambda\Lambda}{}^{8}$Li or $_{\Lambda\Lambda}{}^{10}$Be



Nyaw, A. N. L. et al.,
Bull. Soc. Photogr. Imag. Japan
30, 22– 25 (2020)

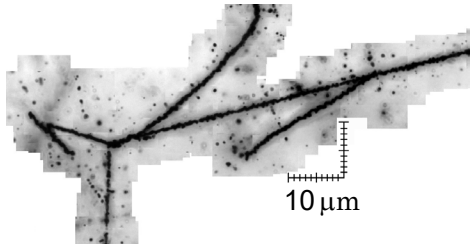
Ξ hypernuclear events



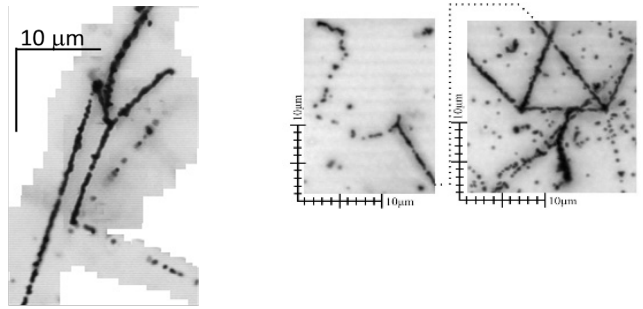
S. H. Hayakawa, et al.,
Phys. Rev. Let., 126, 062501 (2021)

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

K. Nakazawa, et al.,
Prog. Theor. Exp. Phys.
2015, 033D02 (2015)



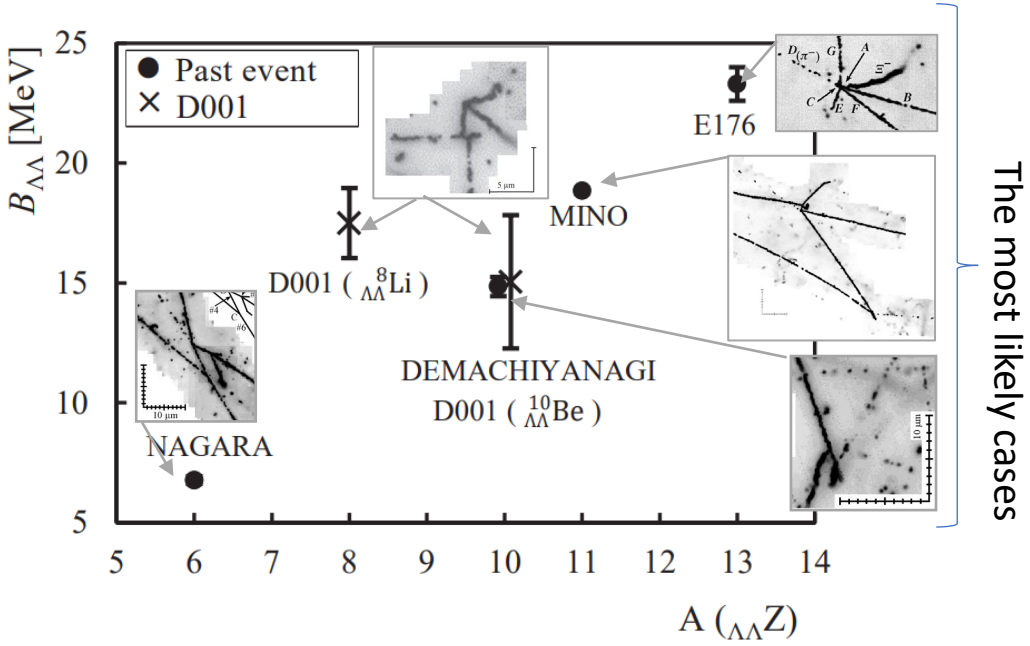
M. Yoshimoto, et al.,
Prog. Theor. Exp. Phys. 2021, 073D02 (2021)



Systematic analysis of double strangeness system using multiple events

Double Λ hypernucleus

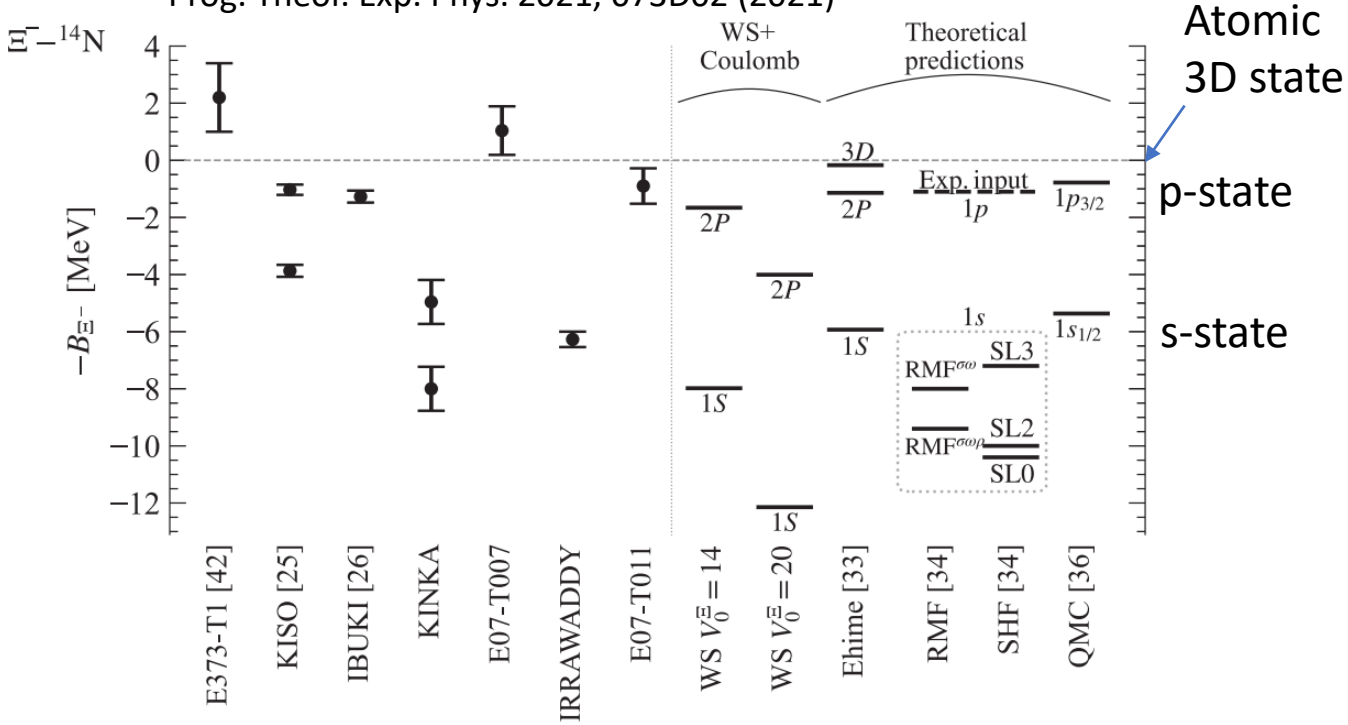
Nyaw, A. N. L. et al.,
Bull. Soc. Photogr. Imag. Japan 30, 22– 25 (2020)



A-dependence of $B_{\Lambda\Lambda}$ can be discussed.

Ξ hypernucleus

M. Yoshimoto, et al.,
Prog. Theor. Exp. Phys. 2021, 073D02 (2021)



Combining experimental data and theoretical calculation,

- p-state: ~1 MeV
- s-state: ~6 MeV

seem likely

List of twin Λ hypernuclear events

Although the ratio of the C, N, and O in emulsion is 0.55 : 0.16 : 0.29, Ξ^--^{14}N event predominates

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

●: Uniquely identified
○: Multiple interpretations

Nucl. Phys. A 828 (2009) 191–232
Nucl. Phys. A 828 (2009) 191–232
AIP Conf. Proc. 2130, 020016 (2019)
Phys. Lett. B 500 (2001) 37.
EPJ A, volume 58, 190 (2022)
PTEP 2021, 073D02 (2021)
PTEP 2021, 073D02 (2021)
Nucl. Phys. A 828 (2009) 191–232
PTEP 2015, 033D02 (2015)
Phys. Rev. Lett., 126, 062501 (2021)
PTEP 2021, 073D02 (2021)
PTEP 2021, 073D02 (2021)

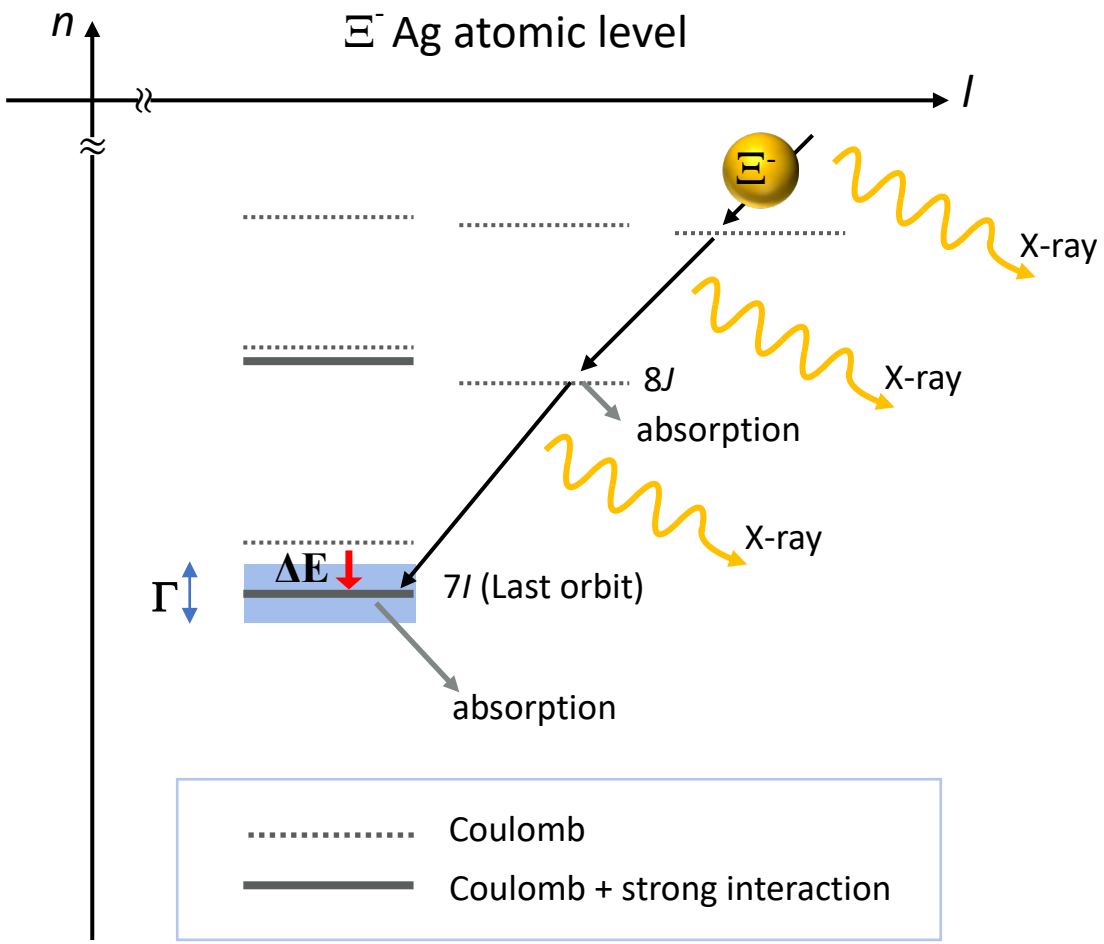
Ξ hypernuclei

Excess?

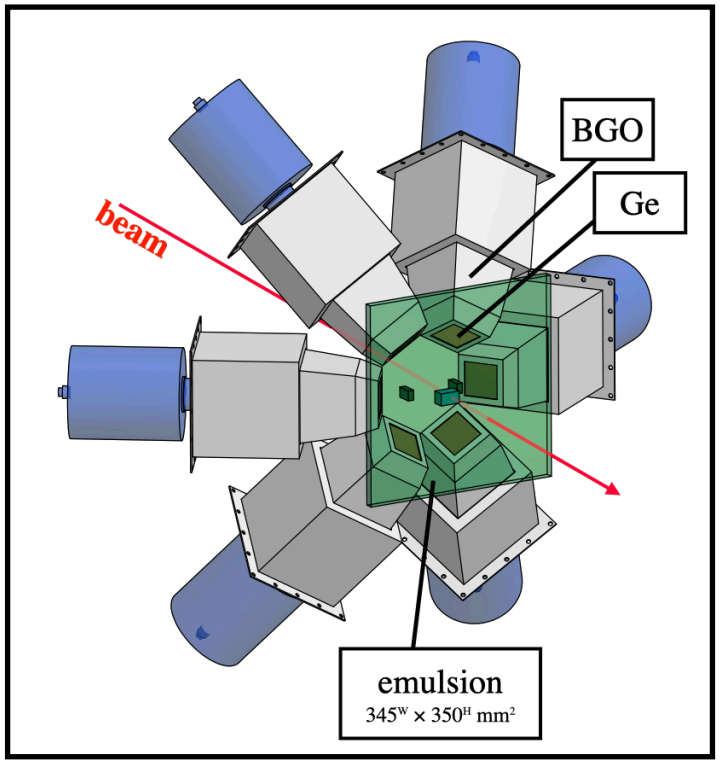
alpha cluster structure?

- Nature of Ξ^- capture process? or biases caused by our analytical methods?
- These identified events are a small fraction of the total.
- Charge identification of daughter particles based on track boldness is important.

The first Ξ^- atomic X-ray spectroscopy measurement



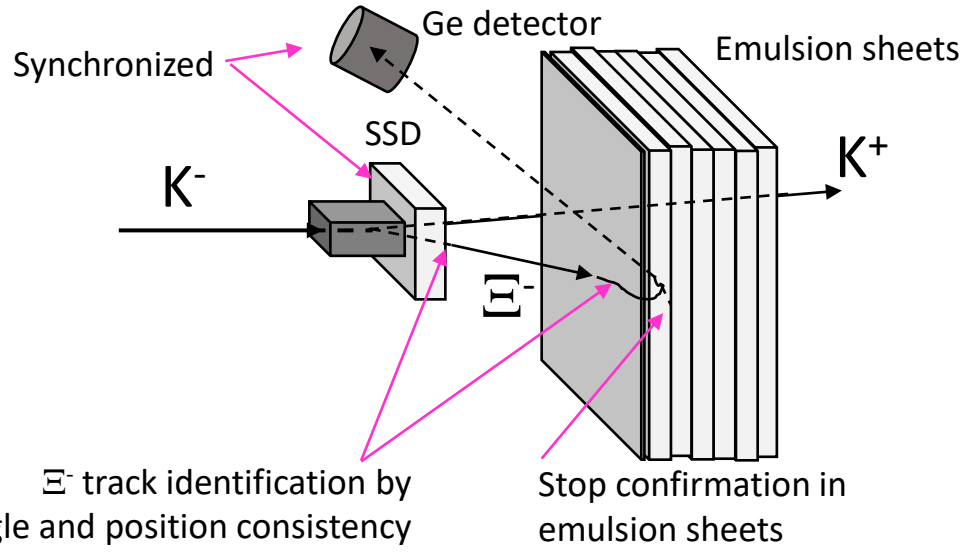
M. Fujita et al., NIM-A 1042 (2022) 167439



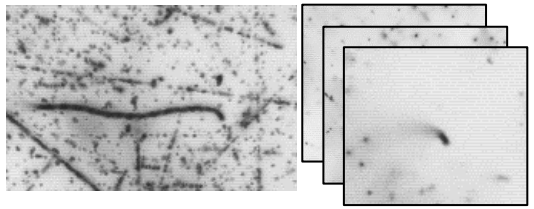
- X-ray energy may be shifted and/or broadened due to the strong interaction
- X-ray spectroscopy is one of the most useful methods

- Dedicated germanium (Ge) detector array, Hyperball-X
- Continuous in-beam calibration
- Background suppression using $Bi_4Ge_3O_{12}$ (BGO)

X-ray measurement using the hybrid method

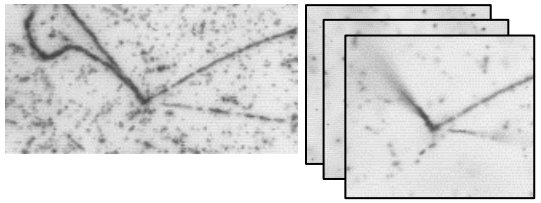


ρ-stop: Stop without nuclear fragment
(It can be a proton)



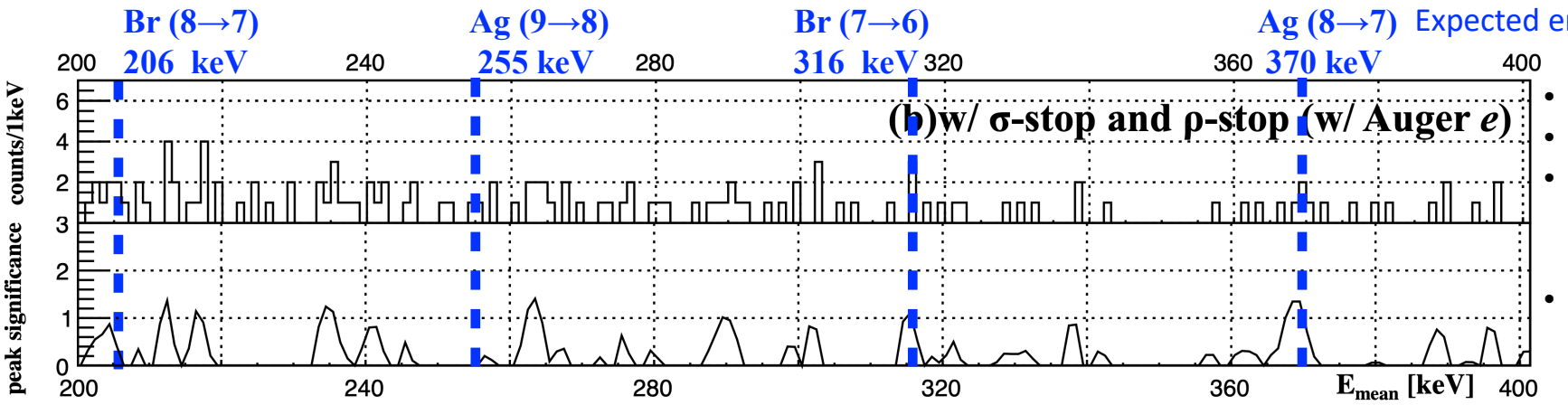
Not used

σ-stop: Stop with nuclear fragment
(almost Ξ-)



Used

Peak search



Expected energy only Coulomb

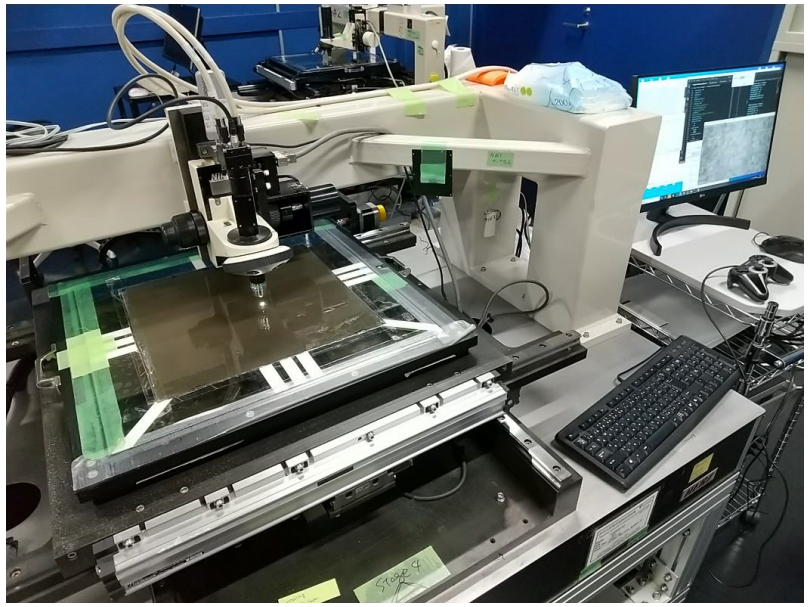
- w/ BGO suppression
- Fit method : log likelihood
- Fit function : Gaussian + constant(BG)
  - $Mean_{Gauss} = E_{mean}$
  - σ_{Gauss} = fixed to σ_{Ge} (0.8 keV)
- Peak significance ≡ $Amp_{gauss}/Amp_{gauss}\,Error$

- No evident peak using current dataset.
- An upper limit of the probability that Ξ- reaches the last orbit was evaluated.
- A paper reporting this result is in review. (PTEP)

Overall scanning method: a technique to search for untriggered events

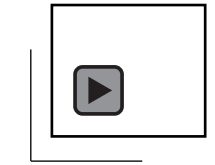
GIFU UNIVERSITY

An upgraded scanning stage developed by Gifu Univ.



	New scanning system (2021)	
Objective lens	x20	
Focal depth	6 μm	
Area of Field of view [μm^2]	530*530	4Mpix CMOS sensor
Frame rate [fps]	160	
Dead time ratio	0.2	by a piezo actuator
scanning speed/day	540 cm^2	
To scan the all E07 sheets	16 years (4 years using 4 stages)	

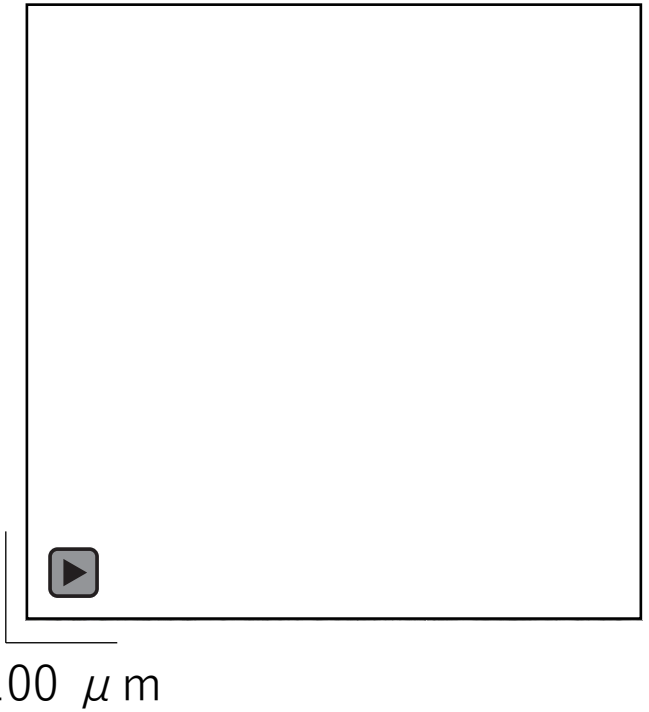
1000cm^2 × both_side × 1000 sheets, 250 days operation per year



100 μm

The Field of view of the microscope used track following

The Field of view of the developed microscope

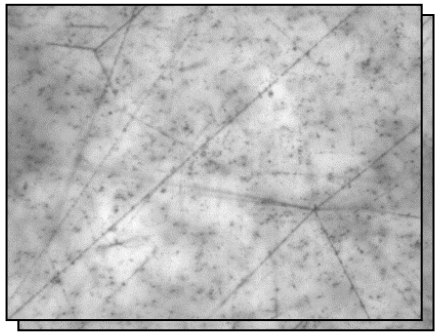


100 μm

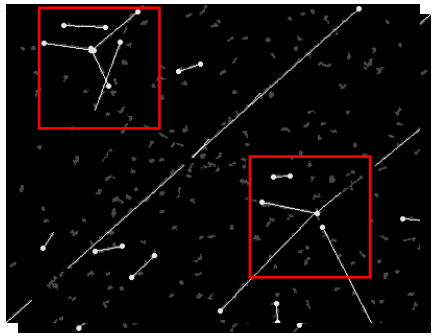
This work has been supported by this project (KAKEN JP19H05147)

Image recognition using machine learning led by RIKEN

Vertex detection

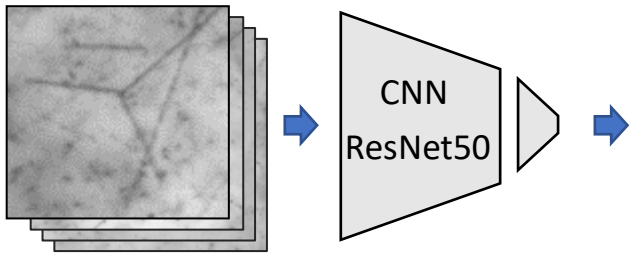


J. Yoshida, et al.,
N.I.M A, 847 (2017) 86-92

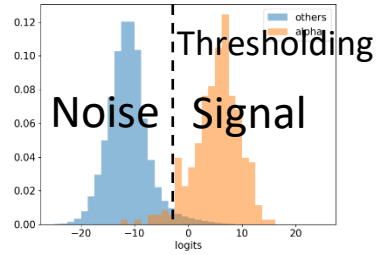


Purity: 0.081 ± 0.006
Efficiency: 0.788 ± 0.056

Classifier based on Convolutional Neural Network

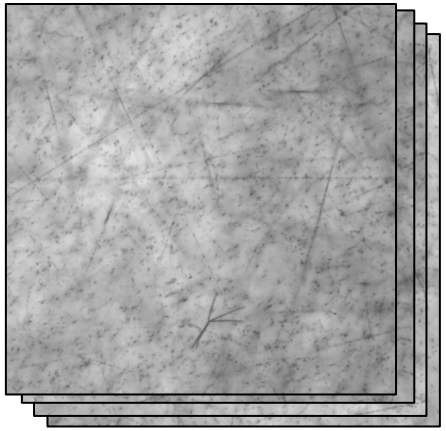


J. Yoshida et al.,
N.I.M. A 989 (2021) 164930



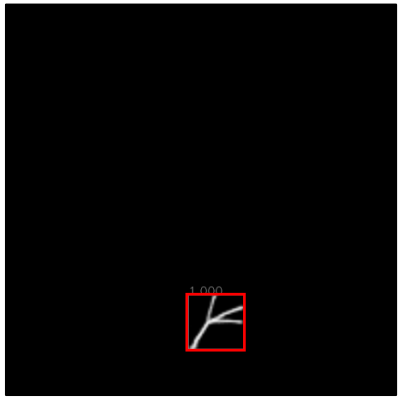
Purity: 0.547 ± 0.025
Efficiency: 0.788

Object detection using Region based CNN



50 μm

Modified
Mask R-CNN



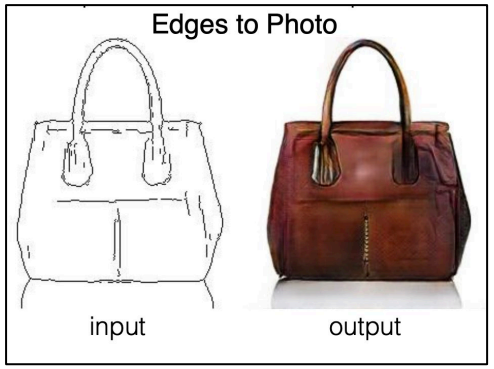
Training data is generated using a style transfer model trained by Generative Adversarial Networks.

Mask R-CNN

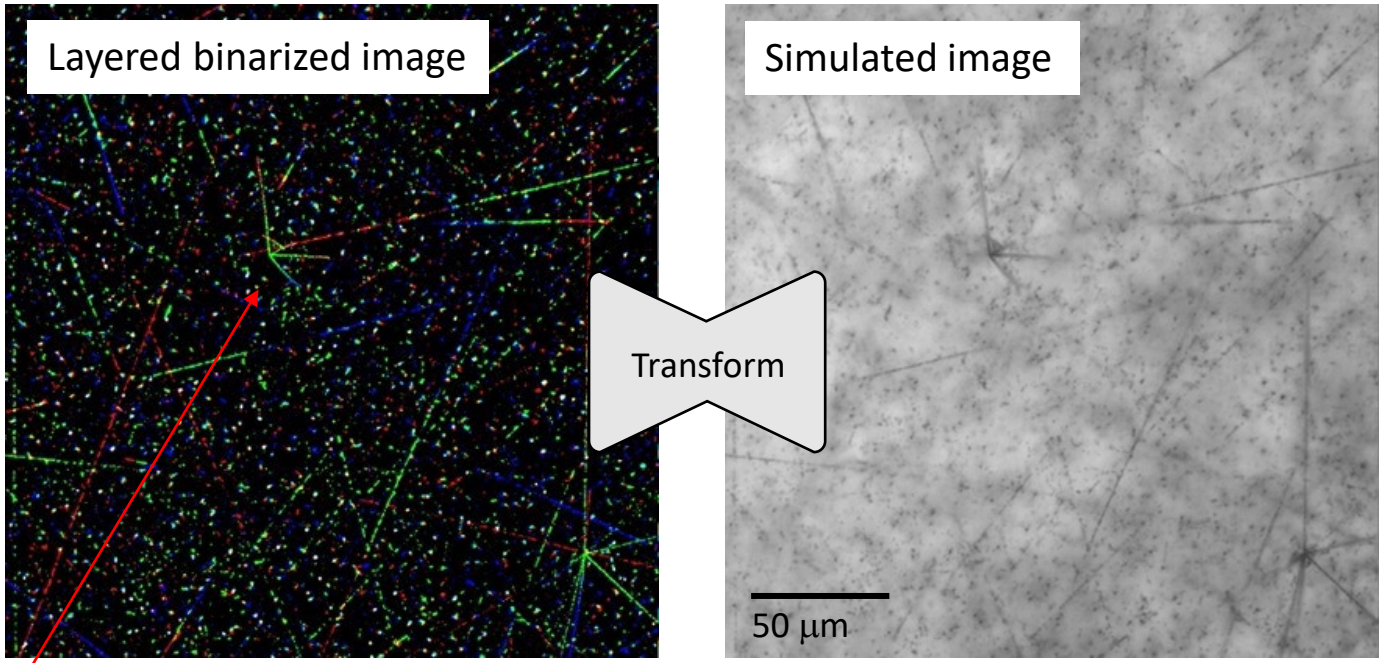
https://github.com/multimodallearning/pytorch-mask-rcnn

Generation of training images using a style transfer technique

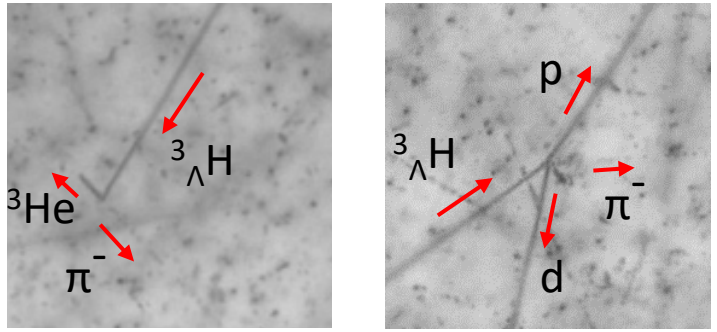
"Pix2pix"

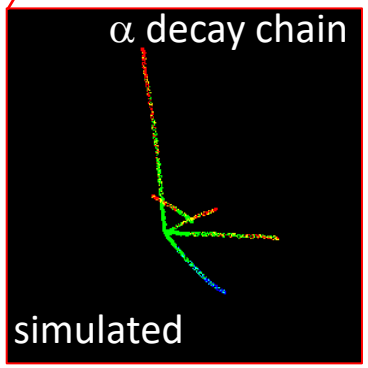


https://arxiv.org/abs/1611.07004



Simulated Hypertriton events



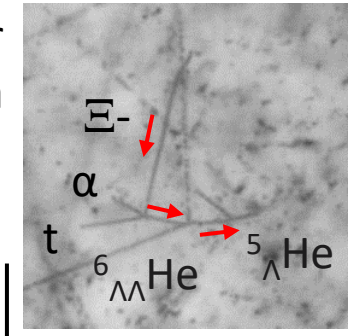


RGB color = depth

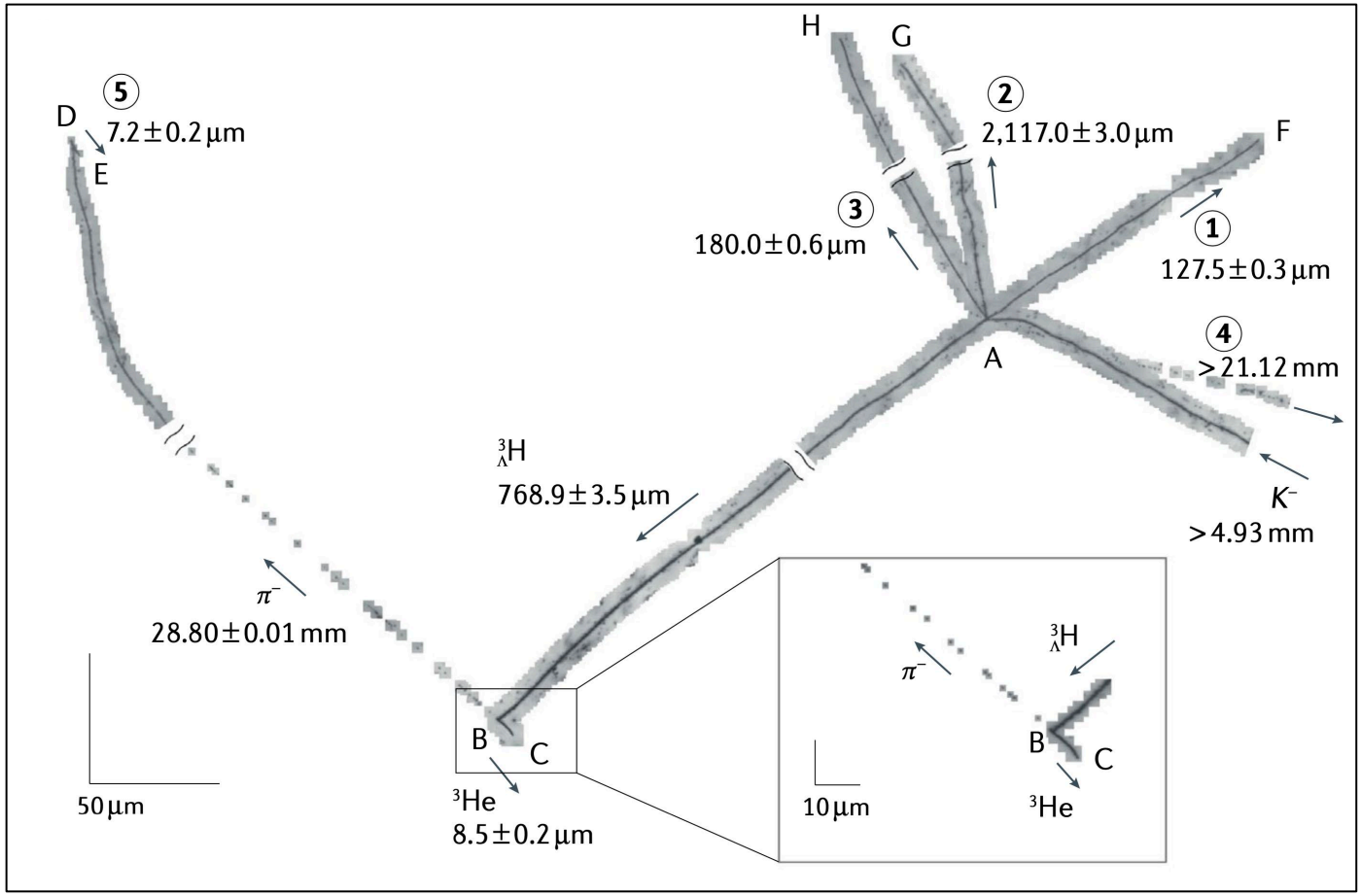
Tracks generated by Monte Carlo simulations

- α decay chain
- Stop and decay of Hypertriton ($^3_\Lambda$H)
  - 2-body decay
  - 3-body decay
- Production and decay of Double Λ hypernucleus etc.

A simulated Double Λ hypernuclear event decayed like Nagara

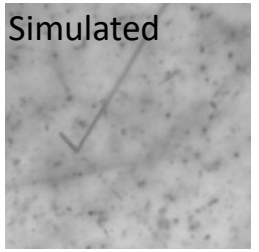


Toward precise measurement of binding energies of hypernuclei



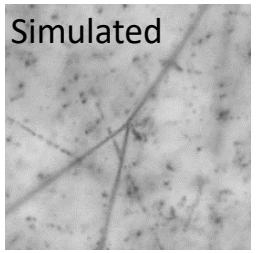
The 1st hypertriton event detected in an emulsion sheet using ML

"New direction of hypernuclear physics"
T.R Saito et.al., Nature Reviews Physics
https://doi.org/10.1038/s42254-021-00371-w



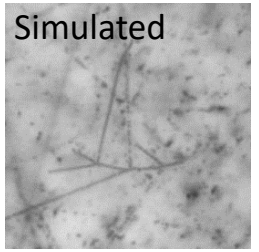
Binding energy of Λ in $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H

Ayumi Kasagi for his Ph.D. thesis
Gifu Univ., RIKEN



Detection of 3-body decays of Hypertritons

Shohei Sugimoto for his Master thesis
Saitama Univ., RIKEN



Detection of double Λ Hypernuclei

Yan He for her Ph.D. thesis
Lanzhou Univ., RIKEN

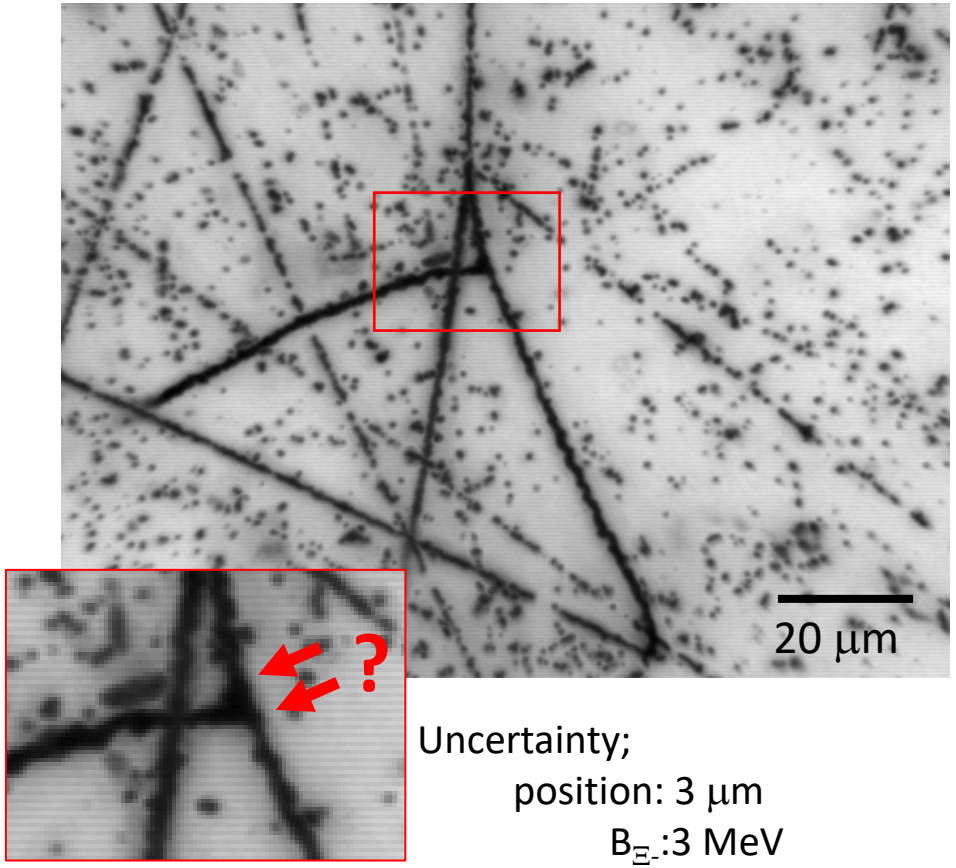
Applications to hypernuclear physics is ongoing.

Analysis of a twin Λ hypernuclei event using X-ray microscopy at SPring-8 (BL47XU)

$\Xi^- + {}^{14}N \rightarrow {}_{\Lambda}{}^{10}Be + {}_{\Lambda}{}^{5}He + n$

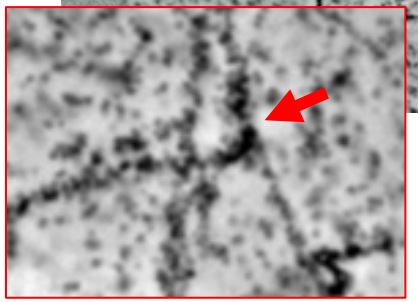
A. Kasagi et al., EPJ A 58, 190 (2022)

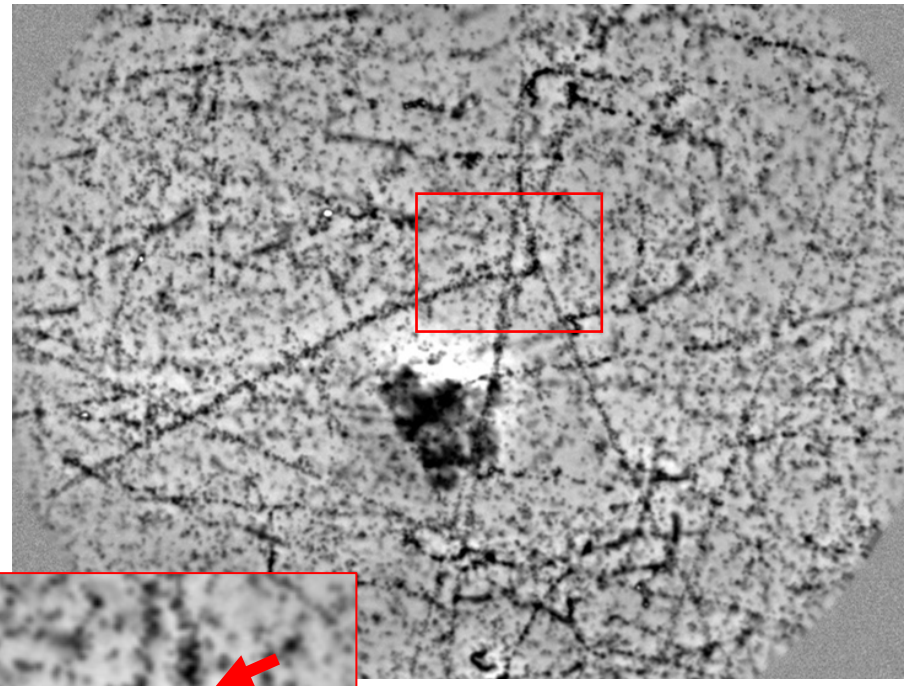
Optical microscopy



Uncertainty;
position: 3 μm
B_{Ξ^-}:3 MeV

X-ray microscopy (+ stereo method)





Uncertainty;
position: 0.04 μm
B_{Ξ^-}: 0.86 MeV

- B_{Ξ^-} : −1.23 ± 0.86 MeV
- It indicates that a Ξ^- atomic state is produced.

- This technique will be applied to charge identification of daughter particles based on track boldness measurement.

Summary:

- Emulsion experiments have been pioneering nuclear systems with double strangeness.

- 47 events of double strangeness including 33 in J-PARC E07 are observed, thus far.
  - Some of them are uniquely identified successfully.
  - A-dependence of $B_{\Lambda\Lambda}$ can be discussed using data of multiple double Λ hypernuclides.
  - Multiple levels of Ξ^- in a ^{14}N nucleus deeper than the atomic 3D level have been observed.

- The first Ξ^- atomic X-ray spectroscopy was conducted, and the probability that Ξ^- reaches the last orbit was evaluated.

Prospects:

- Overall scanning method is being developed to detect untriggered events.
  - Upgrade of scanning systems to readout 10^3 emulsion sheets.
  - Development of image recognition using machine learning techniques.
  - This technique is applying to precise measurement of hypernuclei.

- X-ray microscopy is applied to resolve vertices and charge identification of daughter particles.

E07 Collaboration (Author list of PTEP 2019, 021D02)

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Collaboration on machine learning for nuclear physics

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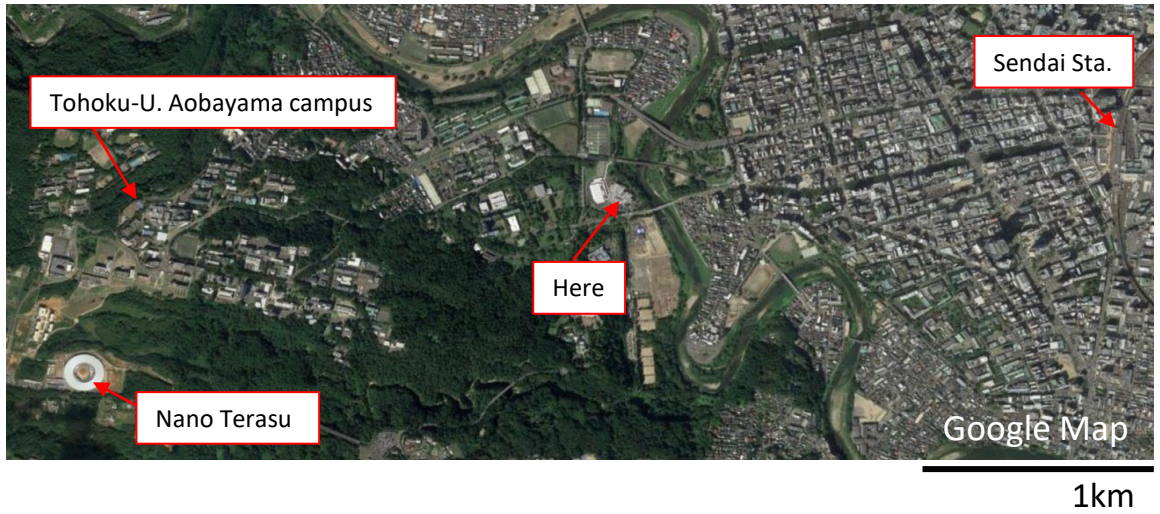
My current work: construction of a new synchrotron radiation facility, Nano Terasu



https://www.sris.tohoku.ac.jp/

- Development of the control systems for
  - X-ray optics devices
  - Light sources in the electron storage ring
- It will be ready in Apr. 2024
- I would like to pioneer new science across various research fields. I look forward to working with you again in the future.