

Hunting Hypernuclei with the KLF

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Chief Scientist

*High Energy Nuclear Physics Laboratory, Pioneering Research Institute (PRI), **RIKEN**, Japan*

Group leader

*HypHI Group, FRS/NUSTAR department, **GSI Helmholtz Center for Heavy Ion Research**, Germany*

Team Director (since April 2026)

*Neutron Frontier Research Team, **RIKEN Center for Advanced Photonics (RAP)**, **RIKEN**, Japan*

Professor

*Graduate School of Science and Engineering, **Saitama University**, Japan*



**8th KLF Collaboration Meeting,
Online, May 6th 2026**

Chart of ordinary nuclei

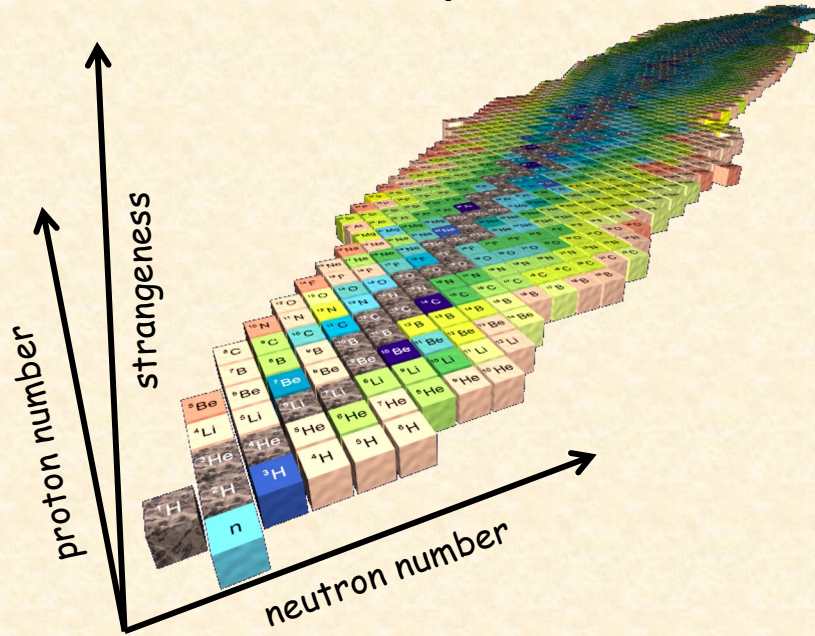


Chart of single-strangeness hypernuclei

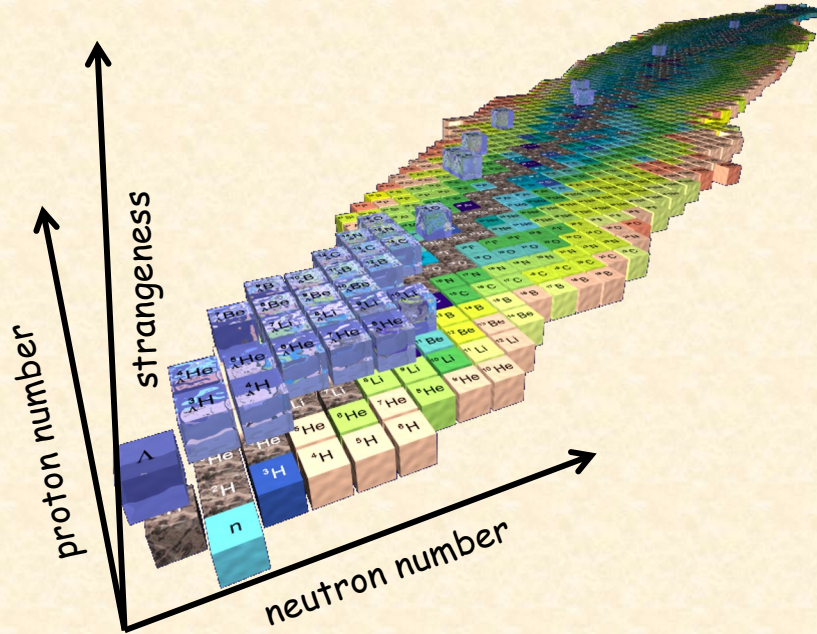


Chart of double-strangeness hypernuclei

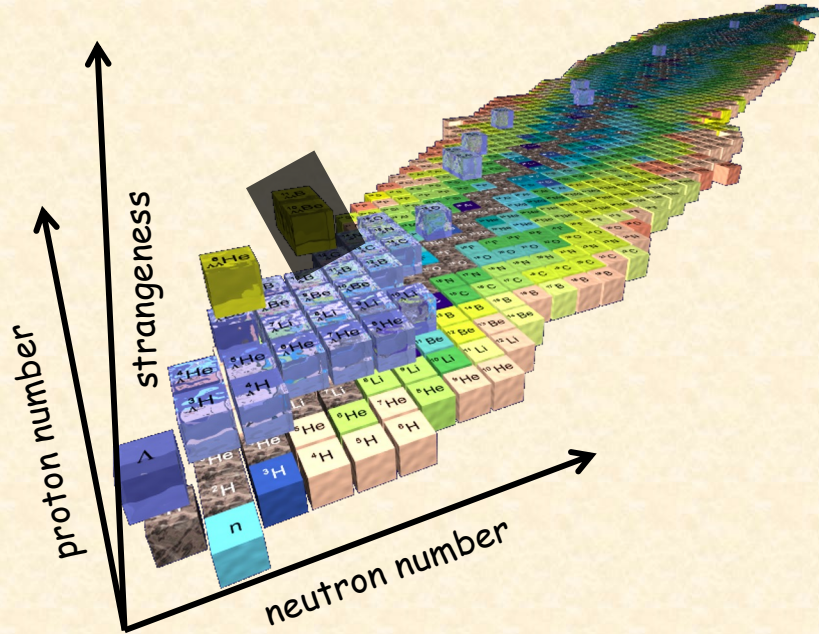
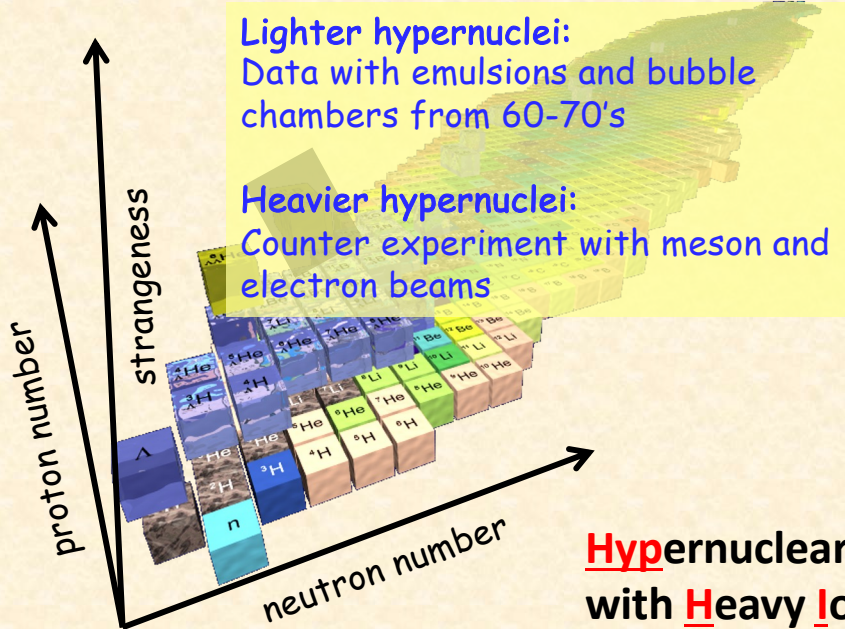


Chart of double-strangeness hypernuclei



Advantage

- Precise spectroscopy
 - Structure in detail (2 MeV res.)
- Clean experiment

Difficulties

- Limited isospin
- Small momentum transfer to separate hypernuclei
- Difficulties on decay studies
- Only up to double-strangeness

Hypernuclear spectroscopy
with **H**eavy **I**on Beam

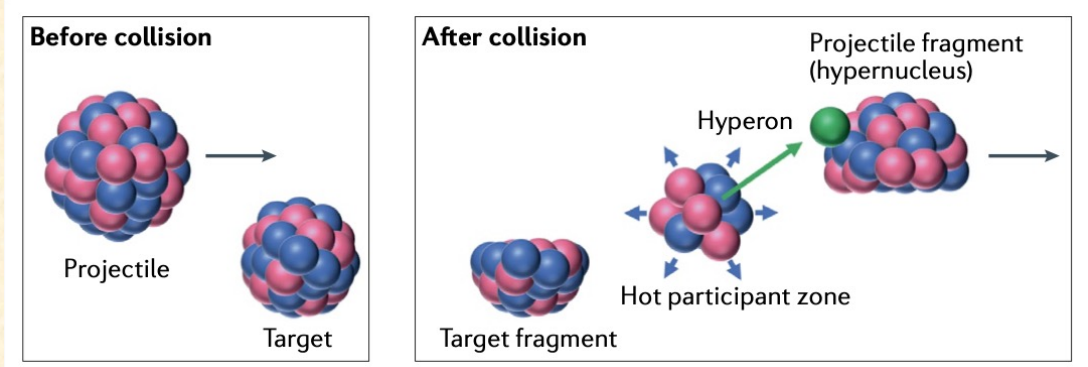
Important objectives:

- (Precise) Energies (binding energy and excited levels)
- Lifetime (including excited states)
- Exoticity
- Nuclear moments

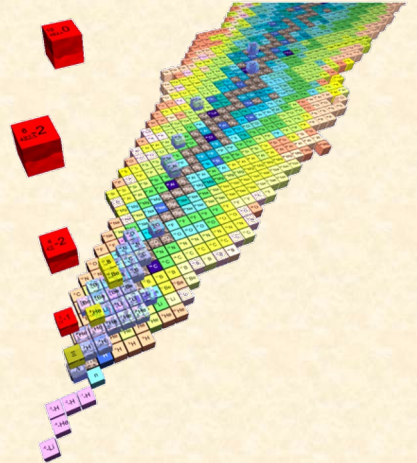
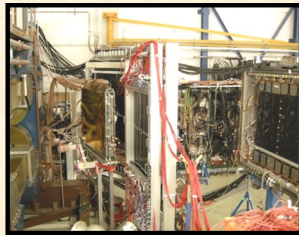
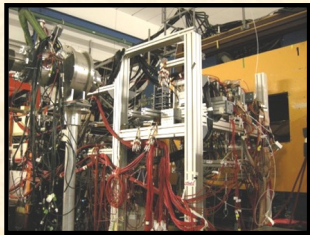
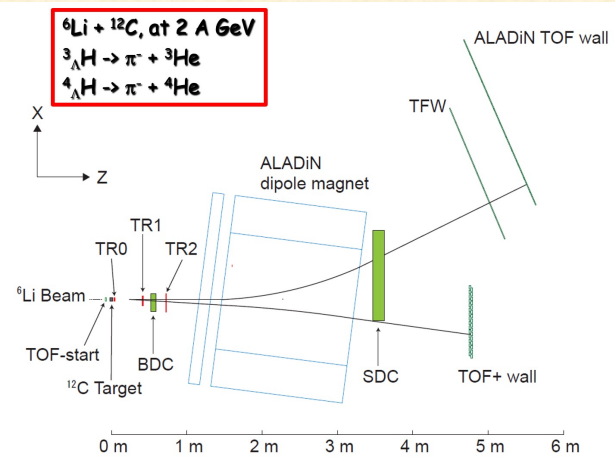
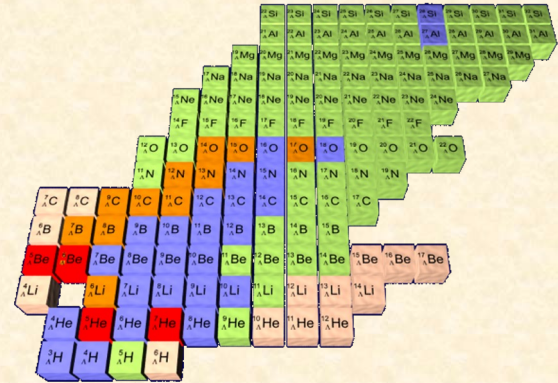
Hypernuclear spectroscopy
with heavy ion beams

HypHI project,
started in 2005

The HypHI Phase 0 at GSI in Germany (2006-2012)



TRS et al., Nature Reviews Physics 3, 803-813 (2021)



Two outcomes (mysteries) by HypHI

Signals indicating $nn\Lambda$ bound state

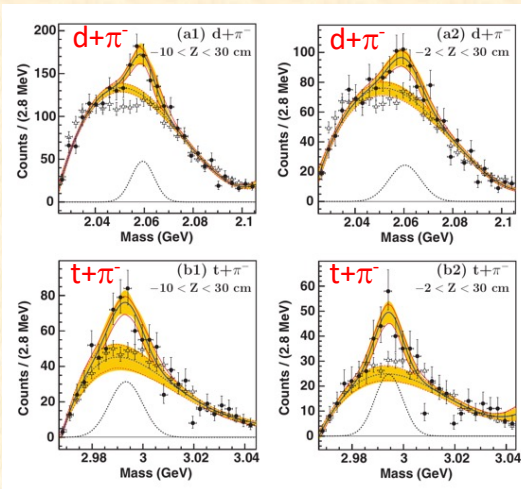
All theoretical calculations are negative

- E. Hiyama et al., Phys. Rev. C89 (2014) 061302(R)
- A. Gal et al., Phys. Lett. B736 (2014) 93
- H. Garcilazo et al., Phys. Rev. C89 (2014) 057001

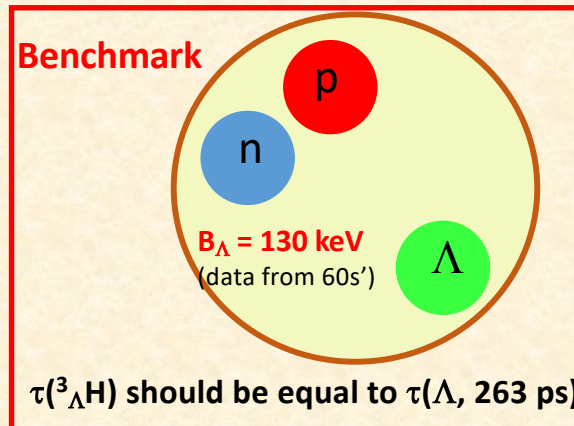
and much more publication

Short lifetime of ${}^3\Lambda\text{H}$ C. Rappold et al., Nucl. Phys. A 913 (2013) 170

- HypHI Phase 0: 183^{+42}_{-32} ps



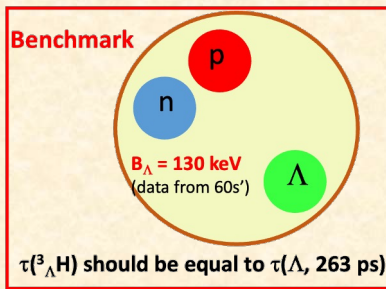
C. Rappold et al., PRC 88 (2013) 041001



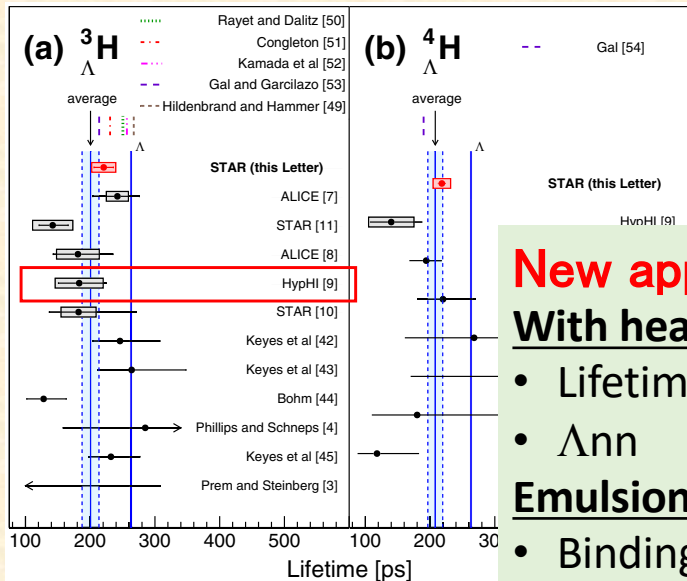
Stimulated other **big** experiments

The world situation of three-body hypernuclei

On hypertriton



Average
 $200 \pm 13 \text{ ps}$



$^3_{\Lambda}\text{H}$ Binding energy

$B_{\Lambda}(^3_{\Lambda}\text{H}) : 0.13 \pm 0.05 \text{ MeV}$

G. Bohm et al., NPB 4 (1968) 511

M. Juric et al., NPB 52 (1973) 1

STAR (2020)

$0.41 \pm 0.12 \pm 0.11 \text{ MeV}$

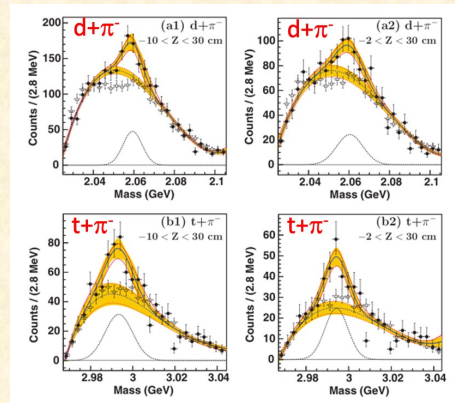
STAR Collaboration,
Nat. Phys. 16 (2020) 409

ALICE

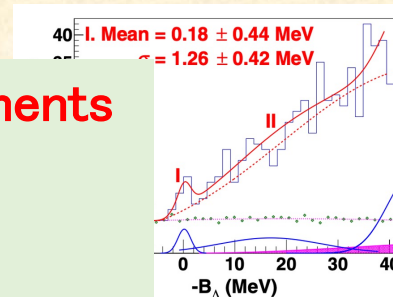
$0.102 \pm 0.063 \pm 0.067 \text{ MeV}$

Phys. Rev. Lett. 131, 102302 (2023)

On Λnn



HypHI., PRC 88 (2013) 041001



ed mass spectrum around the Λnn thresholds were fitted together with the known dentals, the Λ quasifree, the free Λ , and the π one at the threshold is for the small peak, or the additional strength above the predicted

New approaches with new developments

With heavy ion beams:

- Lifetime
- Λnn

Emulsion + Machine Learning

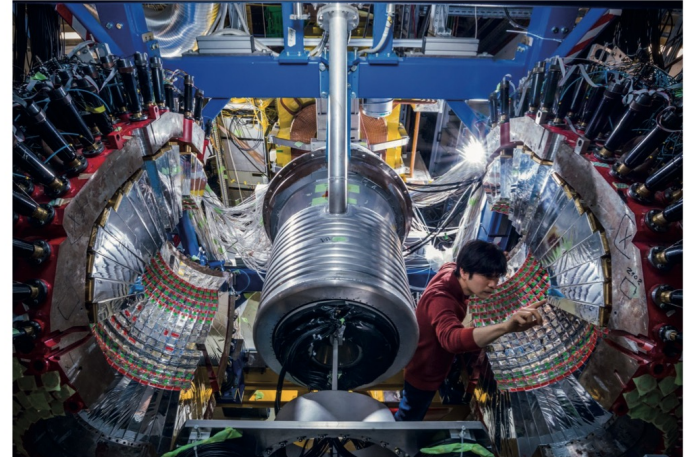
- Binding energy
- Double-strangeness hypernuclei

GSI-FAIR SCIENTIFIC REPORT 2022

An overview of the 2022 achievements in science and technology

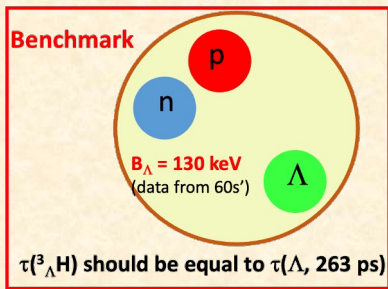


Photos by Jan Hosan and GSI/FAIR

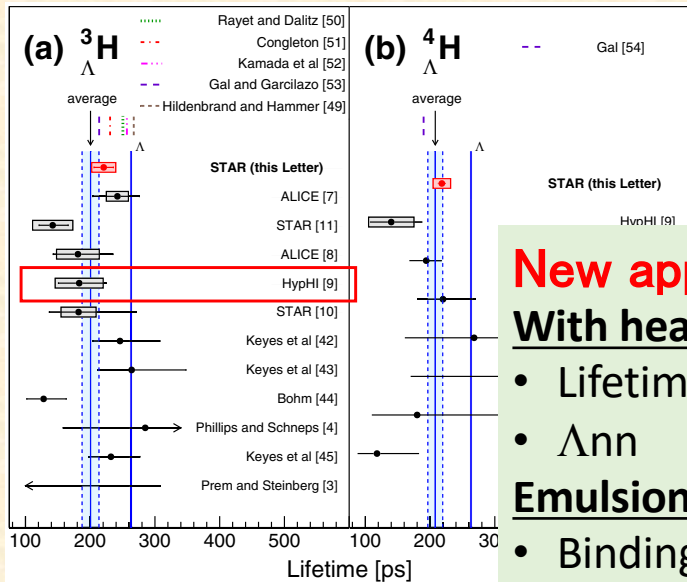


The world situation of three-body hypernuclei

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STAR Collaboration, PRL **128** (2022) 20

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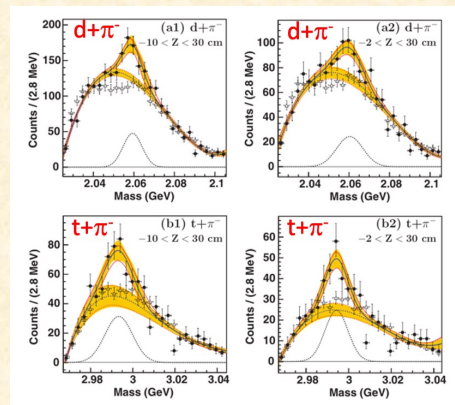
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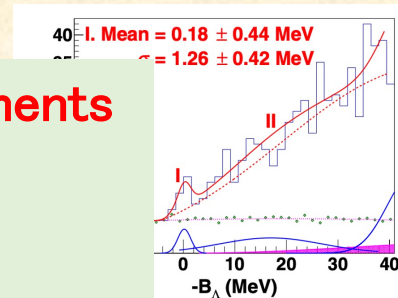
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Emulsion + Machine Learning

- Binding energy
- Double-strangeness hypernuclei

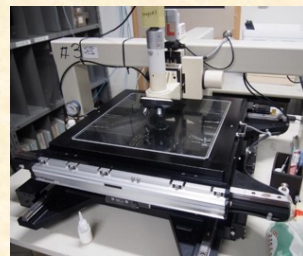


HypHI., PRC **88** (2013) 041001



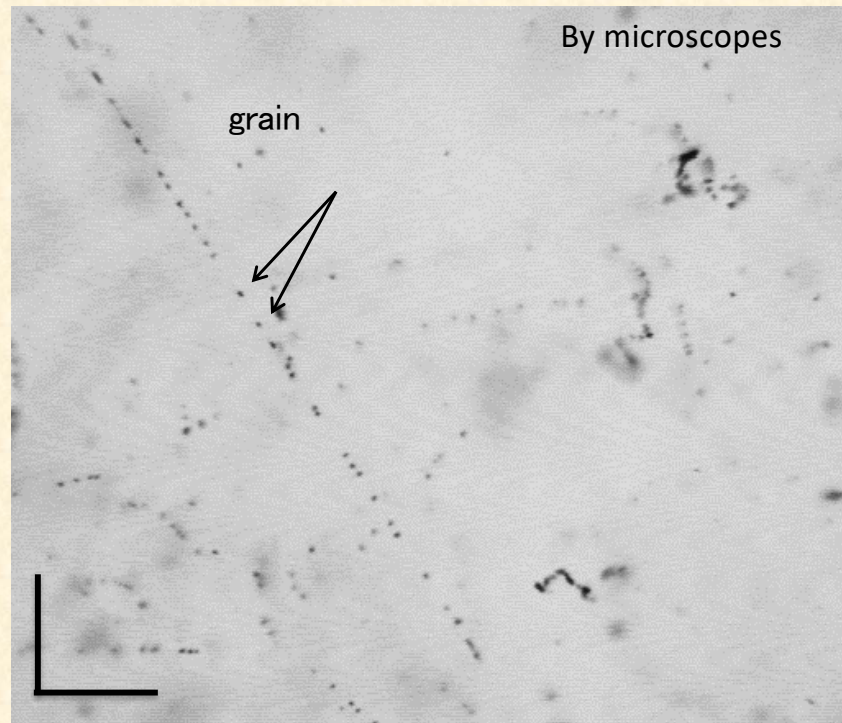
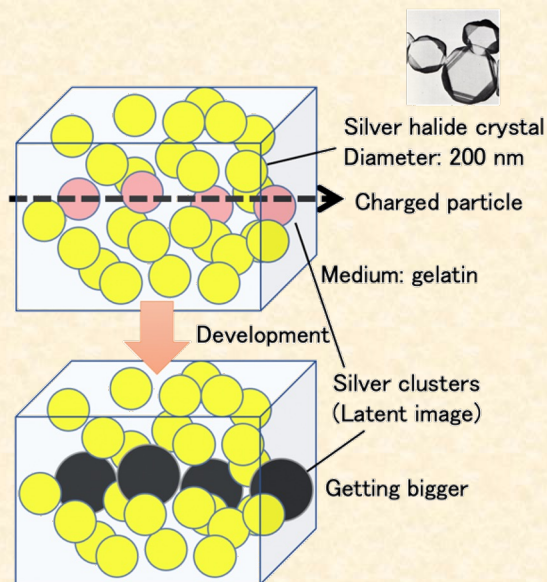
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003., PRC **105** (2022) L051001

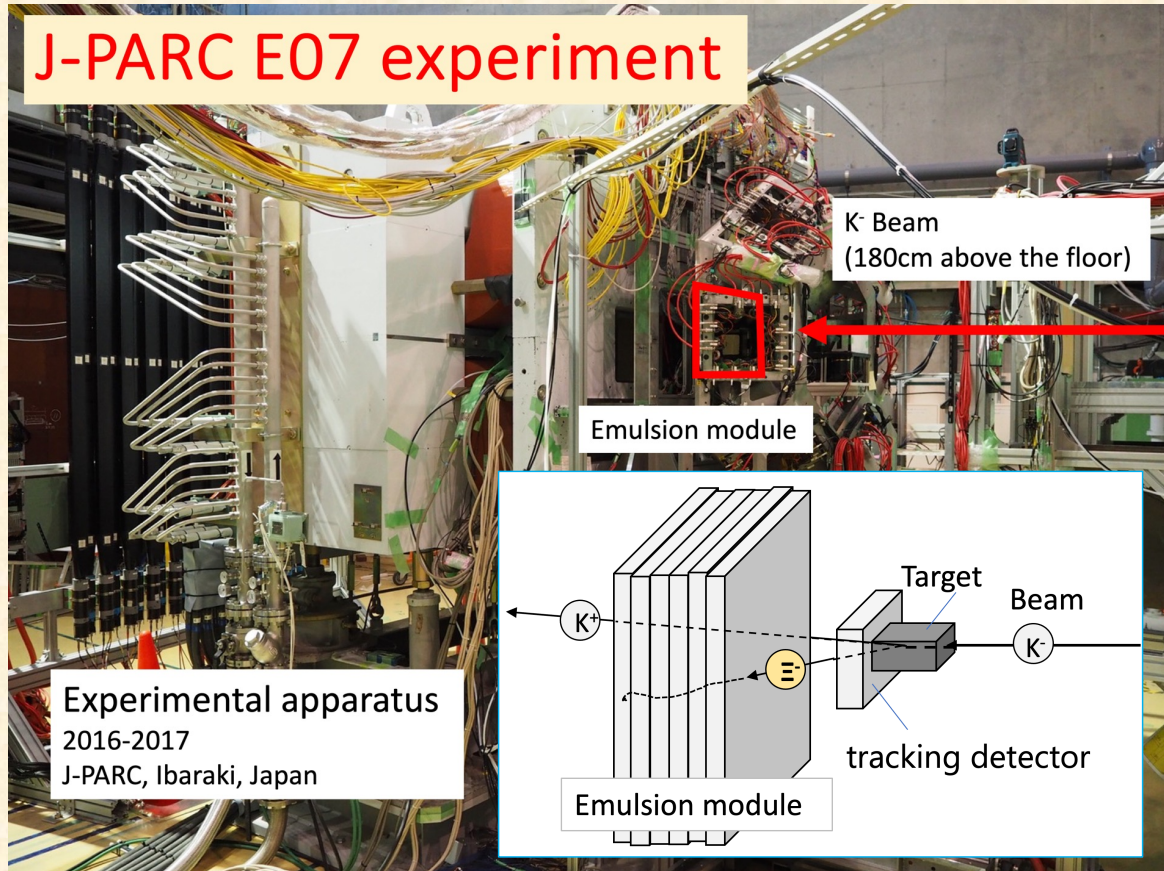
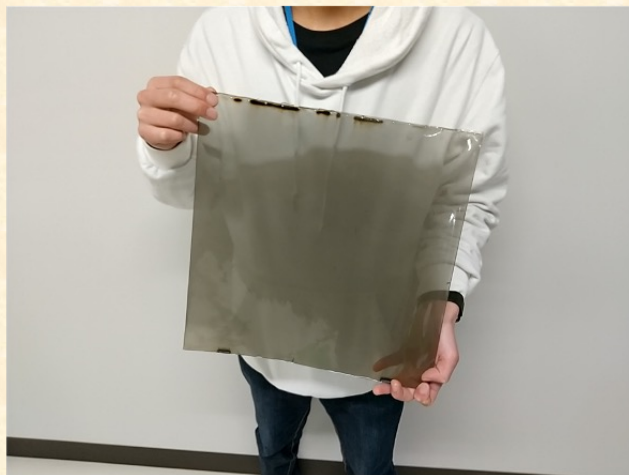


Nuclear Emulsion:

Charged particle tracker with
the best spatial resolution
(easy to be $< 1 \mu\text{m}$, 11 nm at best)

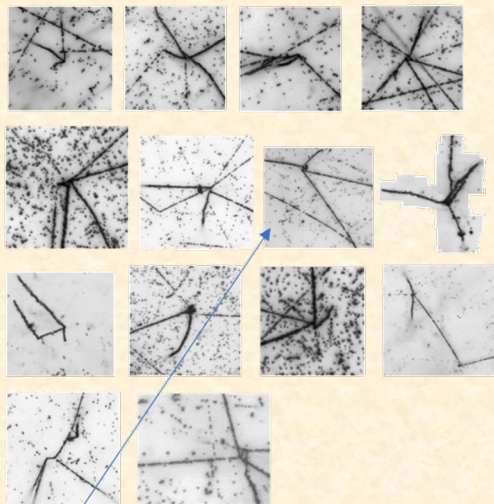


J-PARC E07 experiment



Results from J-PARC E07 (Hybrid method)

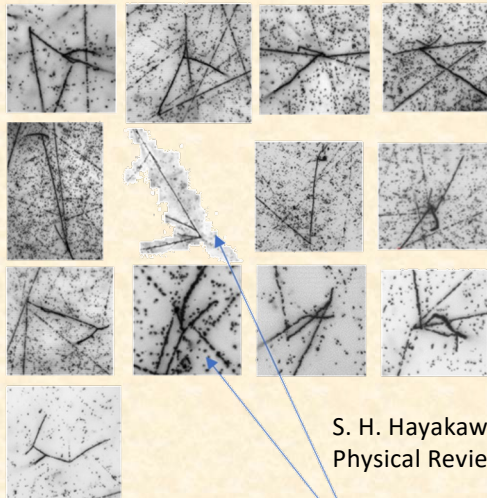
$\Lambda\Lambda$ candidates: 14



$\Lambda\Lambda$ Be

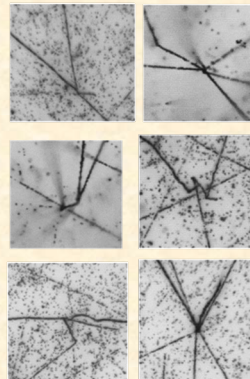
H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

Twin Λ events: 13



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

Others: 6

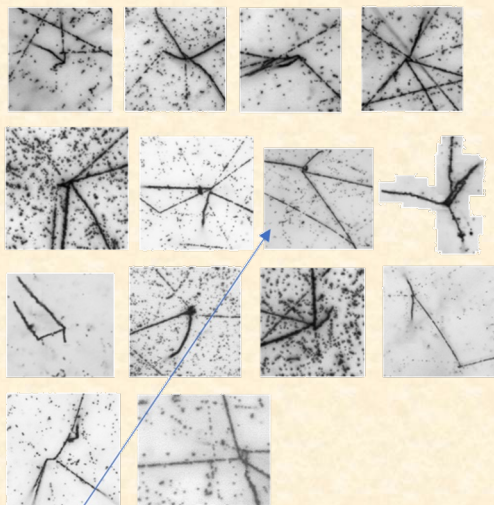


S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

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

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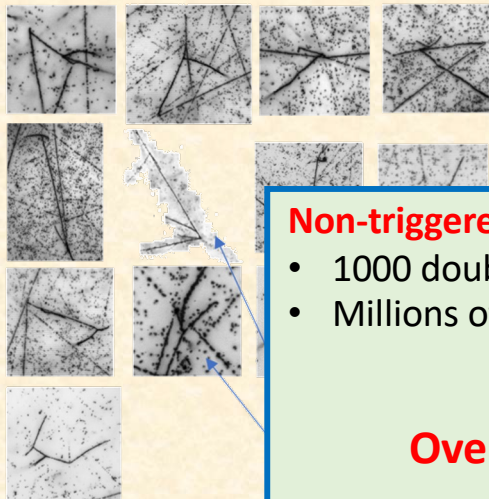
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H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

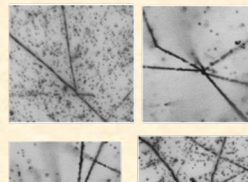
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$^{15}_{\Xi}\text{C}$

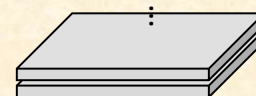
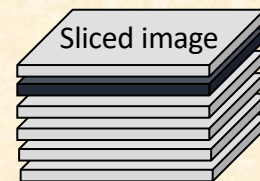
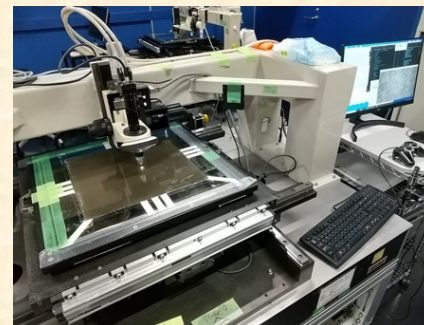
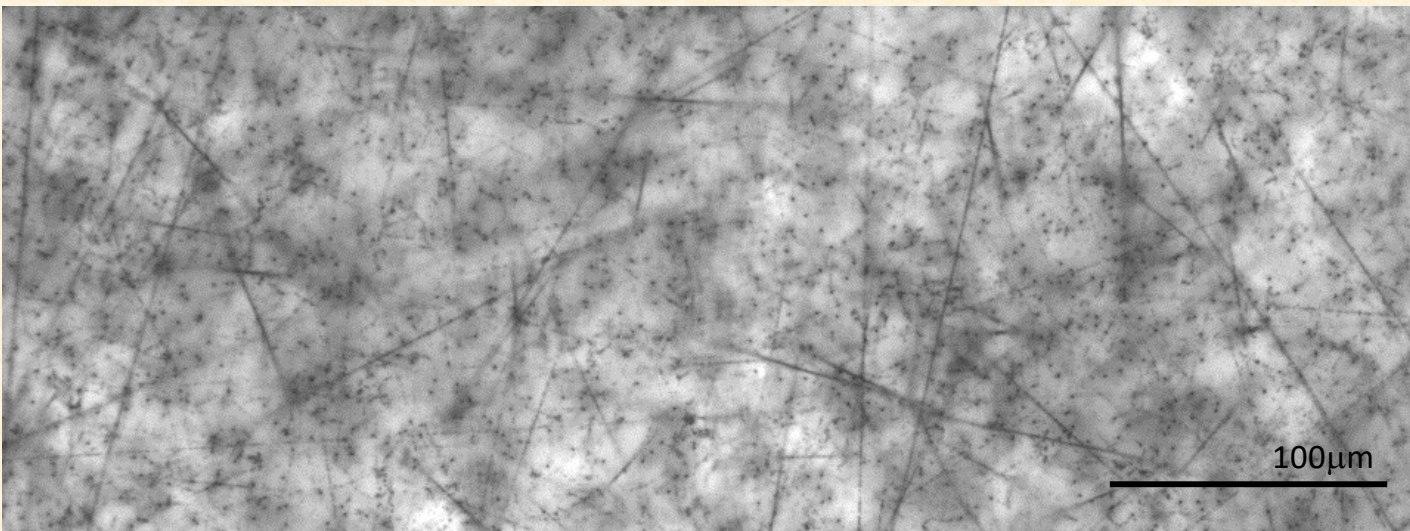
Non-triggered events recorded in 1300 emulsions sheets

- 1000 double-strangeness ($\Lambda\Lambda$ - and Ξ -) hypernuclear events
- Millions of single-strangeness hypernuclear events

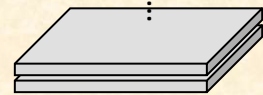
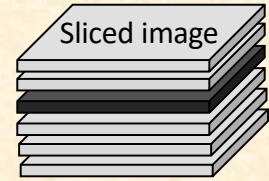
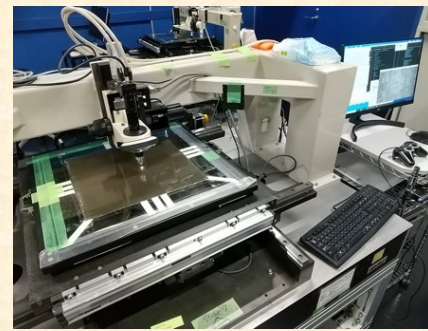
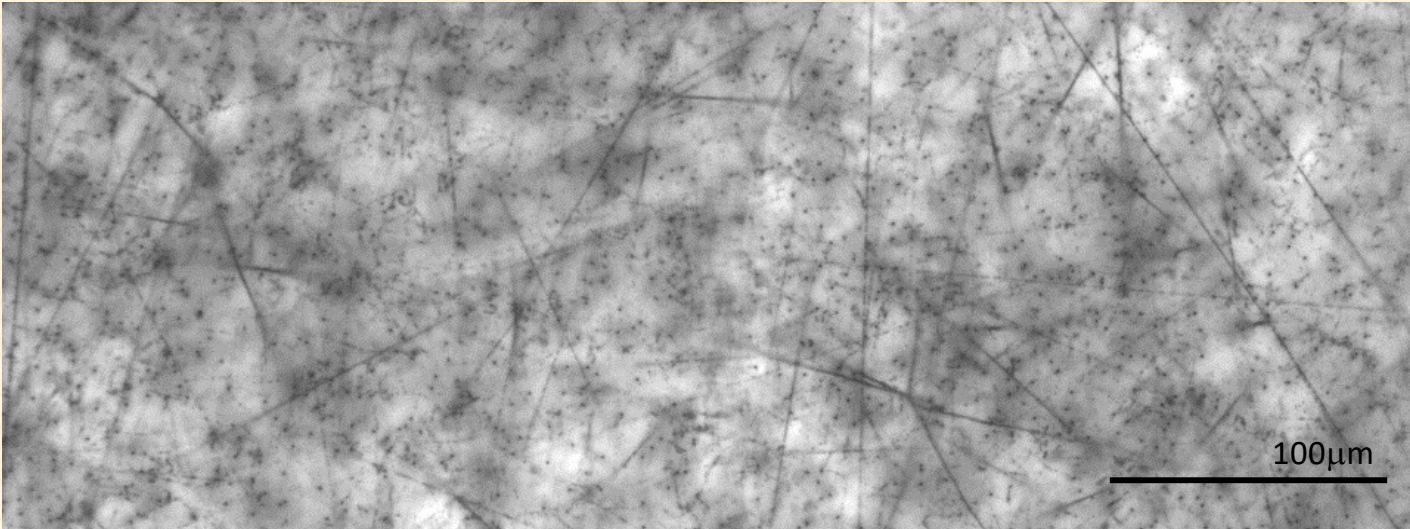


**Overall scanning of all emulsion sheets
(35 X 35 cm² X 1000)**

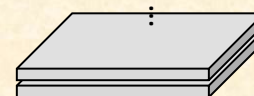
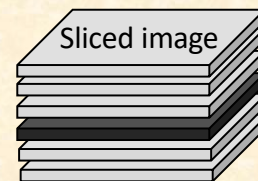
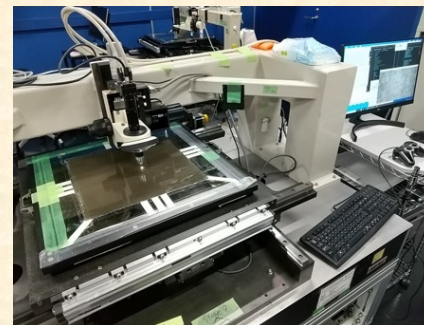
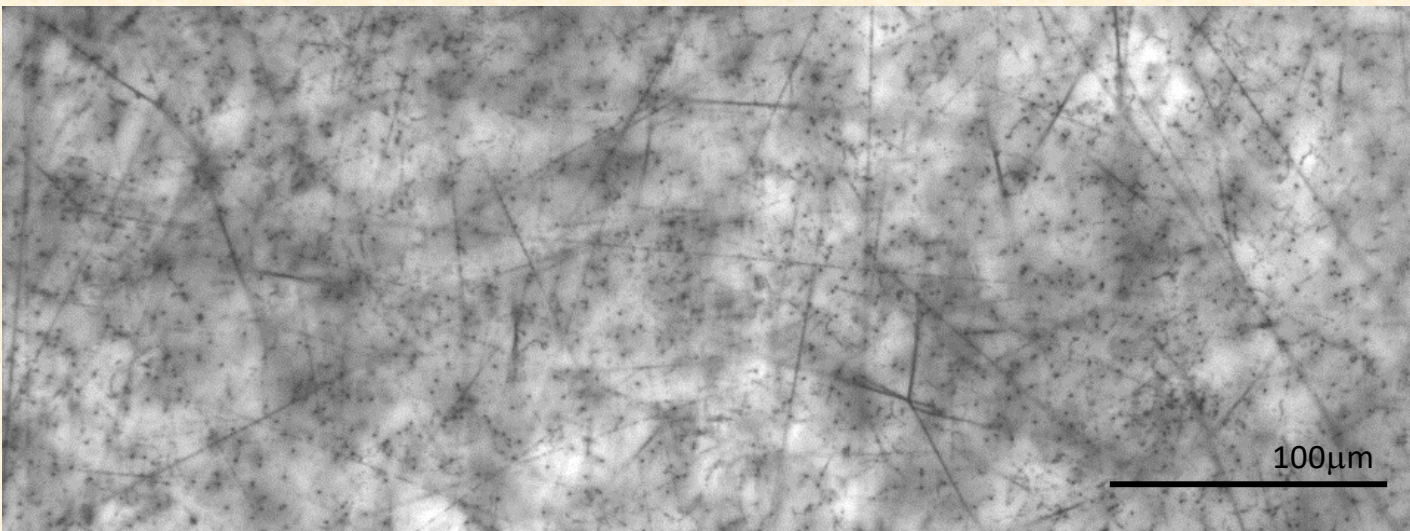
Overall scanning for E07 emulsions



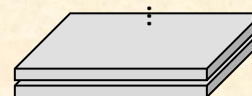
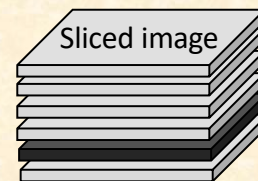
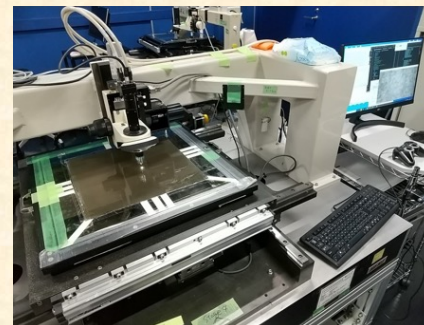
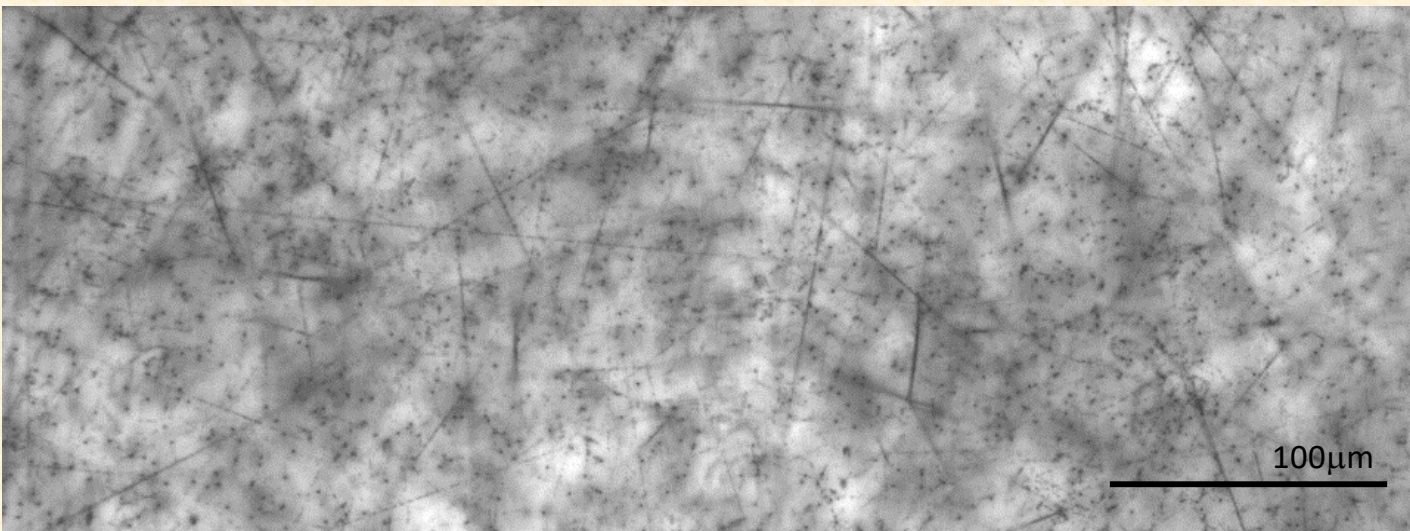
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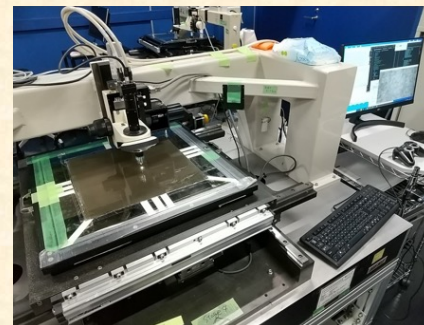
Overall scanning for E07 emulsions



Overall scanning for E07 emulsions



Overall scanning for E07 emulsions



Data size:

- 10^7 images per emulsion (100 T Byte)
- 10^{10} images per 1000 emulsions (100 P Byte)

Number of background tracks:

- Beam tracks: $10^4/\text{mm}^2$
- Nuclear fragmentations: $10^3/\text{mm}^2$

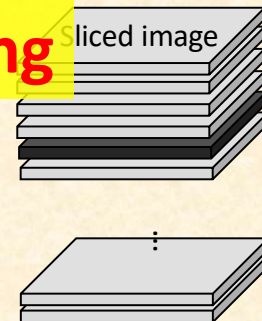
Current equipments/techniques
with visual inspections

560 years

3 years

Machine Learning

Sliced image



100 μm

Millions of single-strangeness hypernuclei
1000 double strangeness hypernuclei (formerly only 5)

Setup for analyzing emulsions at the High Energy Nuclear Physics Laboratory in RIKEN

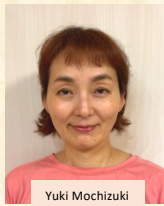
- Hypernuclear physics
- Neutron imaging

Technical staffs working for
emulsion & microscopes

Current members



Risa Kobayashi
(RIKEN)

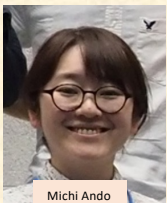


Yuki Mochizuki
(RIKEN)

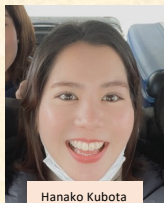


Yuka Bungo
(RIKEN)

Former members



Michi Ando
(RIKEN)



Hanako Kubota
(RIKEN)



Chiho Harisaki
(RIKEN)



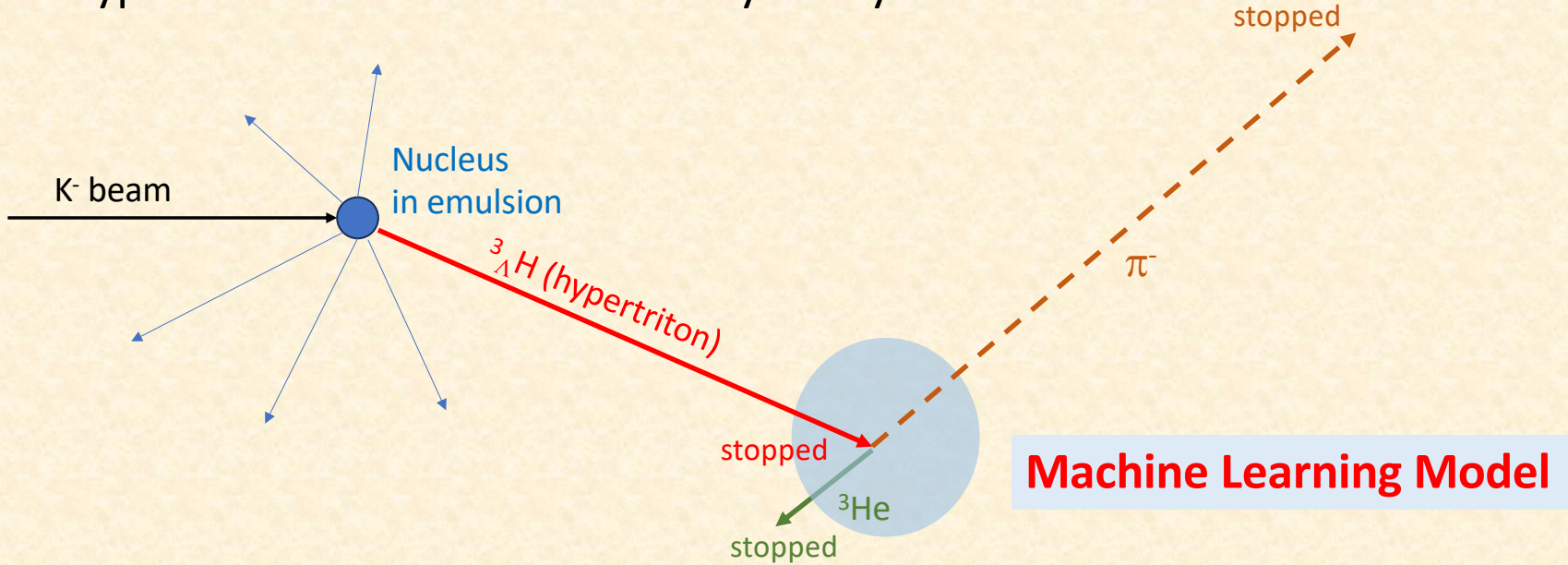
Keiko Sudo
(RIKEN)



Currently 7 microscope stages running

What do we want to dig out?

Hypertriton: π^- mesonic two-body decay



Challenges for Machine Learning Development

MOST IMPORTANT:

- **Quantity and quality of training data**

Ideas : 2018

Implementations: 2020-2021

However,

No existing data for hypertriton with emulsions for training

Our approaches:

Producing training data with

- Monte Carlo simulations
- Image transfer techniques (GAN)

**Developing machine learning models for hypernuclear event detections
(Mask R-CNN)**

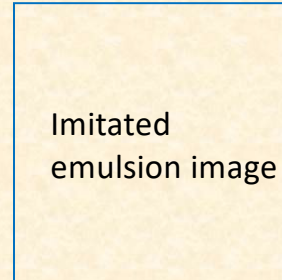
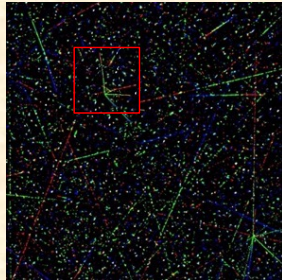
Ayumi Kasagi. Ph.D. thesis (2023)

A.Kasagi et.al, NIM A1056, (2023) 168663

Production of training data

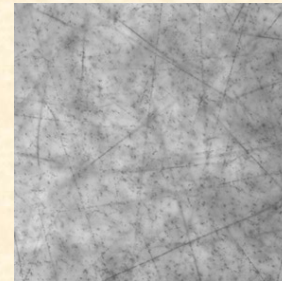
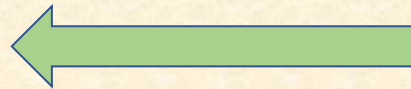
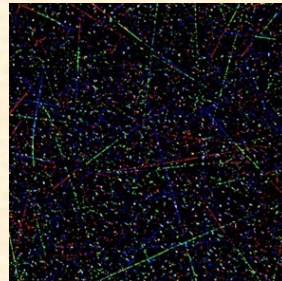
Monte Carlo simulations and GAN(Generative Adversarial Networks)

Binarized tracks from MC simulations
+ background from the real data



GAN: pix2pix

Edges to Photo



Binarized (like for simulations)

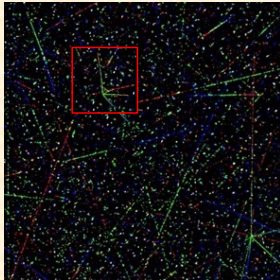
Real emulsion image

Ayumi Kasagi. Ph.D. thesis (2023)
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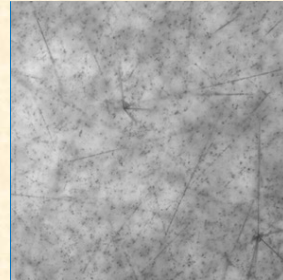
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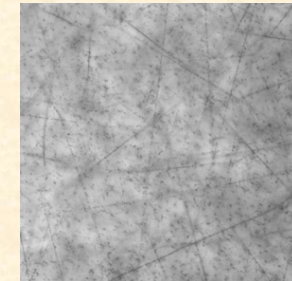
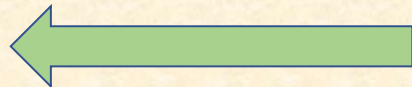
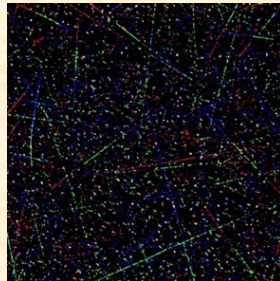


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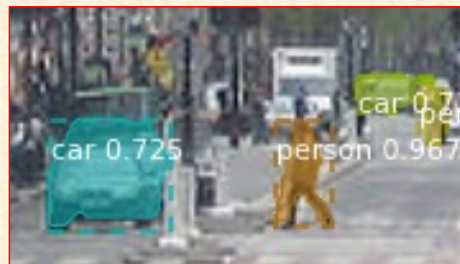
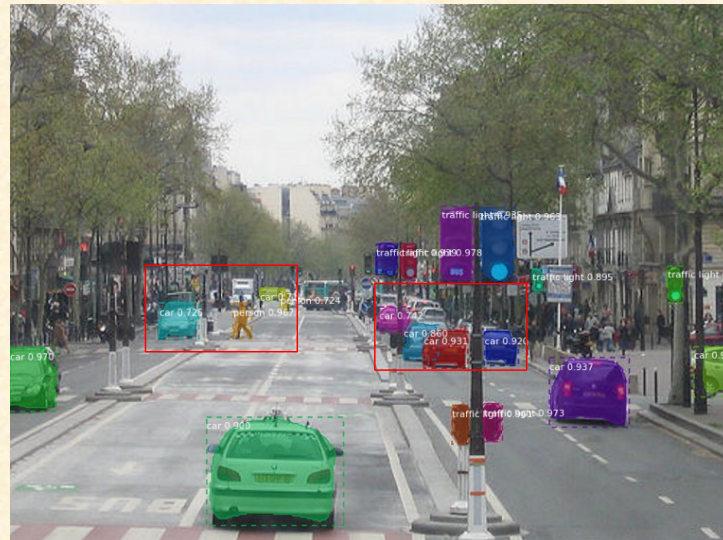
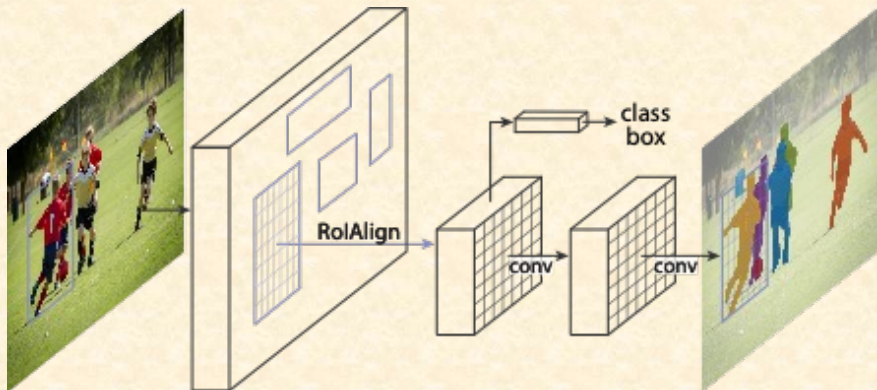
Real emulsion image

Ayumi Kasagi. Ph.D. thesis (2023)

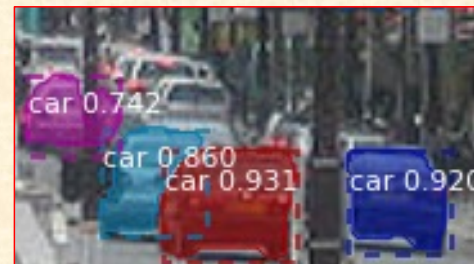
A.Kasagi et.al, NIM A1056, (2023) 168663

Detection of hypertriton events

With Mask R-CNN model



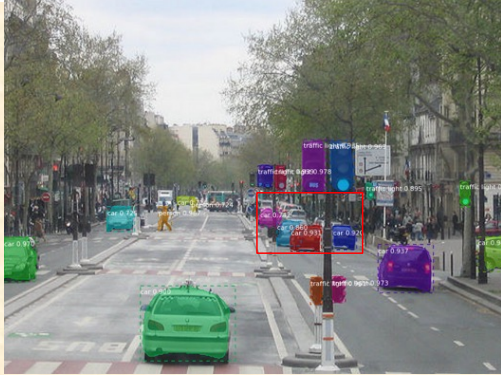
Detection of each object



At large object density

Training of Mask R-CNN with Simulated image

Mask R-CNN



Example of training dataset

Image

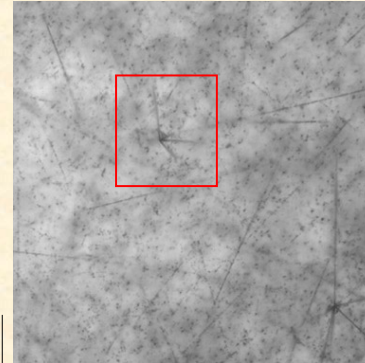
Mask



A Pedestrian dataset

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

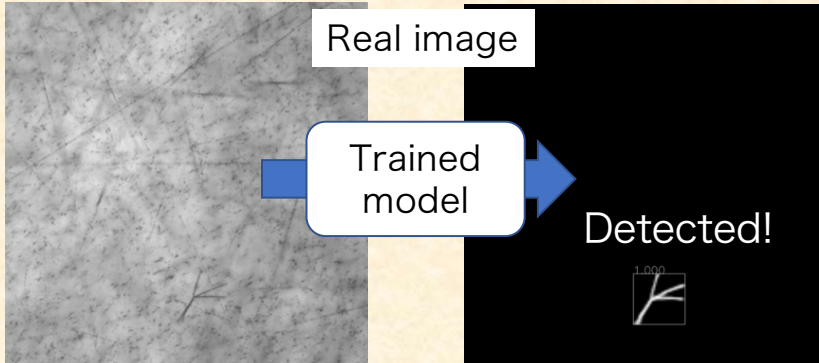
Training data (Simulated image)



Masks are automatically produced

50 μ m

Performance of α -decay detection



50 μ m

Efficiency
Purity

= No. detected/No. total
= Truth Positive/No. candidates

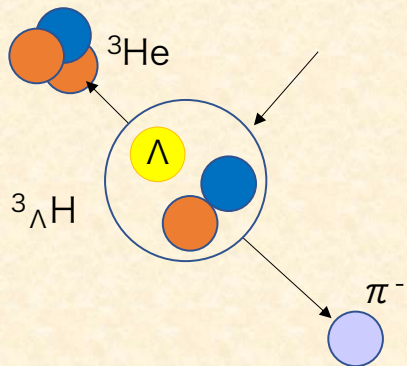
	Efficiency [%]	Purity [%]
Vertex picker	~40%	~1%
Mask R-CNN	~80%	~20%

→ 2nd step done

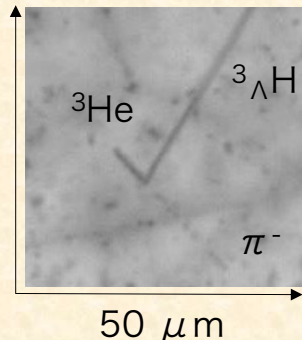
A.Kasagi et.al,
Nucl. Instrum. Meth. A 1056, (2023) 168663.

Hypertriton search with Mask R-CNN

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

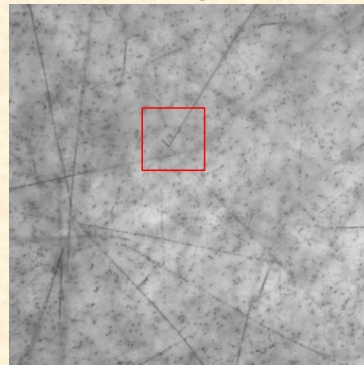


Simulated image

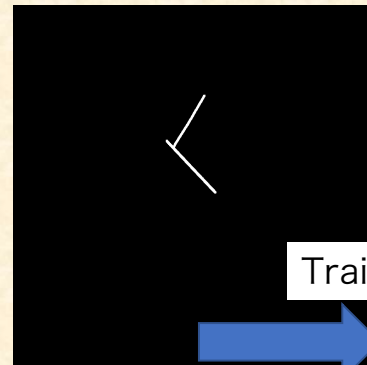


Training dataset (Simulated images)

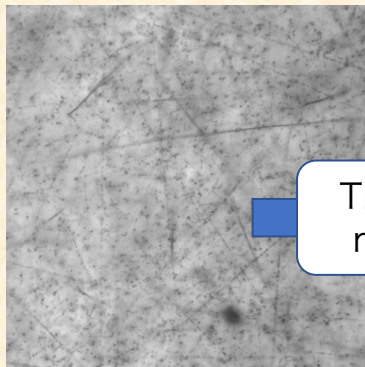
Image



Mask



Real image



Discovery of the first hypertriton event in E07 emulsions

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Perspective | Published: 14 September 2021

New directions in hypernuclear physics

Takehiko R. Saito , Wenbou Dou, Vasyly Drozd, Hiroyuki Ekawa, Samuel Escrig, Yan He, Nasser Kalantar-Nayestanaki, Ayumi Kasagi, Myroslav Kavatsyuk, Enqiang Liu, Yue Ma, Shizu Minami, Abdul Muneem, Manami Nakagawa, Kazuma Nakazawa, Christophe Rappold, Nami Saito, Christoph Scheidenberger, Masato Taki, Yoshiaki K. Tanaka, Junya Yoshida, Masahiro Yoshimoto, He Wang & Xiaohong Zhou

Nature Reviews Physics (2021) | Cite this article

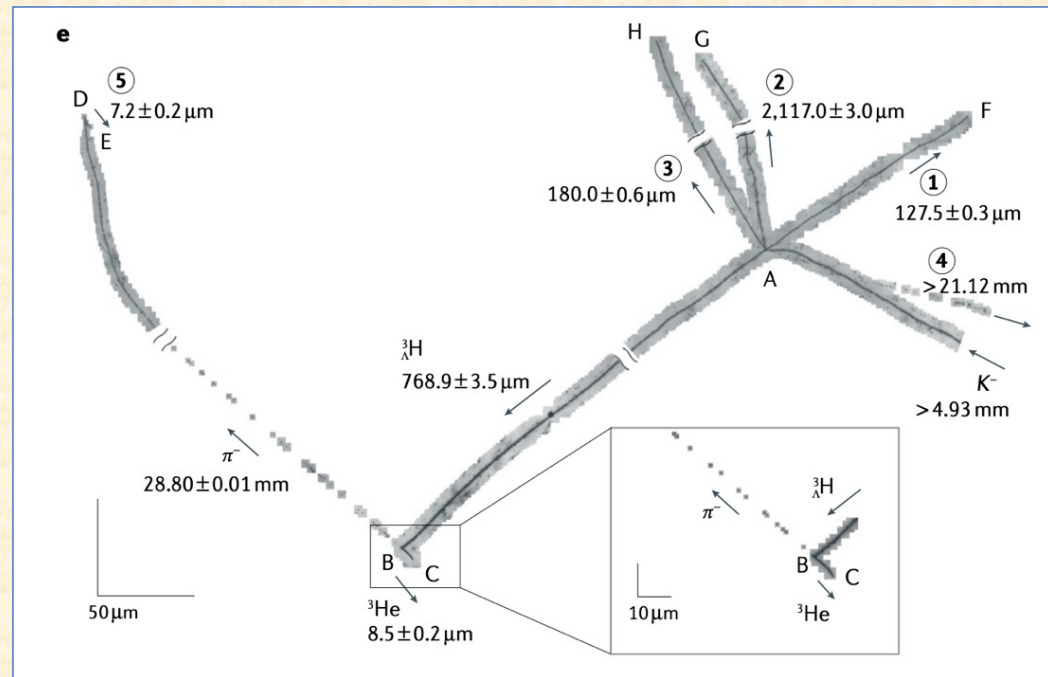
TRS et al., Nature Reviews Physics 3, 803-813 (2021)
Cover of December 2021 issue



Guaranteeing the determination of the hypertriton binding energy SOON

Precision: 28 keV

E. Liu et al., EPJ A57 (2021) 327

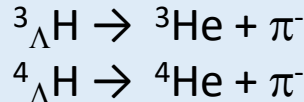
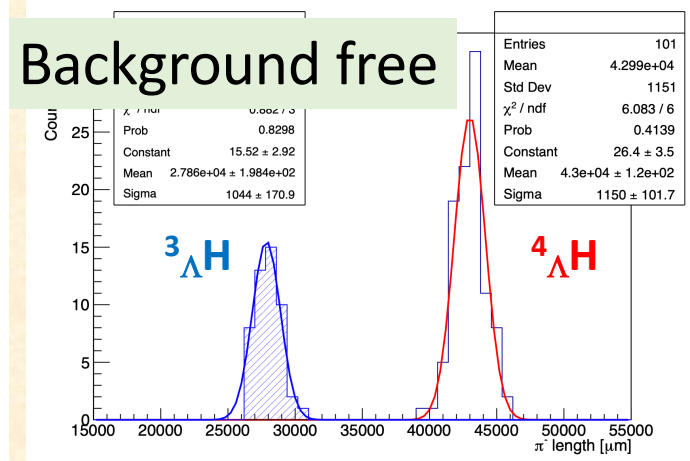
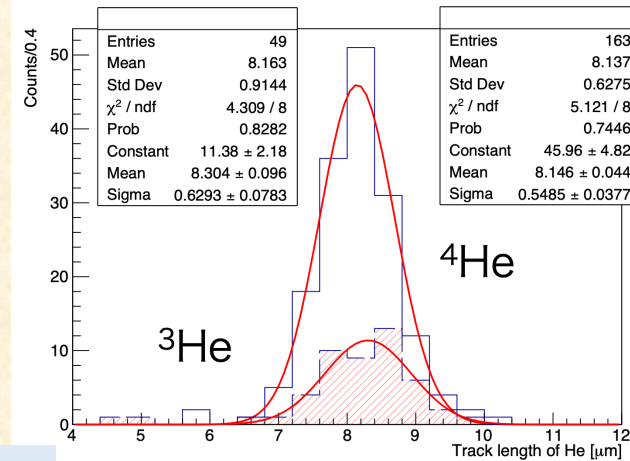
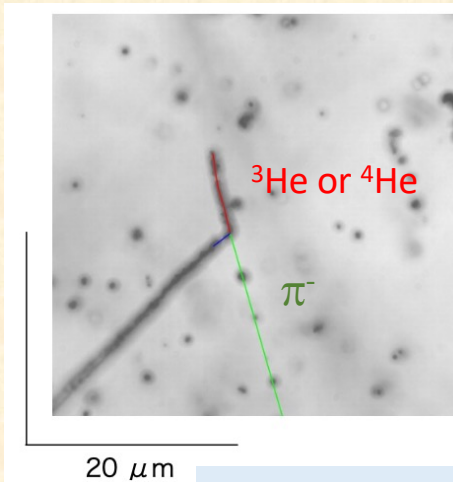


Ayumi Kasagi.
Ph.D. thesis (2023)

Towards the hypertriton binding energy

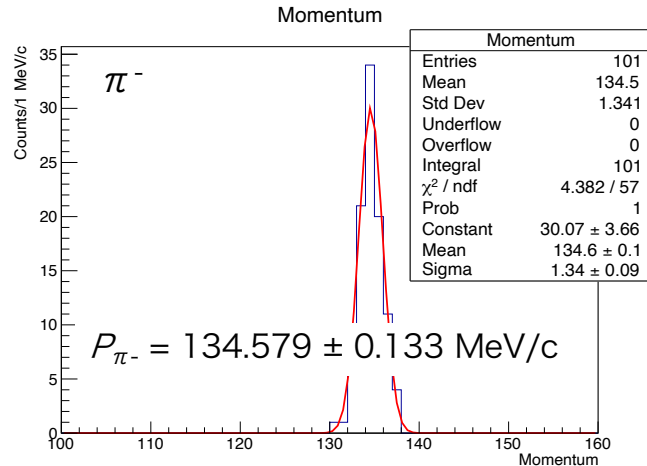
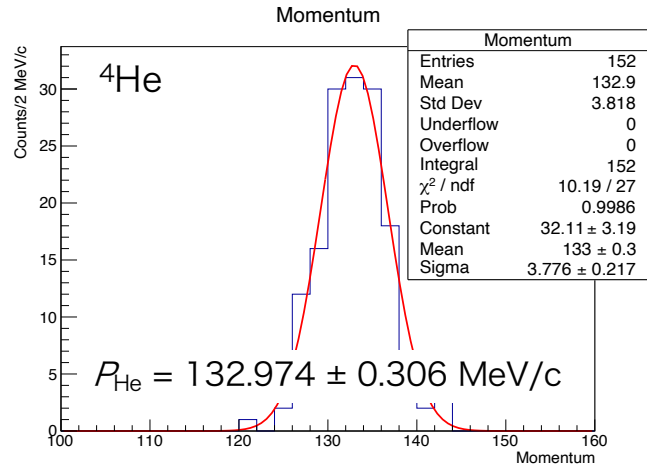
- Calibration of the nuclear emulsion (density/shrinkage) for each event
- Increasing statistics (**so far only 0.6 % of the entire data**)

	Identified	Calibrated
${}^3_{\Lambda}\text{H}$	49	49
${}^4_{\Lambda}\text{H}$	101 (163 detected)	101 (138 detected)

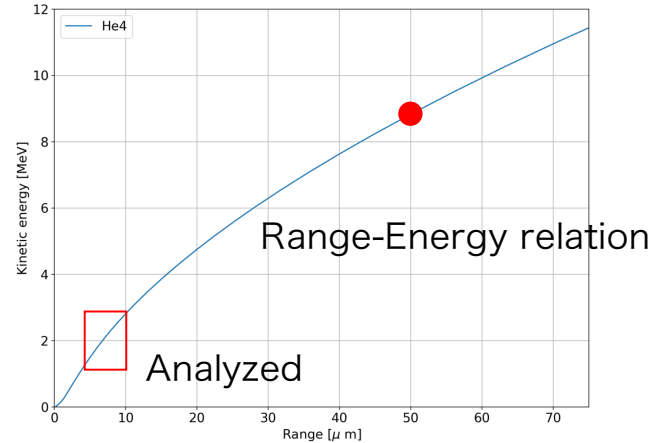


A. Kasagi et al., (**talk in this afternoon today**)

Problems on π^-



MAMI: $P_{\pi^-} = \underline{132.851 \pm 0.011 \text{ (stat.)} \pm 0.101 \text{ (syst.) MeV/c}$
 Nucl. Phys. A 954, 149 (2016)



We confirmed that **the Range-Energy Relation for energetic π^- is not correct**

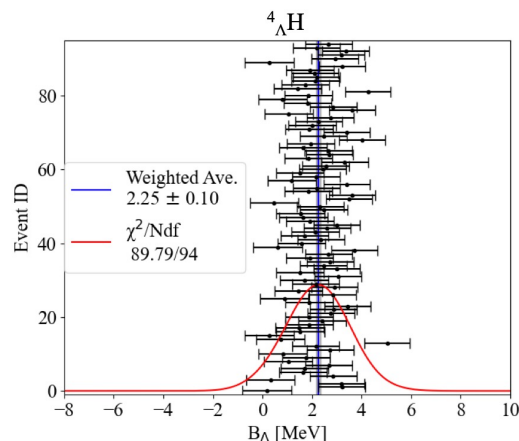
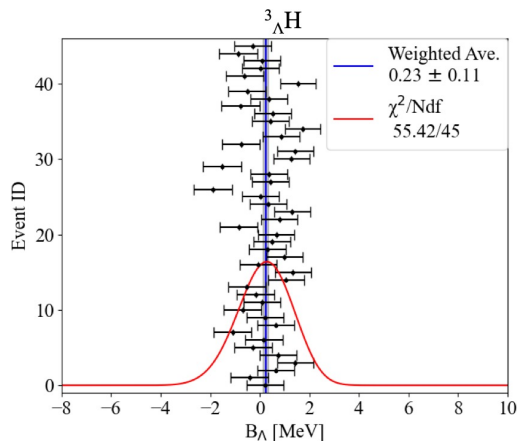
Known Range-Energy Relation is different because the difference of emulsion compositions



May affect emulsion results at KEK (E373) and J-PARC (E07)

A. Kasagi et al., (**talk in this afternoon today**)
 Progress of Theoretical and Experimental Physics,
 Volume 2025, Issue 8, (2025) 083D01

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



MAMI C:

2.12 ± 0.01 (stat.) ± 0.09 (sys.) MeV

${}^3_{\Lambda}\text{H}$ Binding energy

$B_{\Lambda}({}^3_{\Lambda}\text{H}) : 0.13 \pm 0.05$ MeV

G. Bohm et al., NPB **4** (1968) 511

M. Juric et al., NPB **52** (1973) 1

STAR (2020)

$0.41 \pm 0.12 \pm 0.11$ MeV

STAR Collaboration,
Nat. Phys. **16** (2020) 409

ALICE

$0.102 \pm 0.063 \pm 0.067$ MeV

Phys. Rev. Lett. **131**, 102302 (2023)

$({}^3_{\Lambda}\text{H}) B_{\Lambda} = 0.23 \pm 0.11(\text{Stat.}) \pm 0.05(\text{Syst.})$ MeV,

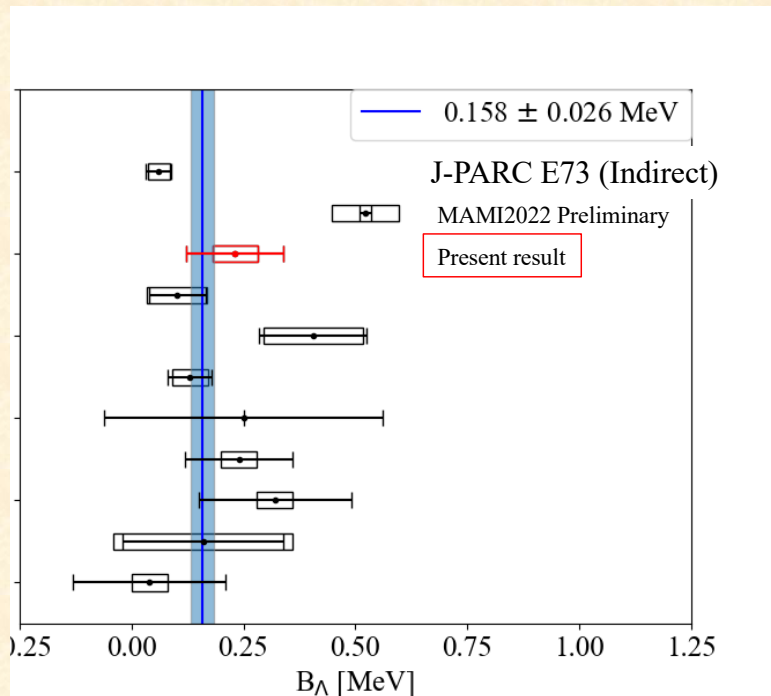
$({}^4_{\Lambda}\text{H}) B_{\Lambda} = 2.25 \pm 0.10(\text{Stat.}) \pm 0.06(\text{Syst.})$ MeV.

0.6 % of the entire data

A. Kasagi et al.,

Progress of Theoretical and Experimental Physics, Volume 2025, Issue 8, (2025) 083D01

Hypertriton binding energy



MAMI (2022)

- 500 keV. Deeper binding?

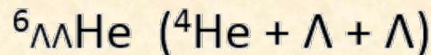
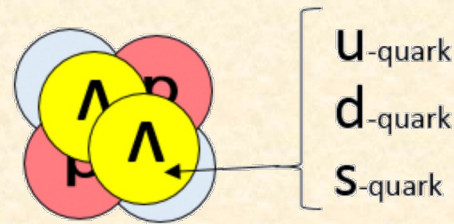
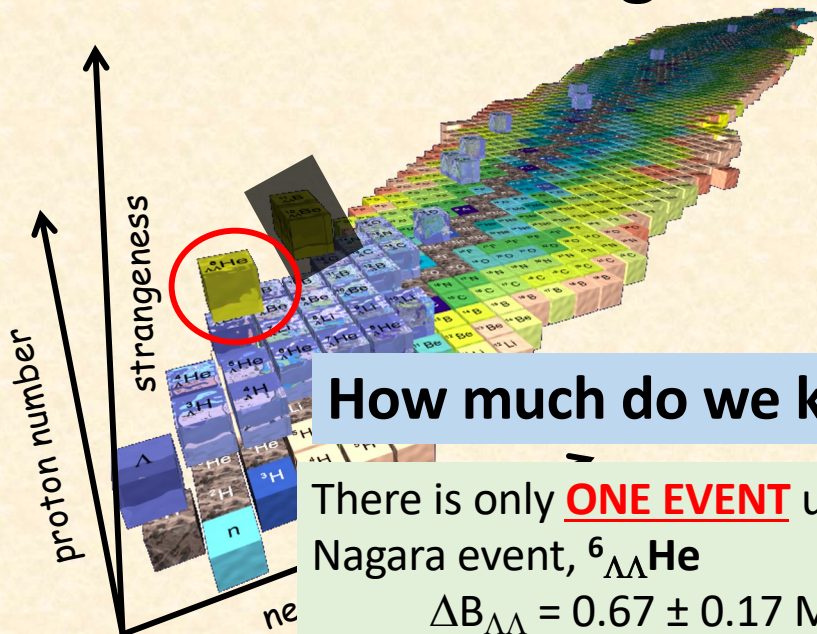
J-PARC E73

- In-direct method (B.R & Production)
(B.R: Emulsion by 1970s)

We need much more precise result

- We can increase statistics by a factor 160
- Systematic uncertainty can be 10 keV with better calibration (measurements at PSI, TRIUMF, and KEK)

Chart of double-strangeness hypernuclei



How much do we know about Λ - Λ interaction?

There is only **ONE EVENT** uniquely unidentified $S=-2$ hypernucleus Nagara event, ${}^6_{\Lambda\Lambda}\text{He}$

$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17 \text{ MeV}$$

- Does the Λ - Λ interaction depend on nuclear medium?
- Do we understand the 3-body force induced by $\Lambda\Lambda$ - ΞN ?

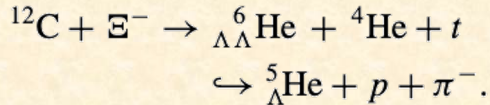
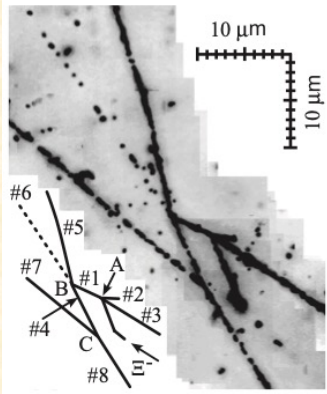
We need more systematic and statistics.

${}^6_{\Lambda\Lambda}\text{He}$ (the Nagara event)

Results in the NAGARA paper

<https://doi.org/10.1103/PhysRevLett.87.212502>

<https://doi.org/10.1103/PhysRevC.88.014003>



VertexA(Production)

$$\Delta B_{\Lambda\Lambda} - B_{\Xi} = 0.69 \pm 0.20 \text{ MeV}$$

VertexB(Decay)

$$\Delta B_{\Lambda\Lambda} = 0.6 \pm 0.6 \text{ MeV}$$

$$B_{\Lambda\Lambda} = 6.79 + 0.91B_{\Xi^-} (\pm 0.16) \text{ MeV}$$

$$\Delta B_{\Lambda\Lambda} = 0.55 + 0.91B_{\Xi^-} (\pm 0.17) \text{ MeV}$$

$$B_{\Lambda\Lambda} = 6.91 \pm 0.16 \text{ MeV}$$

$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17 \text{ MeV}$$

(Assumption: $B_{\Xi^-} = 0.13 \text{ MeV}$ (3D))

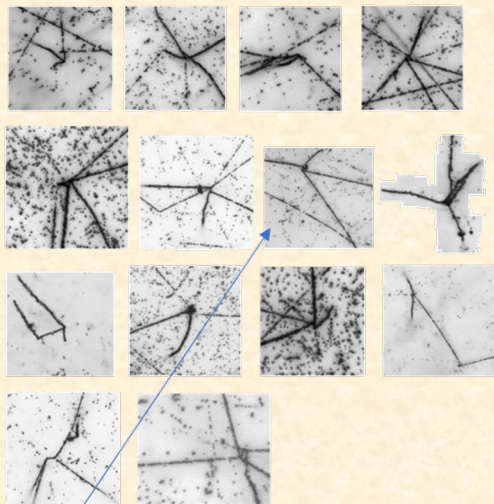


PRELIMINARY

$\Delta B_{\Lambda\Lambda}$: about 2 times larger

Results from J-PARC E07 (Hybrid method)

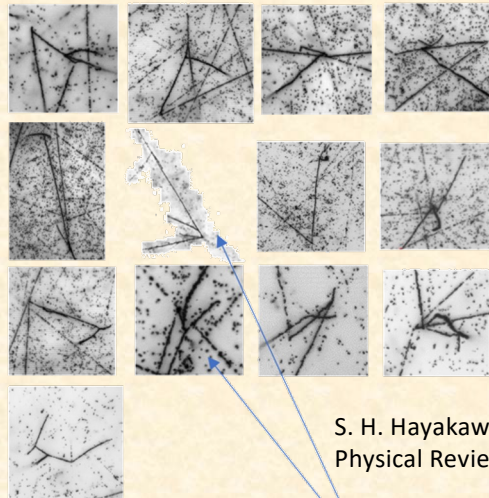
$\Lambda\Lambda$ candidates: 14



$\Lambda\Lambda$ Be

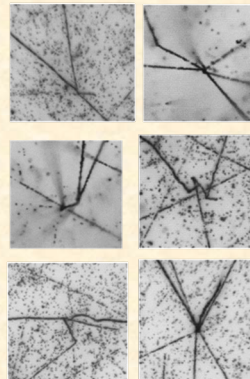
H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

Twin Λ events: 13



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

Others: 6



S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

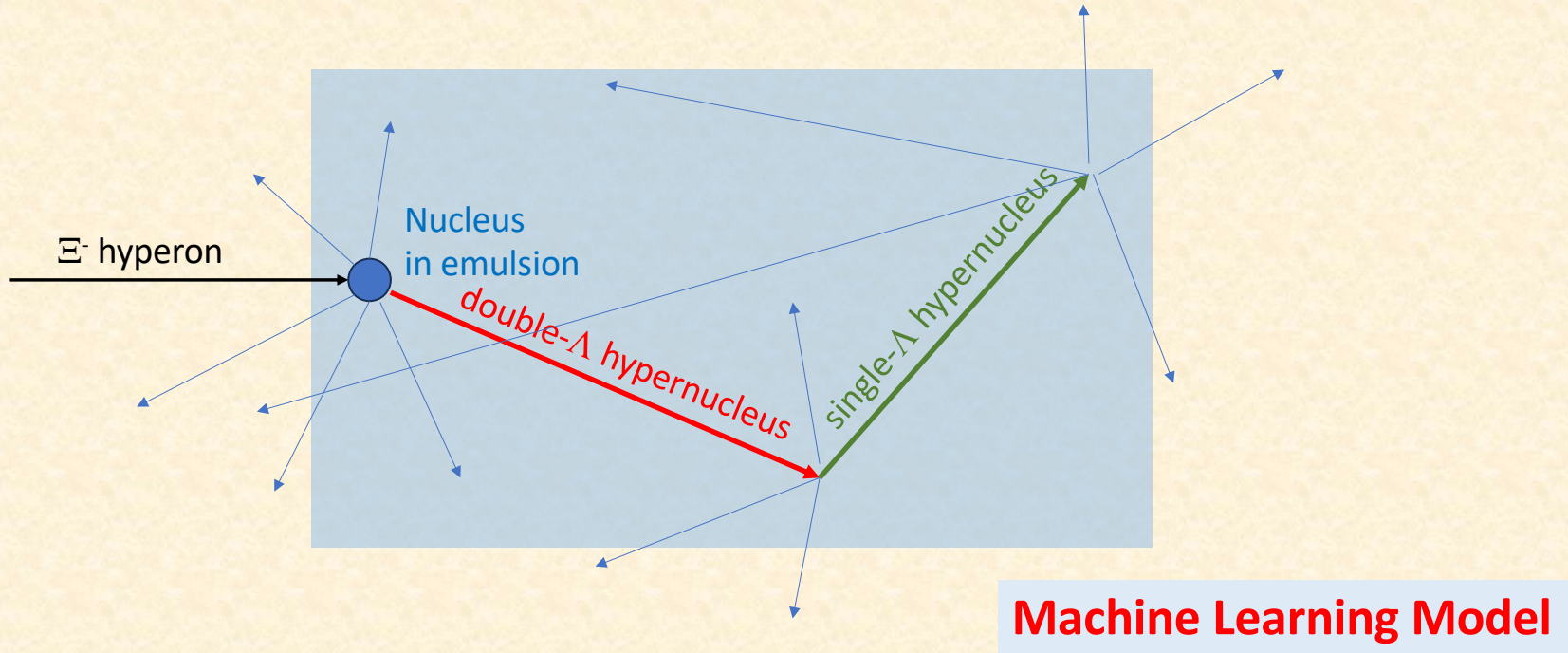
$^{15}_{\Xi}\text{C}$

Only 33 candidates

No unique identification for double- Λ hyp.

What do we want to dig out?

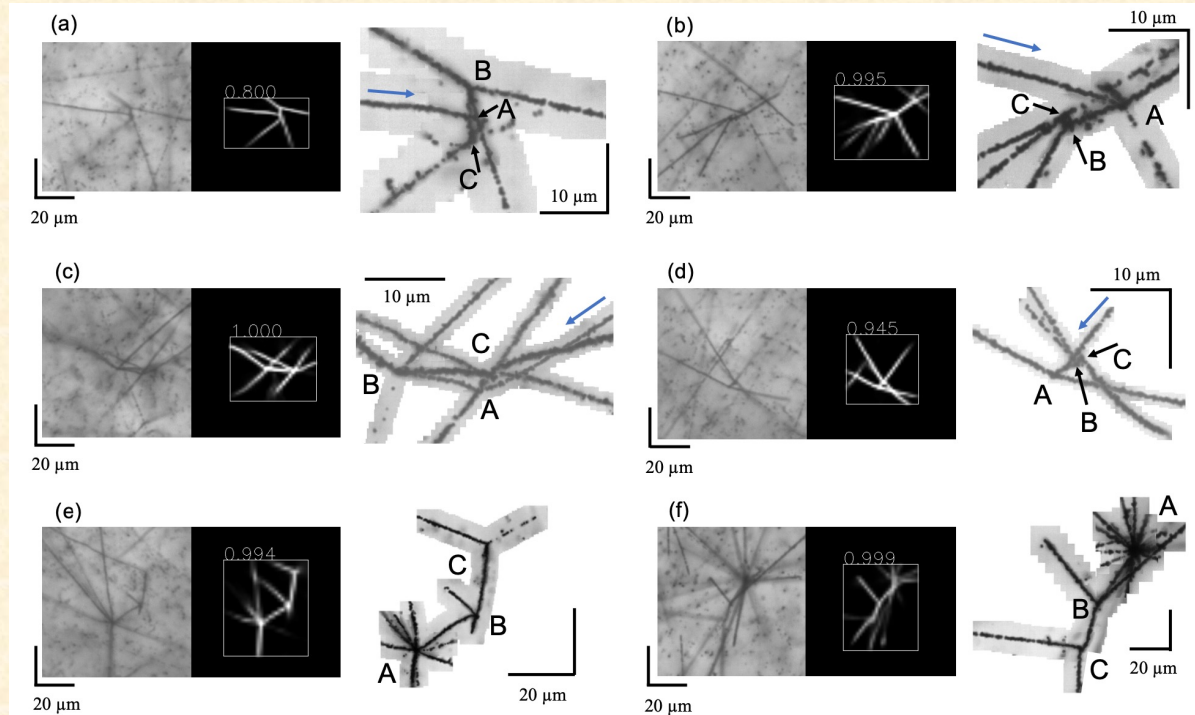
Double- Λ hypernucleus



Searching for double-strangeness hypernuclei

Yan He
(LZU/RIKEN)
Ph.D. thesis

- Analyzed **0.2%** of the entire data, **more than 10 candidates** found.
- Searching for double-strangeness hypernuclei with newly developed machine-learning method is in progress.



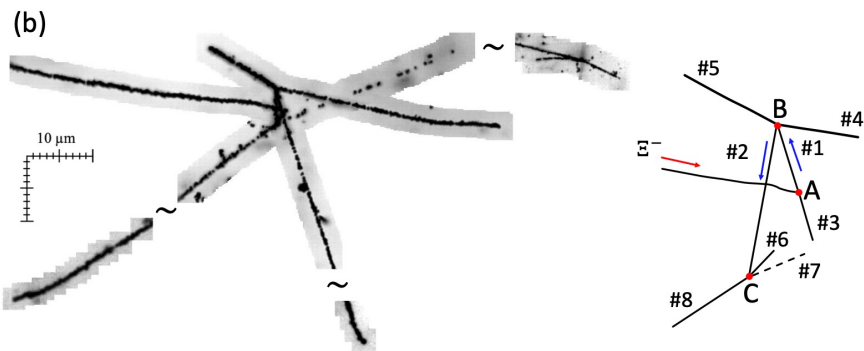
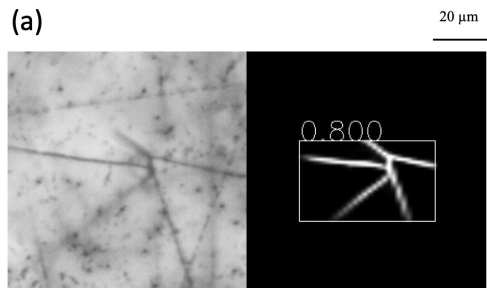
1000 candidates



~5000

Yan He, et al.,
Nucl. Instrum. Meth. A 1073
(2025) 170196

Discovery of double- Λ hypernucleus



$^{13}_{\Lambda\Lambda}\text{B}$:

Uniquely identified

2nd case in the history

$$B_{\Lambda\Lambda} = 25.57 \pm 1.18(\text{stat.}) \pm 0.07(\text{syst.})\text{MeV}$$

$$\Delta B_{\Lambda\Lambda} = 2.83 \pm 1.18(\text{stat.}) \pm 0.14(\text{syst.})\text{MeV}$$

Yan He, et al.,

Nature Communications 16 (2025) 11084

Yan He, Ph.D. thesis, Lanzhou U., 2025

Very successful !!!


nature reviews physics

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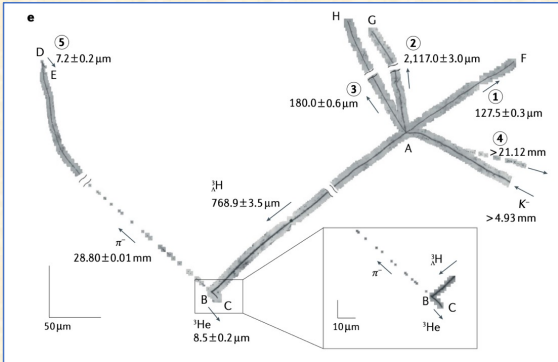
nature > nature reviews physics > perspectives > article

Perspective | Published: 14 September 2021

New directions in hypernuclear physics

Takehiko R. Saito , Wenbou Dou, Vasily Drozd, Hiroyuki Ekawa, Samuel Escrig, Yan He, Nasser Kalantar-Nayestanaki, Ayumi Kasagi, Myroslav Kavatsyuk, Enqiang Liu, Yue Ma, Shizu Minami, Abdul Muneem, Manami Nakagawa, Kazuma Nakazawa, Christophe Rappold, Nami Saito, Christoph Scheidenberger, Masato Taki, Yoshiki K. Tanaka, Junya Yoshida, Masahiro Yoshimoto, He Wang & Xiaohong Zhou

Nature Reviews Physics (2021) | Cite this article

















Nature Reviews Physics, 803-813 (2021)
Press release by RIKEN, Sept 14, 2021

PTEP

Prog. Theor. Exp. Phys. 2025 083D01 (17 pages)
DOI: 10.1093/ptep/ptaf097

Binding Energy of $^3_{\Lambda}\text{H}$ and $^4_{\Lambda}\text{H}$ via Image Analyses of Nuclear Emulsions Using Deep-Learning

A. Kasagi ^{1,2,*}, T. R. Saito ^{2,3,4,†}, V. Drozd ^{2,5}, H. Ekawa ², S. Escrig ^{2,6}, Y. Gao ^{2,7,8}, Y. He ^{2,9}, E. Liu ^{2,7,8}, A. Muneem ², M. Nakagawa ^{2,10}, K. Nakazawa ^{2,11,12}, C. Rappold ⁶, N. Saito ², M. Taki¹, Y. K. Tanaka ², H. Wang ², A. Yanai^{2,4}, J. Yoshida ¹³, and M. Yoshimoto ¹⁴

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PTEP, Volume 2025, Issue 8, (2025) 083D01
Press release by RIKEN, Aug 29, 2025

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Article | Open access | Published: 22 November 2025

Artificial intelligence pioneers the double-strangeness baryon

Yan He , Takehiko R. Saito , Hiroyuki Ekawa, Ayumi Kasagi, Yiming Gao, Enqiang Liu, Kazuma Nakazawa, Christophe Rappold, Masato Taki, Yoshiki K. Tanaka, He Wang, Ayari Yanai, Junya Yoshida & Hongfei Zhang

Nature Communications 16, Article number: 11084 (2025) | Cite this article

3981 Accesses | 39 Altmetric | Metrics

Abstract

Artificial intelligence (AI) is transforming not only our daily experiences but also the technological development landscape and scientific research. In this study, we pioneered the application of AI in double-strangeness hypernuclear studies. Studies that investigate quantum systems with strangeness via hyperon interactions provide insights into fundamental baryon-baryon interactions and contribute to our understanding of the nuclear force and composition of neutron star cores. Specifically, we report the observation of a double- Λ hypernucleus in nuclear emulsion achieved via innovative integration of machine learning techniques. The proposed methodology leverages generative AI and Monte Carlo simulations to produce training datasets combined with object detection AI for effective event identification. Based on the kinematic analysis and charge identification, the observed event was uniquely identified as the production and decay of $\{\{\Lambda\Lambda\}\}$ hypernucleus, resulting from Ξ^- capture by ^{14}N in the nuclear emulsion. Assuming Ξ^- capture in the atomic 3D state, the binding energy of the two Λ hyperons in $\{\{\Lambda\Lambda\}\}$ hypernucleus, $B_{\Lambda\Lambda}$, was determined as $25.57 \pm 1.18(\text{stat.}) \pm 0.07(\text{syst.})$ MeV. The $\Lambda\Lambda$ interaction energy $\Delta B_{\Lambda\Lambda}$ obtained was $2.83 \pm 1.18(\text{stat.}) \pm 0.14(\text{syst.})$ MeV.

Nature Communications 16 (2025) 11084
Press release by RIKEN, Dec 12th, 2025

New proposal at KLF/JLab



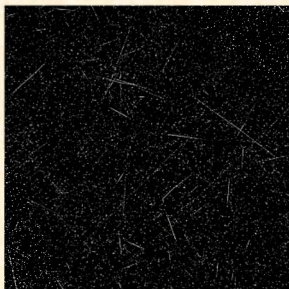
Neutral-K beams behind the Glue-X setup

Hypernuclear station behind the Glue-X

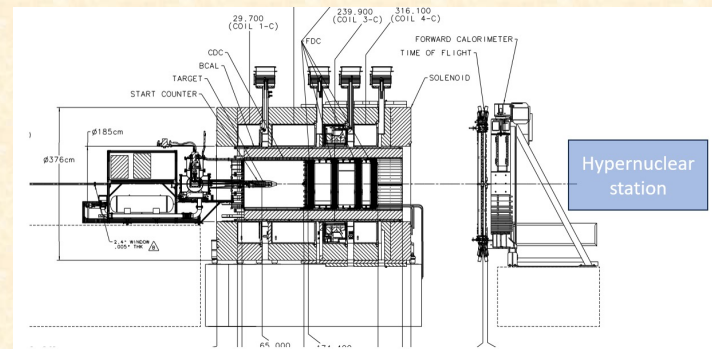
- No beam tracks in the emulsion

- We can leave emulsions, no movement
- Main background: high energy gamma-rays

With K^- beams
like in the J-PARC E07 exp.



With K^0 beams
In the proposed project



- Intensity: 0.7×10^4 anti- K^0 /s
 - Two years from 2027: 200 days per year (a total of 400 days)
 - 2.3 times more than J-PARC E07 (2.3 k double-strangeness hypernuclei) with HIGH QUALITY DATA

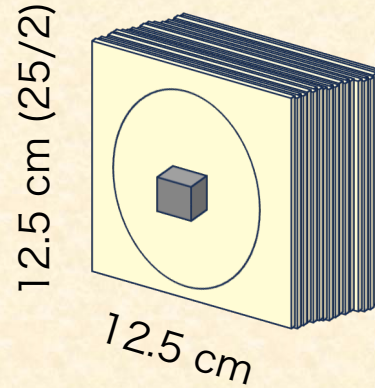
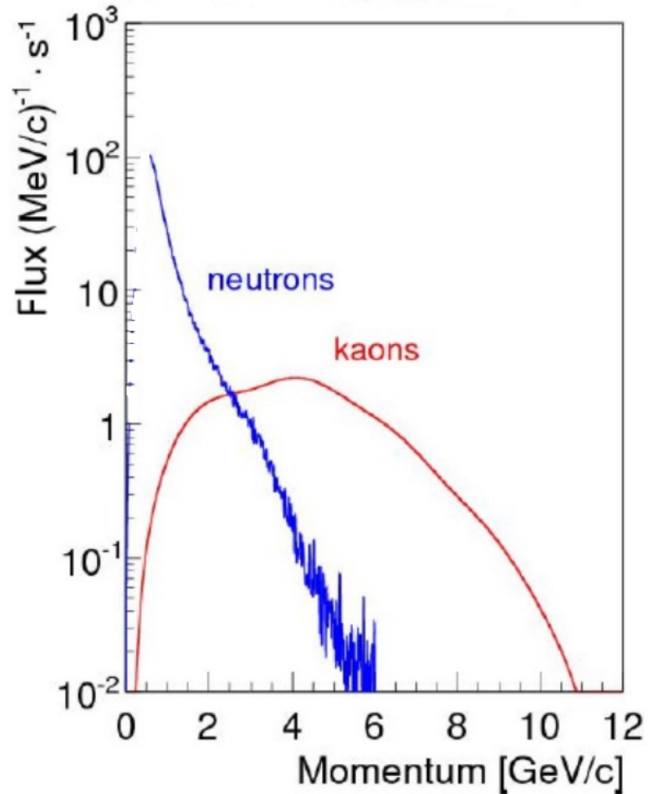
FNTD ($\text{Al}_2\text{O}_3:\text{C},\text{Mg}$)

- Used for neutron imaging
- Recyclable

Wide momentum distribution at KLF

Ω -hyperon can be produced

- Ω -hypernuclei?



Target & Detector (emulsion or FNTD)