Studies of light hypernuclei with heavy ion beams and image analyses

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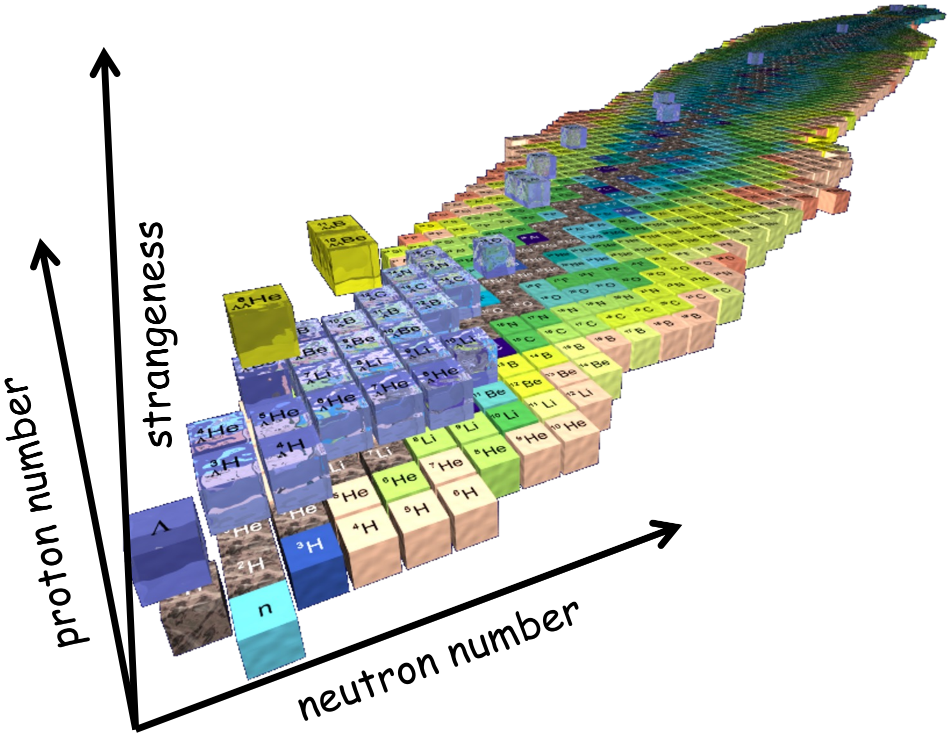
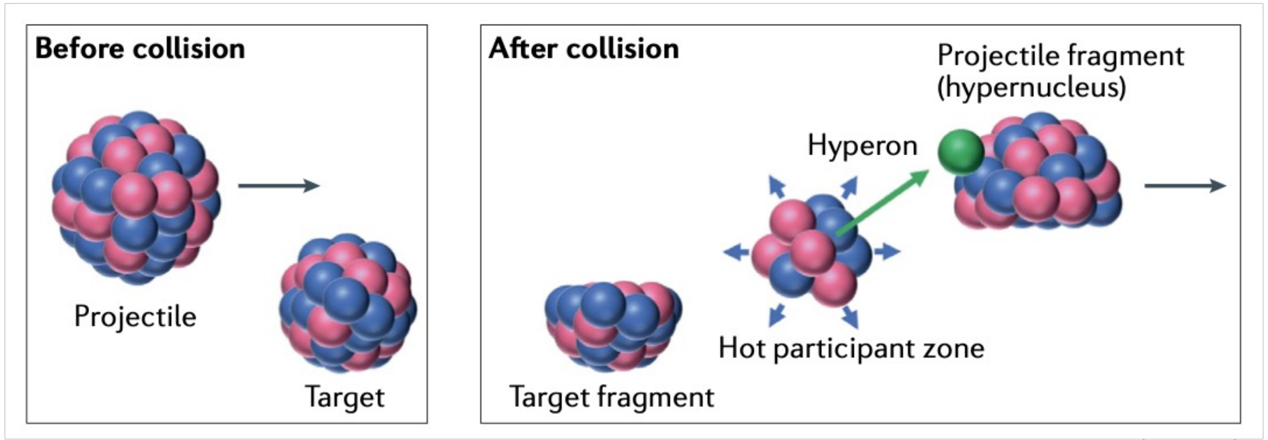
10th International Symposium on Non-Equilibrium Dynamics,
Krabi, Thailand, Islamabad, Pakistan, 25th – 29th November, 2024

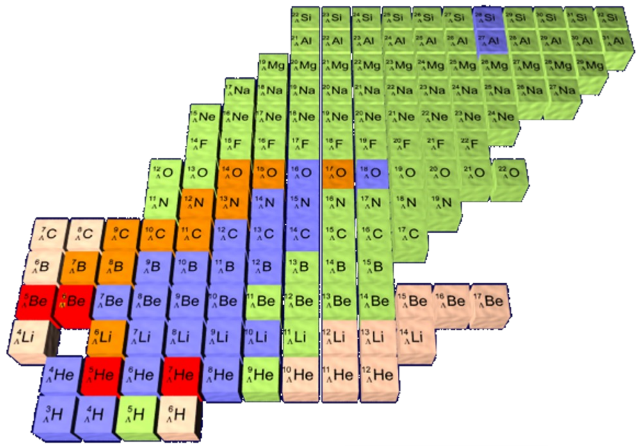
Chart of ordinary nuclei and hypernuclei

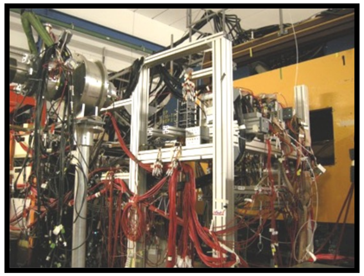


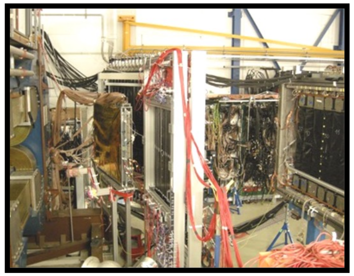
The HypHI Phase 0 at GSI in Germany (2006-2012)

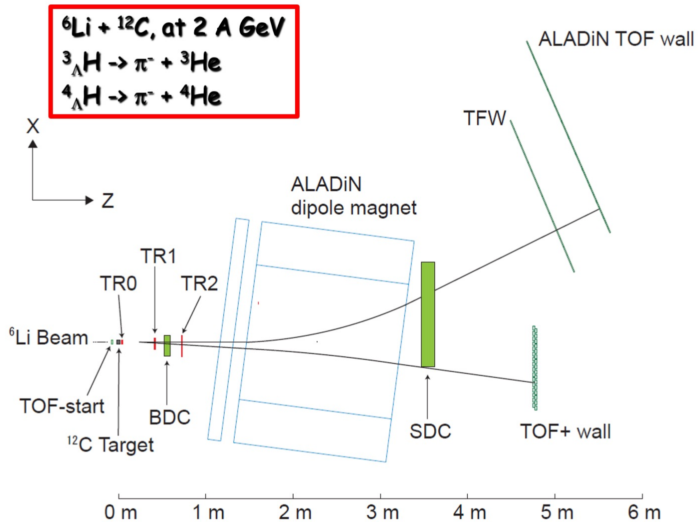


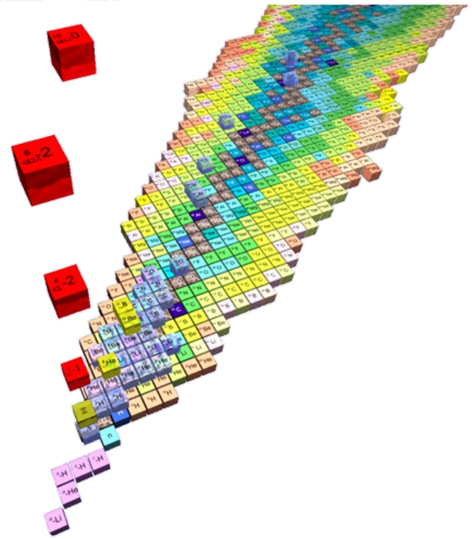
TRS et al., Nature Reviews Physics 3, 803-813 (2021)











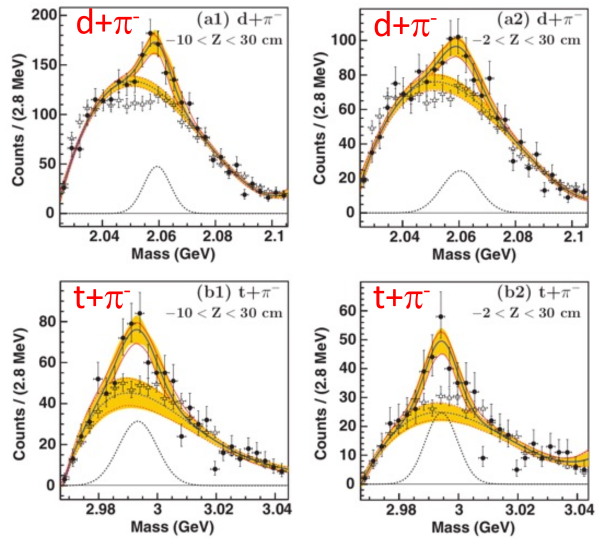
Two outcomes (mysteries) by HypHI

Signals indicating nnΛ bound state

<u>All theoretical calculations are negative</u>

- 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

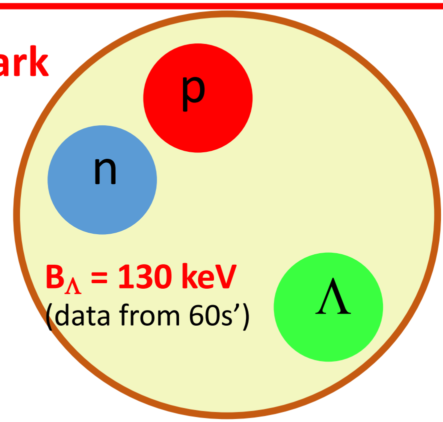


C. Rappold et al., PRC 88 (2013) 041001

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

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

Benchmark



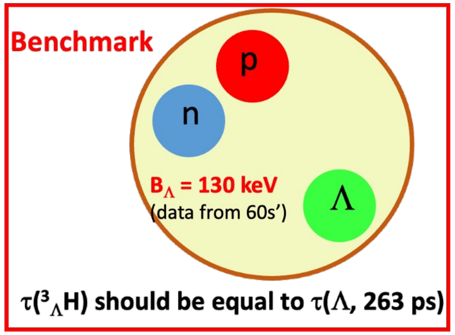
$\tau(^{3}_{\Lambda}H)$ should be equal to $\tau(\Lambda$, 263 ps)

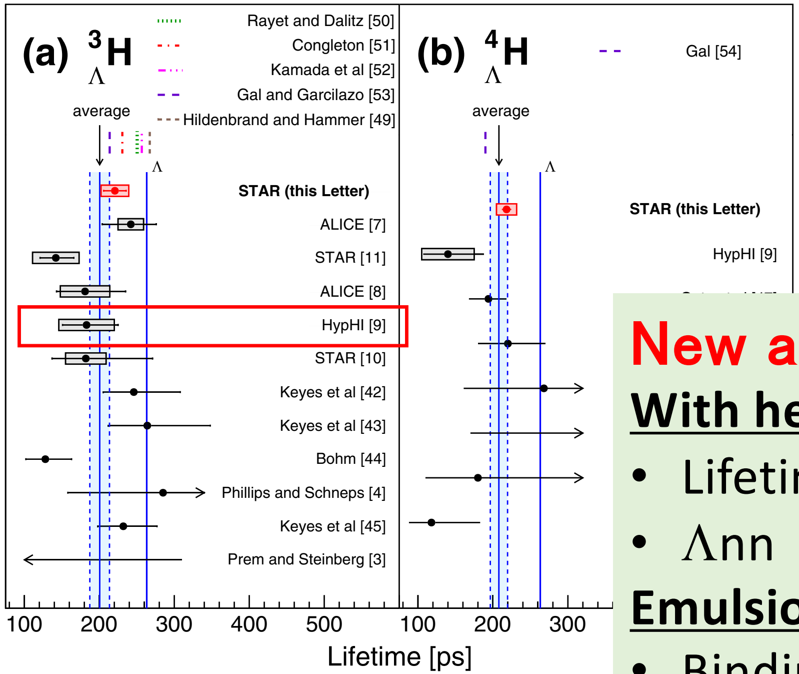
Stimulated other **<u>big</u>** experiments

The world situation of three-body hypernuclei

On hypertriton

Average
200 ± 13 ps





STAR Collaboration, PRL **128** (2022) 20230

On Λnn

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

B_Λ($^3{}_\Lambda$H) : 0.13 ± 0.05 MeV

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

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

STAR (2020)

0.41 ± 0.12 ± 0.11 MeV

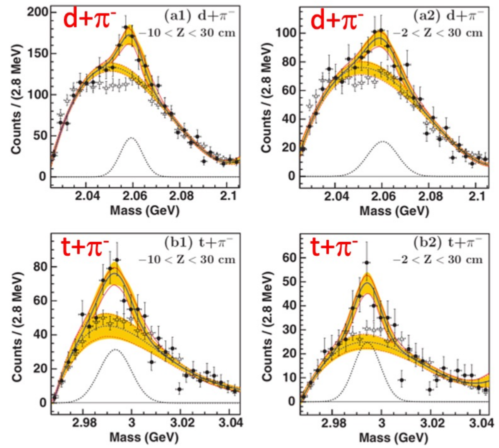
STAR Collaboration,

Nat. Phys. **16** (2020) 409

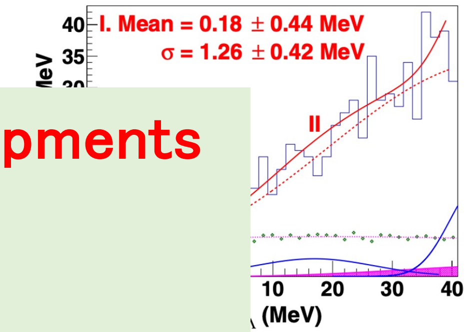
ALICE

0.102 ± 0.063 ± 0.067 MeV

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



HypHI., PRC 88 (2013) 041001



…ectrum around the Λnn thresh- …re fitted together with the known … Λ quasifree, the free Λ, and the …e threshold is for the small peak, …tional strength above the predicted

…PRC 105 (2022) L051001

New approaches with new developments

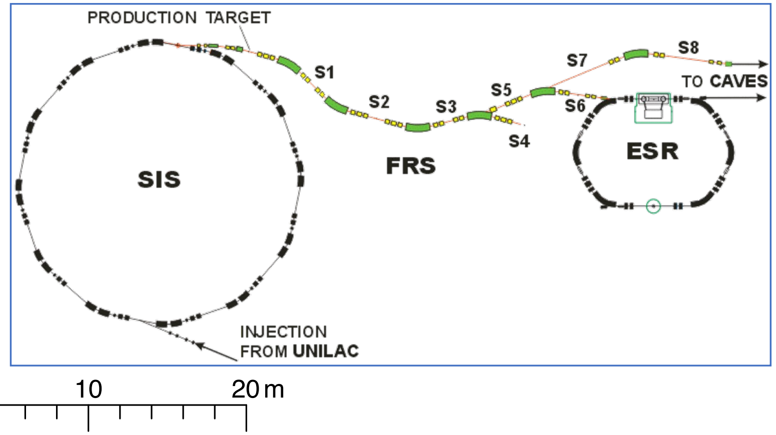
With heavy ion beams:

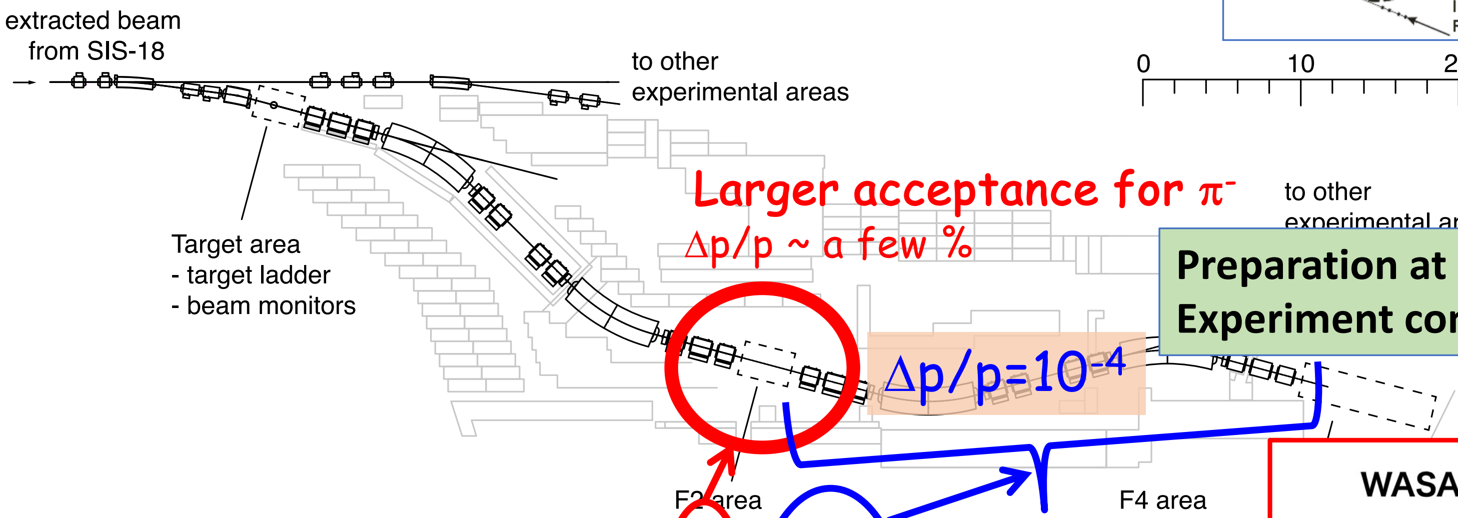
- Lifetime
- Λnn

Emulsion + Machine Learning

- Binding energy

The novel technique with FRS at GSI (2016-)





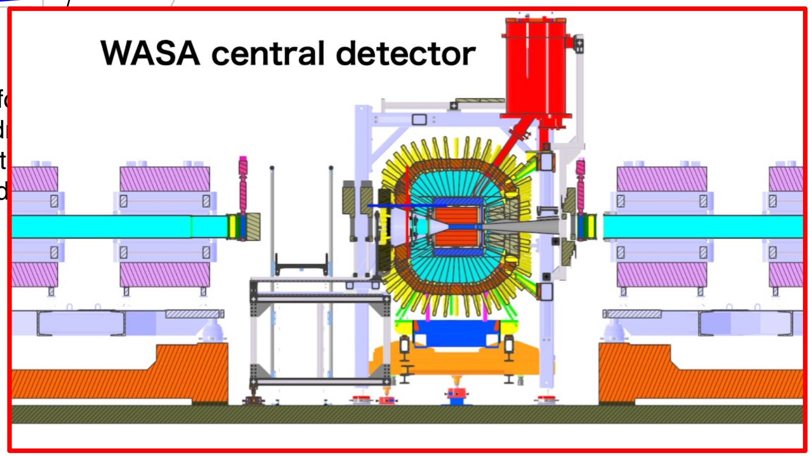
Preparation at GSI started in March 2019
Experiment conducted in January-March 2022

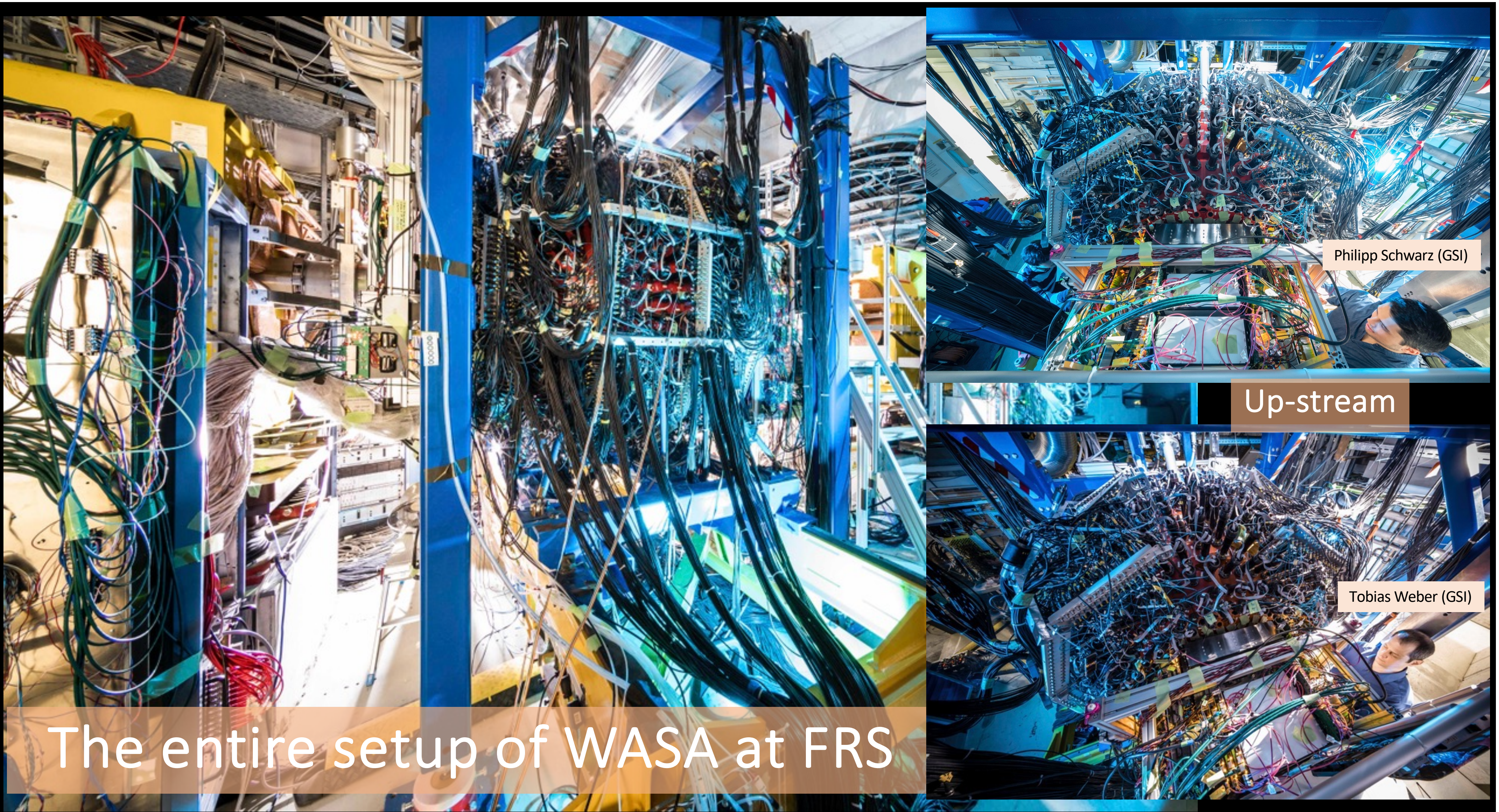
$^{3}_{\Lambda}H \rightarrow \pi^- + {}^{3}He$

$^{4}_{\Lambda}H \rightarrow \pi^- + {}^{4}He$

$nn\Lambda \rightarrow \pi^- + d + n$

With $^{6}Li + ^{12}C$ at 2 A GeV





Photos by Jan Hosan and GSI/FAIR

WASA-FRS in Nature Reviews Physics

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Perspective | Published: 14 September 2021

New directions in hypernuclear physics

Takehiko R. Saito, Wenbou Dou, Vasyl 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

Takehiko R. Saito et al., Nature Reviews Physics, 803-813 (2021)

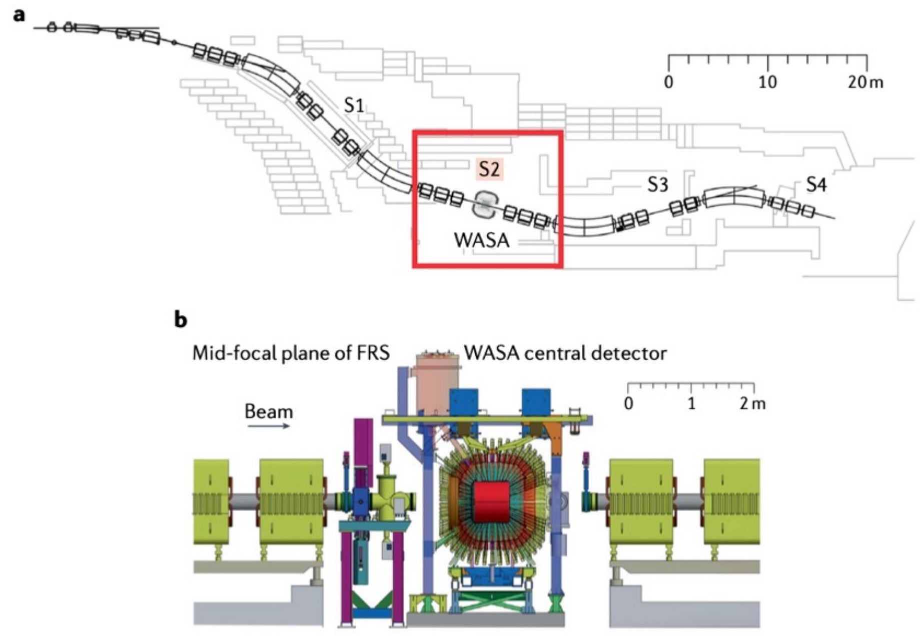

Fig. 1 | **The WASA-FRS hypernuclear experiment. a** | Schematic drawing of the fragment separator (FRS) at GSI. The ^{6}Li primary beams at 2 *A* GeV are delivered to the diamond target located at the mid-focal plane of the FRS, referred to as S2, to produce hypernuclei of interest. Residual nuclei of the π^- weak decays of hypernuclei are transported from S2 to S4 in the FRS, and measured precisely with a momentum-resolving power of 10^{-4}. The π^- mesons produced by the hypernuclear decays are measured at S2 by the Wide Angle Shower Apparatus (WASA) central detector. **b** | The WASA central detector. Panel **b** is adapted with permission from REF.[76].


GSI REPORT 2023-1
GSI-FAIR SCIENTIFIC REPORT 2022
An overview of the 2022 achievements in science and technology
FAIR
Phase-0
Research Program
GSI FAIR
HELMHOLTZ
RESEARCH FOR
GRAND CHALLENGES
Yoshiki Tanaka
(RIKEN)
Photos by Jan Hosan and GSI/FAIR

GSI calendar 2023

Data taking (January – March 2022)

Run	Period	Data size
Commissioning run	28th Jan. - 7th Feb.	7 TB
Physics run for η’ nuclei	22nd Feb. - 28th Feb.	40 TB
Physics run for HypHI	10th Mar. - 19th Mar.	48 TB

92 % of the prop.

Acquired data for S447 (hypernuclei)

Beam	Fragment at S4	Amount	Time	Accepted trigger rate	
^{6}Li beam	^{3}He	3.3×10^{8}	40.9 hours	2600 Hz	**$^{3}_{\Lambda}$H**
	^{4}He	0.9×10^{8}	43.9 hours	1800 Hz	**$^{4}_{\Lambda}$H**
	deuteron	1.8×10^{8}			**nnΛ**
	proton (mid-rapidity)	5.3×10^{6}	3.2 hours	680 Hz	**Λ**
^{12}C beam	^{3}He	1.0×10^{8}	13.5 hours	2400 Hz	**$^{3}_{\Lambda}$H**
	^{9}C	2.4×10^{5}			**$^{9}_{\Lambda}$B**

proton-halo ^{8}B + Λ

The International WASA-FRS collaboration

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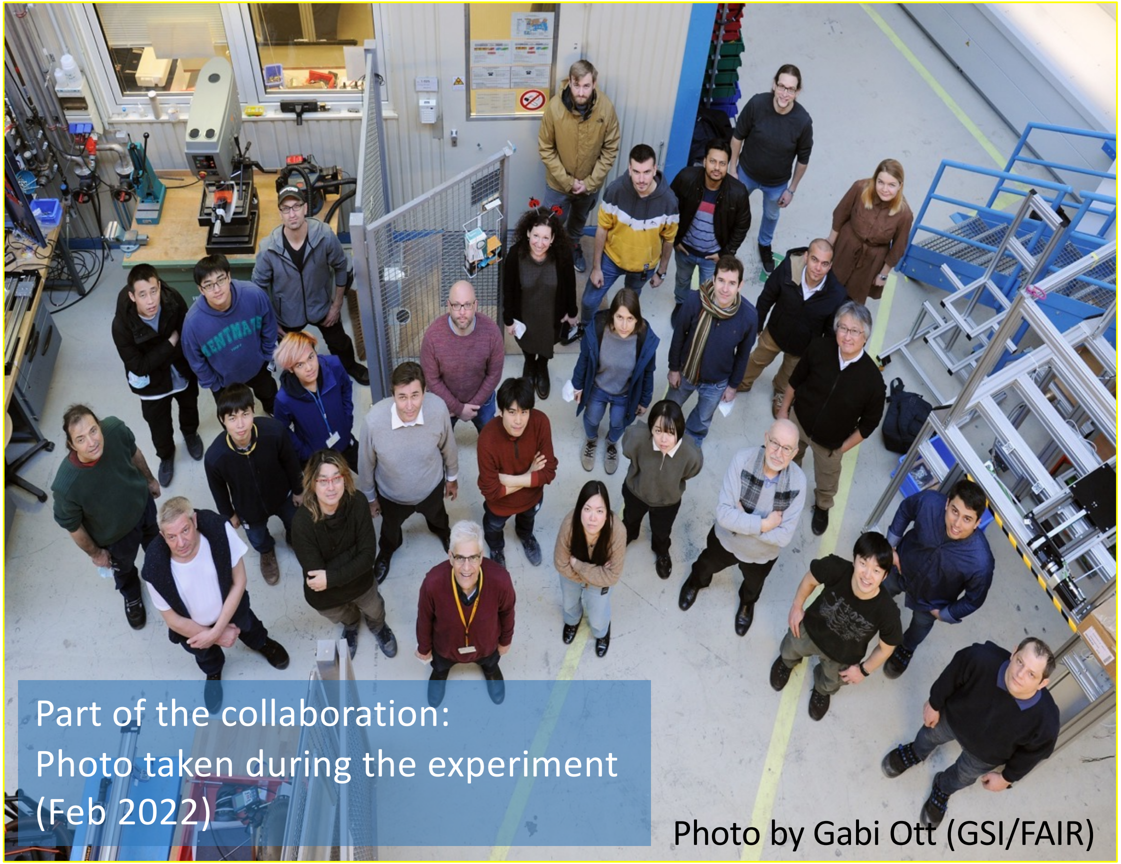
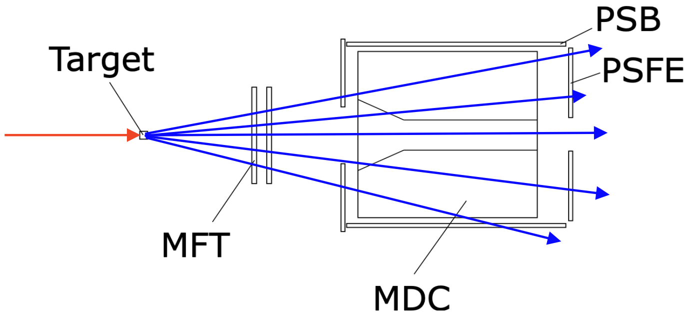


Collaboration of hypernuclear physicists and low-energy nuclear physicists

Graph Neural Network (GNN) for WASA

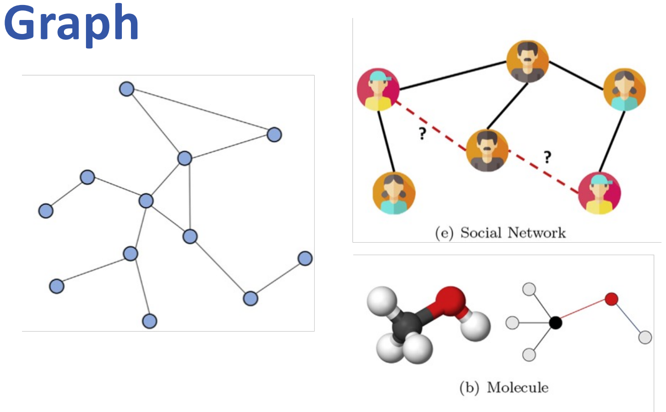
Track Finding



- Multi particles in HI reaction
- Combinatorial background

Track Finding with Graph Neural Network (GNN)

Graph



- Node : Data point
- Edge : Connection

Jie Zhou *et al.*, AI Open 1 (2020) 57–81

Eur. Phys. J. A (2023) 59:103
https://doi.org/10.1140/epja/s10050-023-01016-5
THE EUROPEAN PHYSICAL JOURNAL A
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Special Article - New Tools and Techniques

Development of machine learning analyses with graph neural network for the WASA-FRS experiment

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

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Communicated by Takashi Nakamura

Abstract The WASA-FRS experiment aims to reveal the nature of light Λ hypernuclei with heavy-ion beams. The lifetimes of hypernuclei are measured precisely from their decay lengths and kinematics. To reconstruct a π^- track emitted from hypernuclear decay, track finding is an important issue. In this study, a machine learning analysis method with a graph neural network (GNN), which is a powerful tool for deducing the connection between data nodes, was developed to obtain track associations from numerous combinations of hit information provided in detectors based on a Monte Carlo simulation. An efficiency of 98% was achieved for tracking π^- mesons using the developed GNN model. The GNN model can also estimate the charge and momentum of the particles of interest. More than 99.9% of the negative charged particles were correctly identified with a momentum accuracy of 6.3%.

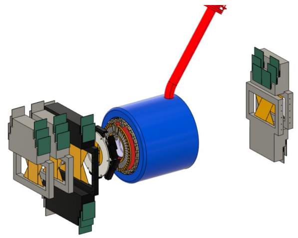
stand it for the middle- and long-range interactions based on a variety of nuclear experiments. To reveal the unknown features of the nuclear force, such as short-range interaction, considering a more detailed structure inside the baryons is essential. All baryons consist of three quarks, and nucleons such as neutrons and protons consist of up and down quarks. By introducing other types of quarks into ordinary nuclear systems, one can study the nuclear force in a more general picture. In particular, because the mass of the strange quark is close to that of the up and down quarks, interactions among these three quarks are described under flavoured-SU(3) symmetry. Therefore, a hyperon, which is a type of baryon that contains strange quark(s), plays an important role in investigating baryon–baryon interactions. As the lifetime of hyperon is short ($\sim10^{-10}$ s), using them as projectiles or targets is difficult. Therefore, hyperon–nucleon interactions have been studied via hypernuclei, which contain at least

Published in EPJA

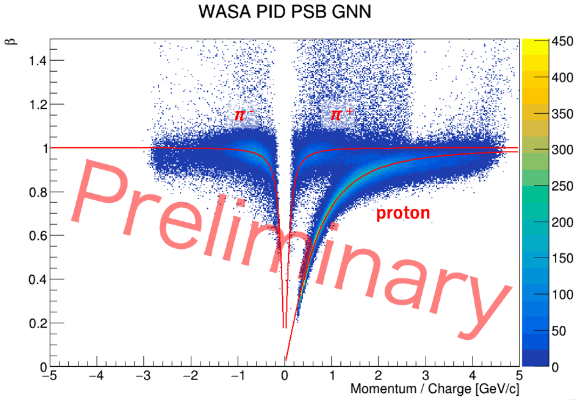
H. Ekawa et al., Eur. Phys. J. A (2023) **59**, 103

DOI : 10.1140/epja/s10050-023-01016-5

Data analyses with the GNN

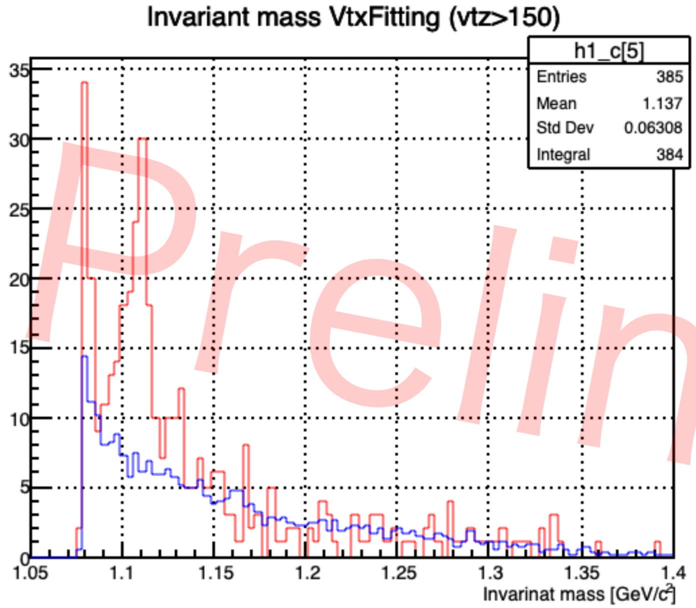


Only **partial data** with
- T0
- Fiber detectors
- MDC
- PSB
- FRS

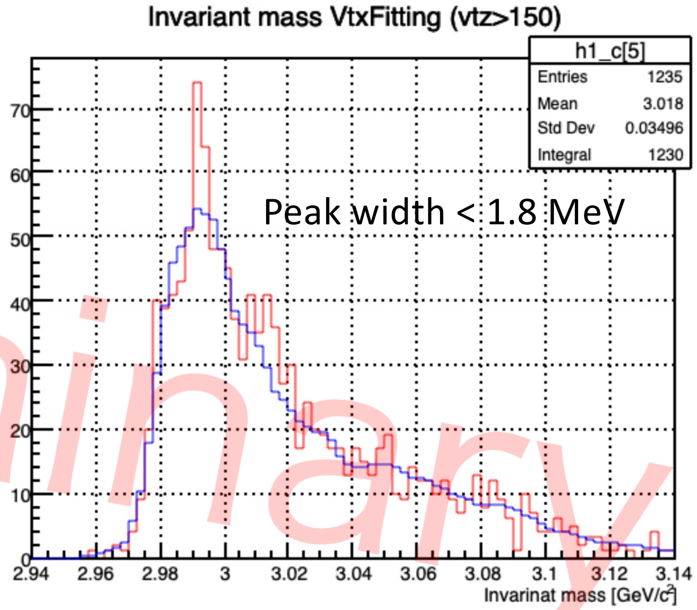


- GNN node clustering score > 0.995
- MDC hit mul. ≧ 6

p (WASA)+π^- (WASA)

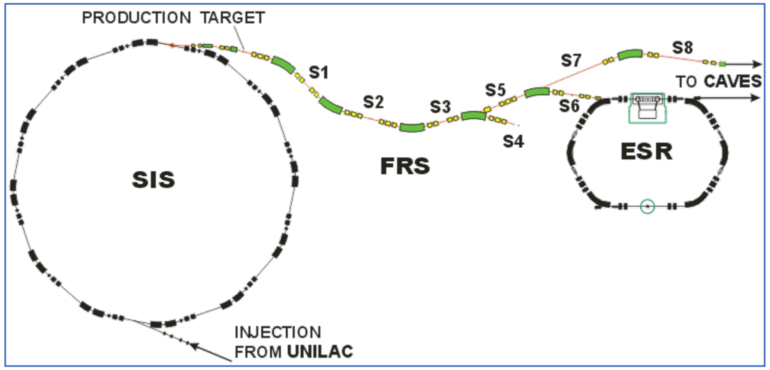


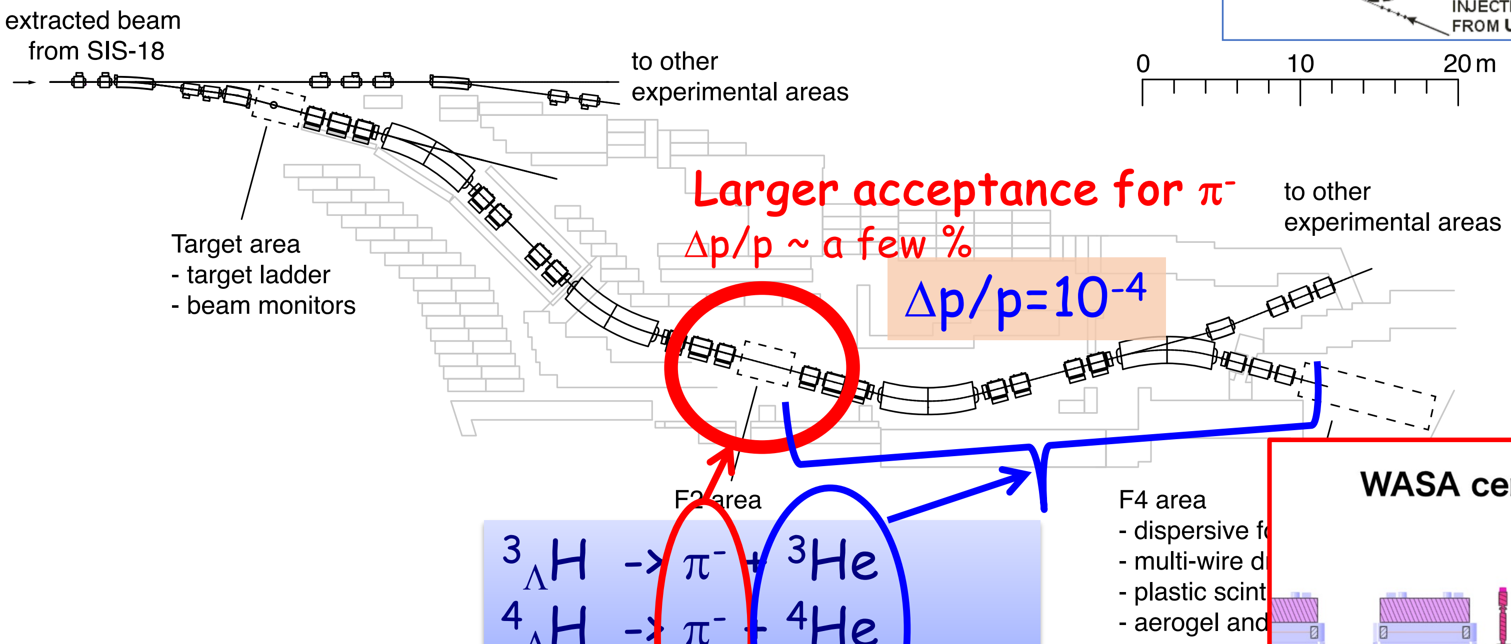
^{3}He (WASA)+π^- (WASA)



Analysis by
H. Ekawa (RIKEN)
Y. Gao (RIKEN/IMP)
A. Yanai (RIKEN/Saitama U)

The novel technique with FRS at GSI (2016-)



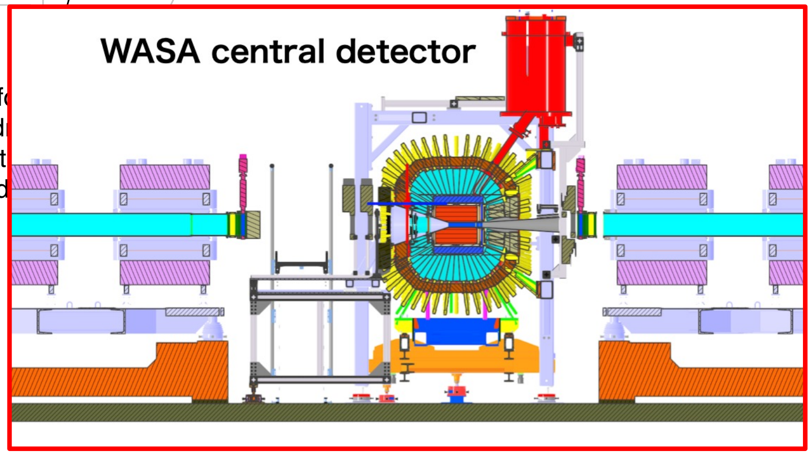


$^3_\Lambda H \rightarrow \pi^- + {}^3He$

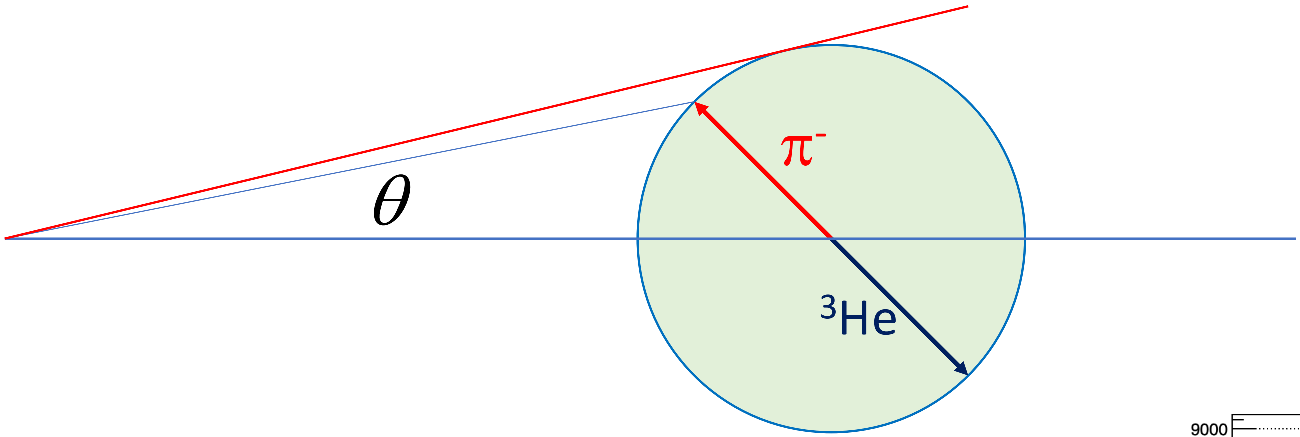
$^4_\Lambda H \rightarrow \pi^- + {}^4He$

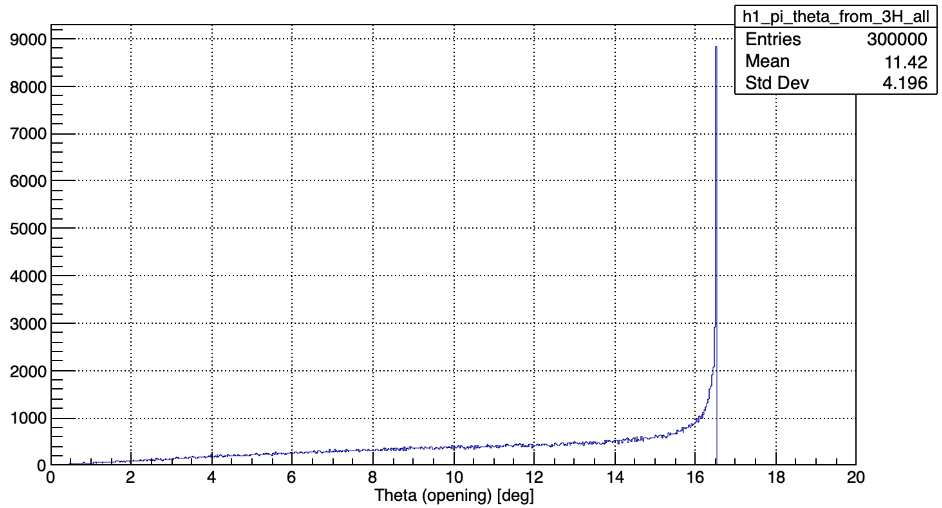
$nn\Lambda \rightarrow \pi^- + d \quad + n$

With $^6Li+^{12}C$ at 2 A GeV



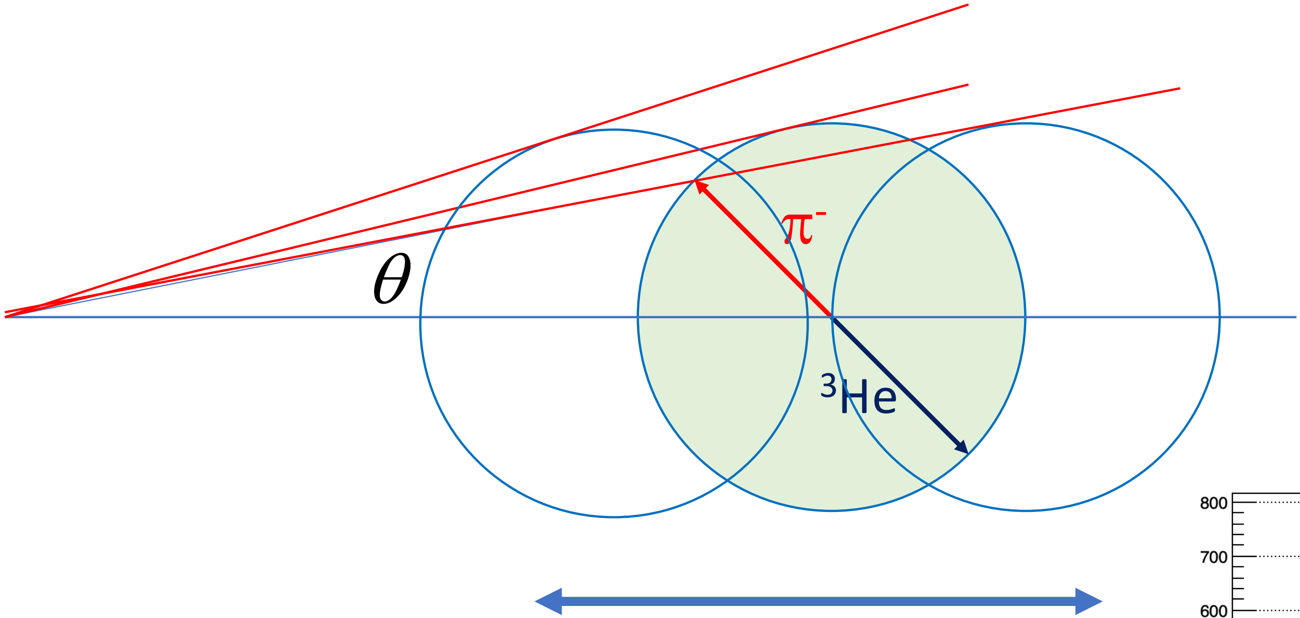
Novel approach to the B.E. with the FRS





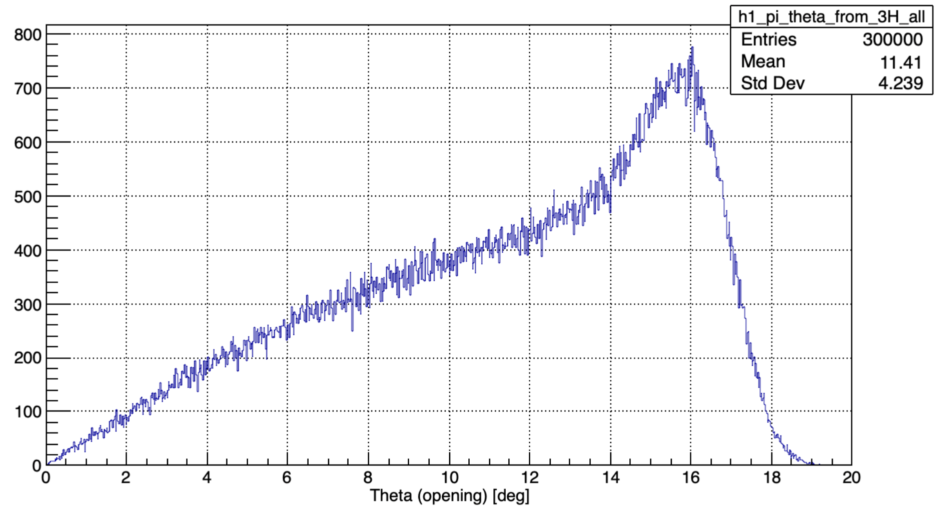
Ideas based on Ivan Mukha et al,
for studying two-proton emitters at the FRS/GSI
Phys. Rev. Lett. 115, 202501, 2015

Novel approach to the B.E. with the FRS

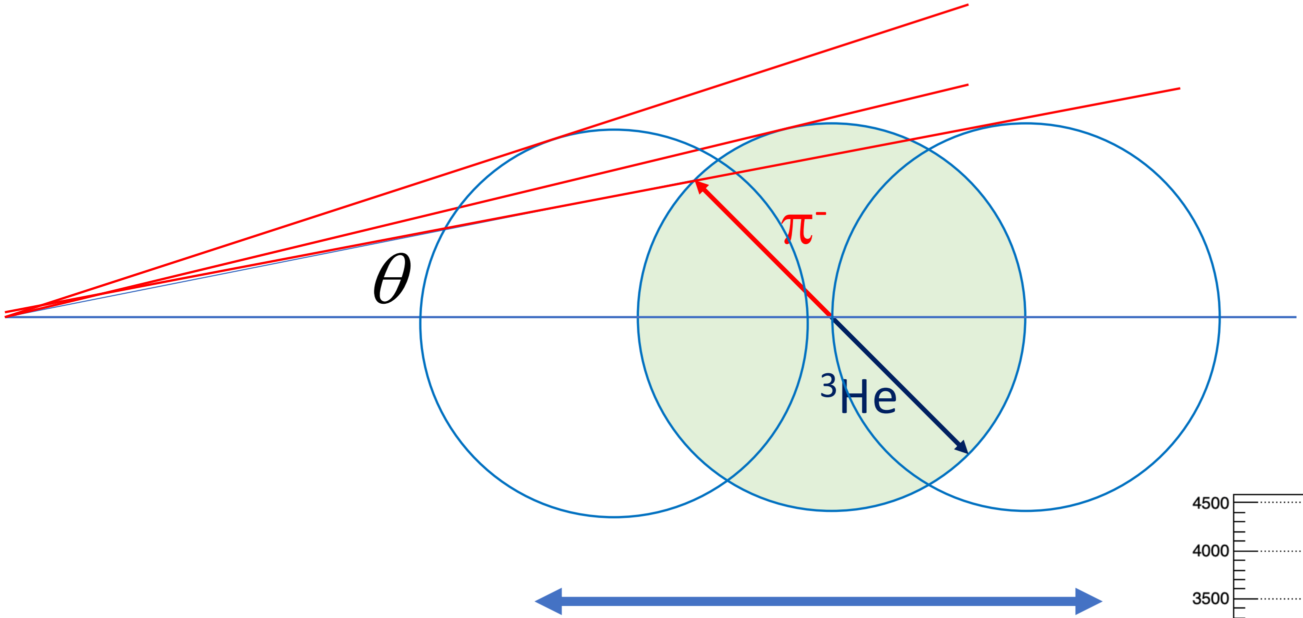


Momentum spread of
produced hypertriton
(5 % in Bρ)

Ideas based on Ivan Mukha et al,
for studying two-proton emitters at the FRS/GSI
Phys. Rev. Lett. 115, 202501, 2015



Novel approach to the B.E. with the FRS

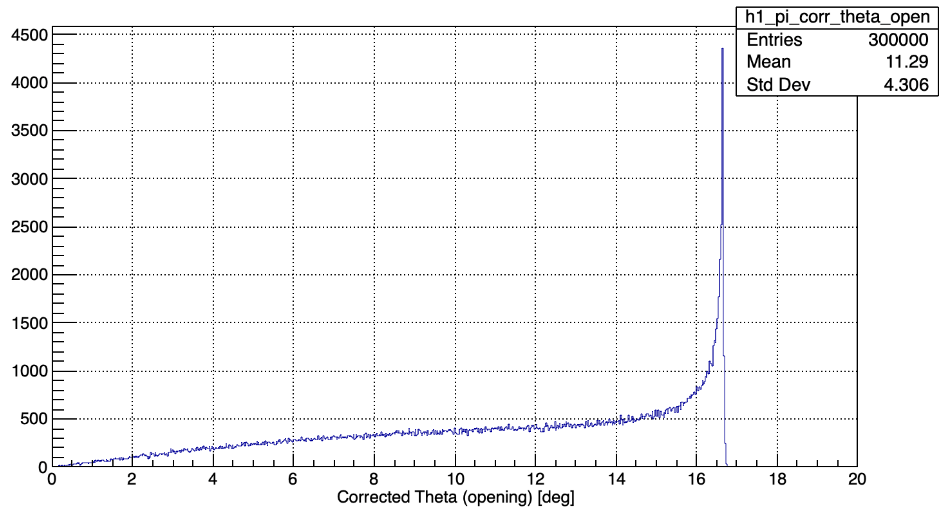


Assuming that the momentum of the hypertriton is the same to the ^{3}He decay residues

$\Delta p/P$ (FRS) = 5×10^{-4}

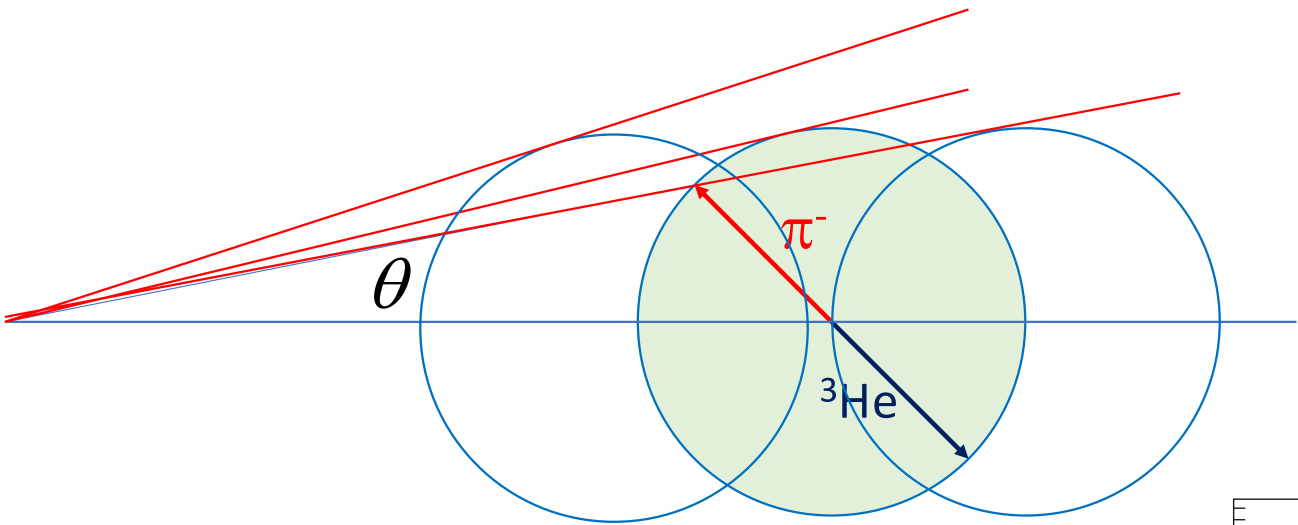
β -> 0.95

Momentum spread of produced hypertriton (5 % in Bρ)



Ideas based on Ivan Mukha et al,
for studying two-proton emitters at the FRS/GSI
Phys. Rev. Lett. 115, 202501, 2015

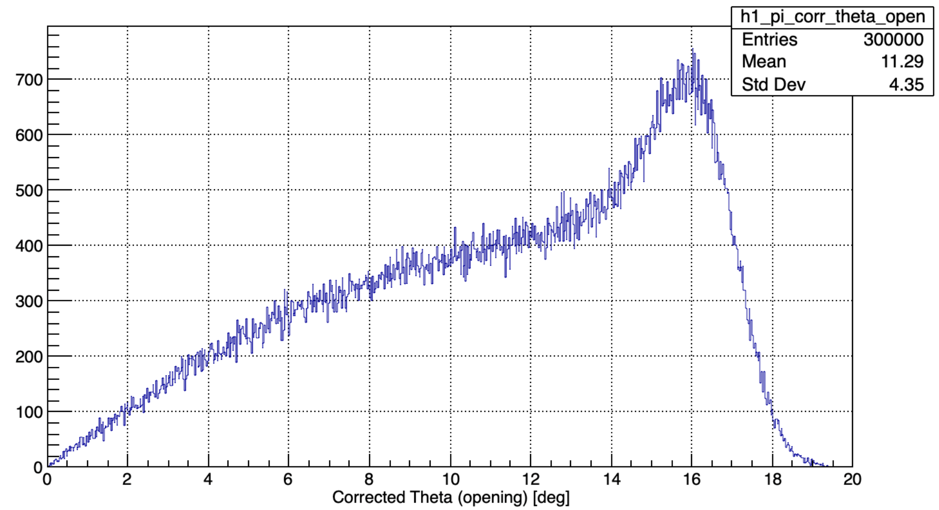
Novel approach to the B.E. with the FRS



Assuming that the momentum of the hypertriton is the same to the ^{3}He decay residues

$\Delta p/P$ (other exp.) = $5x10^{-2}$
β -> 0.95

Momentum spread of produced hypertriton (5 % in Bρ)



Ideas based on Ivan Mukha et al,
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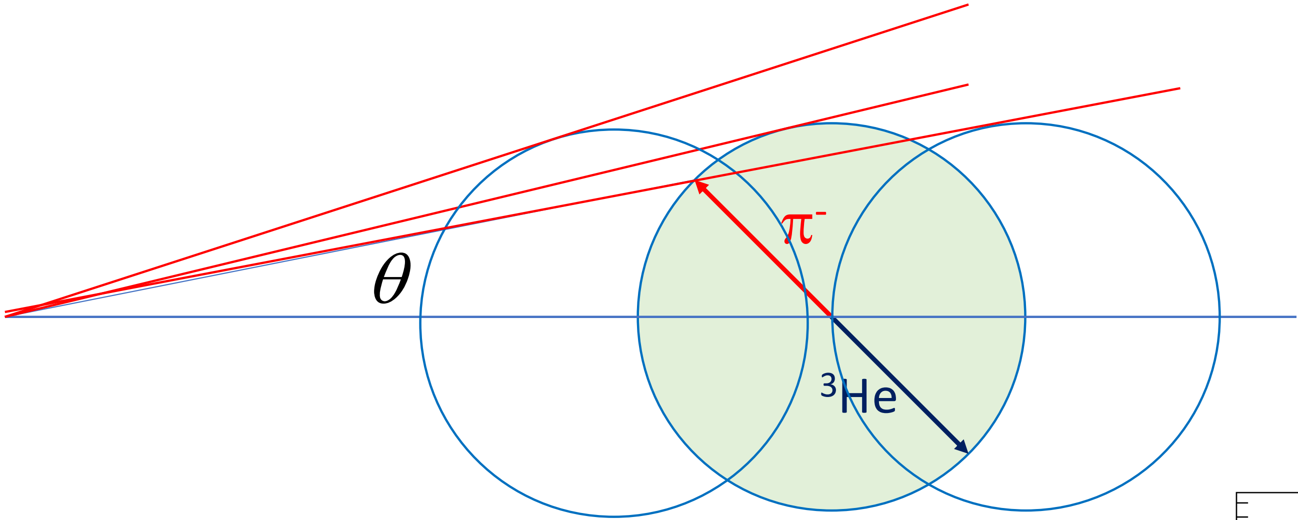
Phys. Rev. Lett. 115, 202501, 2015

Novel approach to the B.E. with the FRS



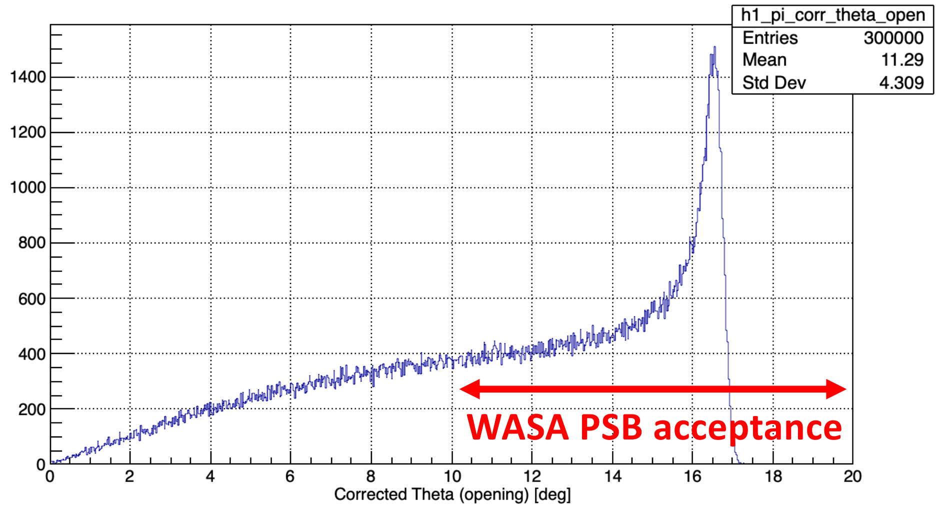
Momentum spread of produced hypertriton (5 % in Bρ)

Assuming that the momentum of the hypertriton is the same to the ^{3}He decay residues

$\Delta p/P$ (FRS) = 5×10^{-4}

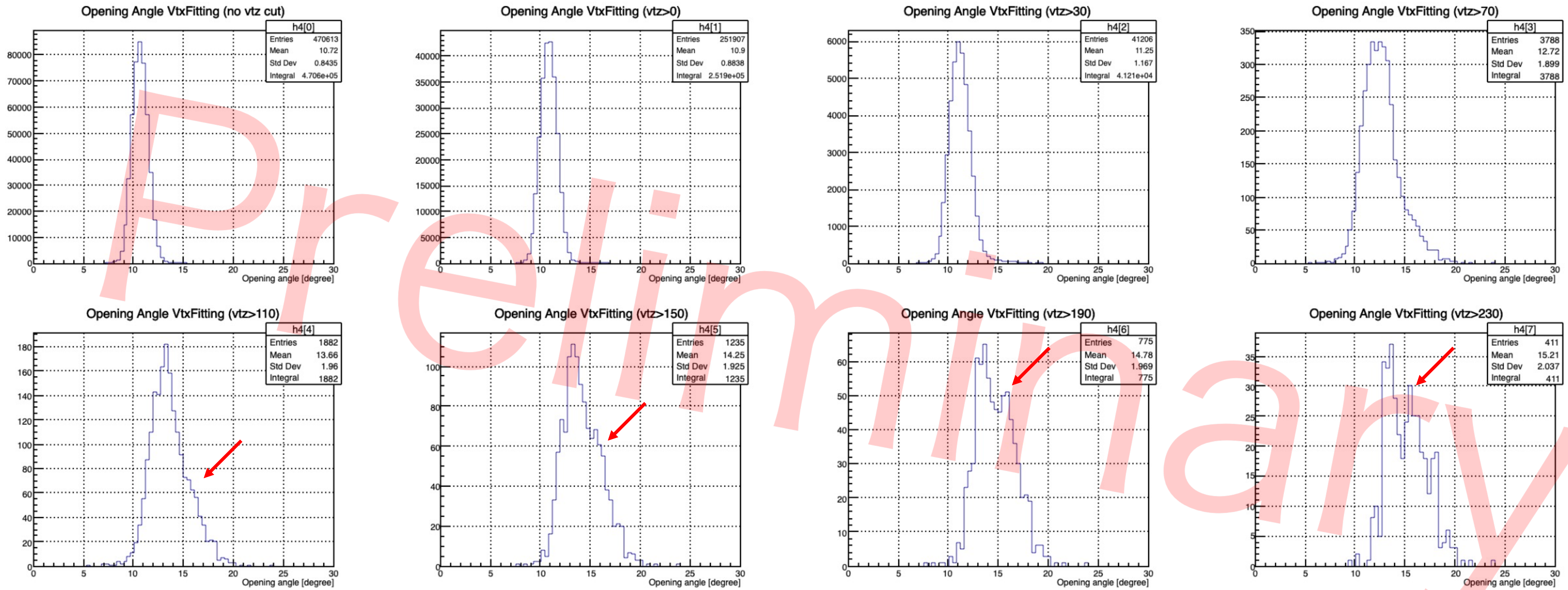
β -> 0.95

Angular res. (WASA) = 3 m rad

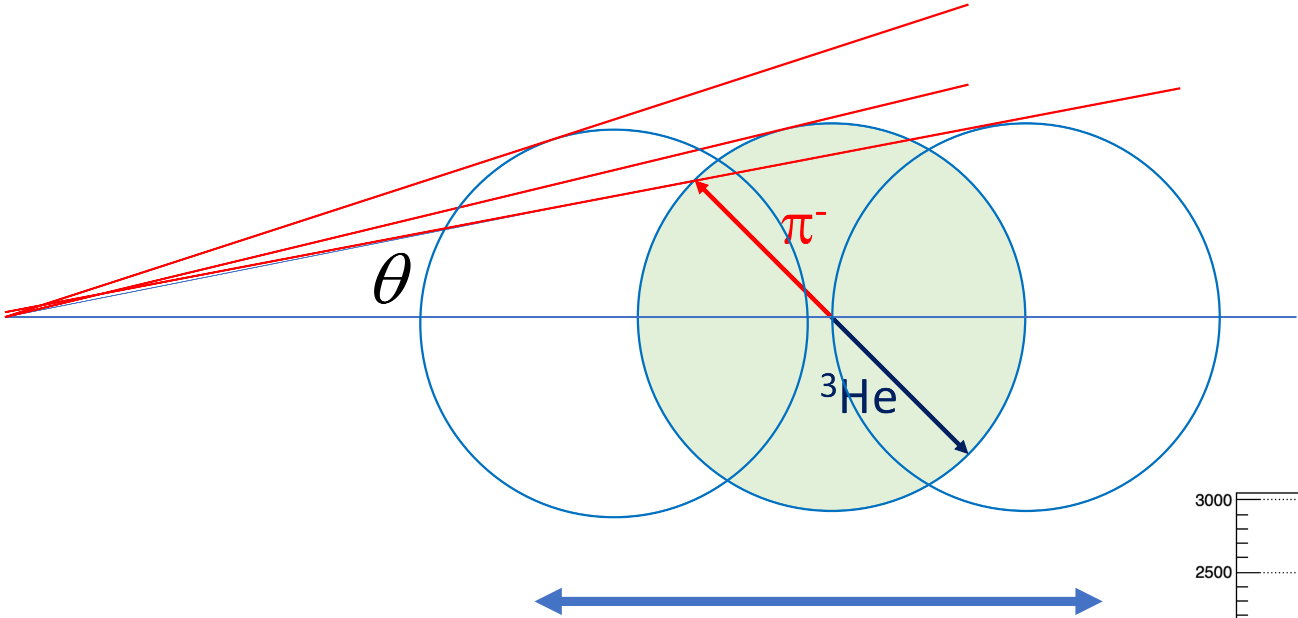


Ideas based on Ivan Mukha et al,
for studying two-proton emitters at the FRS/GSI
Phys. Rev. Lett. 115, 202501, 2015

With the WASA-FRS data



Novel approach to the B.E. with the FRS



Momentum spread of produced hypertriton (5 % in $B\rho$)

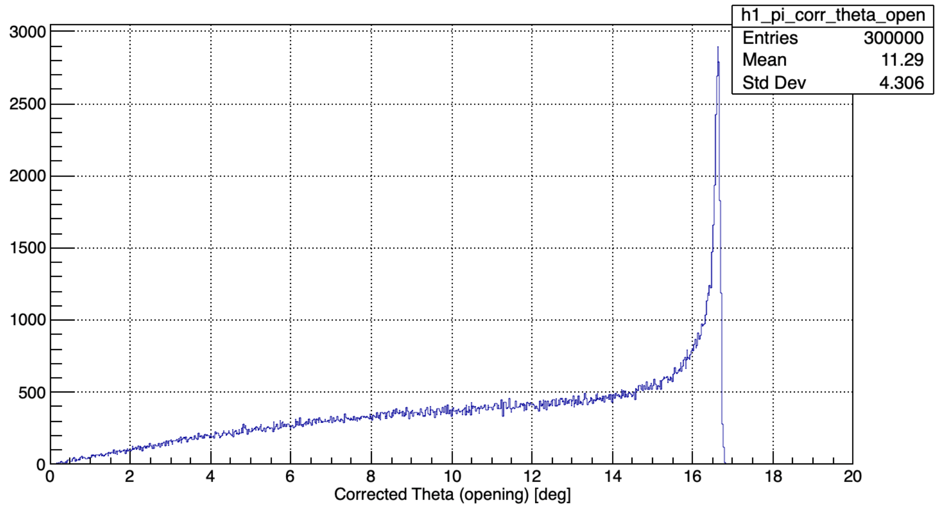
Assuming that the momentum of the hypertriton is the same to the ^{3}He decay residues

$\Delta p/P$ (FRS) = 5×10^{-4}

β -> 0.95

Angular res. = 0.7 m rad

Si detector at R3B/FAIR



Ideas based on Ivan Mukha et al,
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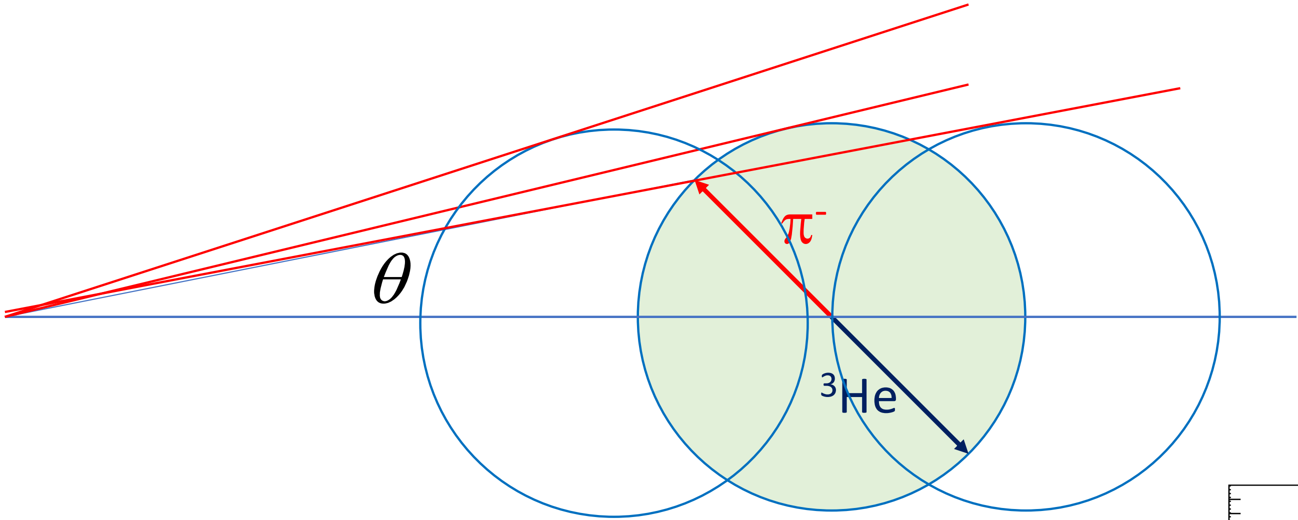
Phys. Rev. Lett. 115, 202501, 2015

Novel approach to the B.E. with the FRS



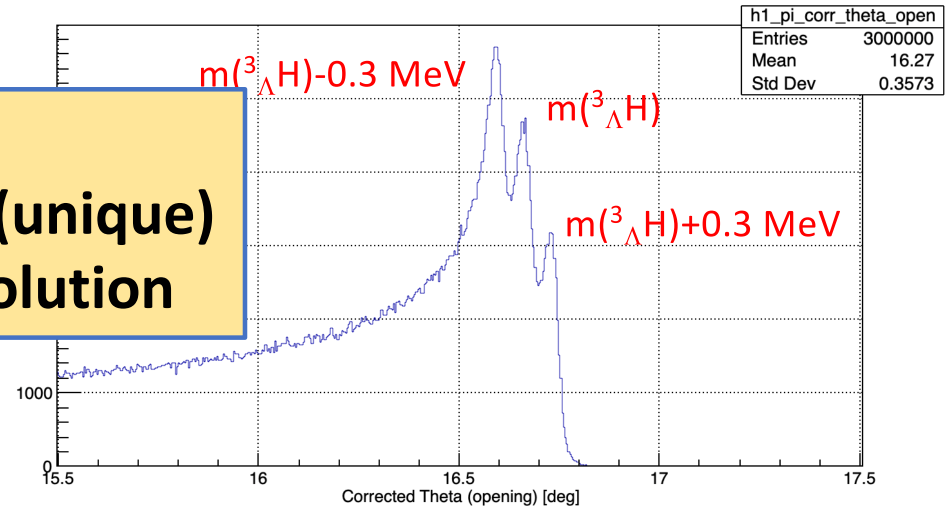
Assuming that the momentum of the hypertriton is the same to the ^{3}He decay residues

$\Delta p/P$ (FRS) = 5x10^{-4}

β -> 0.95

Angular res. = 0.1 m rad

Future possibility

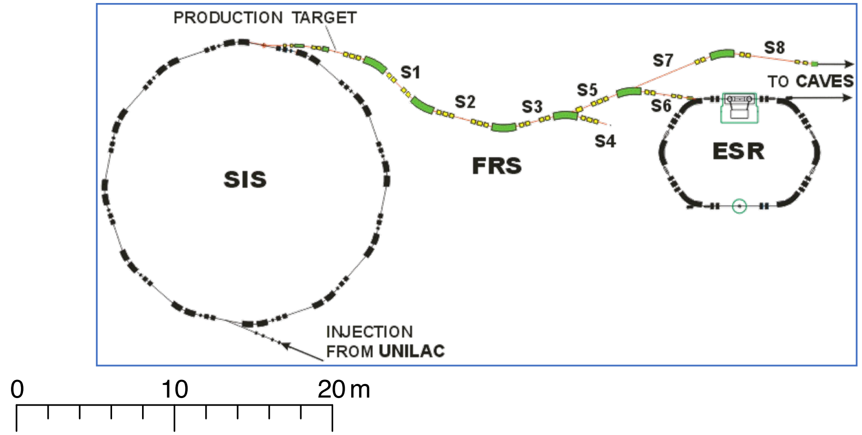


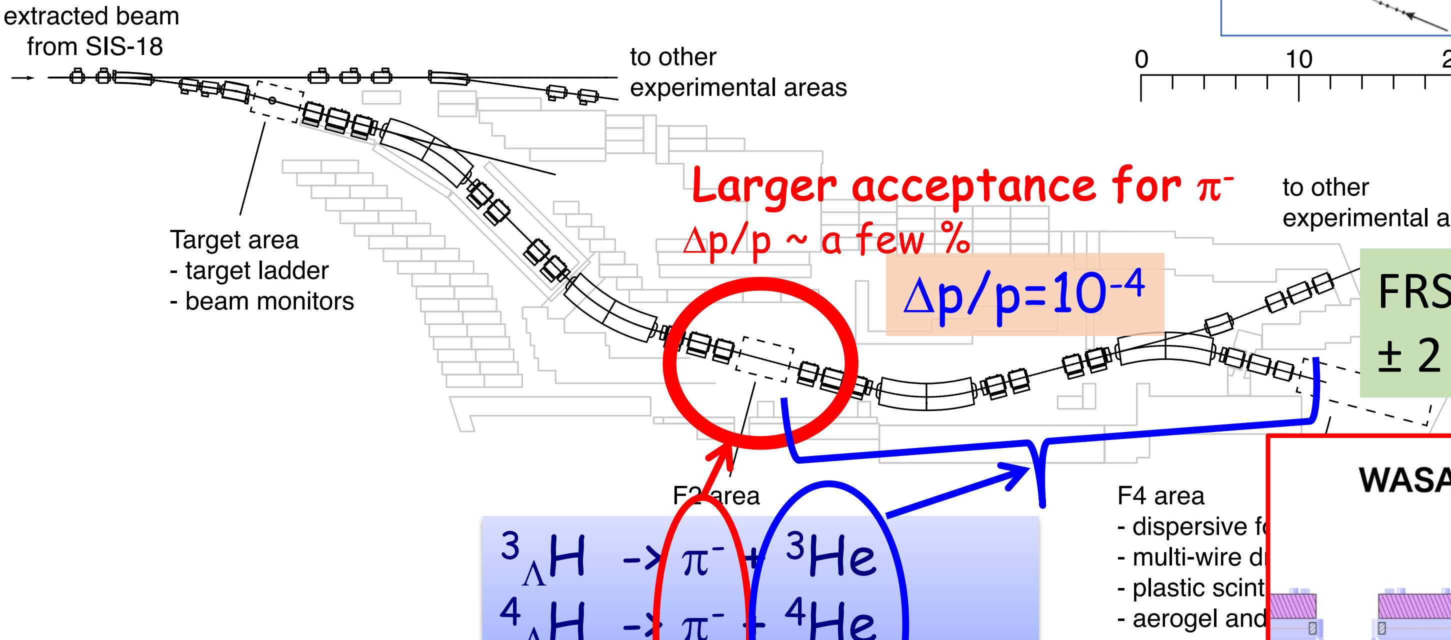
For the precise mass measurements

- **Excellent FRS resolution is mandatory (unique)**
- **Not depending on the momentum resolution**

Ideas based on Ivan Mukha et al,
for studying two-proton emitters at the FRS/GSI
Phys. Rev. Lett. 115, 202501, 2015

The novel technique with FRS at GSI (2016-)





Larger acceptance for π^-

$\Delta p/p$ ~ a few %

$\Delta p/p=10^{-4}$

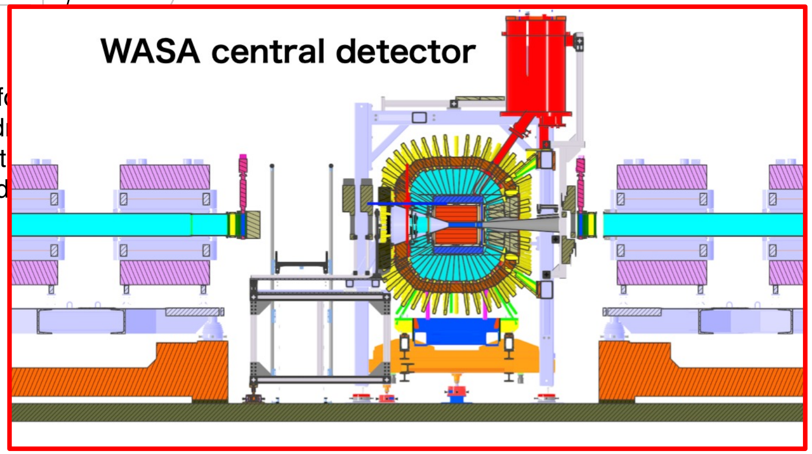
FRS momentum acceptance: ± 2 %

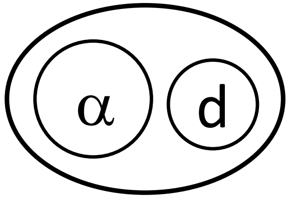
$^{3}_{\Lambda}H \rightarrow \pi^- + {}^{3}He$

$^{4}_{\Lambda}H \rightarrow \pi^- + {}^{4}He$

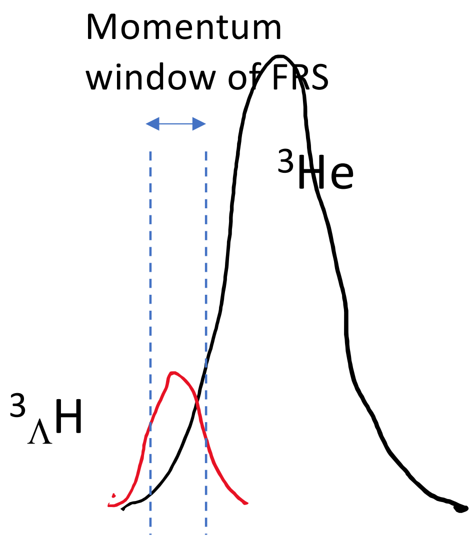
$nn\Lambda \rightarrow \pi^- + d + n$

With $^{6}Li+^{12}C$ at 2 A GeV





Difficulties in the WASA-FRS experiment
^{6}Li + ^{12}C @ 2 A GeV



Distribution of ^{3}He and $^{3}{}_{\Lambda}$H

UrQMD + phase space cut

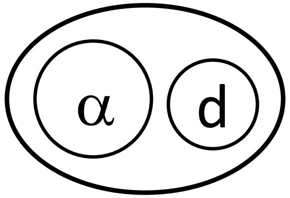
→ Creating distribution of ^{3}He and $^{3}{}_{\Lambda}$H

Is it realistic?

Cross section of ^{3}He is estimated by EPAX

Empirical parameterization of fragmentation cross section

We observed 10 times more than the EPAX estimation



Difficulties in the WASA-FRS experiment

^{6}Li + ^{12}C @ 2 A GeV

Distribution of ^{3}He and $^{3}{}_{\Lambda}$H

UrQMD + phase space cut

→ Creating distribution of ^{3}He and $^{3}{}_{\Lambda}$H

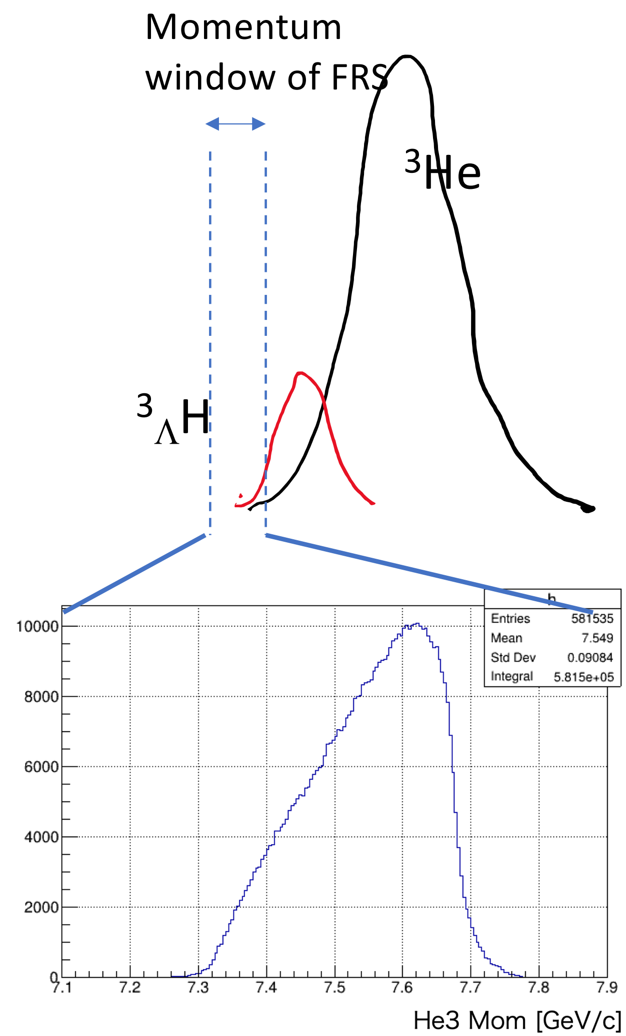
Is it realistic?

Cross section of ^{3}He is estimated by EPAX

Empirical parameterization of fragmentation cross section

We observed 10 times more than the EPAX estimation

We need to collaborate with the EXPERTs



Our challenges on Hypernuclei

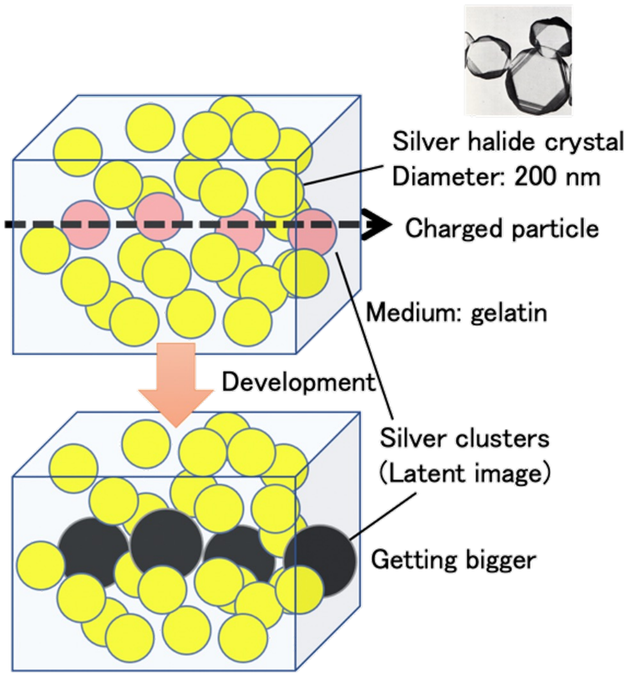
with image analyses
and
machine learning

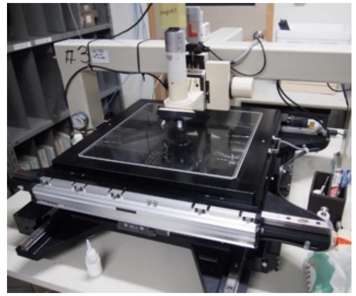
<u>Nuclear Emulsion</u>:

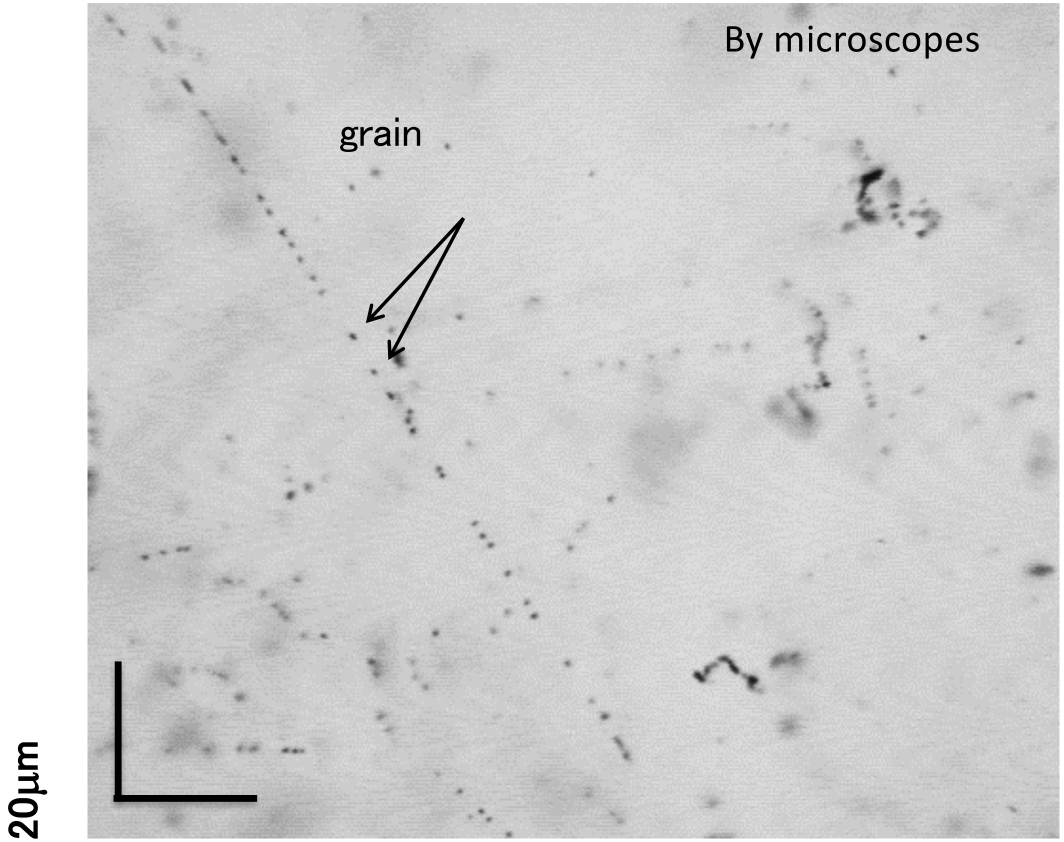
Charged particle tracker with

<u>the best spatial resolution</u>

<u>(easy to be < 1 μm, 11 nm at best)</u>

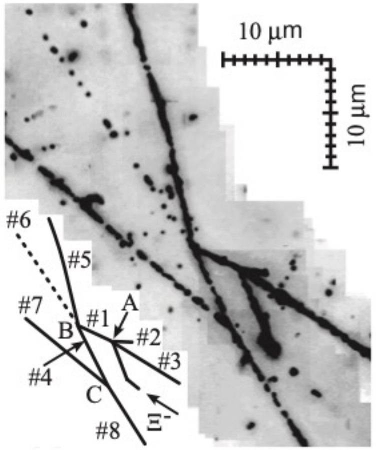






Discovery of $^{6}_{\Lambda\Lambda}He$ (the Nagara event)

Results in the NAGARA paper
https://doi.org/10.1103/PhysRevLett.87.212502
https://doi.org/10.1103/PhysRevC.88.014003



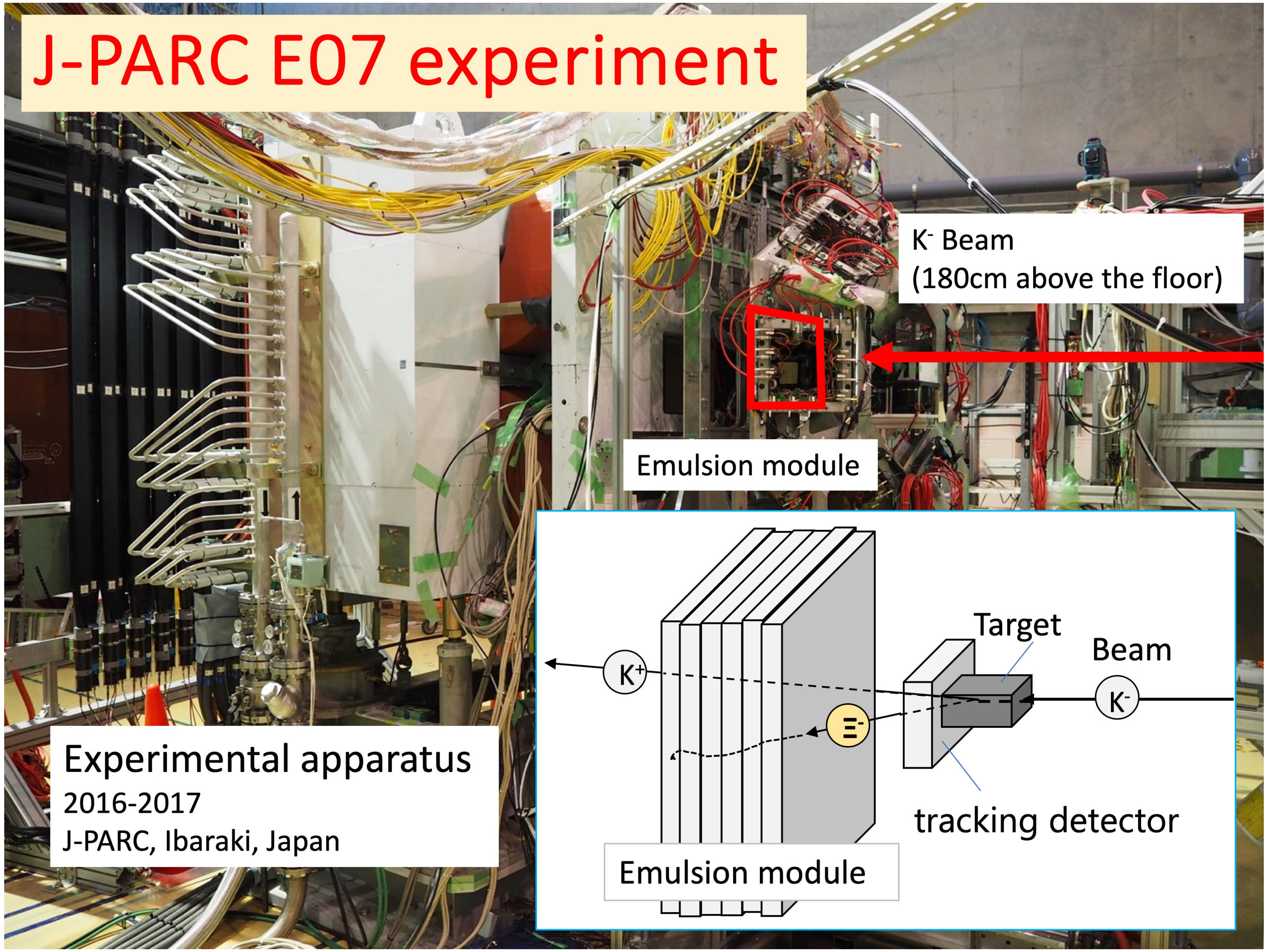
$$^{12}C + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$$
$$\hookrightarrow {}^{5}_{\Lambda}He + p + \pi^- .$$

VertexA(Production)
$\Delta B_{\Lambda\Lambda} - B_{\Xi} = 0.69 \pm 0.20$ MeV
VertexB(Decay)
$\Delta B_{\Lambda\Lambda} = 0.6 \pm 0.6$ MeV

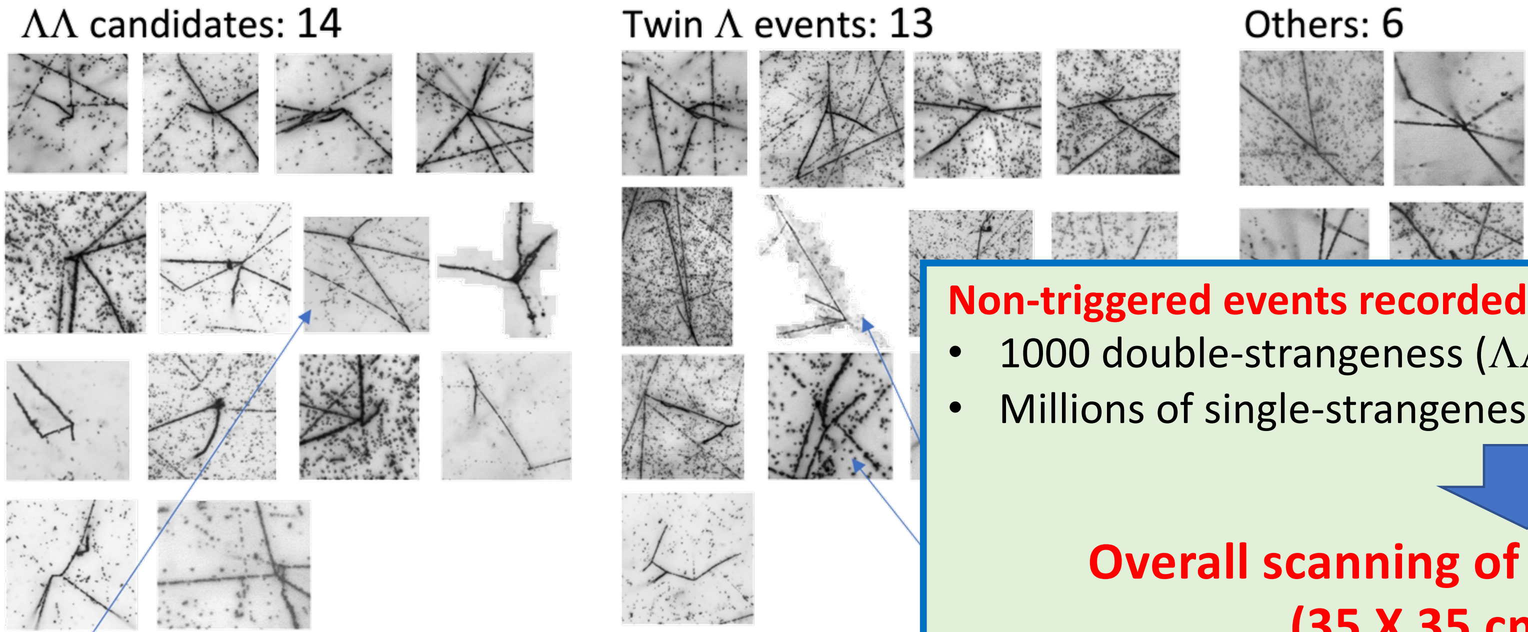
$B_{\Lambda\Lambda} = 6.79 + 0.91 B_{\Xi^-}$ ($\pm$ 0.16) MeV
$\Delta B_{\Lambda\Lambda} = 0.55 + 0.91 B_{\Xi^-}$ ($\pm$ 0.17) MeV

$B_{\Lambda\Lambda} = 6.91 \pm 0.16$ MeV
$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV
(Assumpusion: B_{Ξ^-} = 0.13 MeV (*3D*))

J-PARC E07 experiment



Results from J-PARC E07 (Hybrid method)



Non-triggered events recorded in 1300 emulsions sheets

- 1000 double-strangeness (ΛΛ- and Ξ-) hypernuclear events
- Millions of single-strangeness hypernuclear events

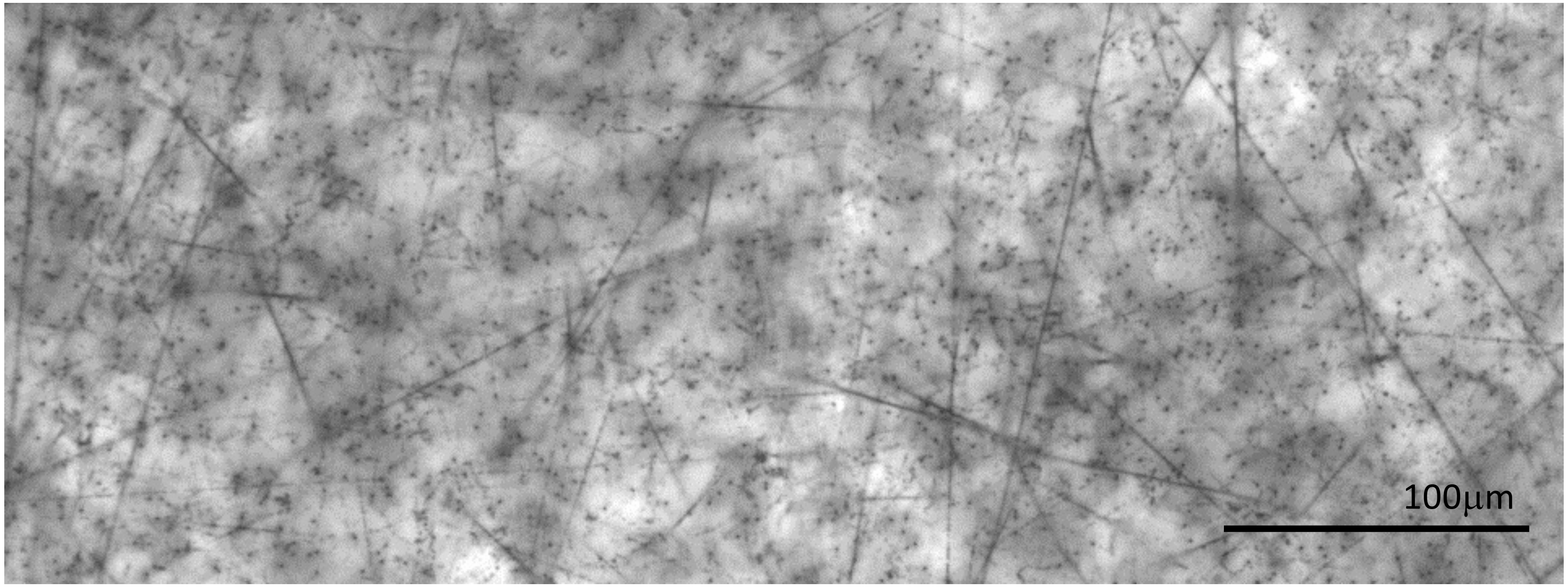
Overall scanning of all emulsion sheets
(35 X 35 cm^2 X 1000)

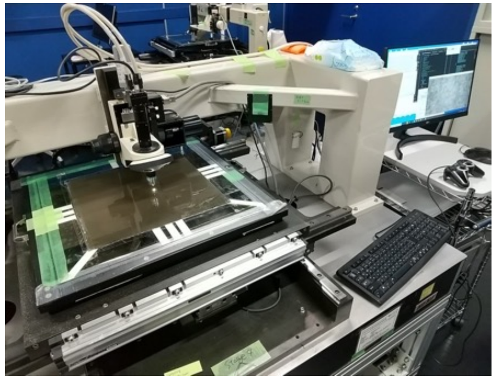
M. Yoshimoto
Prog. Theor. Exp. Phys. 2021, 073D02

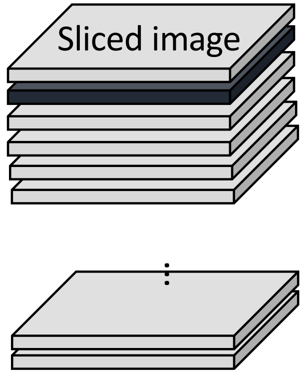
${}^{15}_{\Xi}C$

${}_{\Lambda\Lambda}Be$
H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

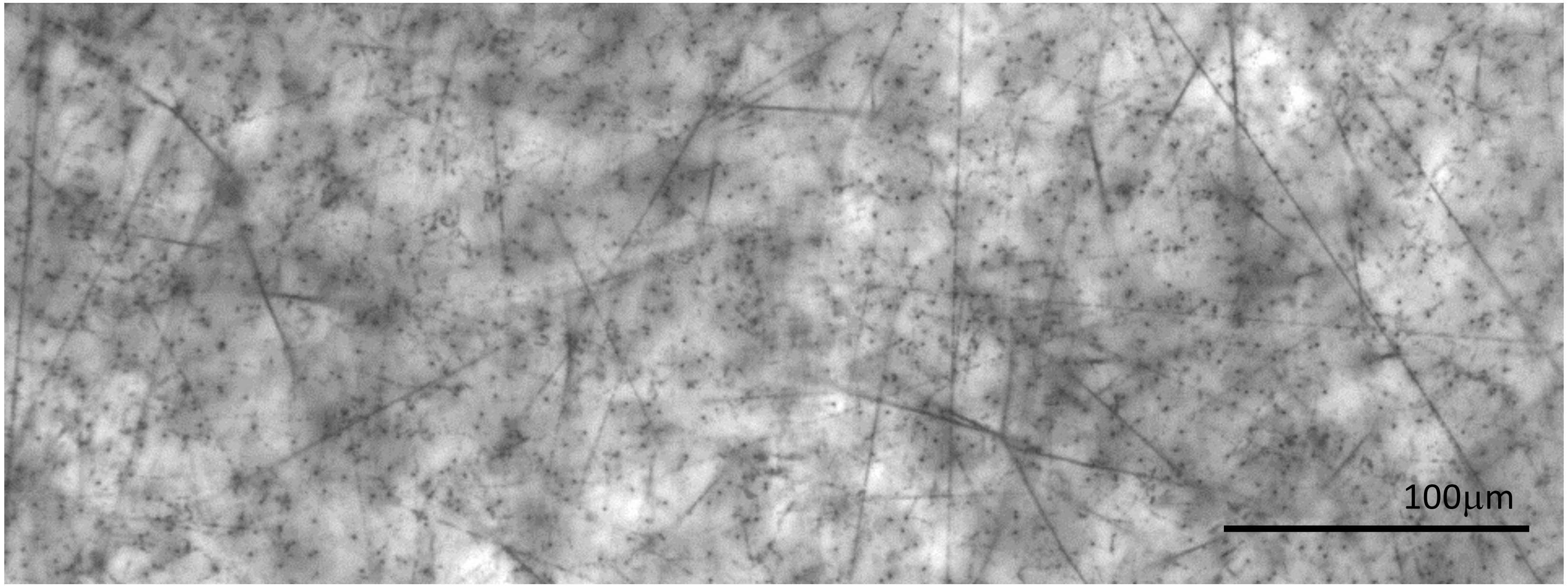
Overall scanning for E07 emulsions

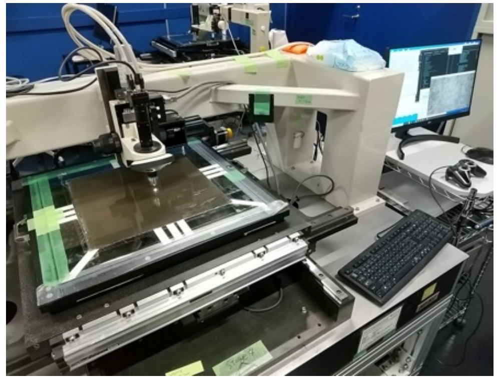


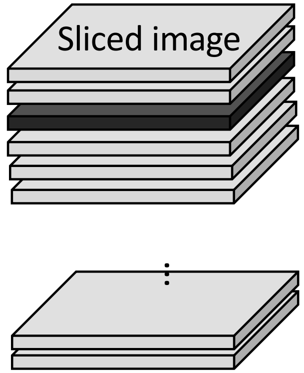




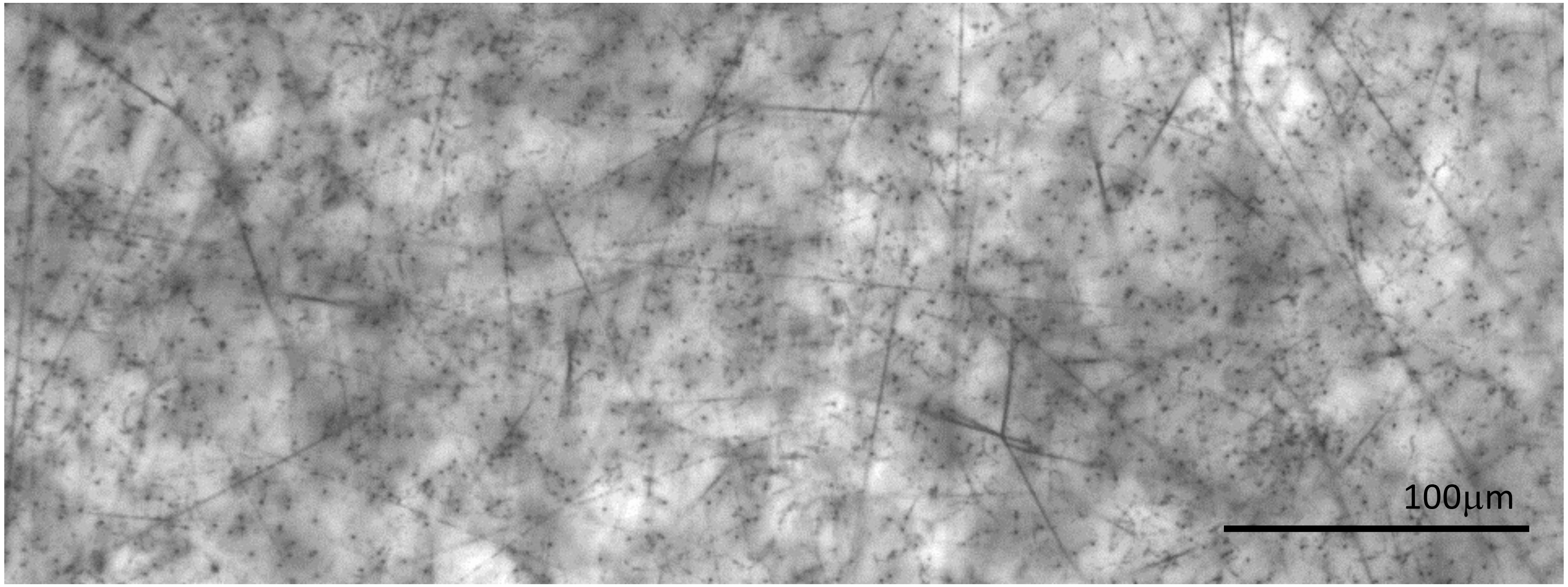
Overall scanning for E07 emulsions

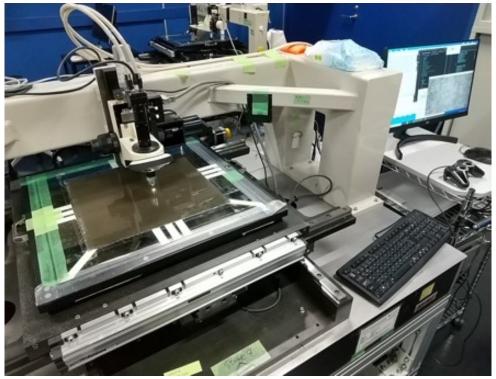


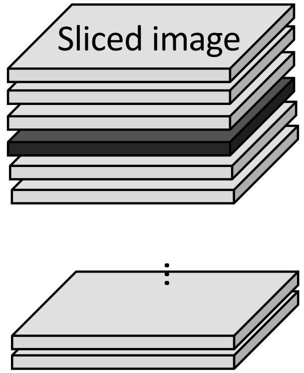




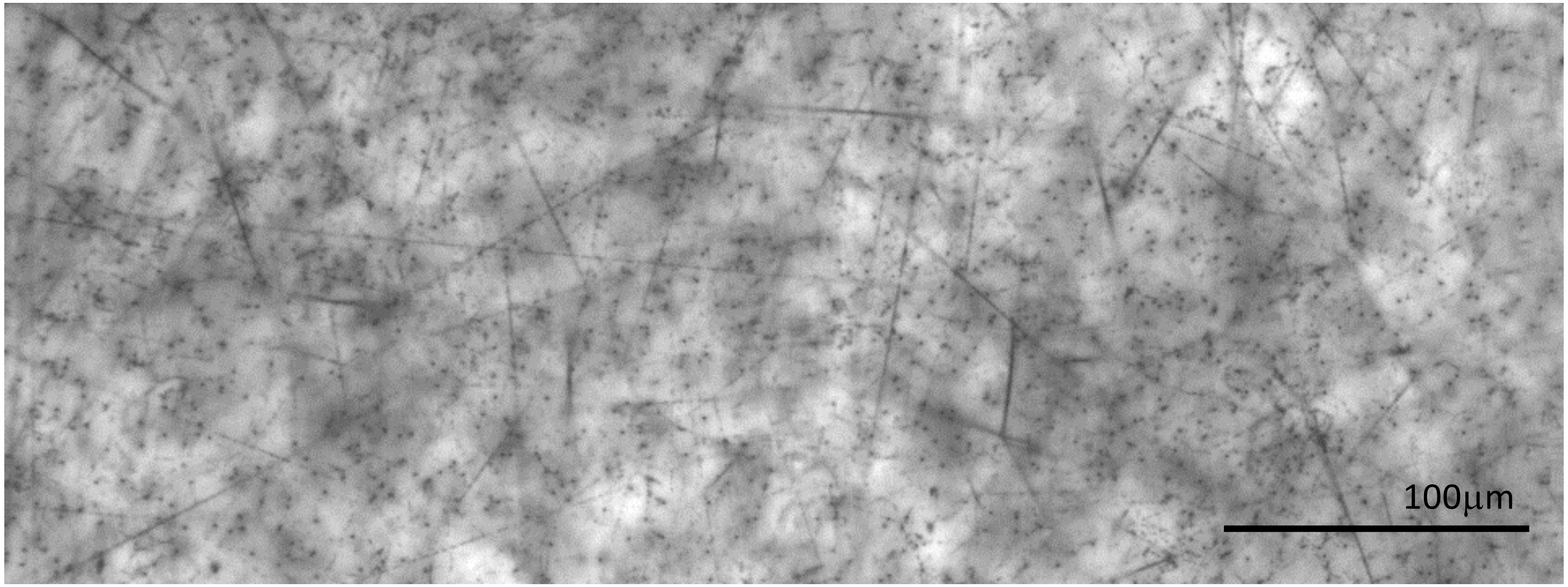
Overall scanning for E07 emulsions

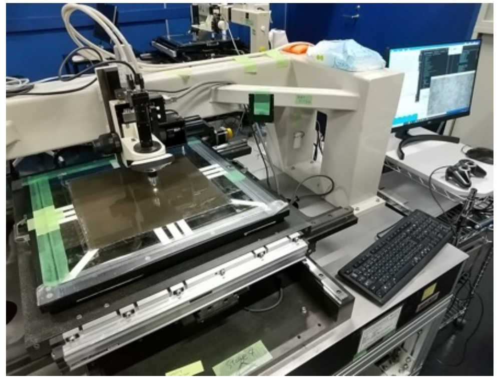


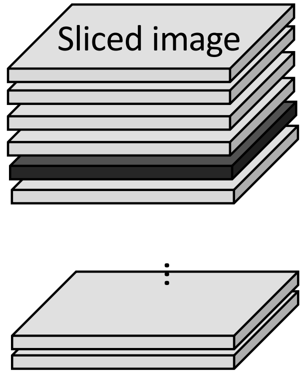




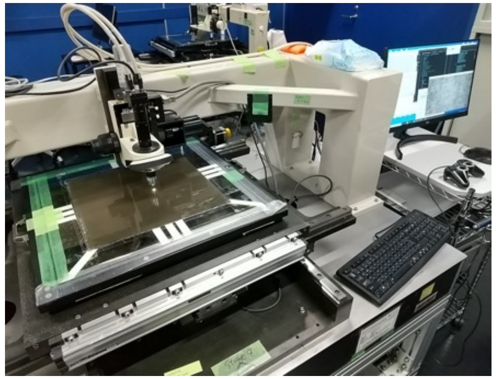
Overall scanning for E07 emulsions

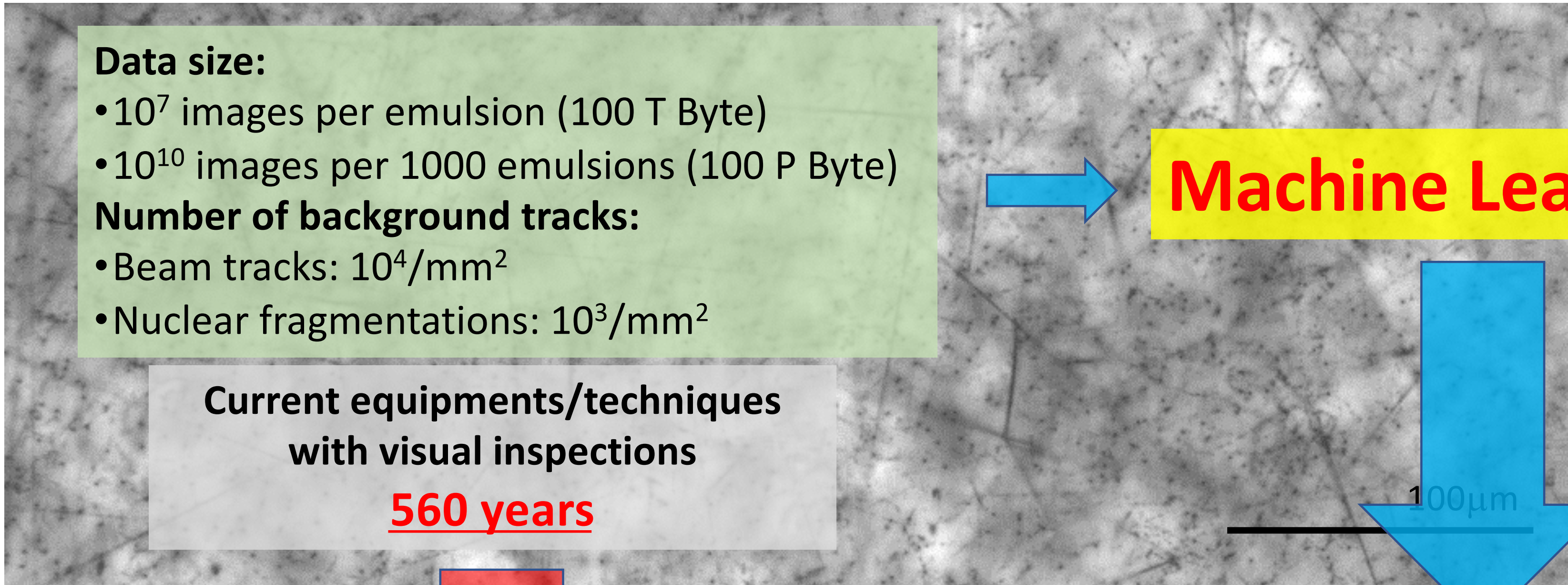






Overall scanning for E07 emulsions





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

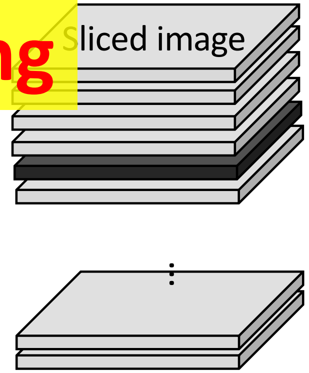
Number of background tracks:
- Beam tracks: $10^4/\text{mm}^2$
- Nuclear fragmentations: $10^3/\text{mm}^2$

Current equipments/techniques with visual inspections

560 years

3 years

Machine Learning



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

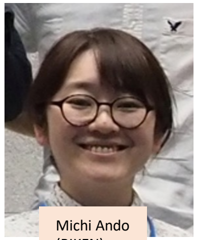
Setup for analyzing emulsions at the High Energy Nuclear Physics Laboratory in RIKEN

- Hypernuclear physics
- Neutron imaging

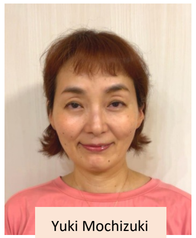
Part-timer staffs working for emulsion & microscopes

Current members

Risa Kobayashi (RIKEN)

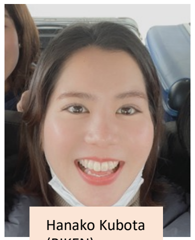


Michi Ando (RIKEN)

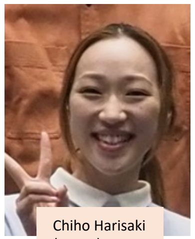


Yuki Mochizuki (RIKEN)

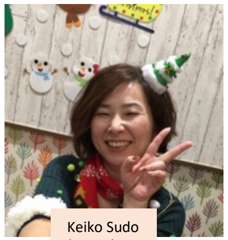
Former members



Hanako Kubota (RIKEN)



Chiho Harisaki (RIKEN)



Keiko Sudo (RIKEN)

Currently 7 microscope stages running

Challenges for Machine Learning Development

Ideas : 2018
Implementations: 2020-2021

MOST IMPORTANT:
- **Quantity and quality of training data**

However,
No existing data for hypertriton with emulsions for training

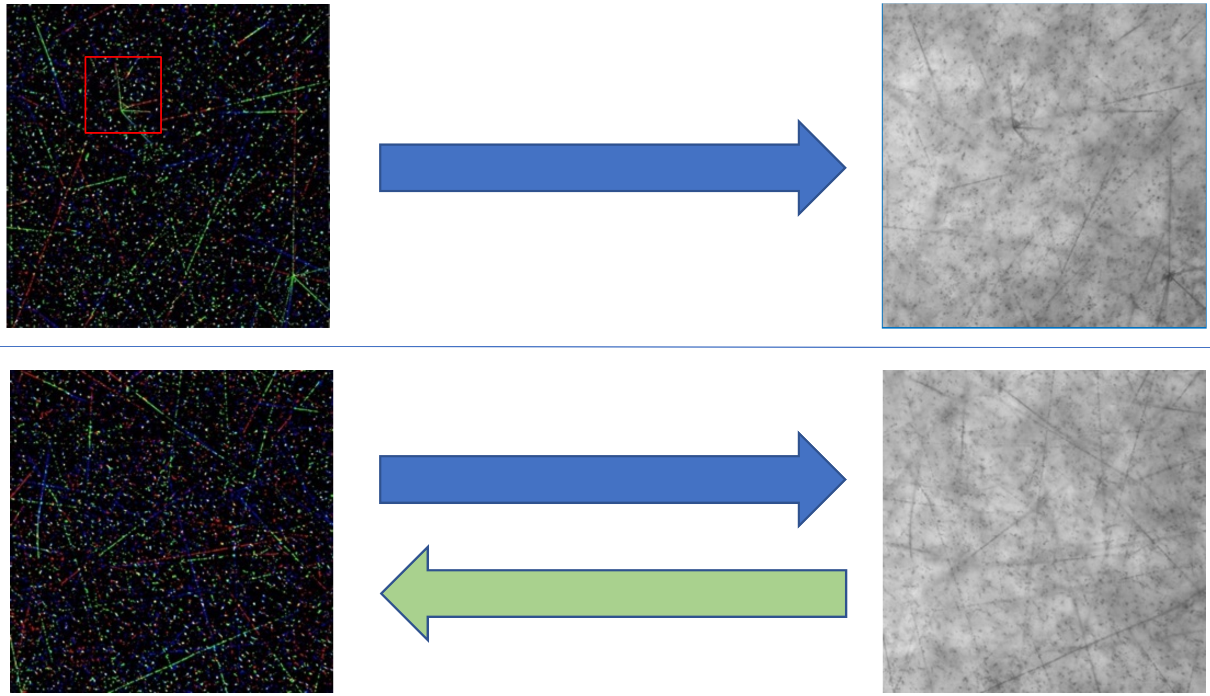
Our approaches:
Producing training data with
- Monte Carlo simulations
- Image transfer techniques

Production of training data

Monte Carlo simulations and GAN(Generative Adversarial Networks)

Binarized tracks from MC simulations
+ background from the real data

Produced training data



Binarized (like for simulations)

Real emulsion image

GAN: pix2pix

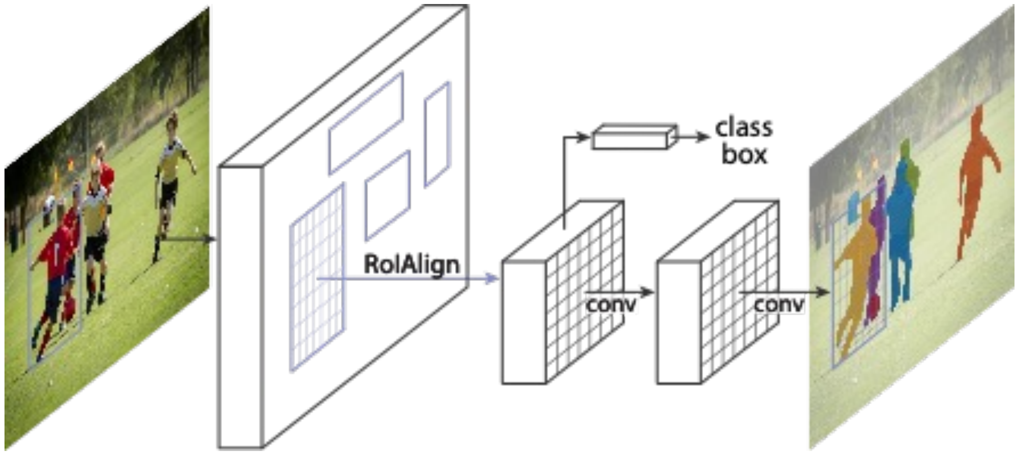
Edges to Photo

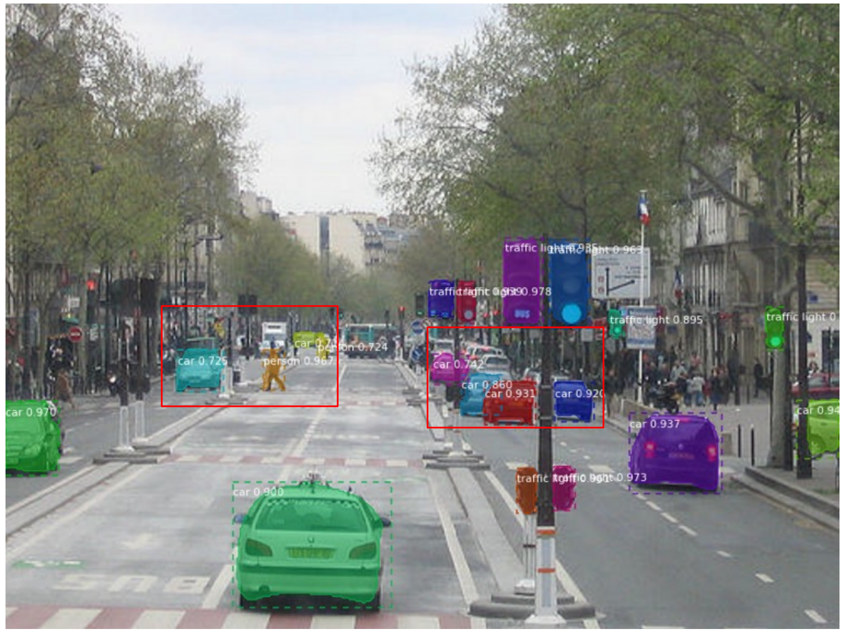
input output

Ayumi Kasagi. Ph.D. thesis (2023)
A.Kasagi et.al, NIM A1056, (2023) 168663

Detection of hypertriton events

With Mask R-CNN model



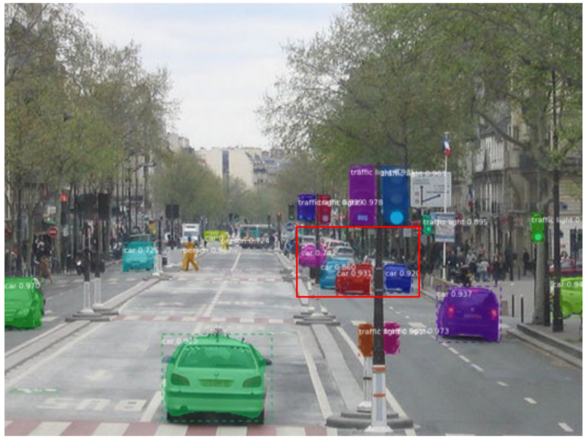


Detection of each object

At large object density

Training of Mask R-CNN with Simulated image

Mask R-CNN

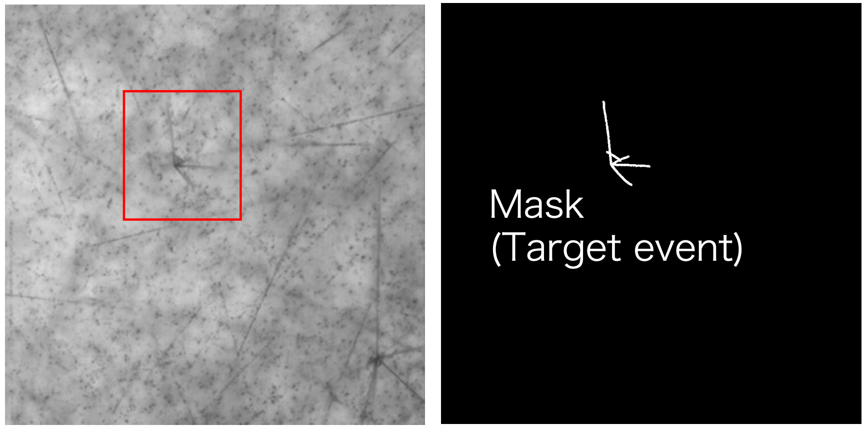


Example of training dataset

A Pedestrian dataset

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

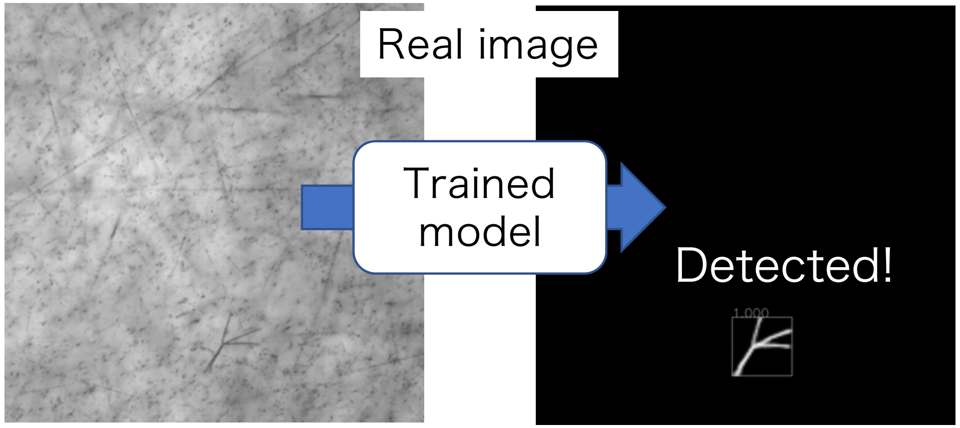
Training data (Simulated image)



50 μm

Masks are automatically produced

Performance of α-decay detection



50 μm

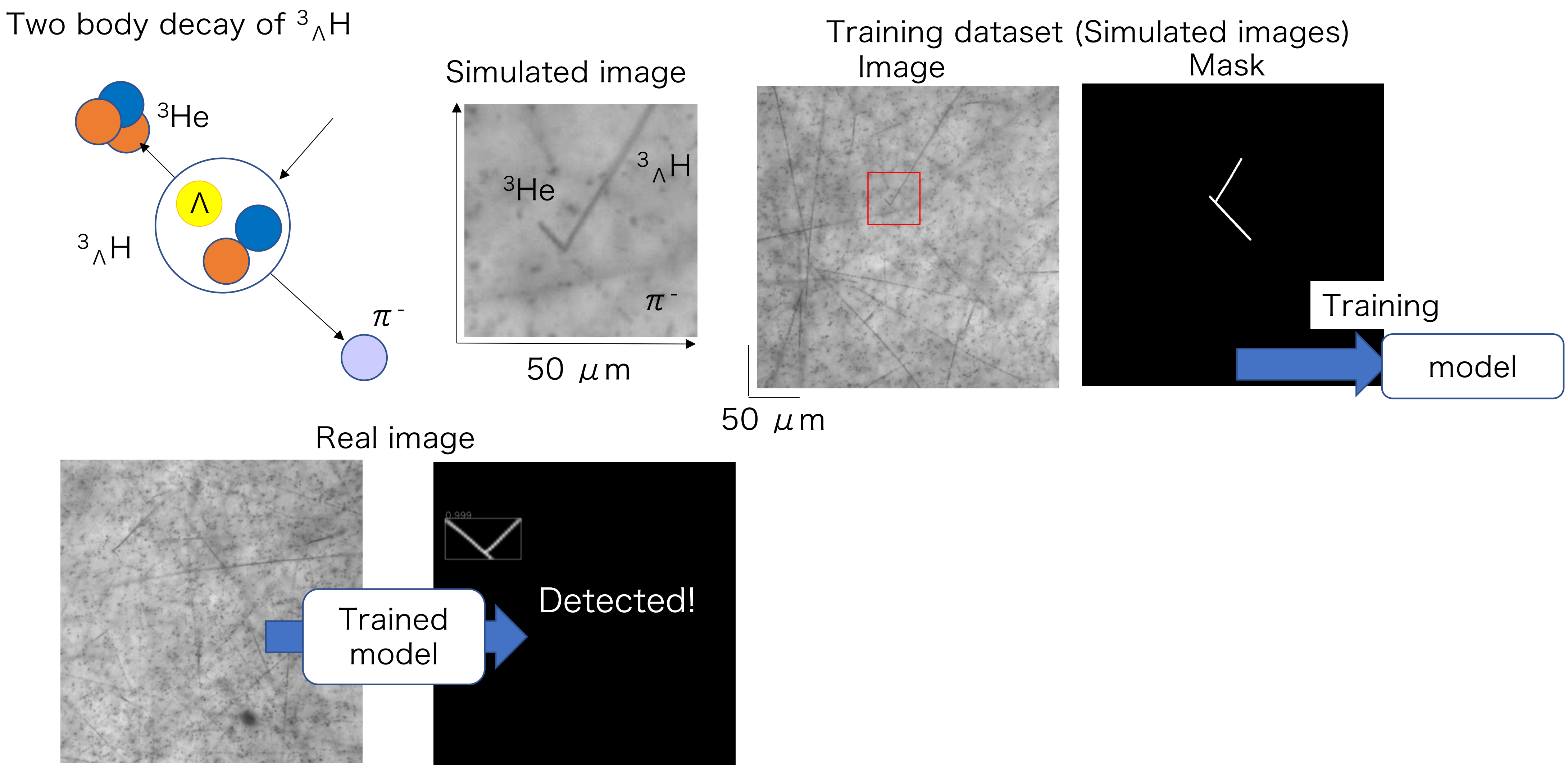
Efficiency = No. detected/No. total
Purity = Truth Positive/No. candidates

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

→ 2^{nd} step done

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

Hypertriton search with Mask R-CNN



Discovery of the first hypertriton event in E07 emulsions

nature reviews physics

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nature > nature reviews physics > perspectives > article

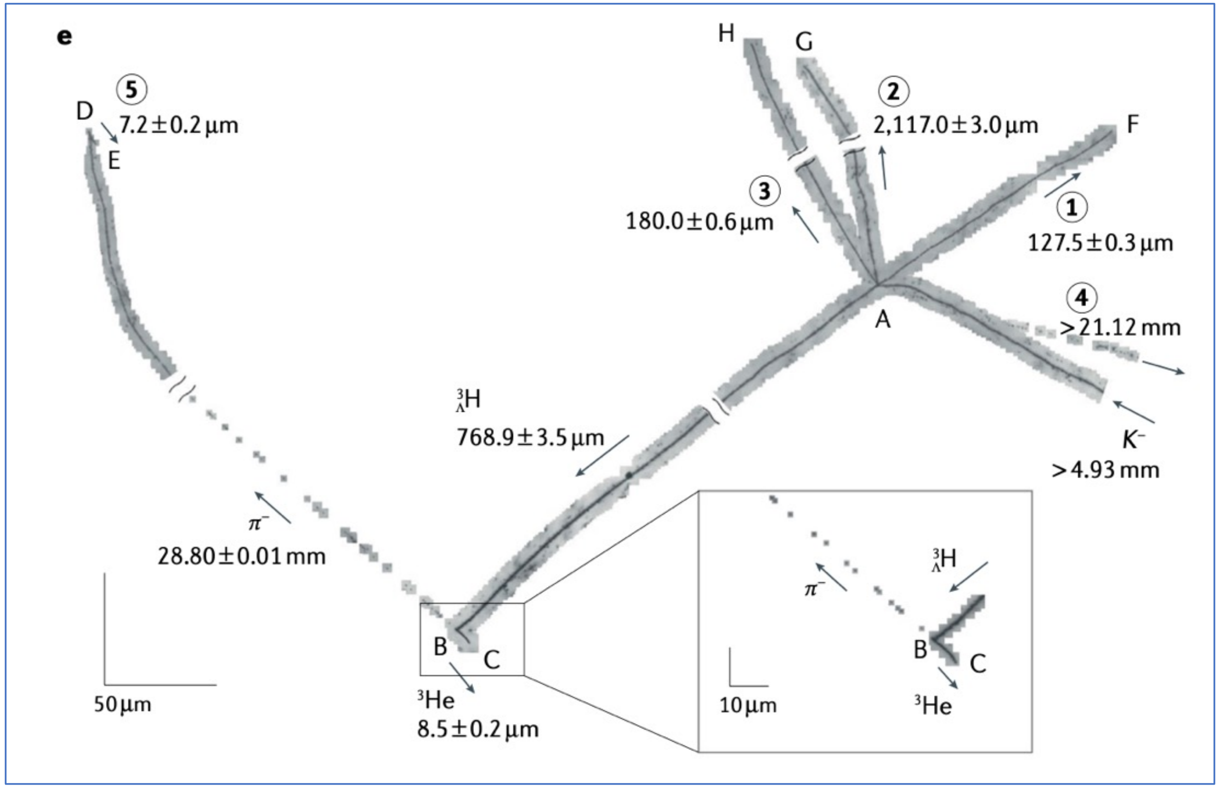
Perspective | Published: 14 September 2021

New directions in hypernuclear physics

Takehiko R. Saito ✉, Wenbou Dou, Vasyl 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

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



Guaranteeing the determination of the hypertriton binding energy SOON

Precision: 28 keV

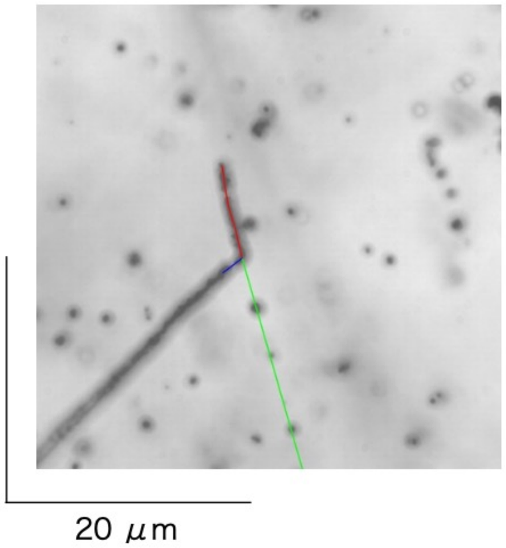
E. Liu et al., EPJ A57 (2021) 327

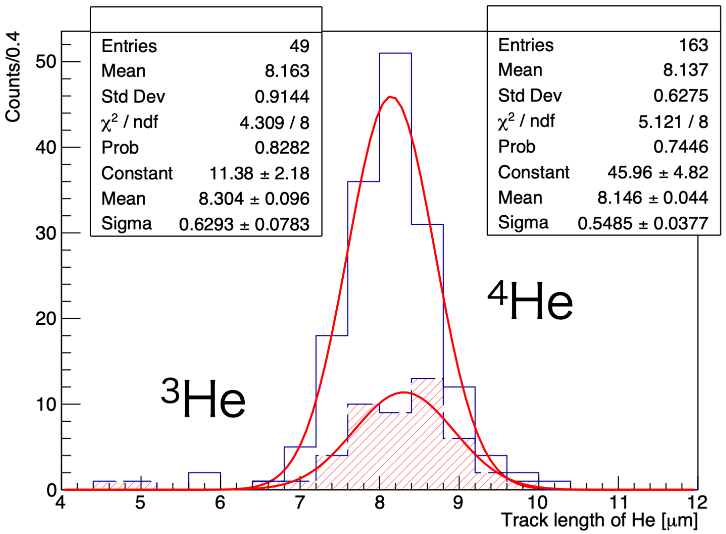
Ayumi Kasagi.
Ph.D. thesis (2023)

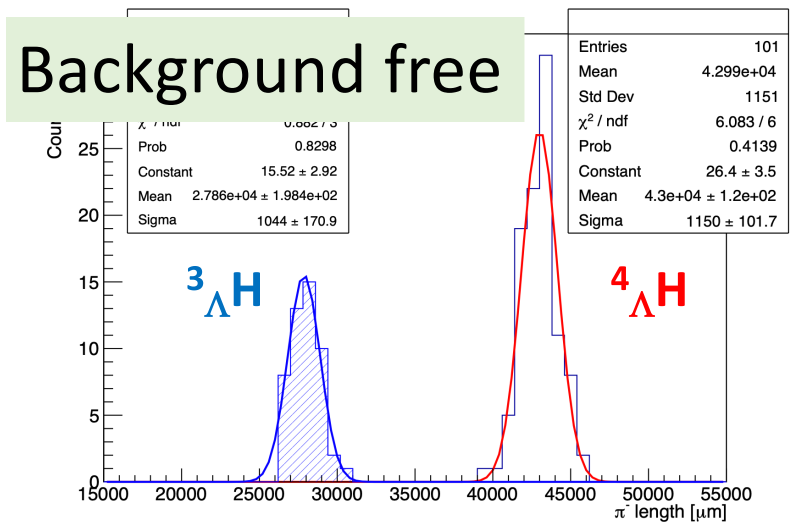
Towards the hypertriton binding energy

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

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

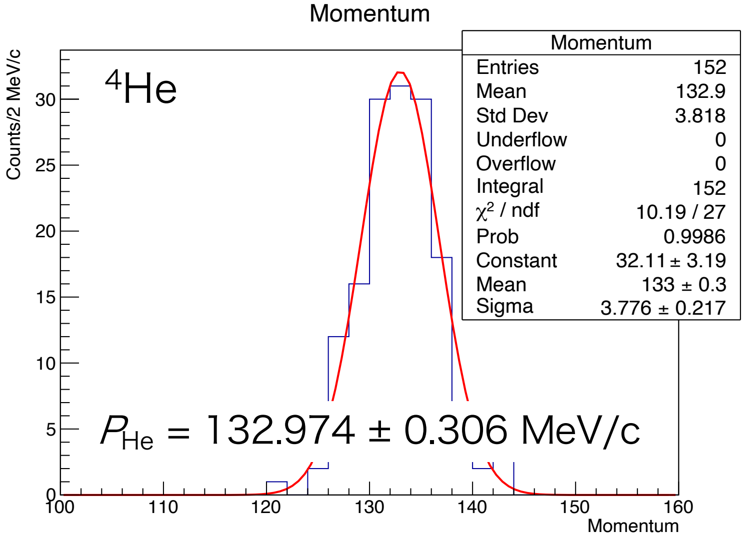


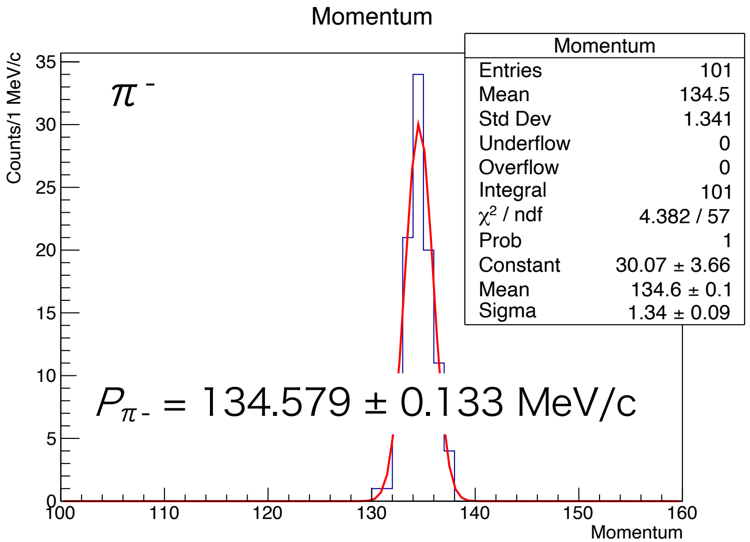




A. Kasagi et al., to be published soon

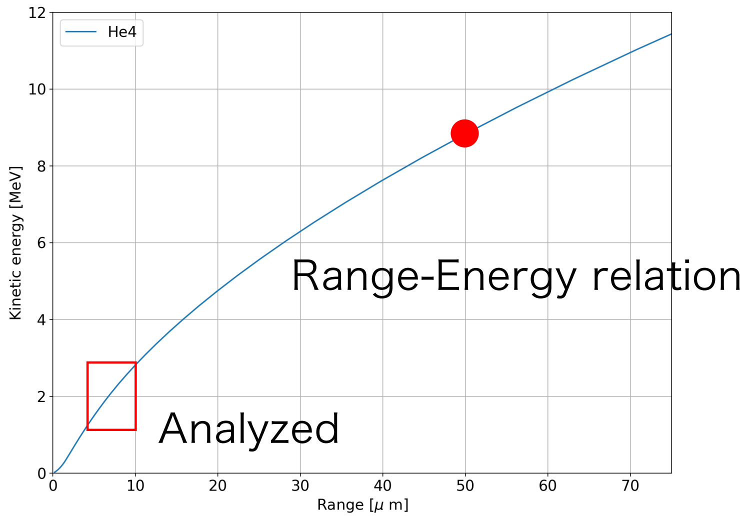
Problems on π^-





MAMI: P_{π^-} = 132.851 ± 0.011 (stat.) ± 0.101 (syst.) MeV/c

Nucl. Phys. A 954, 149 (2016)



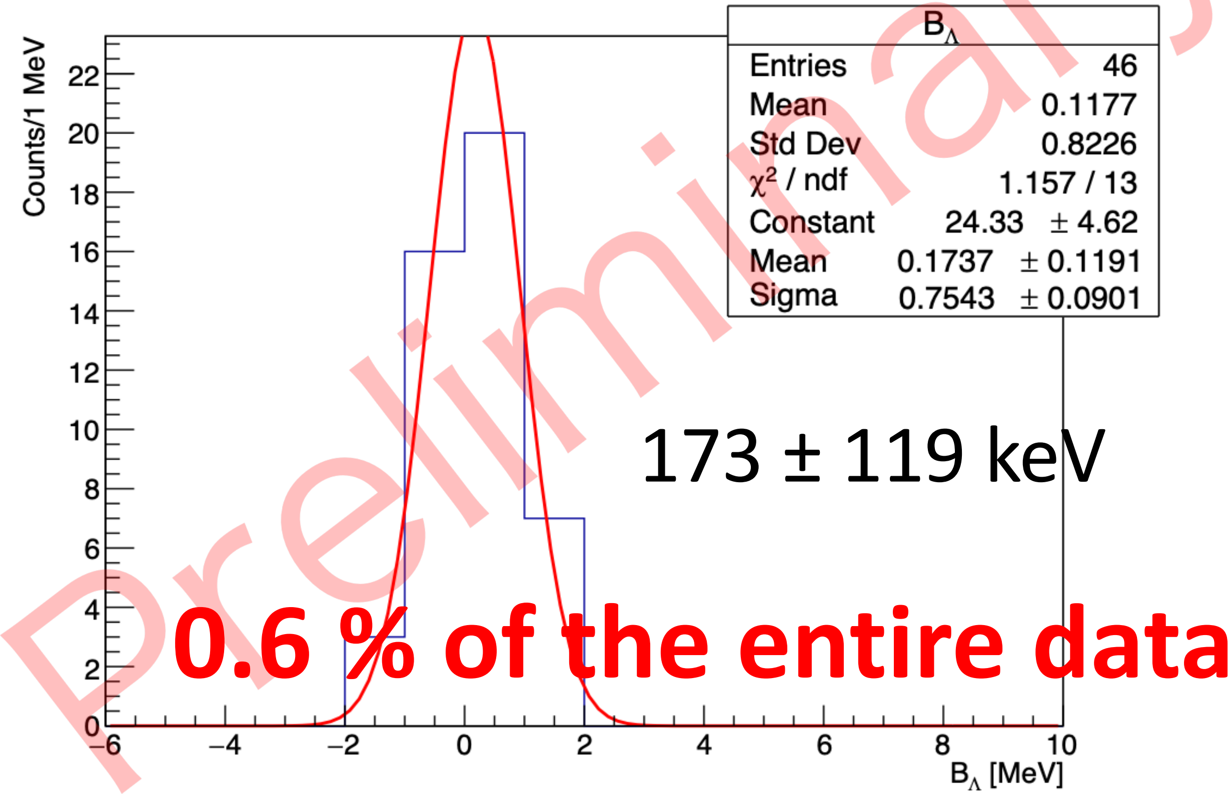
We confirmed that **the Range-Energy Relation for energetic π is not correct**

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., to be published soon

Range of the deduced binding energy



$^3_\Lambda$H Binding energy

$B_\Lambda(^3_\Lambda H)$: 0.13 ± 0.05 MeV

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

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

STAR (2020)

0.41 ± 0.12 ± 0.11 MeV

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

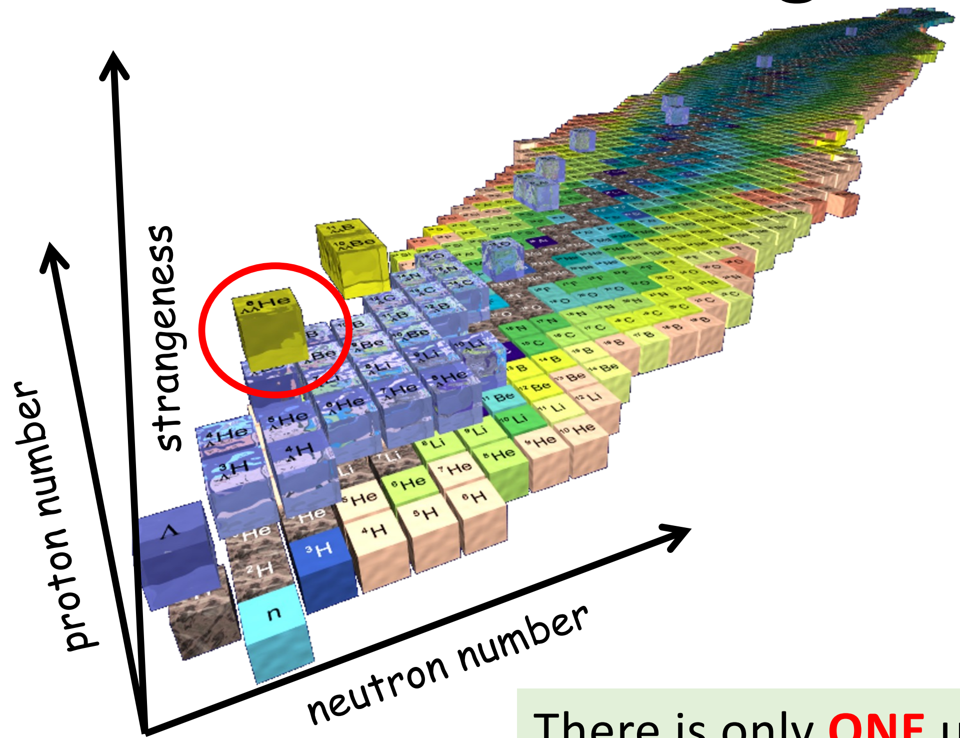
ALICE

0.102 ± 0.063 ± 0.067 MeV

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

A. Kasagi et al., to be published

Chart of double-strangeness hypernuclei

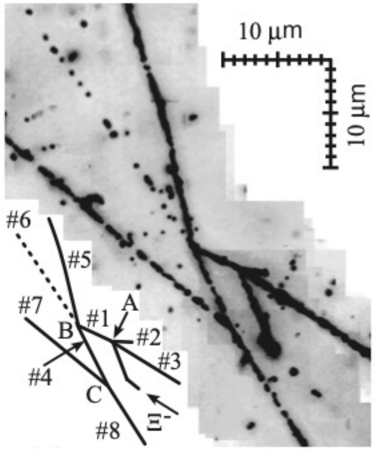


There is only **ONE** uniquely unidentified S=-2 hypernucleus
Nagara event, $^{6}_{\Lambda\Lambda}$**He**
$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

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



$$^{12}\mathrm{C} + \Xi^{-} \rightarrow {}^{\;6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$
$$\hookrightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^{-}.$$

VertexA(Production)
$\Delta B_{\Lambda\Lambda} - B_{\Xi} = 0.69 \pm 0.20$ MeV
VertexB(Decay)
$\Delta B_{\Lambda\Lambda} = 0.6 \pm 0.6$ MeV

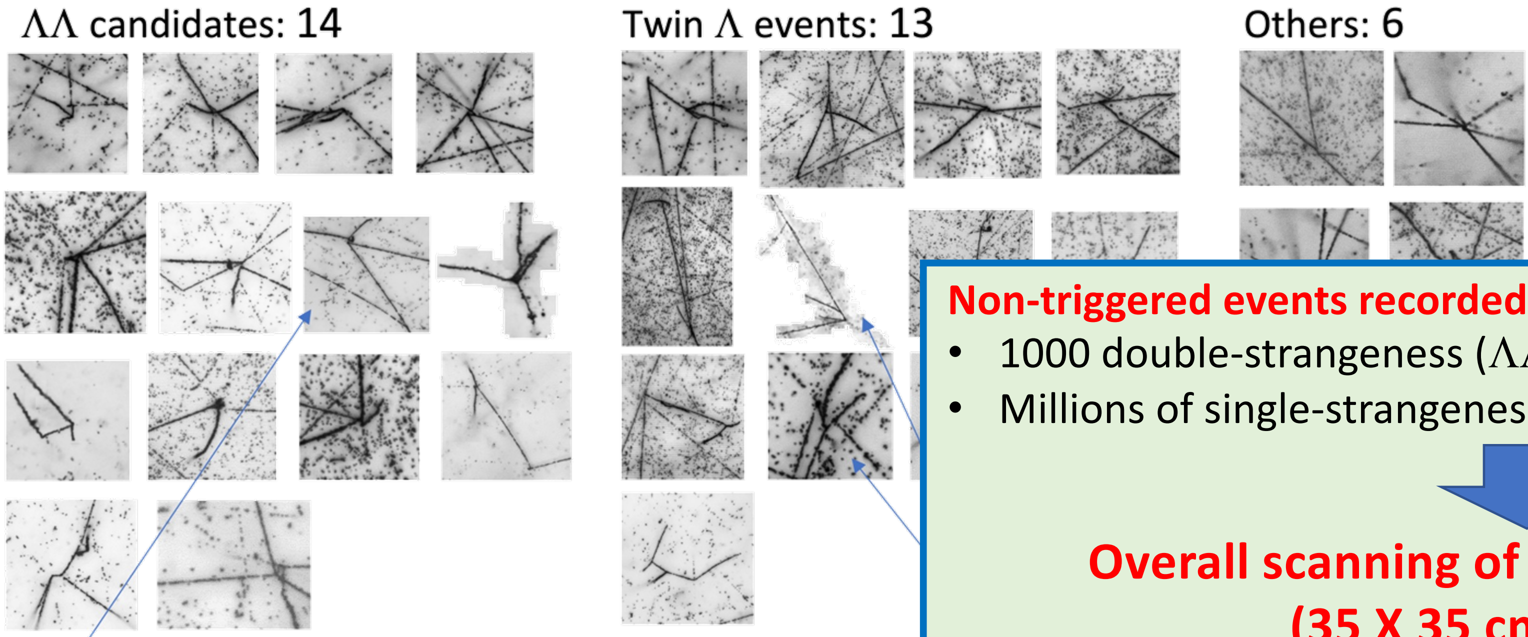
$B_{\Lambda\Lambda} = 6.79 + 0.91 B_{\Xi^-}$ ($\pm$ 0.16) MeV
$\Delta B_{\Lambda\Lambda} = 0.55 + 0.91 B_{\Xi^-}$ ($\pm$ 0.17) MeV

$B_{\Lambda\Lambda} = 6.91 \pm 0.16$ MeV
$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV
(Assumpusion: $B_{\Xi^-} = 0.13$ MeV (*3D*))

$\Delta B_{\Lambda\Lambda}$: 2 – 3 times larger

A. Kasagi et al., to be published

Results from J-PARC E07 (Hybrid method)



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

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

$_{\Lambda\Lambda}Be$
H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

Non-triggered events recorded in 1300 emulsions sheets

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

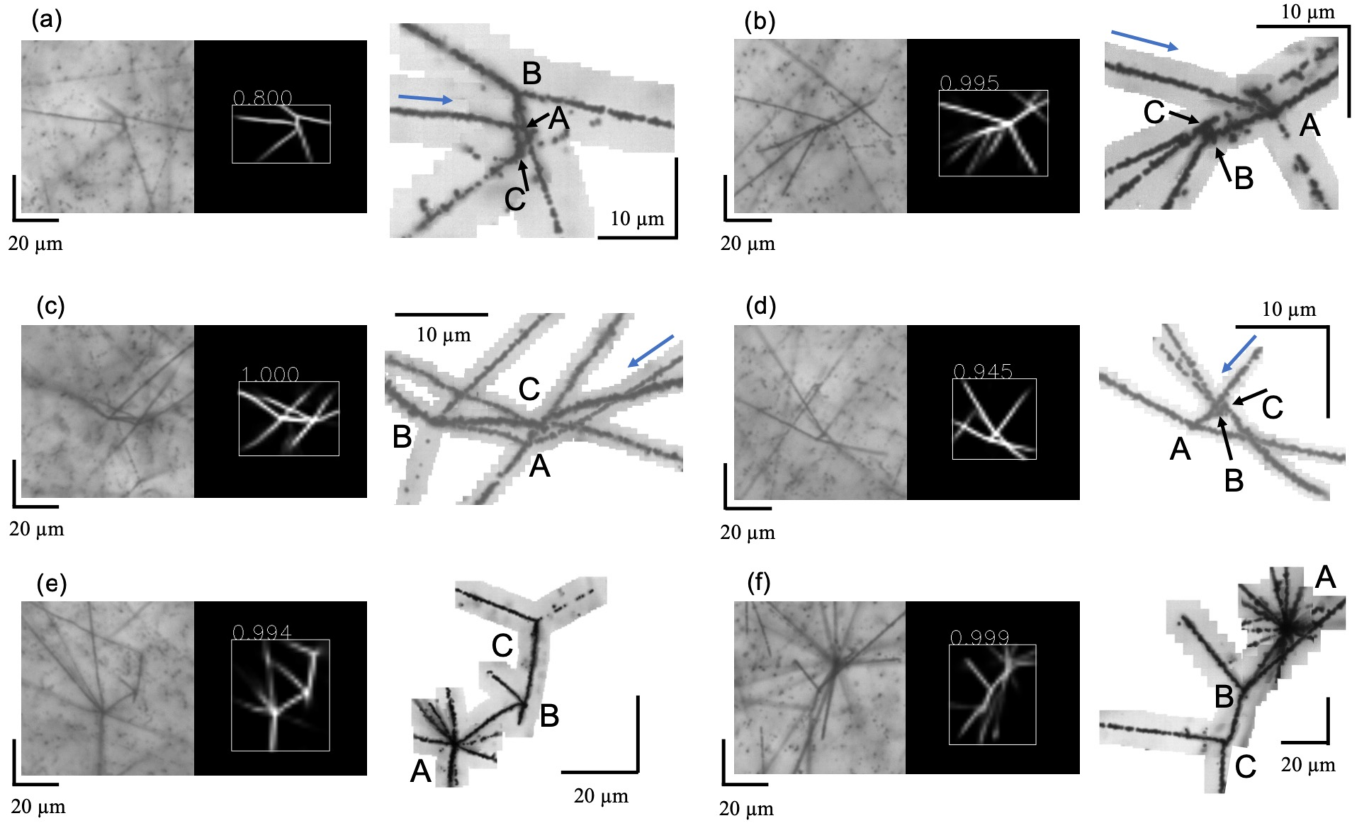
Overall scanning of all emulsion sheets
(35 X 35 cm^2 X 1000)

Only 33 candidates
No unique identification for double-Λ hyp.

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.

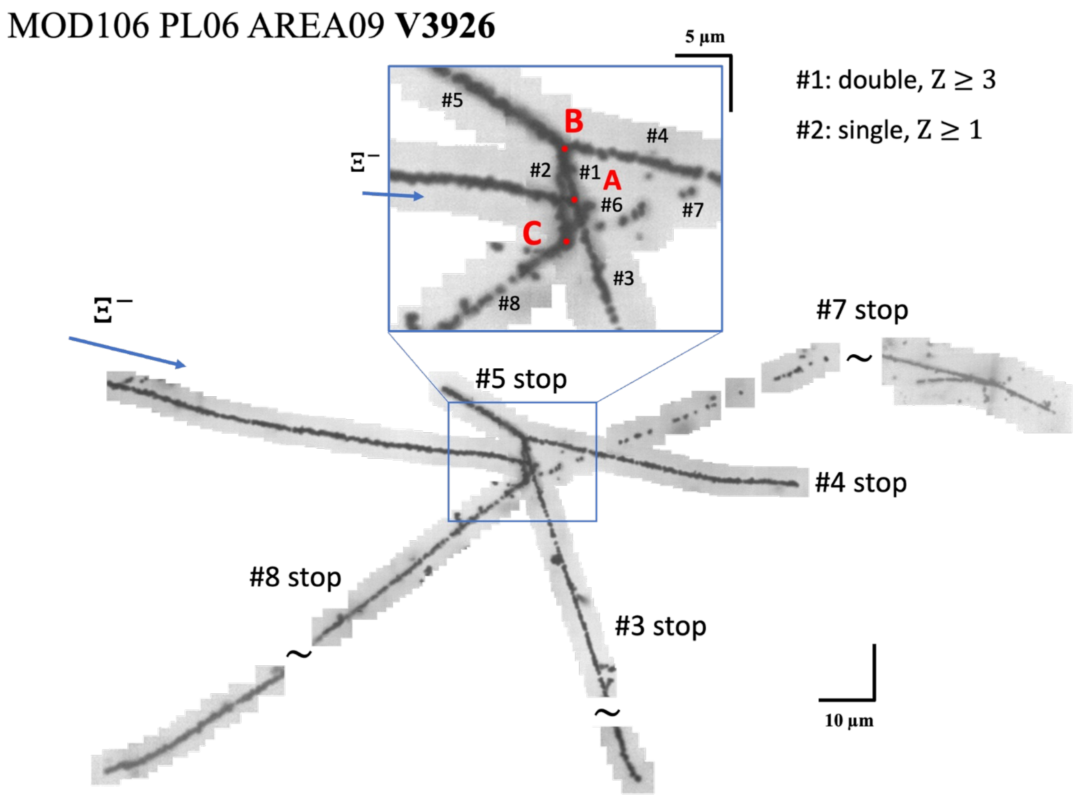


1000 candidates

~5000
(500 can be uniquely identified)

Yan He, et al.,
submitted to NIMA
currently under review

One of potential candidate



As $^{11}_{\Lambda\Lambda}$Be:
Contradicting to the result of the Mino event as $^{11}_{\Lambda\Lambda}$Be (J-PARC E07)

As $^{14}_{\Lambda\Lambda}$C:
Newly discovered
Probably $\Lambda\Lambda$(1S) coupled to 2^+ of ^{12}C

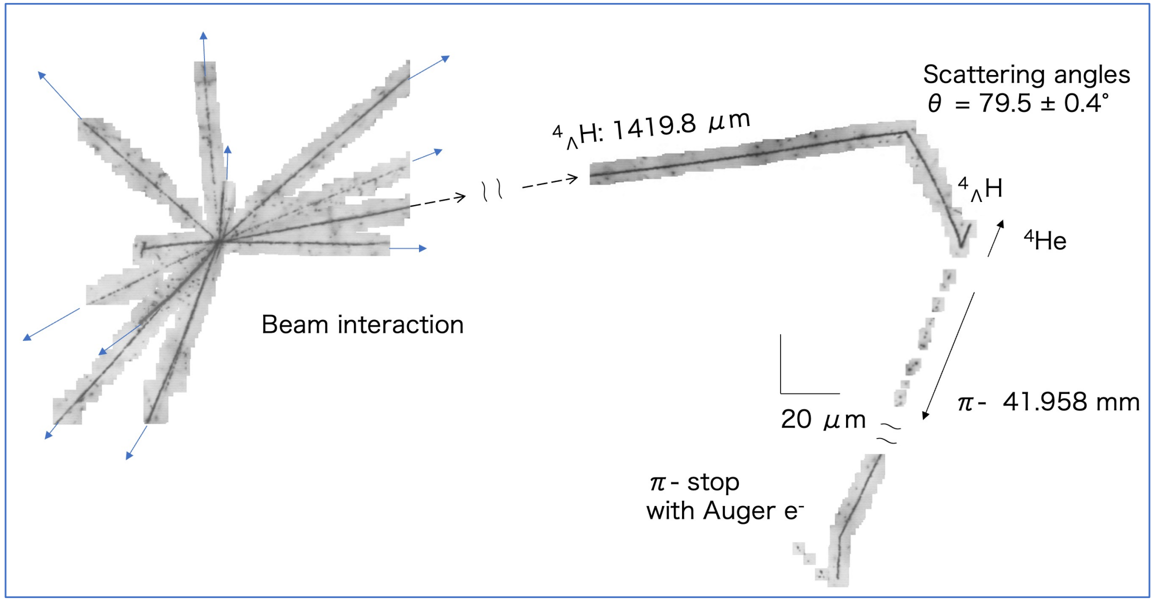
For both cases, the double hypernuclei decay into $^{5}_{\Lambda}$H

New discovery

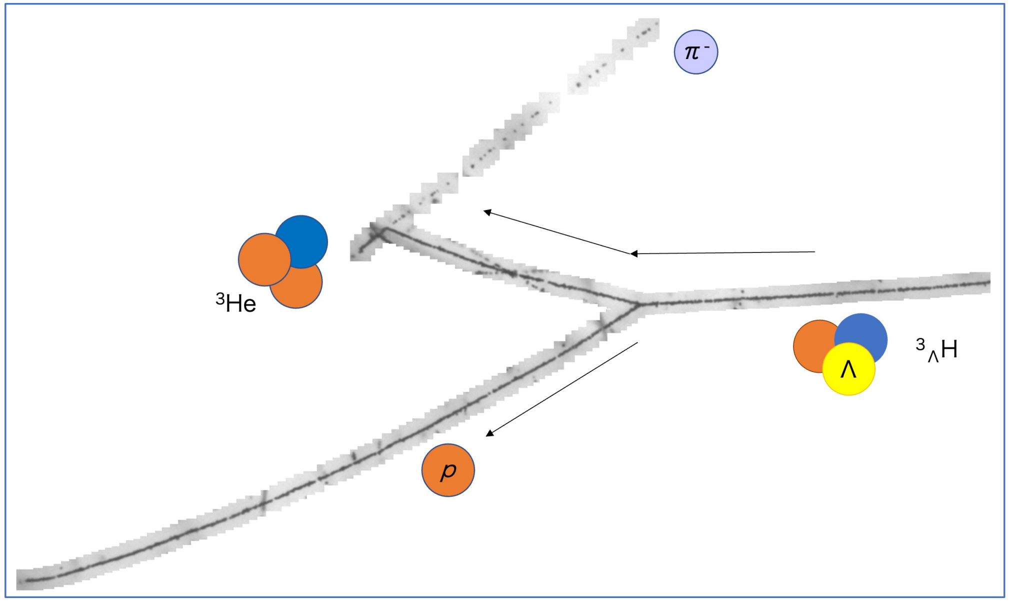
Preliminary

Yan He, et al.,
to be published

Hypernuclear scattering



$^4{}_\Lambda$H scattering



$^3{}_\Lambda$H scattering

Nuclear Emulsion + Machine Learning Collaboration

W. Dou[a,b], V. Drozd[a,c,d], H. Ekawa[a], S. Escrig[a,e], Y. Gao[a,f,g], Y. He[a,h], A. Kasagi[a,i,j], E. Liu[a,f,g], A. Muneem[a,k], M. Nakagawa[a], K. Nakazawa[a,i,l], C. Rappold[e], N. Saito[a], T.R. Saito[a,d,h], S. Sugimoto[a,b], M. Taki[j], Y.K. Tanaka[a], A. Yanai[a,b], J. Yoshida[a,m], M. Yoshimoto[n], and H. Wang[a]

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[d] GSI Helmholtz Centre for Heavy Ion Research, Germany
[e] Instituto de Estructura de la Materia, Spain
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[i] Graduate School of Engineering, Gifu University, Japan
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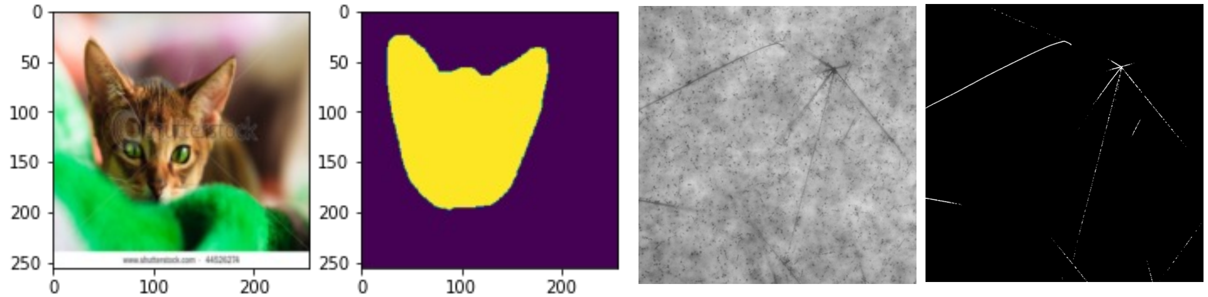
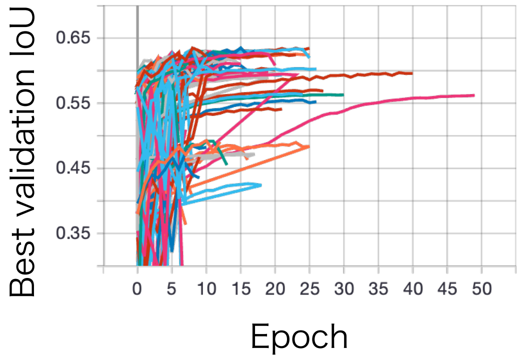
[k] Faculty of Engineering Sciences, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan
[l] Faculty of Education, Gifu University, Japan
[m] Department of physics, Tohoku University, Japan
[n] RIKEN Nishina Center, RIKEN, Japan

Segmentation task to detect hit infomation

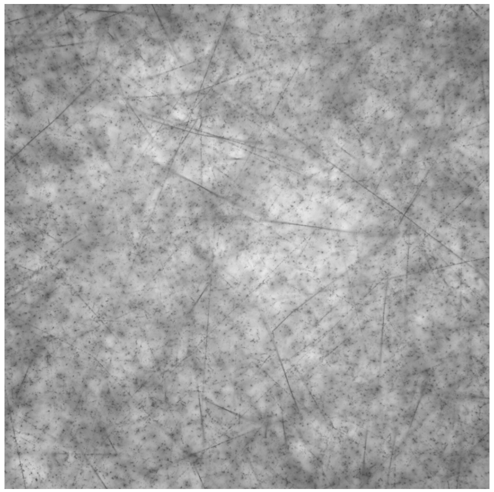
- Binary segmentation (background or track)
- Training from scratch (with 40k surrogate images)



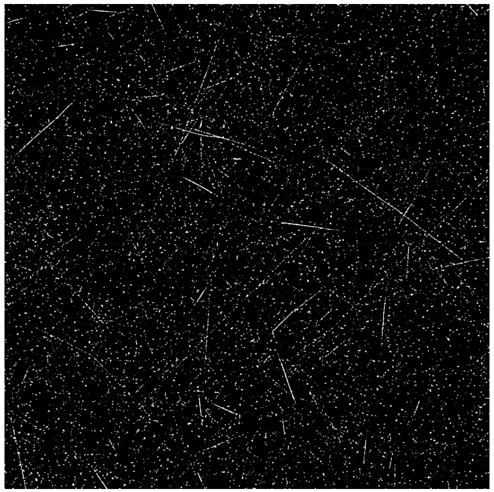
Hyperparameter search with Optuna



IoU	0.659
F1_score	0.795
Accuracy	0.998
Precision	0.748
Recall	0.805



Raw data



Conventional processing

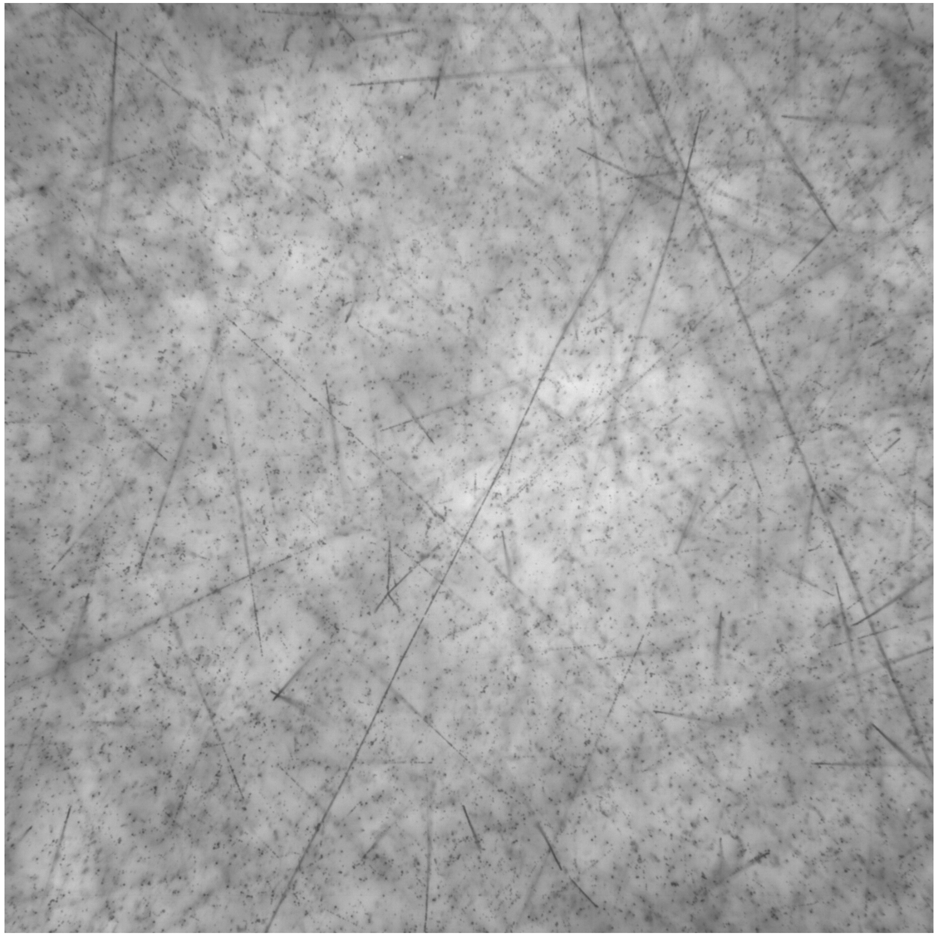
Present work

- Noise reduction
- Datasize: 1/200

→ E07 image data
140 PB -> 750 TB

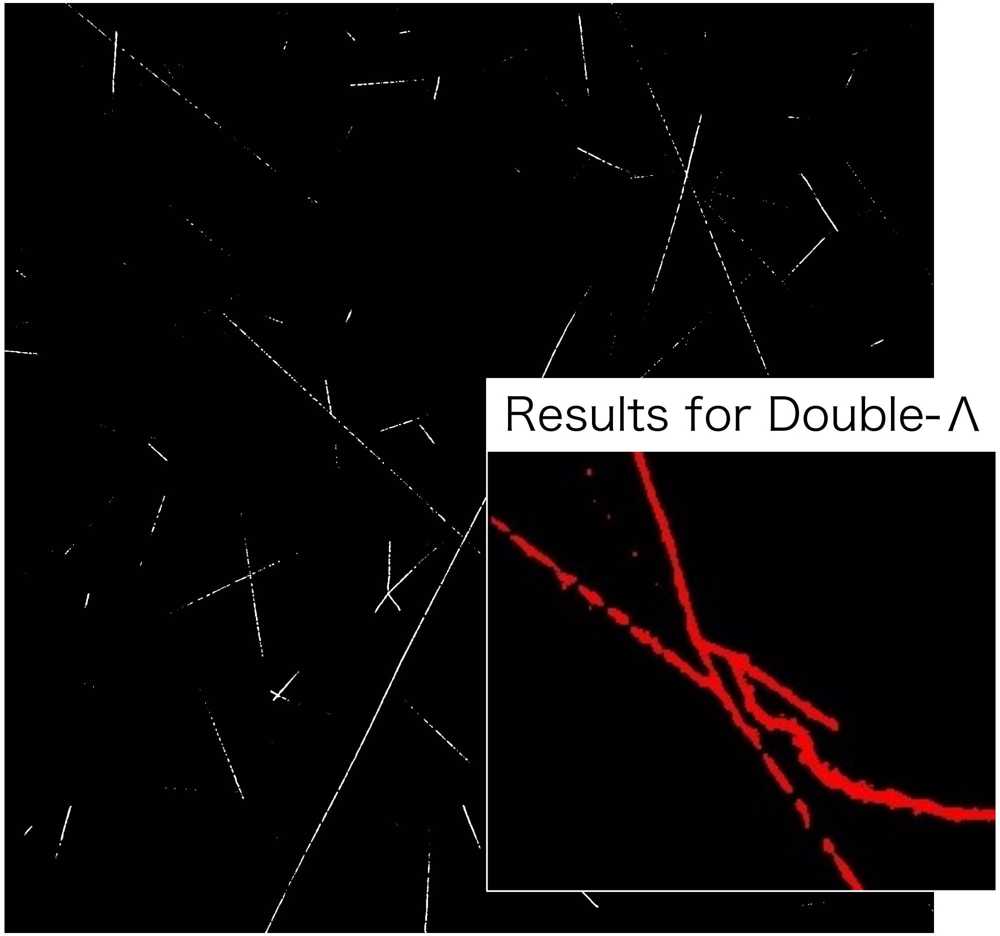
Segmentation task to detect hit infomation

Raw data: 200 MB



100 μm

Segmentation: 1MB

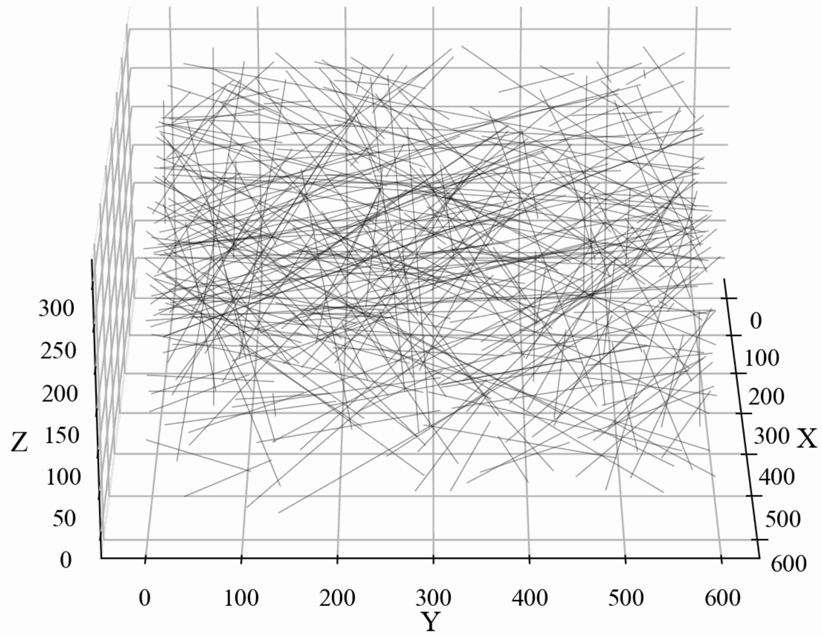


Kasagi, Nakazawa, Rappold, Shimizu, Yokota, to be published

Reconstruction of track

Gabor filter & Connected Components

3D track reconstruction



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

Kasagi, Nakazawa, Rappold, Shimizu, Yokota, to be published

New proposal at KLF/JLab

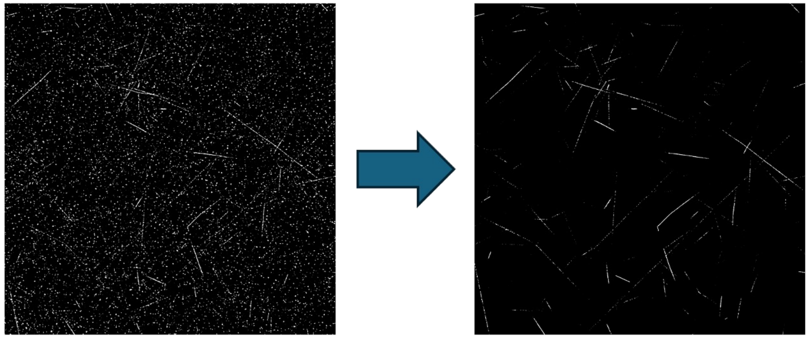
Neutral-K beams behind the Glue-X setup

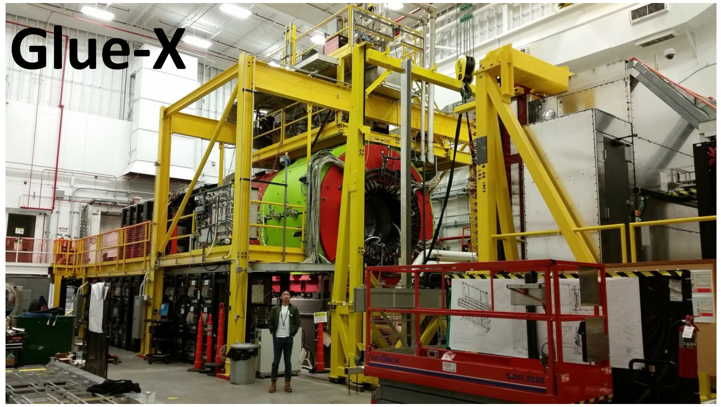
Hypernuclear station behind the Glue-X

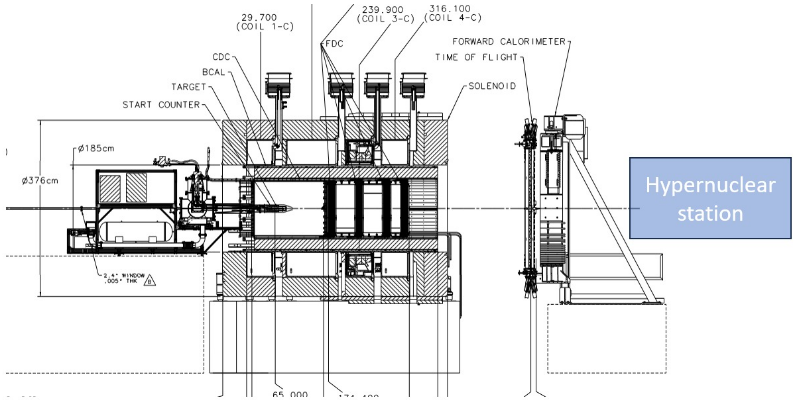
- **No beam tracks in the emulsion**
  - We can leave emulsions, no movement
  - Main background: high energy gamma-rays

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

With K^0 beams
In the proposed project







- Intensity: 0.7 X 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 (Al_2O_3:C,Mg)
- Used for neutron imaging
- Recyclable

New prc

Neutral-K bea

Hypernuclear

- **No beam tra**
  - We can l
  - Main bac

With K⁻ beams
like in the J-PA

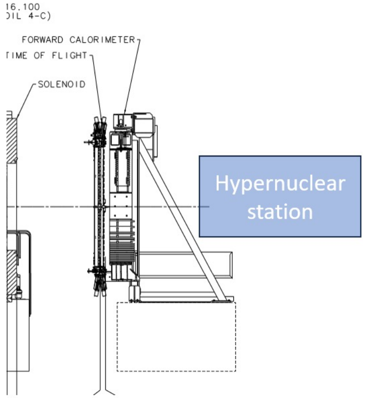
- Intensity: 0.
  - Two year
  - **2.3 time hypernu**

The Hypernuclear station at KLF (Technical Note)

M. Bashkanov*
Department of Physics, University of York, Heslington, York, Y010 5DD, UK

T.R. Saito†
High Energy Nuclear Physics Laboratory, RIKEN, Japan

(Dated: August 19, 2024)



D (Al_2O_3:C,Mg)
sed for neutron
aging
ecyclable