New Approaches to Light Hypernuclei with Heavy Ion Beams, Image Analyses and Machine Learning

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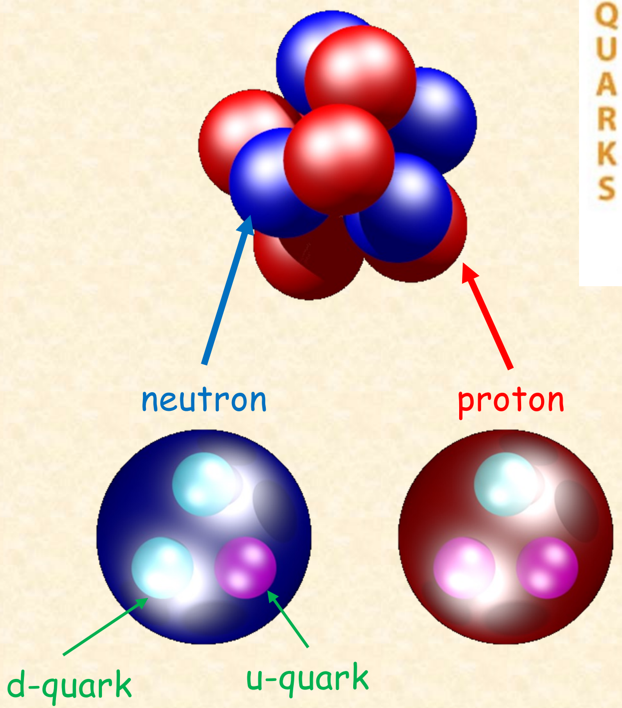
The 14th International Conference on Nucleus Nucleus Collisions (NN2024), Whistler, British Columbia, Canada, 18th – 23rd August, 2024

Quarks and sub-atomic nuclei

Sub-atomic nucleus



Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

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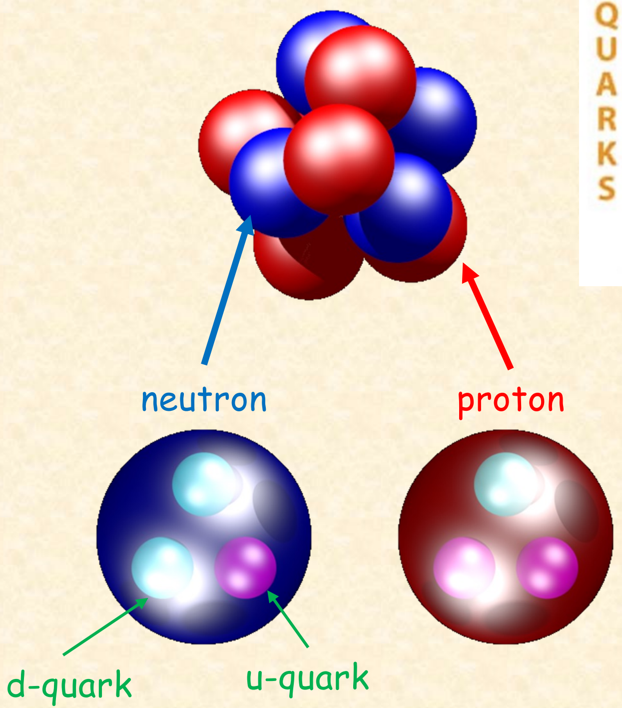

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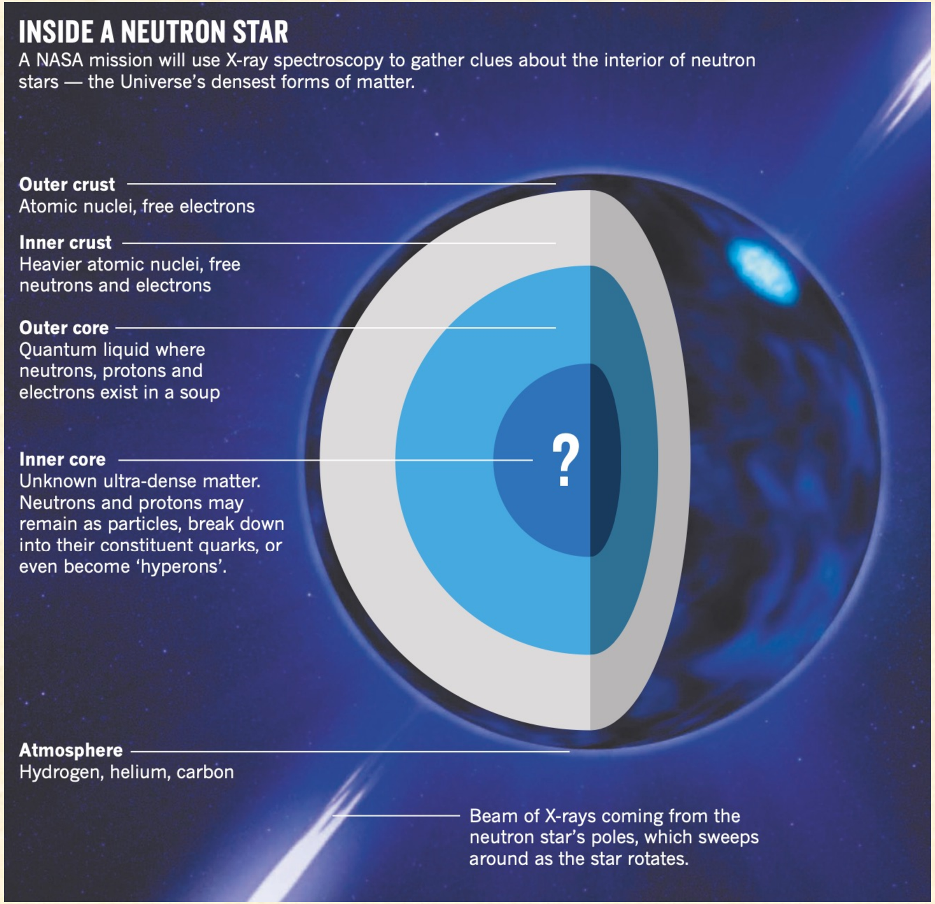
hyperon (Λ)

Lifetime: 10^{-10} s

s-quark: distinguishable from u- and d-quarks



Nature volume 56, page 18 (2017)

Quarks and sub-atomic nuclei

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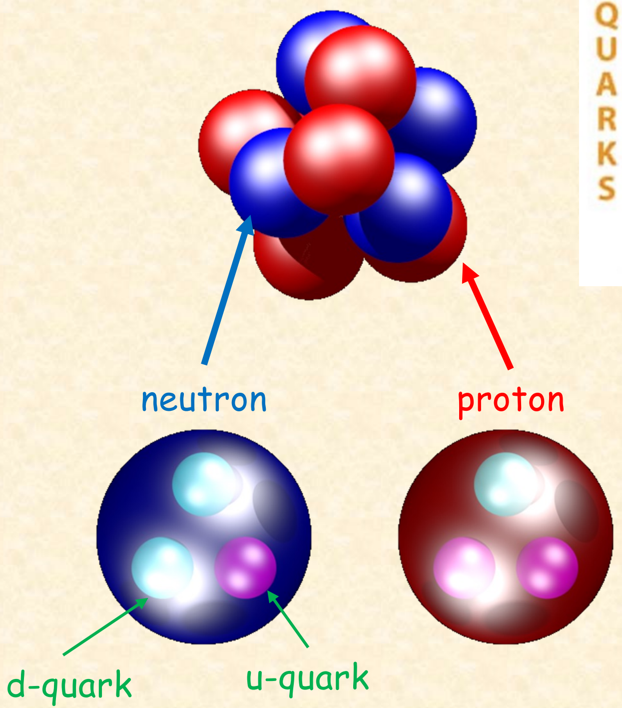

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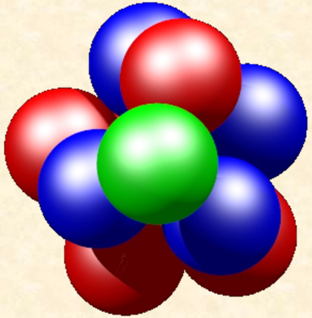
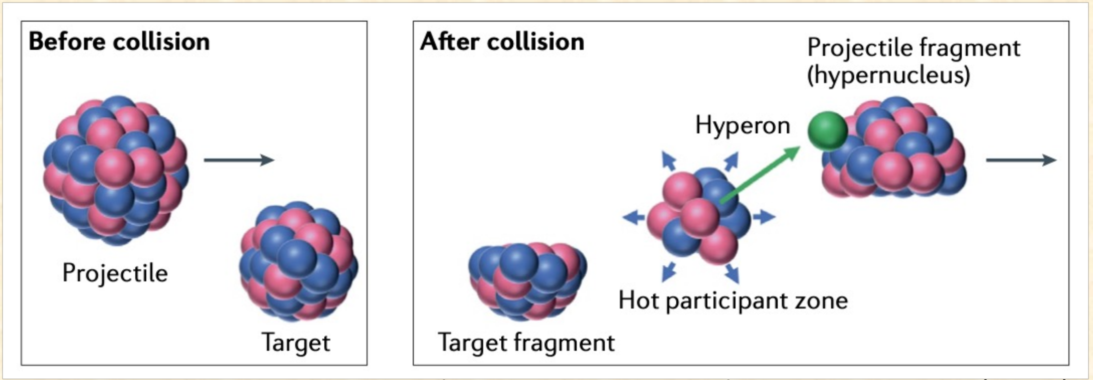
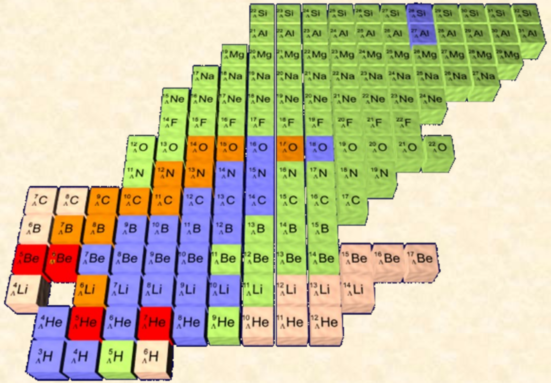


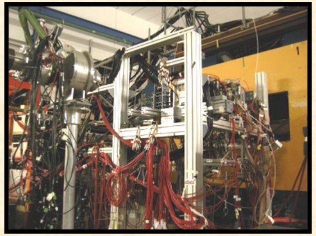
Micro-laboratory to study baryonic-interactions

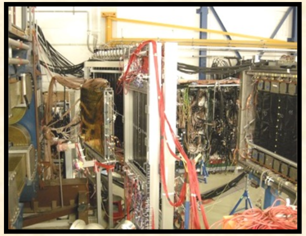
The HypHI Phase 0 at GSI (2006-2012)

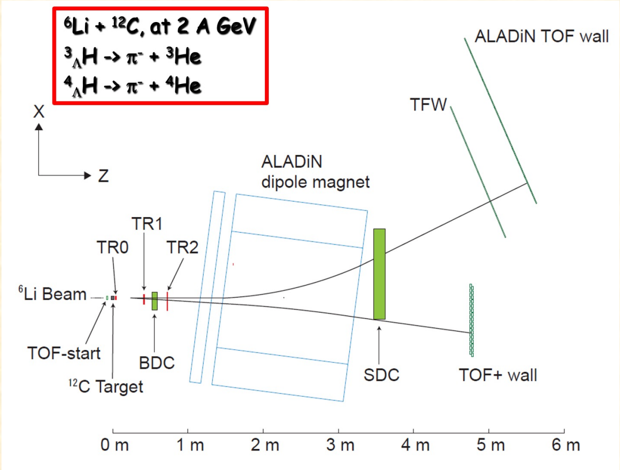


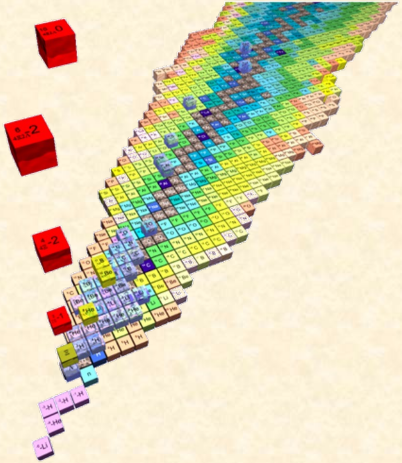
TRS et al., Nature Reviews Physics 3, 803-813 (2021)











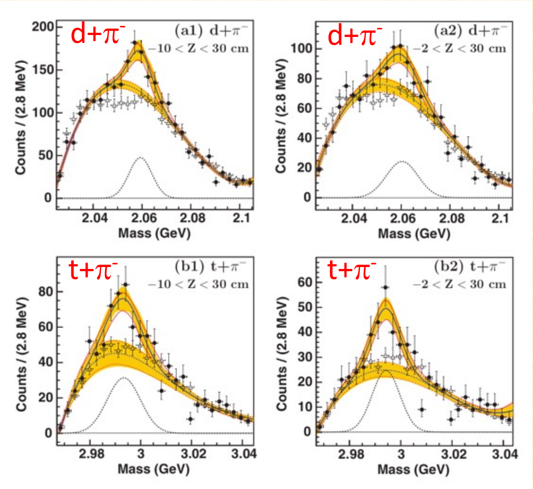
Two outcomes (mysteries) by HypHI

Signals indicating nnΛ 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

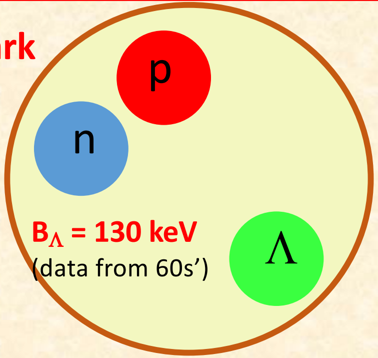


C. Rappold et al., PRC 88 (2013) 041001

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

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

Benchmark



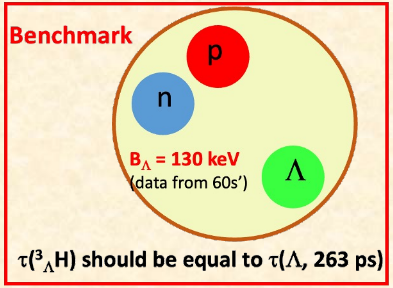
$\tau(^3_\Lambda$H) should be equal to $\tau(\Lambda$, 263 ps)

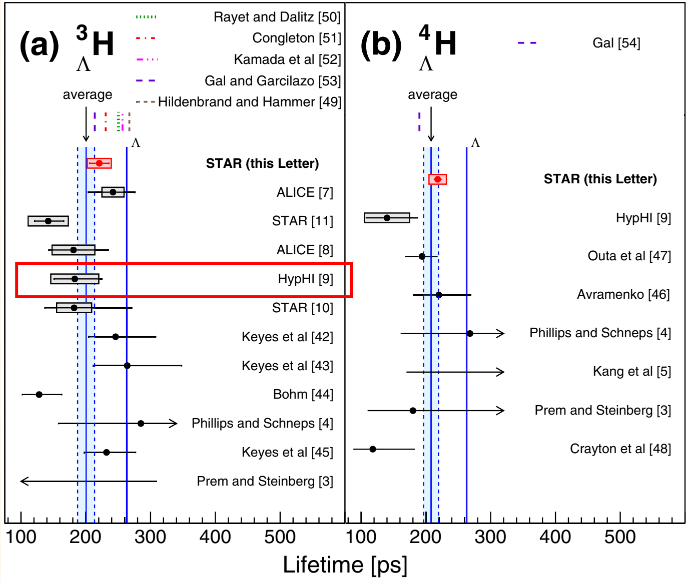
Stimulated other **big** experiments

The world situation of three-body hypernuclei

On hypertriton

Average
200 ± 13 ps





STAR Collaboration, PRL **128** (2022) 202301

On Λnn

$^3_\Lambda$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

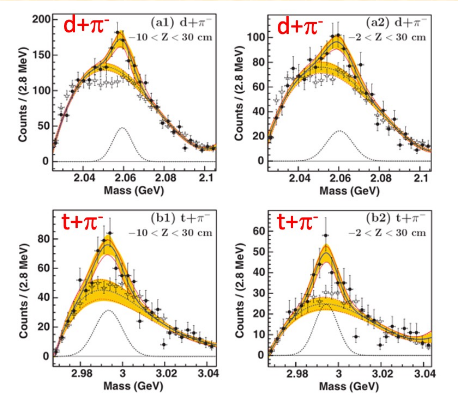
STAR Collaboration,

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

ALICE

0.102 ± 0.063 ± 0.067 MeV

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



HypHI., PRC 88 (2013) 041001

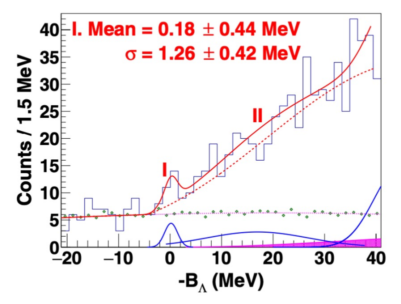


FIG. 5. The enlarged mass spectrum around the Λnn threshold. Two additional Gaussians were fitted together with the known contributions (the accidentals, the Λ quasifree, the free Λ, and the ^{3}He contamination). The one at the threshold is for the small peak, while the broad one is for the additional strength above the predicted quasifree distribution.

JLab E12-17-003., PRC 105 (2022) L051001

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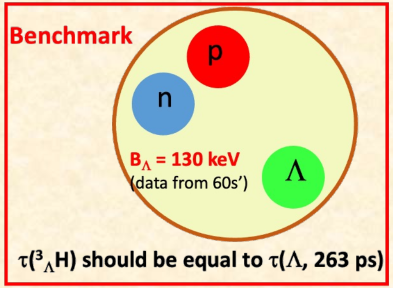

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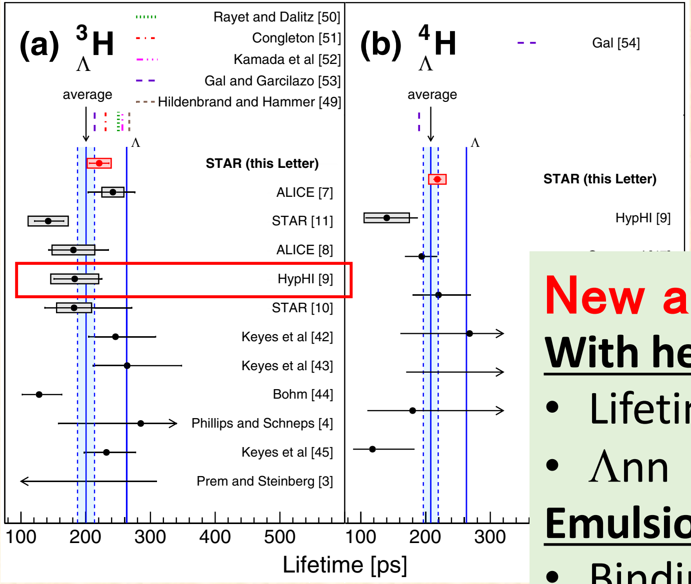

STAR Collaboration, PRL **128** (2022) 2023…

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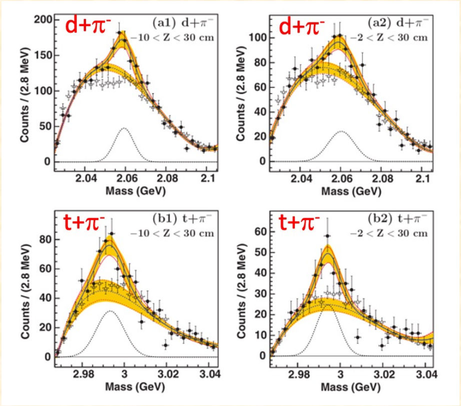

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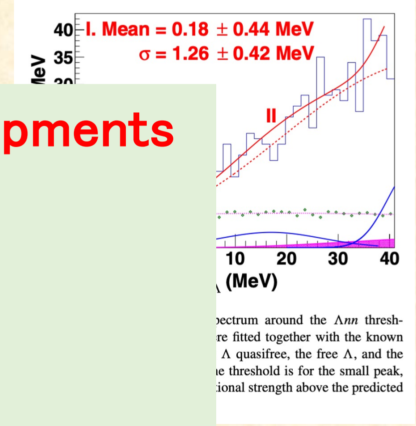


…, PRC 105 (2022) L051001

New approaches with new developments

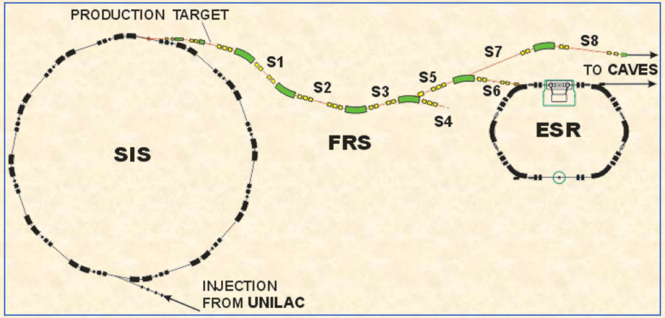
With heavy ion beams:

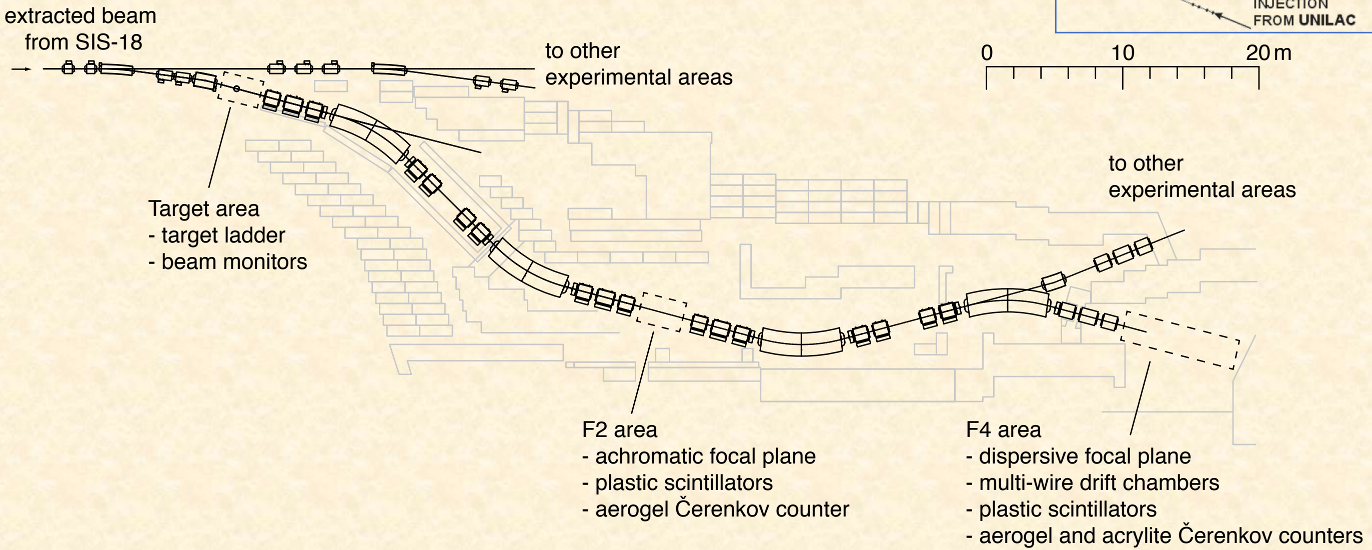
- Lifetime
- Λnn

Emulsion + Machine Learning

- Binding energy

The novel technique with FRS at GSI (2016-)





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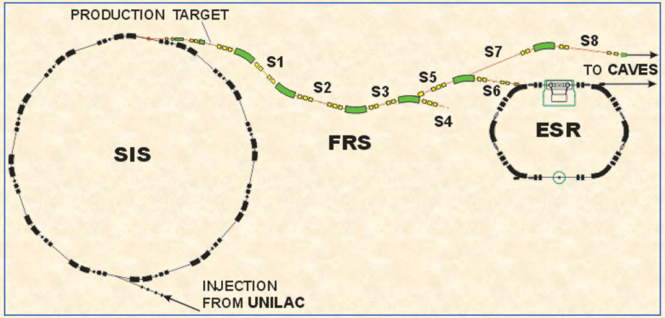

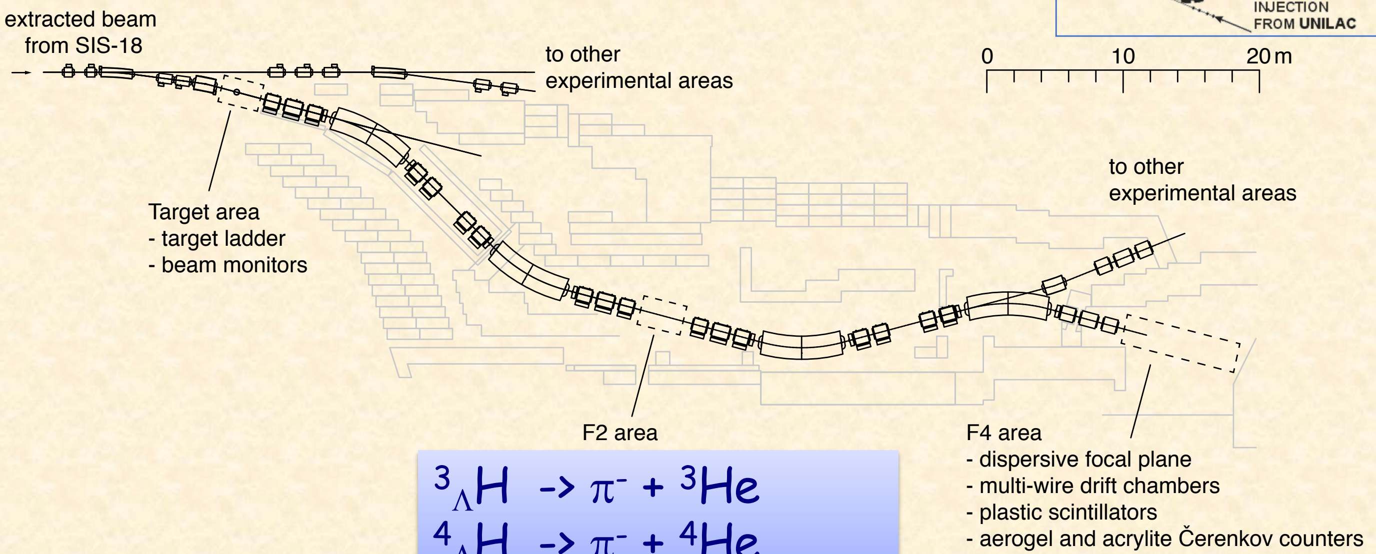

$^{3}_{\Lambda}H \rightarrow \pi^- + {}^{3}He$

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

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

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

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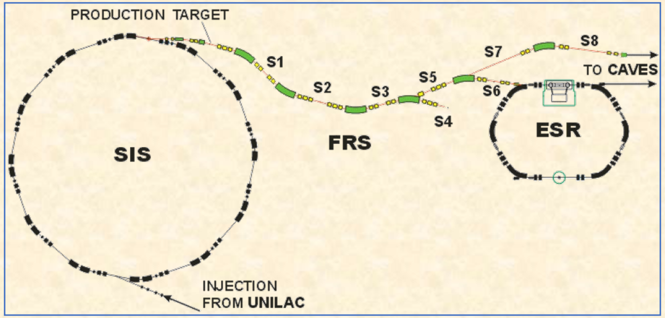

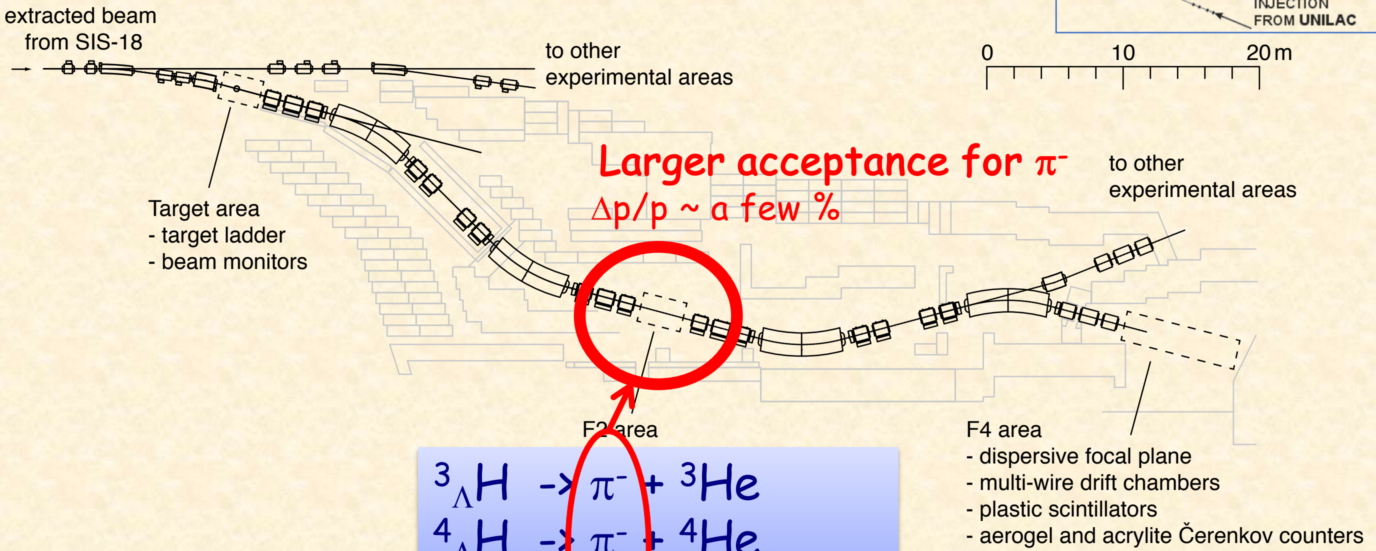

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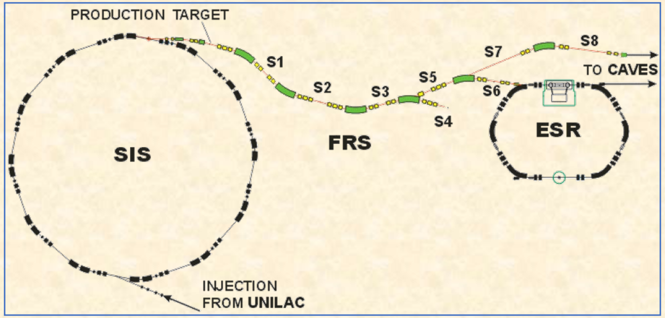

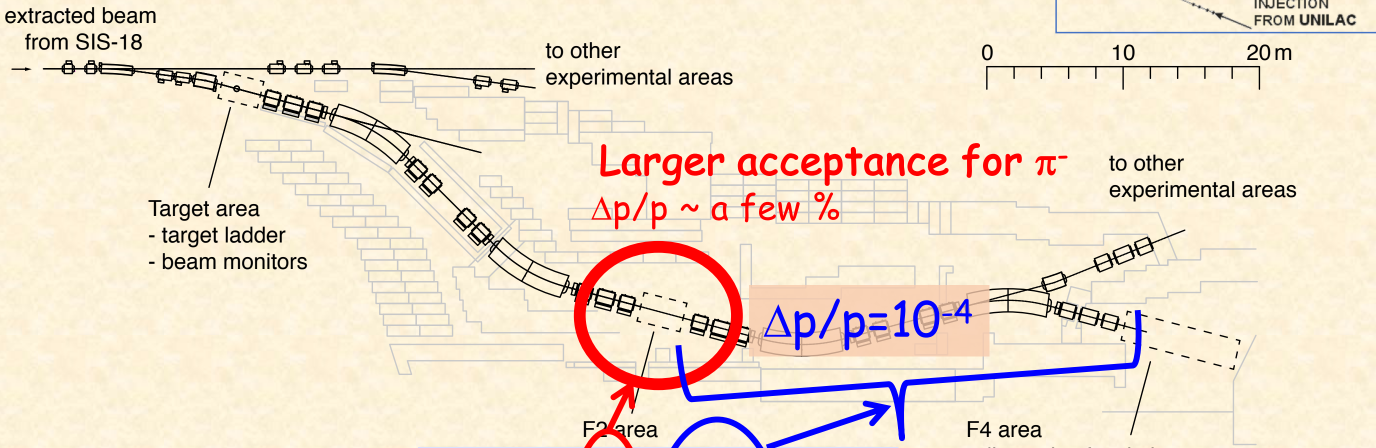

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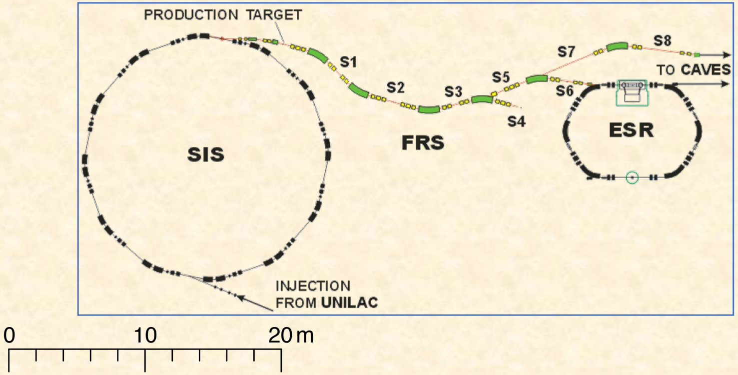

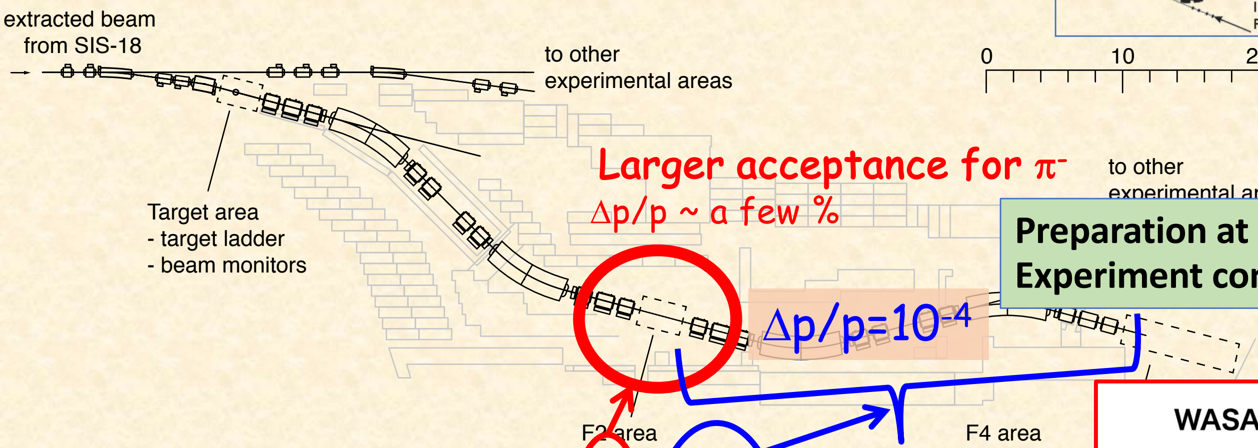

Preparation at GSI started in March 2019
Experiment conducted in January-March 2022

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$^{4}_{\Lambda}\mathrm{H}$ -> π^{-} + $^{4}\mathrm{He}$
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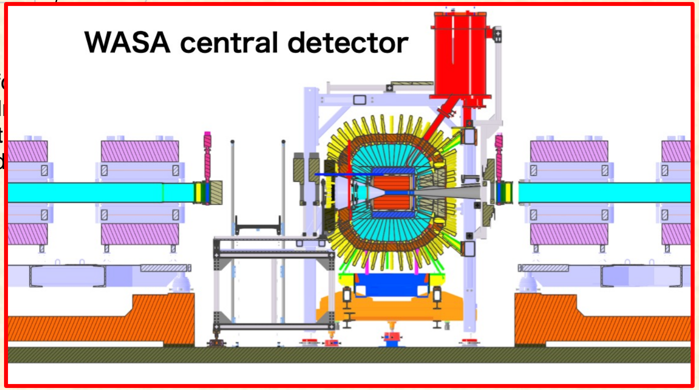
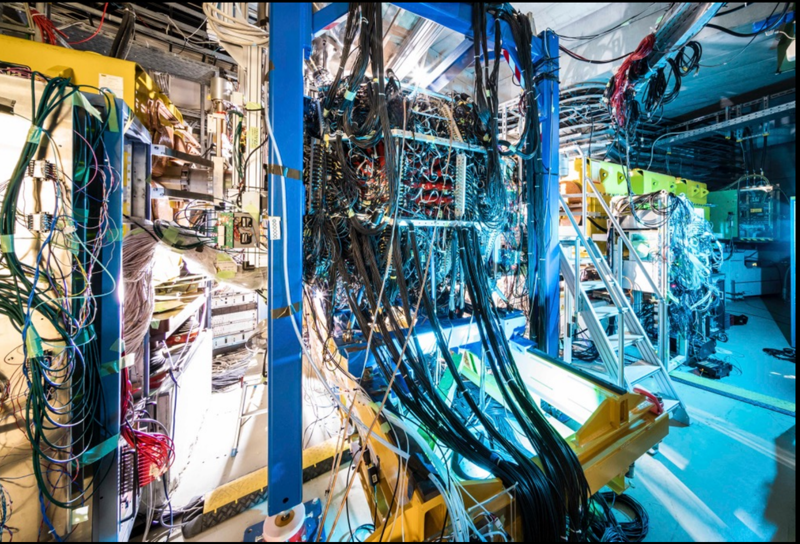
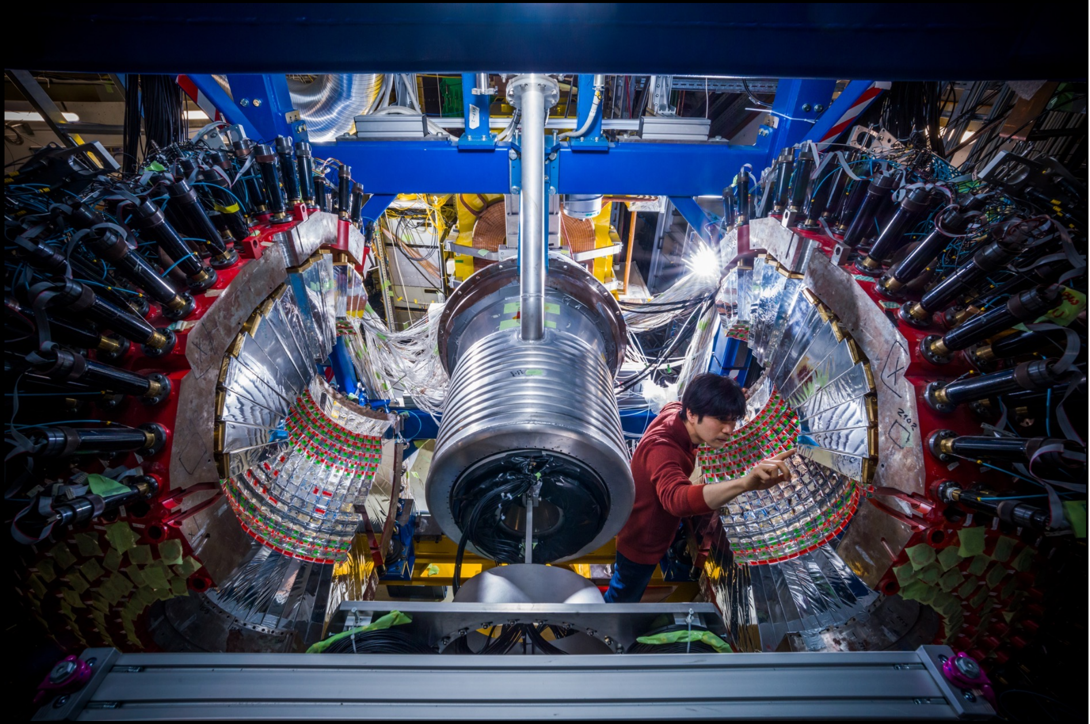
With $^{6}\mathrm{Li}+^{12}\mathrm{C}$ at 2 A GeV







Photos by Jan Hosan and GSI/FAIR

The International WASA-FRS collaboration

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[e]Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany,
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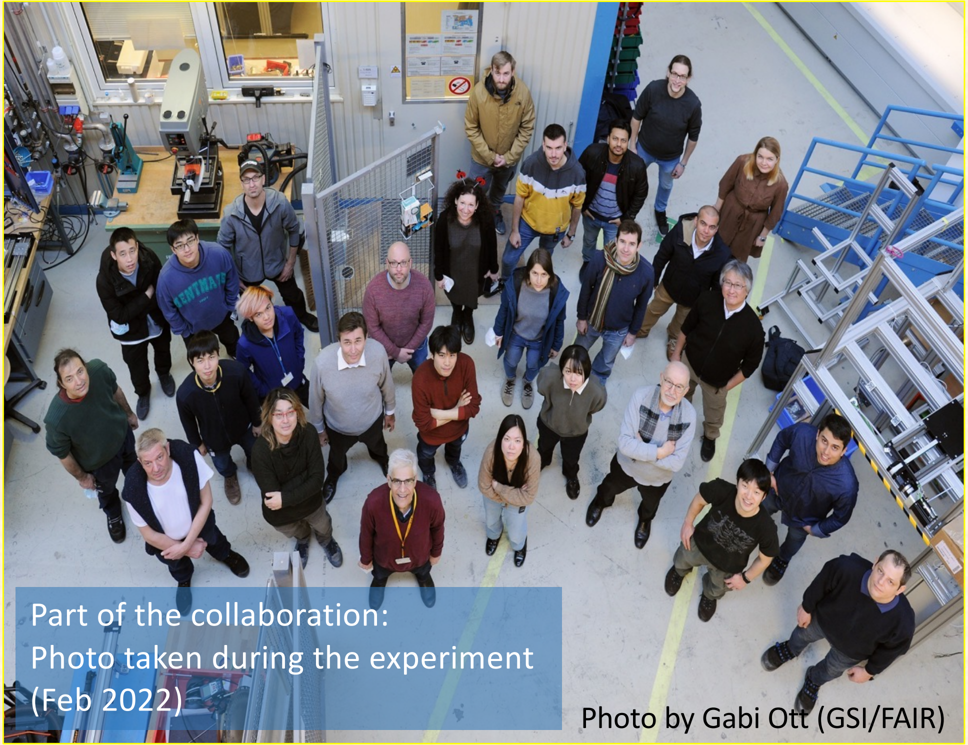
Author list of the EMIS2022 proceedings



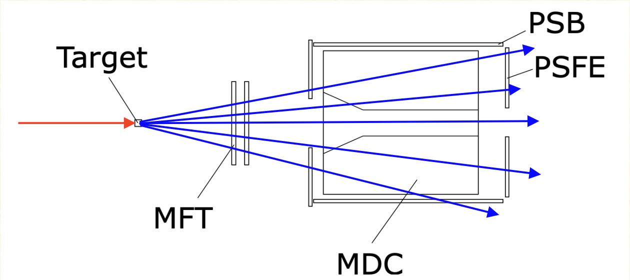
Part of the collaboration:
Photo taken during the experiment
(Feb 2022)

Photo by Gabi Ott (GSI/FAIR)

Collaboration of hypernuclear physicists and low-energy nuclear physicists

Graph Neural Network (GNN) for WASA

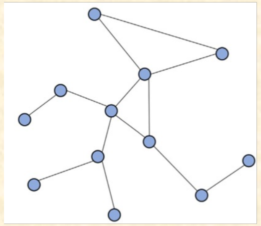
Track Finding

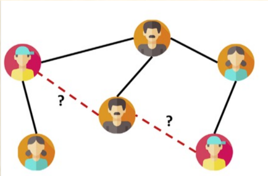


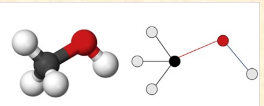
- Multi particles in HI reaction
- Combinatorial background

Track Finding with Graph Neural Network (GNN)

Graph

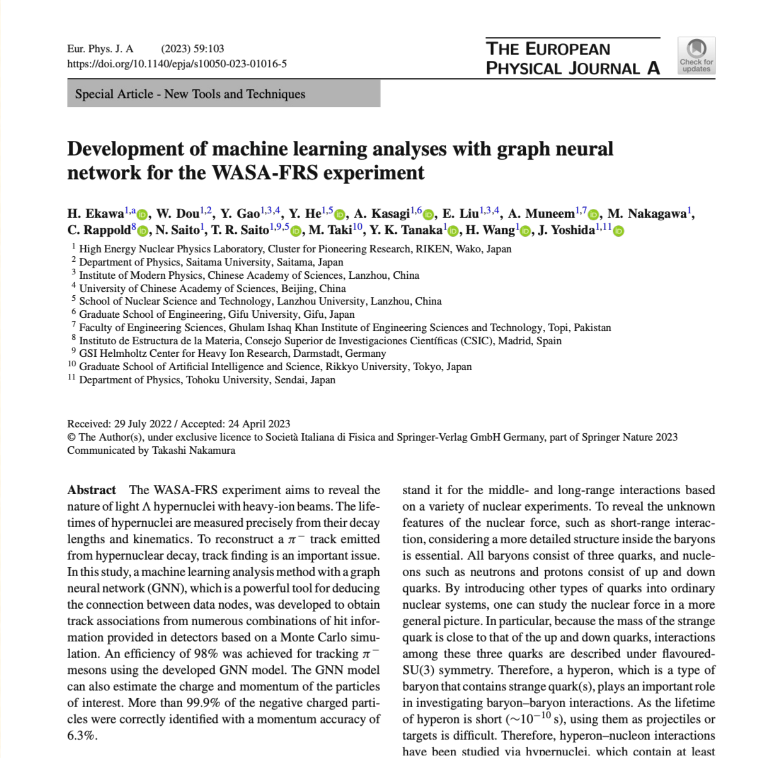



(e) Social Network


(b) Molecule

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

- Node : Data point
- Edge : Connection



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

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]

[1] High Energy Nuclear Physics Laboratory, Cluster for Pioneering Research, RIKEN, Wako, Japan
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[3] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
[4] University of Chinese Academy of Sciences, Beijing, China
[5] School of Nuclear Science and Technology, Lanzhou University, Lanzhou, China
[6] Graduate School of Engineering, Gifu University, Gifu, Japan
[7] Faculty of Engineering Sciences, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Pakistan
[8] Instituto de Estructura de la Materia, Consejo Superior de Investigaciones Científicas (CSIC), Madrid, Spain
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[10] Graduate School of Artificial Intelligence and Science, Rikkyo University, Tokyo, Japan
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Received: 29 July 2022 / Accepted: 24 April 2023

Communicated by Takashi Nakamura

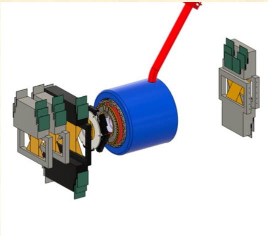
Abstract The WASA-FRS experiment aims to reveal the nature of light Λ hypernuclei with heavy-ion beams. The lifetimes of hypernuclei are measured precisely from their decay lengths and kinematics. To reconstruct a π^- track emitted from hypernuclear decay, track finding is an important issue. In this 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 (~10^{-10} s), using them as projectiles or targets is difficult. Therefore, hyperon–nucleon interactions have been studied via hypernuclei, which contain at least

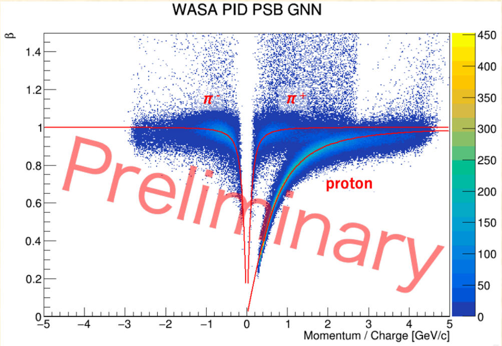
Published in EPJA

H. Ekawa et al., Eur. Phys. J. A (2023) **59**, 103
DOI : 10.1140/epja/s10050-023-01016-5

Data analyses with the GNN

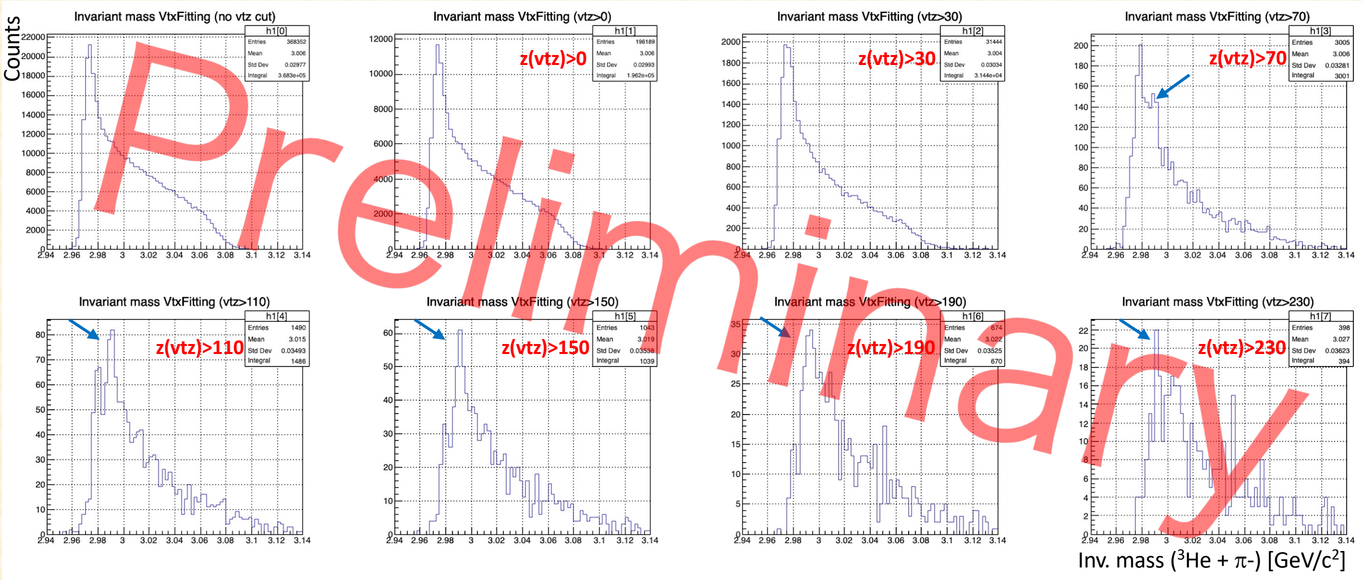


Only **partial data** with
- T0
- Fiber detectors
- MDC
- PSB
- FRS



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

- With vertex fitting, chi2 < 20
- Beam tracking with the T0 hodoscope and two fiber stations



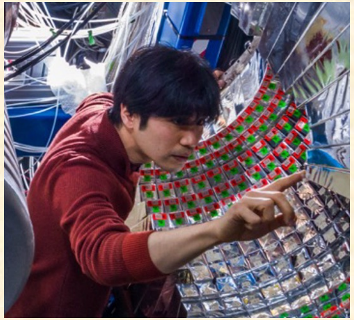
Analysis by
H. Ekawa (RIKEN)
Y. Gao (RIKEN/IMP)
A. Yanai (RIKEN/Saitama U)

Prof. Dr. Dr. h.c. Hans Geissel and the FRS

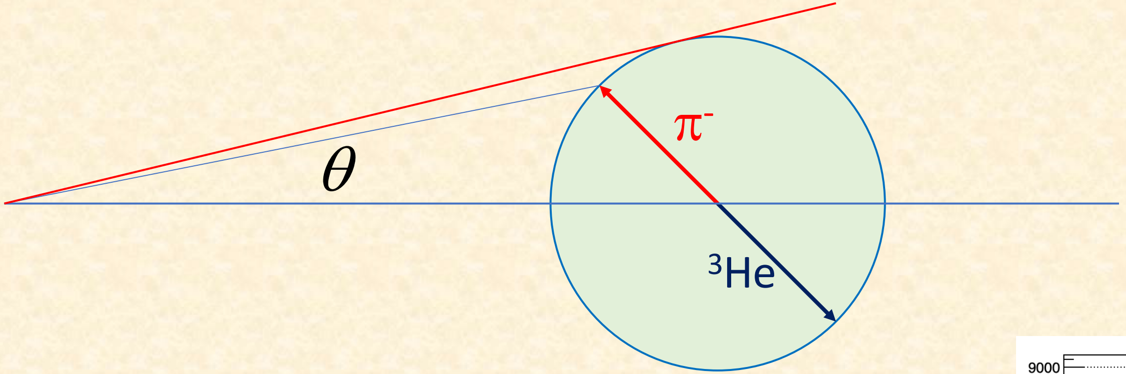
May 13th 1953 – April 29th 2024 (age of 73)

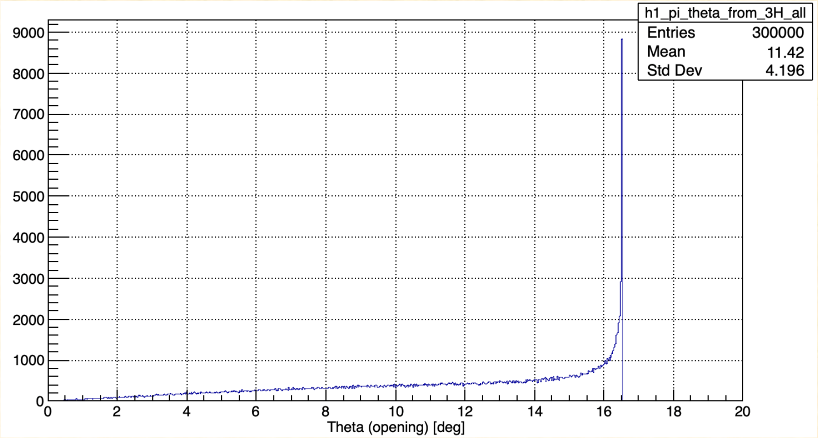
- **The father of the FRS**
- Played a pioneering role for the science programs at GSI
- Fostered many young people

  Including Yoshiki Tanaka



Novel approach to the B.E. with the FRS





Y. Tanaka (RIKEN)
H. Ekawa (RIKEN)
TRS

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

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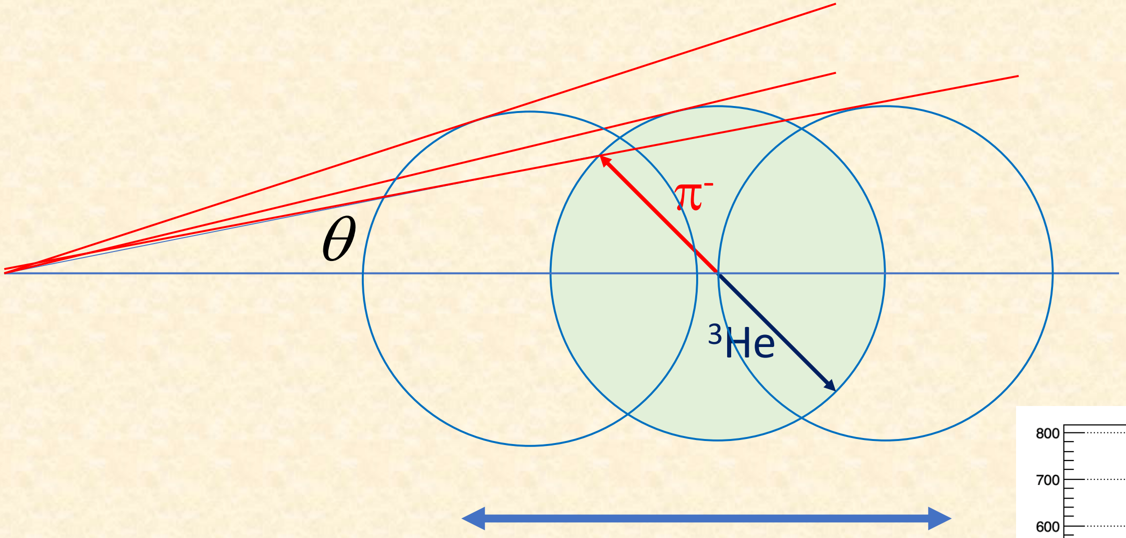
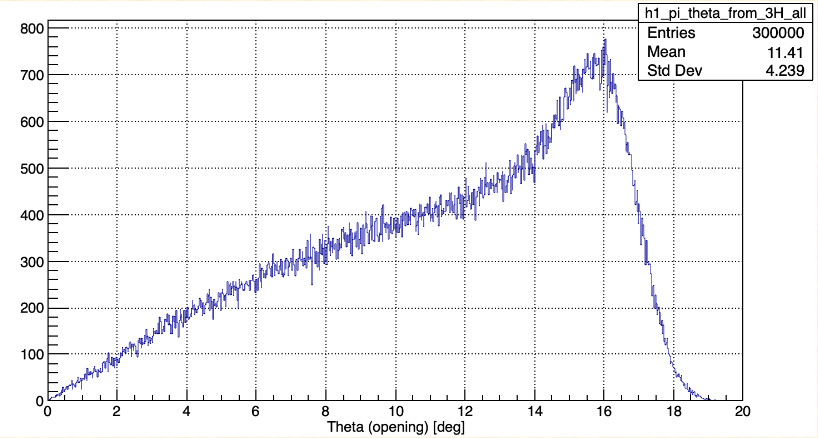


Momentum spread of produced hypertriton (5 % in Bρ)



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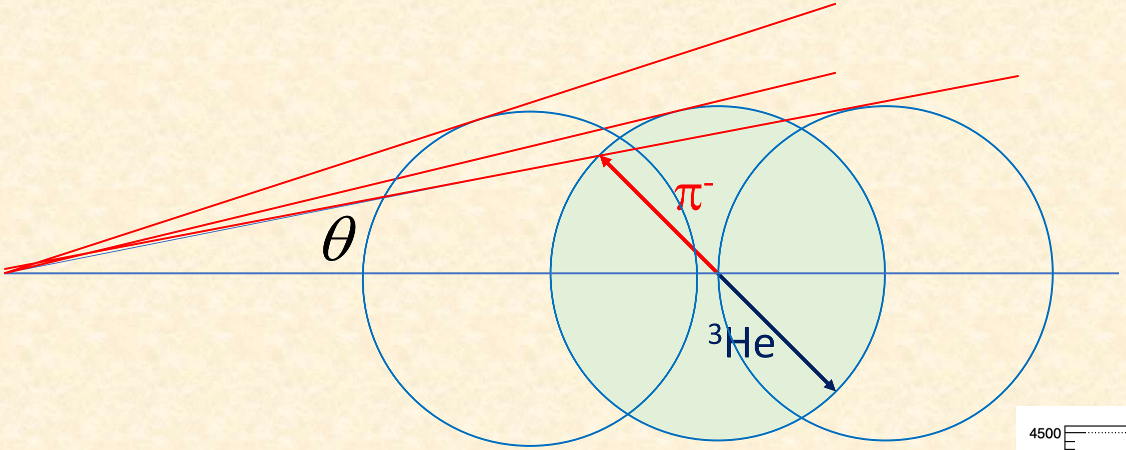
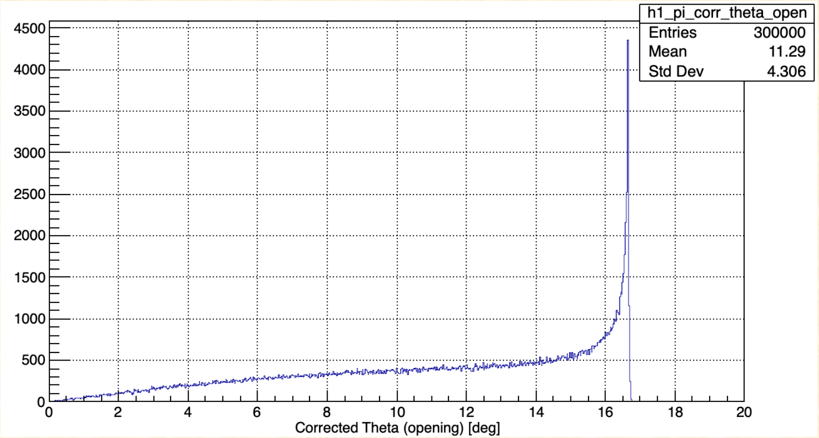


Momentum spread of produced hypertriton (5 % in Bρ)

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

Δp/P (FRS) = 5×10^{-4}

β -> 0.95



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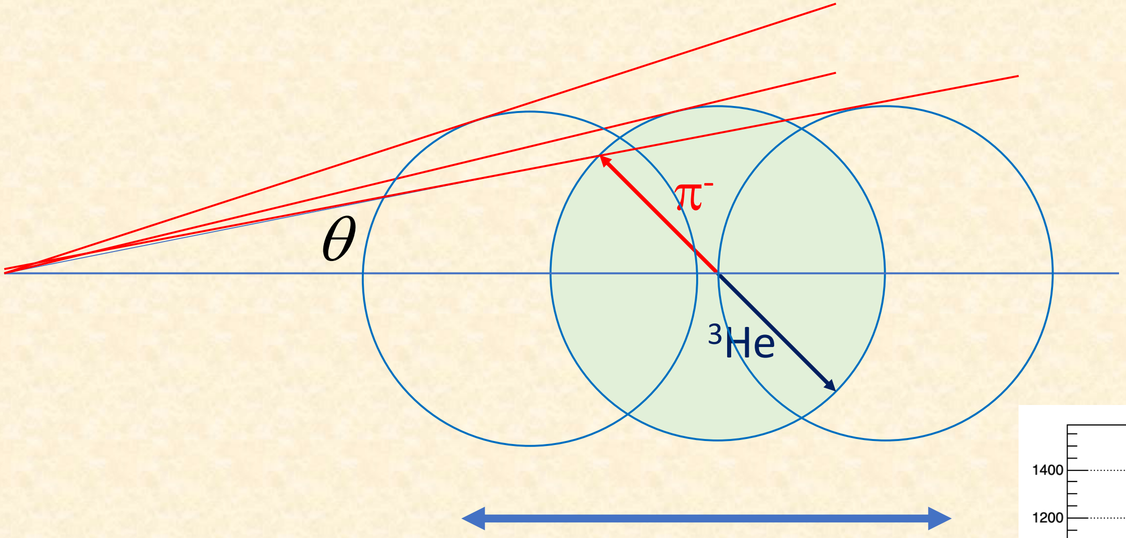

Momentum spread of produced hypertriton (5 % in Bρ)

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Δp/P (FRS) = 5x10^{-4}

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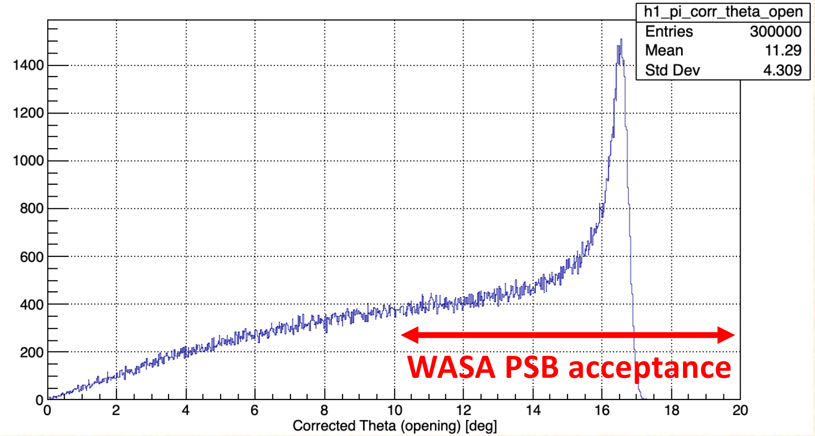
Angular res. (WASA) = 3 m rad



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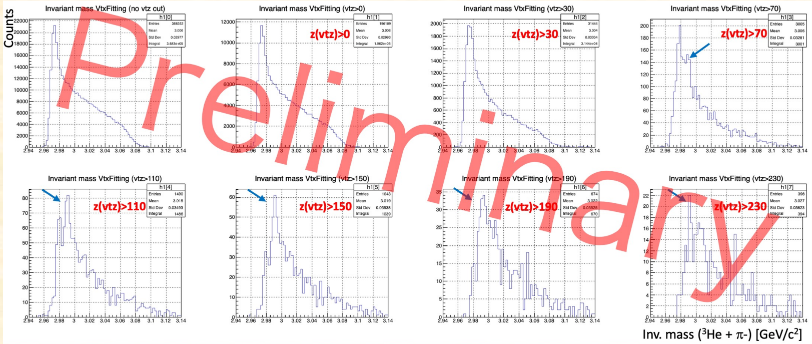
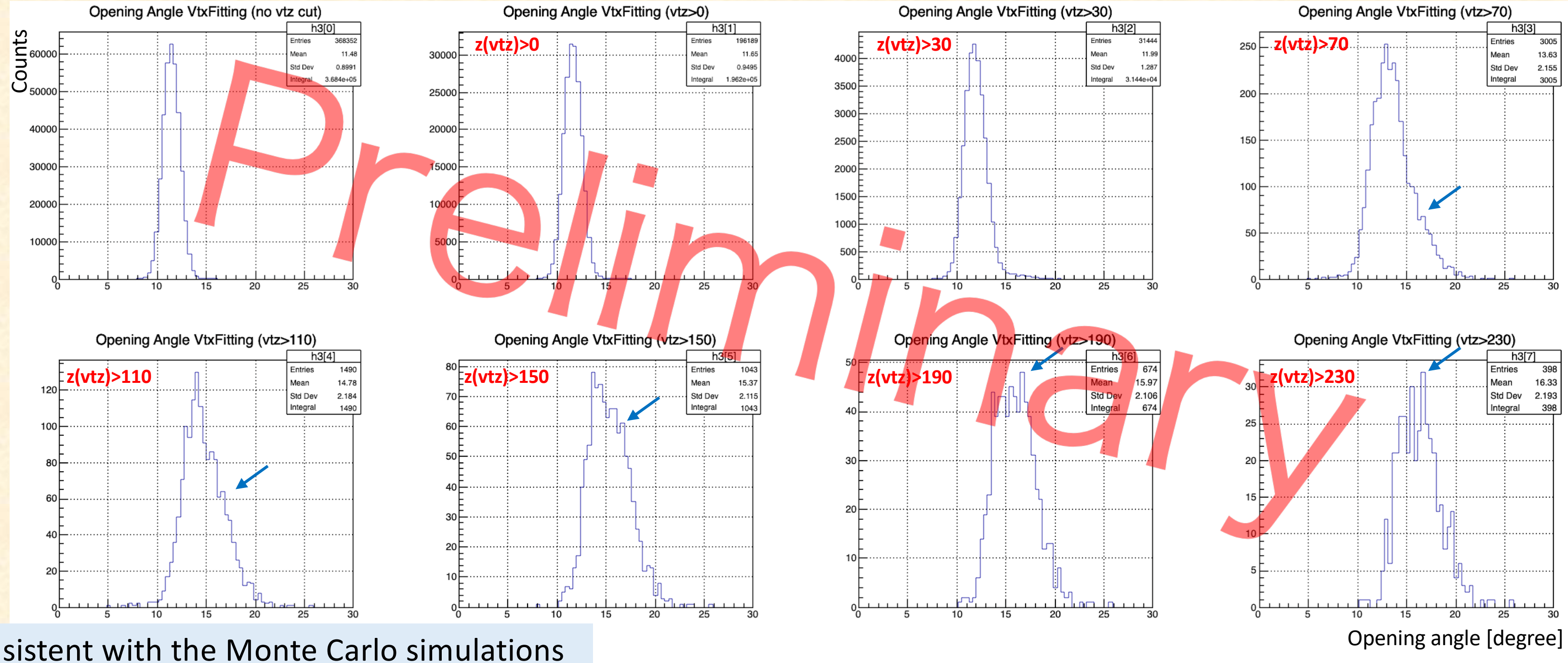
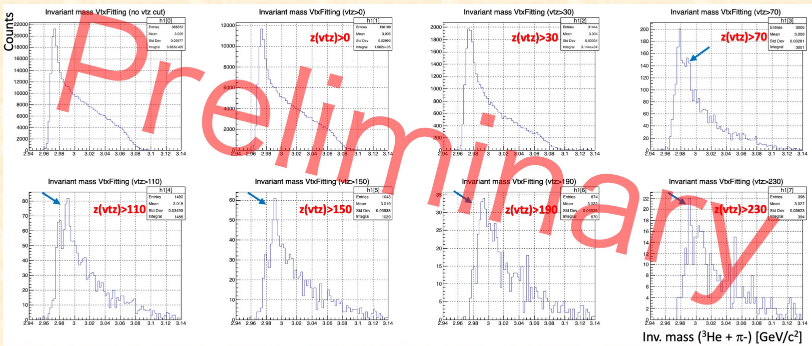


With the WASA-FRS data

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



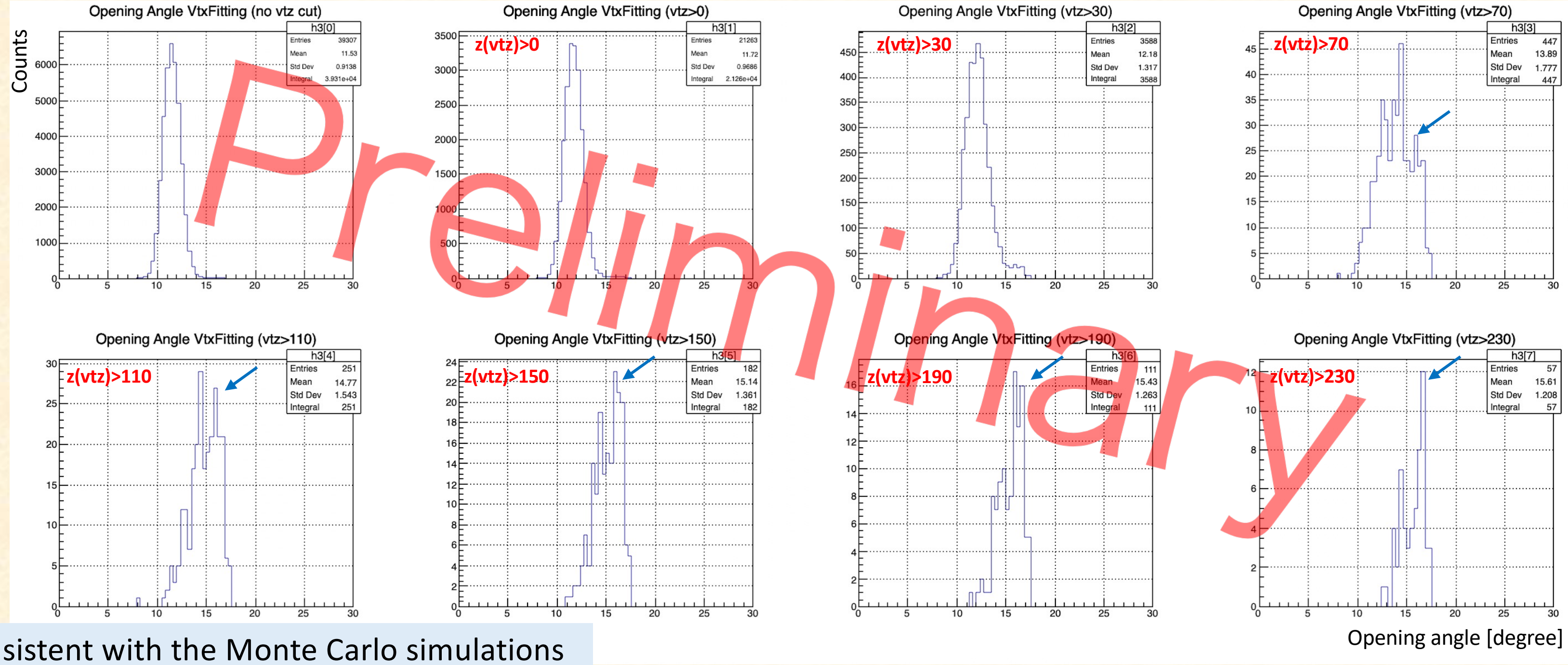
Consistent with the Monte Carlo simulations



With the WASA-FRS data

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

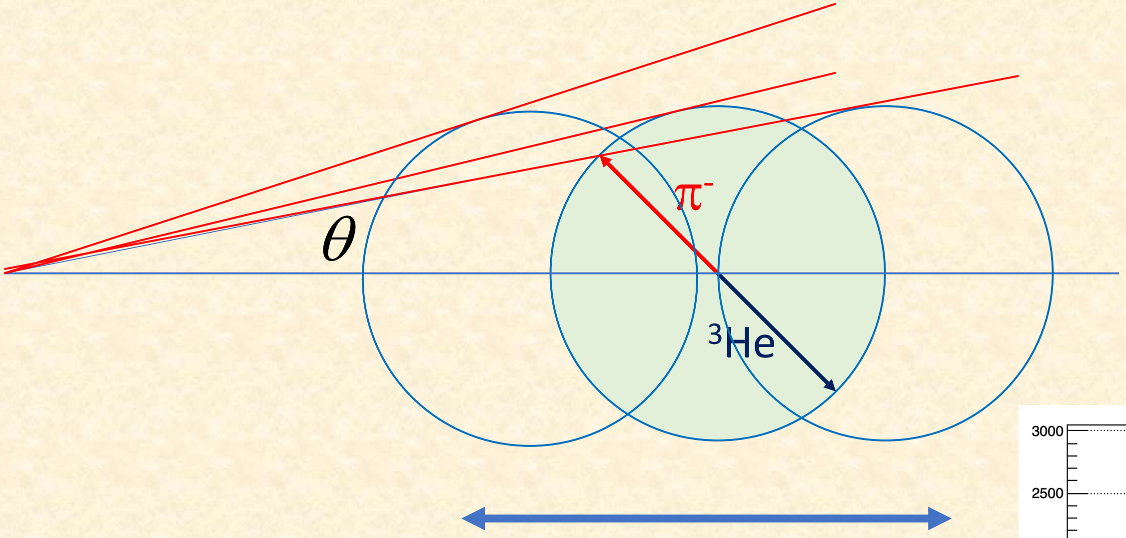
In the mass peak region (2.987 - 2.996 GeV)



Consistent with the Monte Carlo simulations

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



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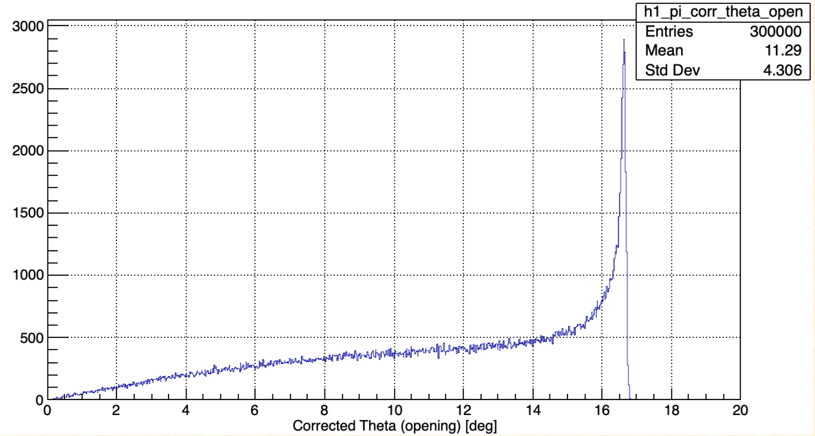
Angular res. = 0.7 m rad

Si detector at R3B/FAIR



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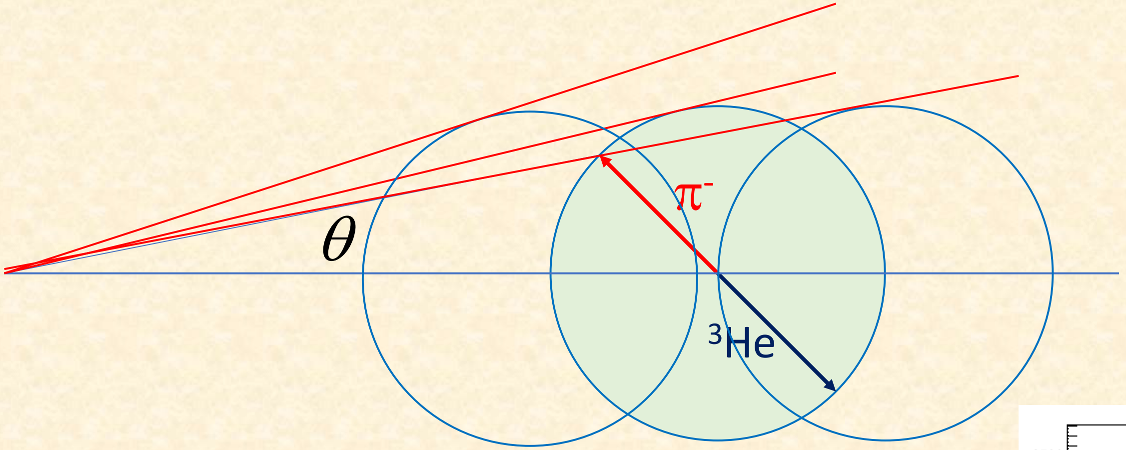

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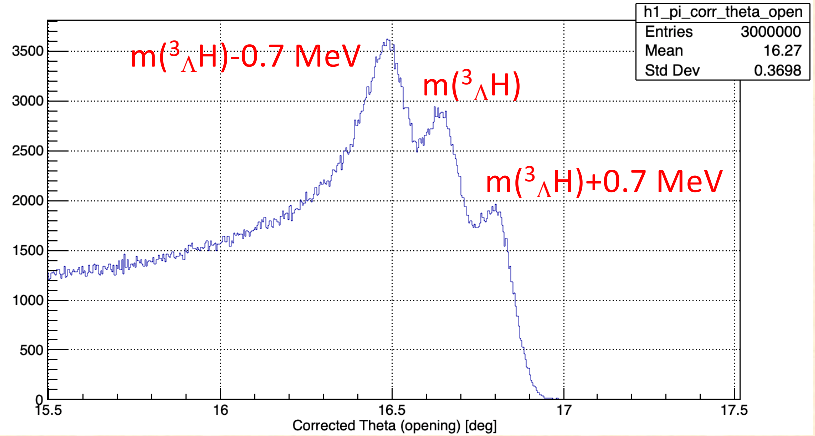

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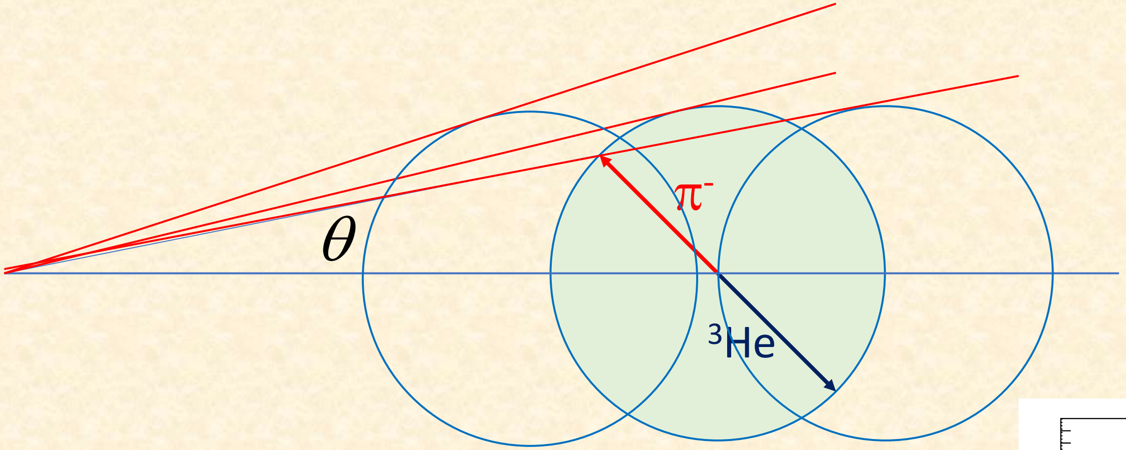


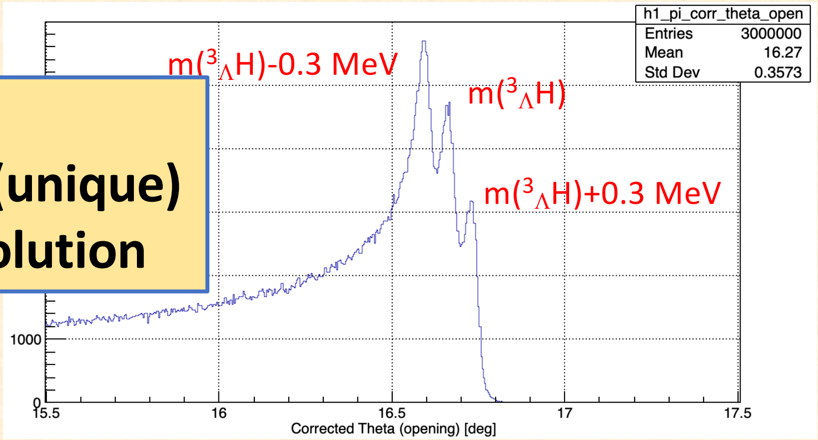
Assuming that the momentum of the hypertriton is the same to the ^{3}He decay residues

$\Delta p/P$ (FRS) = 5×10^{-4}

β -> 0.95

Angular res. = 0.1 m rad

Future possibility at R3B/FAIR



Y. Tanaka (RIKEN)
H. Ekawa (RIKEN)
TRS

For the precise mass measurements

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

Ideas based on Ivan Mukha et al,
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Our challenges on Hypernuclei

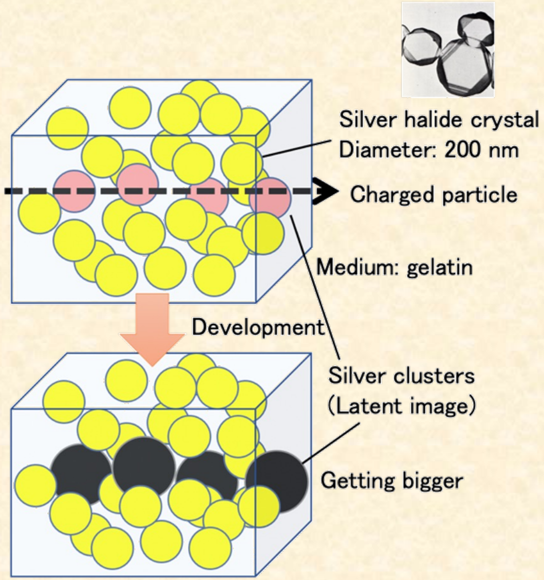
with <u>image analyses</u>
and
<u>machine learning</u>

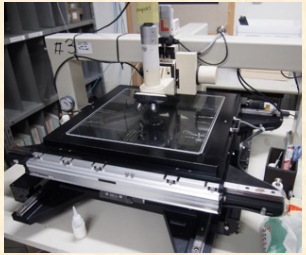
Nuclear Emulsion:

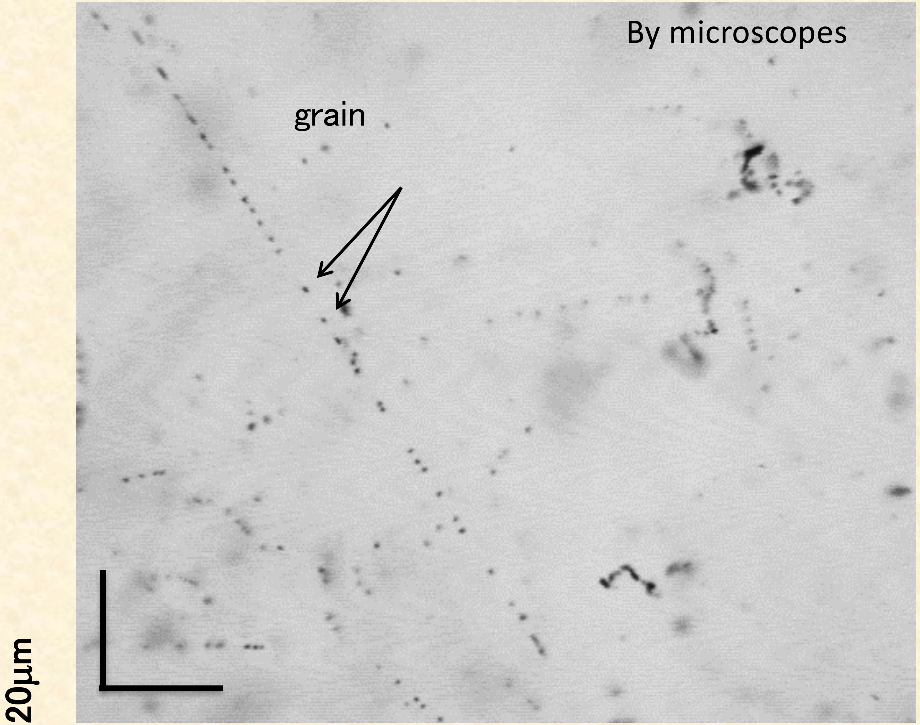
Charged particle tracker with

the best spatial resolution

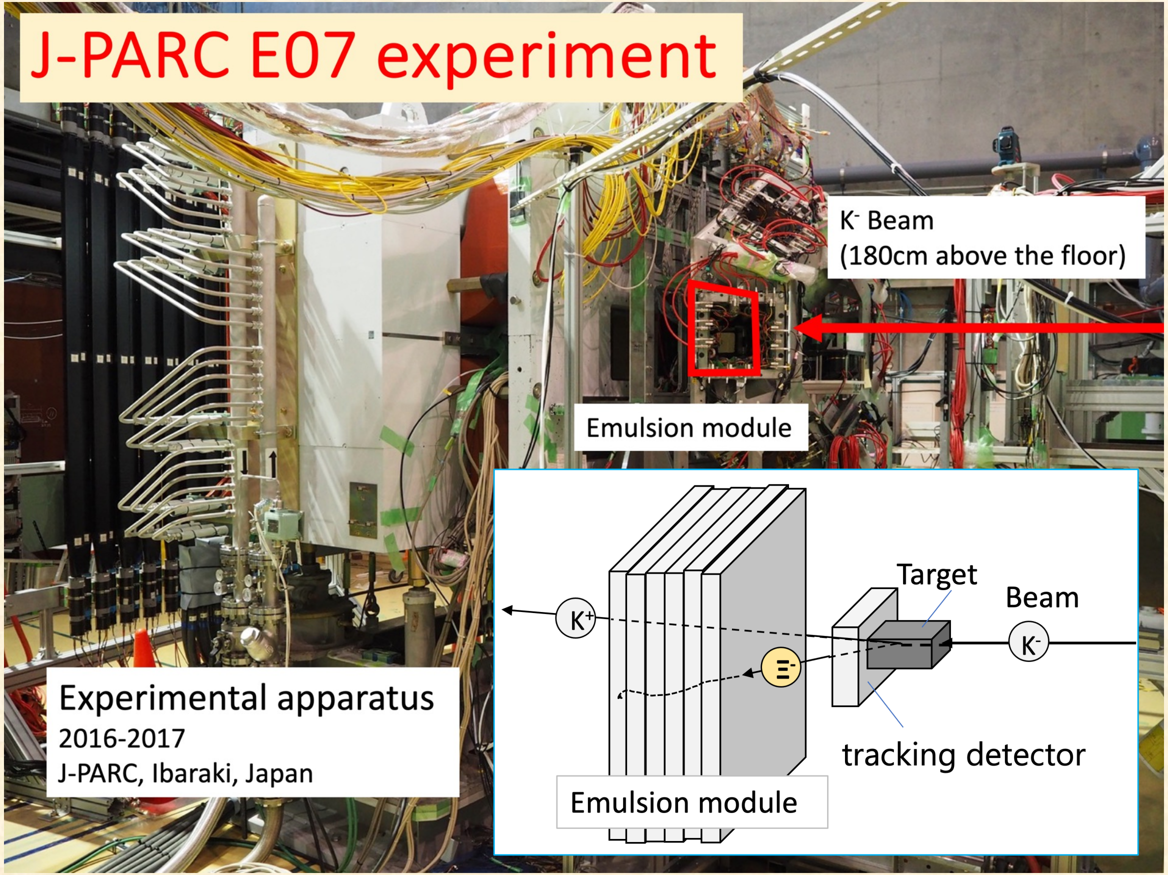
(easy to be < 1 μm, 11 nm at best)







J-PARC E07 experiment

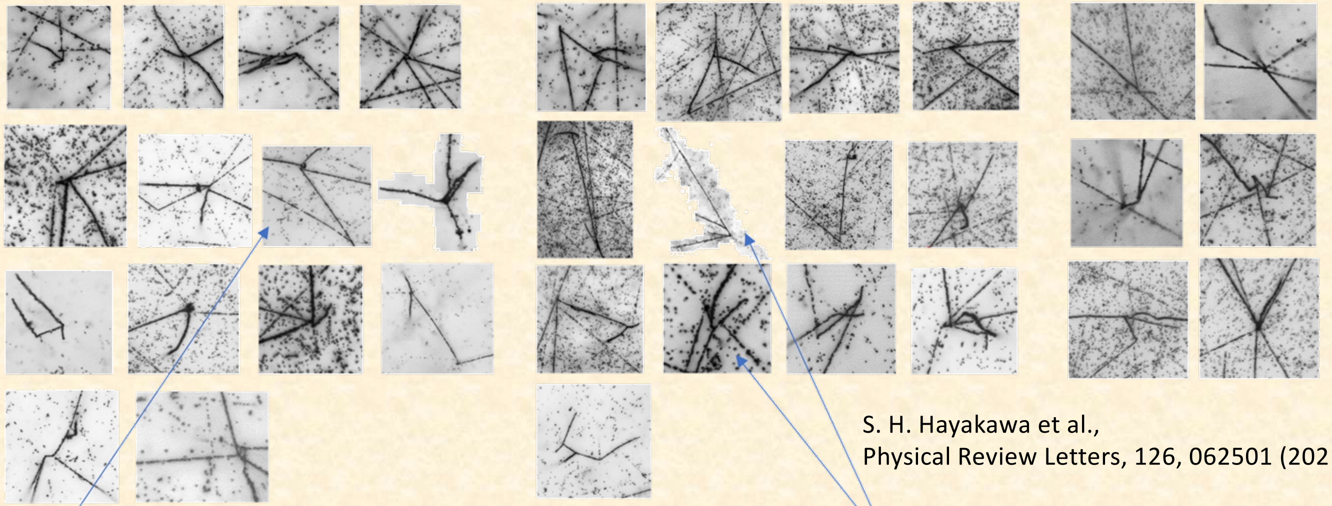


Results from J-PARC E07 (Hybrid method)

$\Lambda\Lambda$ candidates: 14

Twin Λ events: 13

Others: 6



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

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

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

${}_{\Lambda\Lambda}Be$

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

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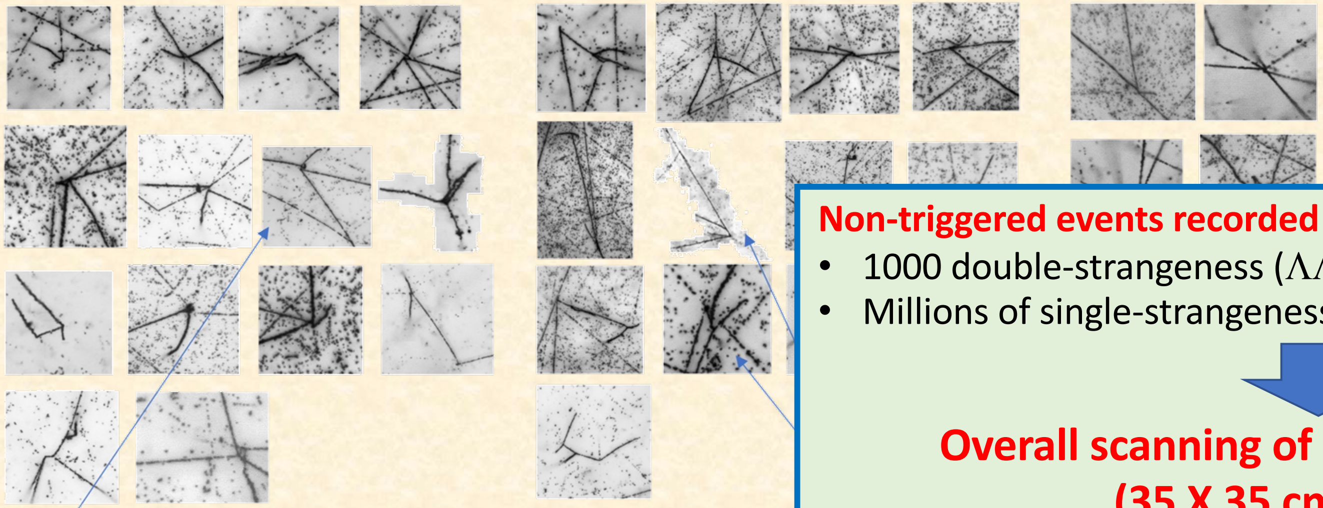


Non-triggered events recorded in 1300 emulsions sheets

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

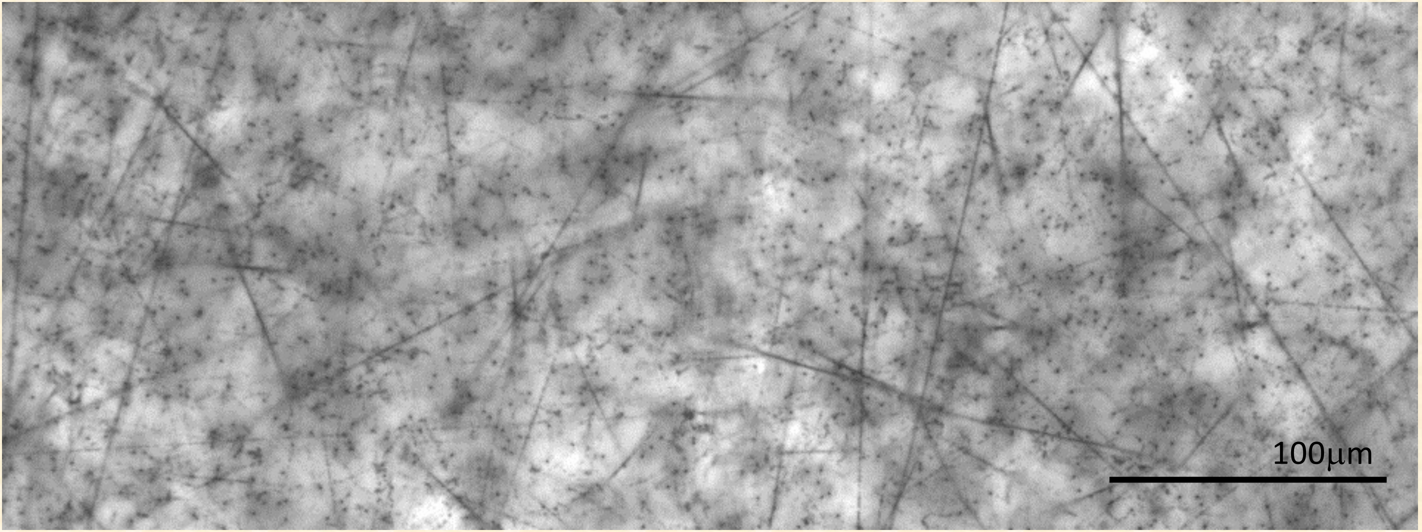
Overall scanning of all emulsion sheets
(35 X 35 cm^2 X 1000)

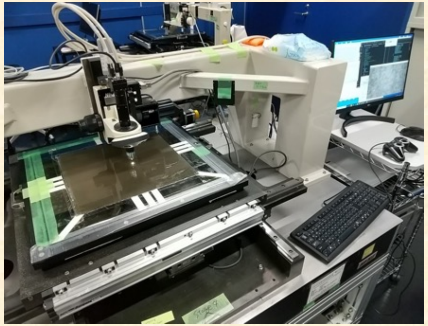
M. Yoshimoto
Prog. Theor. Exp. Phys. 2021, 073D02

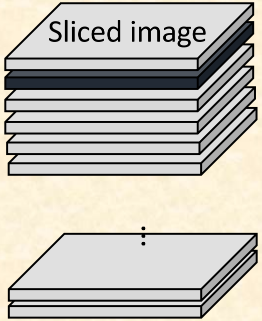
$^{15}_{\Xi}C$

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

Overall scanning for E07 emulsions







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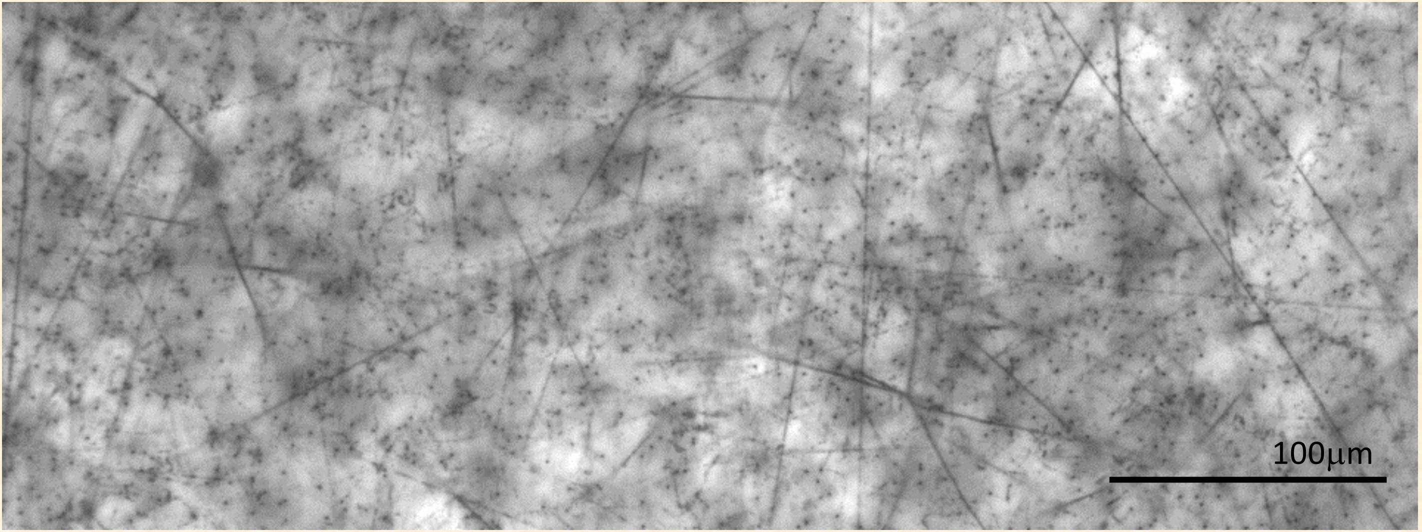

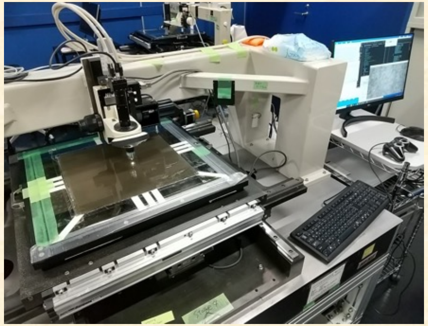

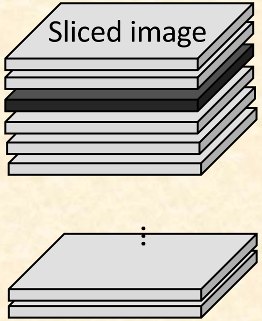

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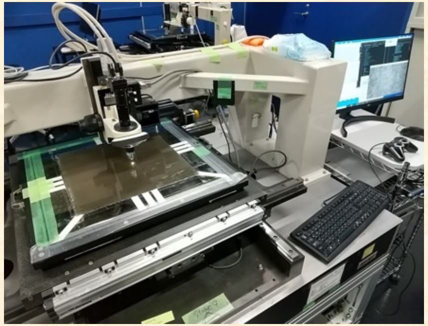

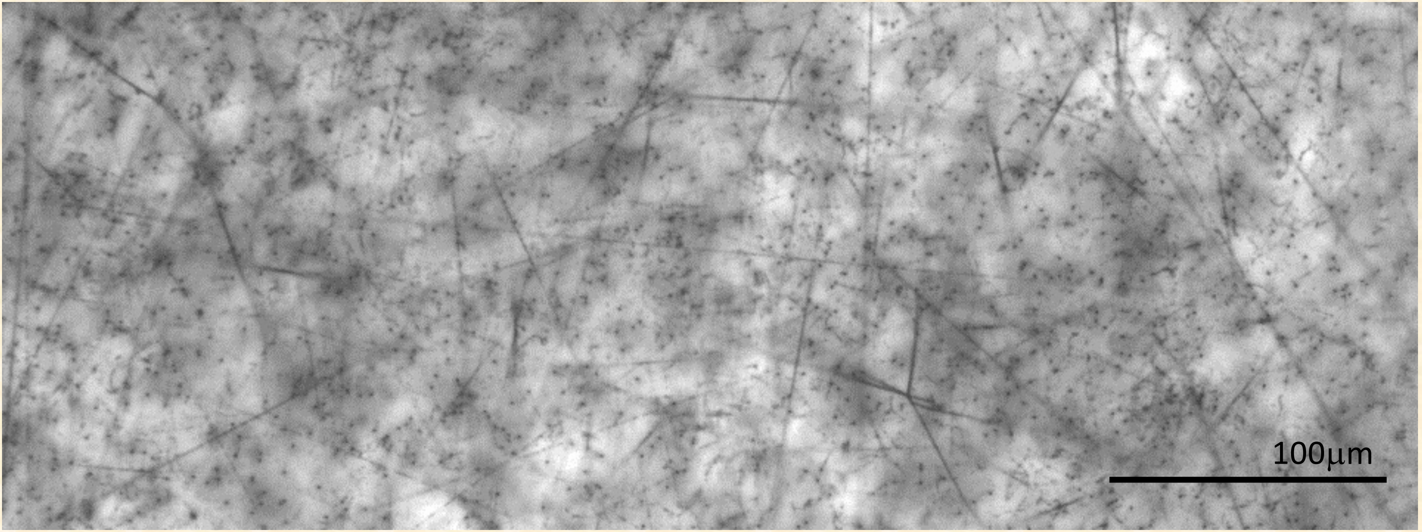

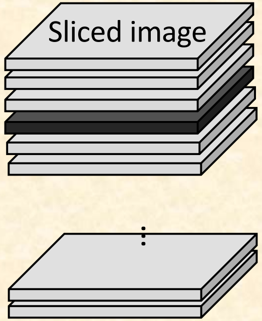

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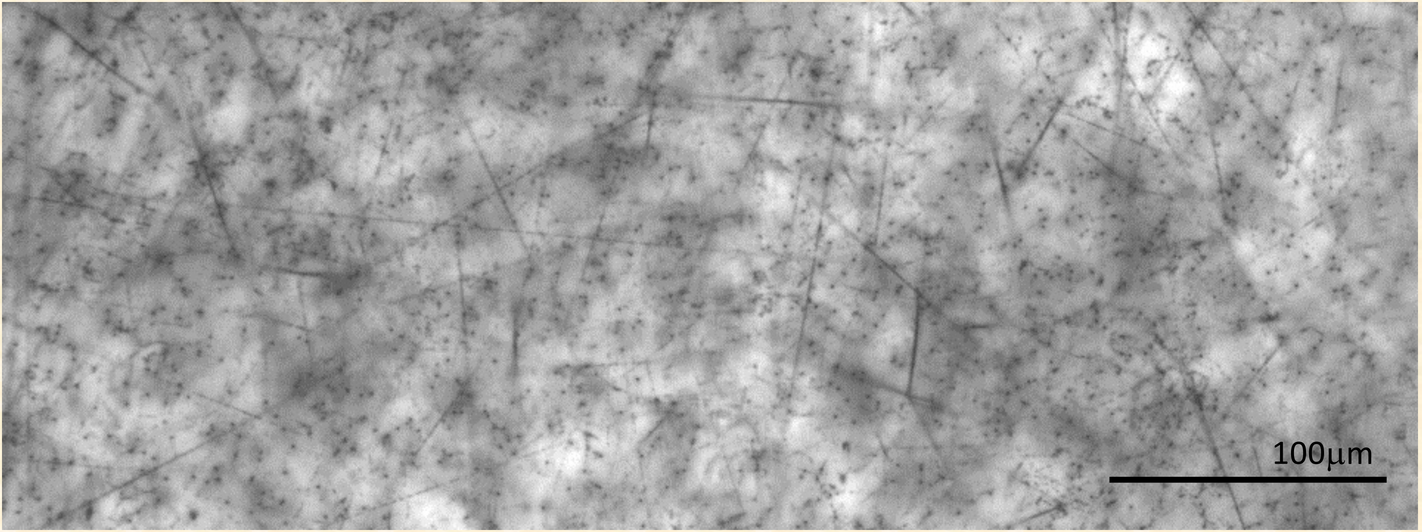

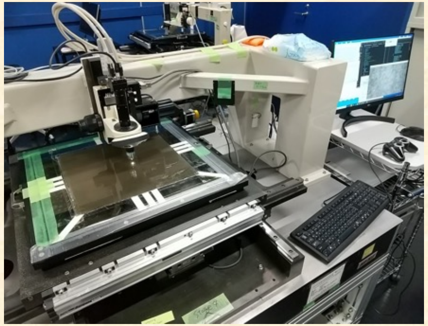

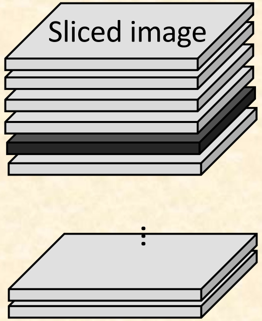

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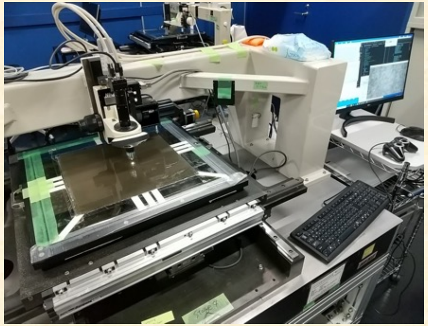
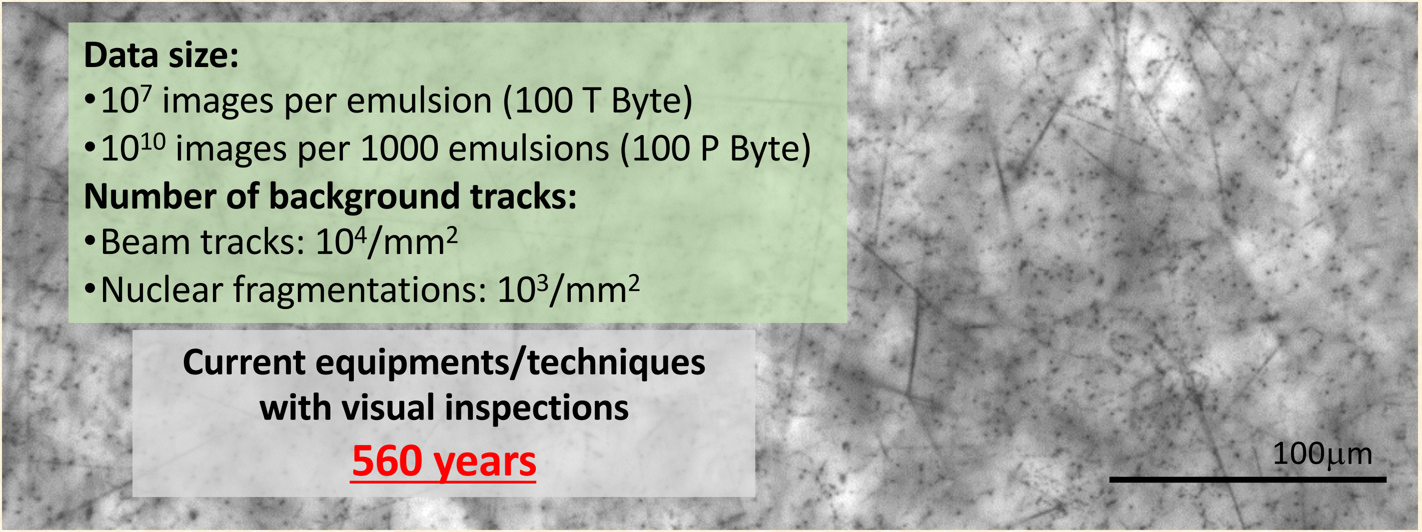


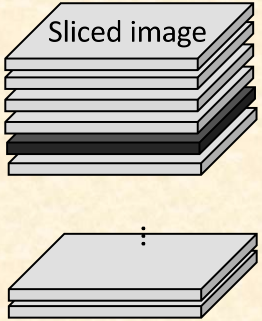


Data size:
- 10^7 images per emulsion (100 T Byte)
- 10^{10} images per 1000 emulsions (100 P Byte)

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

Current equipments/techniques with visual inspections

<u>560 years</u>



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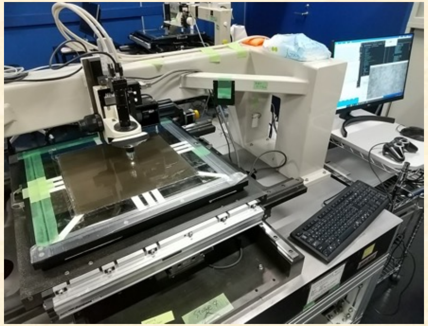

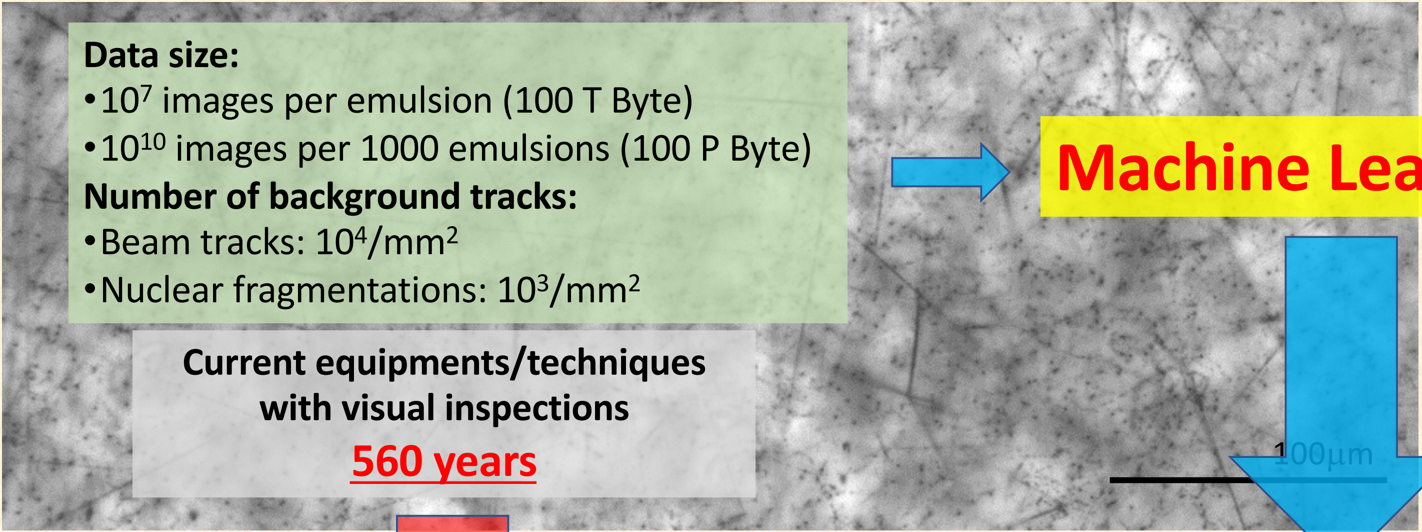

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Number of background tracks:

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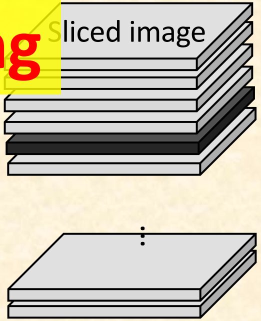
Current equipments/techniques with visual inspections

560 years

3 years

Machine Learning



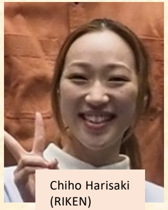
Millions of single-strangeness hypernuclei
1000 double strangeness hypernuclei (formerly only 5)

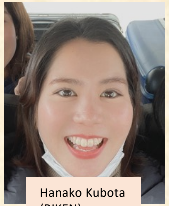
Setup for analyzing emulsions at the High Energy Nuclear Physics Laboratory in RIKEN

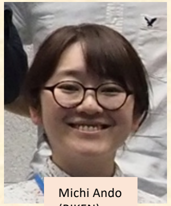
- Hypernuclear physics
- Neutron imaging

Part-timer staffs working for emulsion & microscopes


Risa Kobayashi (RIKEN)


Chiho Harisaki (RIKEN)


Hanako Kubota (RIKEN)


Michi Ando (RIKEN)

Currently 7 microscope stages running

Challenges for Machine Learning Development

MOST IMPORTANT:

- **Quantity and quality of training data**

However,

No existing data for hypertriton with emulsions for training

Our approaches:

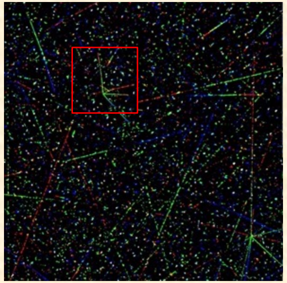
Producing training data with

- Monte Carlo simulations
- Image transfer techniques

Production of training data

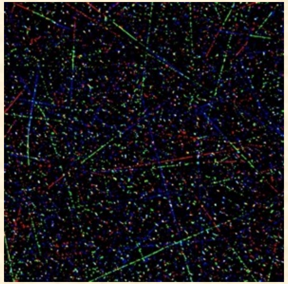
Monte Carlo simulations and GAN(Generative Adversarial Networks)

Binarized tracks from MC simulations
+ background from the real data

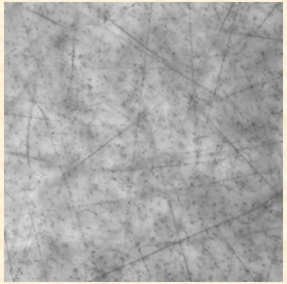


Imitated
emulsion image

GAN: pix2pix



Binarized (like for simulations)



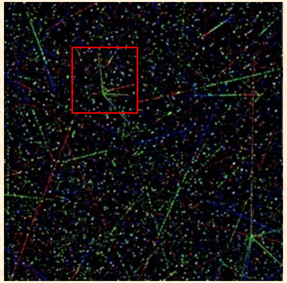
Real emulsion image

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

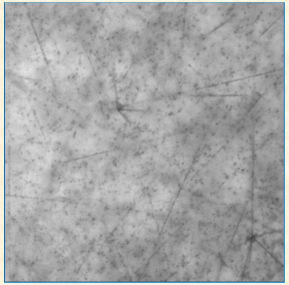
Production of training data

Monte Carlo simulations and GAN(Generative Adversarial Networks)

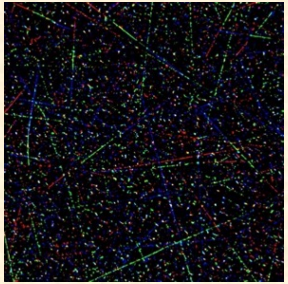
Binarized tracks from MC simulations
+ background from the real data



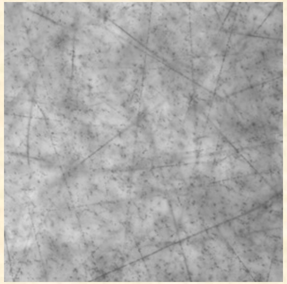
Produced training data



GAN: pix2pix



Binarized (like for simulations)

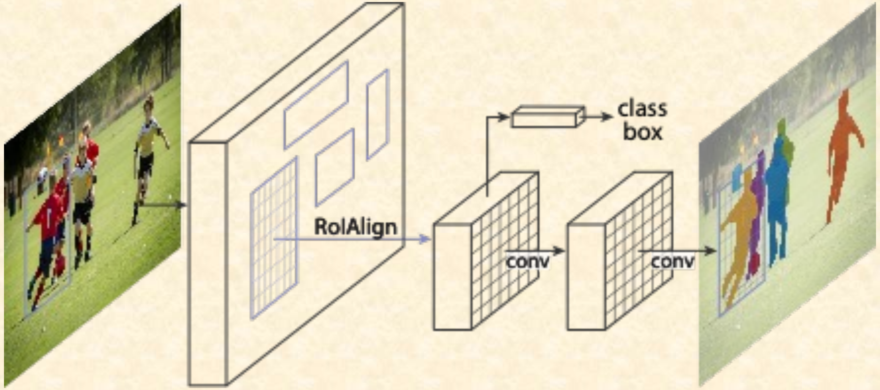


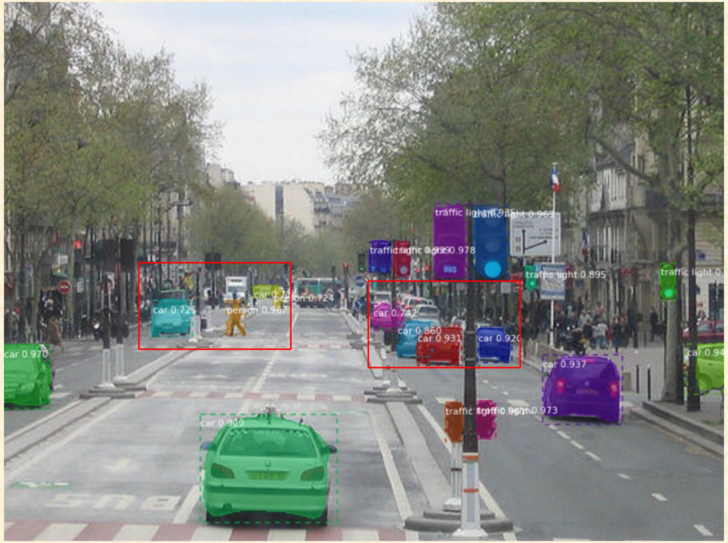
Real emulsion image

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

Detection of hypertriton events

With Mask R-CNN model



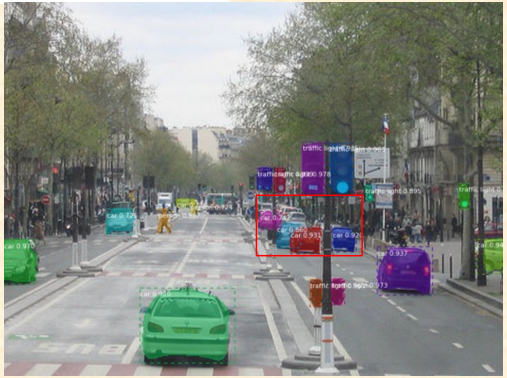


Detection of each object

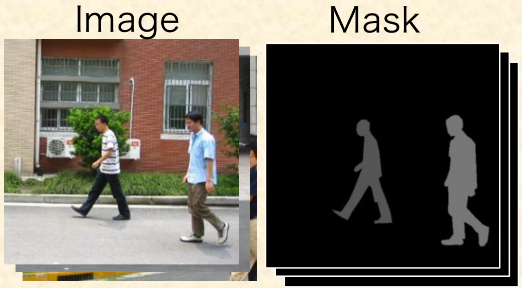
At large object density

Training of Mask R-CNN with Simulated image

Mask R-CNN



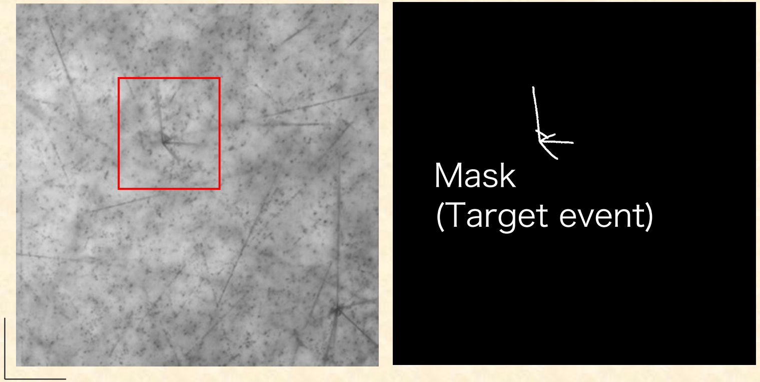
Example of training dataset



A Pedestrian dataset

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

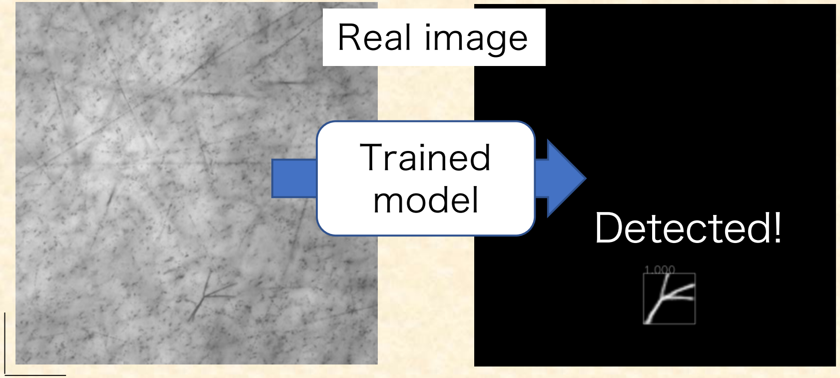
Training data (Simulated image)



50 μm

Masks are automatically produced

Performance of α-decay detection



50 μm

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

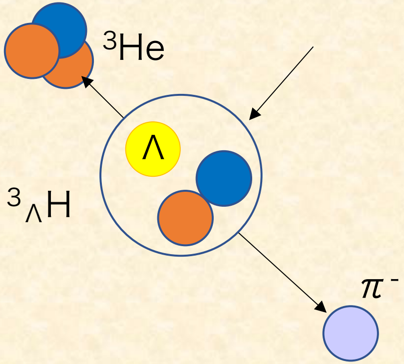
	Efficiency [%]	Purity [%]
Vertex picker	～40%	～1%
Mask R-CNN	～80%	～20%

→ 2nd step done

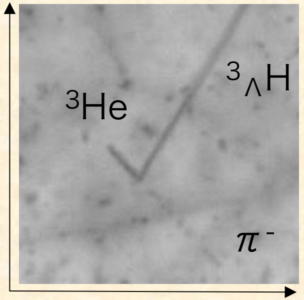
A.Kasagi et.al,
NIM A1056, (2023) 168663.

Hypertriton search with Mask R-CNN

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



Simulated image

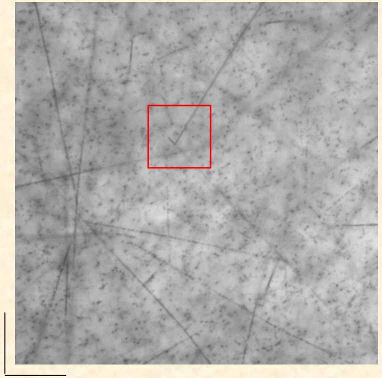


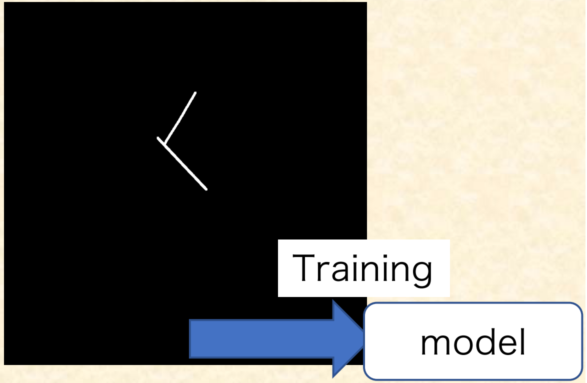
50 μm

Training dataset (Simulated images)

Image

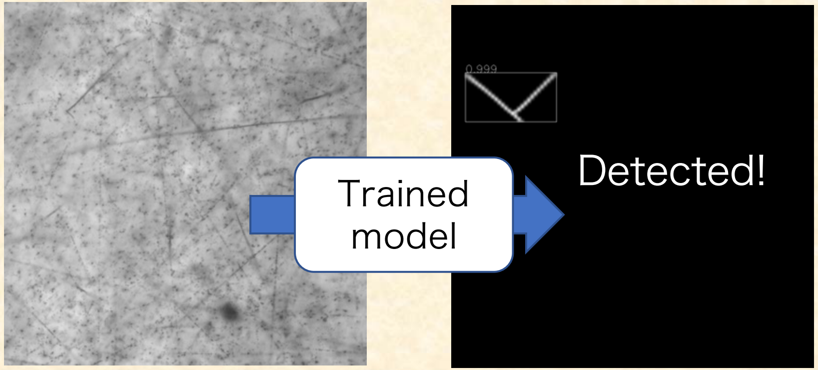
Mask



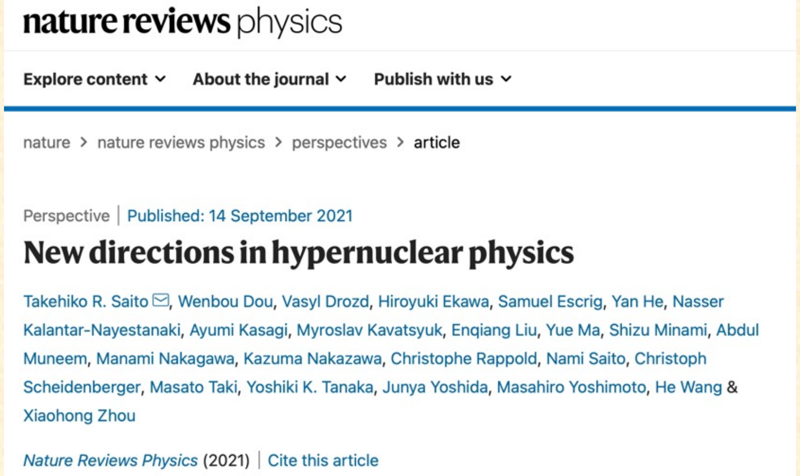


50 μm

Real image



Discovery of the first hypertriton event in E07 emulsions



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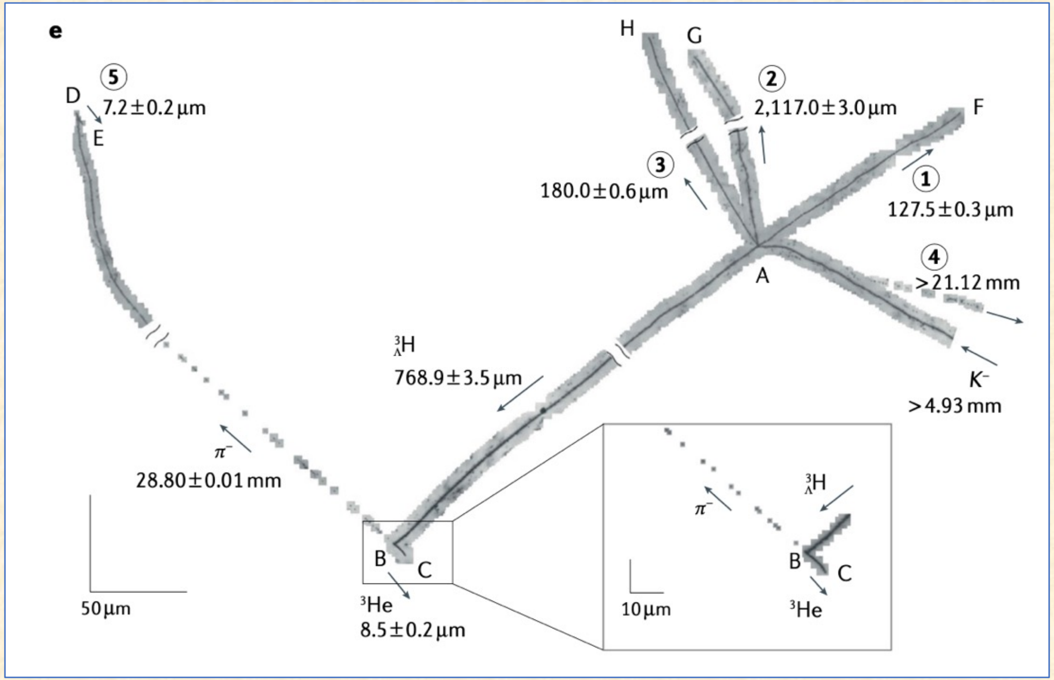
nature > nature reviews physics > perspectives > article

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

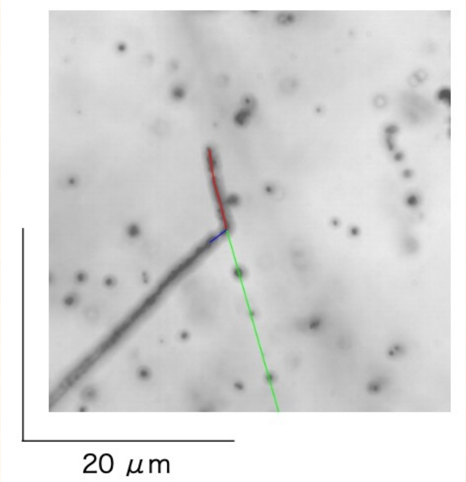
E. Liu et al., EPJ A57 (2021) 327

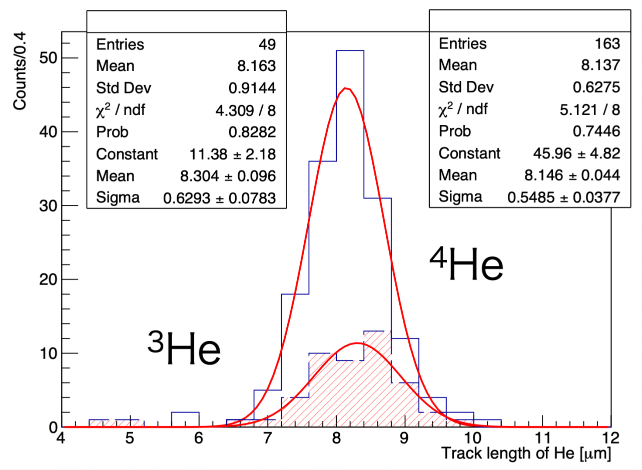
Ayumi Kasagi.
Ph.D. thesis (2023)

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

Towards the hypertriton binding energy

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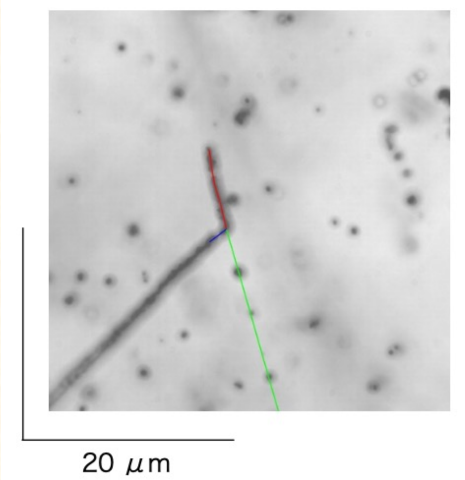
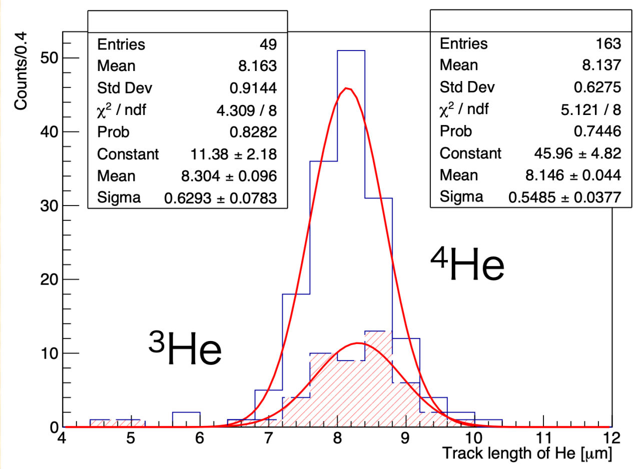
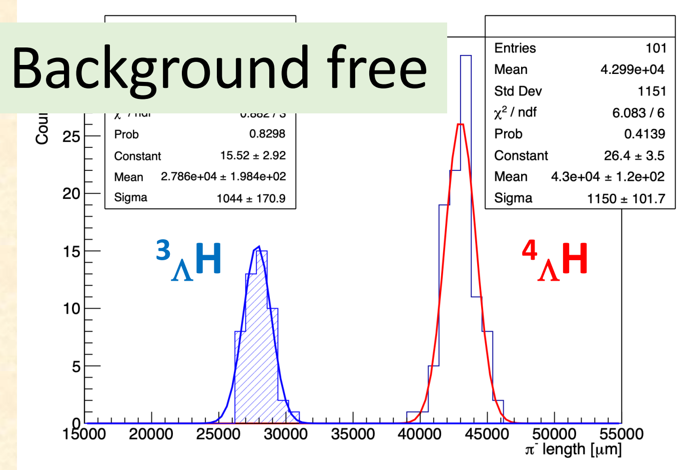
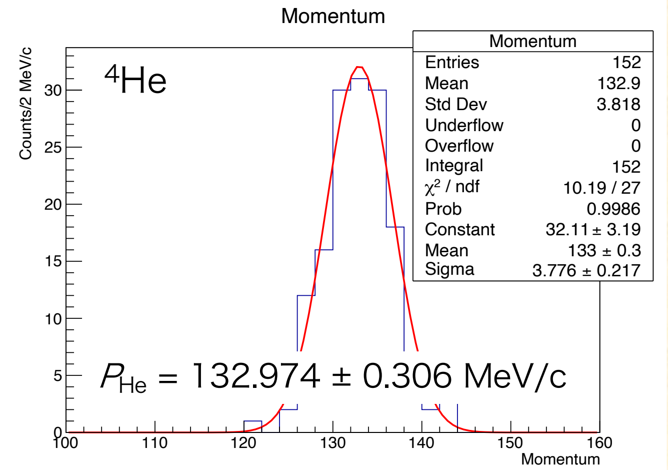


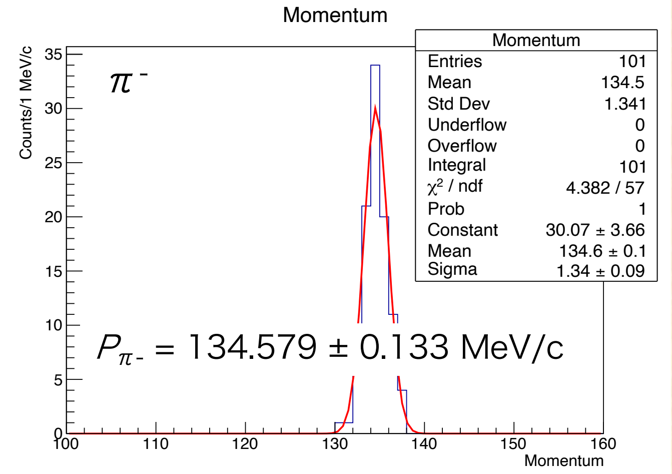




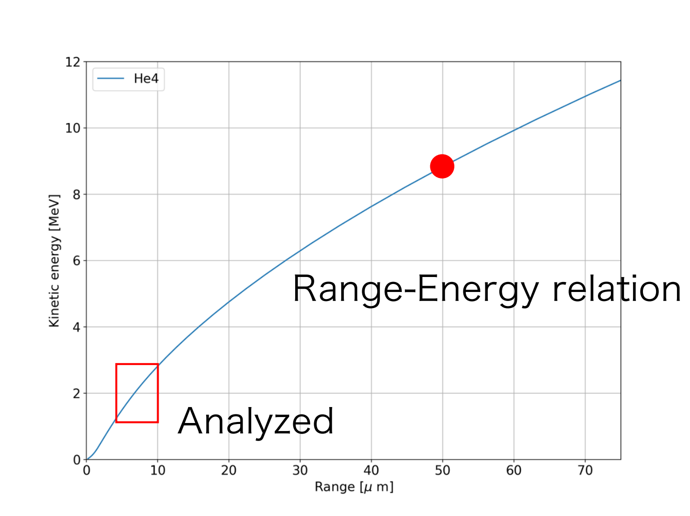
A. Kasagi et al., to be published soon

Problems on π^-





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



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

Affecting all emulsion results at KEK and J-PARC

A. Kasagi et al., to be published soon

Range of the deduced binding energy

Posssible range of $B_\Lambda({}^3_\Lambda H)$: 196 – 693 keV
with about 100 keV uncertainty

(only 0.6 % of the entire data)

${}^3_\Lambda H$ 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

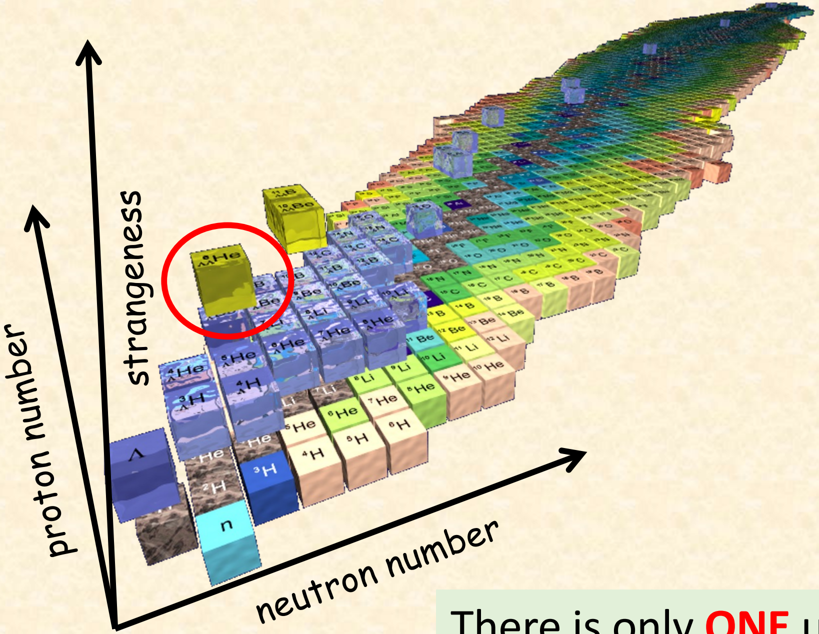
ALICE

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**

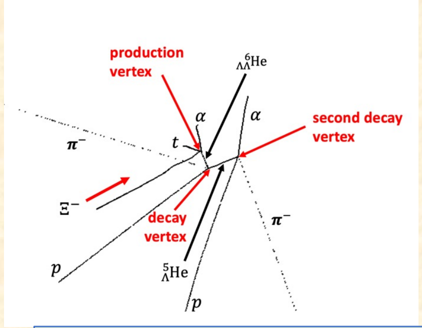
$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

Searching for double-strangeness hypernuclei

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

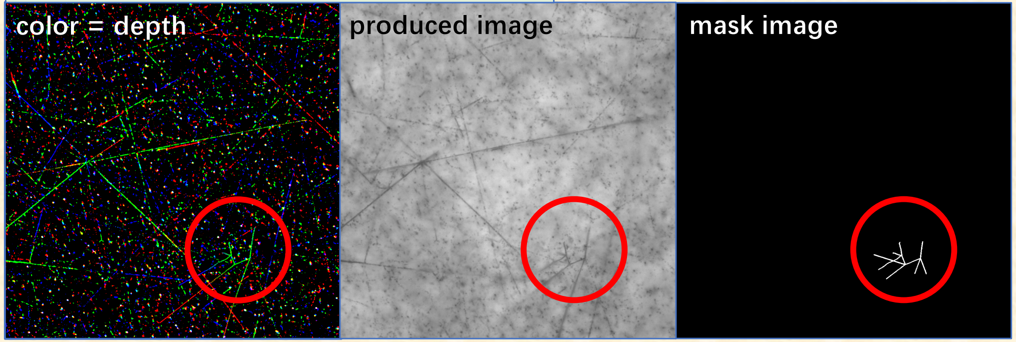
Prepare training dataset

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

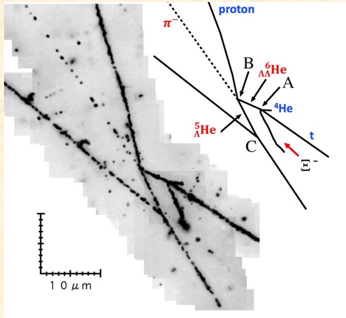


Double-strangeness hypernuclei event topology — **"three vertices"**

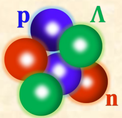
Geant4 simulation, image process, machine learning — GAN: pix2pix



Model performance

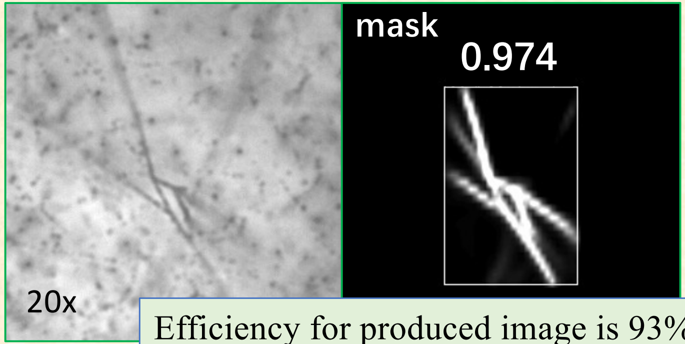


$^{6}_{\Lambda\Lambda}He$



triple-close shell

H.Takahashi et. al, Phys. Rev. Lett. 87 (2001) 212502.



Efficiency for produced image is 93%

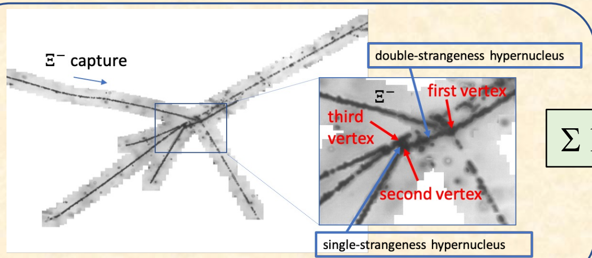
Searching for double-strangeness hypernuclei

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

Current status and near future

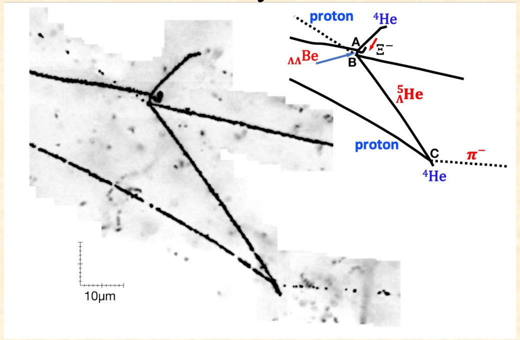
- Analyzed **0.2%** of the entire data, **6 candidates** found.
- Searching for double-strangeness hypernuclei with newly developed machine-learning method is in progress.

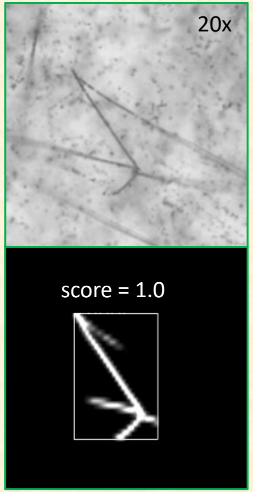
One of new candidates



Σ hypernuclei?

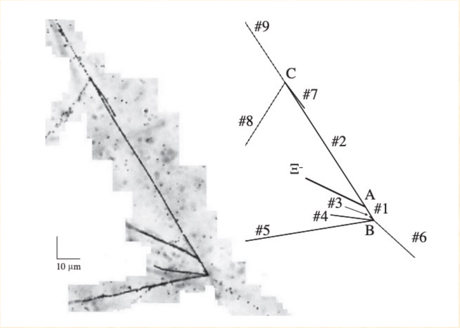
- MINO event from E07 hybrid

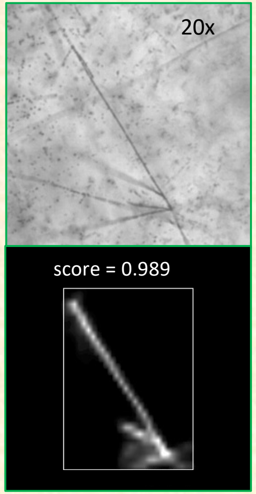




H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02 (2019b) E.

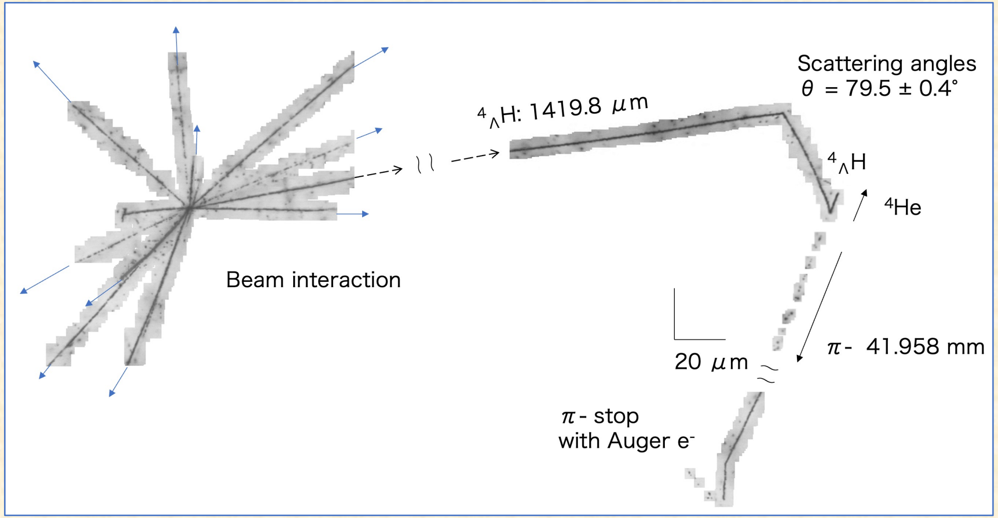
- IBUKI event from E07 hybrid

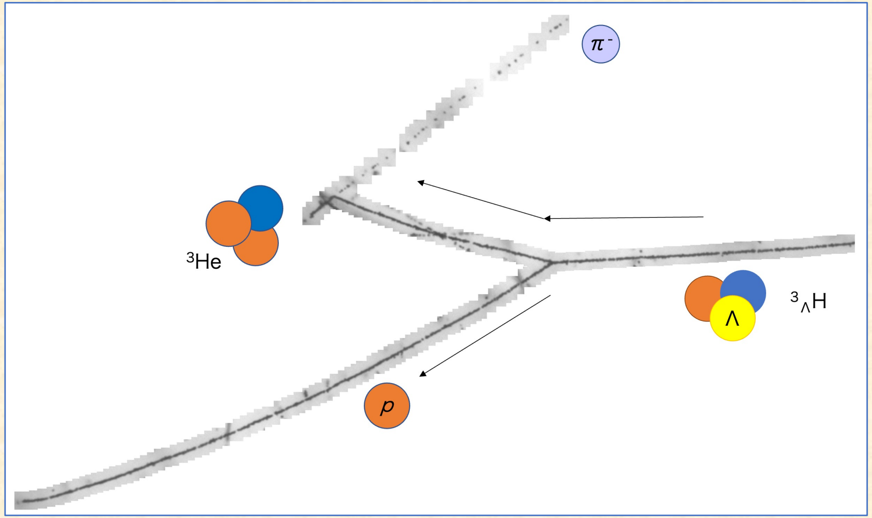




S.H. Hayakawa et al., Phys. Rev. Lett. 126, 062501 (2021)

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]

[a] High Energy Nuclear Physics Laboratory, RIKEN, Japan

[b] Department of Physics, Saitama University, Japan

[c] Energy and Sustainability Research Institute Groningen, University of Groningen, Netherlands

[d] GSI Helmholtz Centre for Heavy Ion Research, Germany

[e] Instituto de Estructura de la Materia, Spain

[f] Institute of Modern Physics, Chinese Academy of Sciences, China

[g] University of Chinese Academy of Sciences, China

[h] School of Nuclear Science and Technology, Lanzhou University, China

[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

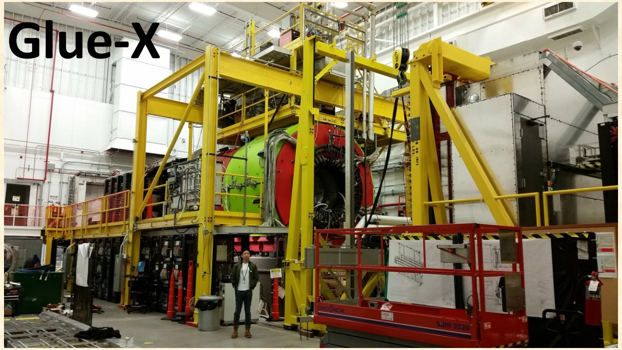
[m] Department of physics, Tohoku University, Japan

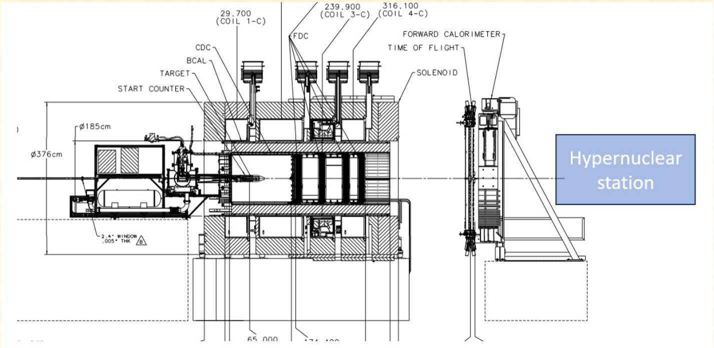
[n] RIKEN Nishina Center, RIKEN, Japan

New proposal at KLF/JLab

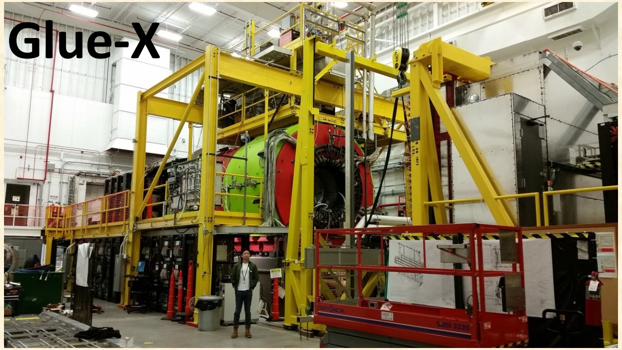
Neutral-K beams behind the Glue-X setup

Hypernuclear station behind the Glue-X





New proposal at KLF/JLab

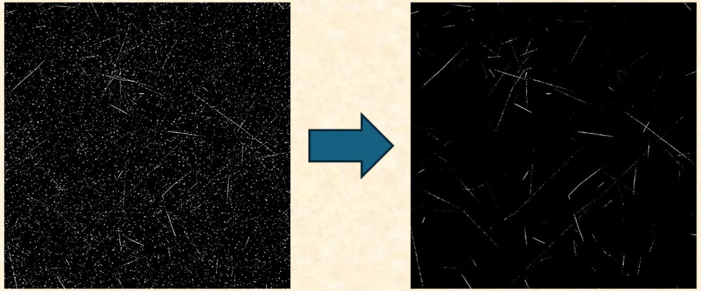


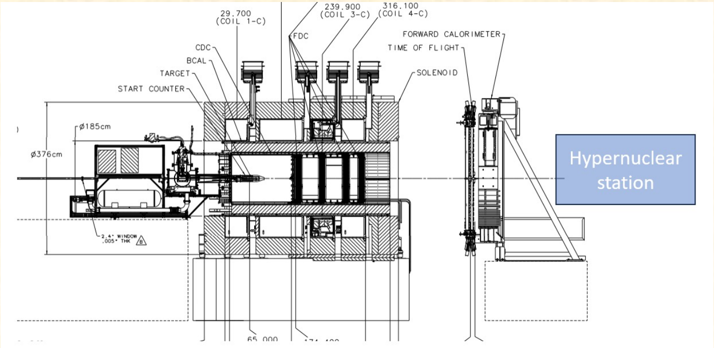
Neutral-K beams behind the Glue-X setup

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

New pro

Neutral-K

Hypernuc

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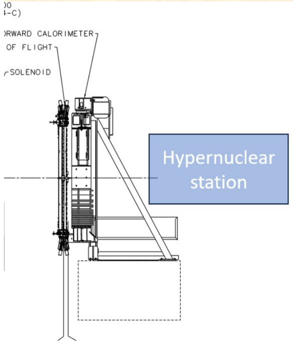
  - **2.3**
    hype

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)



FNTD (Al_2O_3:C,Mg)
- Used for neutron imaging
- Recyclable

High Energy Nuclear Physics laboratory at CPR/RIKEN

Assistant:

Yukiko Kurakata

Staff scientists:

Yoshiki Tanaka, He Wang

Postdocs:

Hiroyuki Ekawa

Ph.D. Students:

Yiming Gao (IMP), Yan He (LZU), Wenzhen Xu (Shandong U.), Ayari Yanai (Saitama U.)

Technical staffs:

Michi Ando, Risa Kobayashi

Trainee:

Snehankit Pattnaik (Bochum U. and GSI)

Visiting researchers:

Ayumi Kasagi (Rikkyo U.), Kazuma Nakazawa (Gifu U.)

Associated members:

Vasyl Drozd (Groningen U., defending Ph.D.), Samuel Escrig (CSIC-Madrid, writing Ph.D. thesis), Enqiang Liu (IMP, defending Ph.D.), Abdul Muneem (GIK)

Chief scientists:

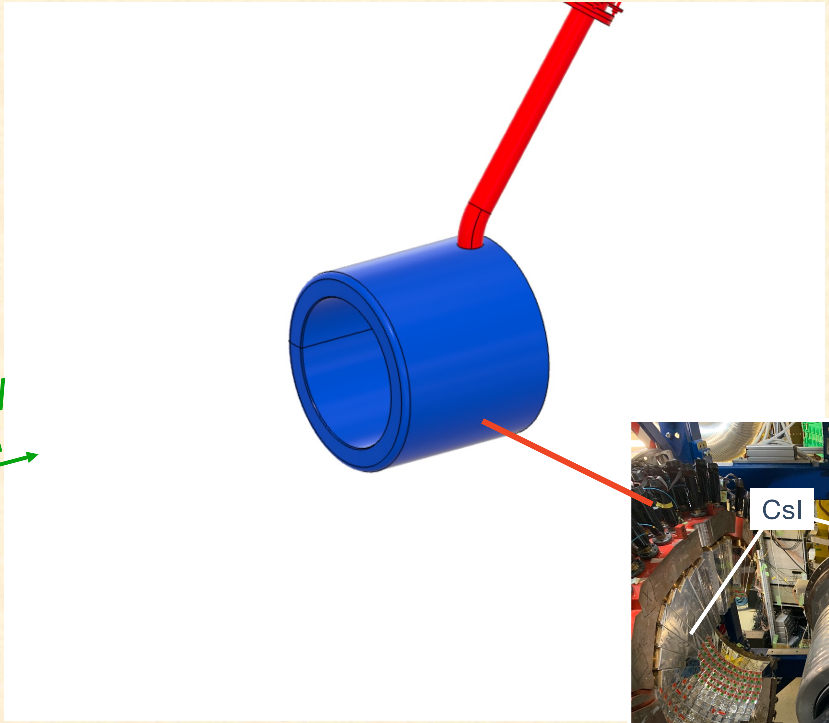
Take R. Saito

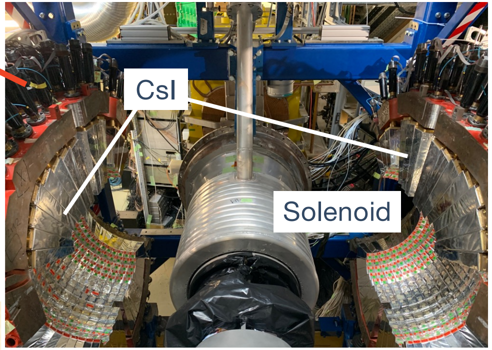
Takehiko R. Saito
takehiko.saito@riken.jp

The WASA-FRS setup

Existing	Newly developed
WASA Solenoid CsI MDC	PSB / PSFE / PSBE / T0 Fiber Trackers Cryogenics Readout electronics

^{6}Li / ^{12}C, 1.96 A GeV Beam





The WASA-FRS setup

Existing	Newly developed
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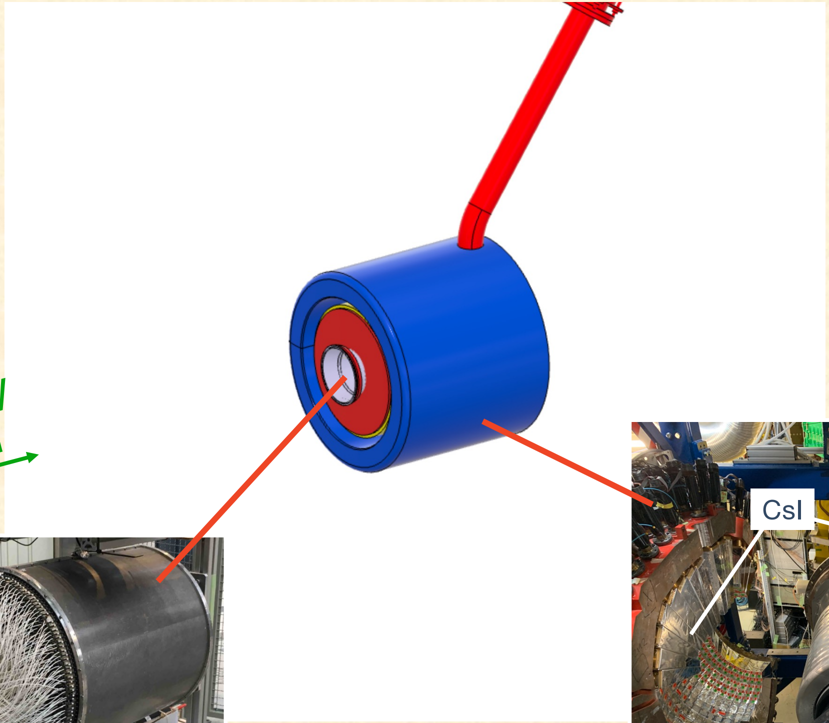
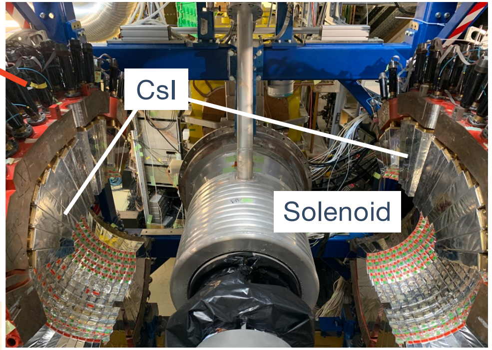
CsI	Fiber Trackers
MDC	Cryogenics
	Readout electronics

^{6}Li / ^{12}C, 1.96 A GeV Beam

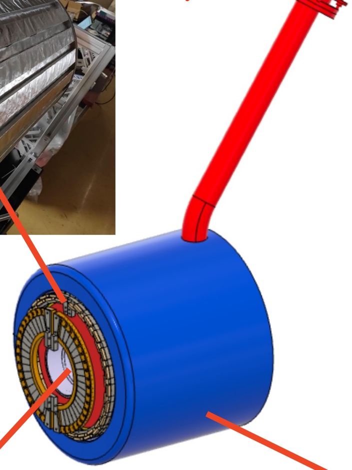


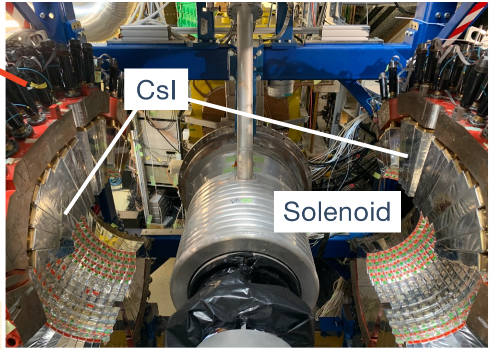


The WASA-FRS setup

Existing	Newly developed
WASA Solenoid CsI MDC	PSB / PSFE / PSBE / T0 Fiber Trackers Cryogenics Readout electronics

R. Sekiya et al., Nucl. Instrum. Meth. A **1034** (2022) 166745





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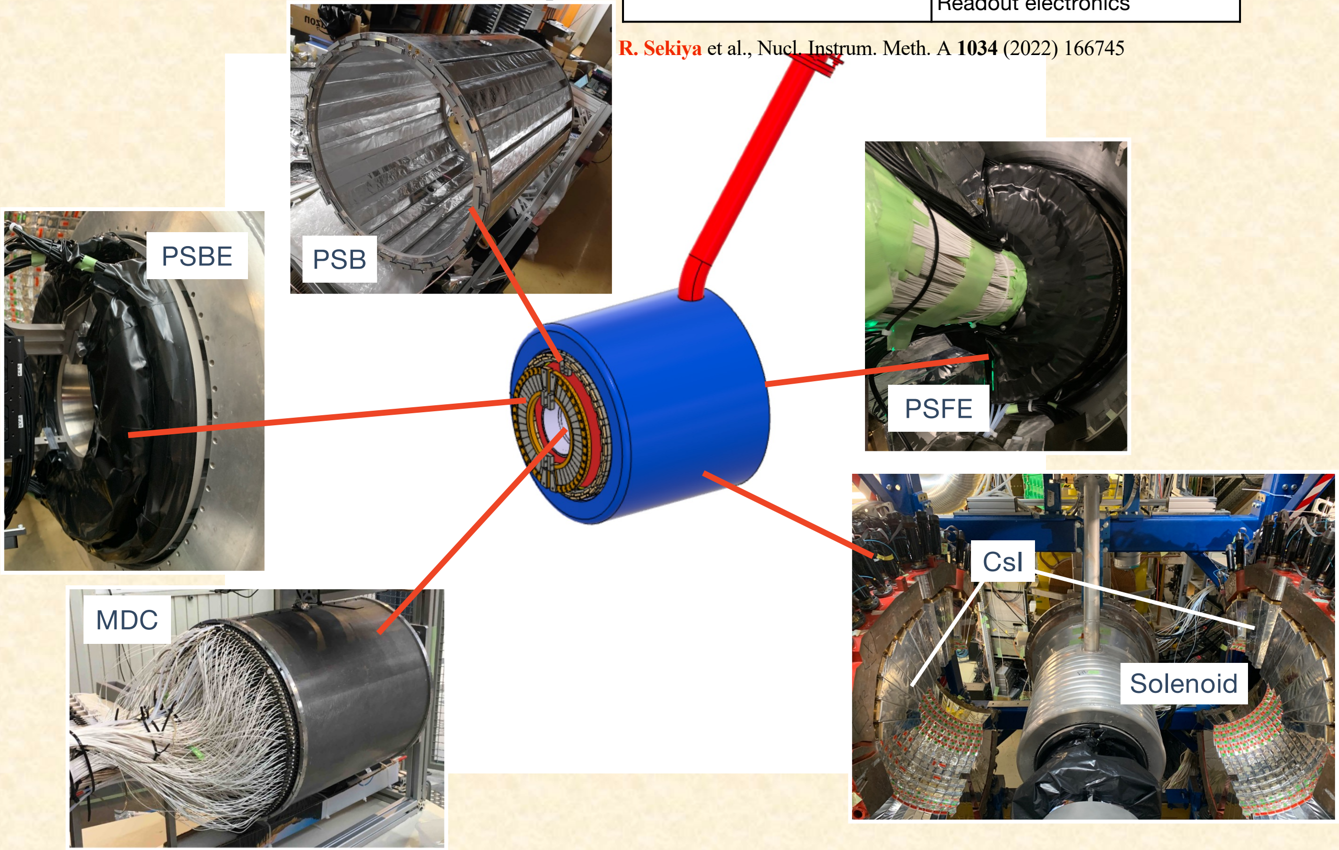

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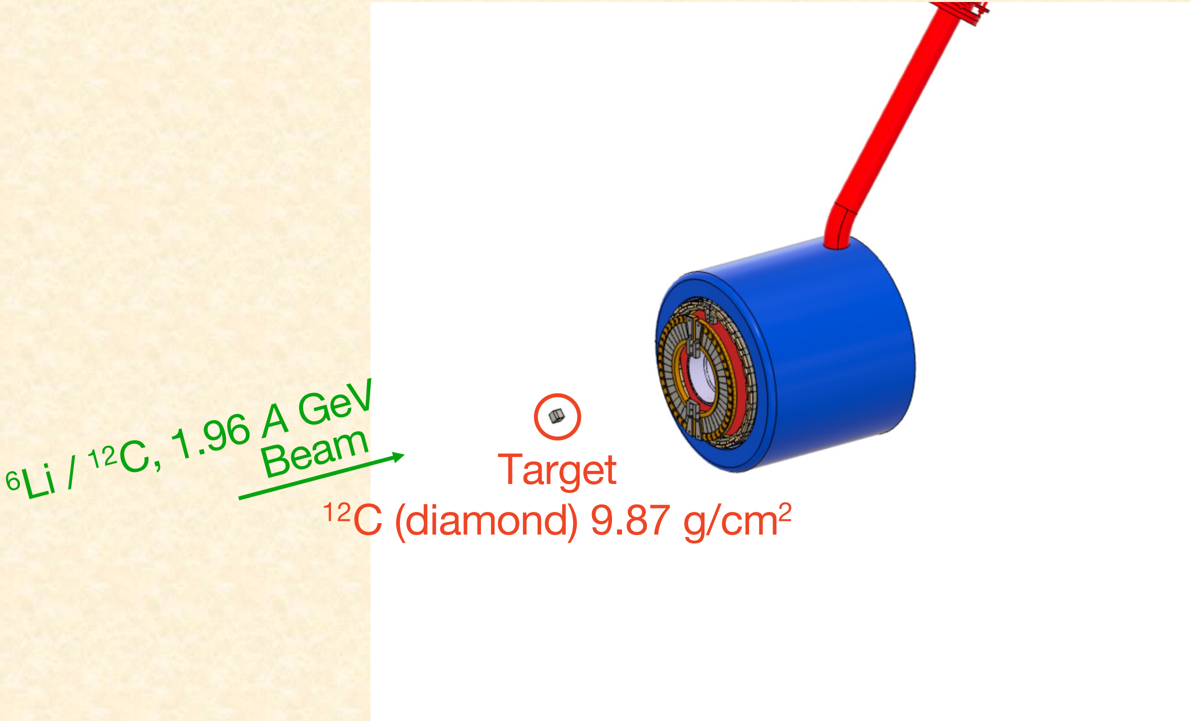

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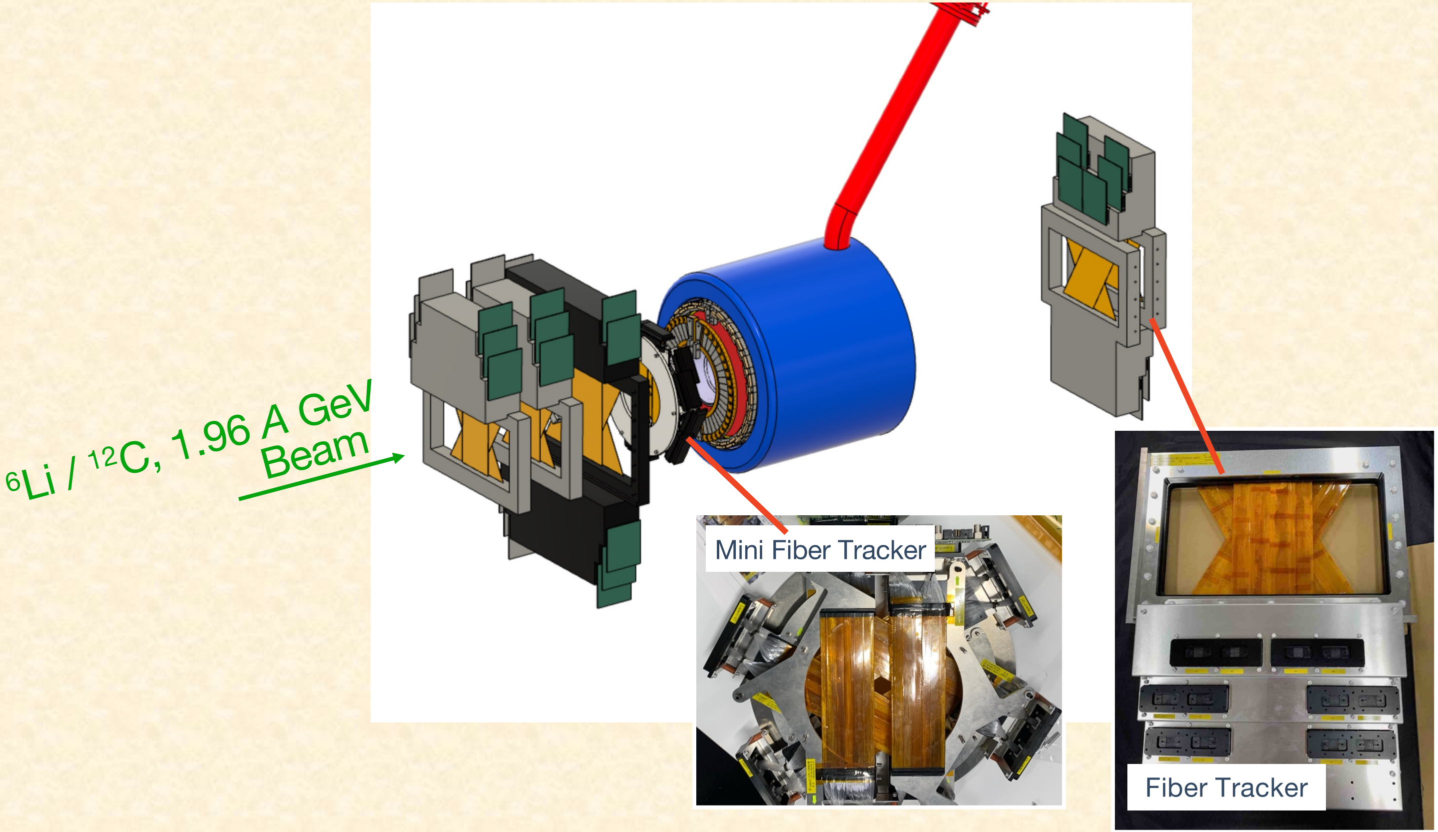

The WASA-FRS setup

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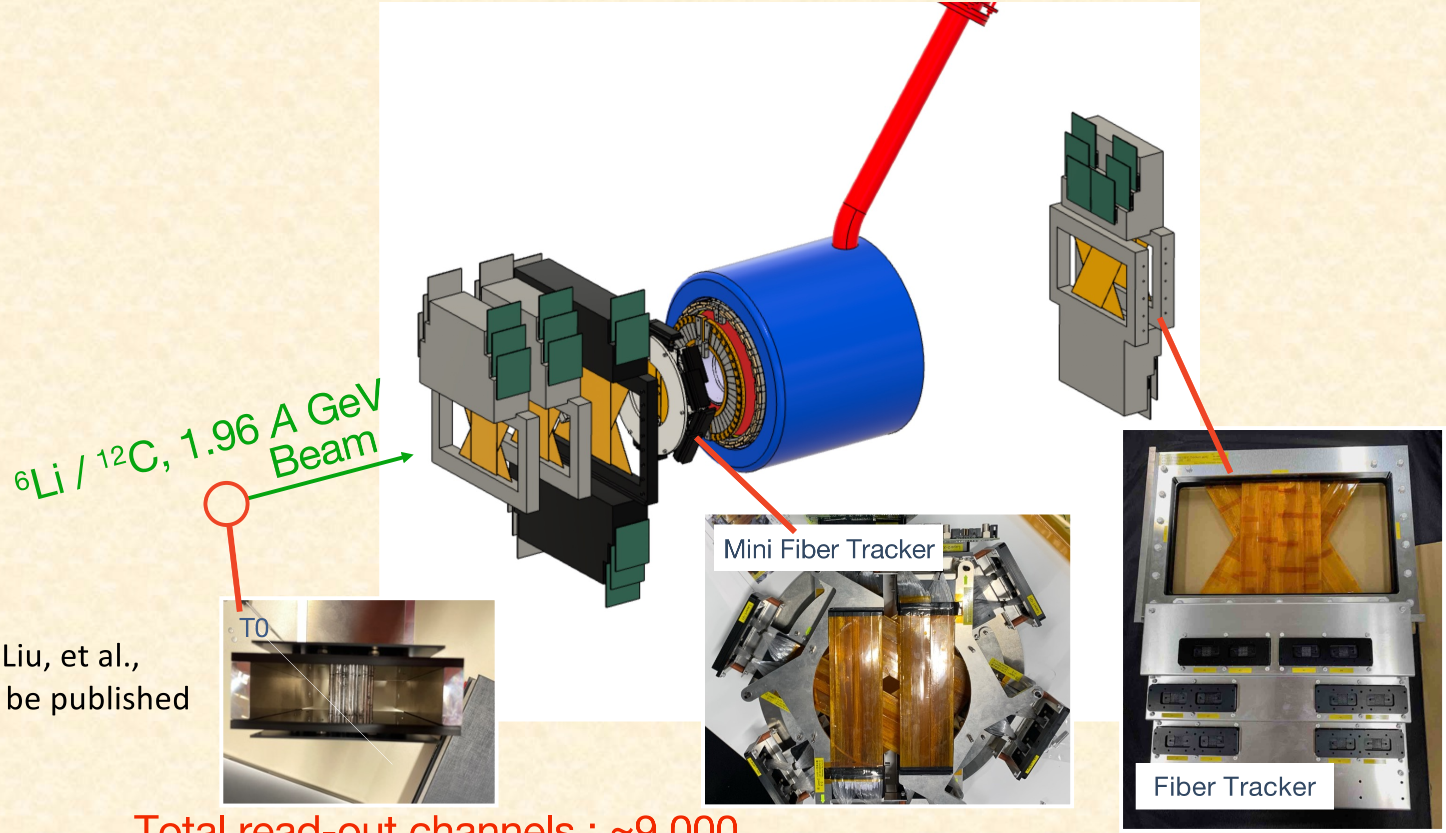


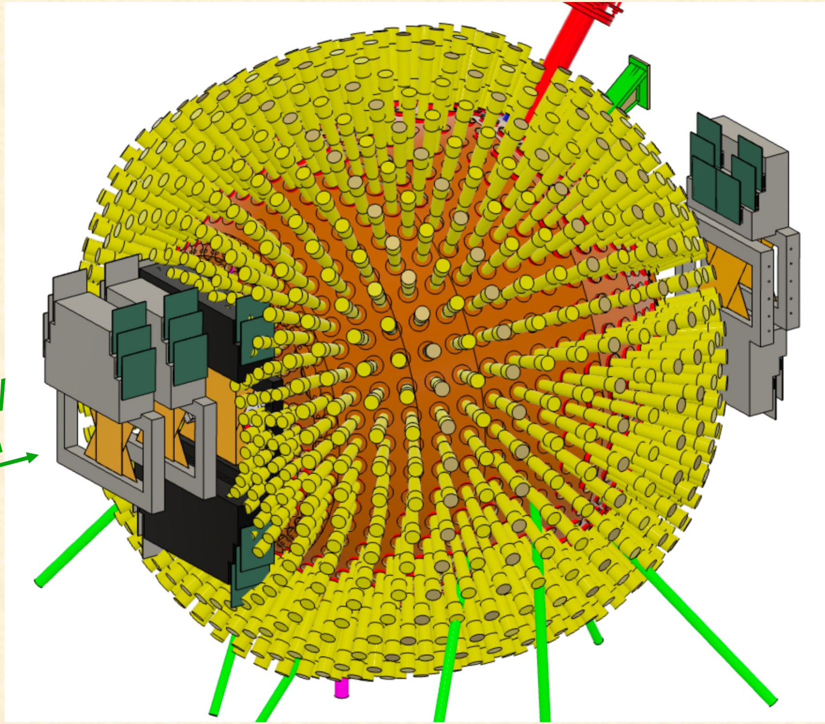
E. Liu, et al.,
to be published

Total read-out channels : ~9,000

The WASA-FRS setup

Existing	Newly developed
WASA Solenoid CsI MDC	PSB / PSFE / PSBE / T0 Fiber Trackers Cryogenics Readout electronics

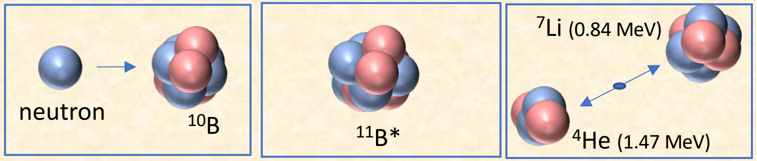
^{6}Li / ^{12}C, 1.96 A GeV
Beam



Total read-out channels : ~9,000

Neutron imaging with nuclear emulsion

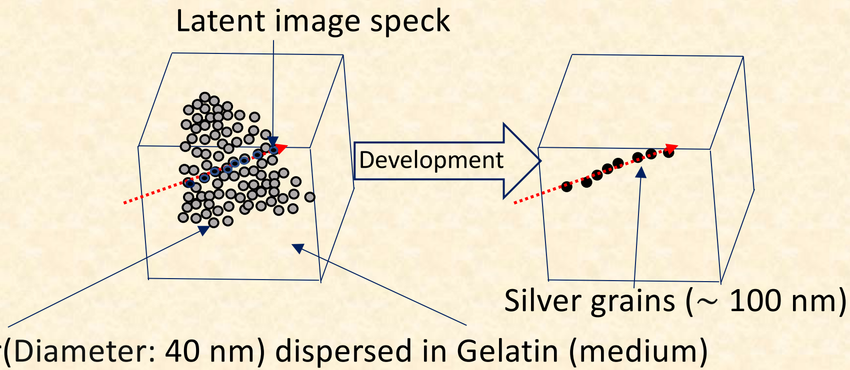
Neutron-Boron reaction



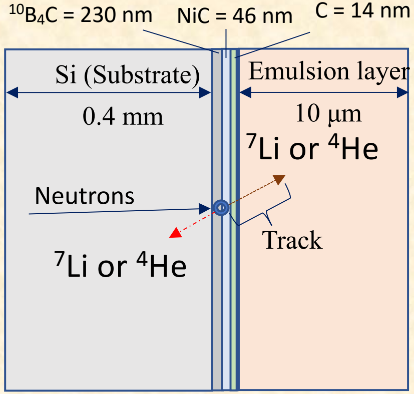
Neutron absorbed by ^{10}B

Basic principle: Nuclear emulsion

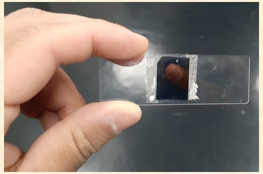
- Records the three-dimensional trajectory of charged particles
- High spatial resolution: sub- μm



Structure of neutron detector



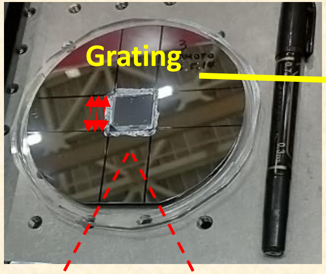
Photograph of detector



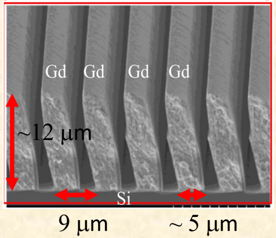
Neutron Imaging with nuclear emulsion at J-PARC MLF

Neutron imaging of gadolinium-based grating slit with a periodic structure of 9 μm

Gd slit

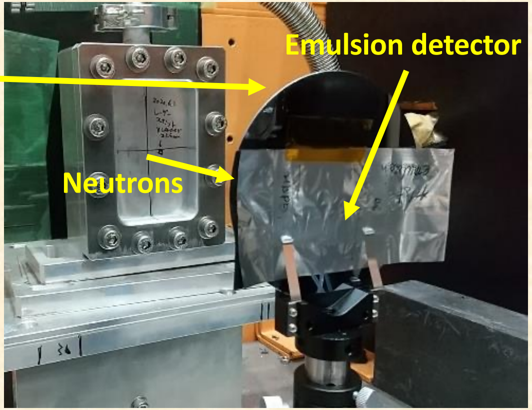


SEM image of fabricated Gd grating

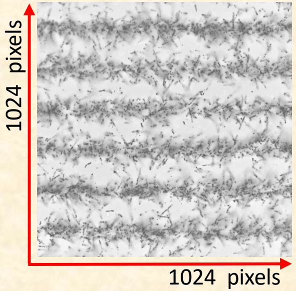


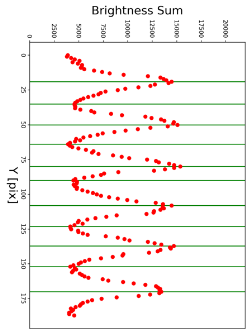
T. Samoto *et al.*, 2019
Jpn. J. Appl. Phys. 58 SDDF12

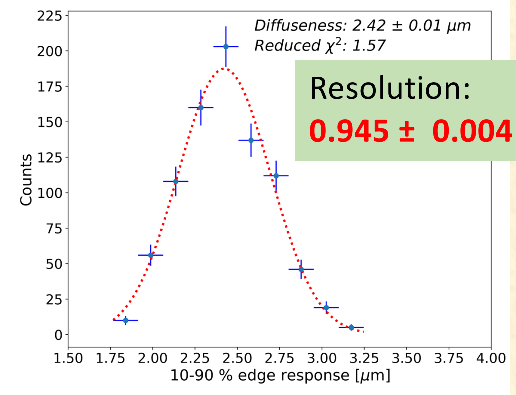
Neutron beam port



Divergence: X = 0.3 mrad, Y = 10 mrad
Estimate: 2×10^6 n / cm^2 / sec @ 700kW
Distance between grating and B layer: ~ 1.5 mm
Neutron irradiation = 3 hours







165 images

Resolution:
0.945 ± 0.004 μm in 1 σ

A. Muneem *et al., J. Appl. Phys. 133, 054902-1-16 (2023)*
A. Muneem, Ph.D. thesis, GIK Institute, Pakistan, 2023

Chart of ordinary nuclei

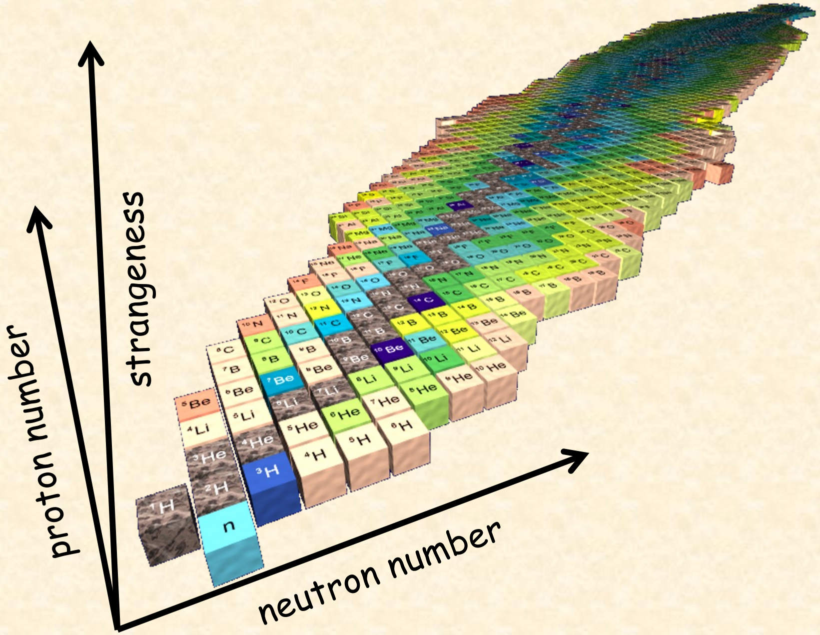
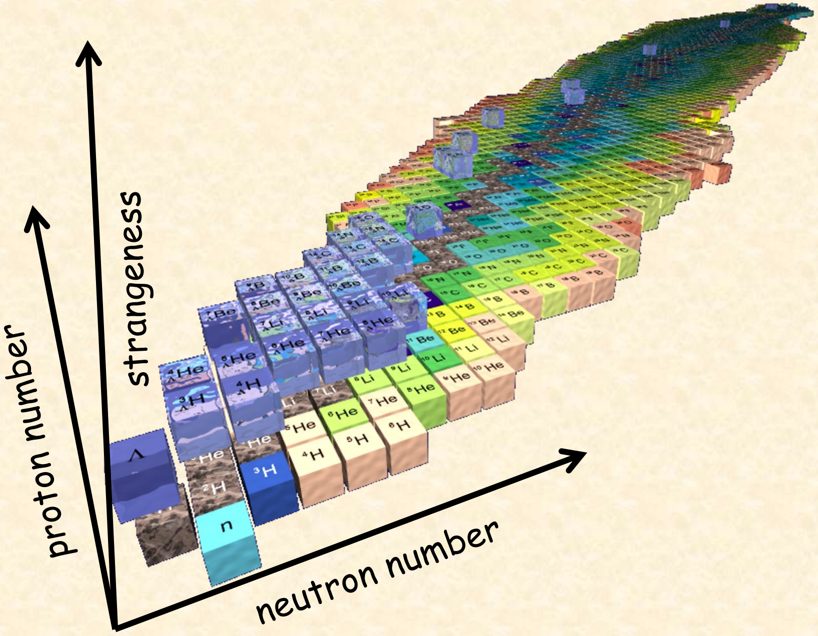


Chart of single-strangeness hypernuclei



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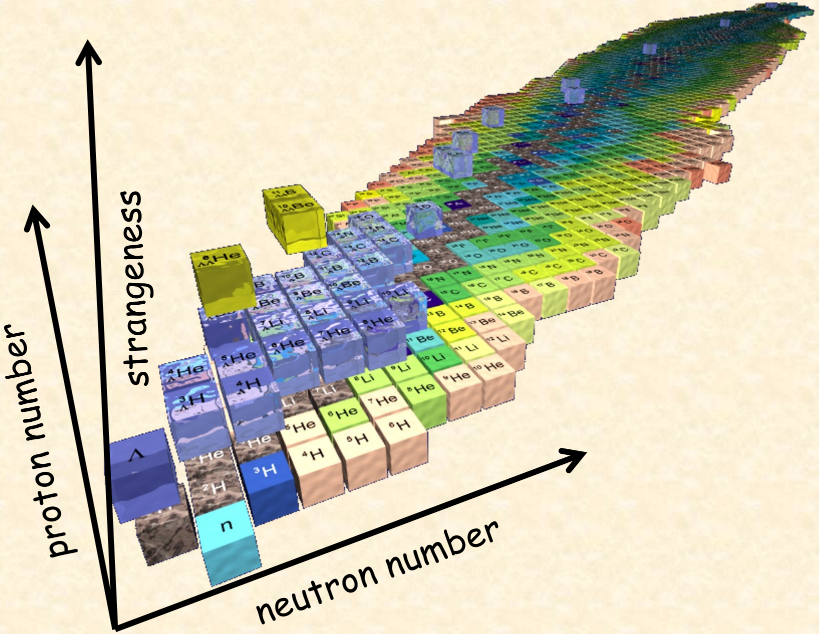
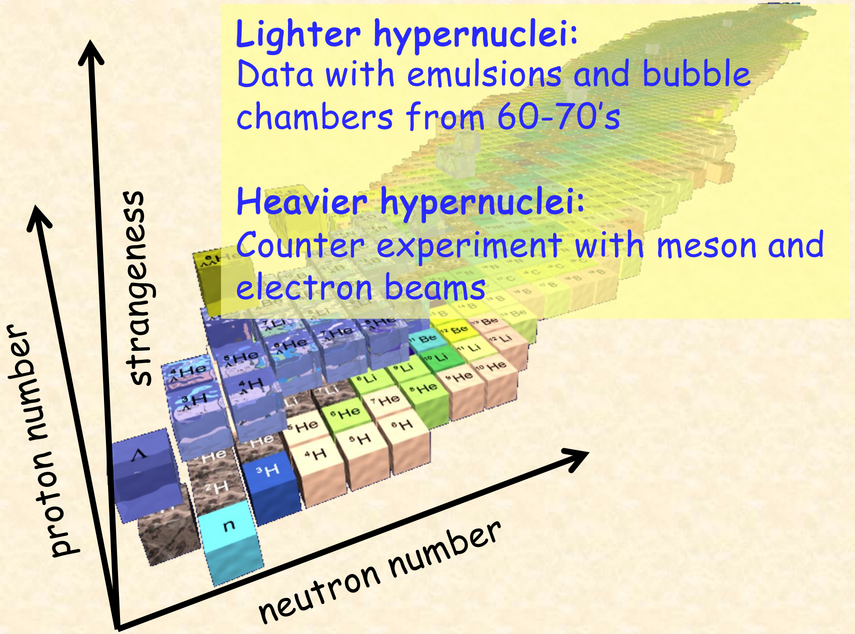


Chart of double-strangeness hypernuclei

Lighter hypernuclei:
Data with emulsions and bubble chambers from 60-70's

Heavier hypernuclei:
Counter experiment with meson and electron beams



Advantage

- Precise spectroscopy
    - Structure in detail
- Clean experiment

Difficulties

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

Hypernuclear spectroscopy with heavy ion beams

HypHI project, started in 2005

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