The WASA-FRS hypernuclear experiment and developments of machine learning analyses with graph neural network

Hiroyuki Ekawa[a]

for the WASA-FRS Collaboration, the Super-FRS Experiment Collaboration,
and the WASA-FRS machine learning Collaboration

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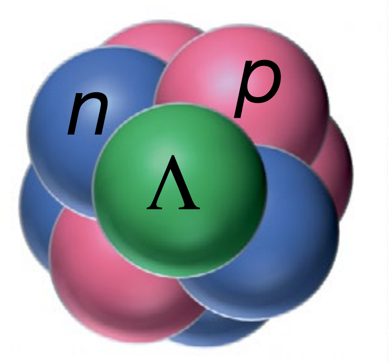
5th - 9th Jun., 2023
The 20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023)

Hypernuclear Production with Heavy-Ion

Hypernucleus



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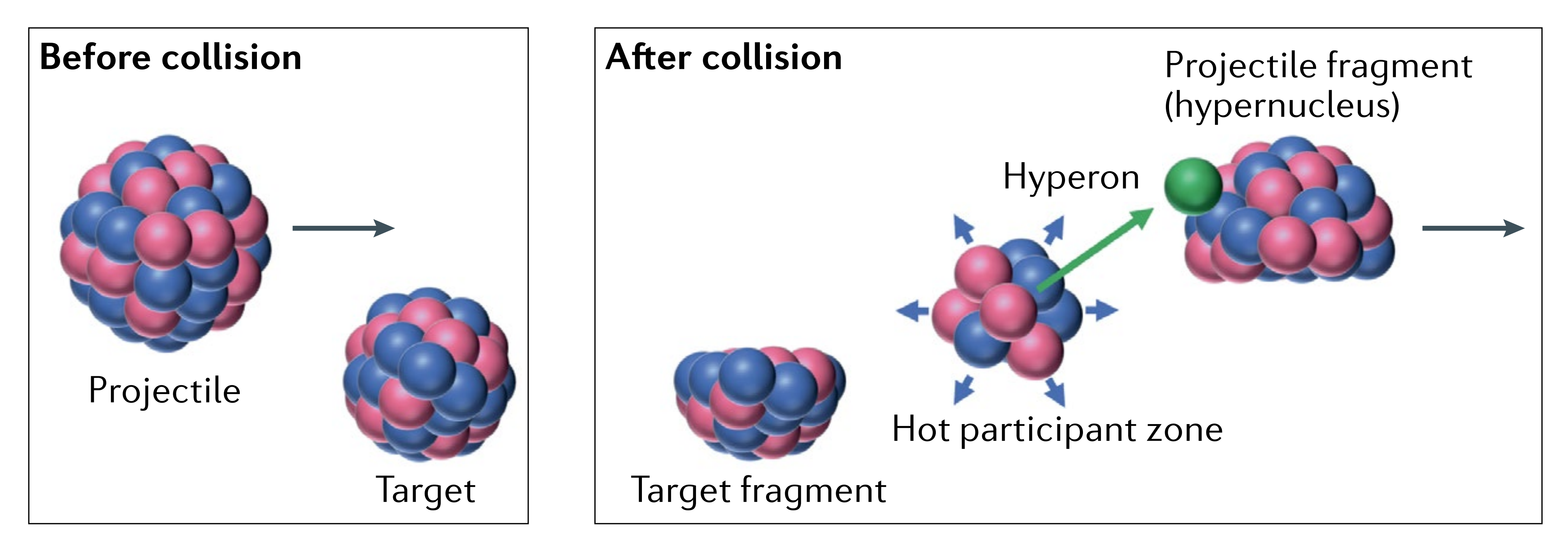


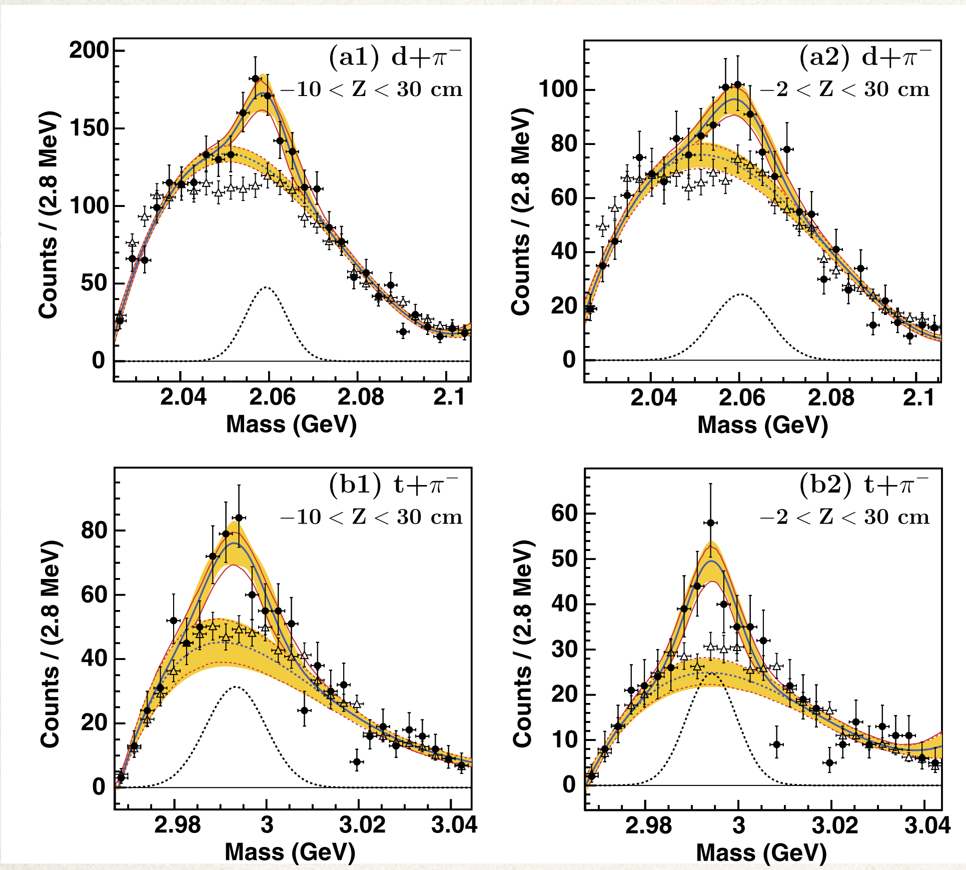
T. R. Saito et al., Nat Rev Phys **3** (2021) 803
DOI : 10.1038/s42254-021-00371-w

- Λ production + Fragmentation
- Invariant mass
- HypHI Phase 0 at GSI in 2009
  - ^{6}Li beam at 2 *A* GeV to ^{12}C target

C. Rappold et al., NPA **913** (2013) 170
C. Rappold et al., PLB **747** (2015) 129

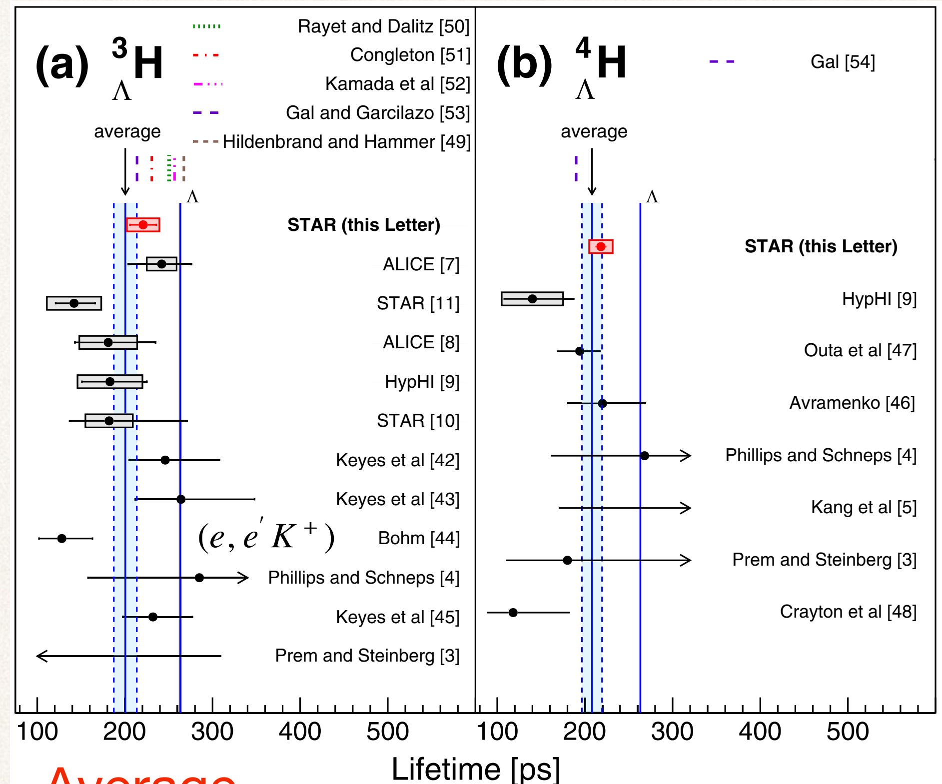
Two Puzzles from HypHI Phase 0

Indication of nnΛ



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

Short lifetime of $^3_\Lambda$H



Average
200 ± 13 ps

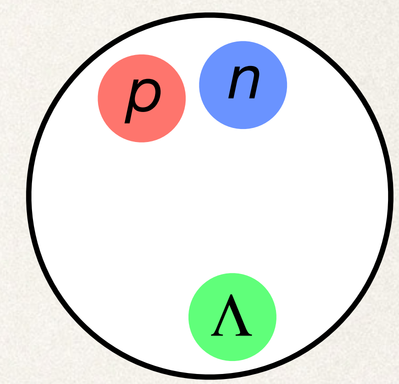
STAR Collaboration, PRL **128** (2022) 202301

$^3_\Lambda$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



τ_Λ = 263 ps

$^3_\Lambda$H lifetime

(Stat.) (Syst.)

HypHI : 183 $^{+42}_{-32}$ ± 37 ps
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ALICE : 181 $^{+54}_{-39}$ ± 33 ps → 242 $^{+34}_{-38}$ ± 17 ps
ALICE Collaboration, PLB **754** (2016) 360 → ALICE Collaboration, PLB **797** (2019) 134905

STAR : 142 $^{+24}_{-21}$ ± 29 ps → 221 ± 15 ± 19 ps
STAR Collaboration, PRC **97** (2018) 054909 → STAR Collaboration, PRL **128** (2022) 202301

JLab E12-17-003 ^{3}H(e, e'K$^+$)

K. Itabashi et al., Few-Body Systems **63** (2022) 16

B. Pandey, et al., Phys. Rev. C **105** (2022) L051001

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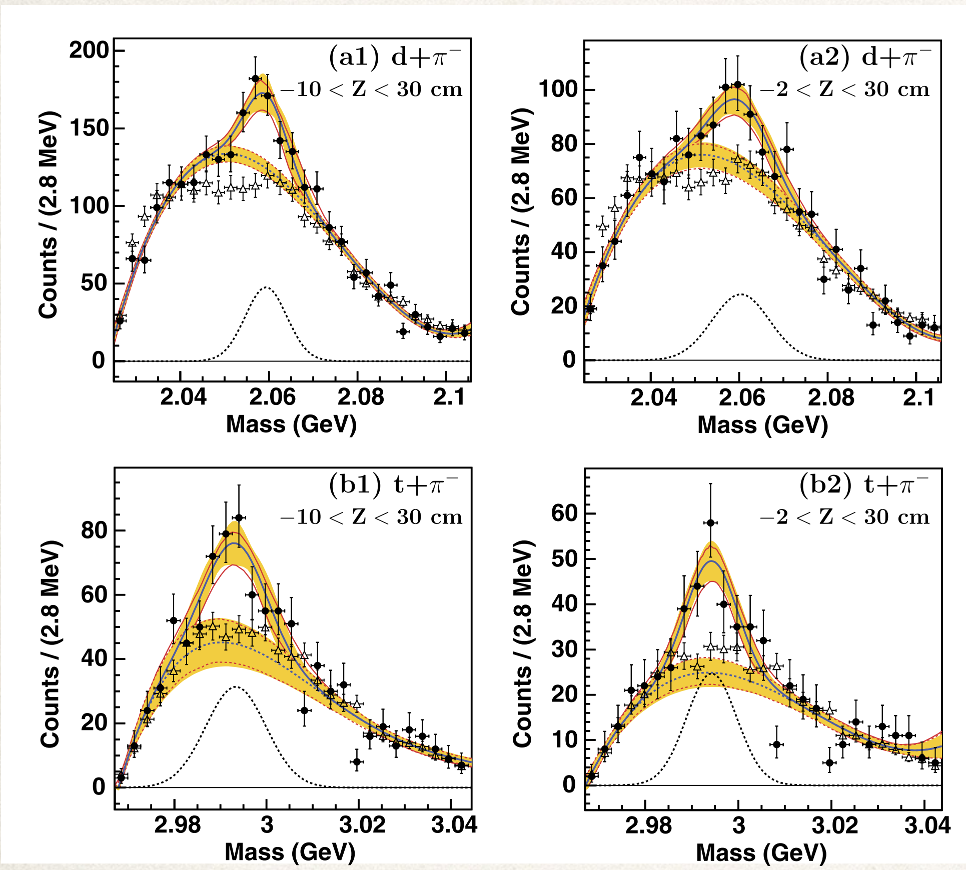

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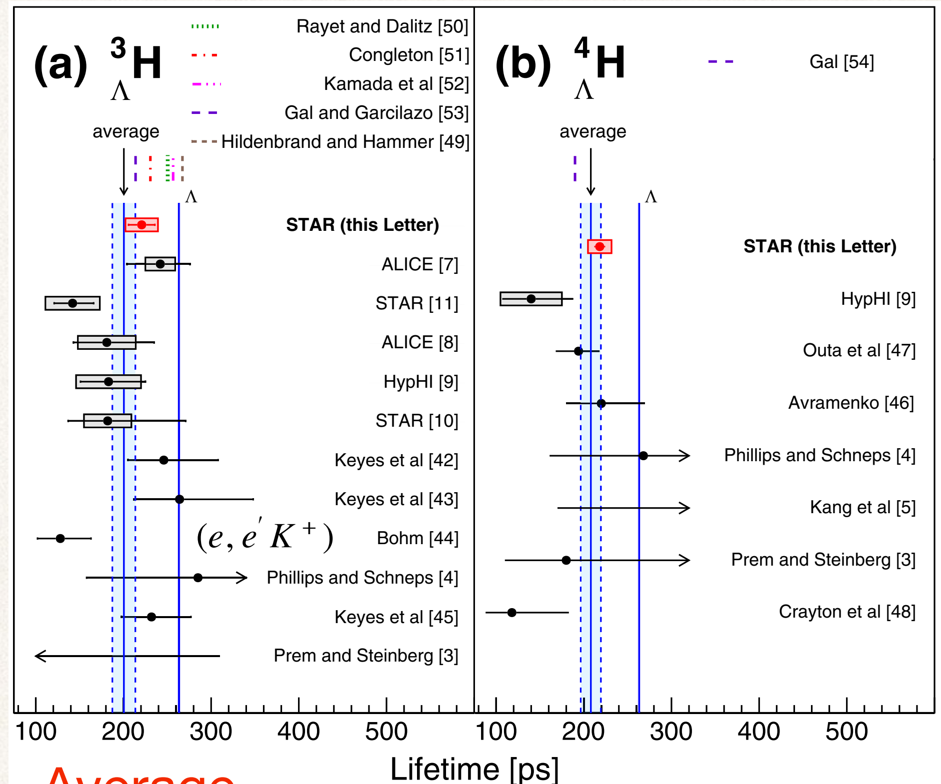

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STAR (2020)
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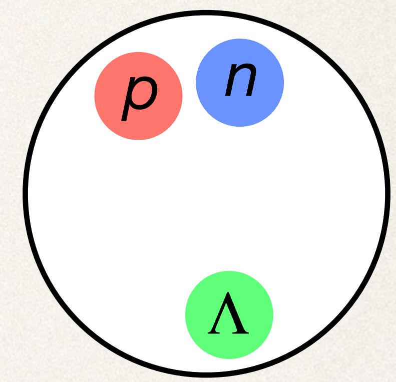
STAR Collaboration, Nat. Phys. **16** (2020) 409



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Two Puzzles from HypHI Phase 0

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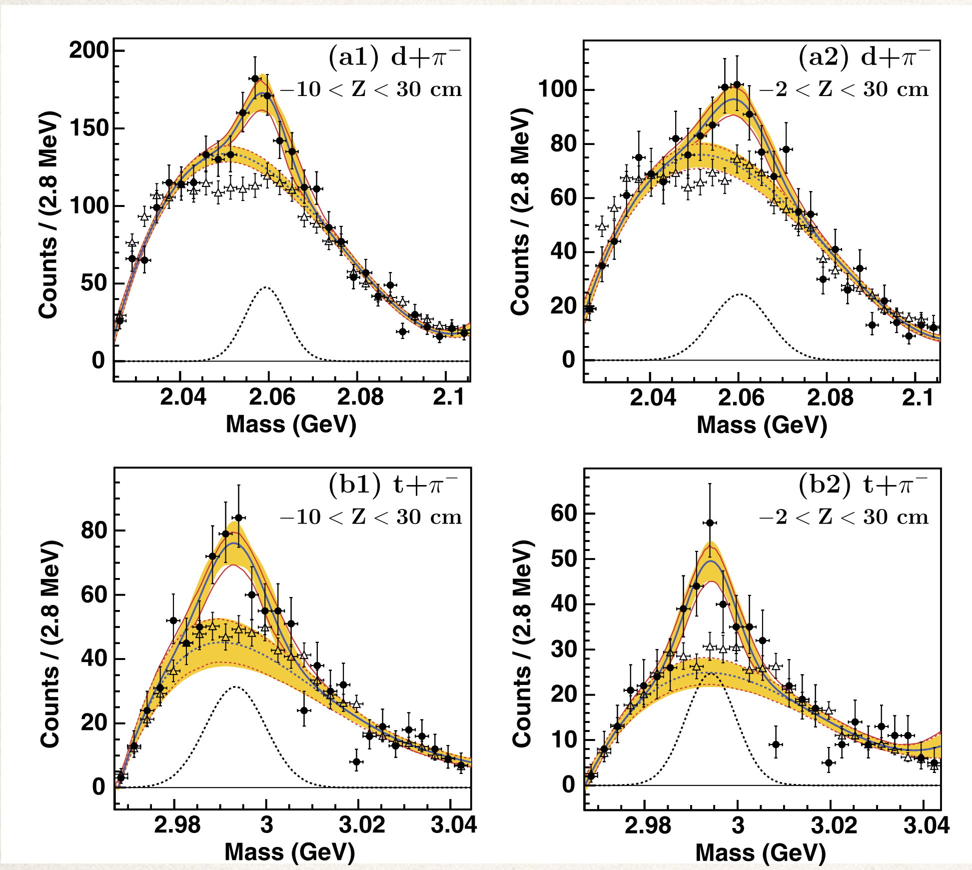

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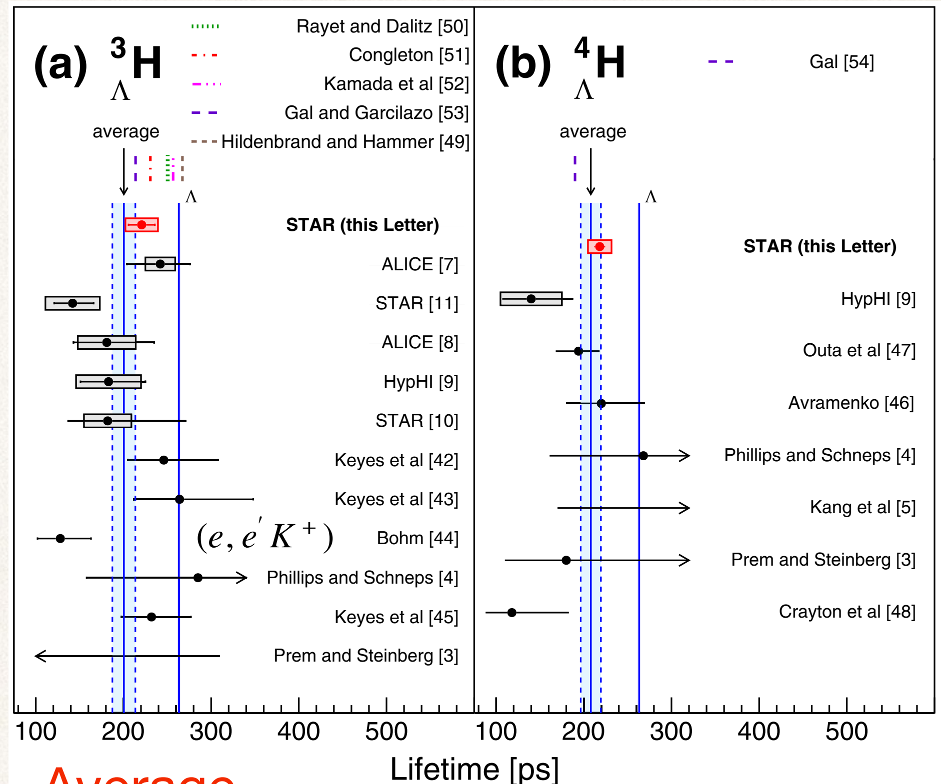

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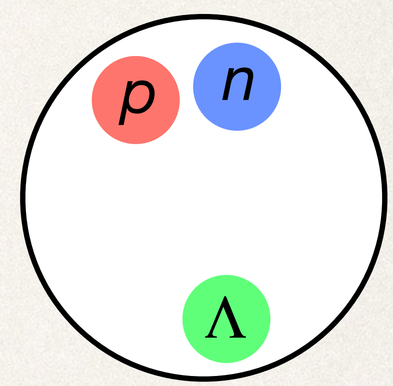
Takehiko Saito's talk, Jun 8, 2023, 5:05 PM



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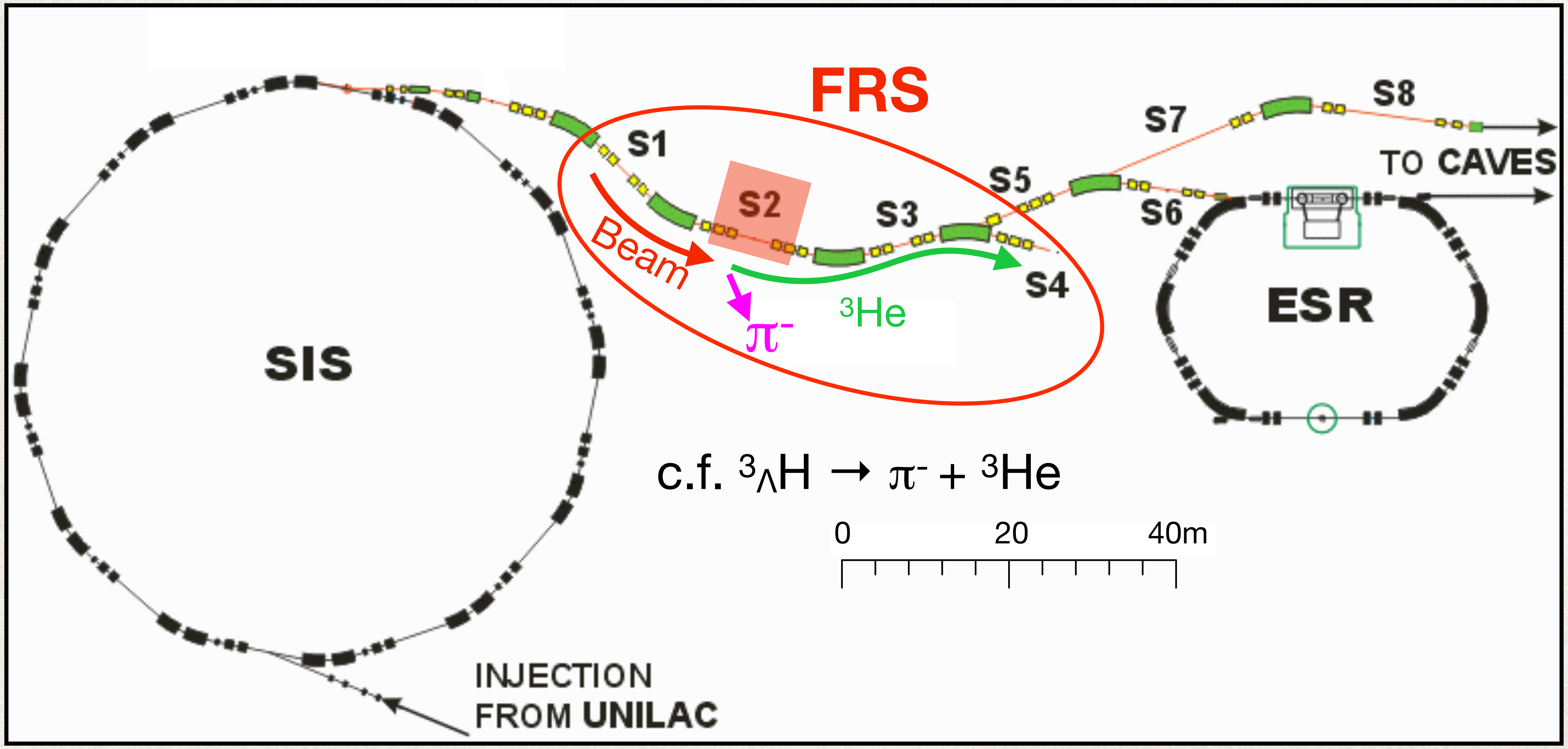
New and more precise measurement is necessary !

WASA-FRS HypHI

WASA-FRS Experiment at GSI (HypHI, η'-nuclei)

- FRS : momentum resolution : $\Delta p/p = 10^{-4}$
  (**FR**agment **S**eparator)
- WASA ← used at COSY in Jülich
  (**W**ide **A**ngle **S**hower **A**pparatus)
- Beam : ^{6}Li / ^{12}C with 1.96 *A* GeV
- Target : ^{12}C (diamond) 9.87 g/cm^2
- Objective (HypHI)
  - $^{3}_{\Lambda}H \rightarrow \pi^- + {}^{3}He$
  - $^{4}_{\Lambda}H \rightarrow \pi^- + {}^{4}He$
  - $nn\Lambda \rightarrow \pi^- + d + n$



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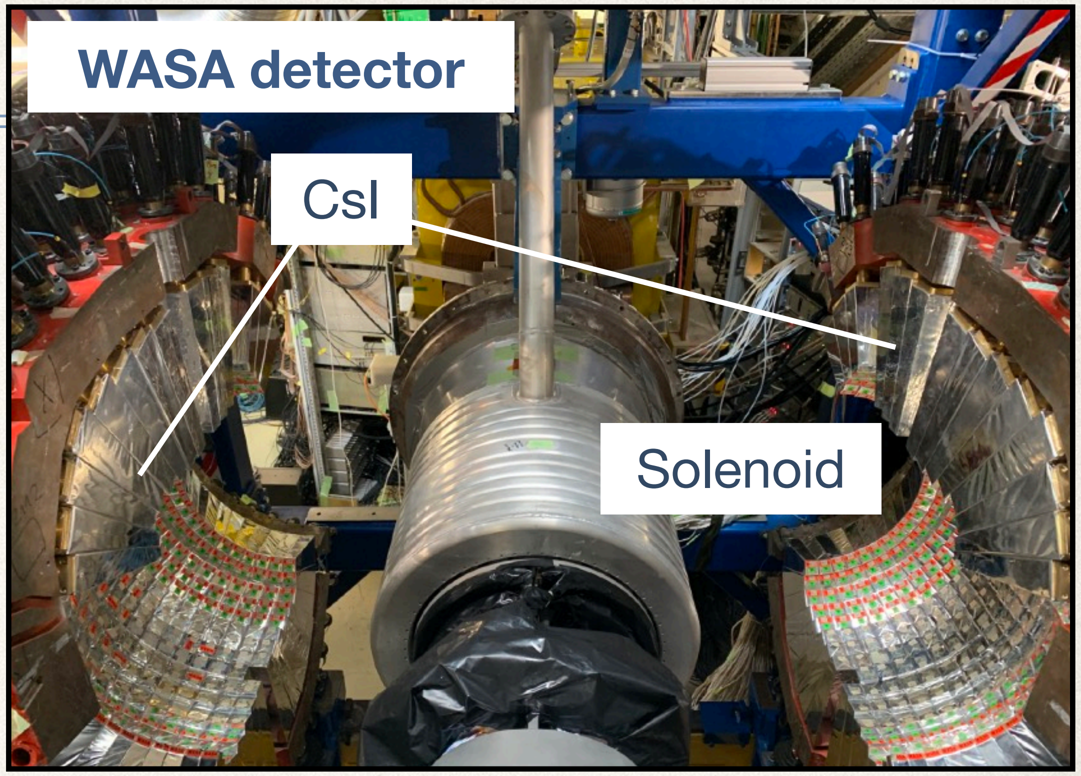

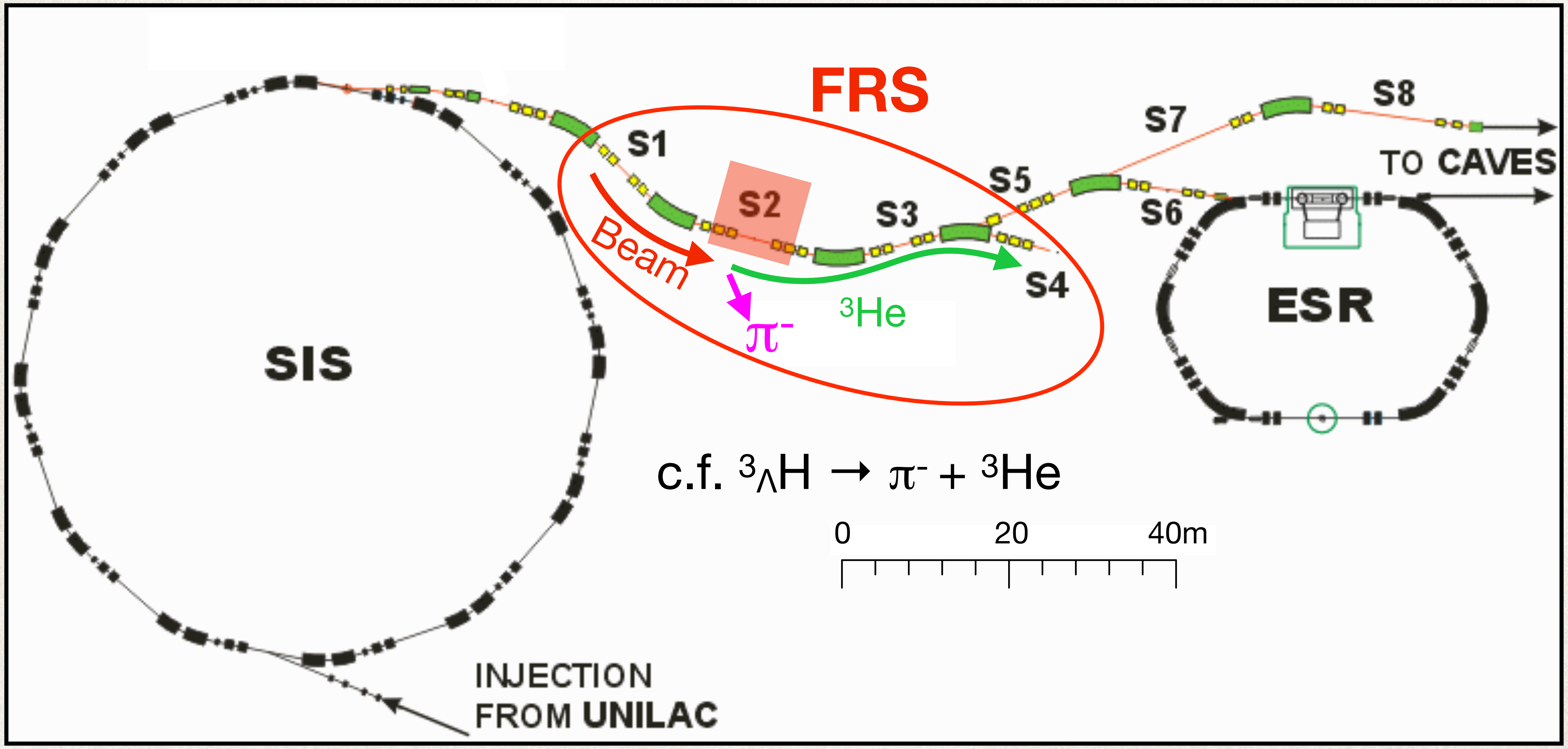

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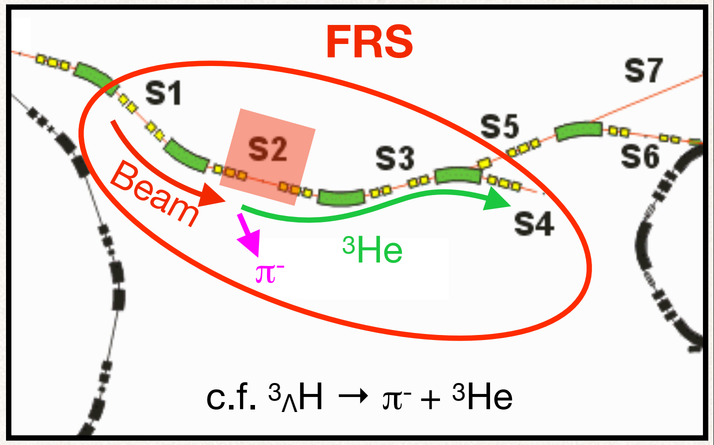

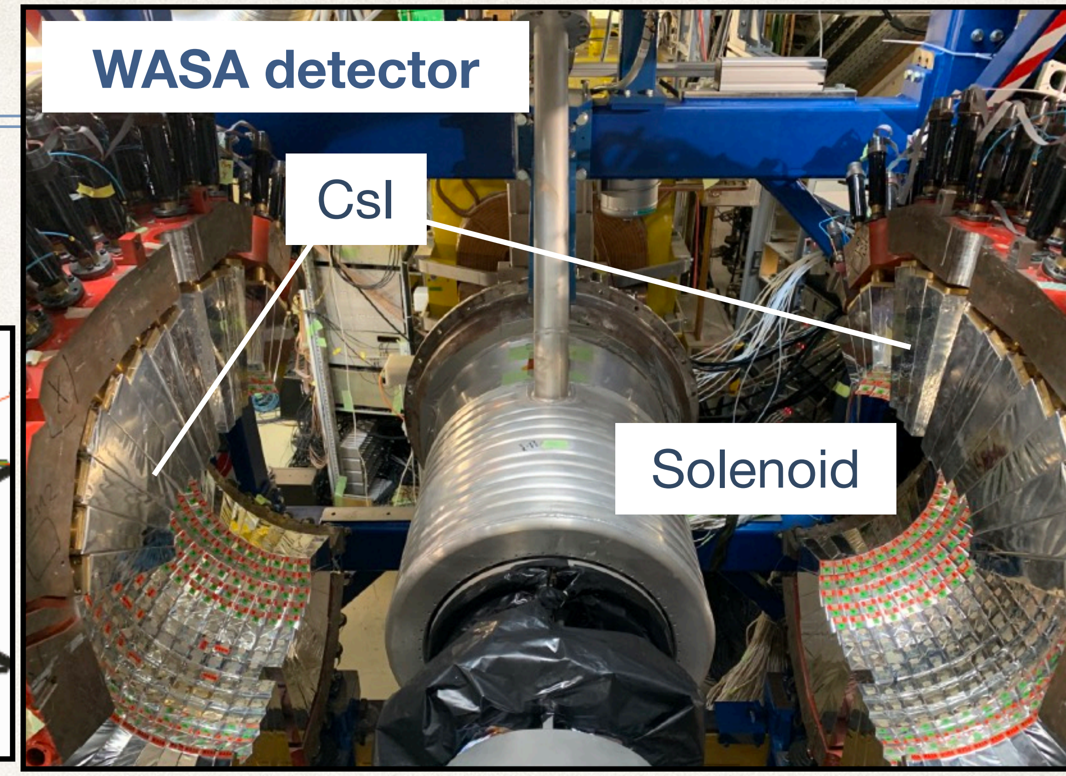

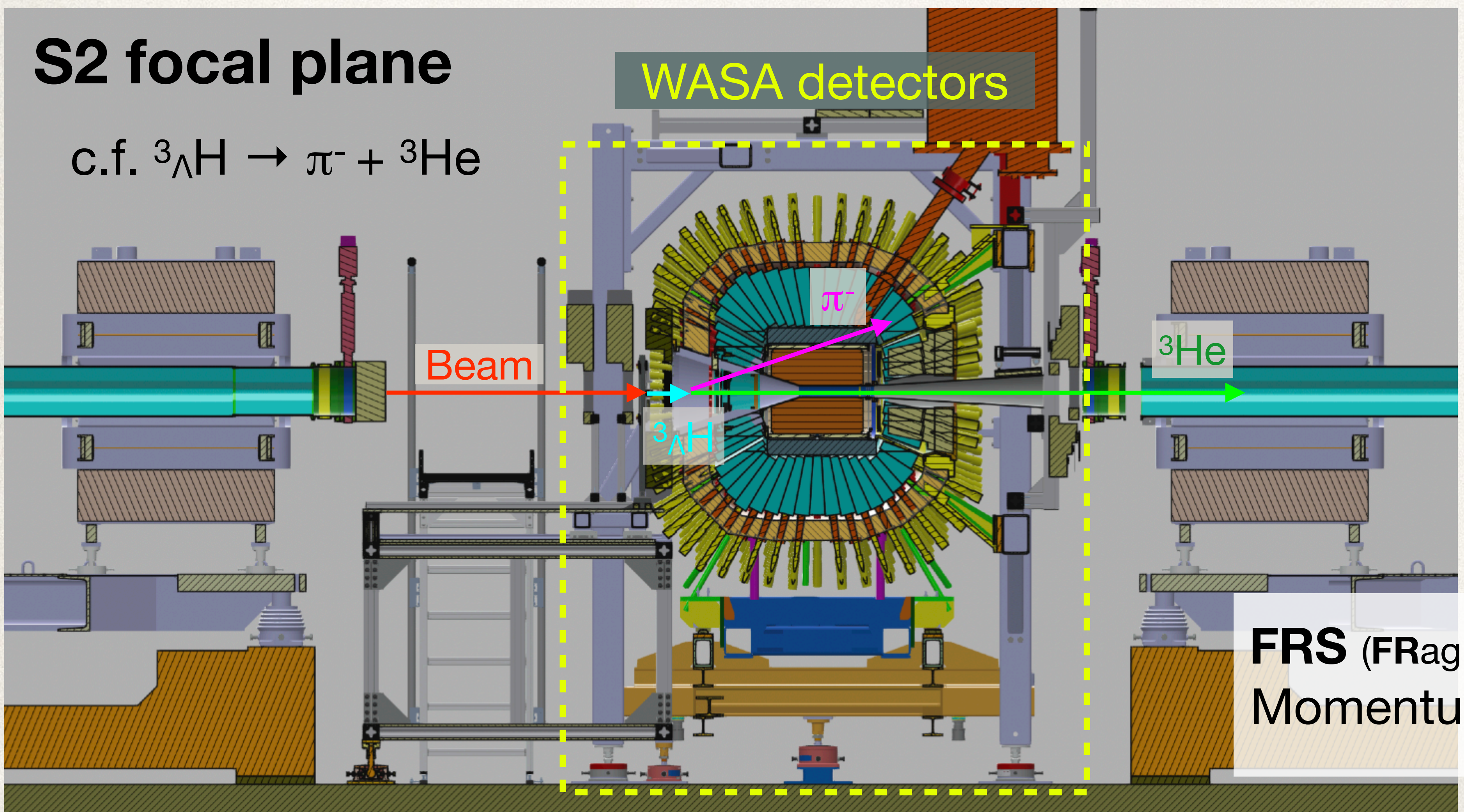

MC simulation
4 days measurement
Significance : 120 σ
Lifetime accuracy : 8 ps

Data taking
Jan. - Mar. 2022

FRS (**FR**agment **S**eparator)
Momentum resolution : $\Delta p/p = 10^{-4}$

WASA Setup

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

Magnetic field : 1 T (at center)

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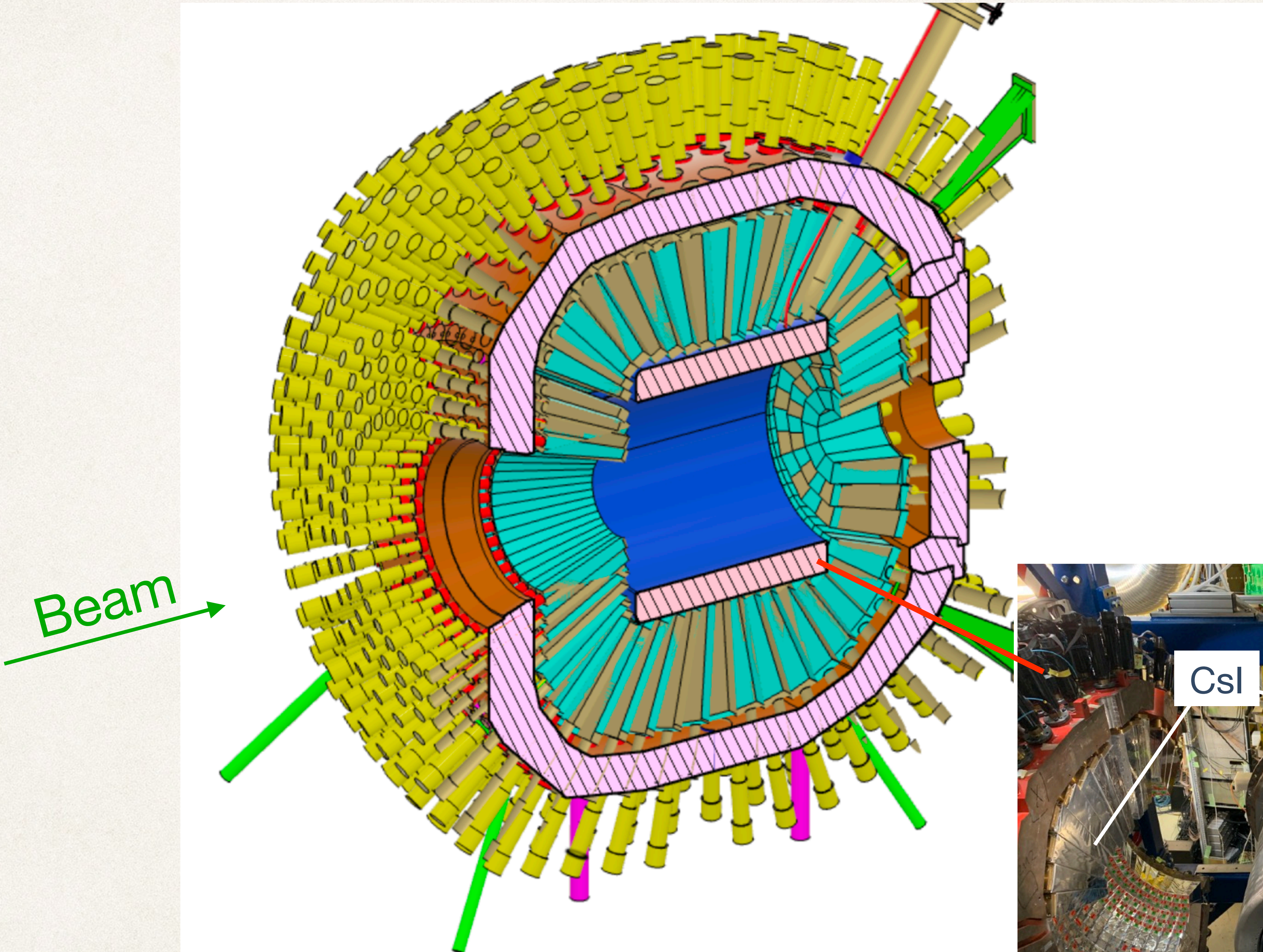

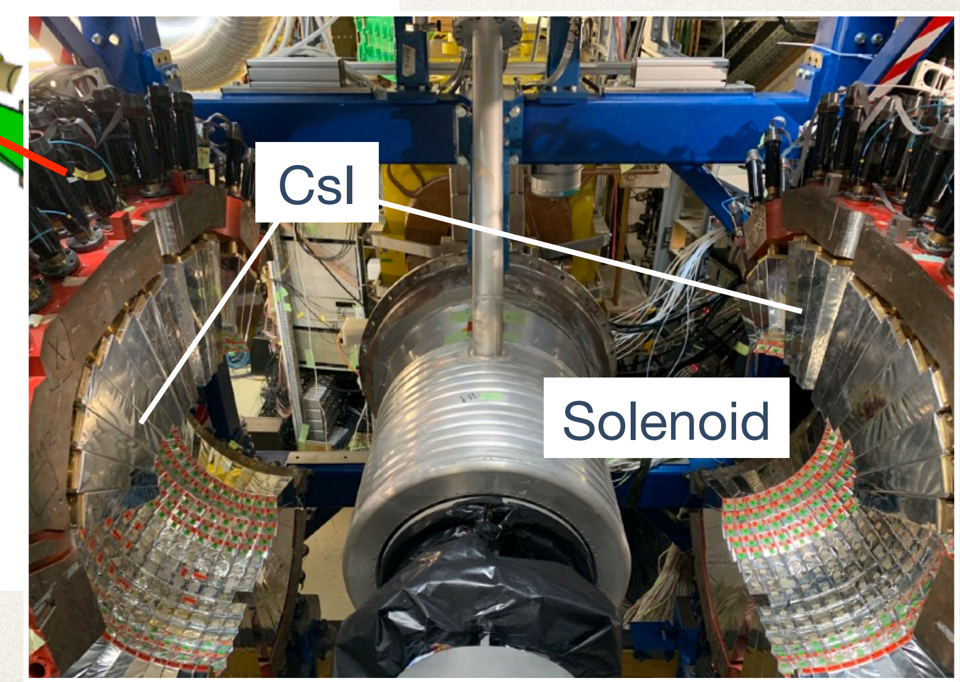

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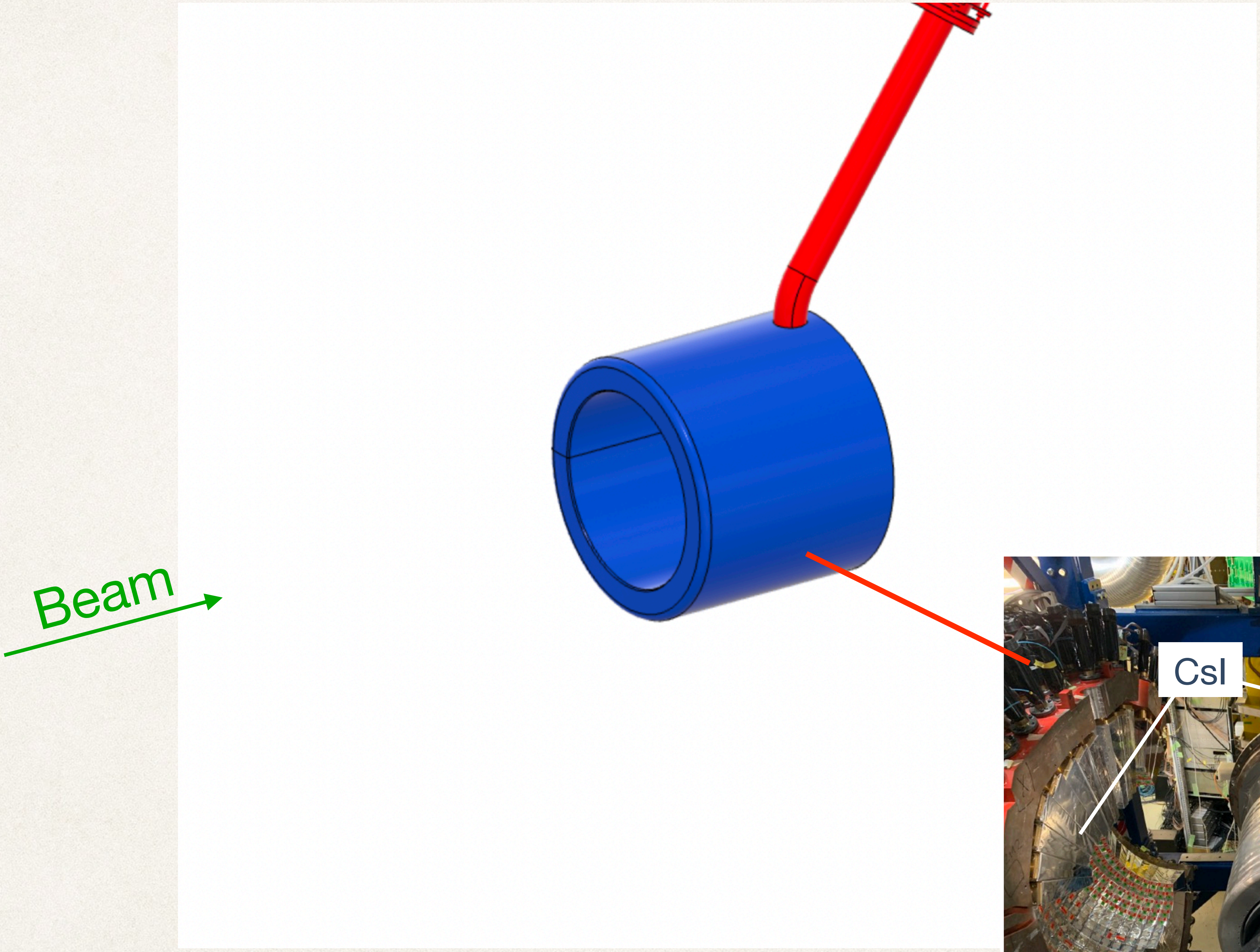

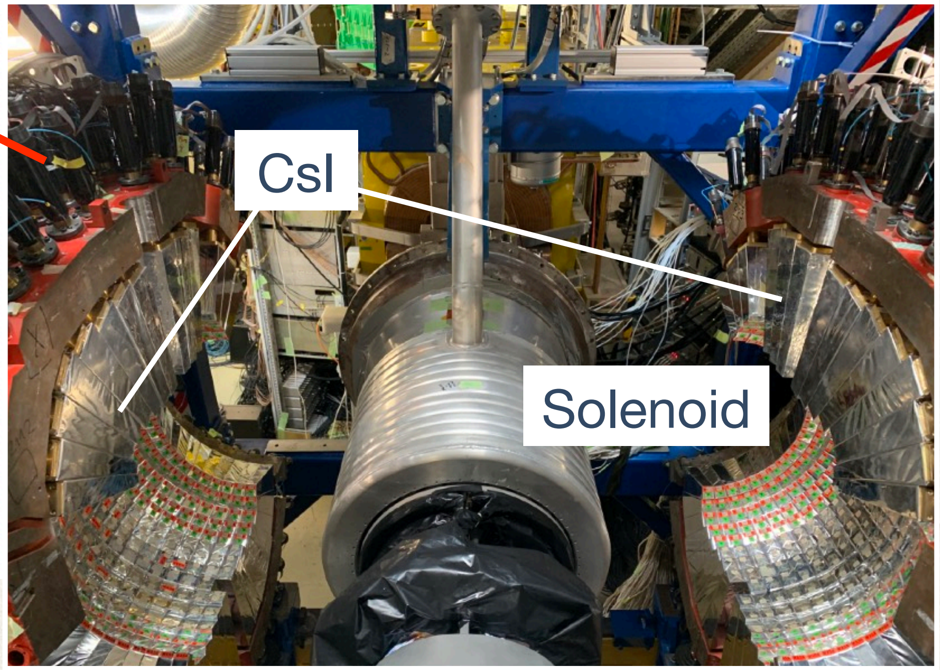

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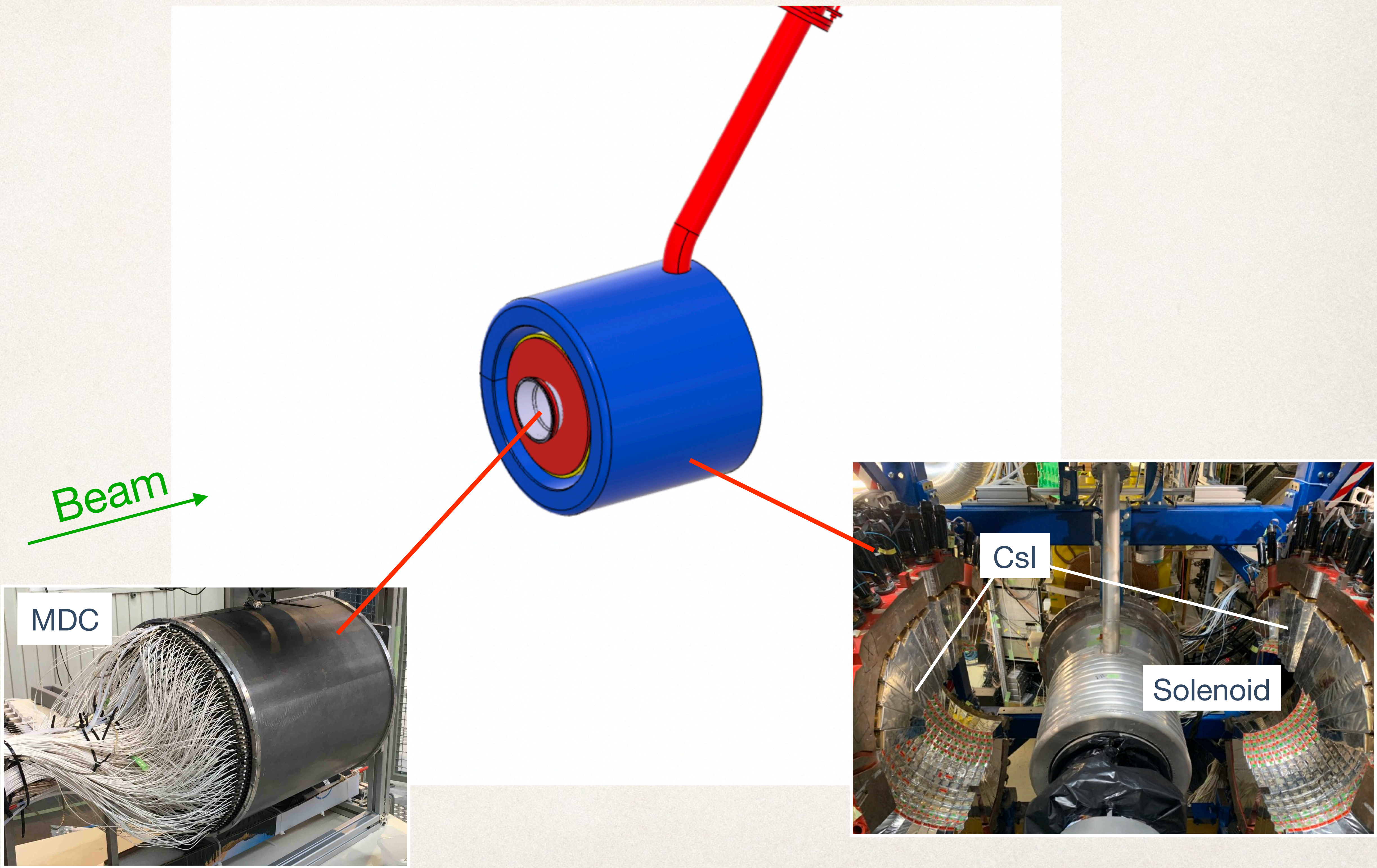

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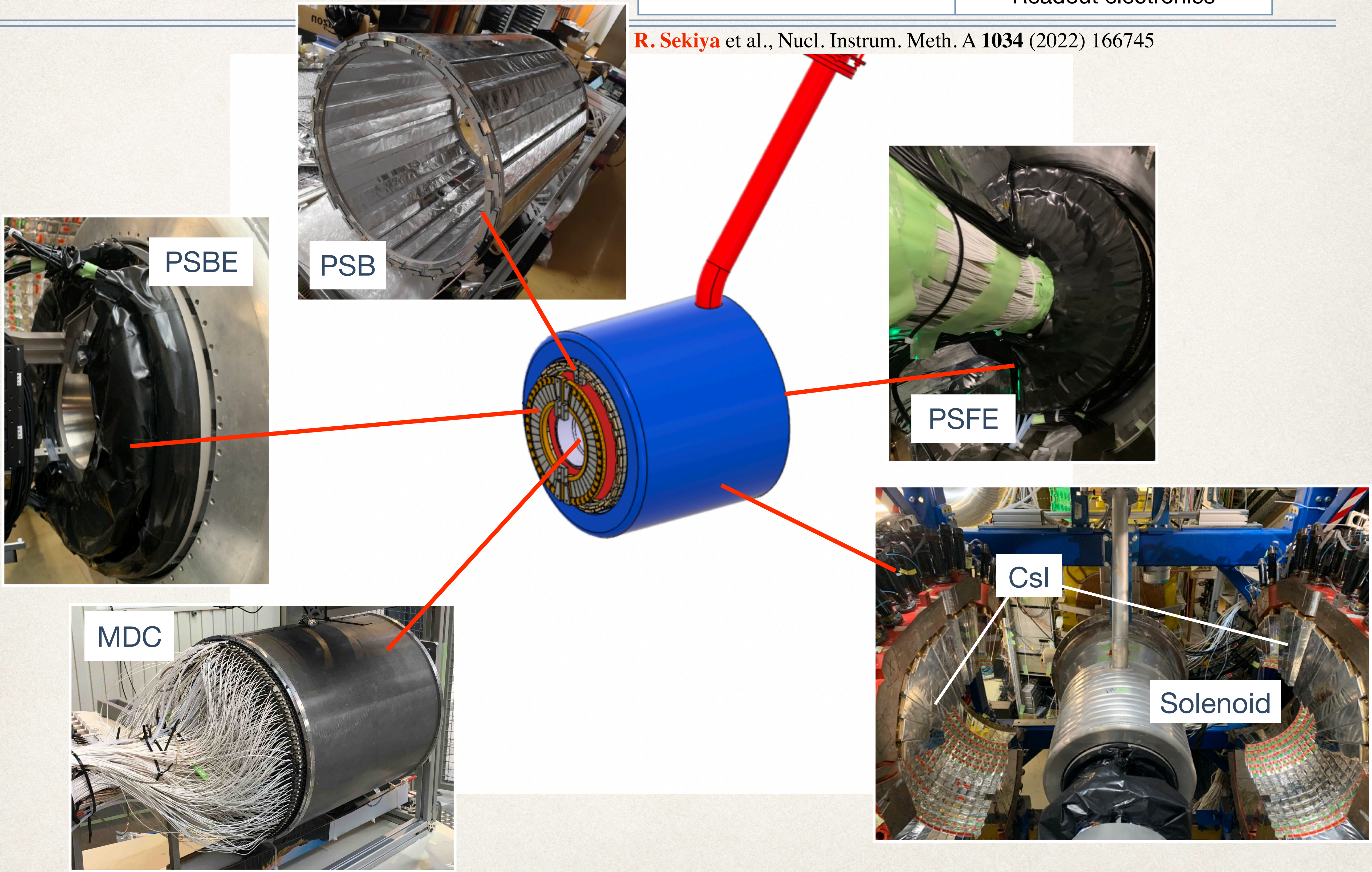
R. Sekiya et al., Nucl. Instrum. Meth. A **1034** (2022) 166745



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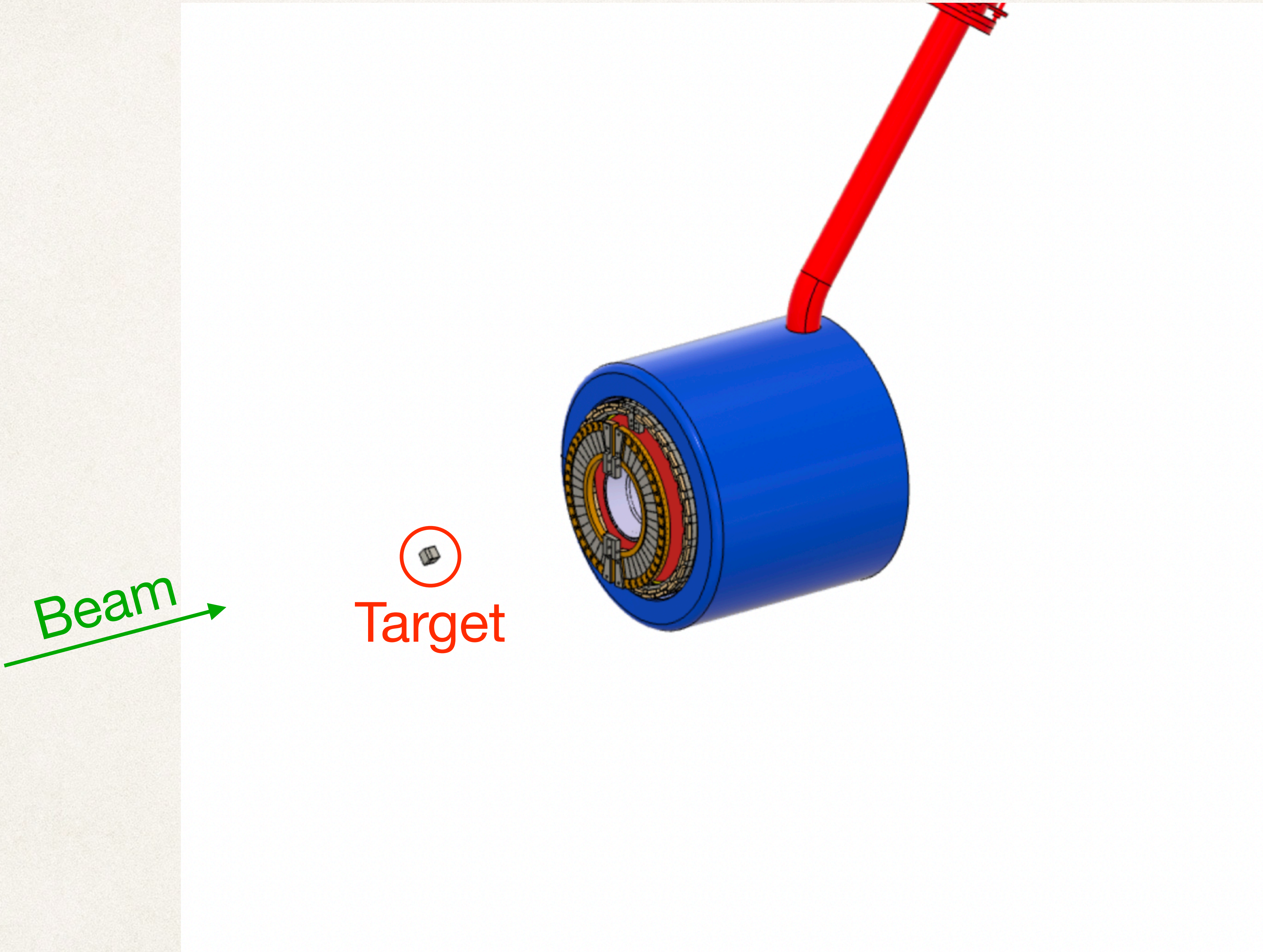

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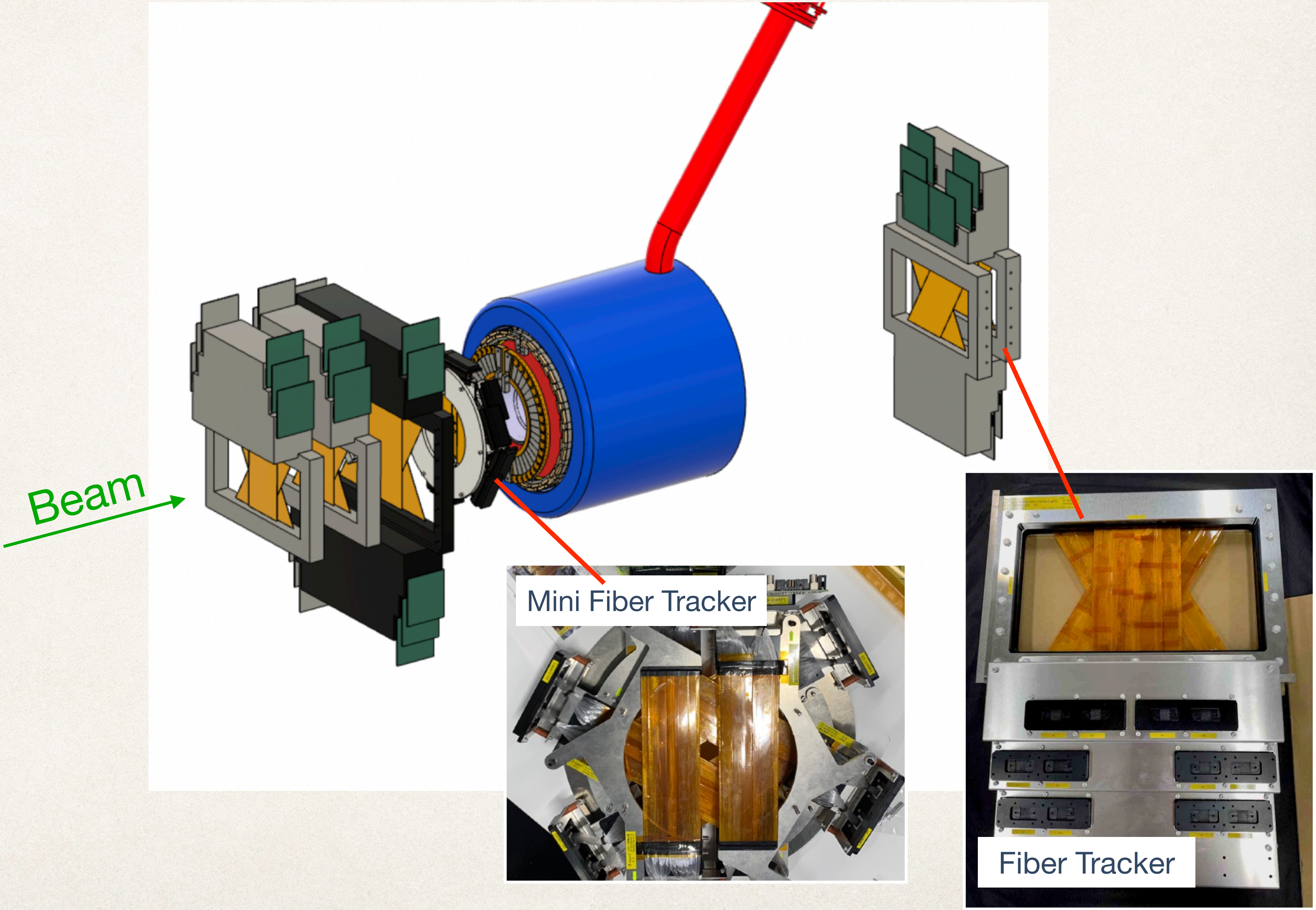

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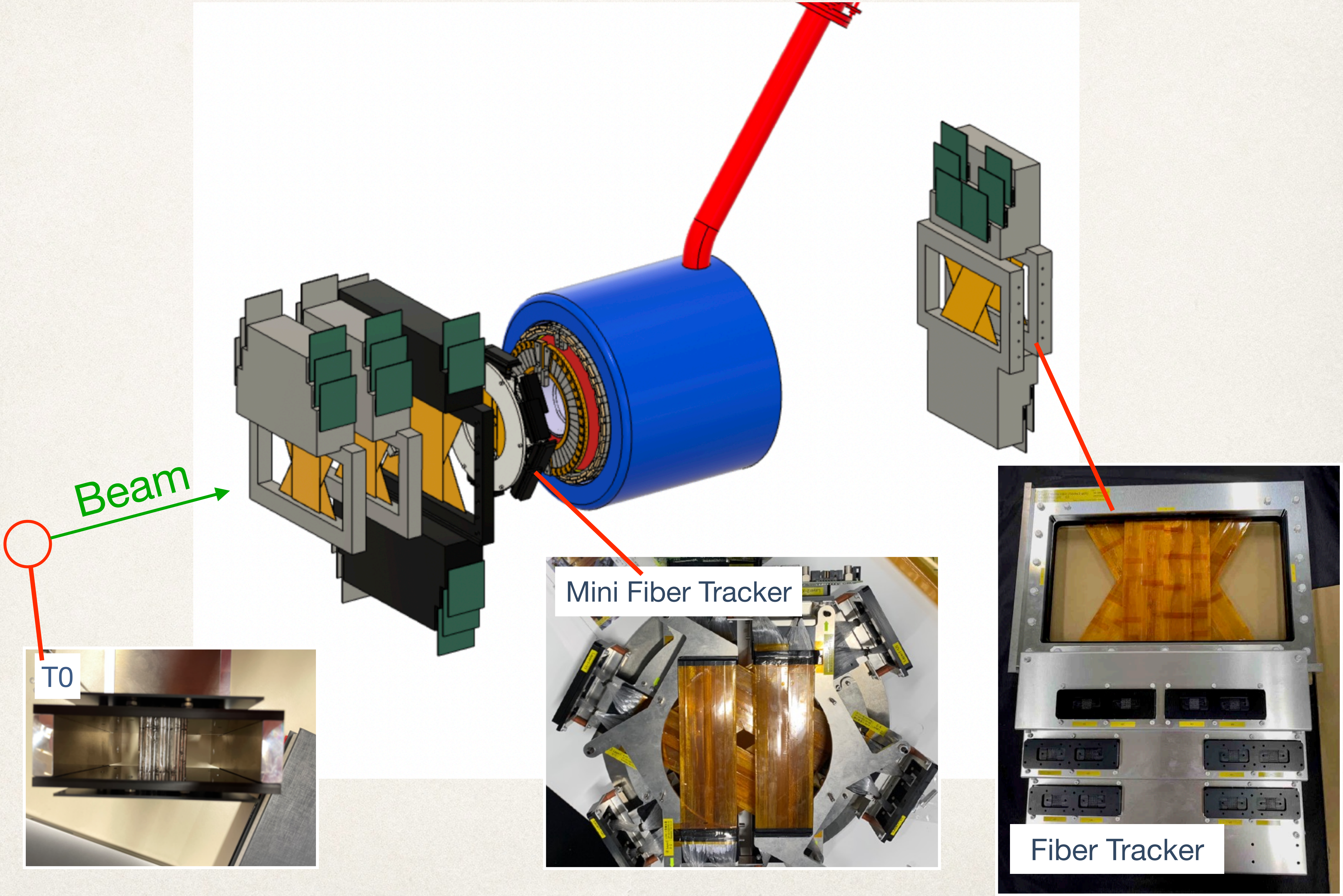

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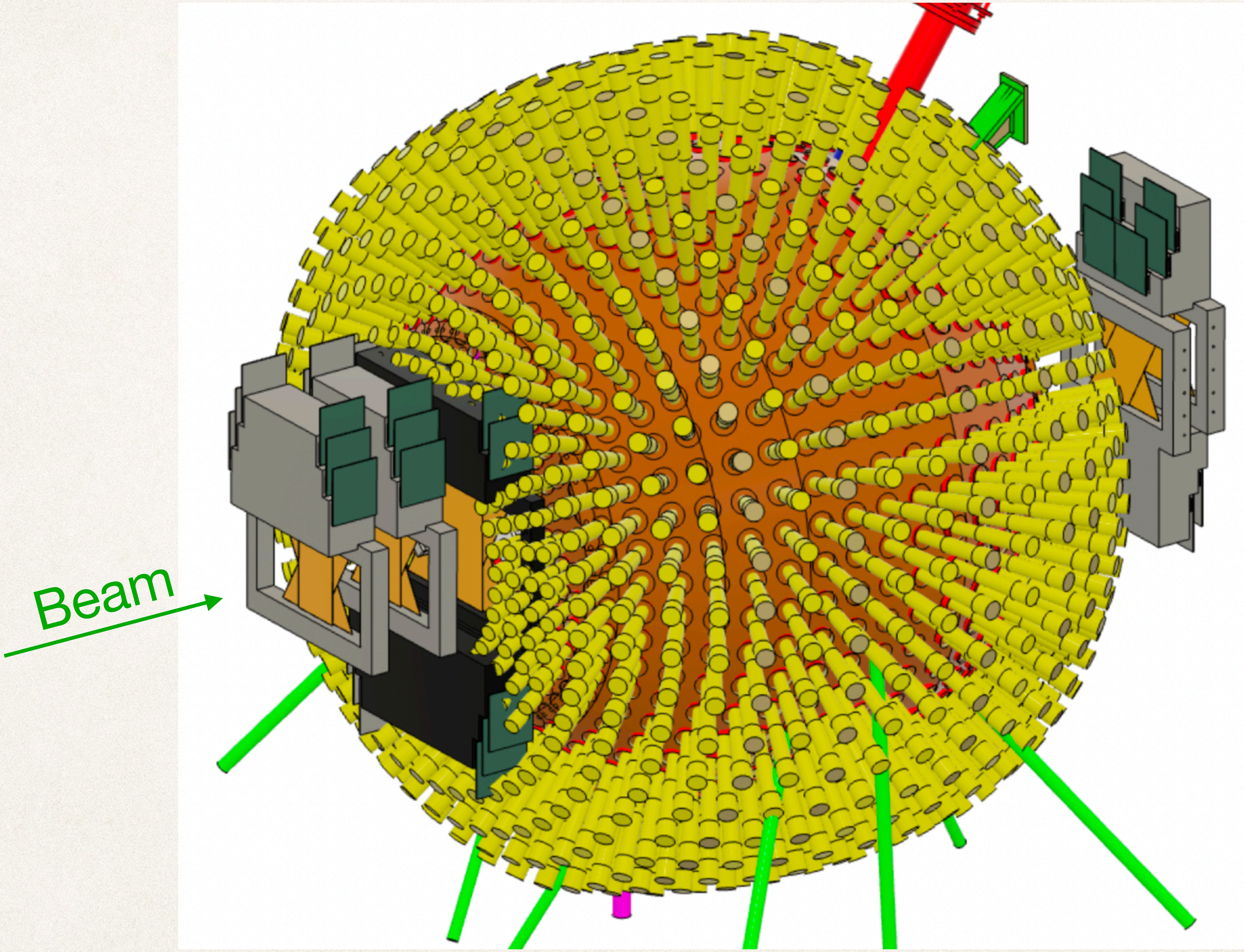

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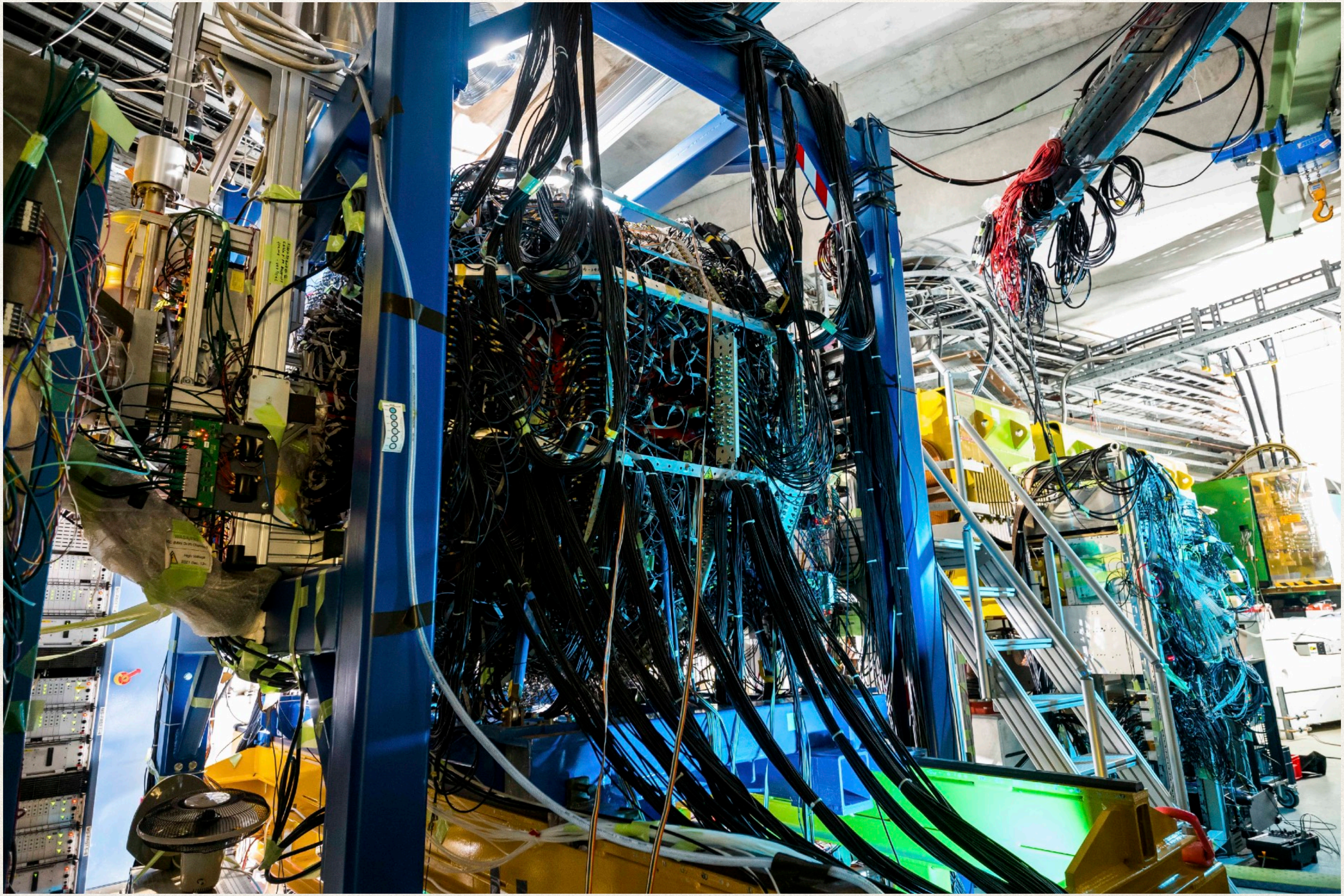
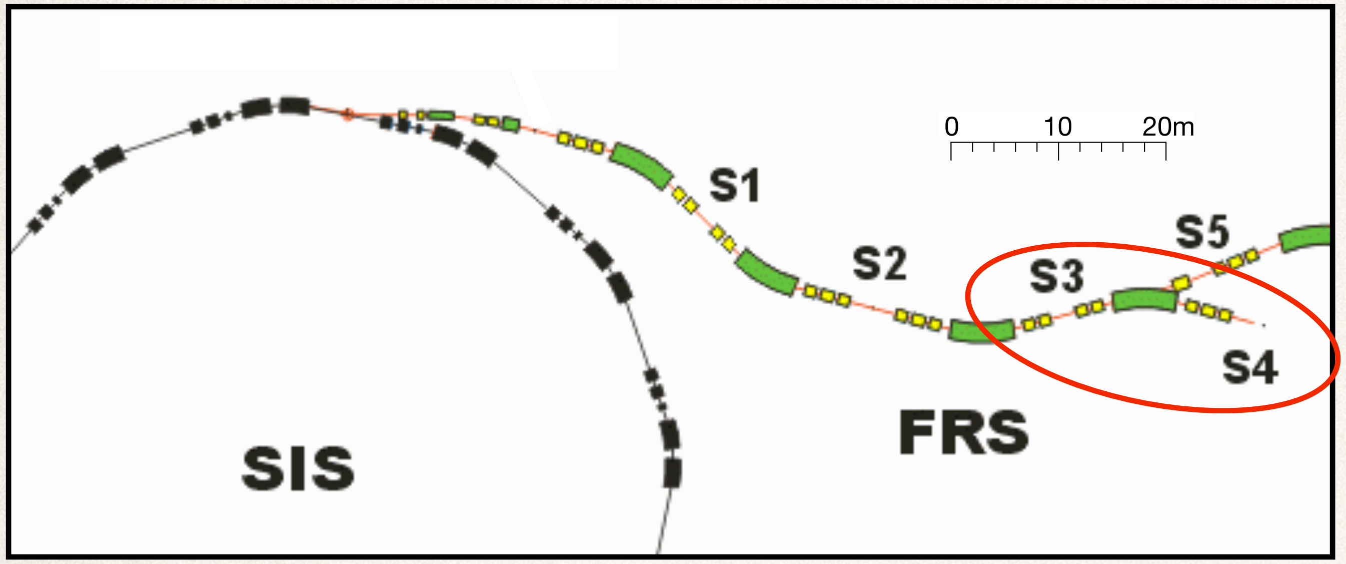


Photo by Jan Hosan and GSI/FAIR

FRS Analysis

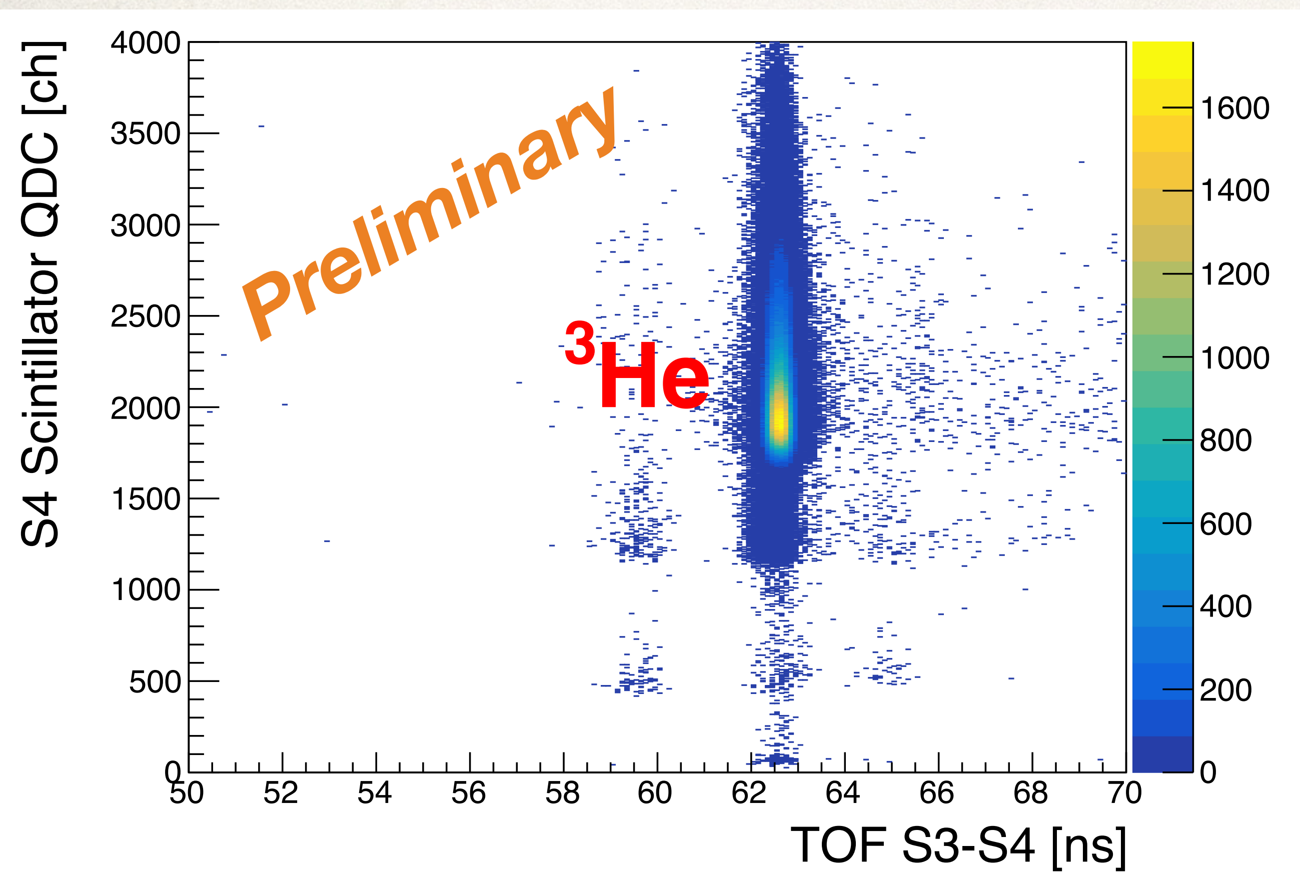


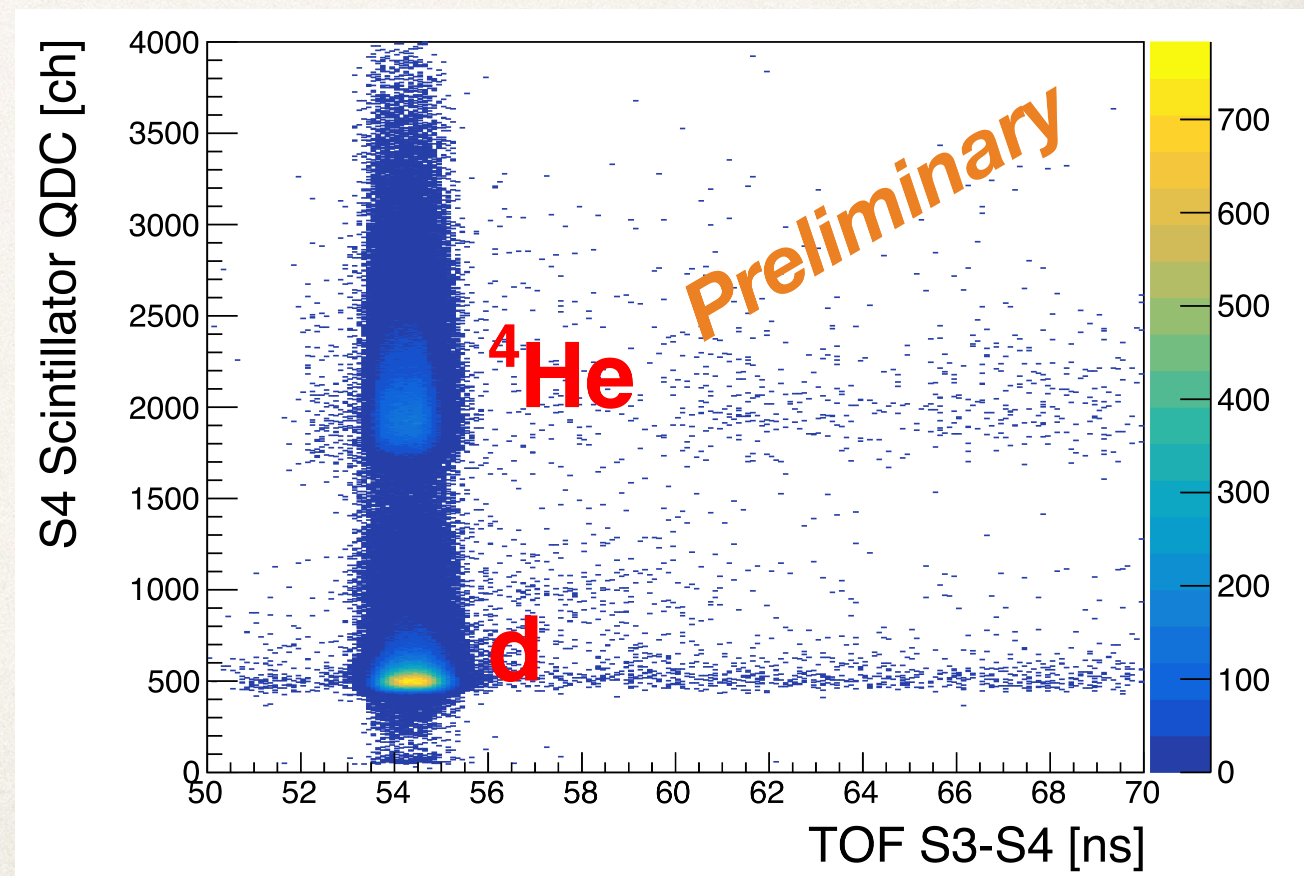
Fragments PID

- identified in S3 - S4
- Plastic scintillators
- TOF, dE

Momentum and Angle reconstruction

- S2 DFTs & S4 MWDC
- Momentum : 5×10^{-4} (σ)
- Angular : ~0.8 mrad (σ)





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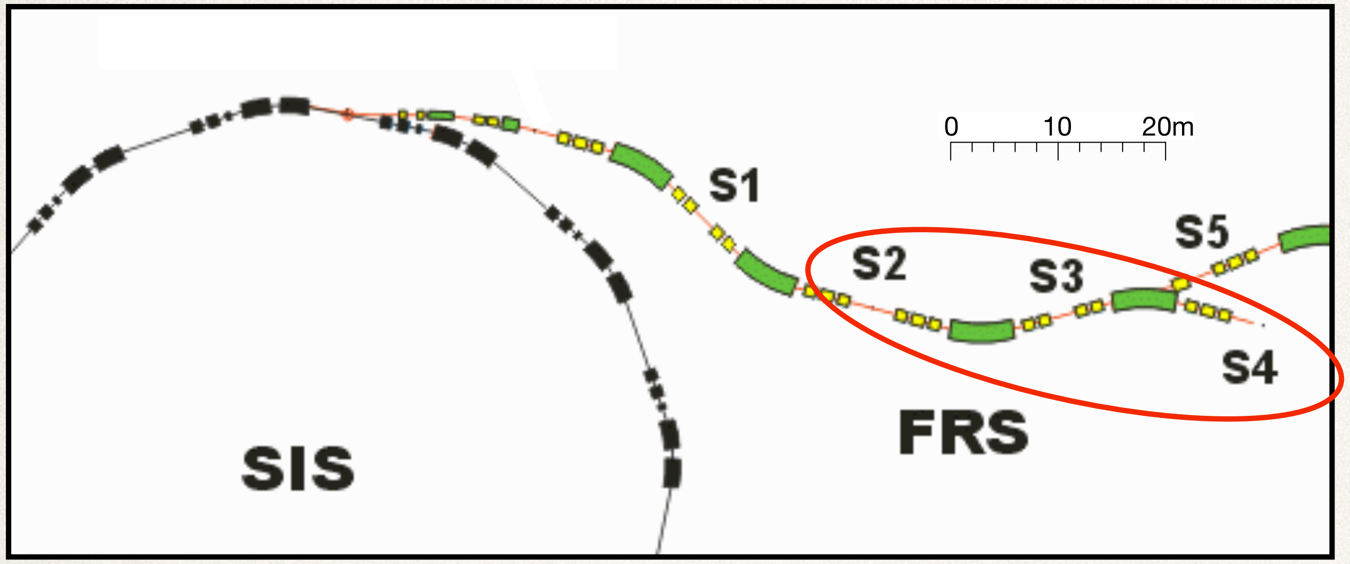

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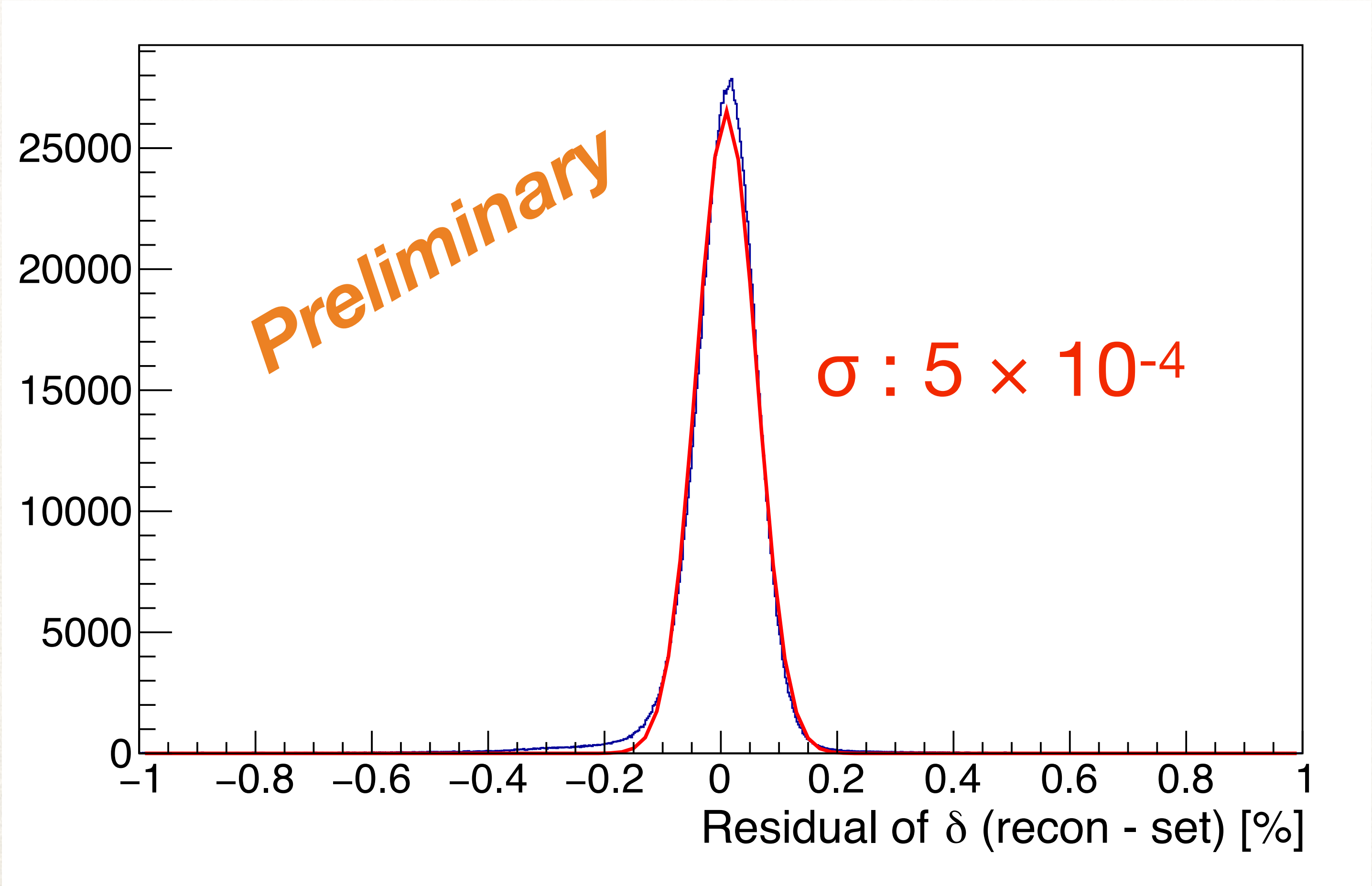

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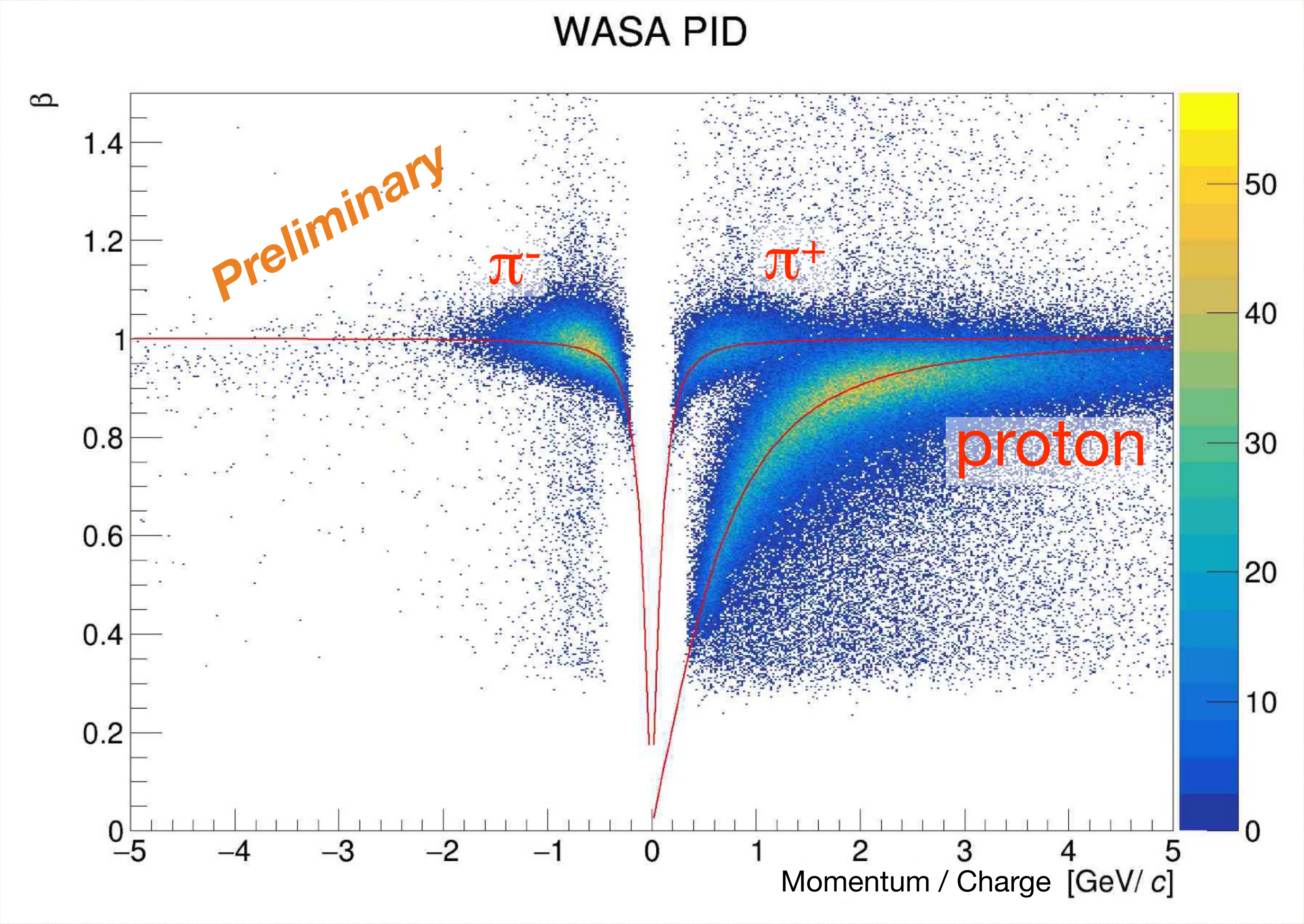
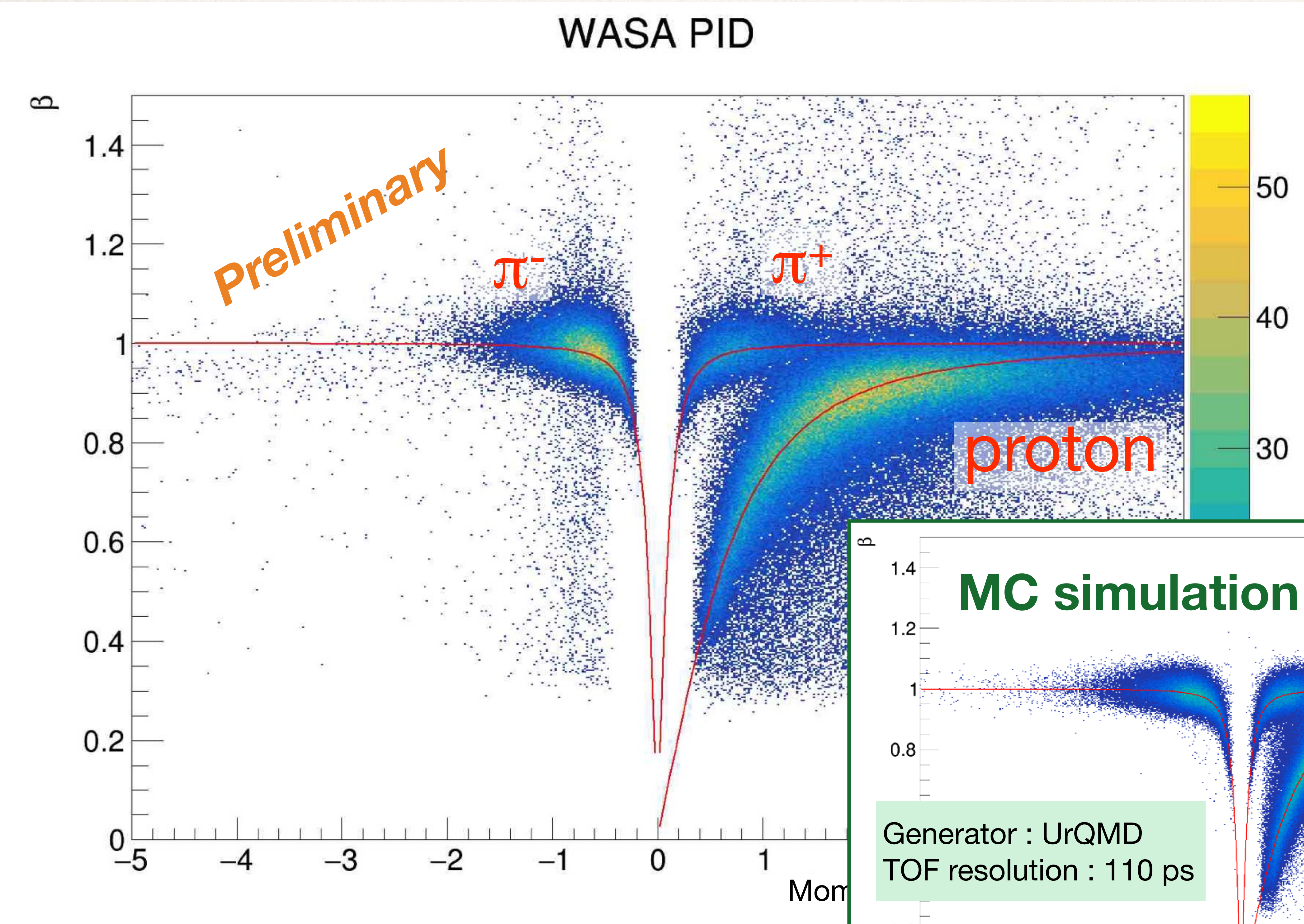
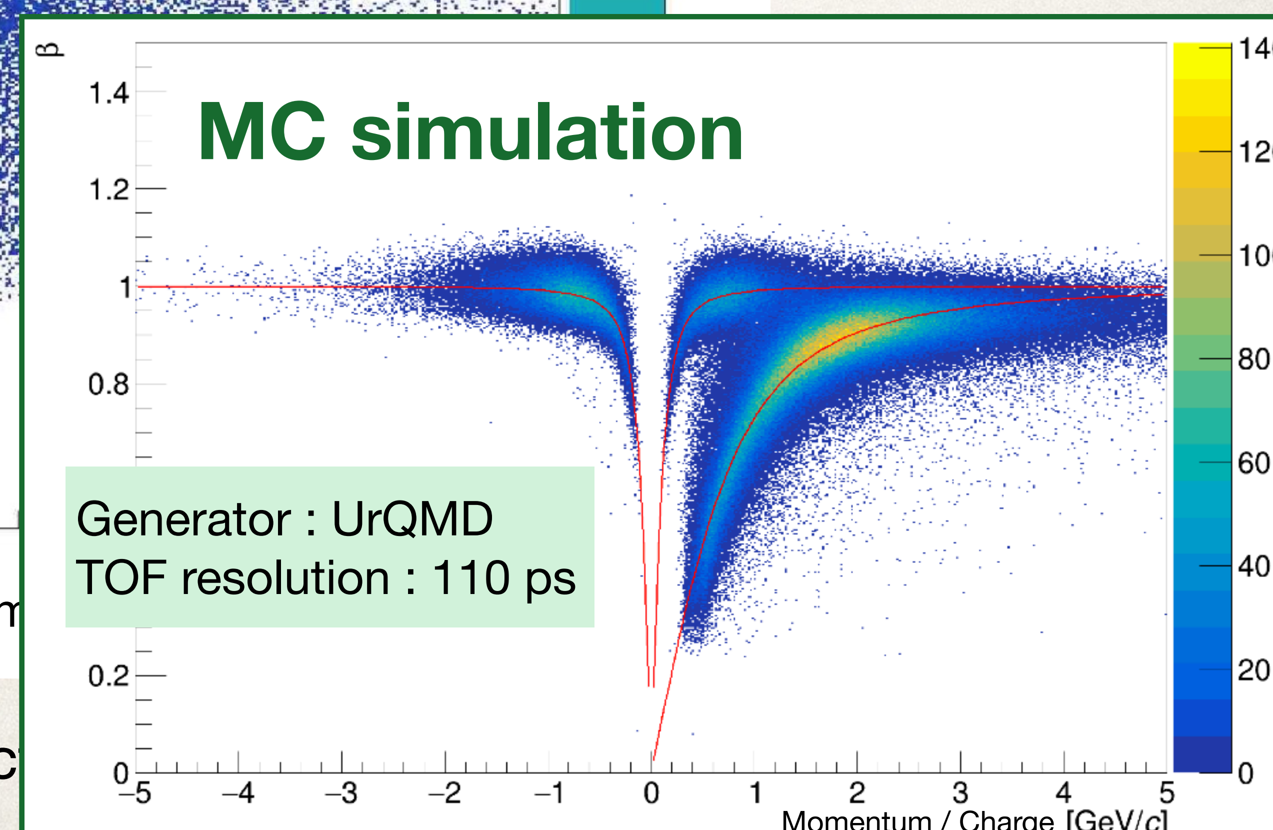


Charged particles going to the WASA central detectors are reconstructed

WASA PID





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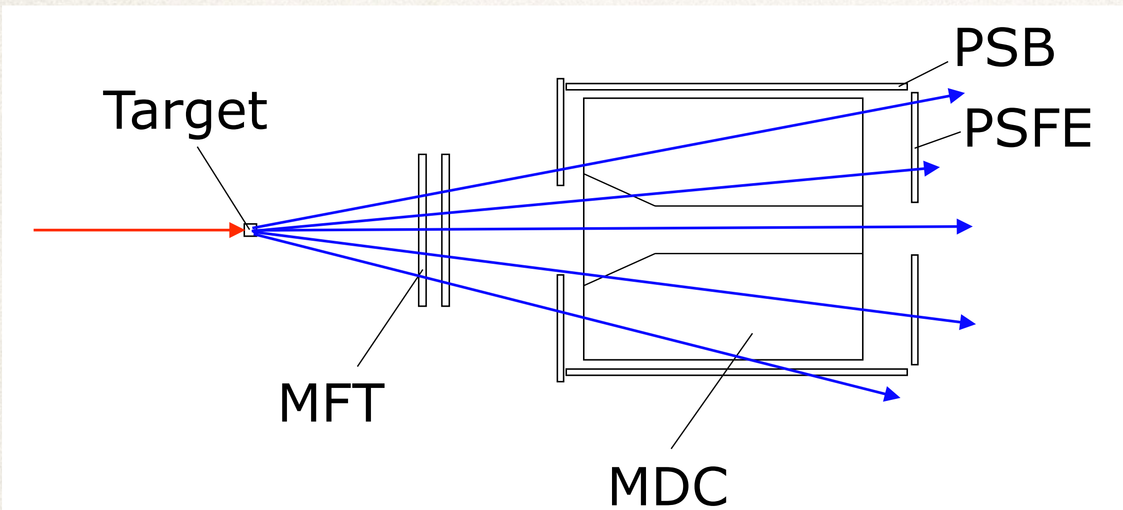
Track Finding with Graph Neural Network

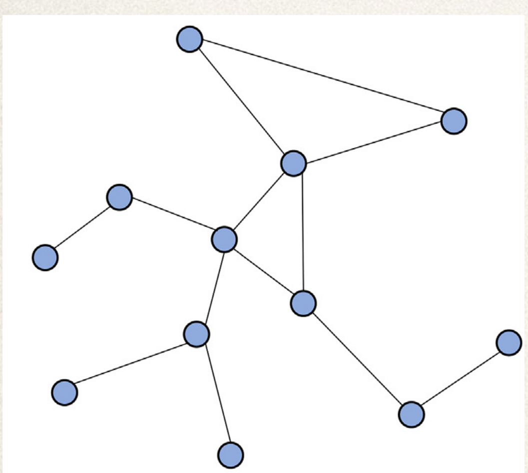
Track Finding

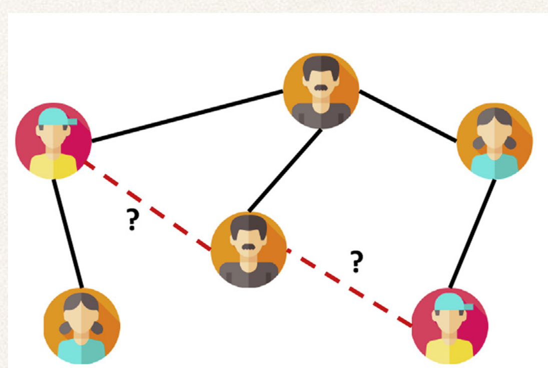


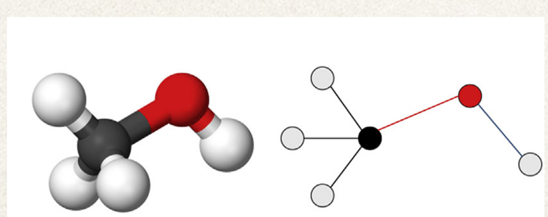
- Multi particles in HI reaction
- Combinatorial background

Track Finding with Graph Neural Network (GNN)

Graph

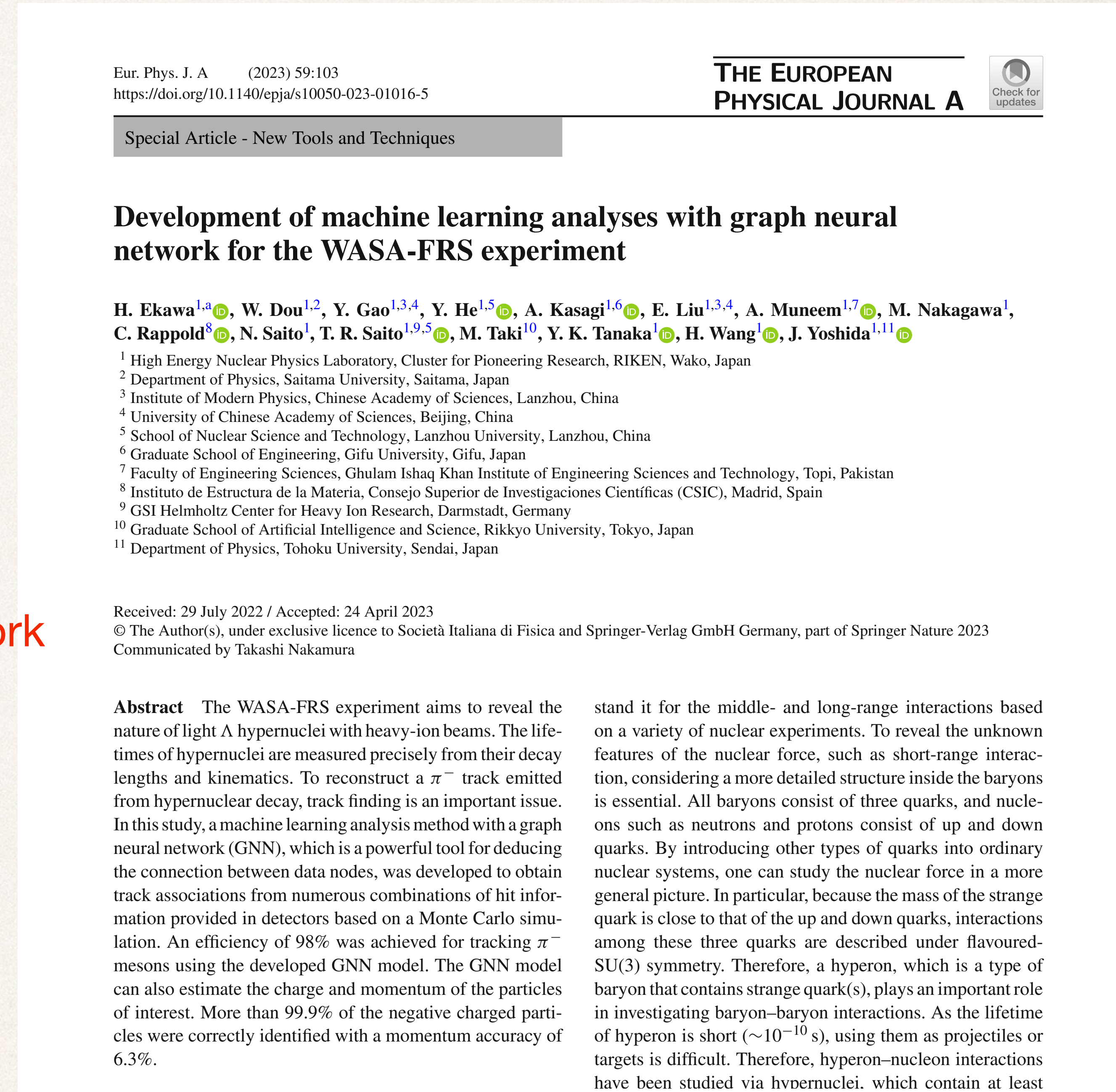



(e) Social Network


(b) Molecule

- 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

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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[2] Department of Physics, Saitama University, Saitama, Japan
[3] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
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[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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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 ($\sim 10^{-10}$ 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 (May 2023)

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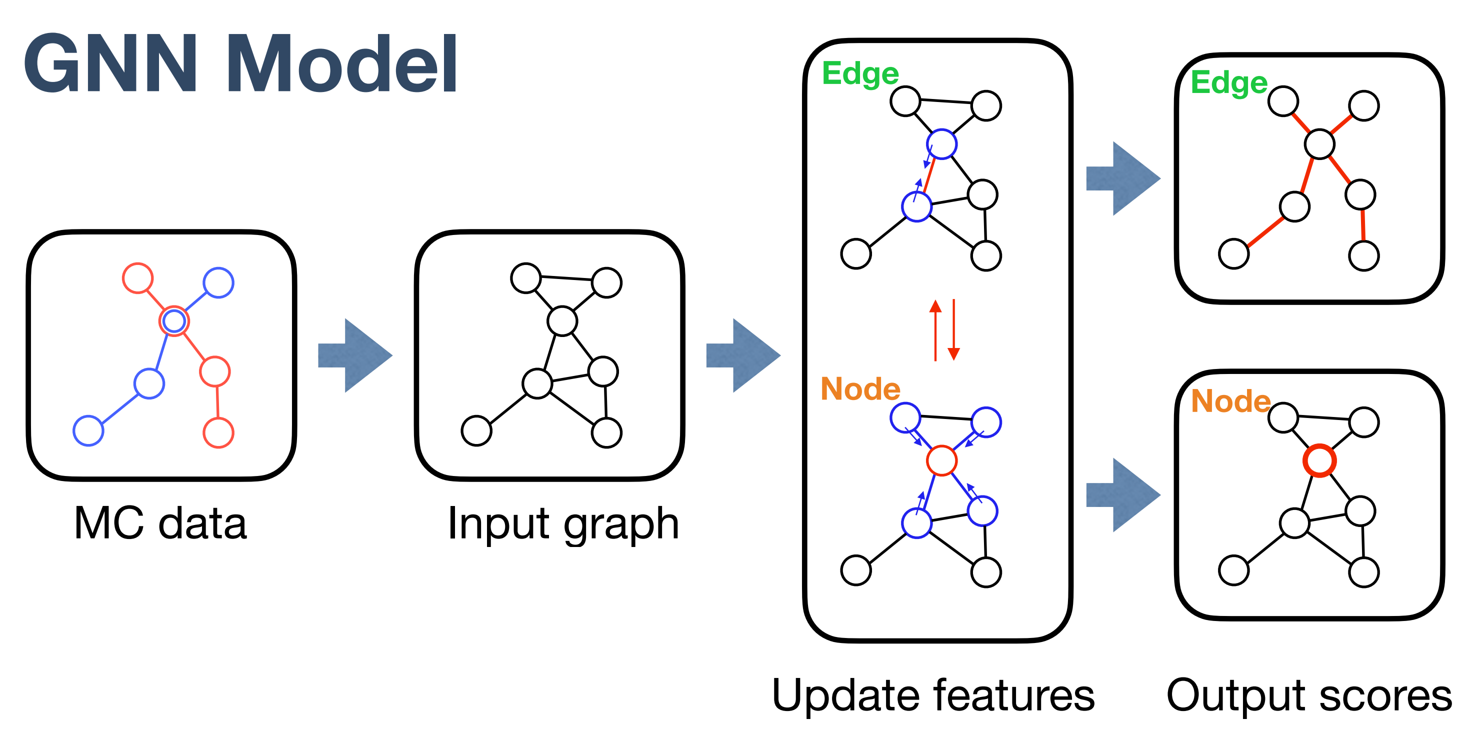
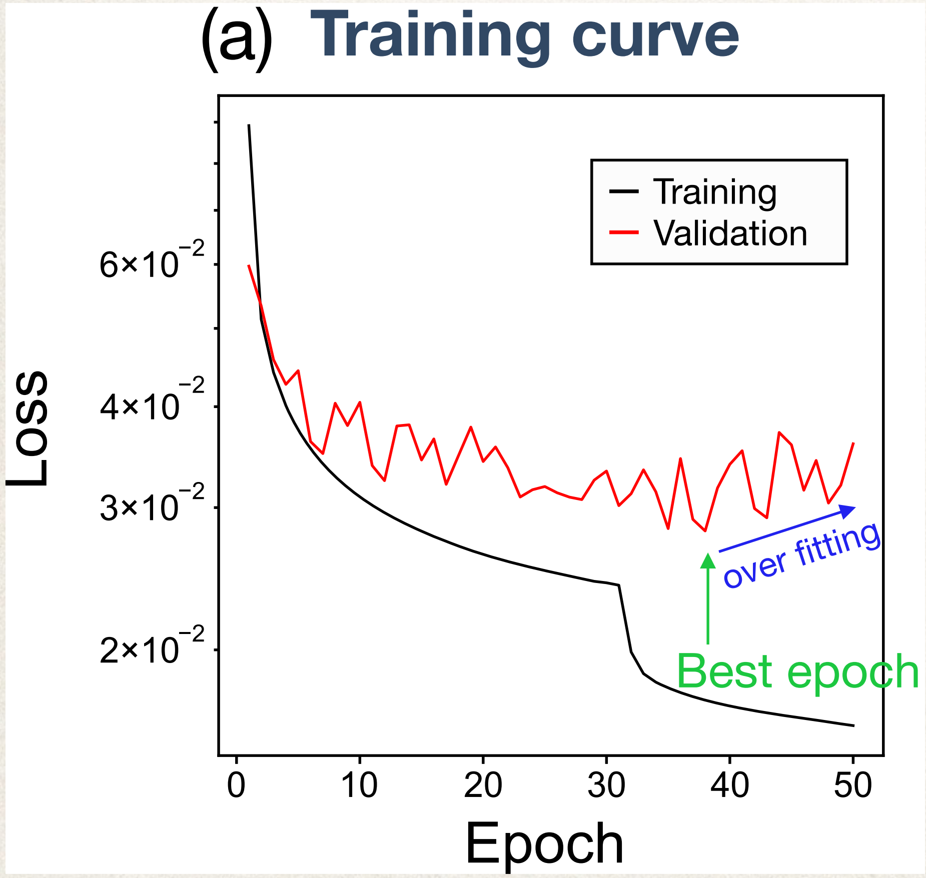
DOI : 10.1140/epja/s10050-023-01016-5

GNN Node Clustering

Machine Learning

- PyTorch + PyTorch Geometric
- Monte Carlo (MC) simulation
  - Training, Validation, Test
- Learning object
  - Edge : ON / OFF
  - Node : Shared / Not-Shared





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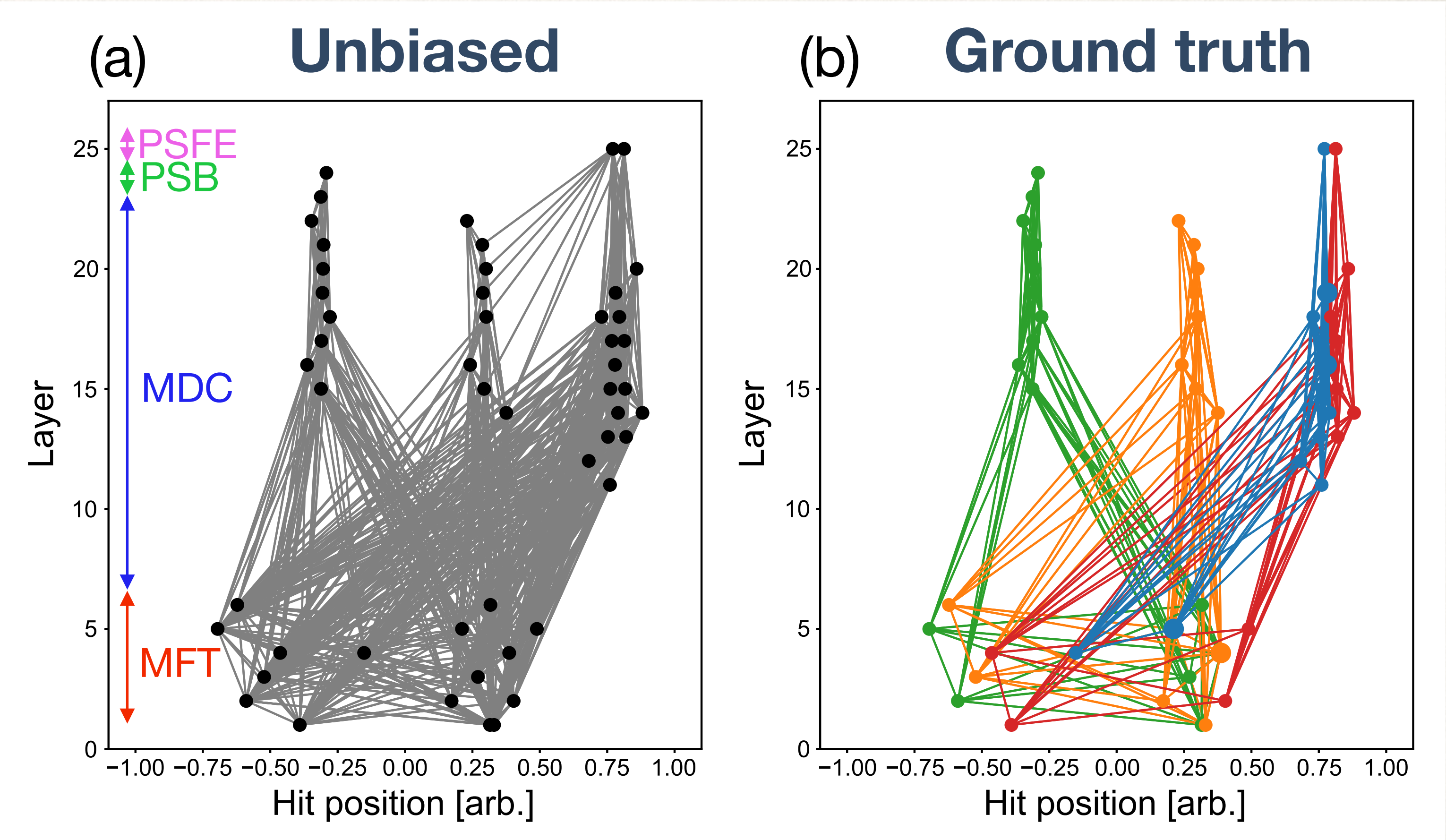
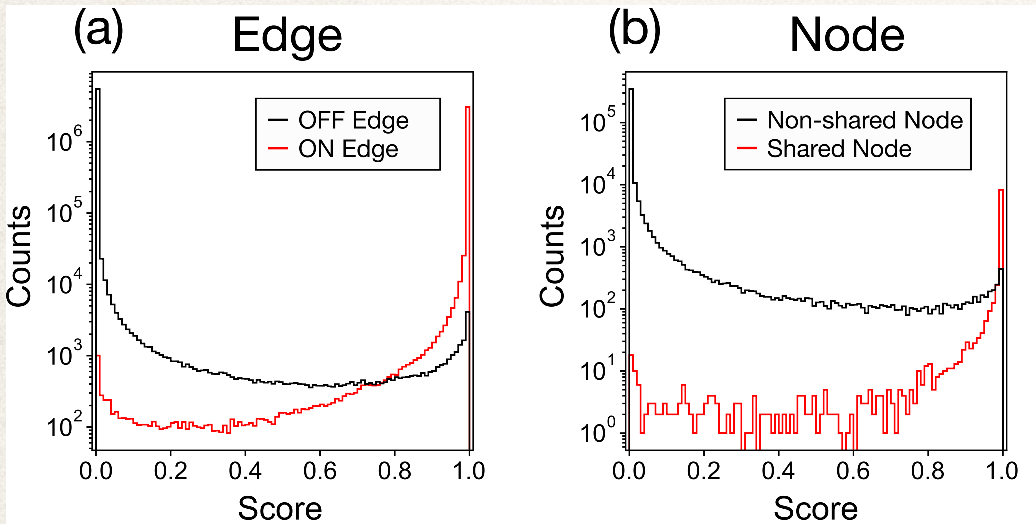


Node clustering Result

Score

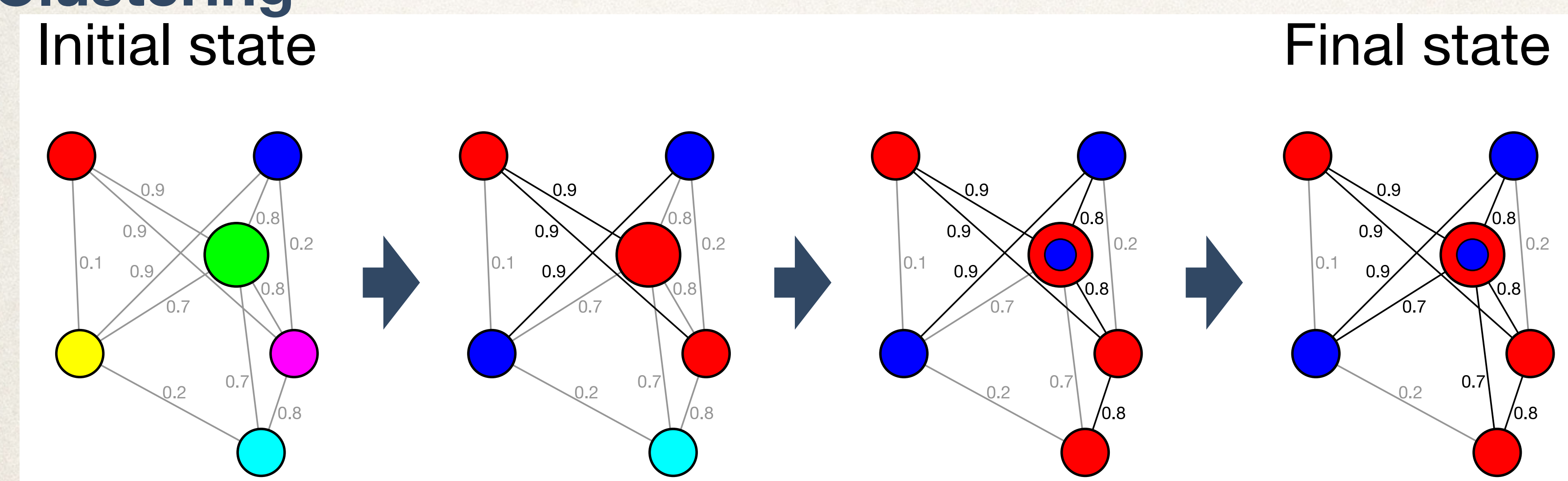


Classification

	True Positive	False Positive
Edge	99.78%	0.54%
Node	98.52%	1.6%

Threshold : 0.5

Clustering



Make groups depending on edge and node scores

Performance

Data size	Clustering efficiency for π^-	Clustering efficiency for others	Training time [h/epoch]
100k	96.3%	95.1%	0.6
300k	97.4%	96.2%	2.0
1M	98.1%	97.1%	7.5

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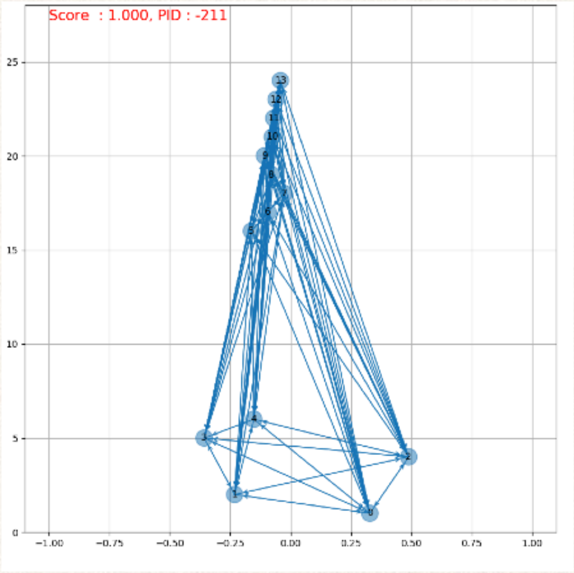
GNN Momentum and Charge Estimation

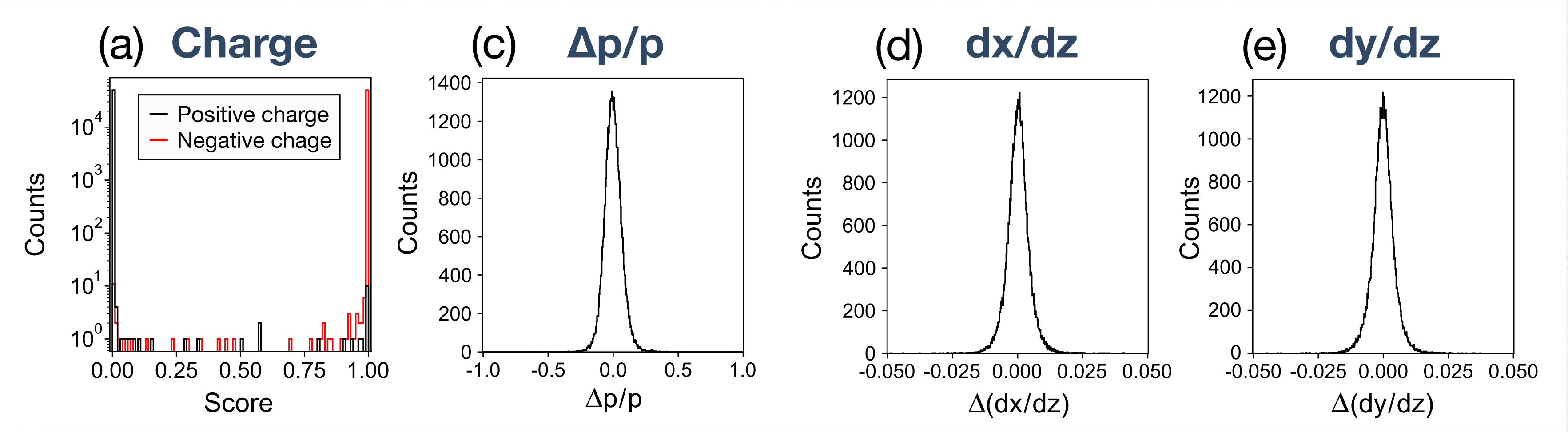
Machine Learning
- Similar to Node clustering
- Global feature
- Learning object
  - Charge : + / -
  - Momentum : |p|, dx/dz, dy/dz

Graph structure



- One track is extracted
- Full connected
- Define global feature

Performance



cf. Kalman filter

Δp/p : 9.9 %

Δ(dx/dz), Δ(dy/dz) : 3.0 mrad

Data size	Eff.	False-positive	$\frac{\Delta p}{p}$	$\Delta \frac{dx}{dz}$ [mrad]	$\Delta \frac{dy}{dz}$ [mrad]	Training time[h/epoch]
500k	99.70%	0.07%	9.9%	6.1	6.0	0.2
1M	99.82%	0.04%	8.5%	5.3	5.3	0.4
2M	99.92%	0.03%	6.8%	4.1	4.1	0.8
4M	99.95%	0.04%	6.3%	3.7	3.7	1.5

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Summary and prospect

- WASA-FRS hypernuclear experiment aims to study light hypernuclei
  - Lifetime of hypertriton and ${}^{4}_{\Lambda}H$
  - Existence of nnΛ
- Data taking has been successfully carried out in Jan. - Mar. 2022
- Analysis of WASA detectors and FRS are ongoing
  - WASA : Tracking, PID
  - FRS : Momentum and angle reconstruction
- GNN analyses have been developed by MC simulation
  - Node clustering, Momentum and charge estimation

Prospect

- GNN analyses will be applied to the WASA-FRS data soon
- Combined analysis with WASA and FRS