

Neutrino-Nucleus Interaction Measurements with Nuclear Emulsion Detectors in the NINJA Experiment

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Tokyo Denki University

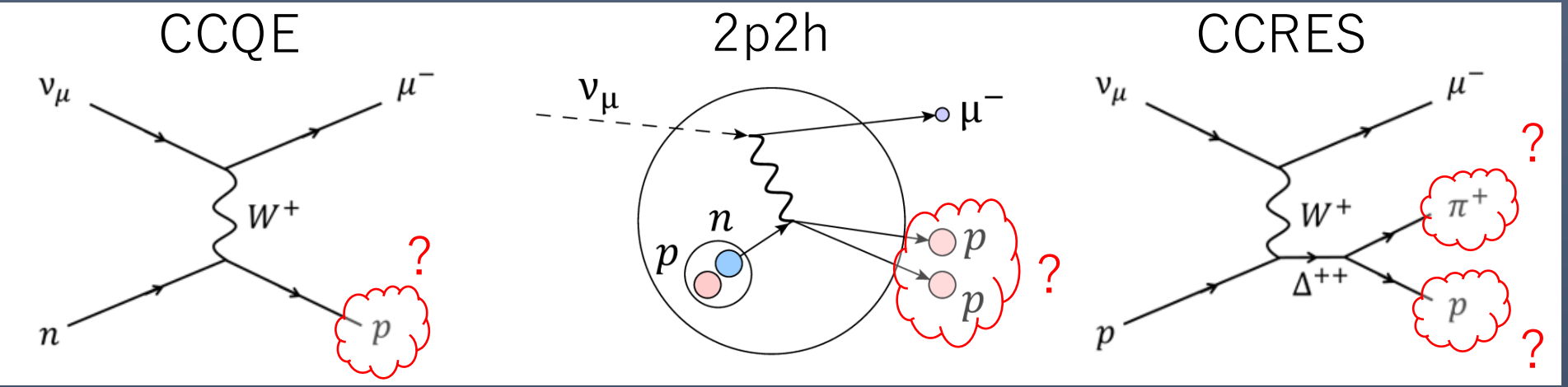
Asian Forum for Accelerators and Detectors 2026,
Shanghai, China, Oct. 14 – 16, 2026

Introduction : Neutrino – Nucleus interactions

The ν interaction uncertainty due to nuclear effects, such as a nucleon-nucleon correlation and final state interactions (FSIs), is a thorny problem.

n-p, p-p, n-n

re-scattering, absorption, particle production, ⋯



FSIs generate or hide the particles.

It is important to measure low-momentum protons and pions to understand ν – nucleus interactions, including nuclear effects.

Challenge: Large target mass is essential, while high resolution generally requires many readout channels.

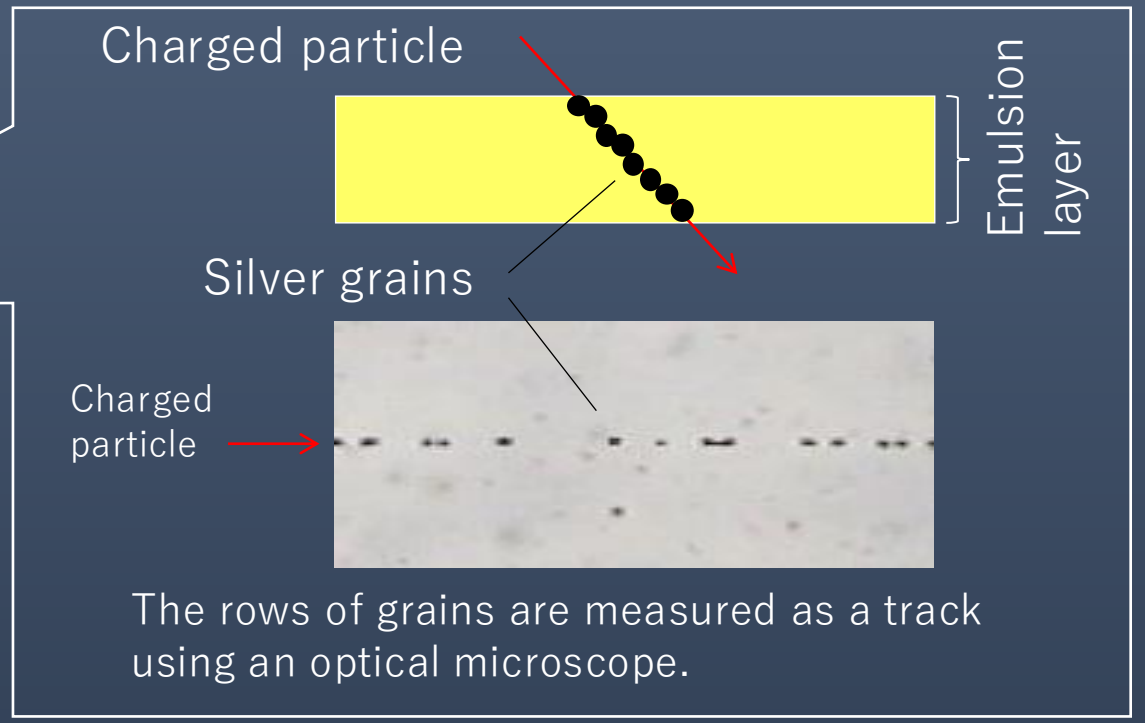
Nuclear emulsion film

Emulsion detector provides both large target mass and extremely high spatial resolution.

- A kind of silver halide photographic films.
- Three-dimensional tracking detector for charged particles.
  - Sub-μm spatial resolution
  - No dead time



Films (Yellow), Iron plates(Silver)



The rows of grains are measured as a track using an optical microscope.

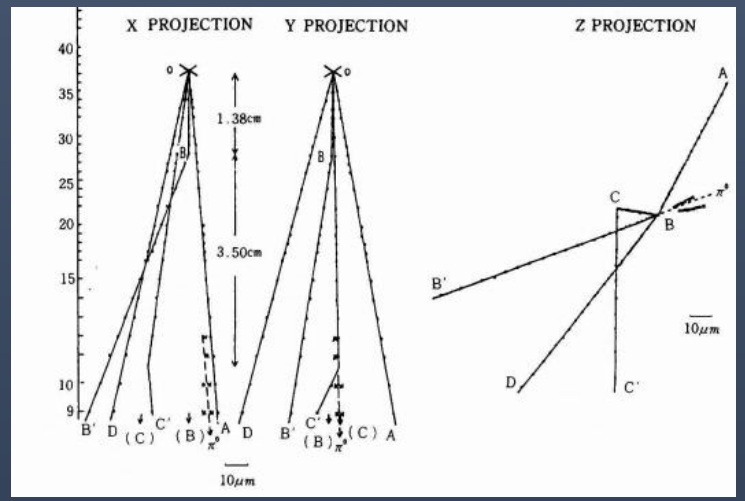
Applications of emulsion films for particle physics

Unique physics studies using an advantage of sub-μm spatial resolution.

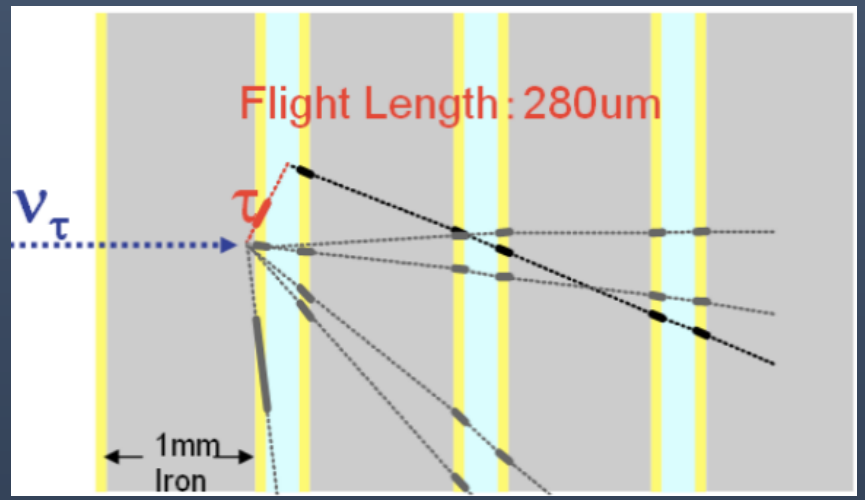
1971	Discovery of X-particle (Charm particle) in cosmic-ray experiment (K. Niu, et al.)
1978-1983	$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis, lifetime measurements of charm particles (E531)
1990-2000	$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis, physics analysis of charm particles (CHORUS)
1994-2001	Discovery of tau-neutrino (DONUT)
2015	Discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation (OPERA)

The successful results were obtained in the high energy region above several tens GeV.

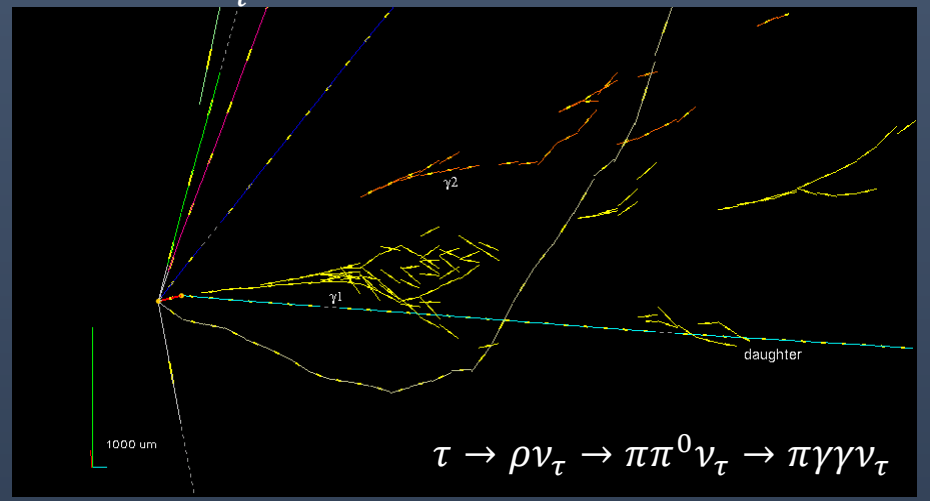
X particle discovered in cosmic-ray



ν_τ observation



First ν_τ candidate event in OPERA



Applications of emulsion films for particle physics

Unique physics studies using an advantage of sub-μm spatial resolution.

1971	Discovery of X-particle (Charm particle) in cosmic-ray experiment (K. Niu, et al.)
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On the other hand, what is interesting topics in recent years?

One of the important topics in particle physics is a search for the *CP* violation in the lepton sector.

→ Long-baseline neutrino oscillation experiments around the 1GeV.

Low energy region

NINJA Experiment

Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

Country: Japan Croatia the UK (3 Institutes, ~50 researchers)

We aim to study neutrino-nucleus interactions using the emulsion detector.

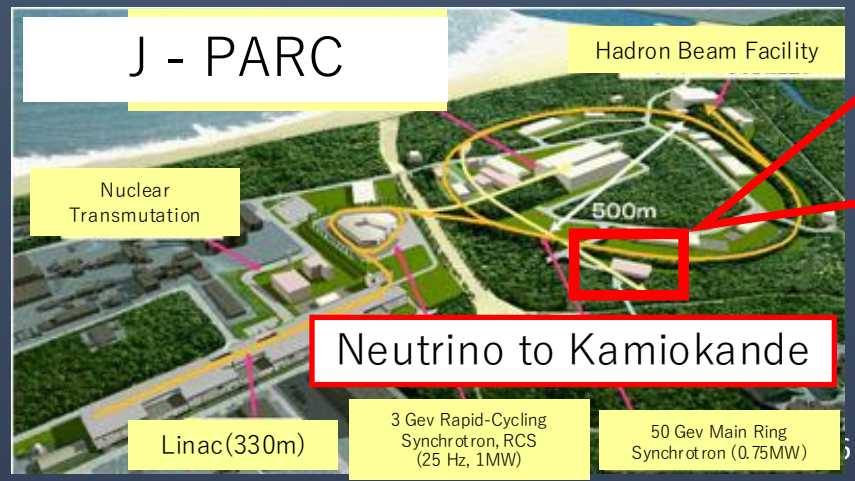
→ Various targets (Fe, H_2O, C, etc.)

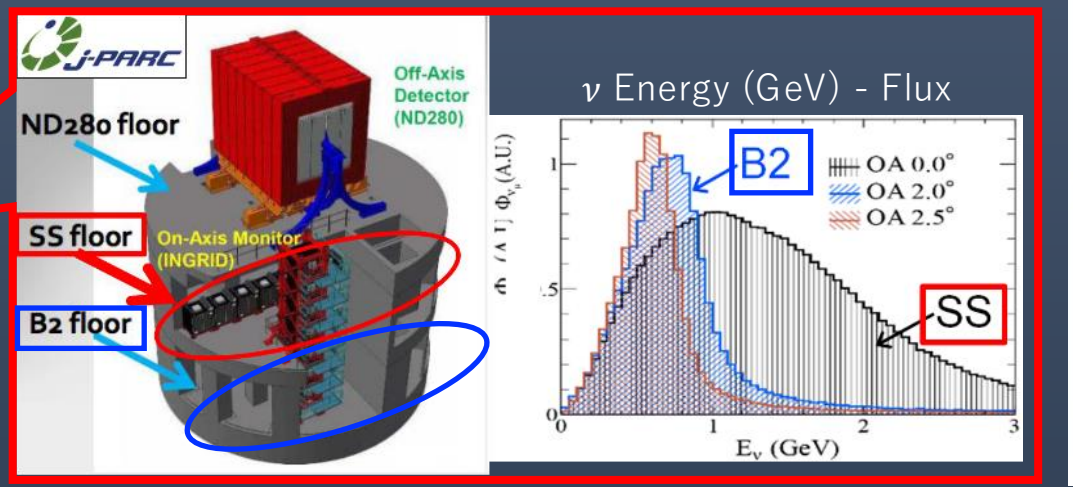
→ Low momentum thresholds ~ 200 MeV/c for protons

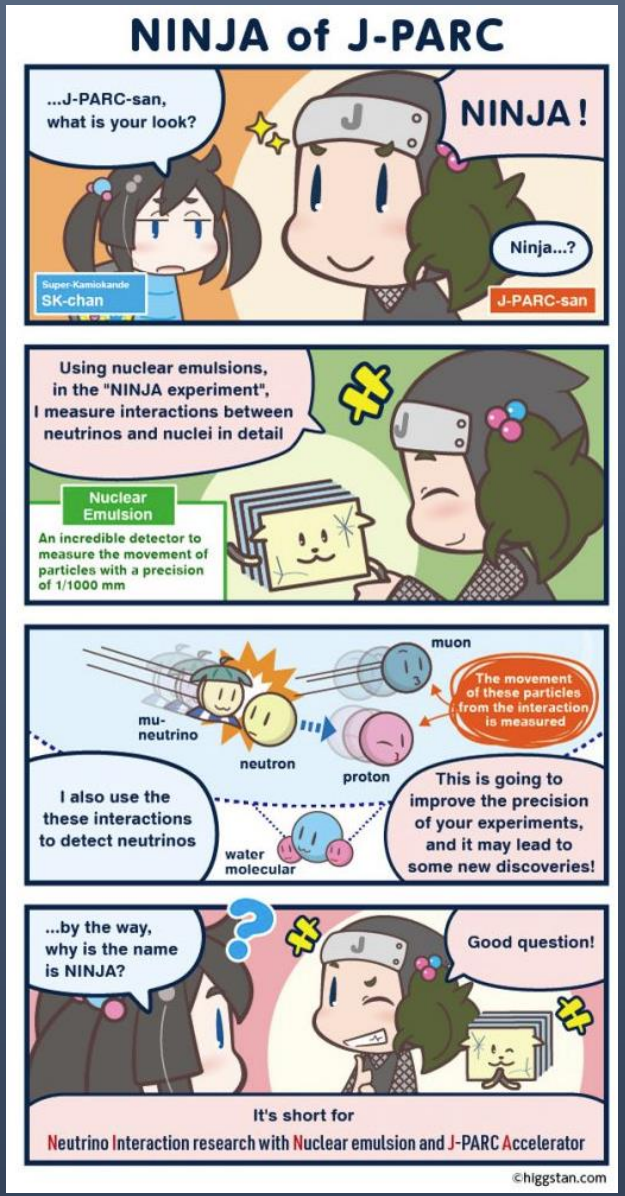
2015：Pilot run（Fe）— Feasibility study at J-PARC

2016 – 2021：Detector runs（Fe, H_2O, D_2O）— Detector performance check

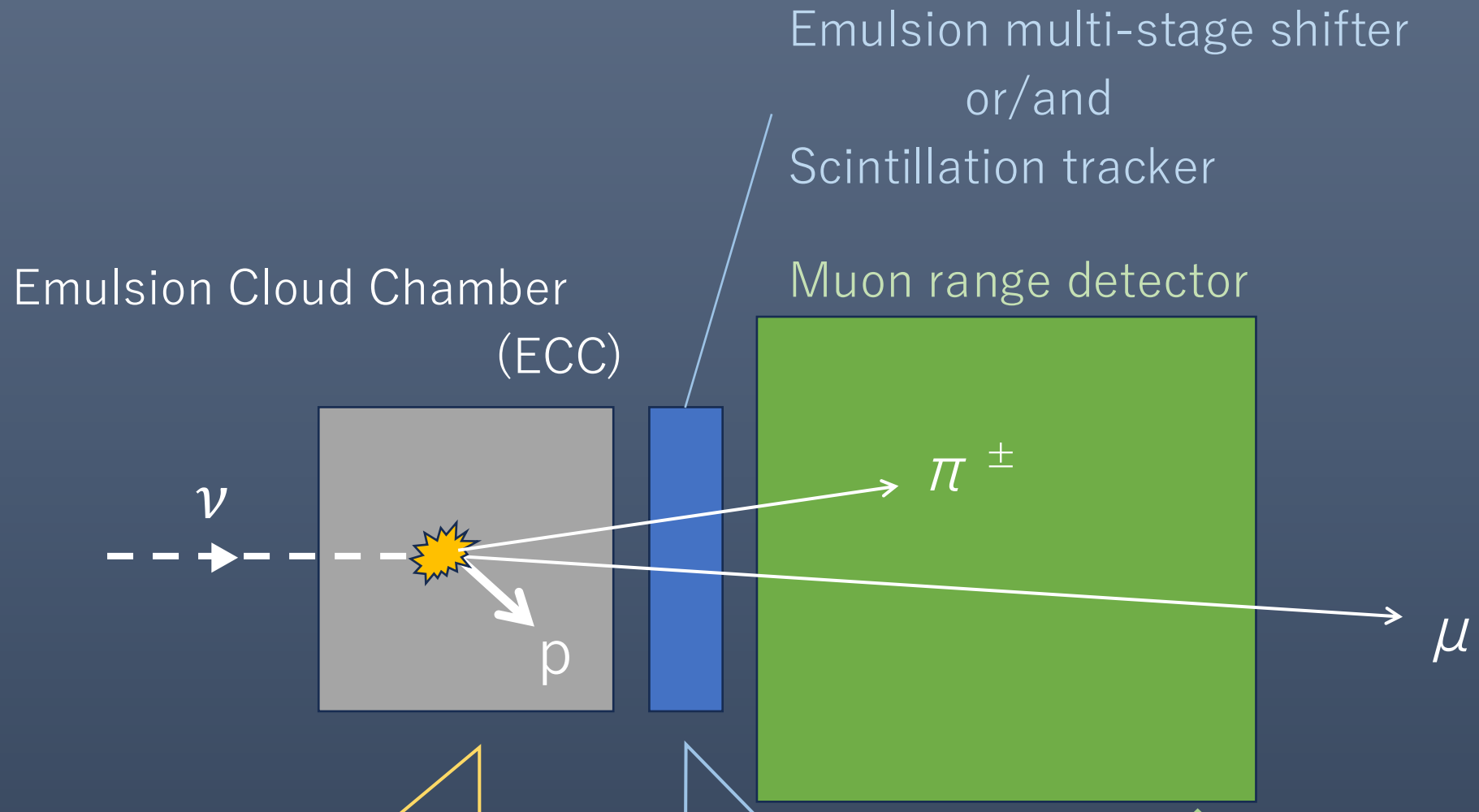
2019 – 2026：Physics runs（H_2O, Fe, CH）— ν -nucleus interaction study



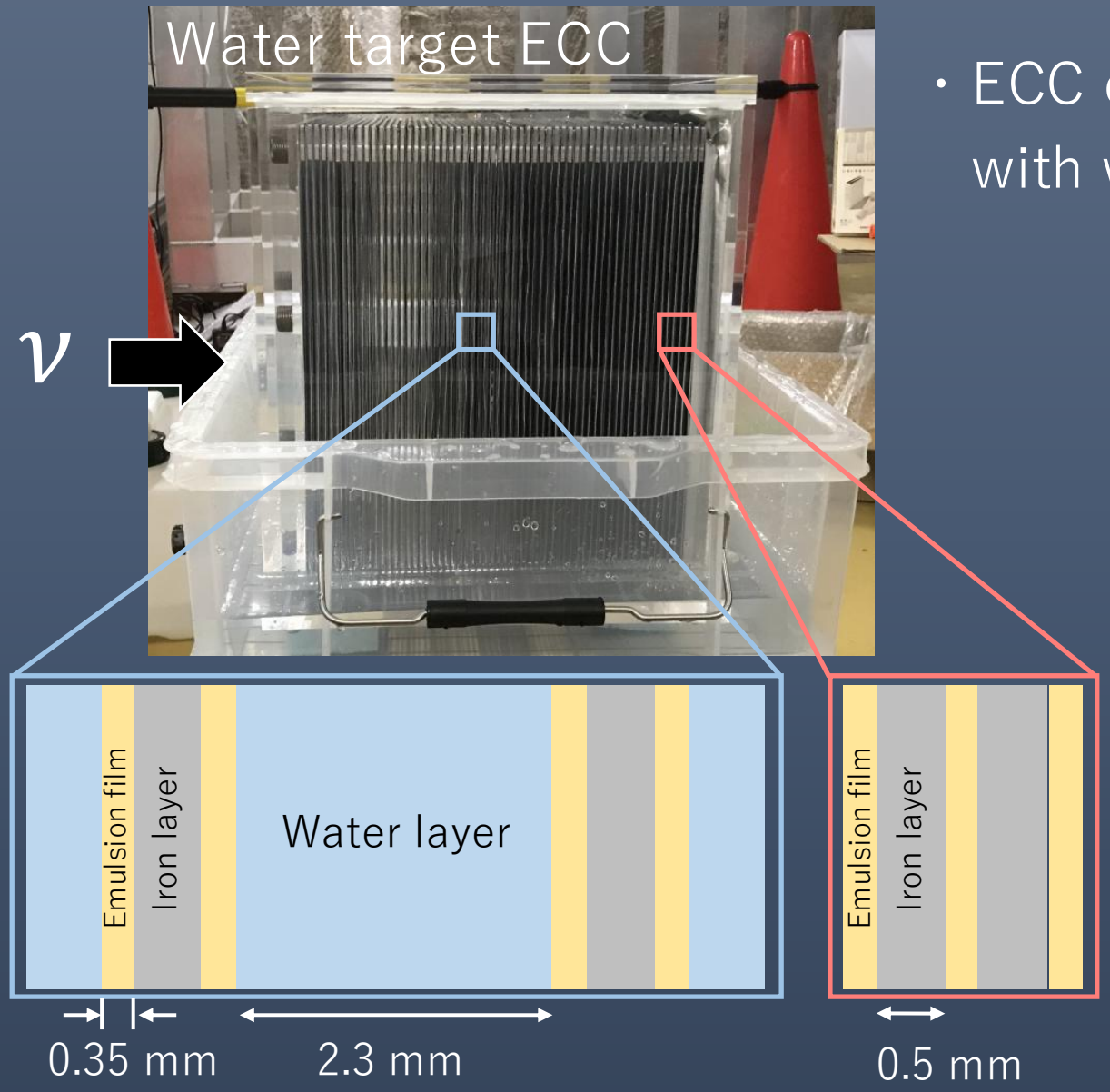




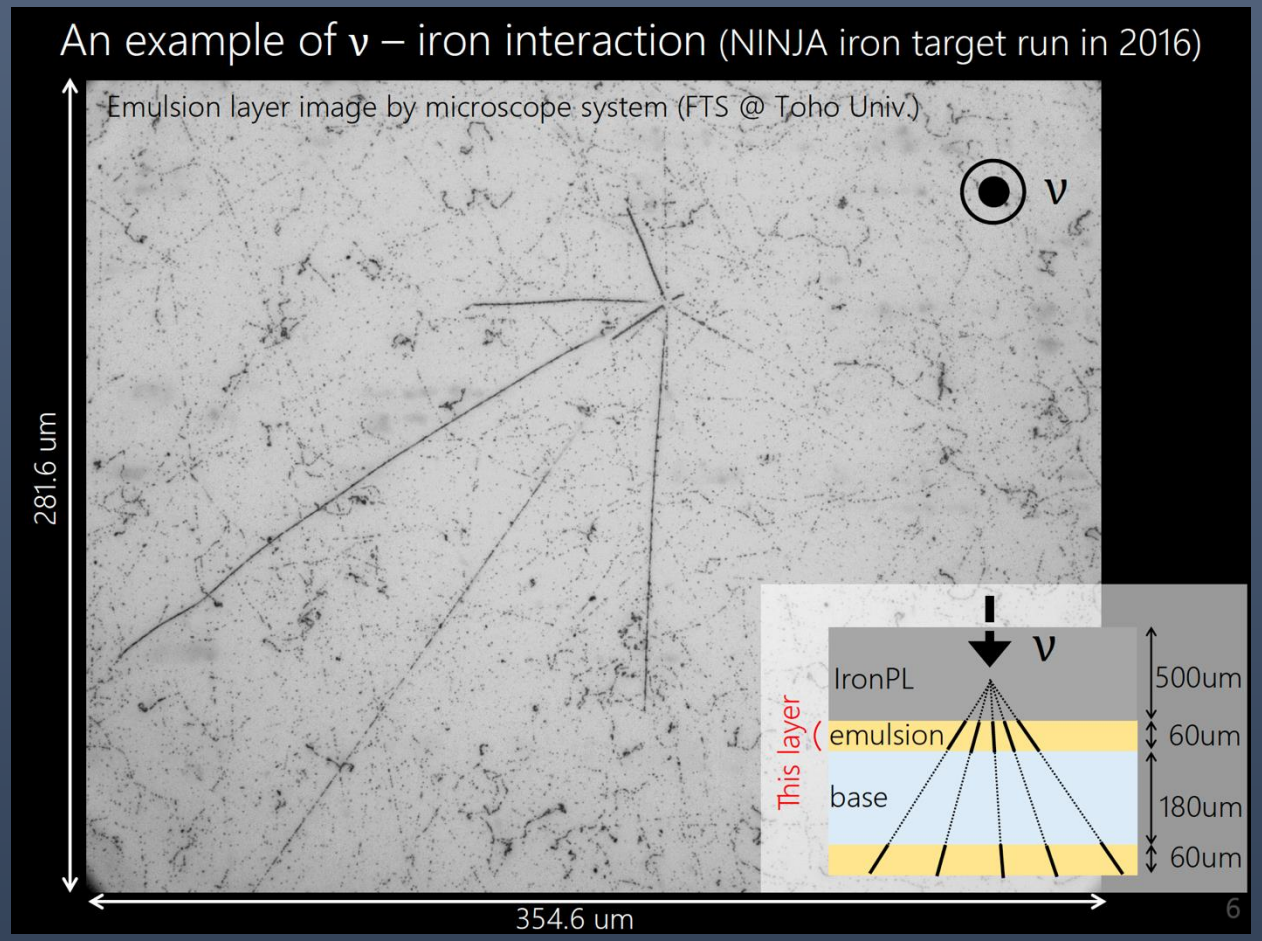
NINJA Experiment : Detector concept



Emulsion Cloud Chamber (ECC)



- ECC consists of emulsion films interleaved with water and iron layers.

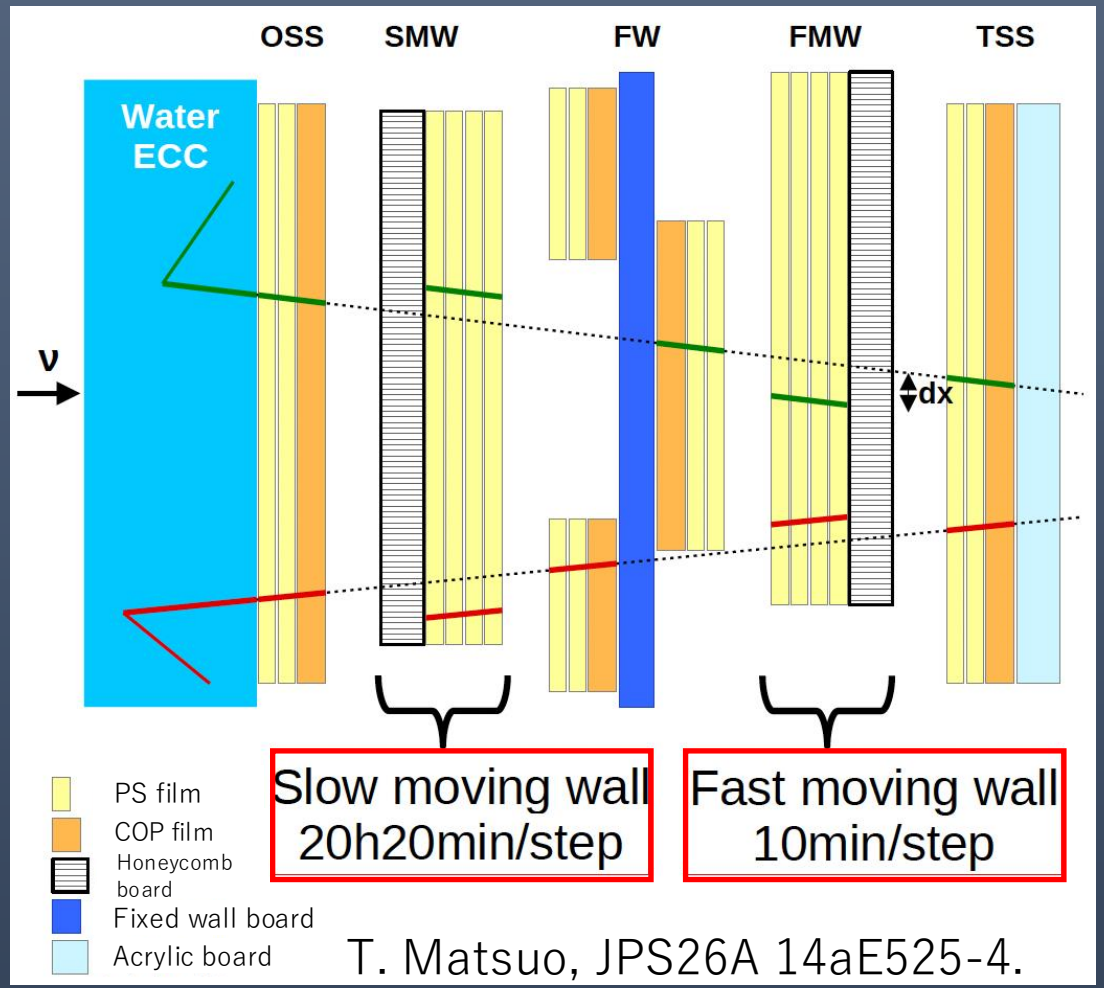


T. Hayakawa, JPS26A 15pG723-8.

Large Emulsion Shifter 2



- The SMW and FMW move at fixed time intervals, assigning timing information to tracks based on their recorded unique relative positions.

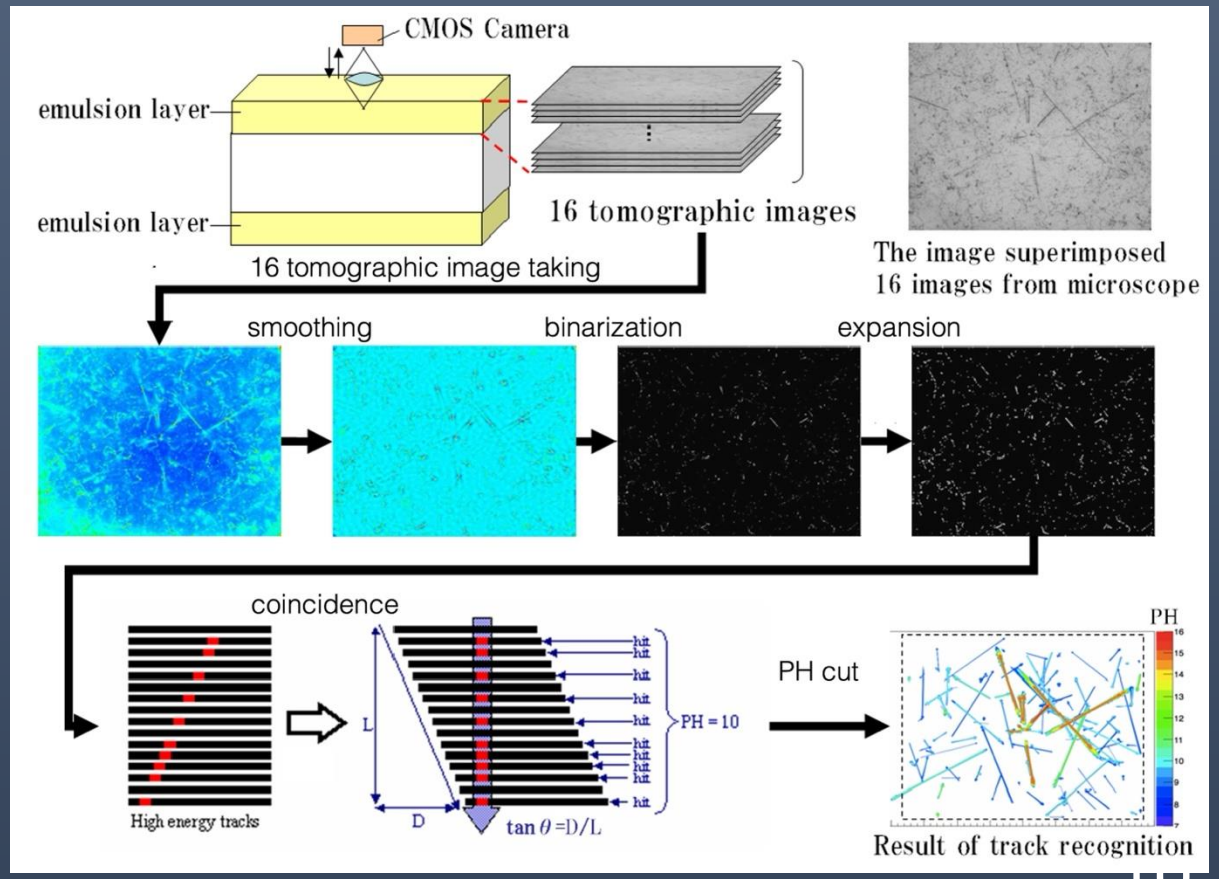


Emulsion Scanning System

After developing and swelling treatments, tracks in emulsion film are scanned by the auto-scanning systems.

Hyper-Track Selector 2 (HTS-2) @ Nagoya Univ.

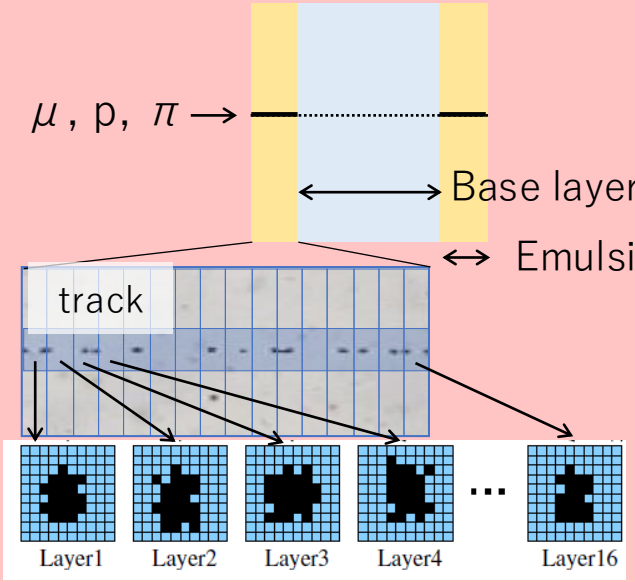




dE/dx & momentum measurments in the ECC

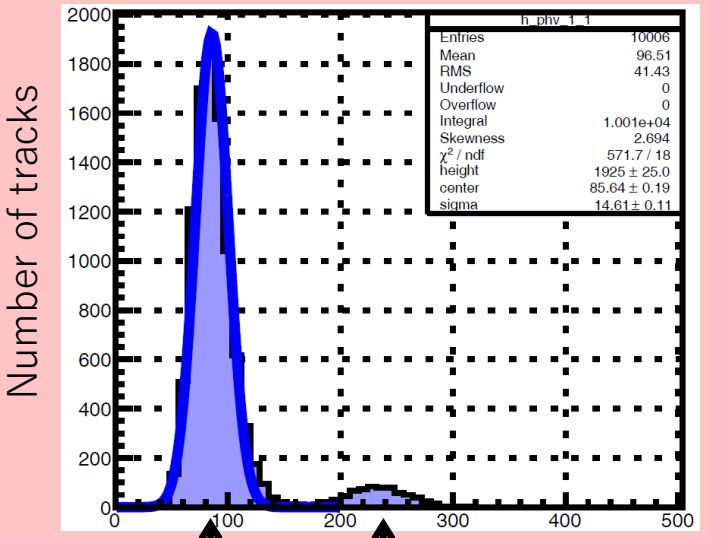
Volume Pulse Height (VPH)

➡ VPH is a measure of dE/dx.



NIM A **556**, 482 (2006).

VPH distribution (ECC tracks)



VPH is the sum of
the number of CMOS sensor hit pixels in all tomographic 16 layers.

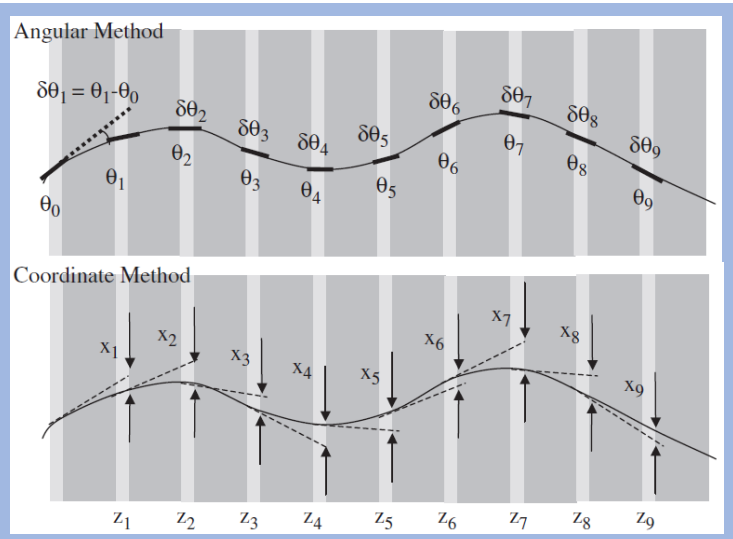
Momentum measurements in iron ECC

Measure momentum in three ways and use the best method for each track.

Range – energy relation for a short track (error : 4—6%)

Measurement of Multiple Coulomb Scattering

- Angular method (error : 30—40%)
  Measurement of the angular difference.
- Coordinate method (error : 25—30%)
  Measurement of the positional displacement.



NIM A **574**, 192 (2007).

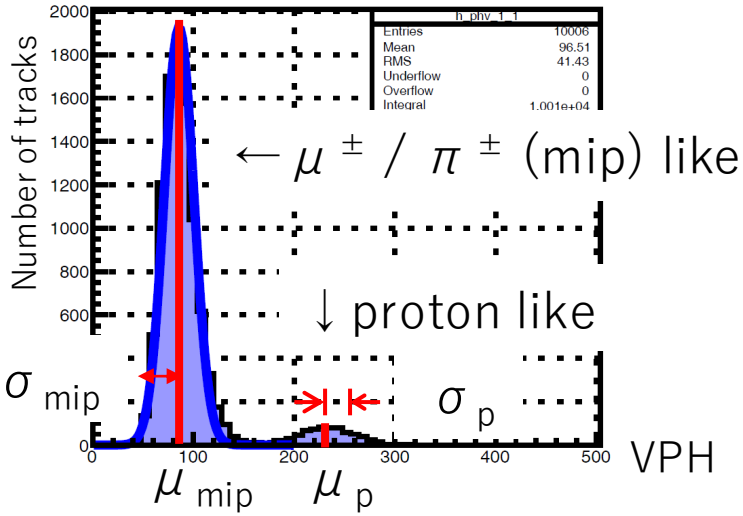
Particle identification of protons and pions (Detector run, FHC)

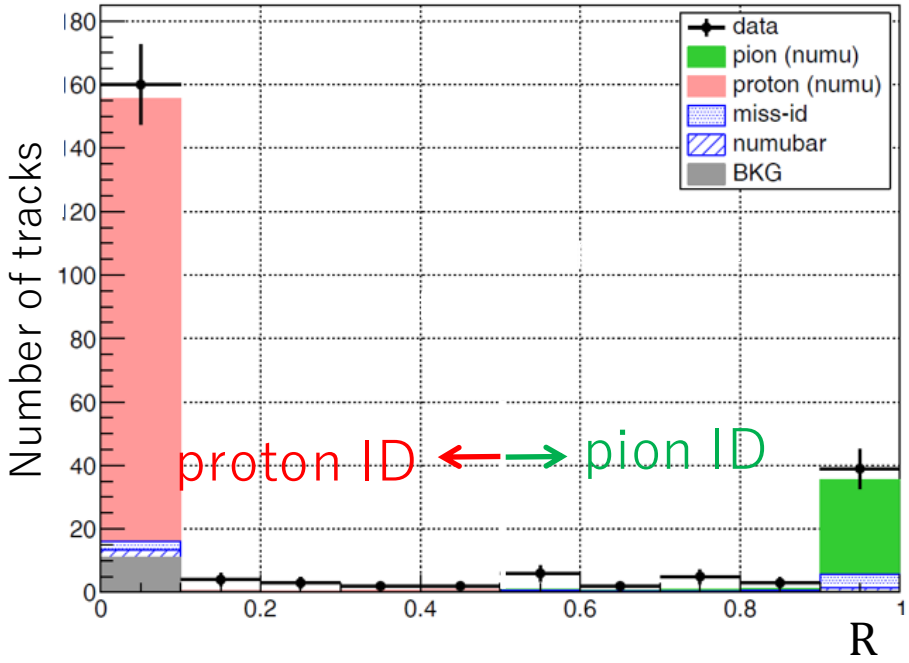
Likelihood function

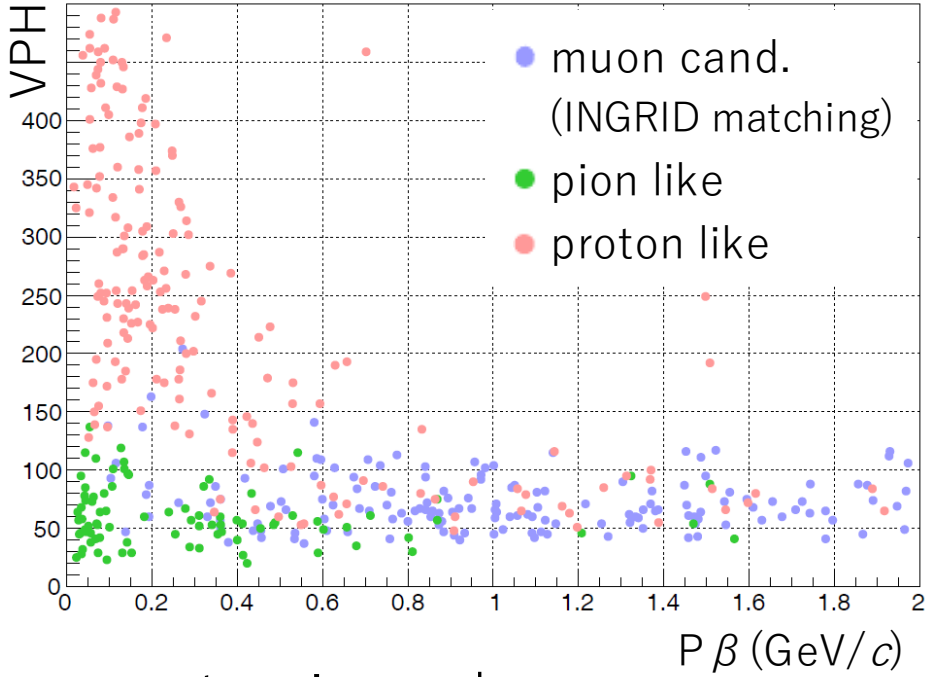
$$L = \frac{1}{\sqrt{2\pi}\sigma_{p\beta,angle}} \exp\left[\frac{-(VPH-\mu_{p\beta,angle})^2}{2\sigma^2_{p\beta,angle}}\right]$$

Likelihood Ratio

$$R = \frac{L_{mip\ like}}{L_{mip\ like}+L_{proton\ like}}$$



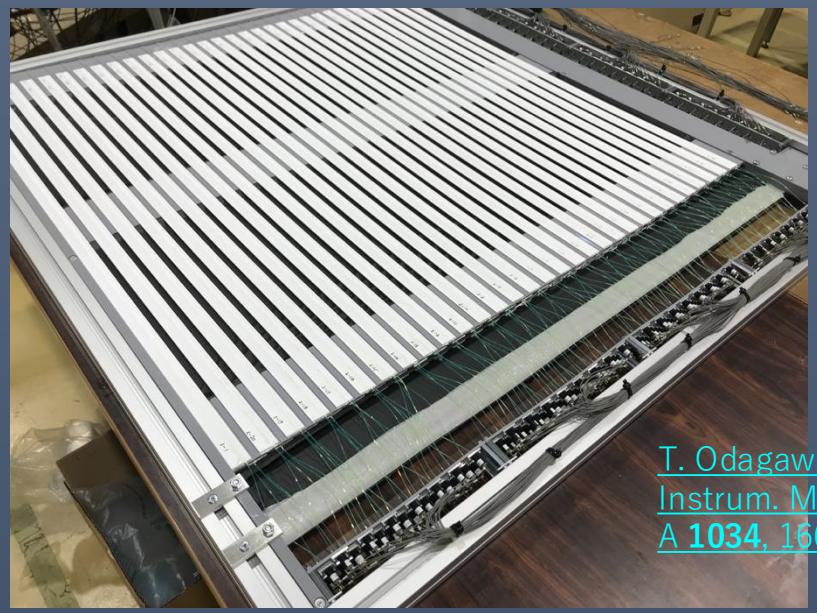




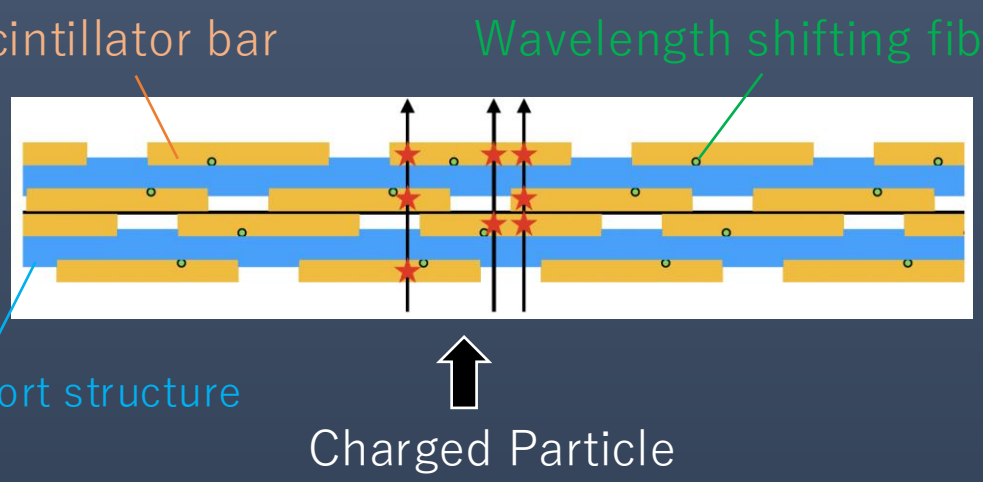
→ p / $\pi^{\pm}$ separation using VPH and momentum is good.

Scintillation Tracker (ST)

ST used in the 2019 and 2023 Physics Run

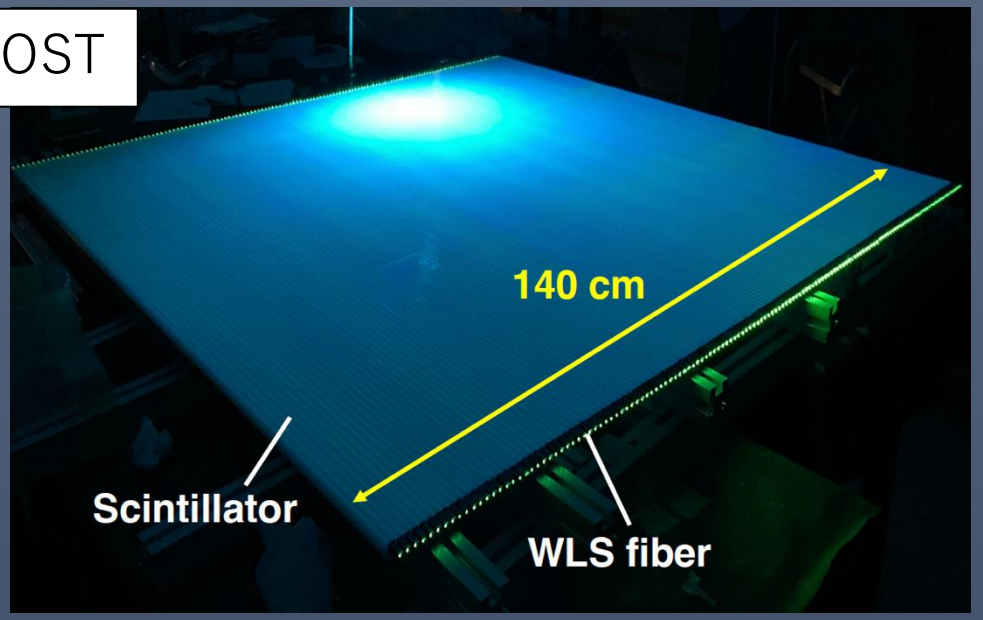


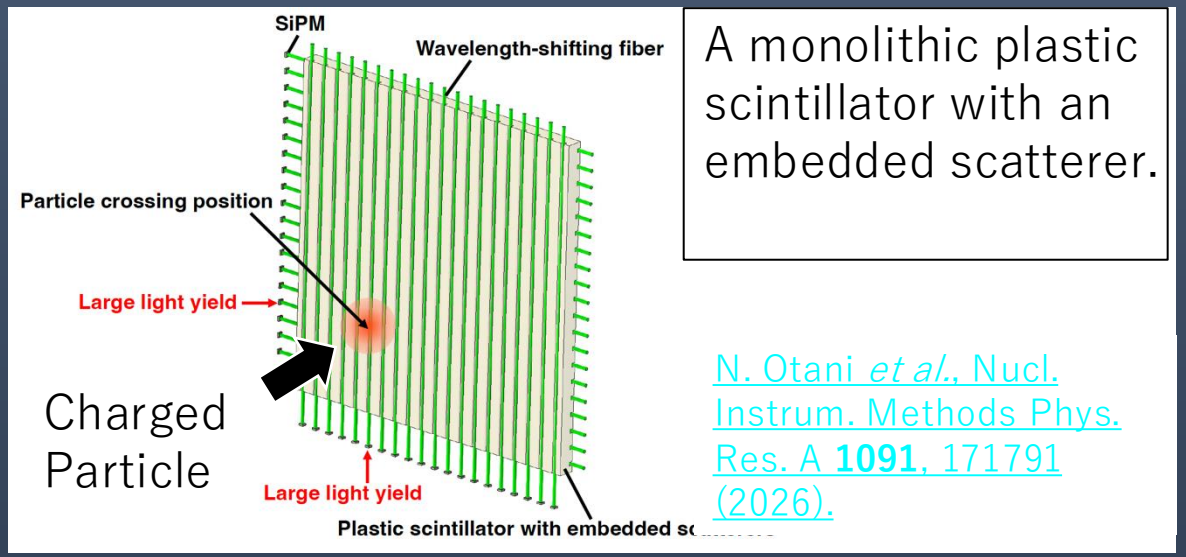
T. Odagawa, *et al.*, Nucl. Instrum. Methods Phys. Res. A **1034**, 166775 (2022).



New type ST used in the 2025 Physics Run

FROST





A monolithic plastic scintillator with an embedded scatterer.

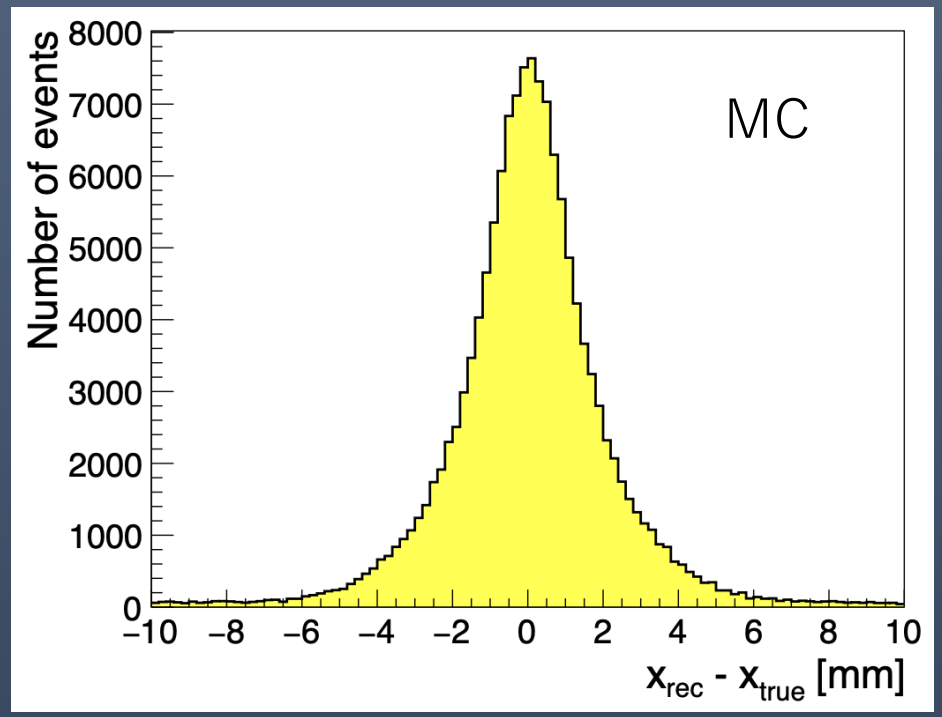
N. Otani *et al.*, Nucl. Instrum. Methods Phys. Res. A **1091**, 171791 (2026).

FROST

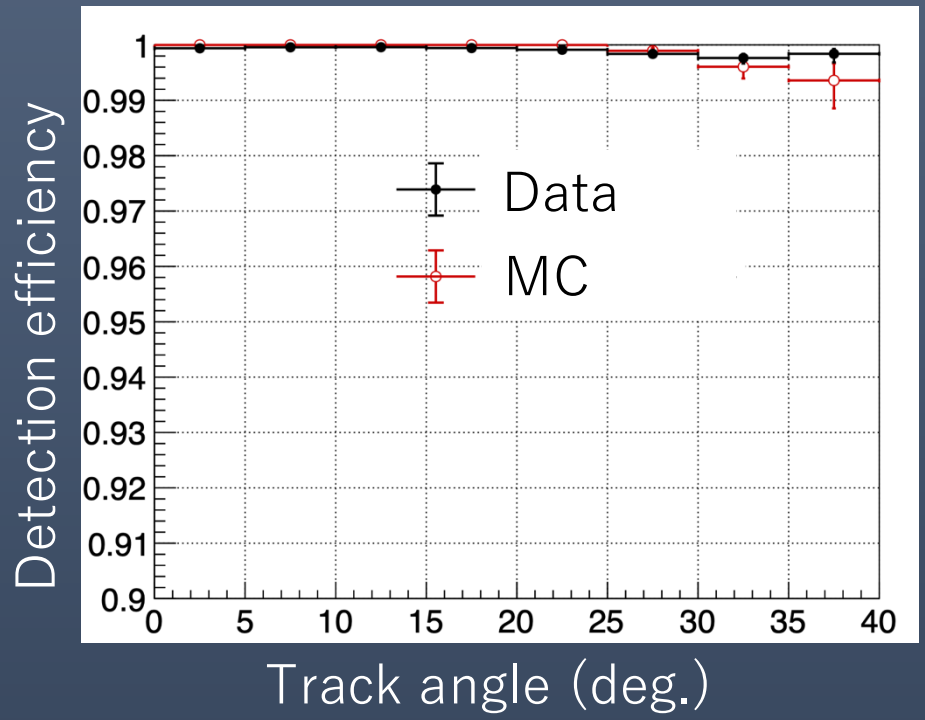
N. Otani, JPS26A 14aE525-3.
N. Otani, *et al.*, Nucl. Instrum. Methods Phys. Res. A **1091**, 171791 (2026).

Fiber-**R**eadout m**O**nolithic and **S**catterer-embedded scintillator **T**racker (FROST)

Detection efficiency and the upper limit on the position resolution for single-particle hits using muon passing through FROST.



positional resolution is 1.77 mm in the simulation



$$\varepsilon = 99.946 \pm 0.006\%$$

Detector run $\langle E_\nu \rangle = 1.49$ GeV (FHC) : ν_μ CC Cross section

Iron int.: 183 events

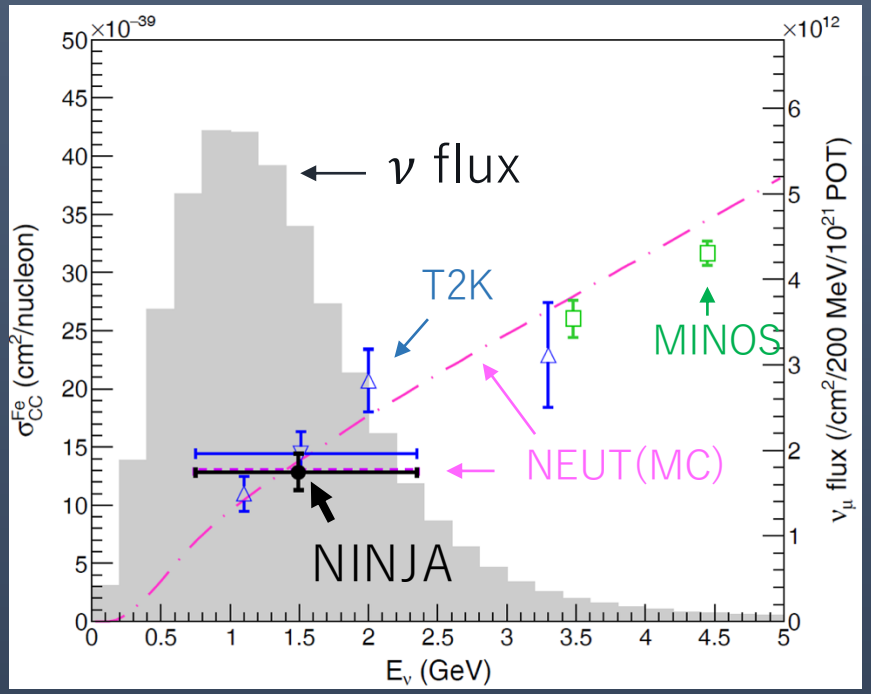
H. Oshima *et al.*, PTEP 2021, 033C01 (2021).
H. Oshima *et al.*, PRD 106, 032016 (2022).

Flux averaged CC inclusive cross section:

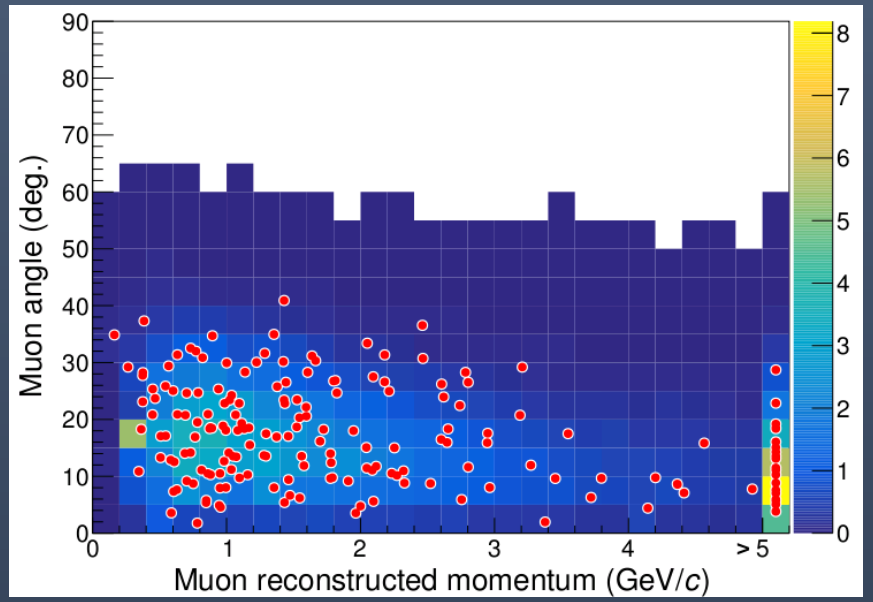
	Result $\times 10^{-38}$ (cm^2/nucleon)	MC $\times 10^{-38}$	T2K(INGRID) $\times 10^{-38}$
$\sigma_{\mathrm{CC}}^{\mathrm{Fe}}$	$1.28 \pm 0.11(\mathrm{stat.})^{+0.12}_{-0.11}(\mathrm{syst.})$	1.30	$1.444 \pm 0.002(\mathrm{stat.})^{+0.189}_{-0.157}(\mathrm{syst.})$
$\sigma_{\mathrm{CC\ phase\ space}}^{\mathrm{Fe}}$	$0.84 \pm 0.07(\mathrm{stat.})^{+0.07}_{-0.06}(\mathrm{syst.})$	0.87	$0.859 \pm 0.003(\mathrm{stat.})^{+0.12}_{-0.10}(\mathrm{syst.})$

Phase space: $\theta_\mu < 45°, P_\mu > 400$ MeV/c

Cross section



Muon emission angle vs. momentum



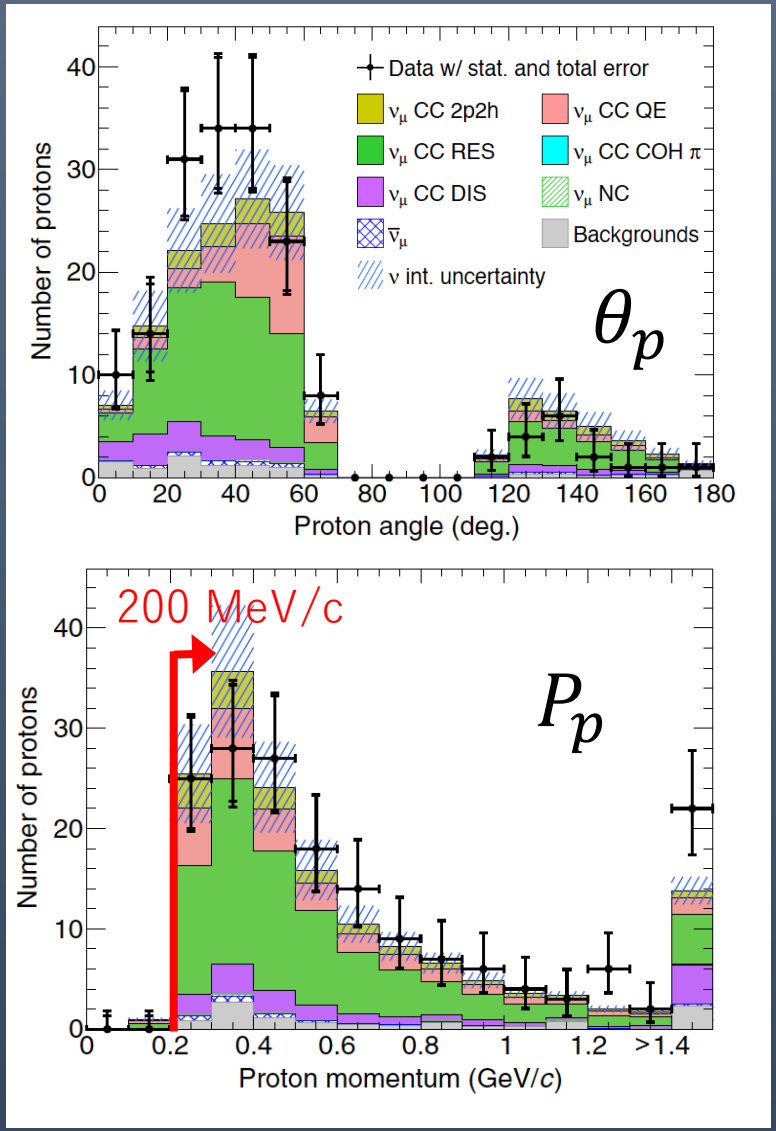
→ The results demonstrated the reliability of the detector and data analysis.

Detector run $\langle E_\nu \rangle = 1.49$ GeV (FHC) : Proton & Pion results

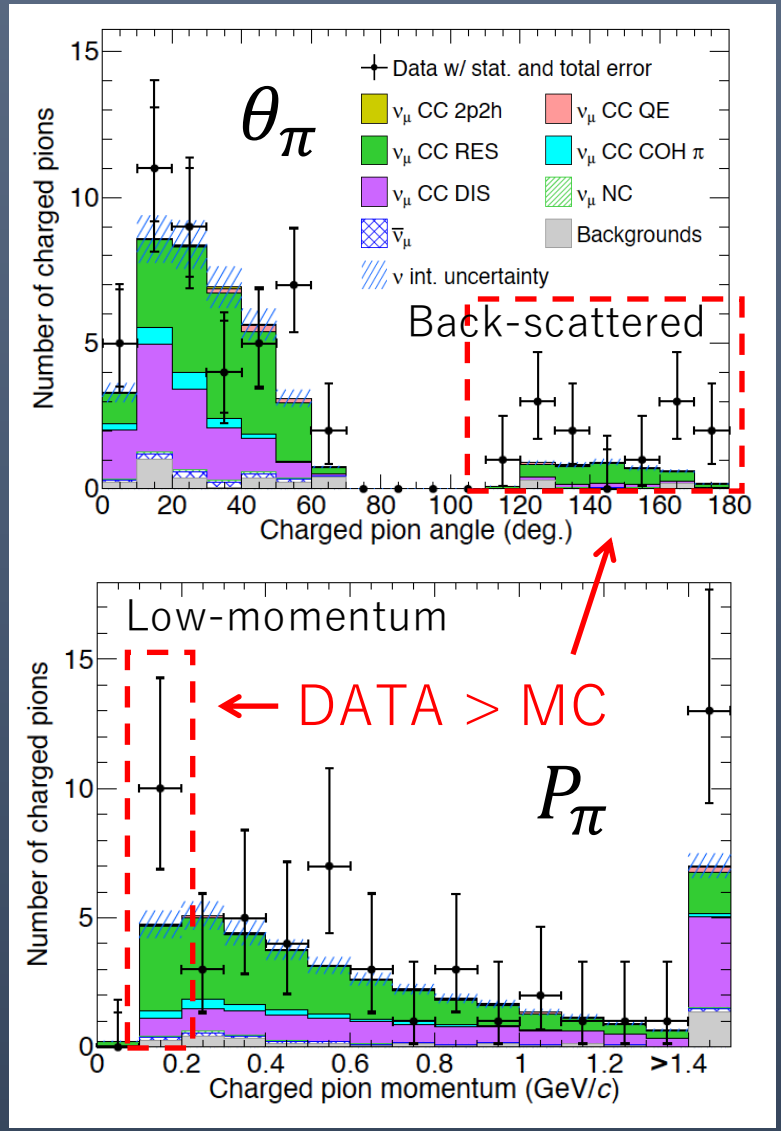
Iron int.: 183 events

H. Oshima *et al.*, PRD 106, 032016 (2022).

Data release



Data are generally consistent with the MC prediction.



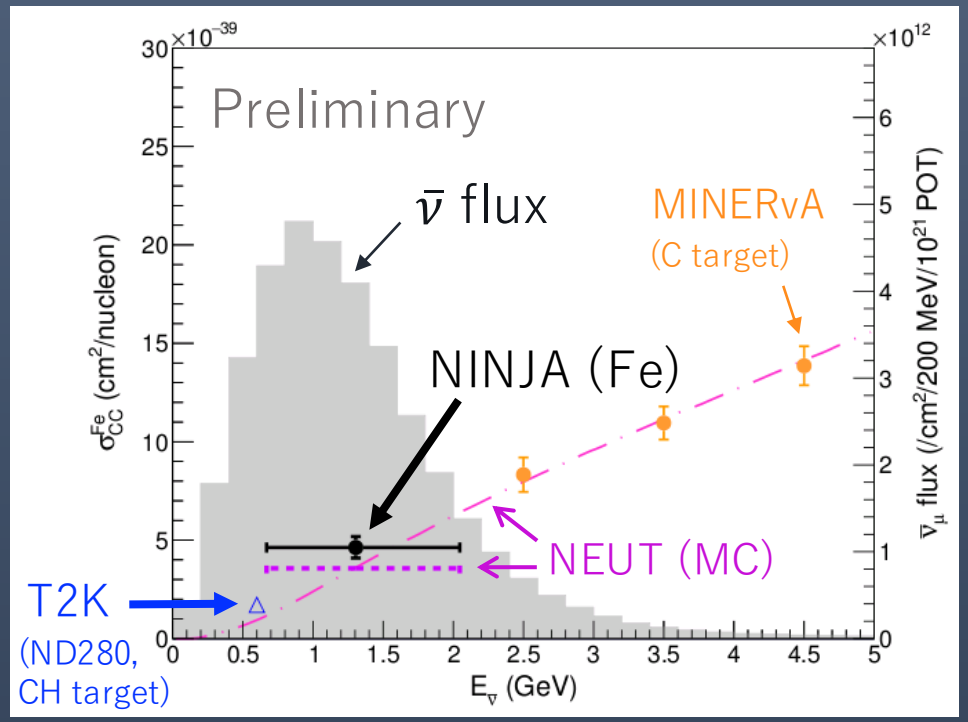
Problems of π production or FSI models?

Detector run $\langle E_{\bar{\nu}} \rangle = 1.30$ GeV (RHC) : $\bar{\nu}_\mu$ CC Cross section

Iron int.: 770 events ⟵ Statistics of the number of events in RHC is around 4 times as large as that of FHC.

	Result $\times 10^{-39}$ (cm^2/nucleon)	MC $\times 10^{-39}$
σ_{CC}^{Fe}	$4.63 \pm 0.23(\text{stat.})^{+0.53}_{-0.48}(\text{syst.})$	3.57
$\sigma_{CC\ \text{phase space}}^{Fe}$	$3.85 \pm 0.20(\text{stat.})^{+0.42}_{-0.40}(\text{syst.})$	3.22

Phase space:
$\theta_\mu < 45°$,
$P_\mu > 400$ MeV/c



NINJA (Fe target):
(MC − DATA)/DATA
= (3.57 − 4.63)/4.63 = − 23%

T2K (ND280, CH target):
(MC − DATA)/DATA
= (1.31 − 1.71)/1.71 = − 23%

→ The NEUT prediction is 23% lower than that of the data of both NINJA and T2K.

→ There is possibility that the number of events predicted by NEUT is small.

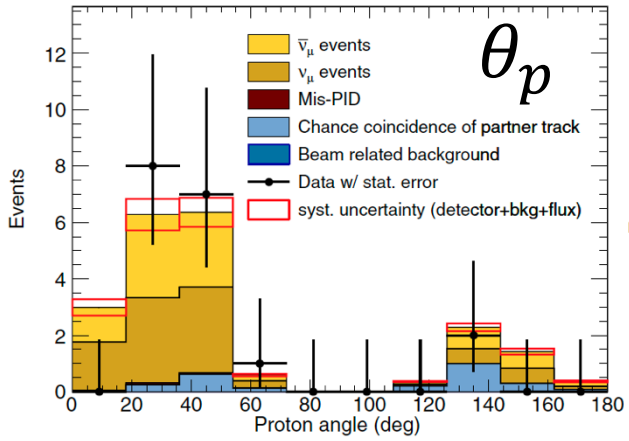
Detector run $\langle E_{\bar{\nu}} \rangle = 1.30$ GeV (RHC) : Proton & Pion results

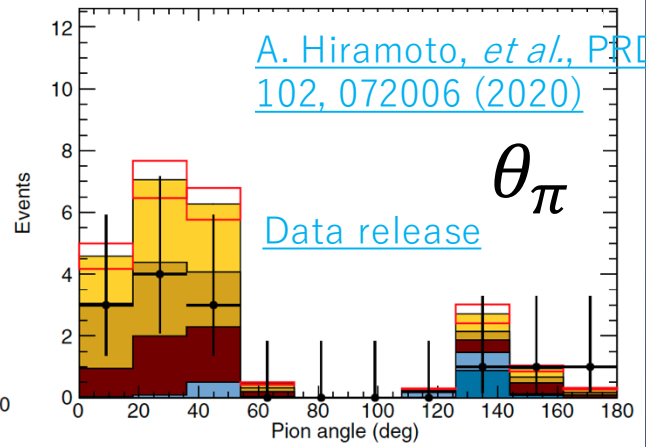
Water int.: 86 events

Iron int.: 770 events

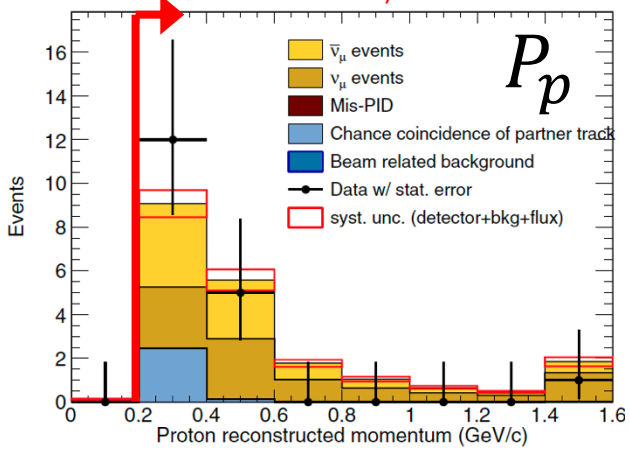
Proton

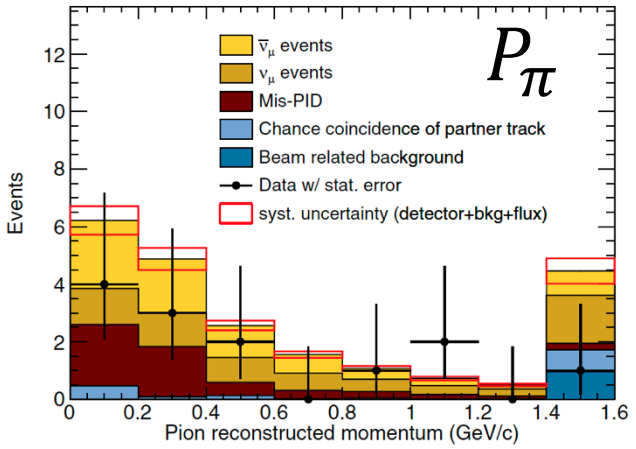
Pion





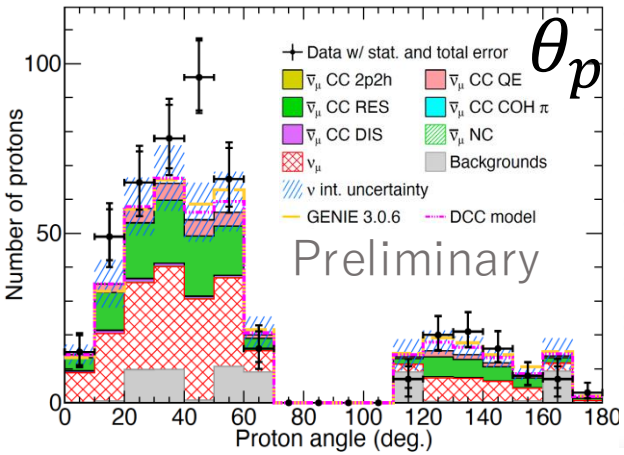
200 MeV/c

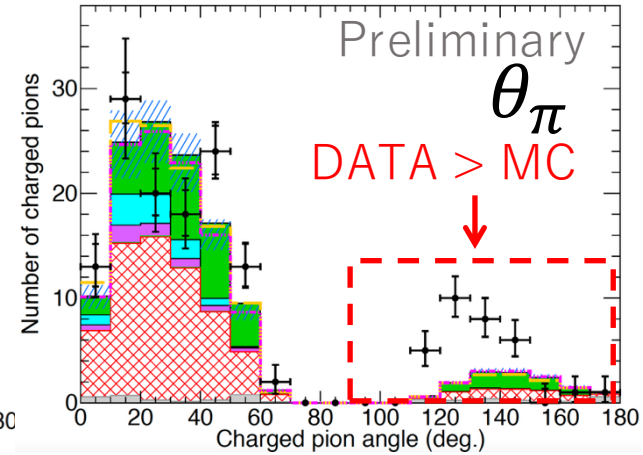




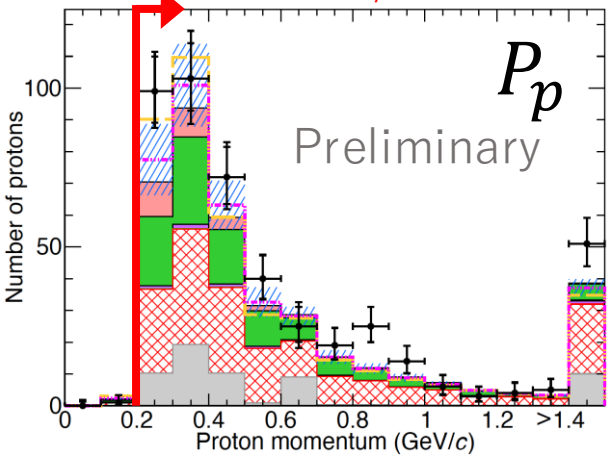
Proton

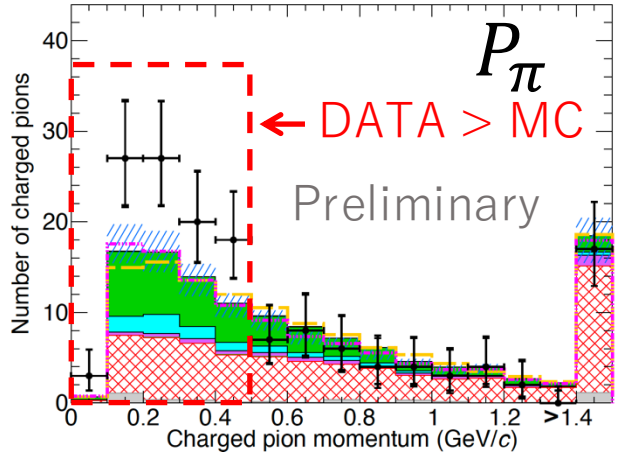
Pion





200 MeV/c





Proton: Data are generally consistent with the MC prediction.

Pion: Water → Data < MC

Iron → Low momentum & Backward pion: Data > MC

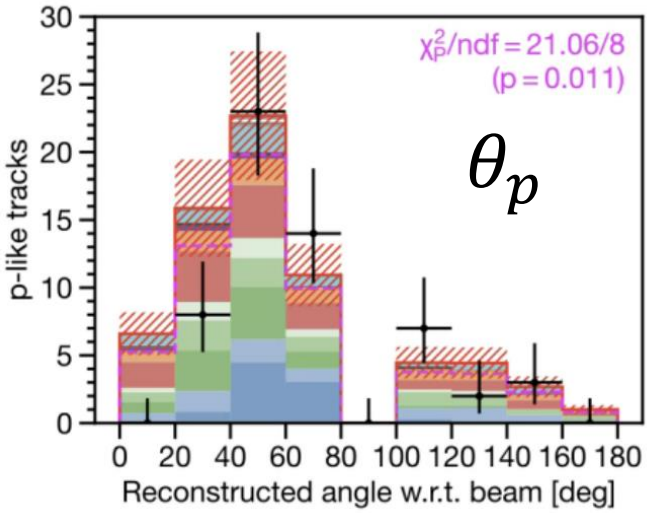
} Problems of π production or FSI models?

Physics run $\langle E_\nu \rangle = 1.04$ GeV (FHC) : Proton & Pion results

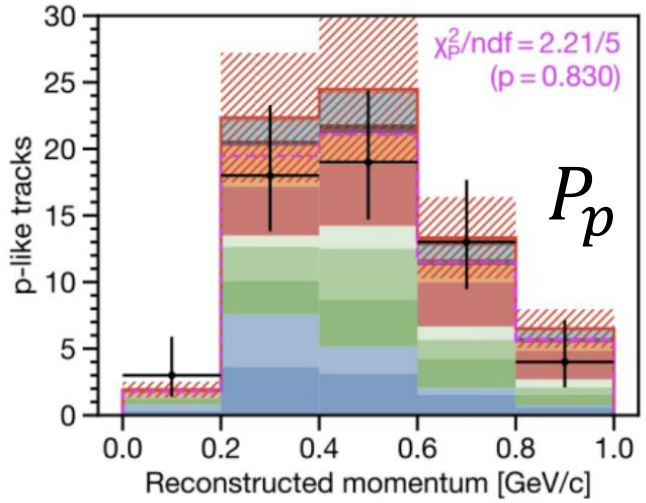
※ 5% of the NINJA first Physics Run data.

A. Kasumi, S. Han, et al., arXiv:2608.16063 (2026).

Proton

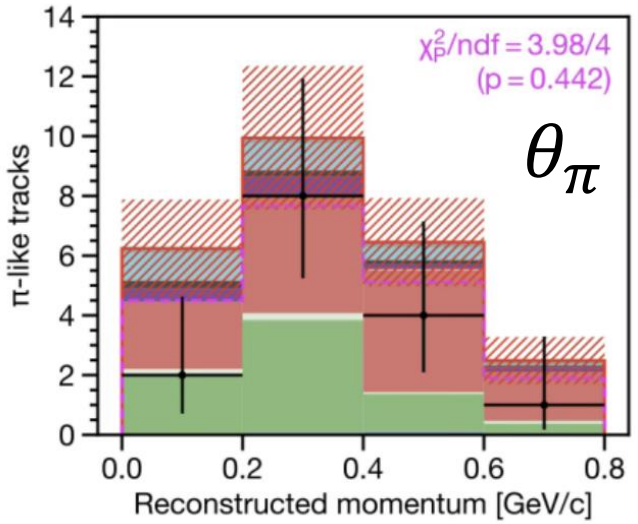


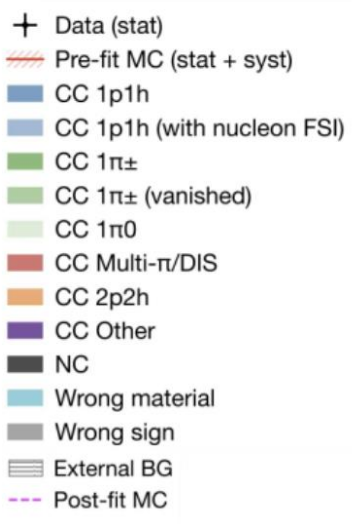
A deficit is observed at $0° < \theta < 40°$.
More statistics and further study are needed.

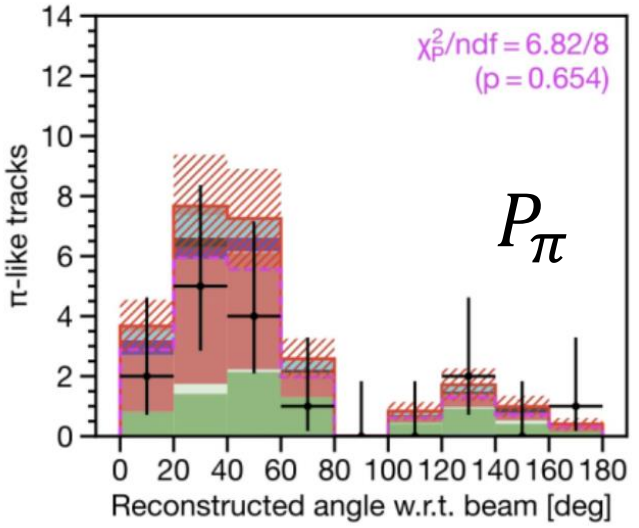


Momentum distributions are consistent within statistical uncertainties.

Pion







No significant discrepancy beyond the statistical uncertainty.

Summary

- NINJA studies neutrino–nucleus interactions using a hybrid detector consisting of ECCs, an emulsion shifter, and a scintillation fiber tracker.
  → High spatial resolution to low-momentum protons and charged pions.

- We successfully measured low-momentum protons and charged pions and compared the data with MC predictions.
  → The detector runs demonstrated the capability and reliability of the NINJA detector and analysis.

- Data–MC differences are beginning to emerge in the NINJA data.
  → We are extending the analysis to a larger event sample for higher-statistics measurements.


Backup

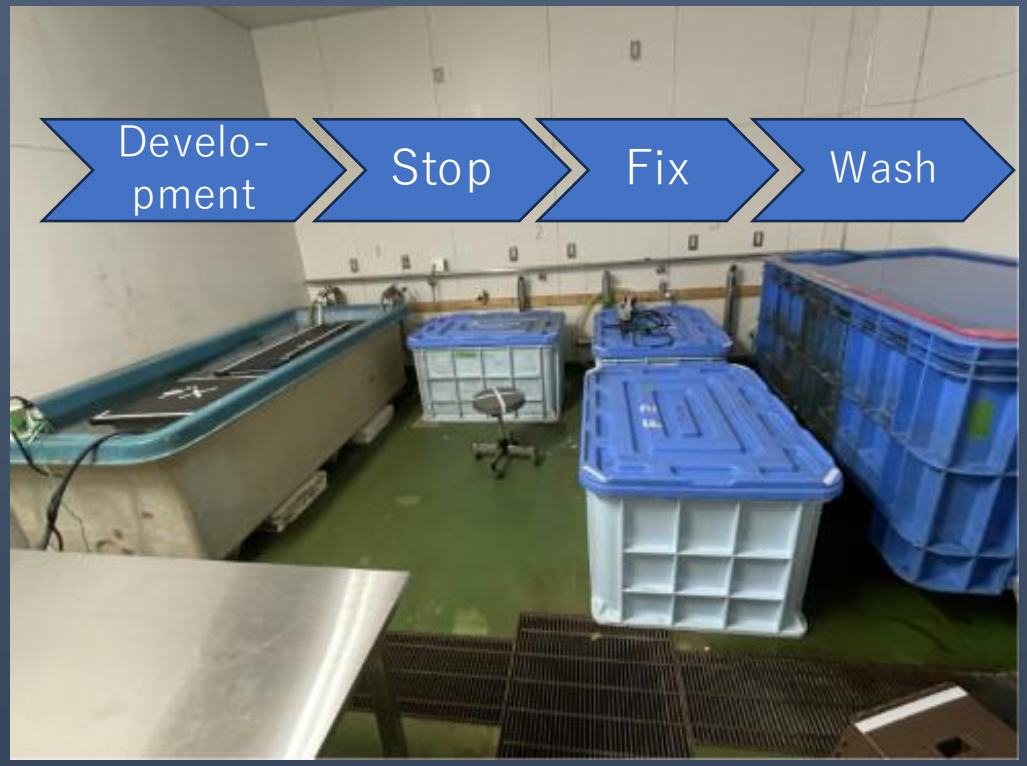
Film development / Track scanning

Development

Latent images in the emulsion transformed into visible rows of grains during development.

Swelling

Restore the emulsion thickness, which shrank during development, to the same thickness as during the experiment.

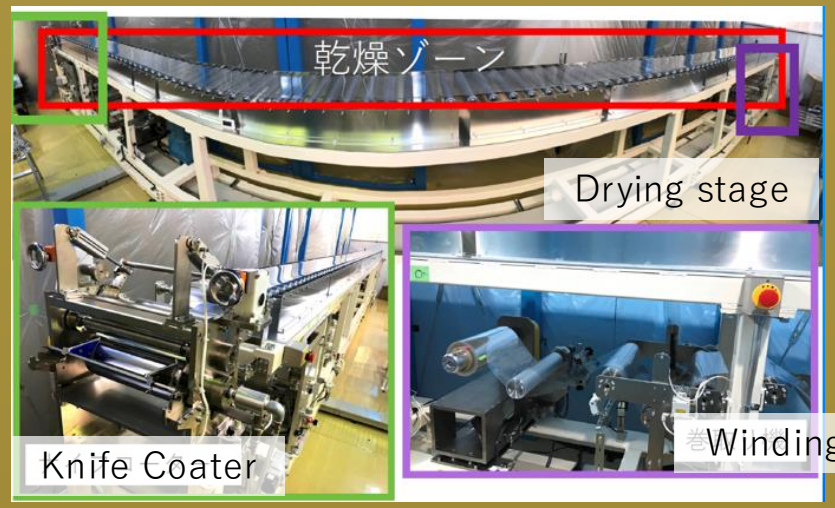




Emulsion Production/Readout System & Detector Upgrades

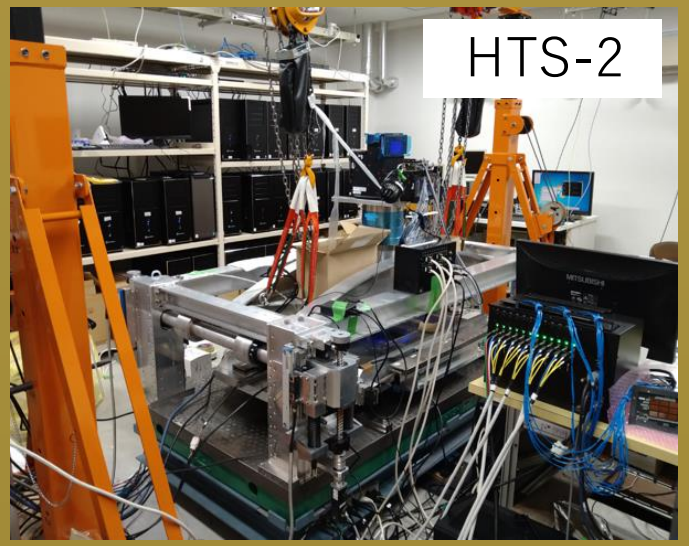
Equipment developments

Automatic emulsion pouring system



→ ×10 faster than hand made

New high speed emulsion scanning system

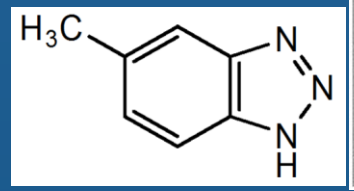


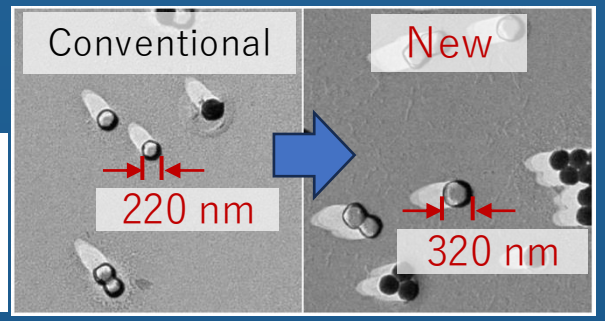
→ ×5 faster than current system

Detector upgrades

Refreshable large AgBr crystal size gel

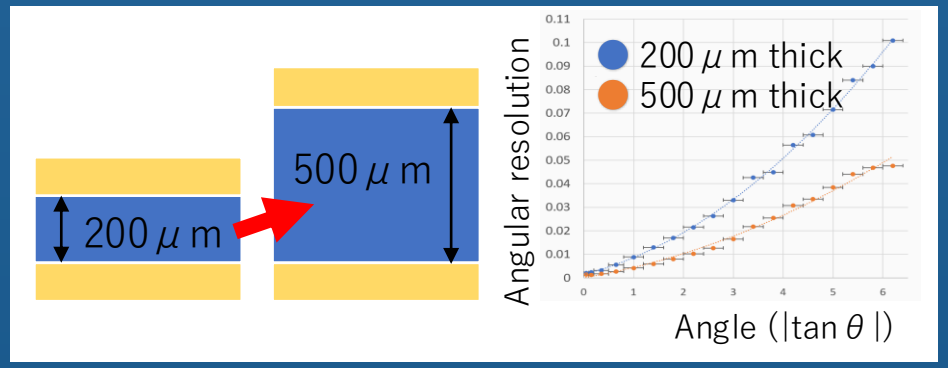
5-methyl benzotriazole





→ necessary for HTS2 to scan tracks with fast & high efficiency.

Thicker-base emulsion film



→ Improve angular resolution