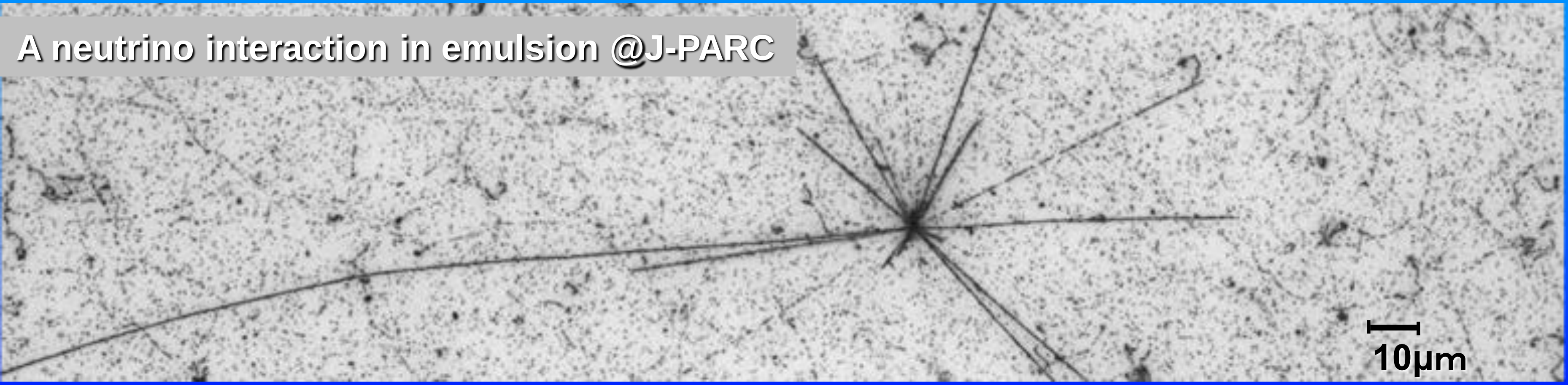
NINJA

INSTITUTE FOR ADVANCED RESEARCH NAGOYA UNIVERSITY SINCE 2002

Using nuclear emulsions to measure neutrino flux and cross-sections

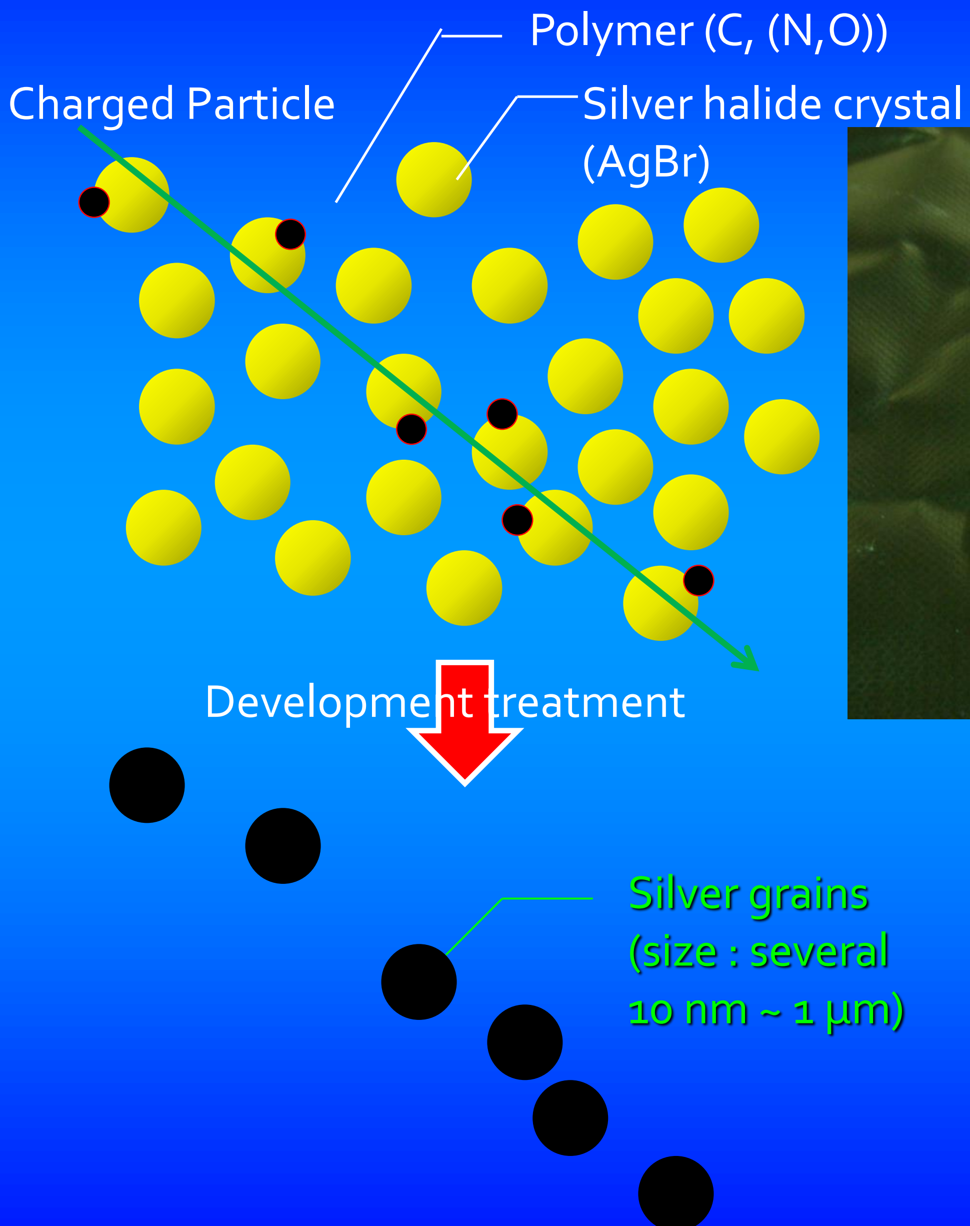
Neutrino-water cross-section measurements in the NINJA experiment (J-PARC E71)

Tsutomu Fukuda (IAR/F-lab, Nagoya Univ.)
tfukuda@flab.phys.nagoya-u.ac.jp

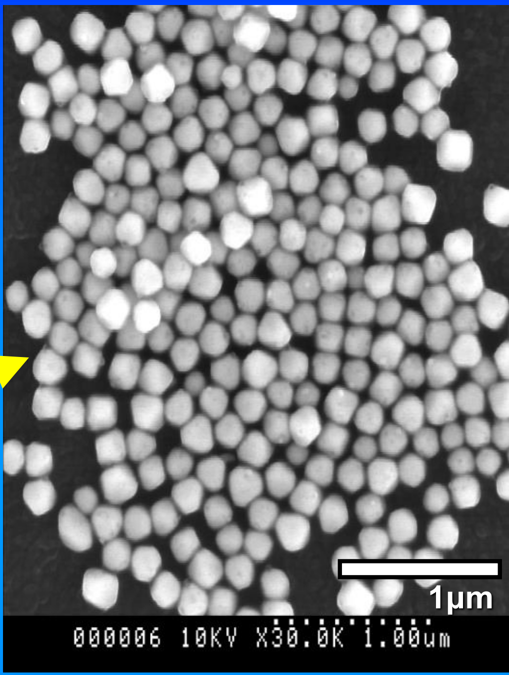


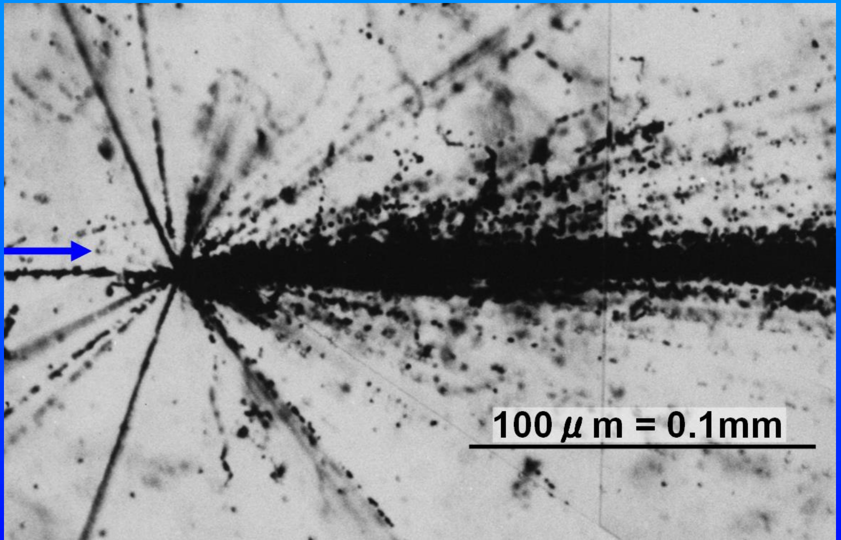
ESSnuSB/EuroNuNet annual meeting, 22th Oct. 2019 @IRB, Zagreb, Croatia

Nuclear Emulsion



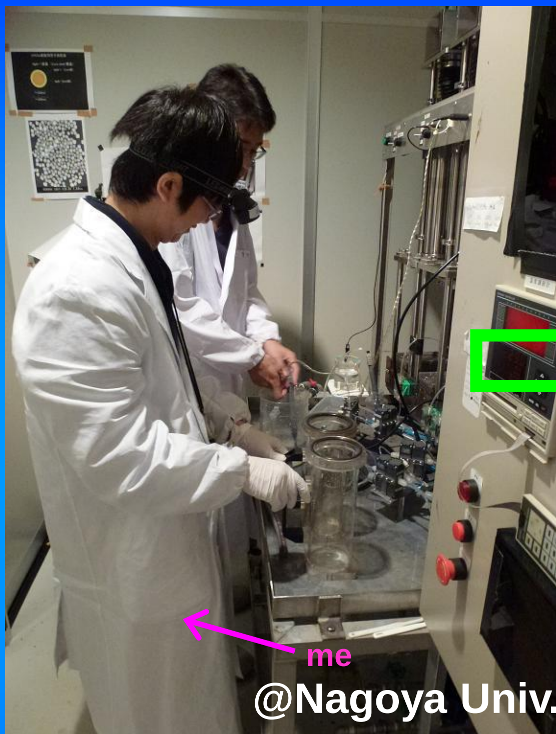
AgBr・I crystal

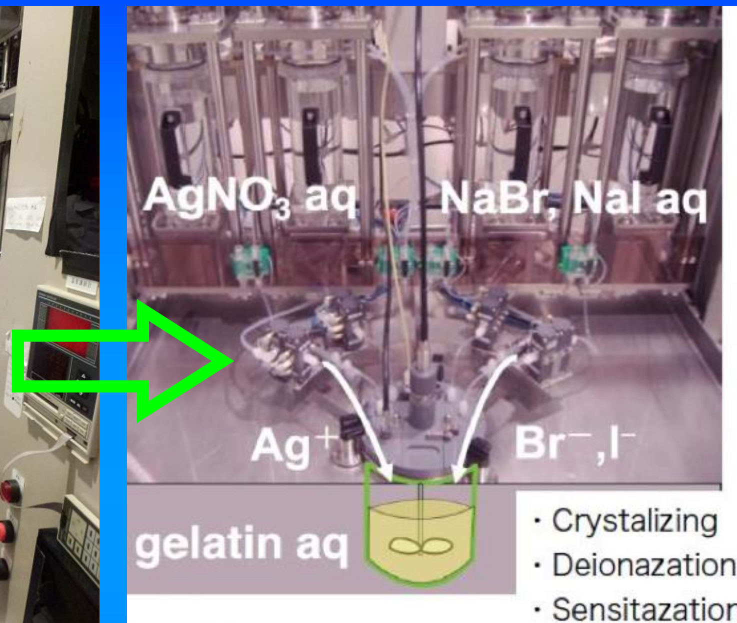




Emulsion film production in the lab

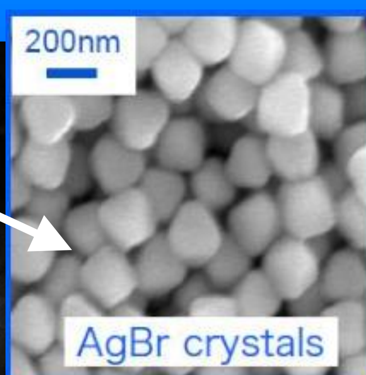
Nuclear emulsion film is made at Nagoya Univ.

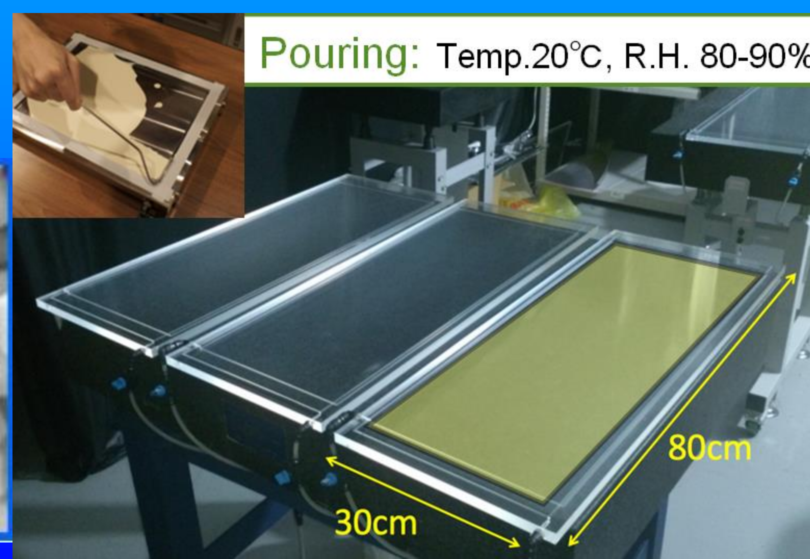




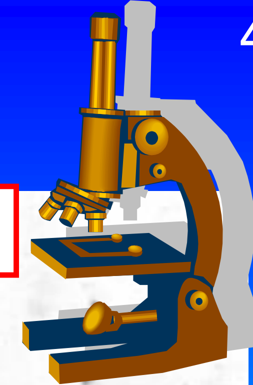
- Preparing liquid
- Gel production
- Gel melting
- Pouring
- Drying

Gelatin + crystal





Nuclear Emulsion

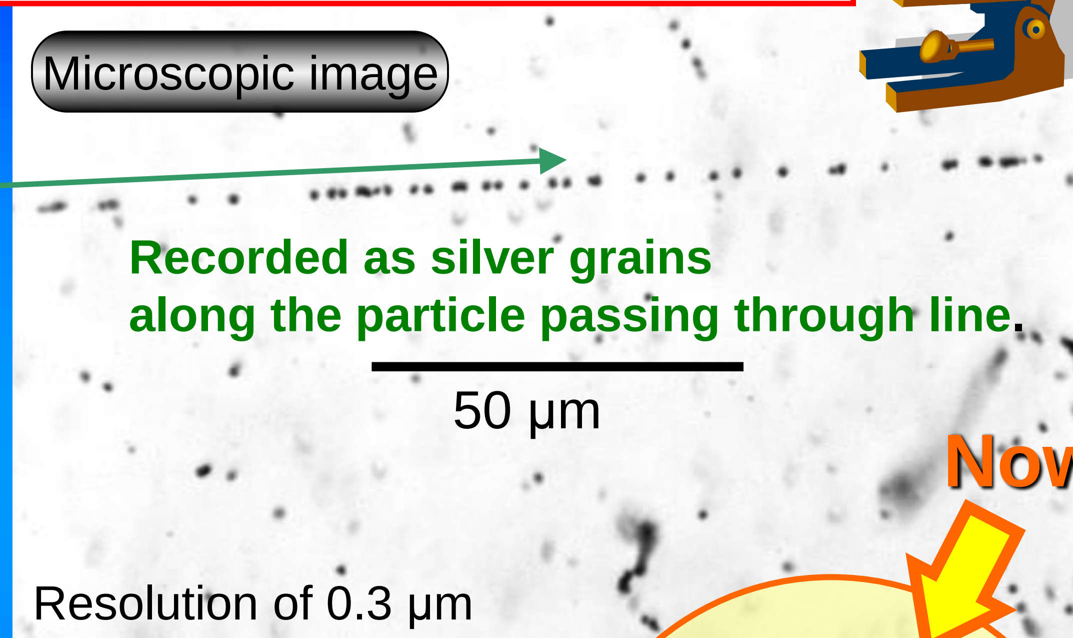


1896 (A.H.Becquerel)
Discovery of Radioactivity
1947 (C.Powell et al.)
Discovery of π

F-lab.

1971 (K.Niu et al.)
Discovery of charm particle in cosmic-ray
1986 (K.Niwa et al., E531)
*Indirect observation of ν_τ
2001 (K.Niwa et al., DONUT)
Direct observation of ν_τ
2015 (K.Niwa et al., OPERA)
Discovery of ν_τ appearance

Sub micron resolution 3D tracker



＊see
A.Blondel, arXiv:1812.11362v2,
G. Feldman's slide@Rencontres du Vietnam 2019

Now

Fermilab E531
1978-1983

CHORUS
1990-2000

DONUT
1994-2005

OPERA
2001-2019

NINJA
2015-

SHiP
2026-

Neutrino experiment with Nuclear Emulsion in Nagoya Univ.

Detector list of accelerator-based neutrino experiment

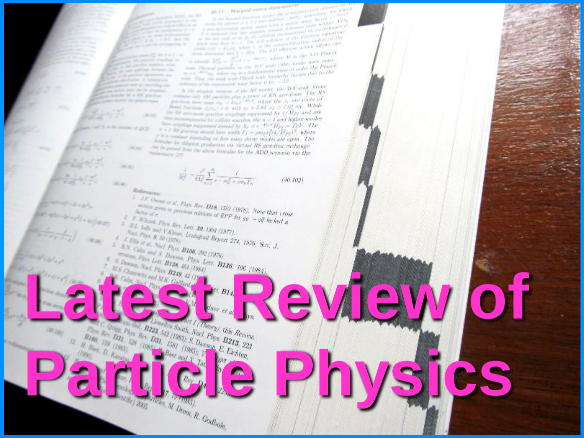


Table 34.9: Properties of detectors for accelerator-based neutrino beams.

Name	Type	Target	Mass* (t)	Location	$\langle E_\nu \rangle$ (GeV)	Dates
Lederman et al.	Spark	Al	10	BNL	0.2–2	1962
CERN-spark	Spark	Al	20	CERN	1.5	1964
Serpukhov	Spark	Al	20	IHEP	4	1977
Aachen-Padova	Spark	Al	30	CERN	1.5	1976–77
Gargamelle	Bubble	Freon	6	CERN	1.5,20	1972,1977
BEBC	Bubble	H,D,Ne-H	2–42	CERN	50,150 & 20	1977–84
SKAT	Bubble	Freon	8	IHEP	4	1977-1987
ANL-12ft	Bubble	H,D	1–2	ANL	0.5	1970
BNL-7ft	Bubble	H,D	0.4–0.9	BNL	1.3,3	1976–82
Fermilab-15ft	Bubble	D,Ne	1–20	FNAL	50,180&25,100	1974–92
CITF	Iron	Fe	92	FNAL	50,180	1977–83
CDHS	Iron	Fe	750	CERN	50,150	1977–83
MINOS	Iron	Fe	980,5.4k	FNAL	4–15	2005–2016
INGRID	Iron	Fe	99	J-PARC	0.7–3	2009–
Super-Kamiokande	Cherenkov	H_2O	22,500	Kamioka	0.6	1996–
K2K-1kt	Cherenkov	H_2O	25	KEK	0.8	1998–2004
MiniBooNE	Cherenkov	CH_2	440	FNAL	0.6	2002–12
HWPF	Scintillation	CH_2	2	FNAL	2	2014–
LSND	Scintillation	CH_2	130	LANL	0.06	1993–98
NOvA	Scintillation	CH_2	300,14k	FNAL/Ash River	2	2013–
SciBar	Scintillation	CH	12	KEK/FNAL	0.8,0.6	2004,2007–8
ICARUS	LArTPC	Ar	760	LNGS	20	2006–12
Argoneut	LArTPC	Ar	0.025	FNAL	3	2009–10
MicroBooNE	LArTPC	Ar	170	FNAL	0.8	2014–
FNAL-E-531	Emulsion	Ag, Br	0.009	FNAL	25	1984
CHORUS	Emulsion	Ag, Br	1.6	CERN	20	1995
DONuT	Emulsion	Fe	0.26	FNAL	100	1997
OPERA	Emulsion	Pb	1.3k	LNGS	20	2006–12
NINJA	Emulsion	Fe	0.001	J-PARC	0.6	2016–
[illegible]	[illegible]	[illegible]	[illegible]	CERN	20	1977
[illegible]	[illegible]	[illegible]	[illegible]	CERN	20	1983
[illegible]	[illegible]	[illegible]	[illegible]	BNL	1.3	1987
[illegible]	[illegible]	[illegible]	[illegible]	BNL	3	1990
NOMAD	Hybrid	CH	3	CERN	20	1995–98
CCFR	Hybrid	Fe	690	FNAL	90,260	1991
NuTeV	Hybrid	Fe	690	FNAL	70,180	1996–97
MINERvA	Hybrid	[illegible]	[illegible]	FNAL	[illegible]	2009–
T2K-ND280	Hybrid	[illegible]	[illegible]	J-PARC	[illegible]	2009–

* Fiducial.

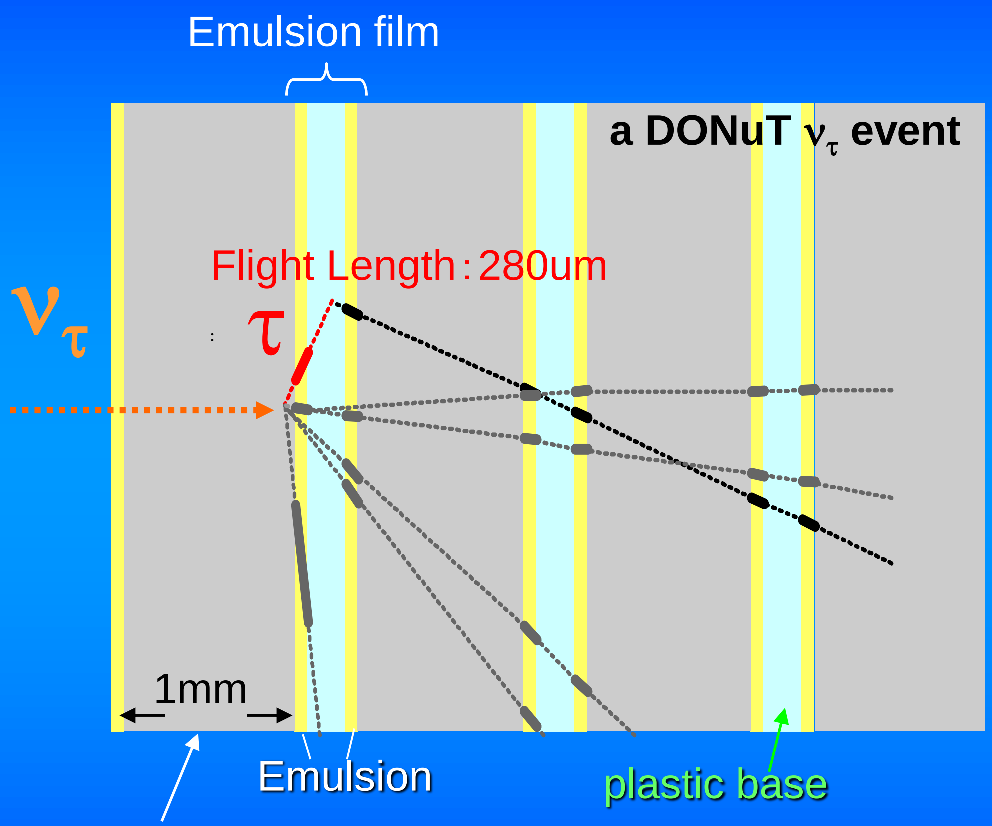
NINJA

detector, with 1,300 t of emulsion, to make the first direct observation of the appearance of ν_τ in a ν_μ beam. Recently, the NINJA collaboration has developed an emulsion cloud chamber detector to observe neutrinos in the J-PARC neutrino beam [227].

227. T. Fukuda *et al.*, PTEP **2017**, no. 6, 063C02 (2017).

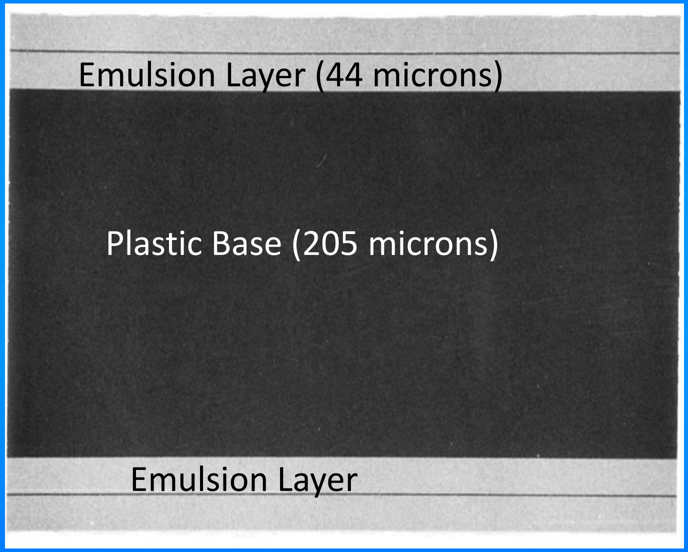
We hope to publish our cross-section results

Emulsion Cloud Chamber (ECC)



DONuT : Iron 1mm
OPERA : Lead 1mm
NINJA : Iron 0.5mm, Water 2.3mm

basic detector: AgBr crystal,
size = 0.2 micron
detection eff.= 0.16/crystal
10^{13} "detectors" per film

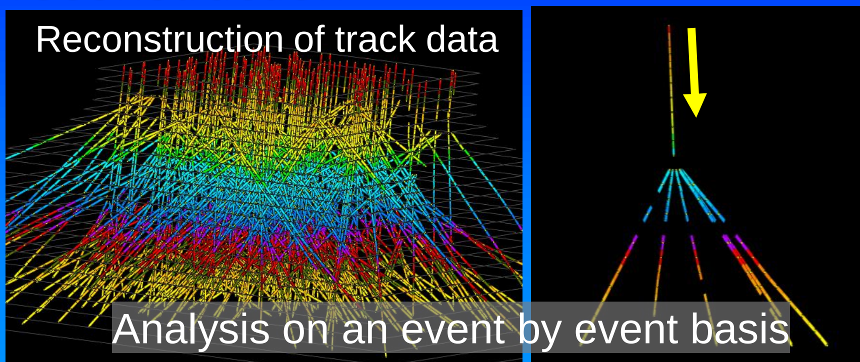


44-70μm emulsion gel were coated on both sides of the ~200μm-thick plastic base.

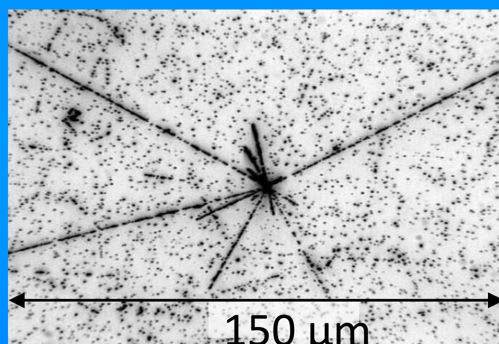
Sandwich structure of emulsion films and target material.

Nuclear Emulsion Detector

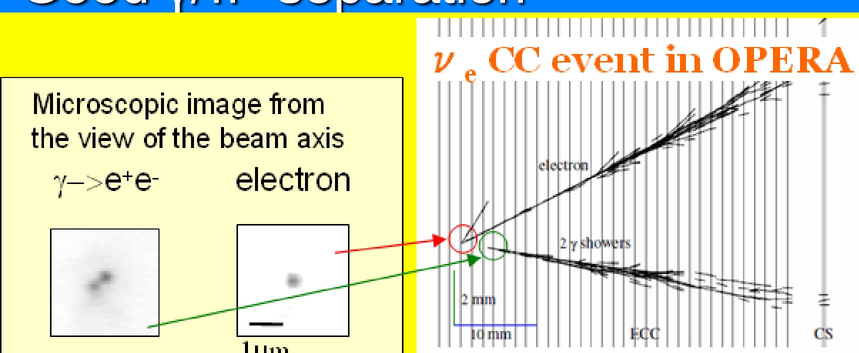
3D reconstruction



4π detection

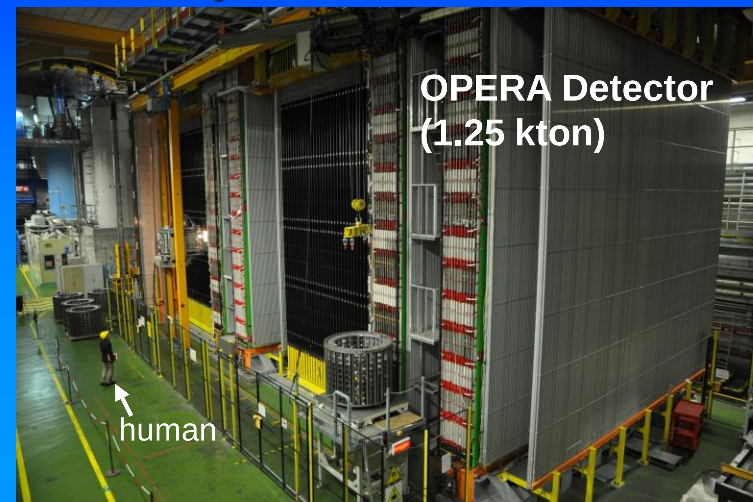


Good γ/π^0 separation

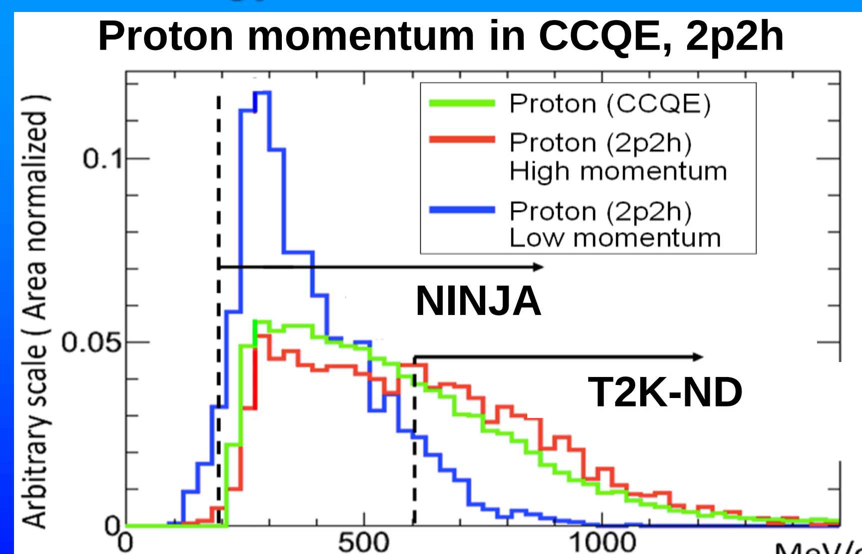


Low BG from ν_μ NC π^0 production

Scalability



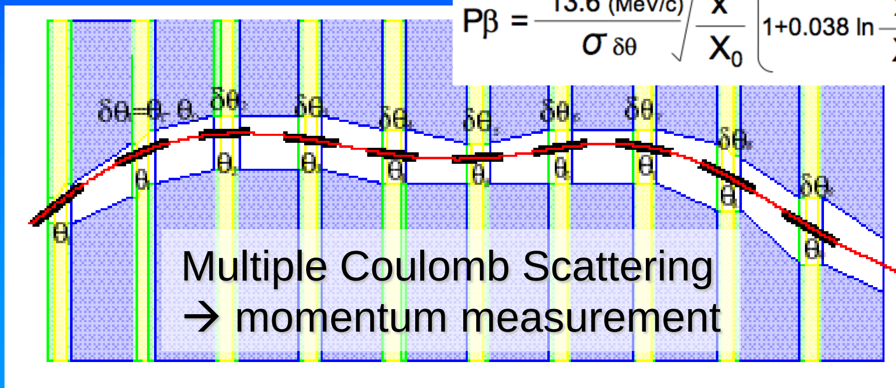
Low energy threshold



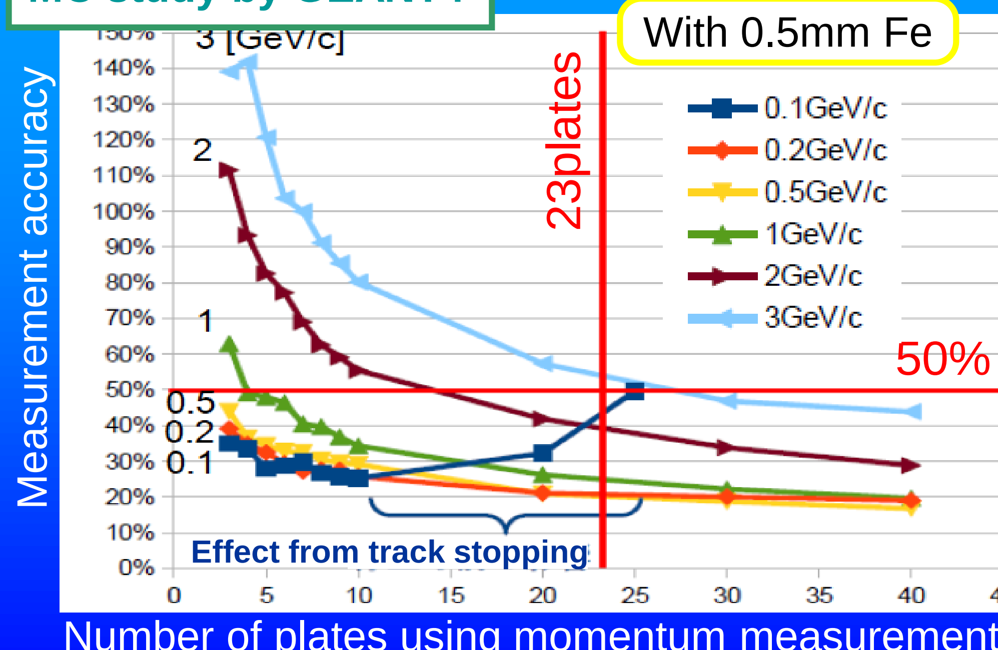
Particle ID

pβ measurement by the MCS method

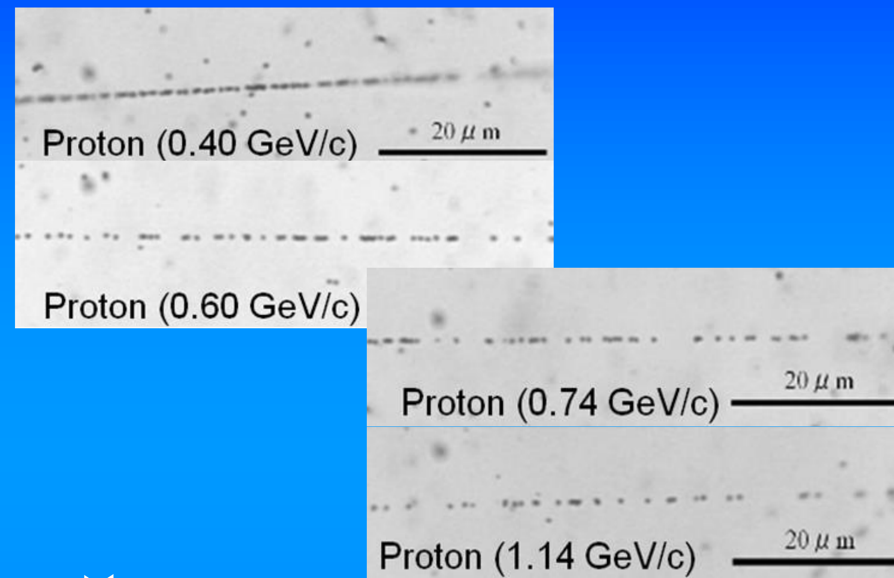
$$P\beta = \frac{13.6\ (\mathrm{MeV/c})}{\sigma_{\delta\theta}} \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

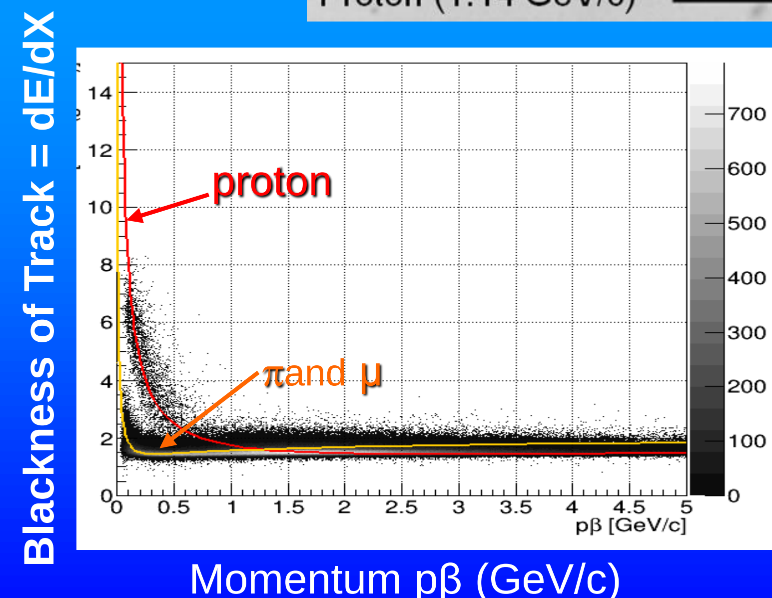


MC study by GEANT4

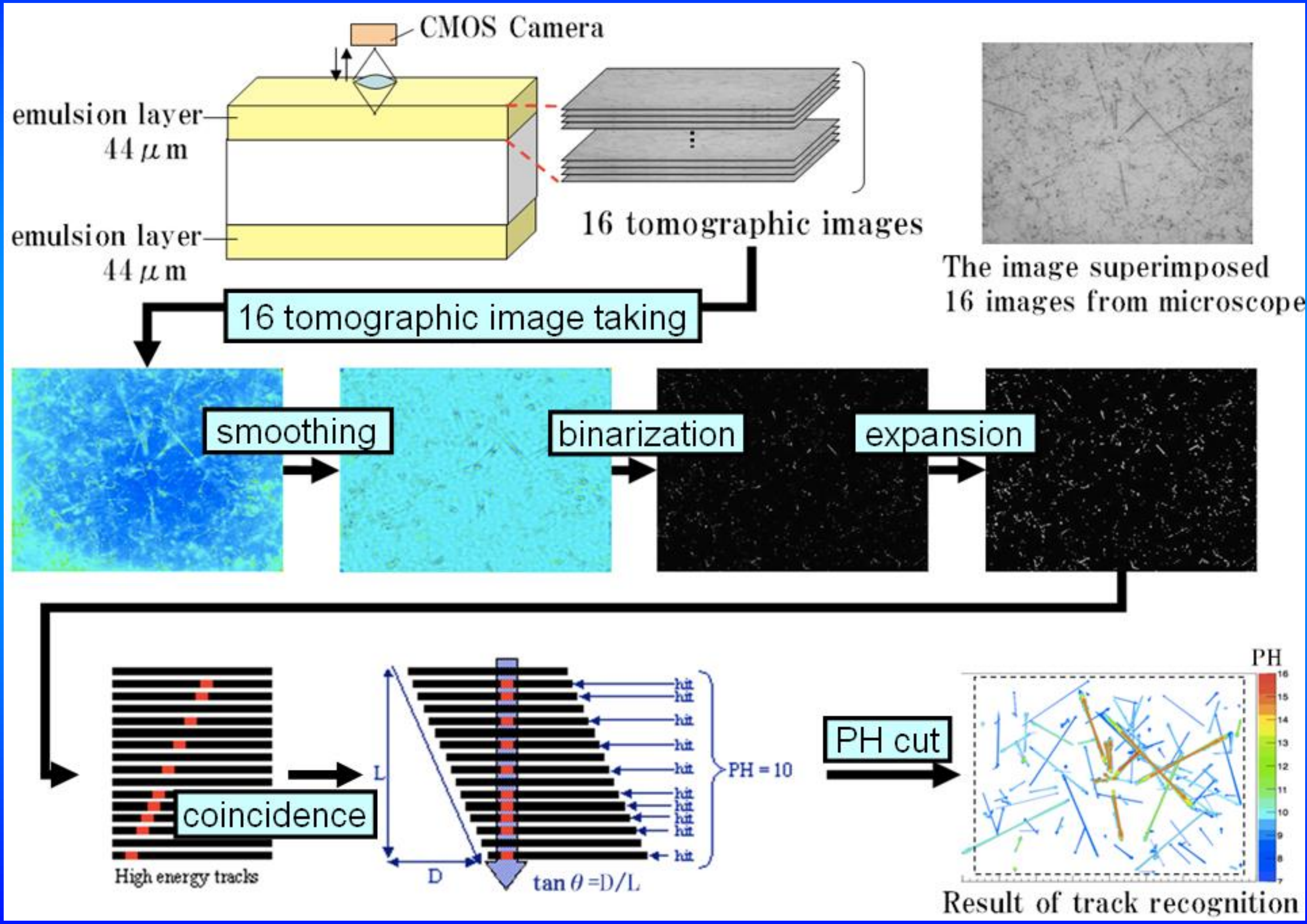


dE/dx measurement by track blackness

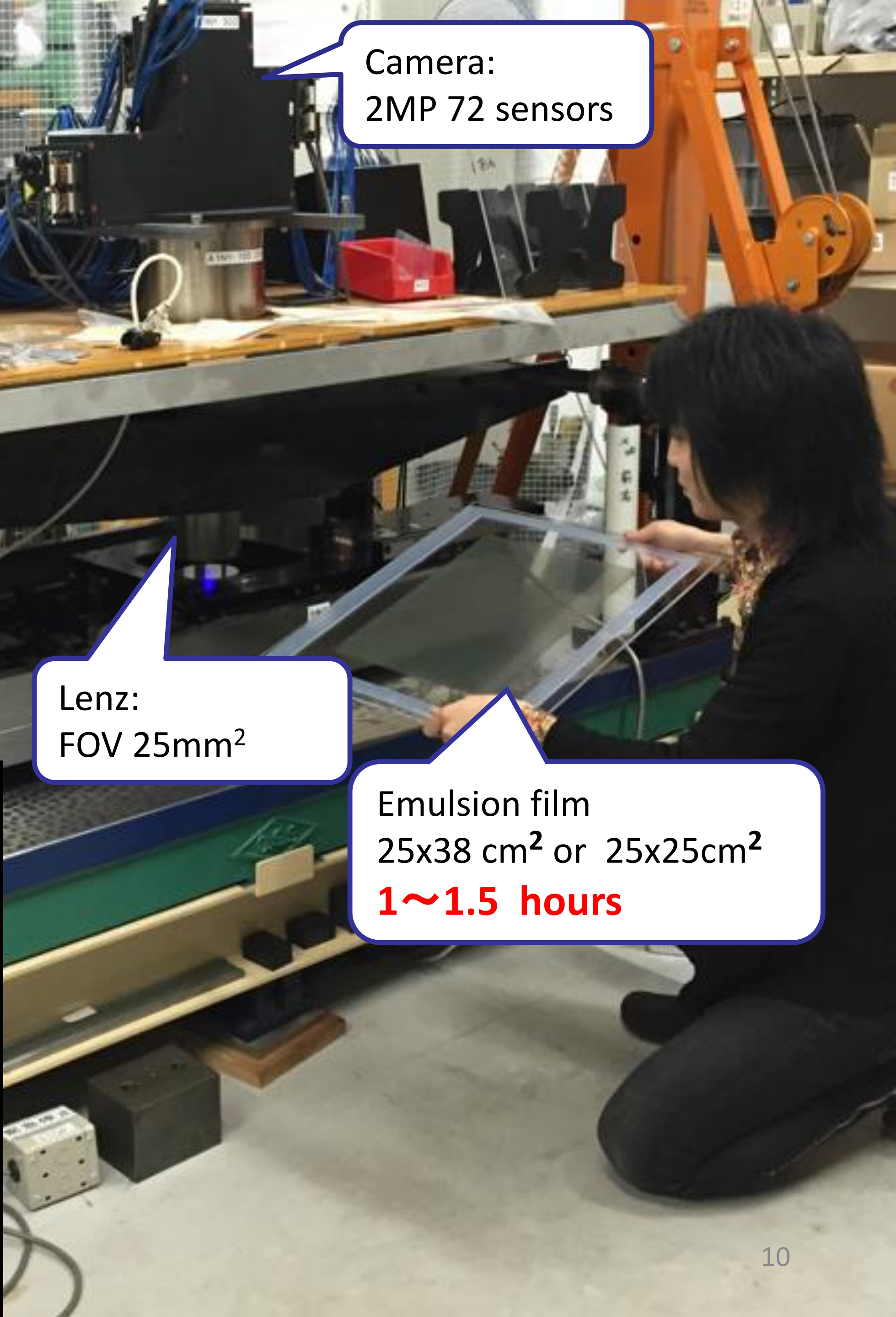


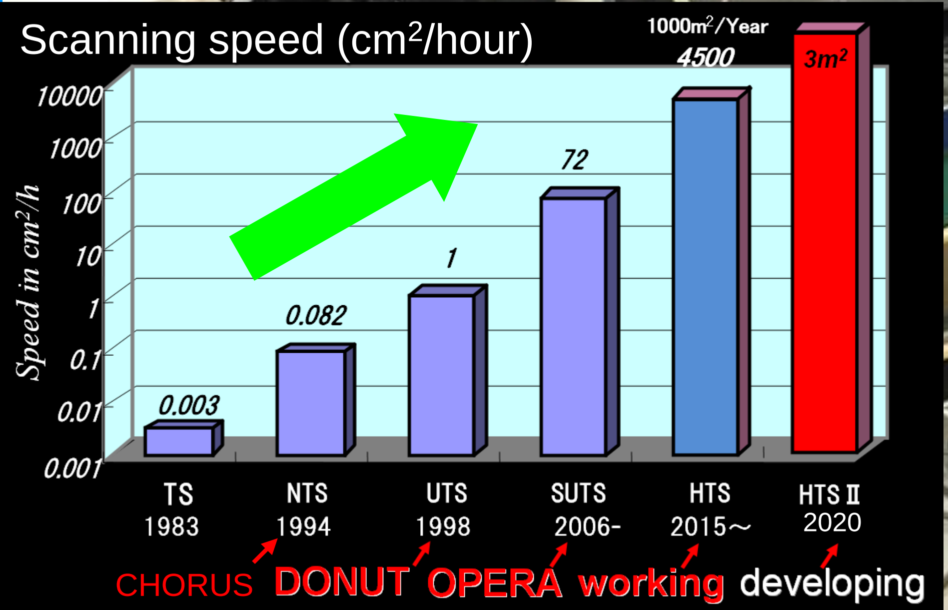


Automatic track recognition

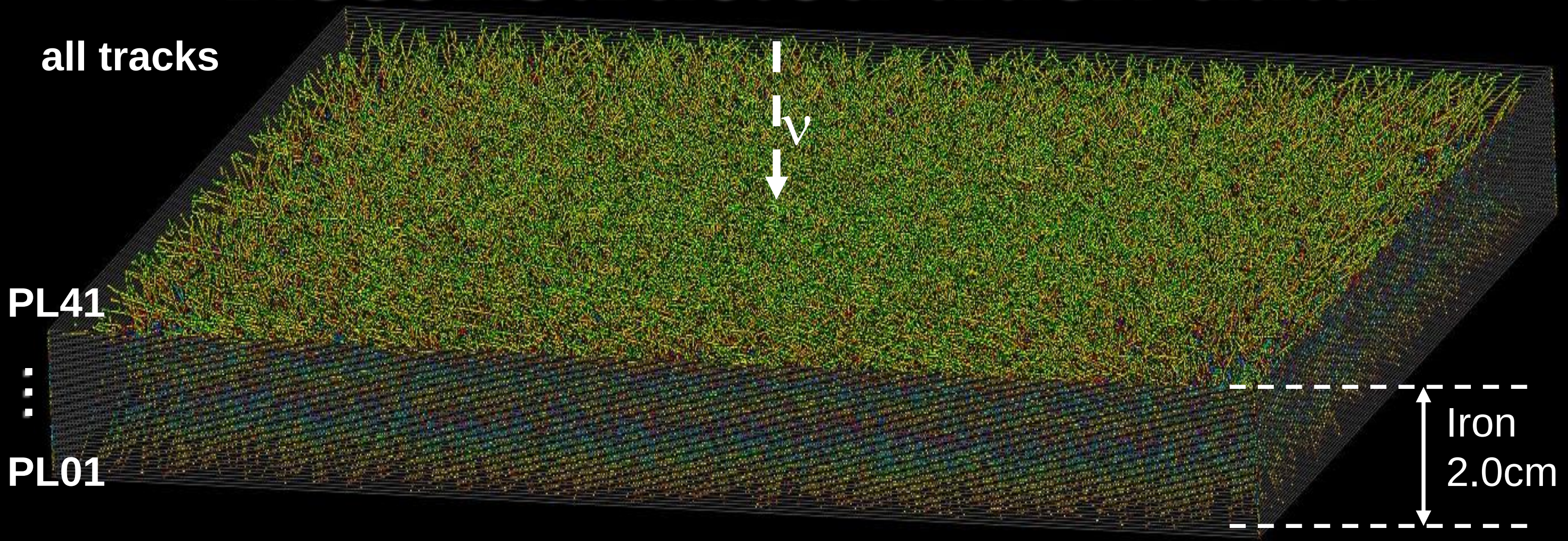


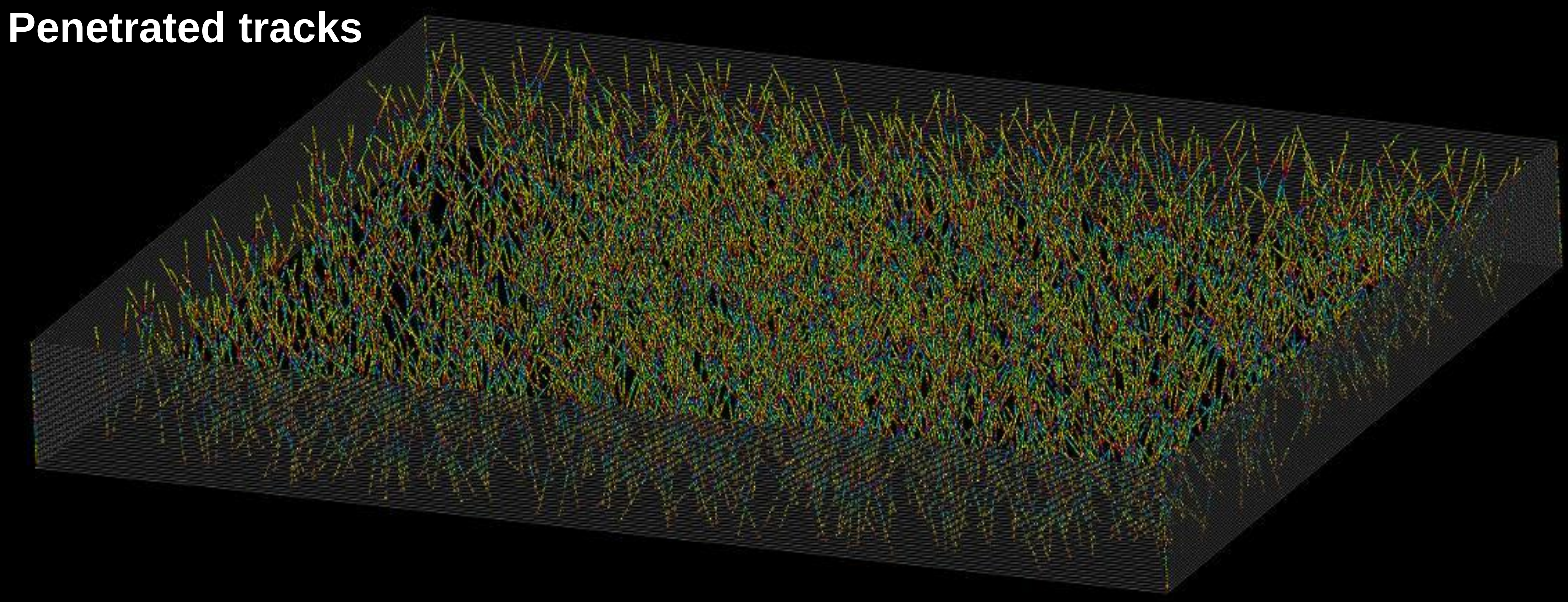
Hyper Track Selector



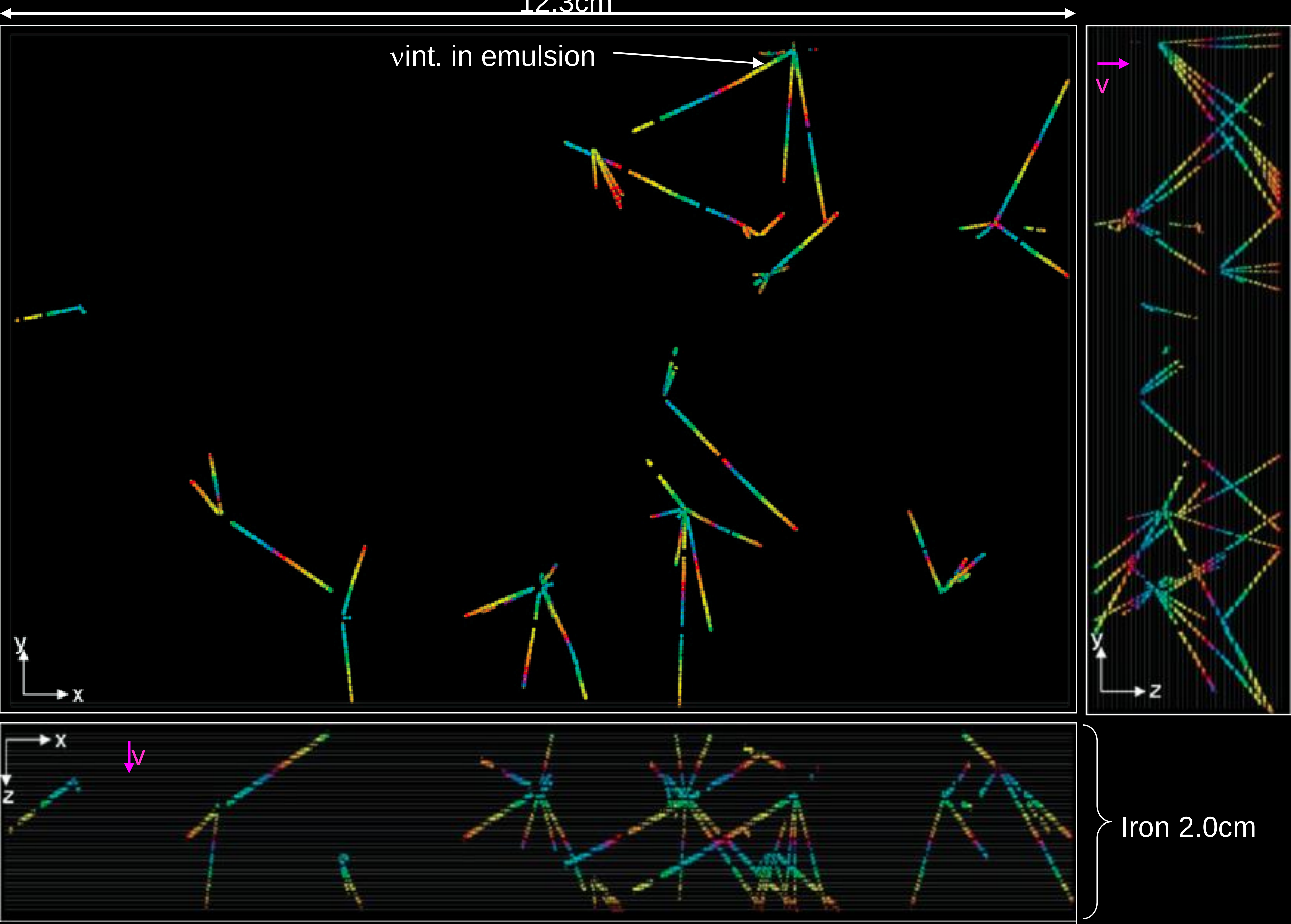


Reconstructed track data

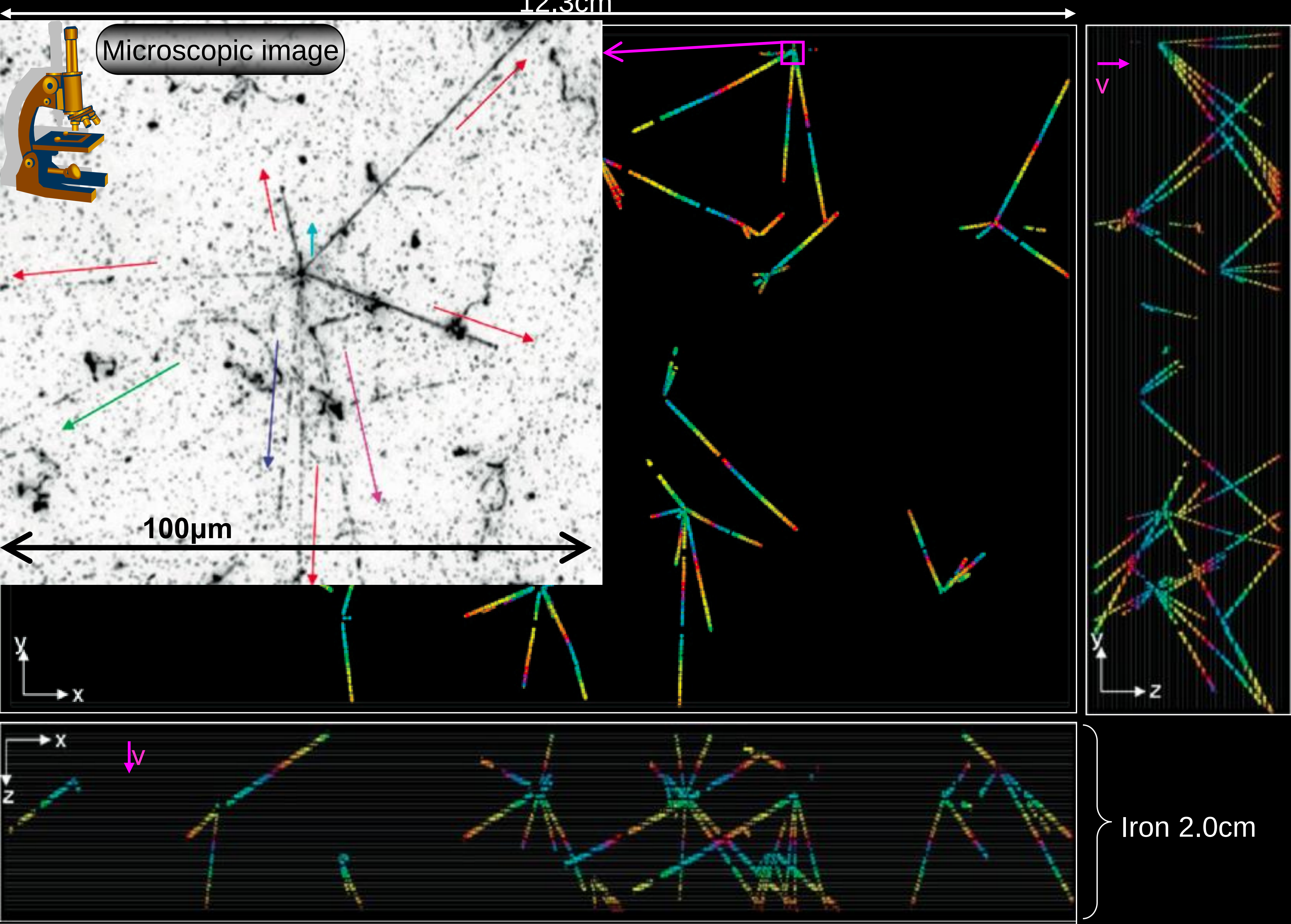




NINJA: Feasibility study: 2kg Iron target ECC

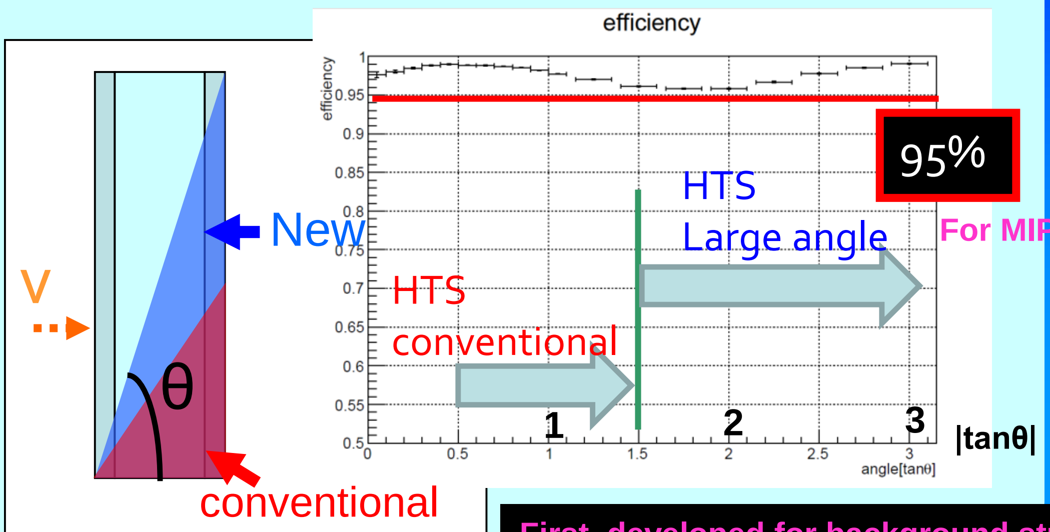


NINJA: Feasibility study: 2kg Iron target ECC



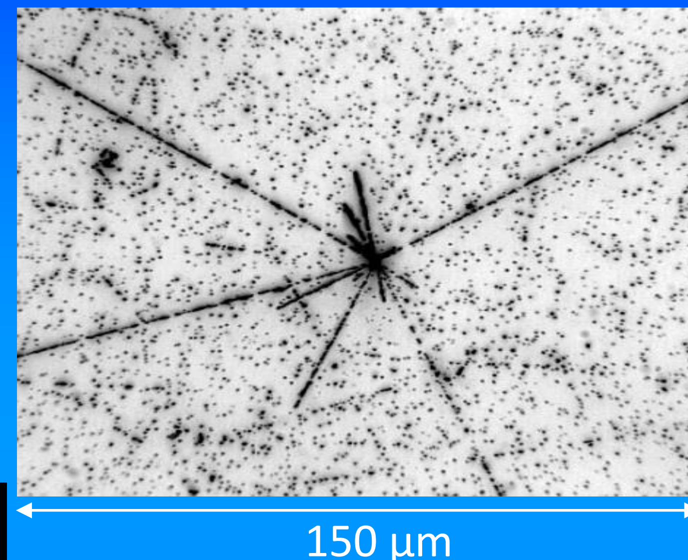
Large angle scanning

High speed & Large angle Scanning

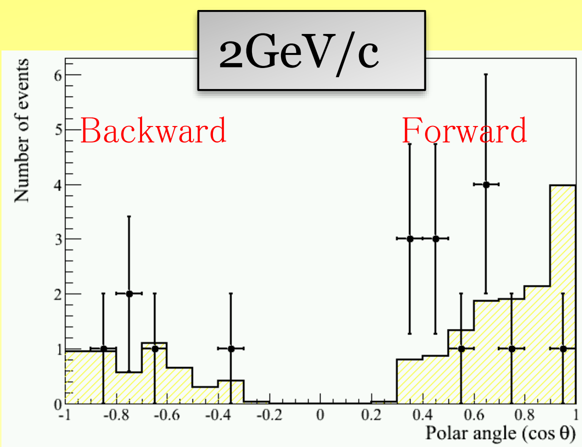


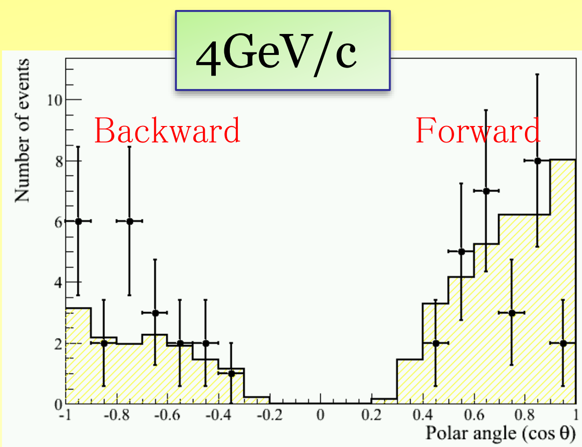
First, developed for background study in the OPERA experiment

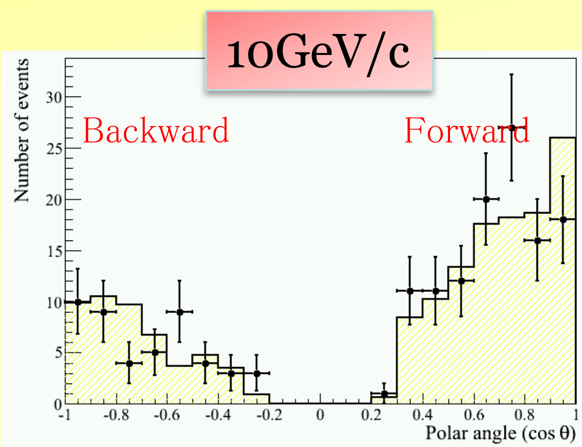
- For slow proton detection



Emission angle (cosθ) of nuclear fragment in hadron interactions

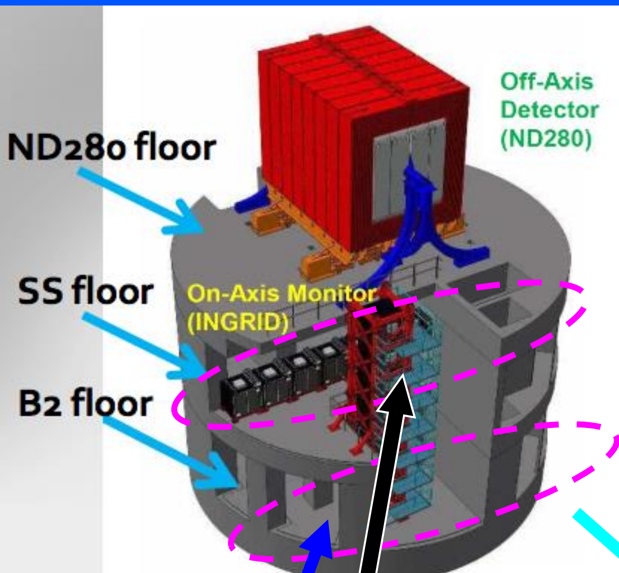




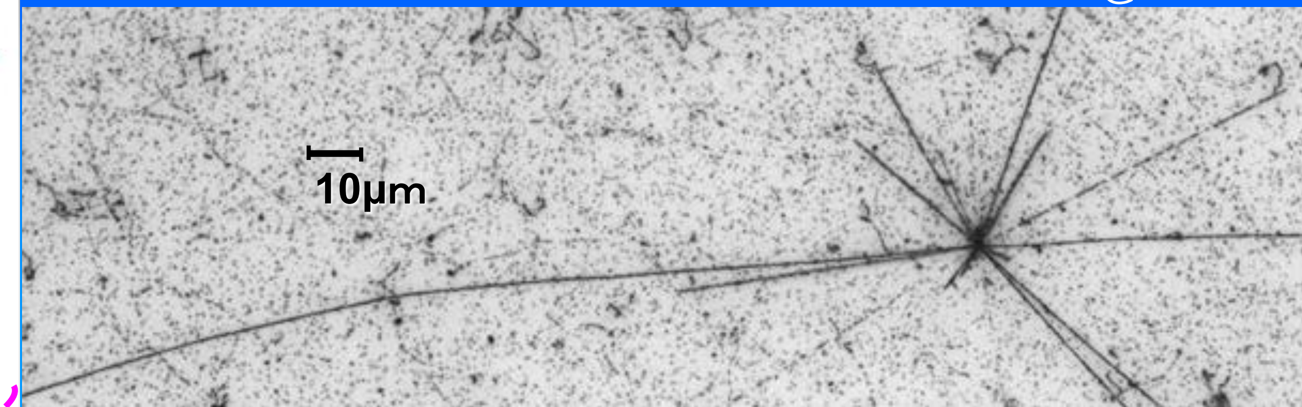


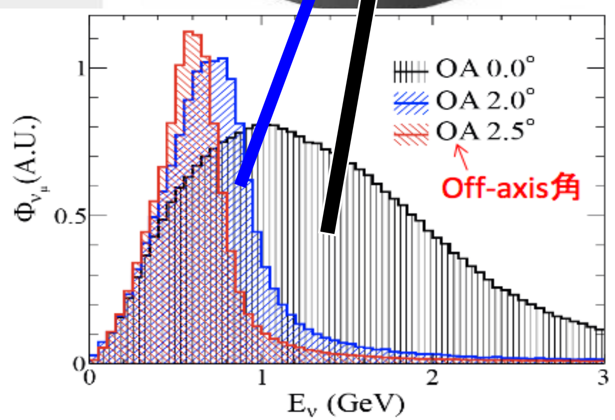
NINJA Experiment

Neutrino **I**nteraction research with **N**uclear emulsion and **J**-PARC **A**ccelerator

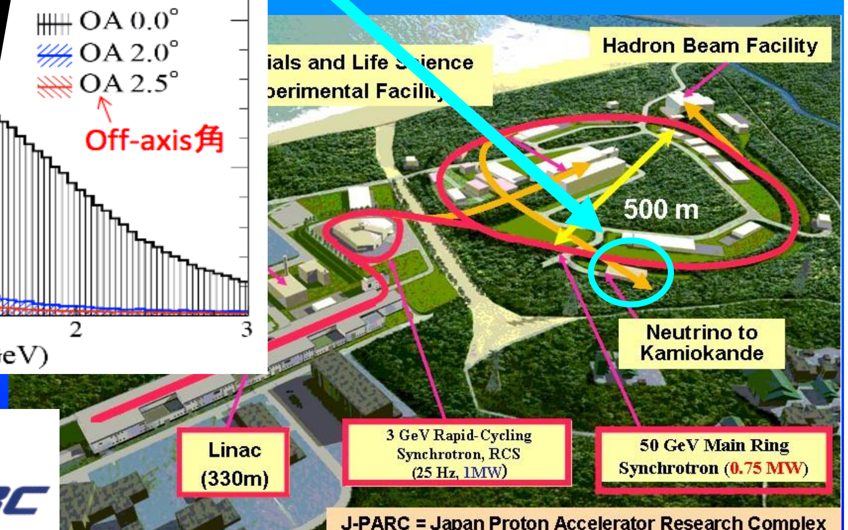


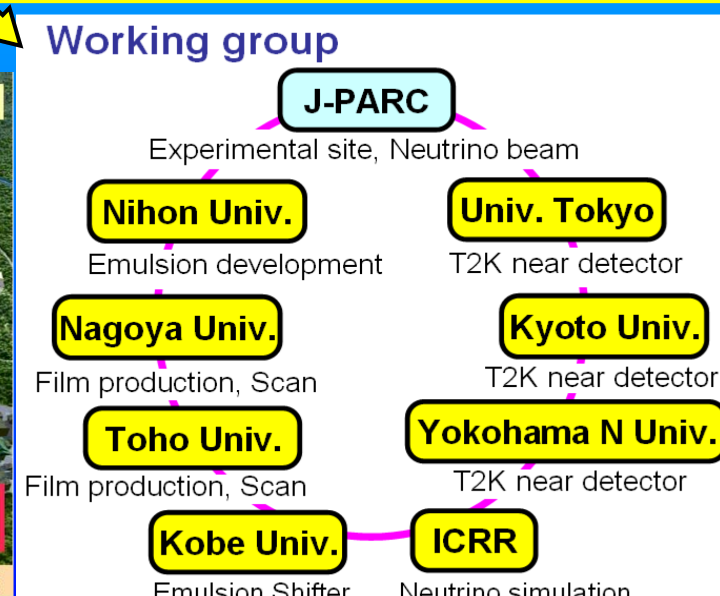
A neutrino interaction in emulsion @J-PARC





A collaborative project with some member of OPERA and T2K





NINJA Collaboration

(＊ Spokesperson)

Nihon University: Y. Hanaoka, S. Ito, K. Kashiwabara, S. Kodama, S. Mikado

Nagoya University: T. Fukuda*, H. Kawahara, R. Komatani, M.Komatsu, M. Komiyama, K. Morishima, M. Morishita, M. Naiki, M. Nakamura, Y. Nakamura, N. Naganawa, N. Nakano, T. Nakano, A. Nishio, H. Rokujo, O. Sato, K. Sugimura, L. Suzui, Y. Suzuki, T. Takao, R. Watanabe

Toho University: Y. Kosakai, T. Matsuo, K. Mizuno, Y. Morimoto, S. Ogawa, H. Oshima, H. Takagi, H. Shibuya

Kobe University: S. Aoki

ICRR, University of Tokyo: Y. Hayato

Yokohama National University: A. Minamino, Y. Tanihara

Kyoto University: A. Ajmi, A. Hiramoto, A. K. Ichikawa, T. Kikawa, T. Nakaya, T. Odagawa, K. Yasutome

University of Tokyo: M. Yokoyama

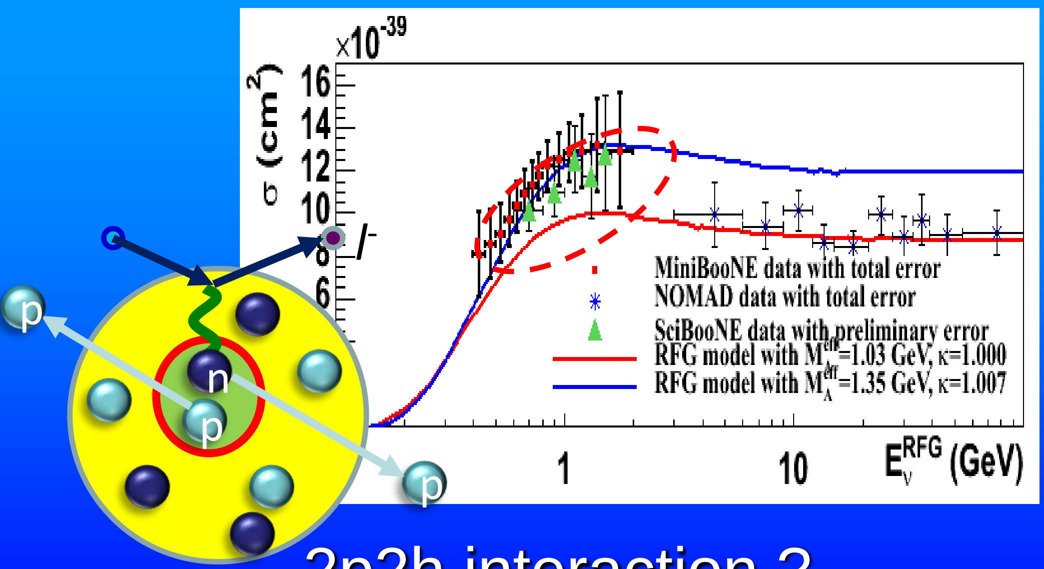
Physics Motivation

Sub-Multi GeV Neutrino interaction

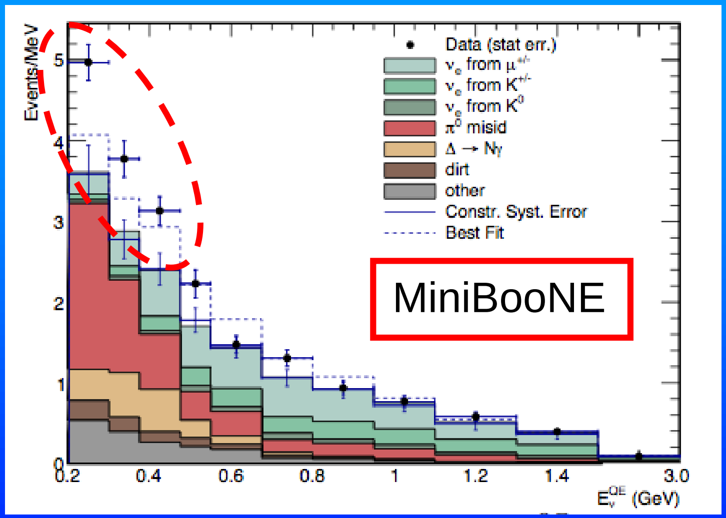
- Major source of uncertainty in ν oscillation analysis
- ν_e anomaly from several experiments (sterile ν ?)

Need to more understand the neutrino-nucleus interaction !

1. Confirmation and cross-section measurement of 2p2h int.
2. Exclusive measurement of ν_μ, ν_e- water cross-sections

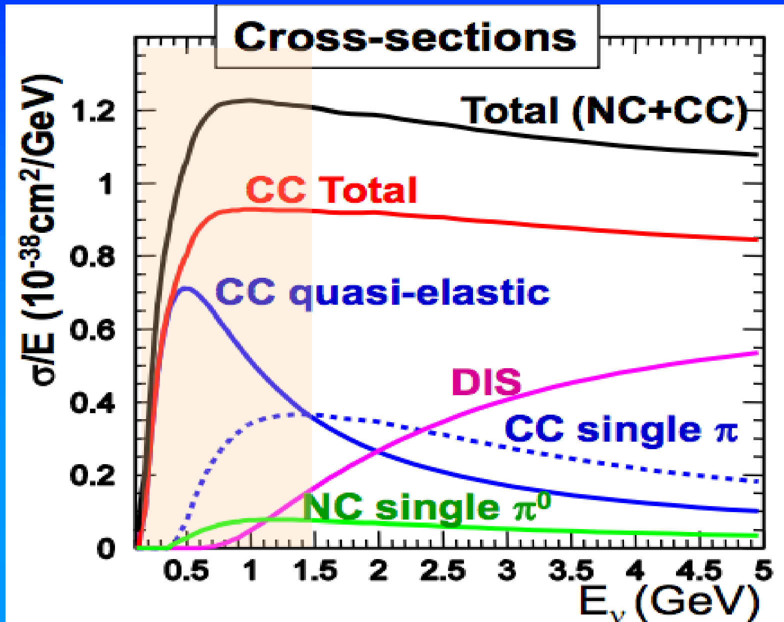


2p2h interaction ?

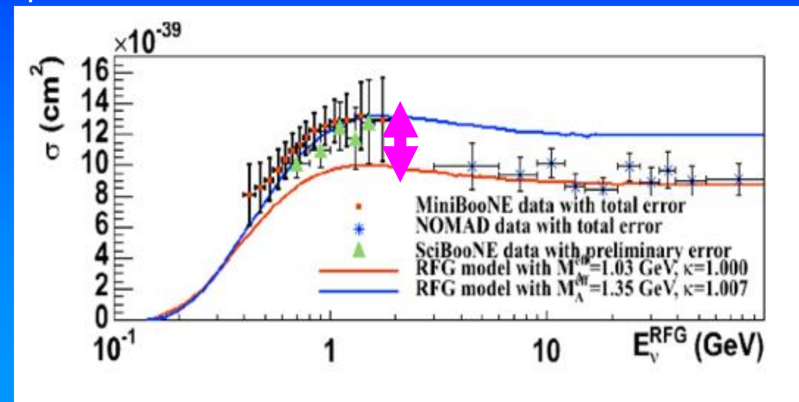


Effect from Sterile Neutrino ?

NINJA Low energy neutrino interactions

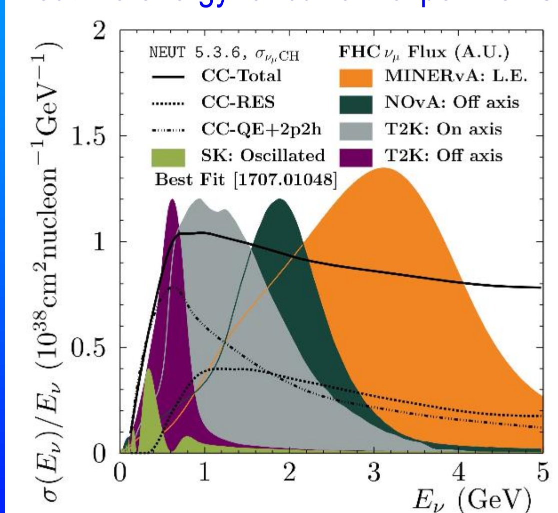


ν_μ-Carbon CCQE like cross-section

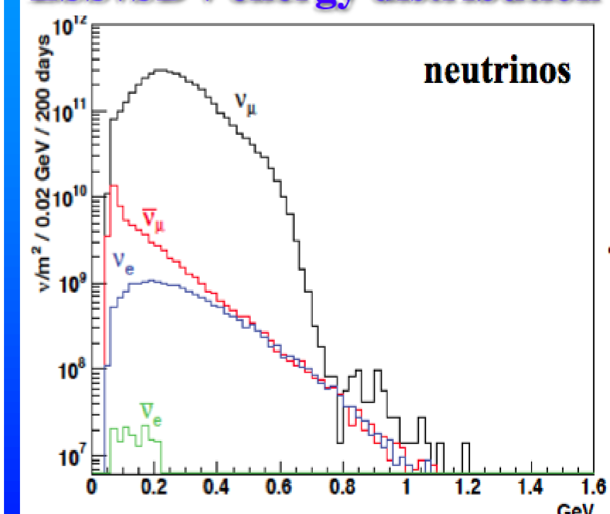


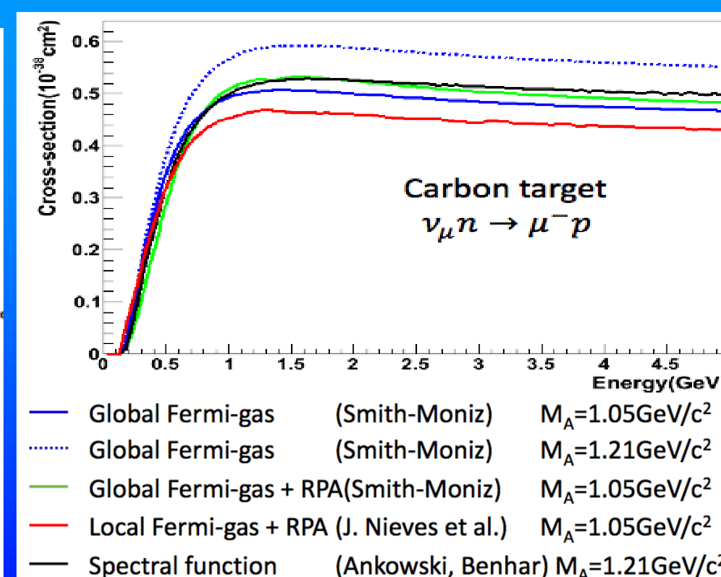
There are discrepancy between low and high energy (CCQE puzzle)

Neutrino energy for current experiments



ESSνSB ν energy distribution





L. Pickering, NuFact2019 | M. Dracos, NuFact2019 | Y. Hayato, NuInt2018

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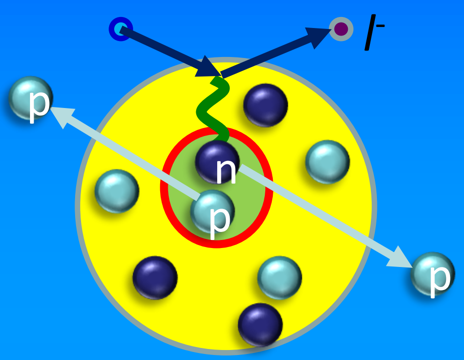
Multi-nucleon reaction (2p2h)

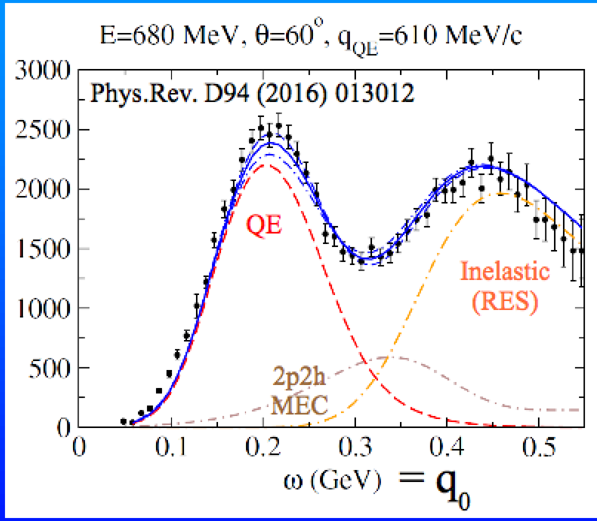
In cross-section of CCQE-like events, measured value is much larger than the simple model predictions → new interaction process (2p2h) ?



- **There is experimental indication of binding nucleon pair from electron scattering experiment. → Need to apply in neutrino scattering experiment.**
- **2p2h is judged as CCQE with the detector which can not detect protons. → Source of CCQE puzzle ?**
- **There is no clear result in neutrino scattering experiment so far. it's important to obtain positive proof.**

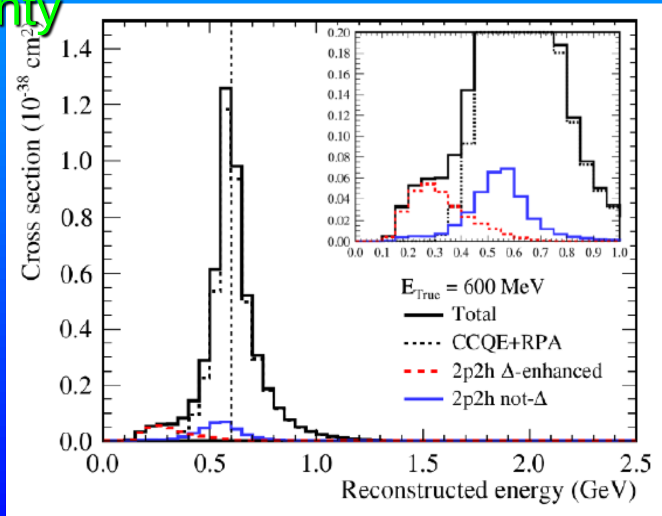
Neutrino energy reconstruction of CCQE like event at far detector is wrong if 2p2h process is exist.
→ large systematic uncertainty

Electron scattering experiment



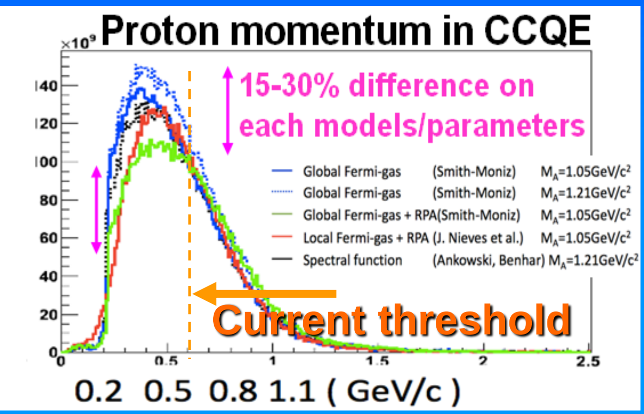
CCQE: $\nu_\mu + n \rightarrow \mu^- + p$
→ 2 body reaction

2p2h: **2protons are emitted**
$\nu_\mu + (n, p) \rightarrow \mu^- + p + p$
→ 3 body reaction



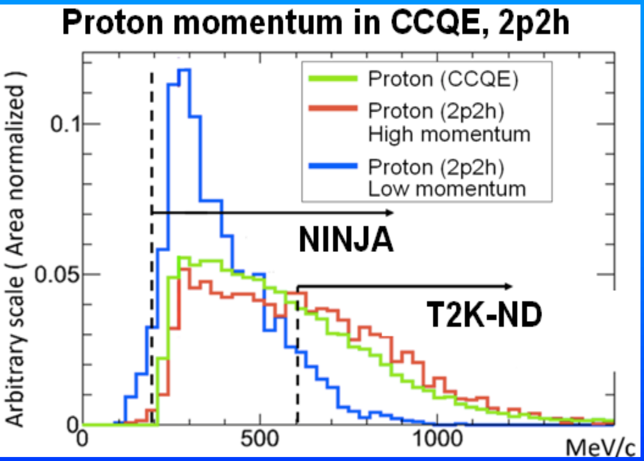
Low energy proton measurement

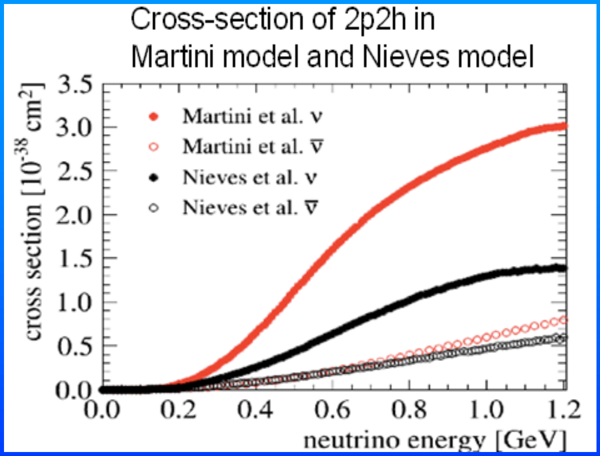
Actually, even CCQE has still large model dependence.
Low energy proton Information is Important to study CCQE model.



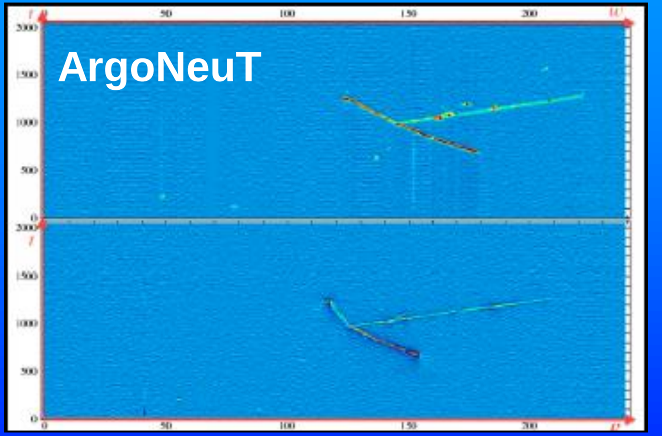
2p2h

- Some general models predict that back-to-back protons are emitted from binding nucleon pair in neutrino event.
- Large model dependence.
- There are some models binding pn pair in iso-scaler nucleus from theorist. But no calculated result in non-iso -scaler target.





Back-to-back proton event in Liquid Argon detector（low statistics）



Clear result and Xsec measurement in water is needed.

Roadmap

Since the end of 2014, we have demonstrated the basic performance of emulsion detector in test experiments.

Pilot RUN — Feasibility study at J-PARC

J-PARC T60/T66/T68 experiment

Detector RUN — Detector performance check

Target mass: 1- 60kg

Physics RUN Ⅰ — Neutrino-nucleus interaction study

Target mass: 100- 300kg

New proposal (E71)

Physics RUN Ⅱ — Search for sterile neutrino

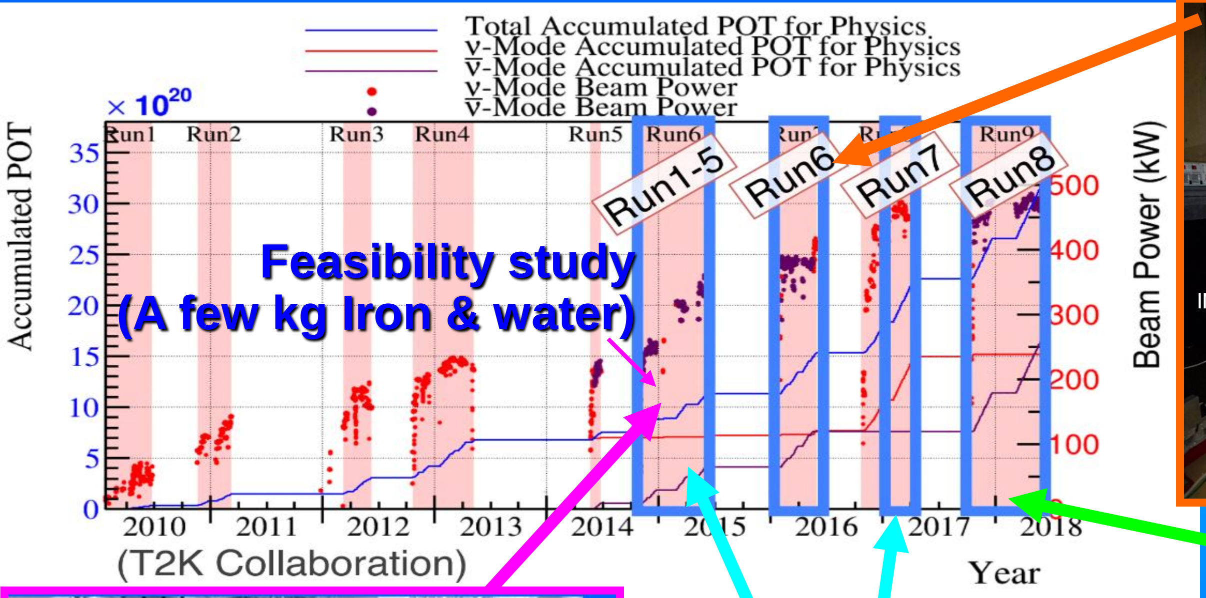
Target mass: several tons

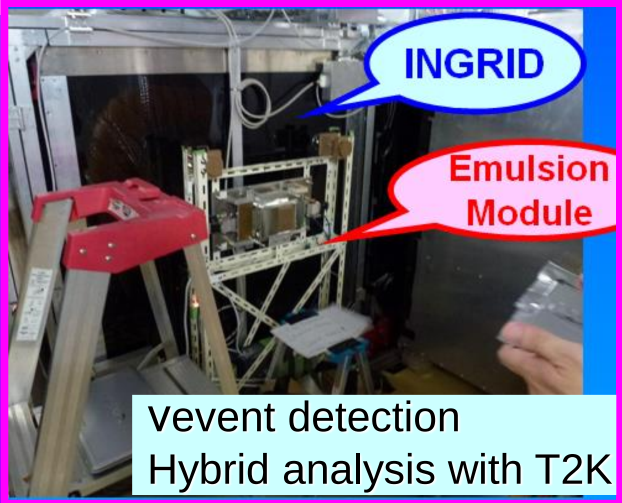
Physics run will be started from Nov. 2019.

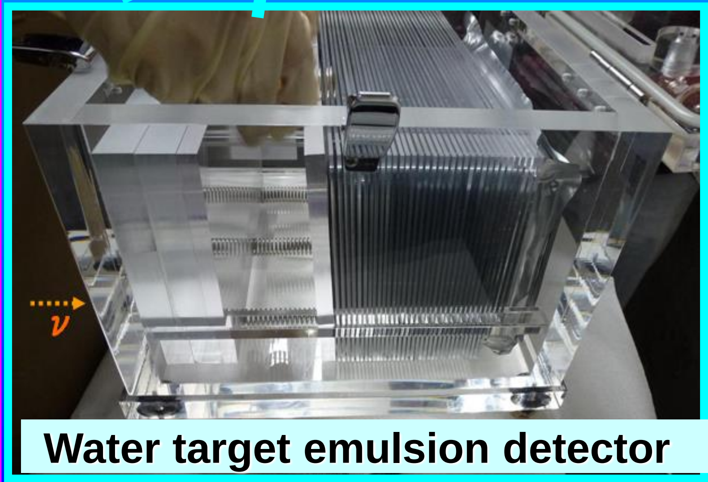
NINJA

ν exposure of NINJA

Since the end of 2014, we have demonstrated the basic performance of emulsion detector in test experiments.



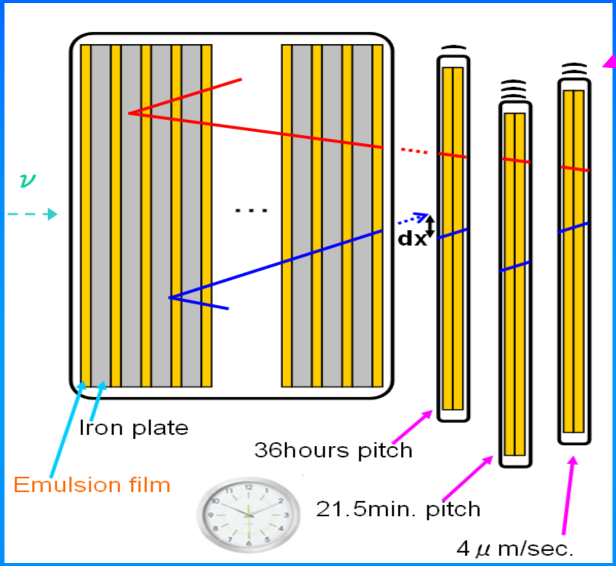




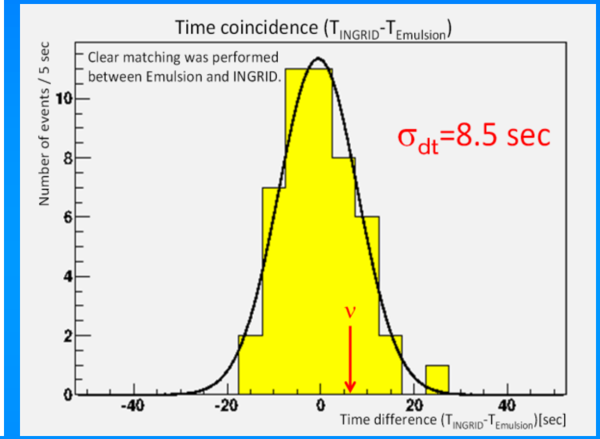
Detector Run: Iron ECC + ES + MRD

Target: Iron~40kg, Beam: 0.4×10^{20}POT Neutrino mode

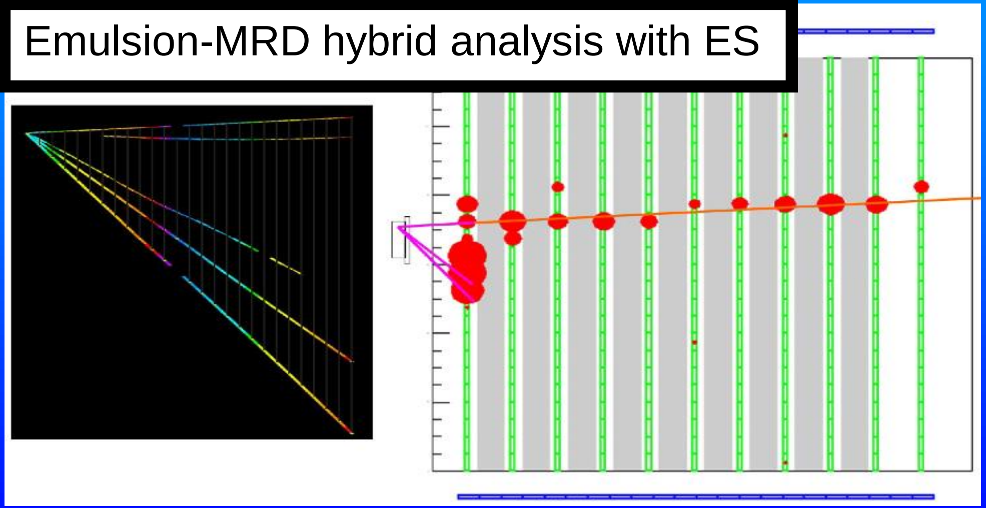
Emulsion Shifter



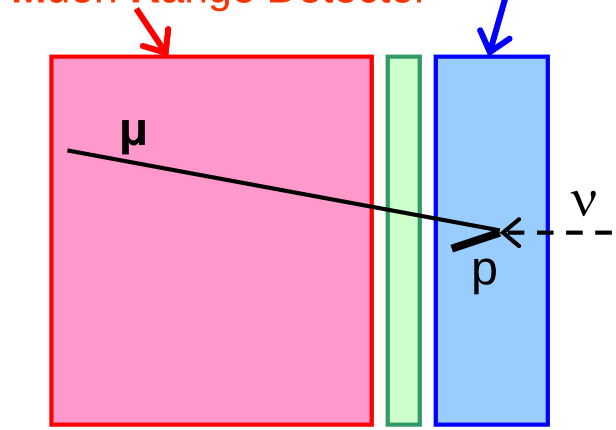
Shifter-MRD



Emulsion-MRD hybrid analysis with ES



Conceptual design

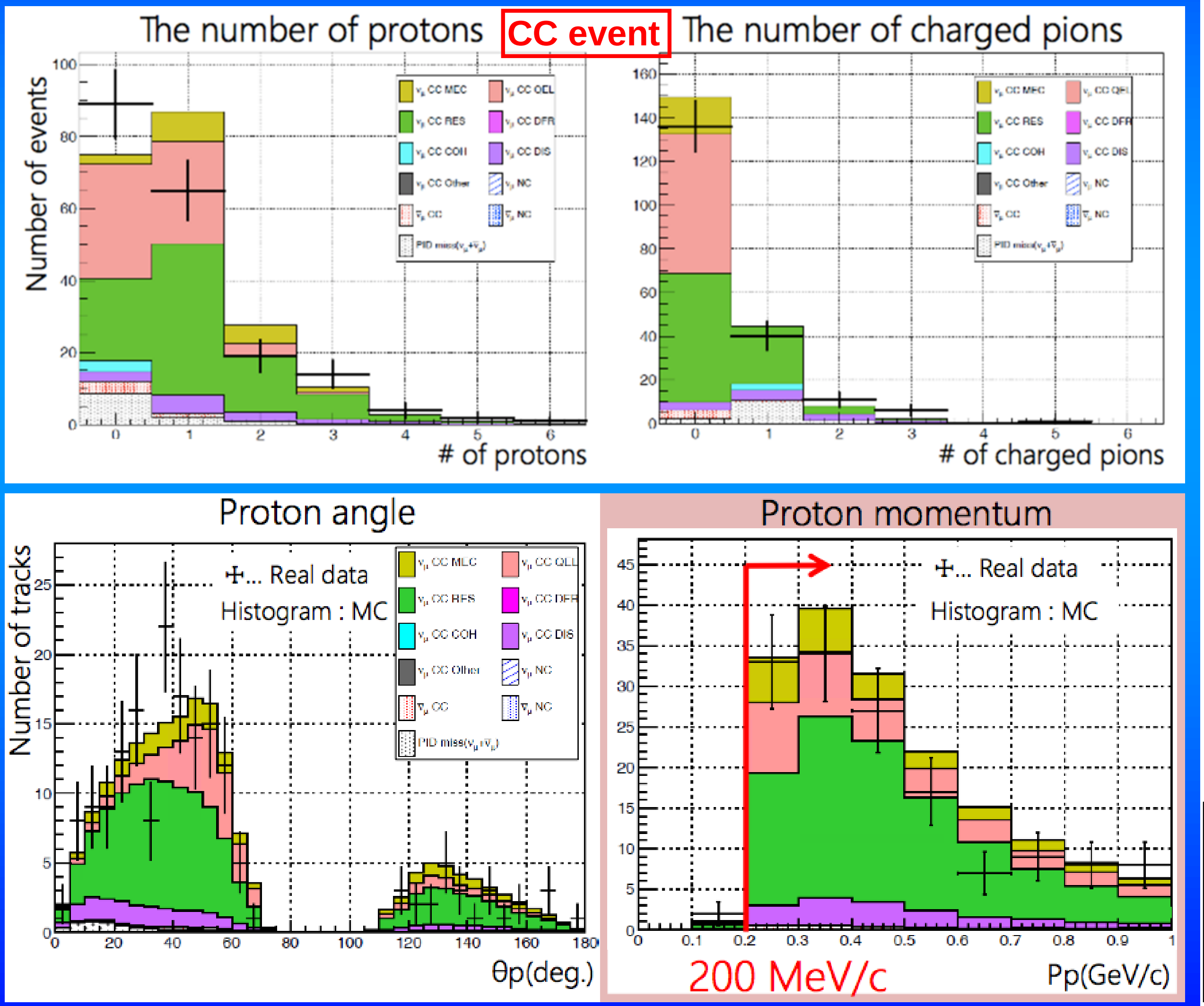


ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

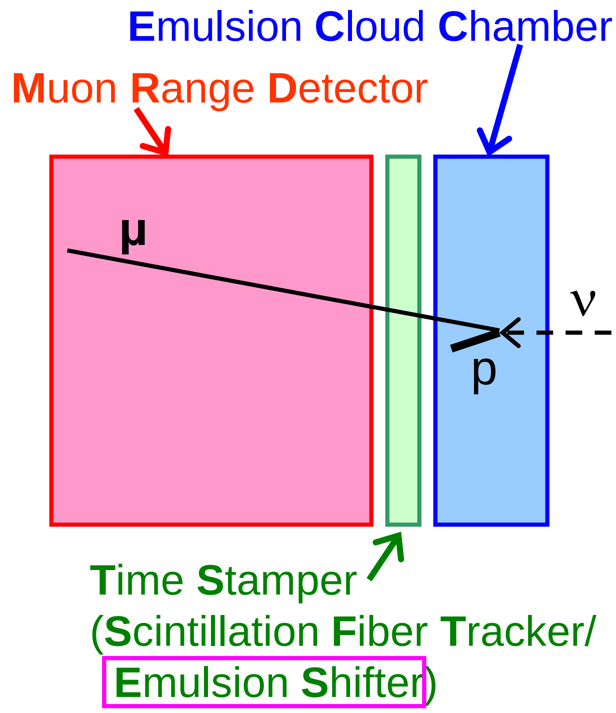
NINJA

Detector Run: Iron ECC + ES + MRD

Target: Iron~40kg, Beam: 0.4x10^{20}POT Neutrino mode

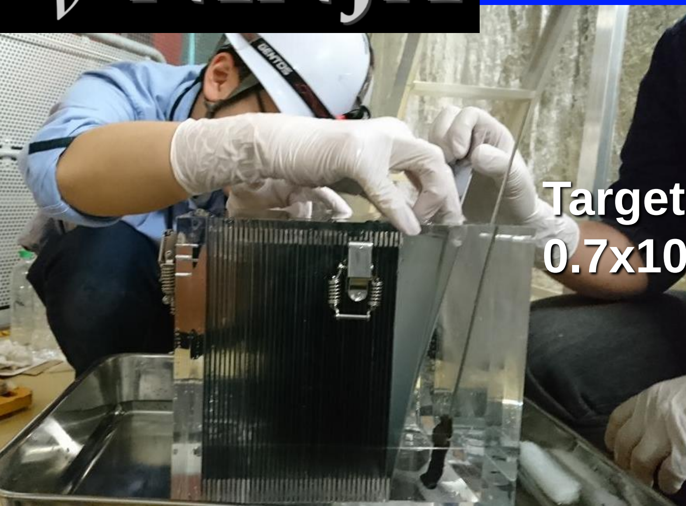


Conceptual design

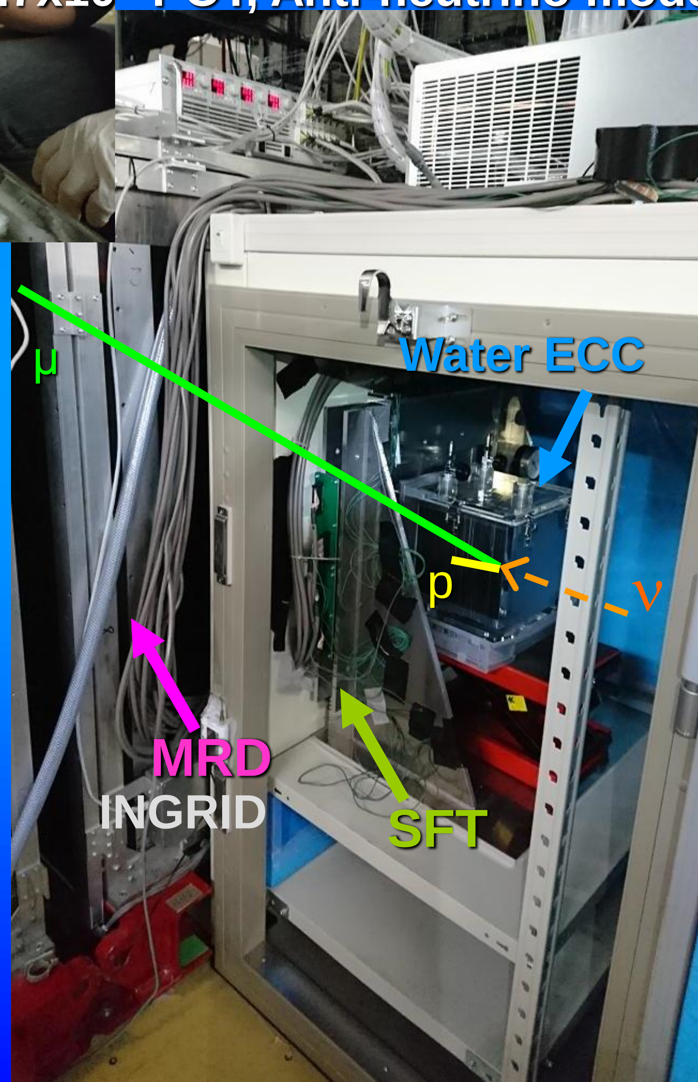


ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

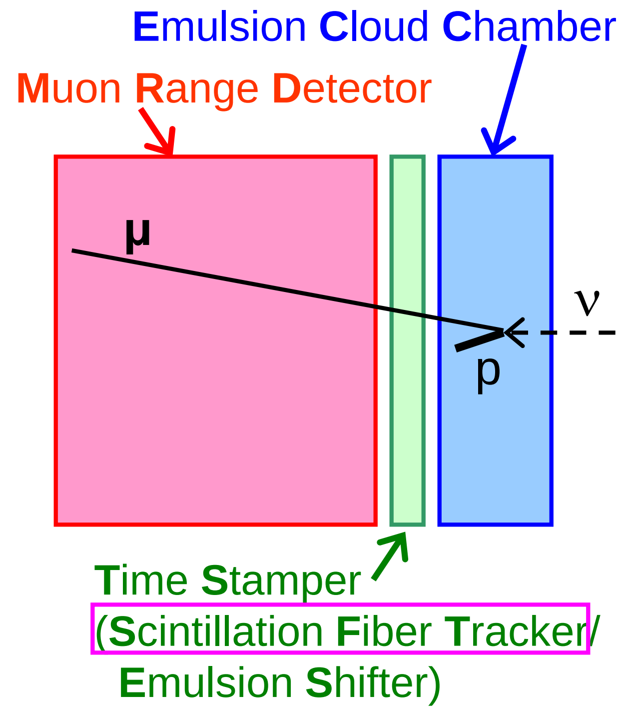
Detector Run: Water ECC + SFT + MRD



Target: Water~4kg,
0.7×10^{21} POT, Anti-neutrino mode

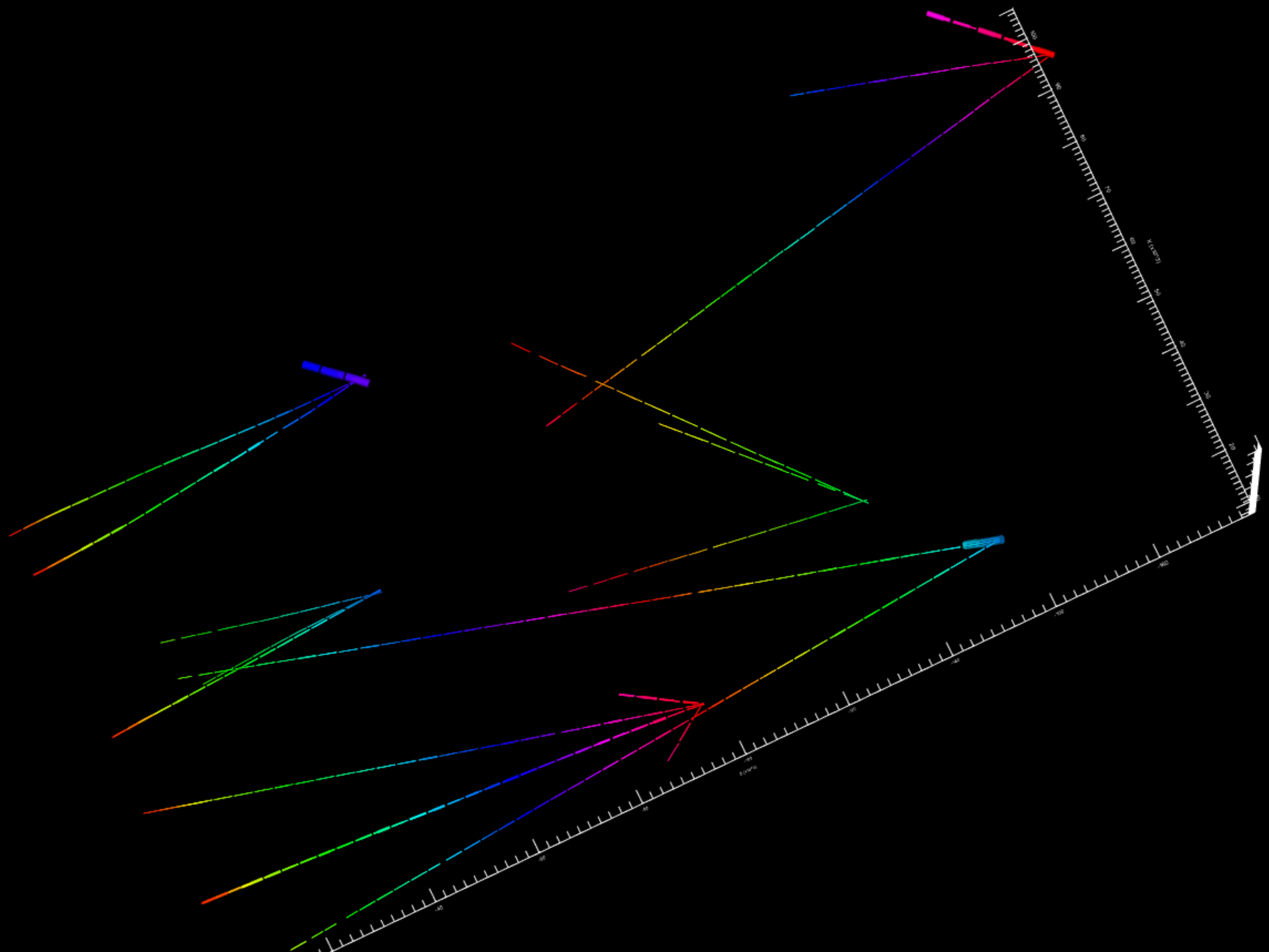


Conceptual design

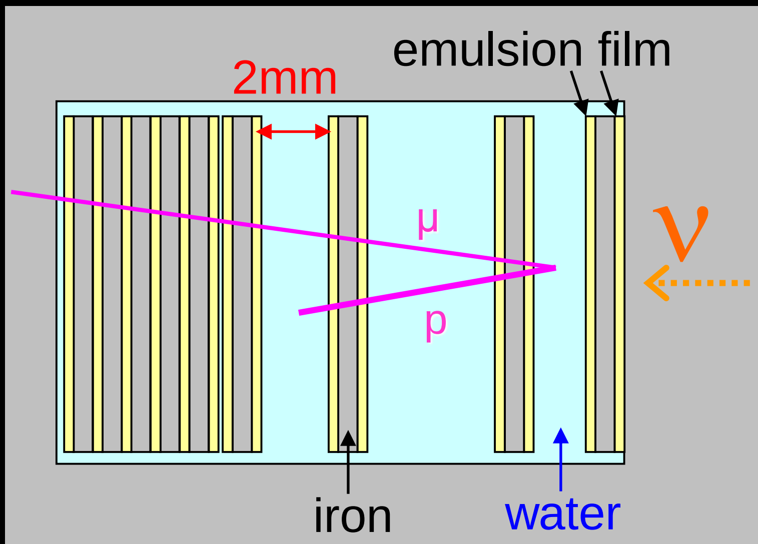


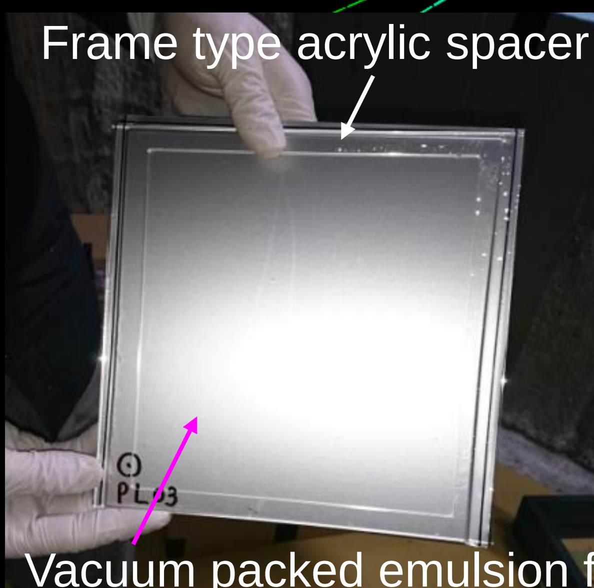
ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

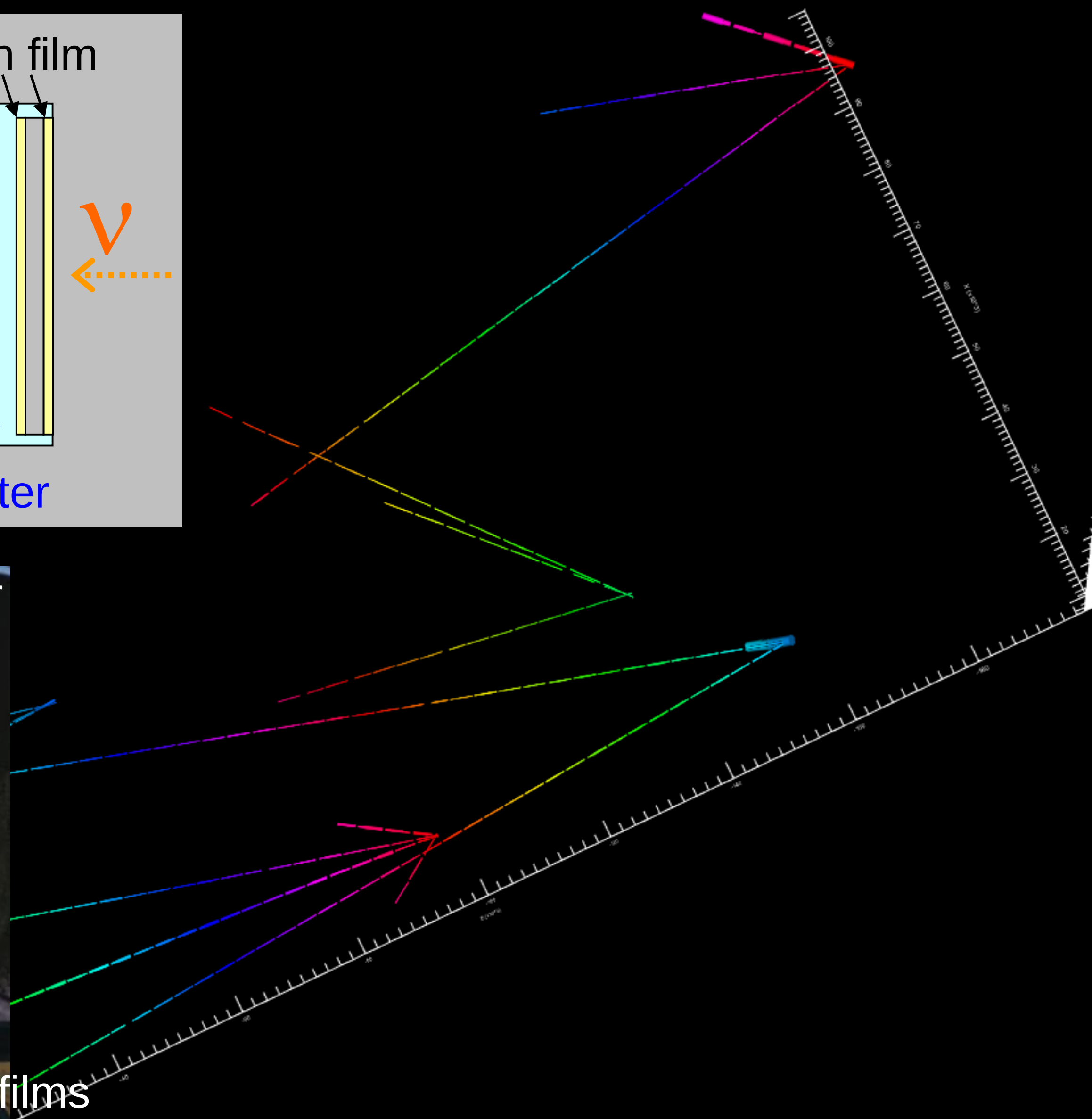
$\bar{\nu}$-water interactions



$\bar{\nu}$-water interactions

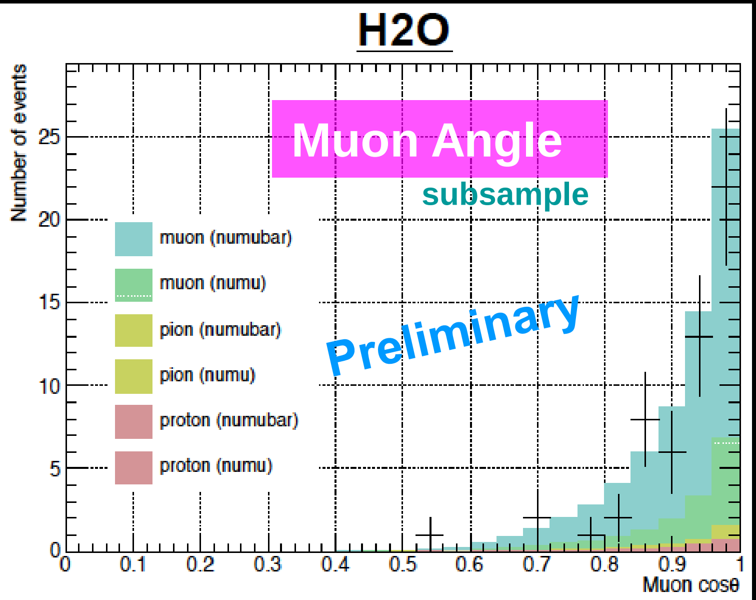


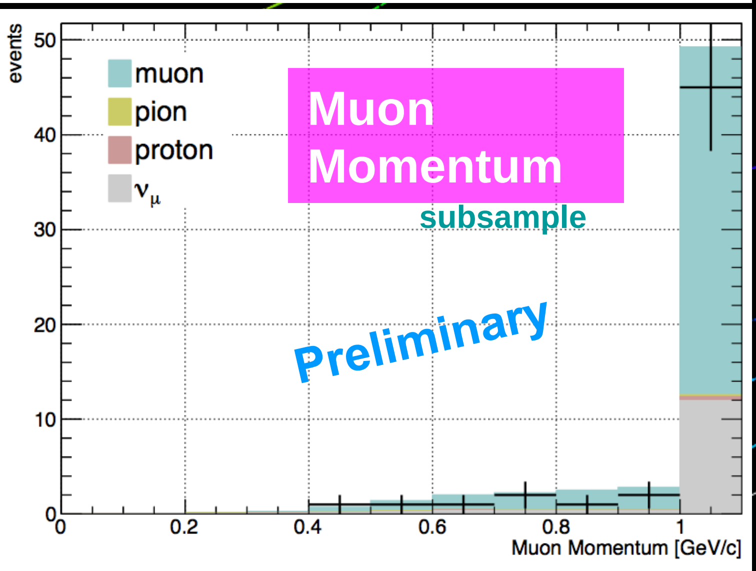


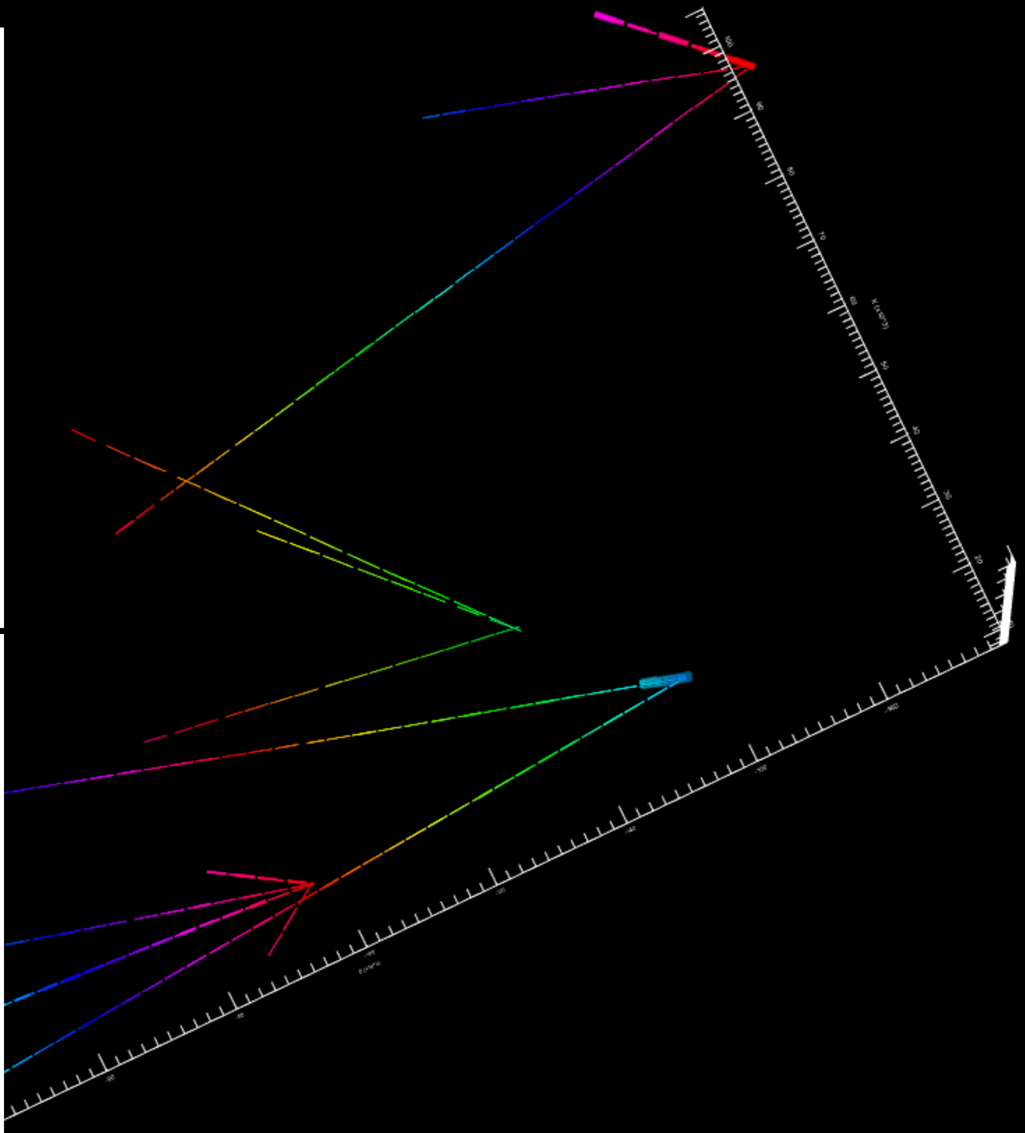


NINJA

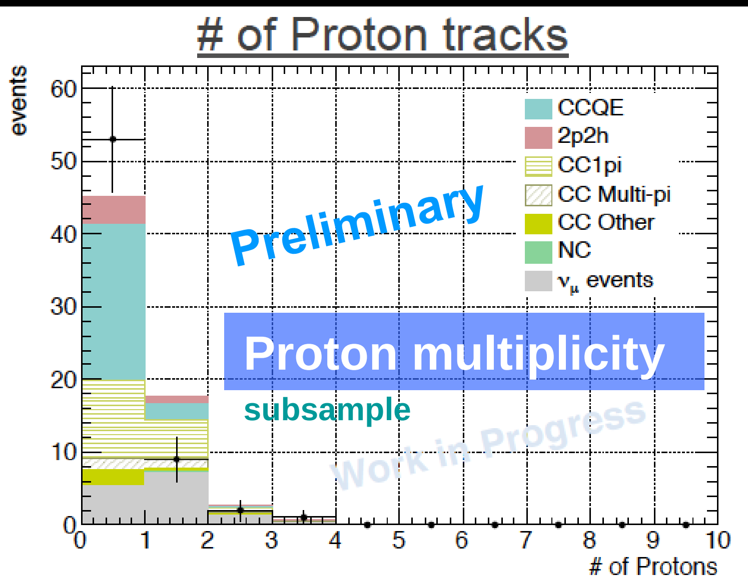
$\bar{\nu}$-water interactions

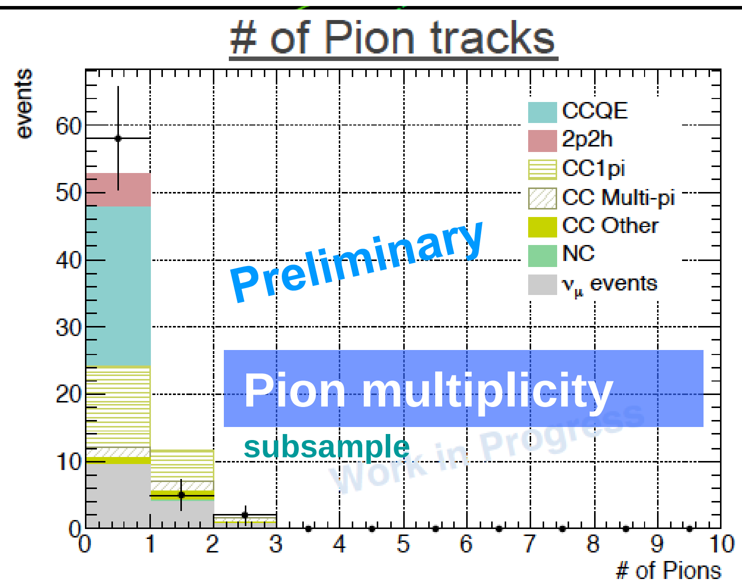


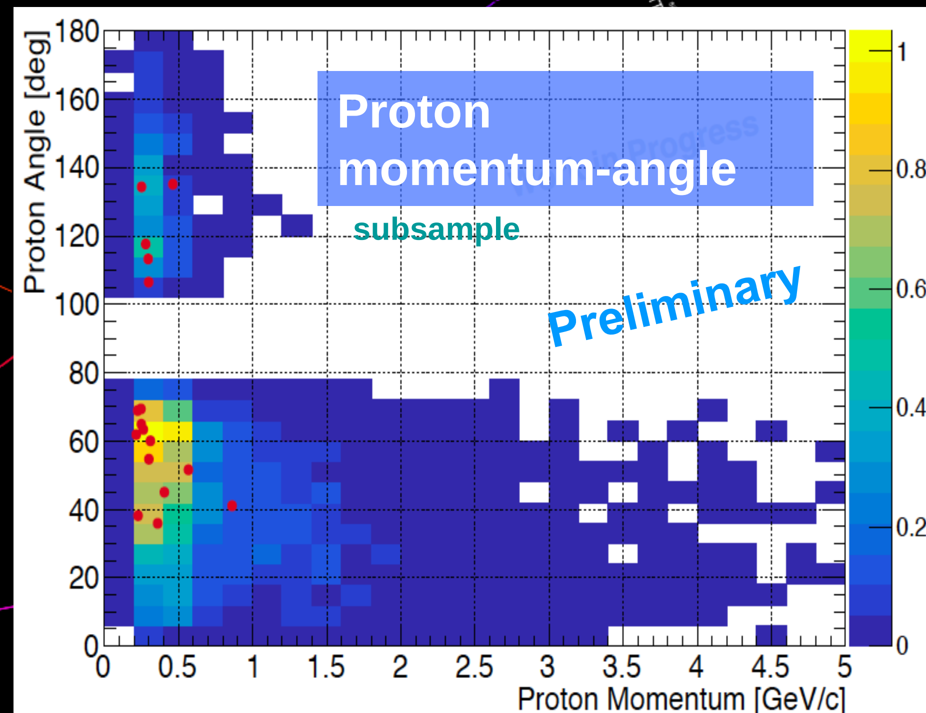




$\bar{\nu}$-water interactions







NINJA

Physics Run (J-PARC E71)

We proposed a new experiment (Physics Run) to study neutrino-nucleus interactions with large statistics in 2019.

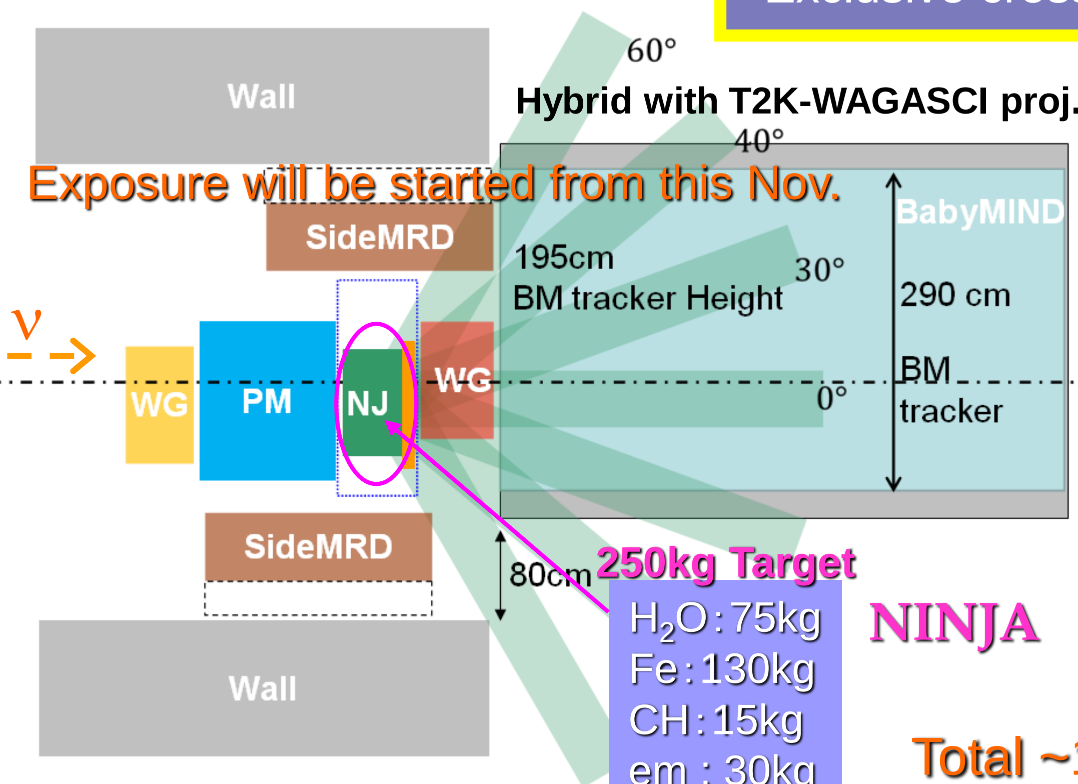
Approved by J-PARC PAC

Sub-Multi GeV Neutrino interaction

- Confirmation and cross-section measurement of 2p2h
- Exclusive cross-section measurement of ν_μ and ν_e

Detector setup @J-PARC B2 floor

Exposure will be started from this Nov.

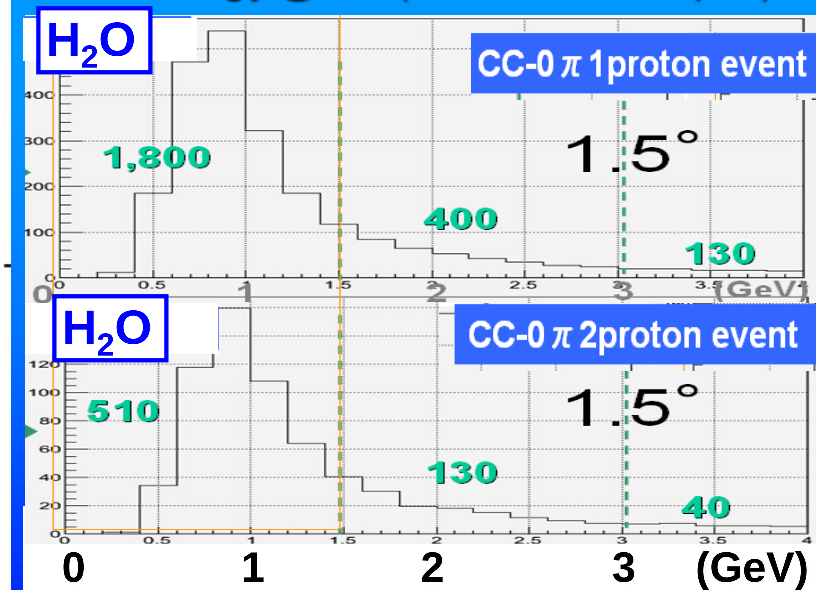


250kg Target

H_2O : 75kg
Fe : 130kg
CH : 15kg
em : 30kg

NINJA

ν energy@B2 (total 1.0×10^{21} pot)

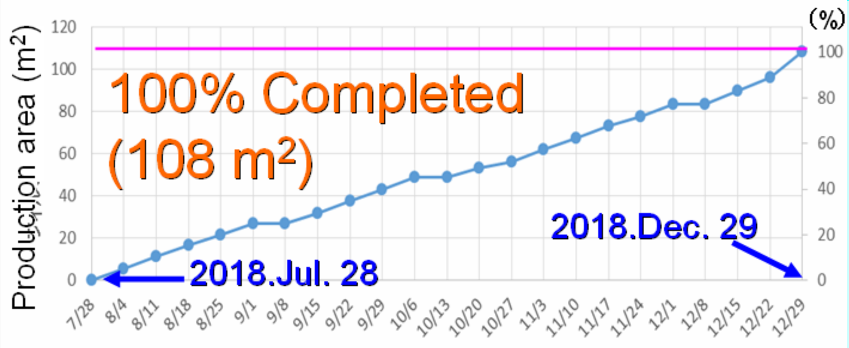


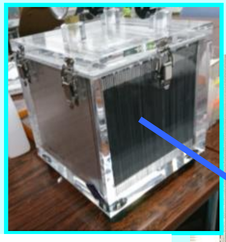
Total ~16,000 ν events will be corrected.

Detector components

Emulsion film production

25cm x 25cm films: ~1300 films
34cm x 102cm films : ~ 25 films
~42grains/100μm → 99% tracking eff.





Water ECC

Baby MIND

MRD for T2K-WAGASCI project
- 33 Magnet Modules (1.5T)
- 18 Detector Modules

Detection efficiency >97%
Charge identification eff > 90%
Momentum resolusion~10%

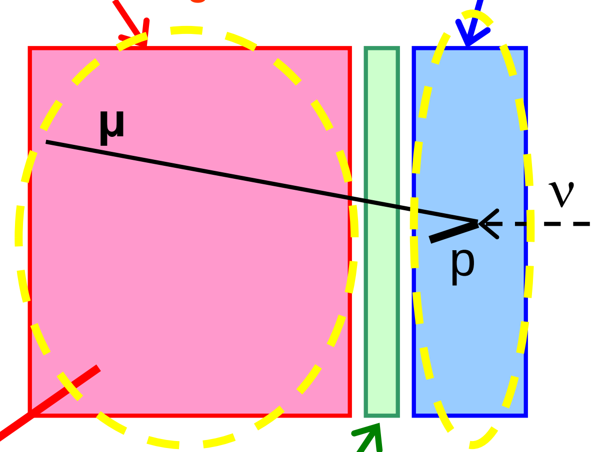
→ NINJA-WAGASCI hybrid plan
We (NINJA) can use Baby MIND for MRD.

μ^+/μ^- separation → $\nu_\mu / \bar{\nu}_\mu$ separation

Conceptual design

Emulsion Cloud Chamber

Muon Range Detector



Time Stamper
(Scintillation Fiber Tracker/
Emulsion Shifter)

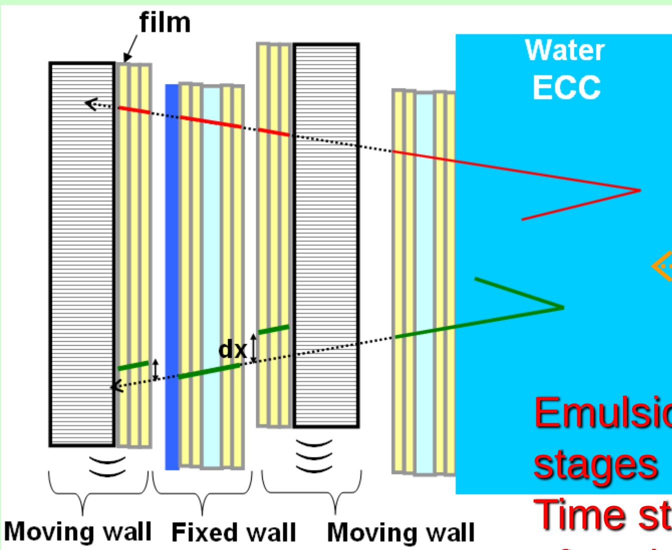
ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

NINJA

Detector components

Emulsion Shifter

ECC→ES: 4hour time stamp

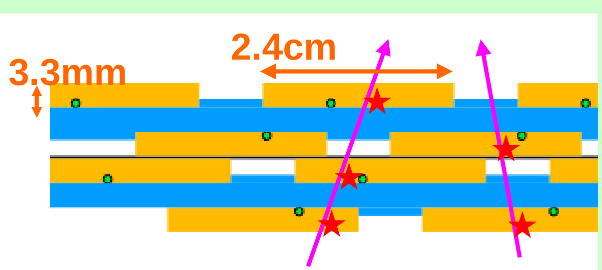


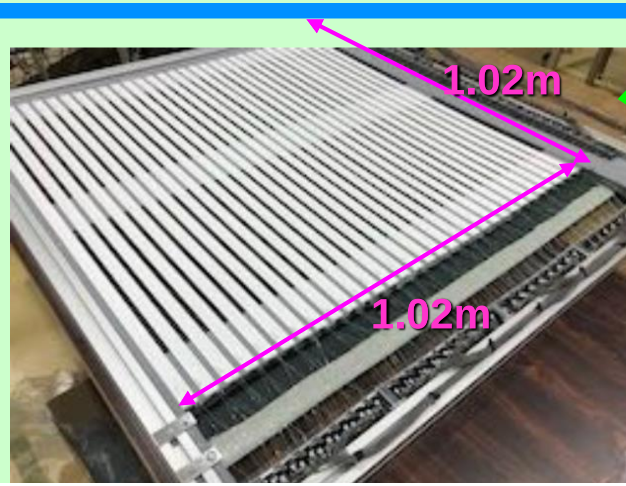
4 hour/step
4 day/step

Emulsion films are set on moving stages controlled by stepping motor. Time stamp is given by coincidence of each stages.

Scintillating Tracker

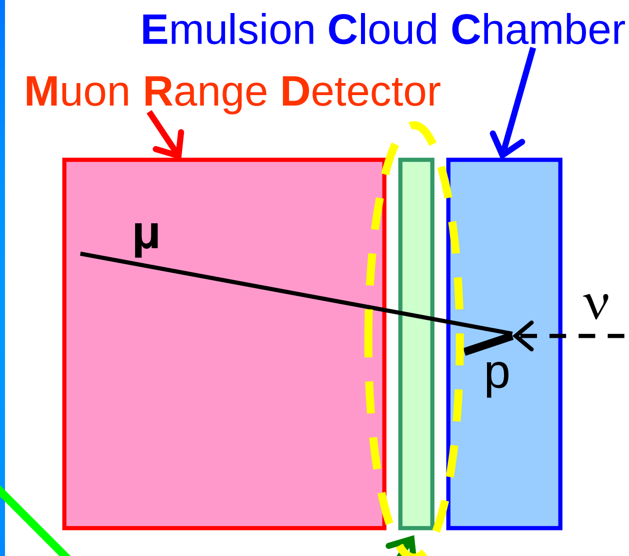
Position resolution is improved by using hit/unhit combination.
→ ~1.7mm position resolution





ES→ST: 10 nsec level time stamp

Conceptual design



Time Stamper
(Scintillation ~~Fiber~~ Tracker/
Emulsion Shifter)

ECC→ event analysis
MRD→ muon identification
TS → event connection between ECC and MRD

Measurements

Analysis:

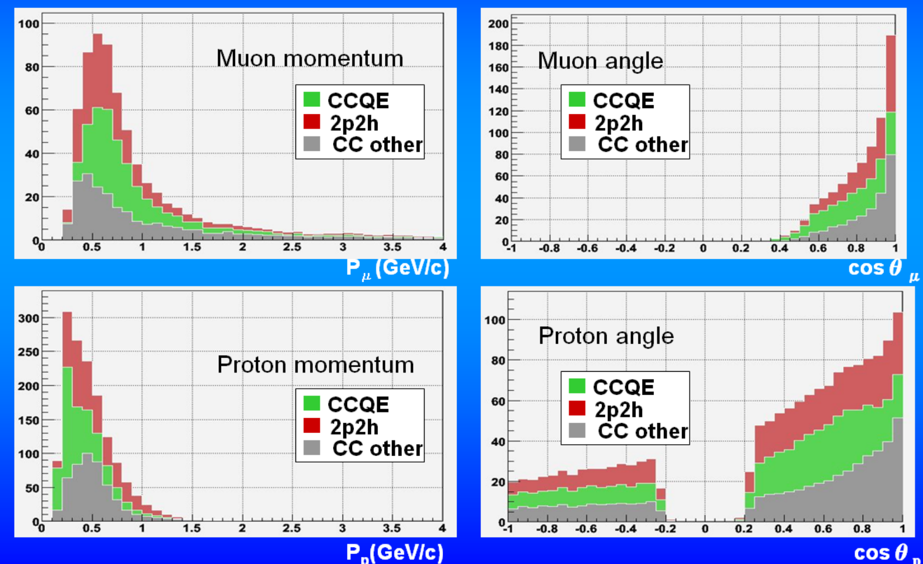
Momentum measurement :
Range,Multiple Coulomb Scattering in ECC
Range in Baby MIND (only for μ)
dE/dx measurement :
Blackness of tracks in ECC
μID : Baby MIND

→ (Double) differential cross section measurement

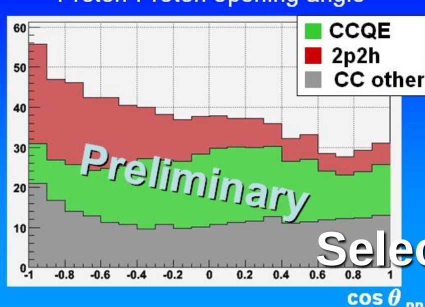
CC 0π2p event (2p2h enriched events)

Number of events (68kg water target, 1.0×10^{21} pot)

Already applied μ angle acceptance and proton detection threshold



Proton-Proton opening angle



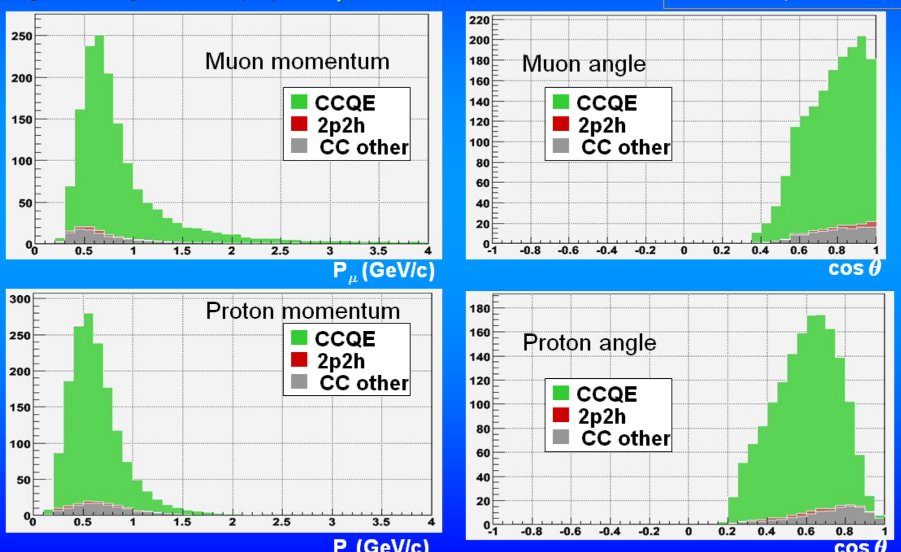
Selection will be optimized

CC 0π1p event (CCQE enriched events)

Number of events (68kg water target, 1.0×10^{21} pot)

Already applied μ angle and proton detection threshold

OA > 60°, CA > 150°



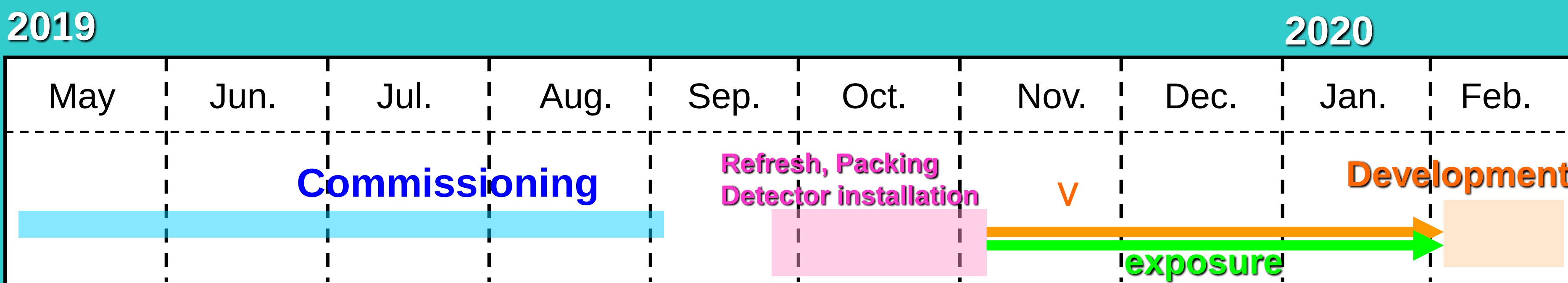
Not only proton but also pion will be measured with low energy threshold.

NINJA

Schedule (E71)

Totally >1.0x10^{21} pot @ 2 times exposure (E71a, b)

E71a (~0.5x10^{21} pot) ← **Our first Physics Run**



Emulsion scan and analysis will be started from Mar. 2020.

E71b will be started from 2022 after J-PARC accelerator upgrade

(>~0.5 x 10^{21} pot)

2.5x ~ 7.5x scale → ν_e measurements

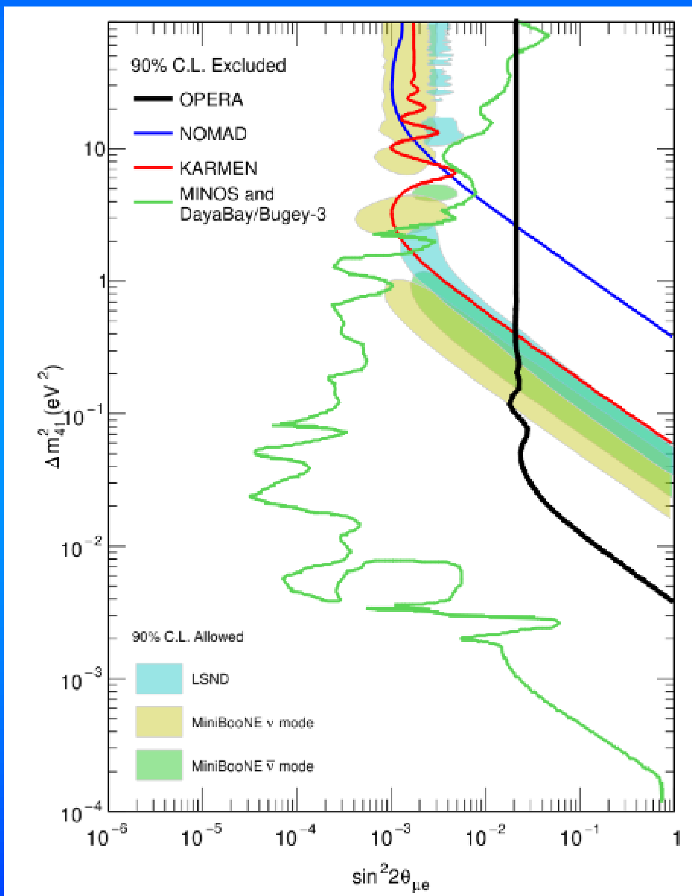
NINJA

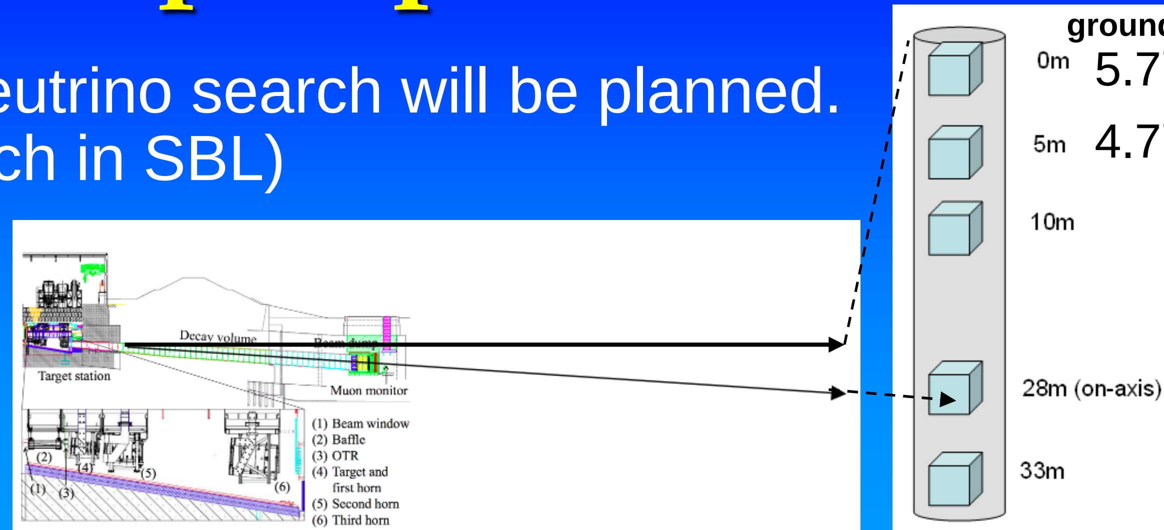
Detector preparation is completed.

Water ECCs will be installed next week !!

NINJA Future prospects

- After E71b, sterile neutrino search will be planned. (ν_e appearance search in SBL)

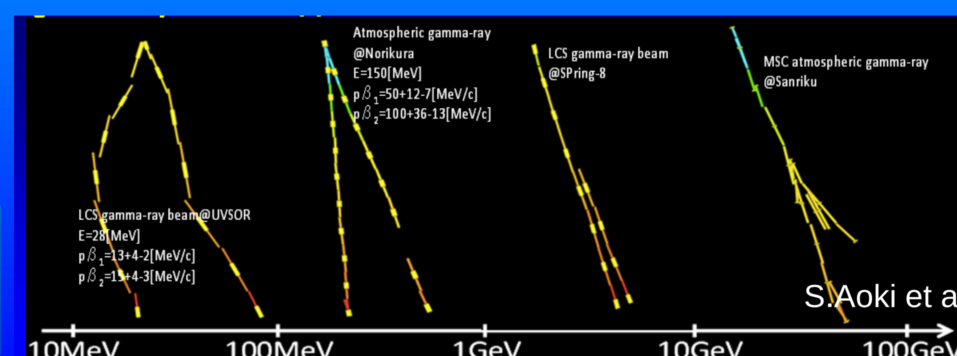




L=280m, <E$_\nu$>~350MeV@off axis(4°) → L/E~1

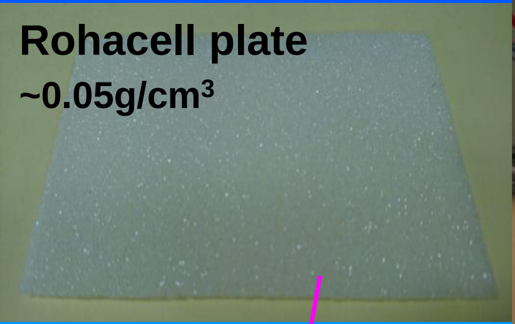
- Use iron target ECC
- Electron energy measurement by MCS
- ν energy reconstruction with CCQE
- low energy π/μID with emulsion (dE/dX-Range or direct check stop point)

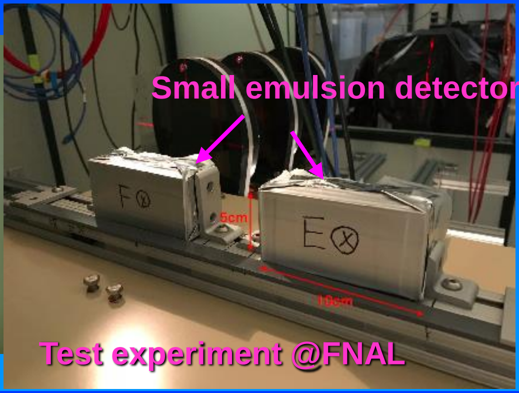
If use water ECC, we can investigate ν- water interactions in ESSnuSB region

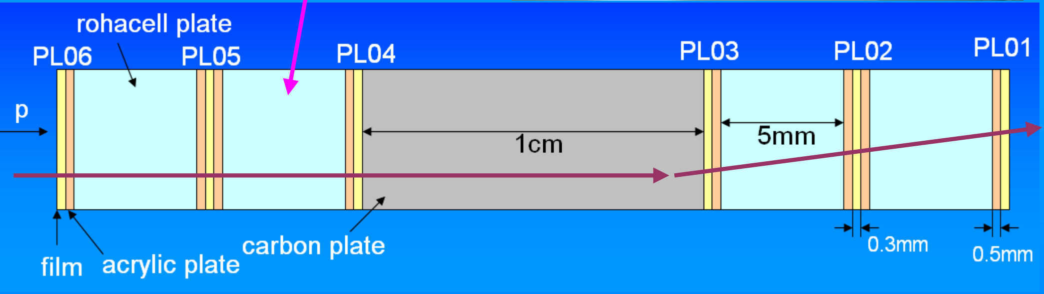


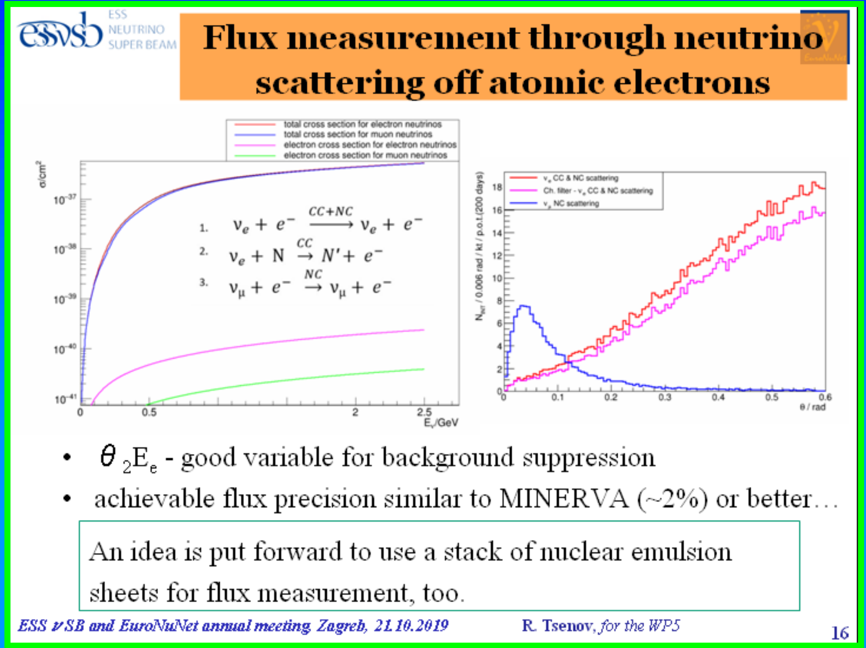
Prospects related ESSnuSB

- Flux measurement





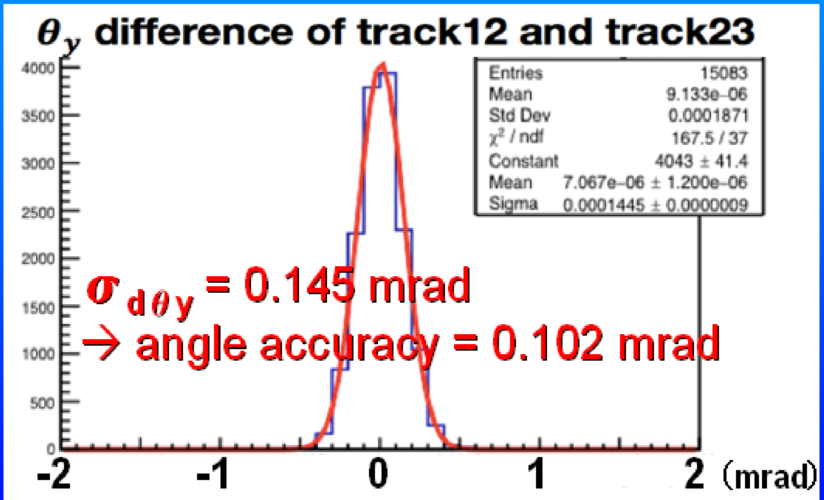


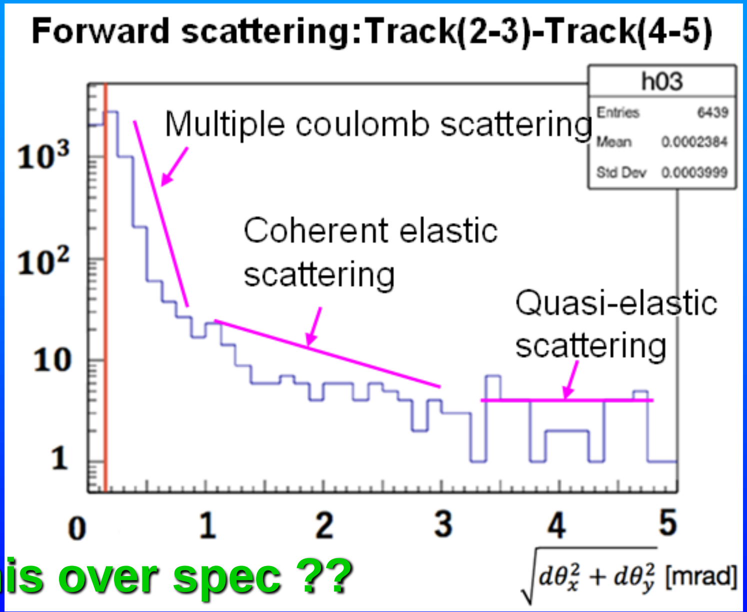


- $\theta^2 E_e$ - good variable for background suppression
- achievable flux precision similar to MINERVA (~2%) or better…

An idea is put forward to use a stack of nuclear emulsion sheets for flux measurement, too.

ESS νSB and EuroNuNet annual meeting, Zagreb, 21.10.2019 R. Tsenov, *for the WP5* 16

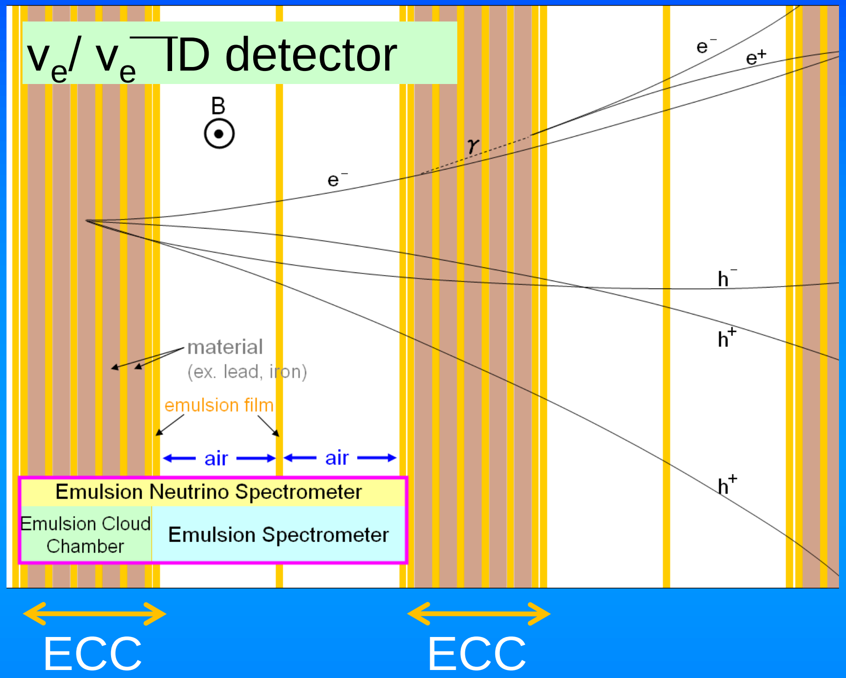




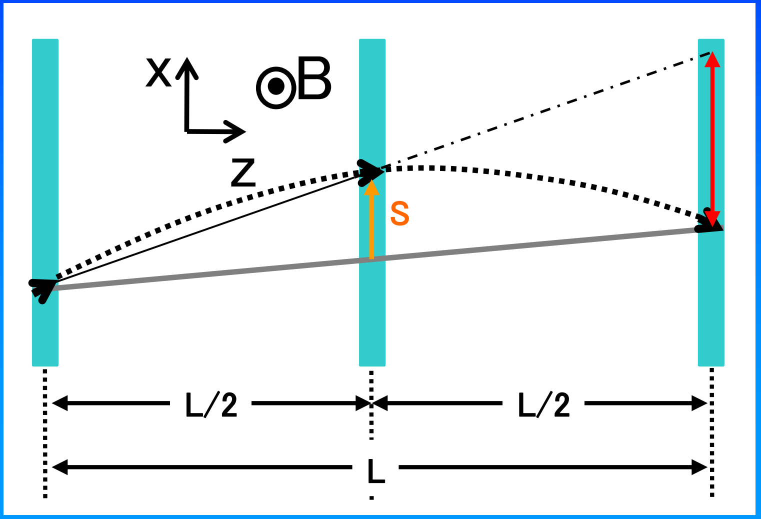
Is this over spec ??

Prospects related ESSnuSB

- $\nu_e/\overline{\nu}_e$ separation → Emulsion Spectrometer



Principle



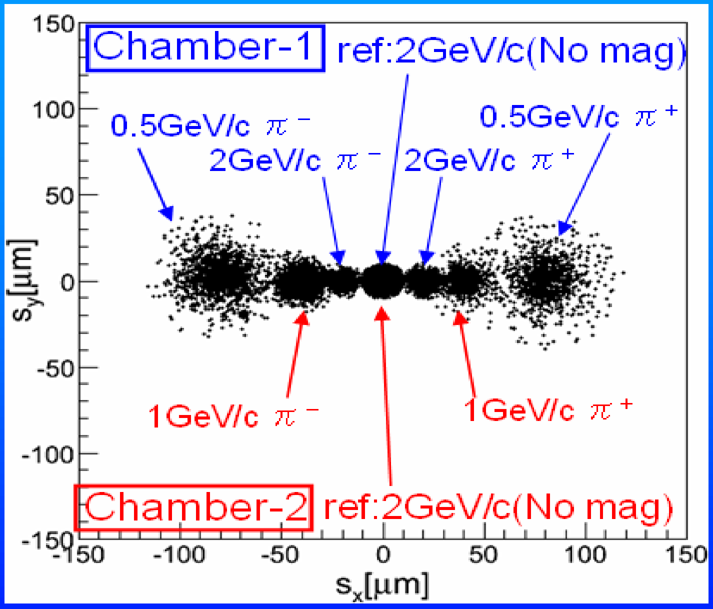
This technology will be applied in SHiP experiment

Can we apply this in low energy region ?

(Basically we reconstruct multi track vertex to recognize ν_e interactions (reduce BKG from π^0))

(One electron missing)

Anyway we can try to estimate, let's discuss.



Test beam : 15mm gap, B = 1T

Summary

- Precise neutrino-water interactions is important for future neutrino oscillation analysis. (especially, **2p2h** and ν_e)
- We are performing a neutrino experiments at J-PARC to study low energy neutrino - nucleus interactions by introducing nuclear emulsion (**NINJA Experiment, T60/T66/T68, E71**).
- Neutrino beam exposure for our first Physics Run (E71a) will be started in the beginning of this Nov.
- We also plan to implement second Physics Run (E71b) and sterile neutrino search.
- Discussion about contribution with nuclear emulsion for future neutrino physics is very welcome for us.