viking: END emulsion detector

Tsutomu Fukuda (Institute for Advanced Research/F-lab. Nagoya Univ.)
on behalf of the NINJA Collaboration

1st ESSNuSB+ WP5 in-person Workshop, Kalamata, 18th May. 2023

Short introduction

福田　努

FUKUDA, Tsutomu（Nagoya U., Japan）

2003-2018(2022): OPERA experiment

→ **Discovery of ν_τ appearance（2015）**

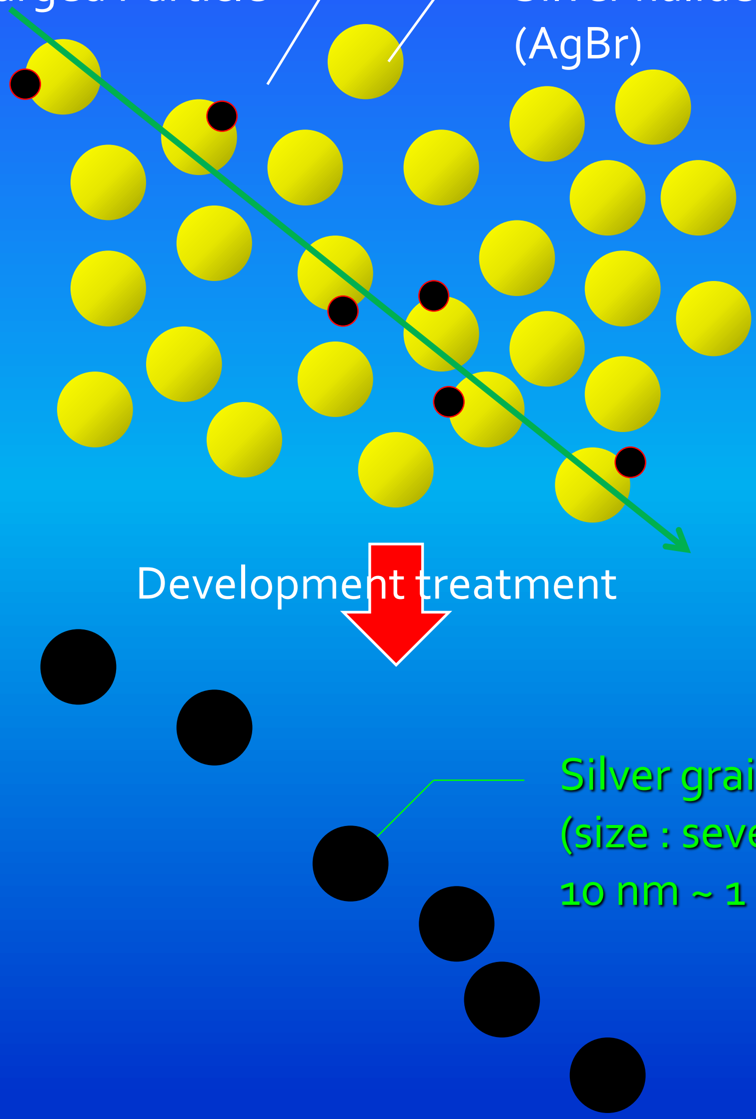
- Emulsion detector preparation
- Establishment of neutrino event analysis
- Hadron interaction study → BKG reduction of ν_τ
- Development of new analysis methods for emulsion detector

2015-Current　: NINJA experiment (Spokesperson)

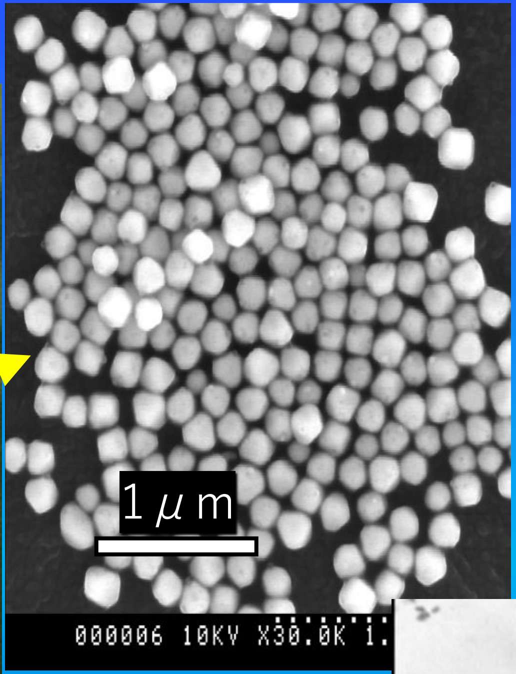
→ **Neutrino interaction study at J-PARC**

- Research proposal
- Building the collaboration
- Demonstration of the experimental concept
- **Physics Run start (2019～)**

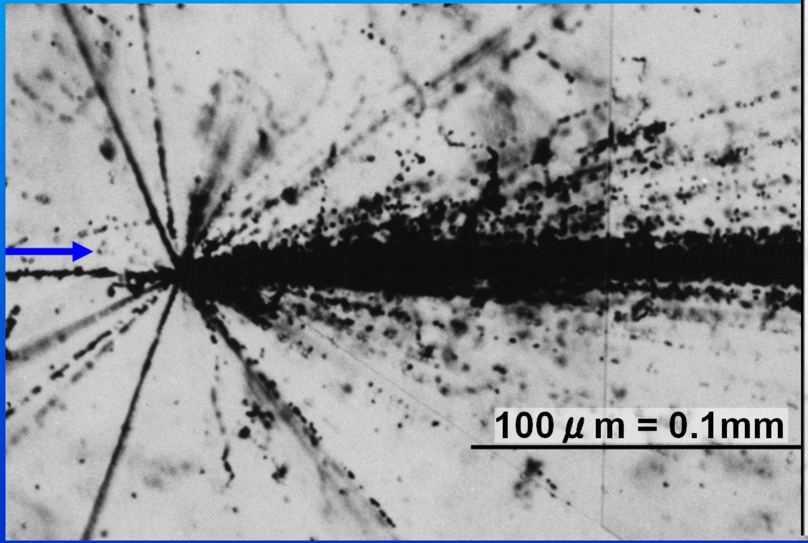
What is emulsion?



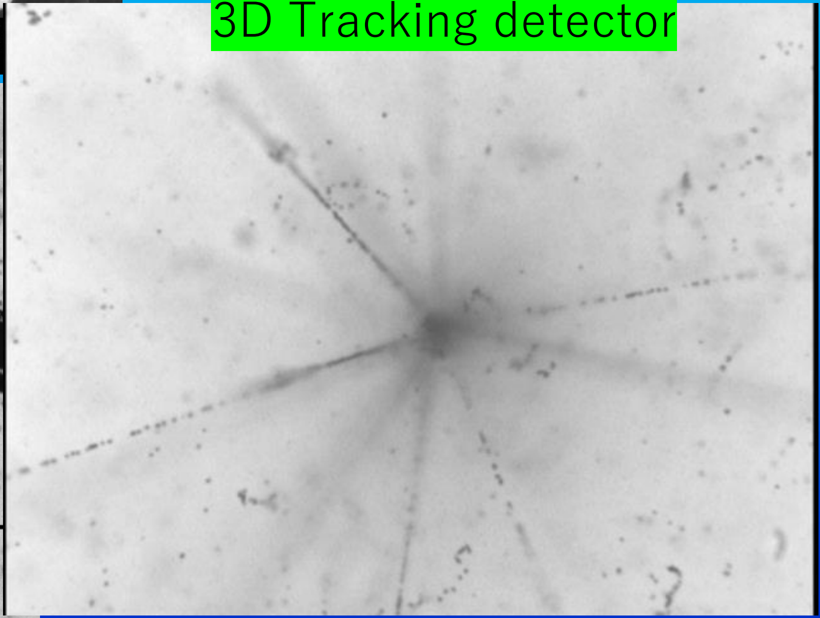
AgBr・I crystal



One of Photo film

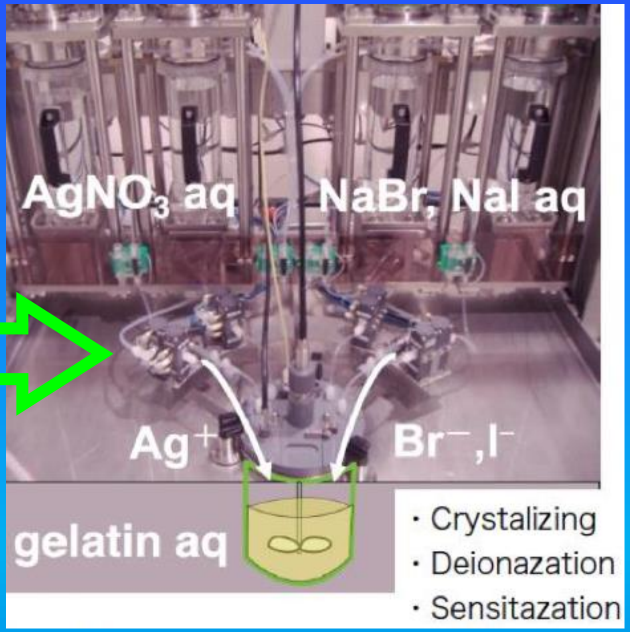


3D Tracking detector



Emulsion film production

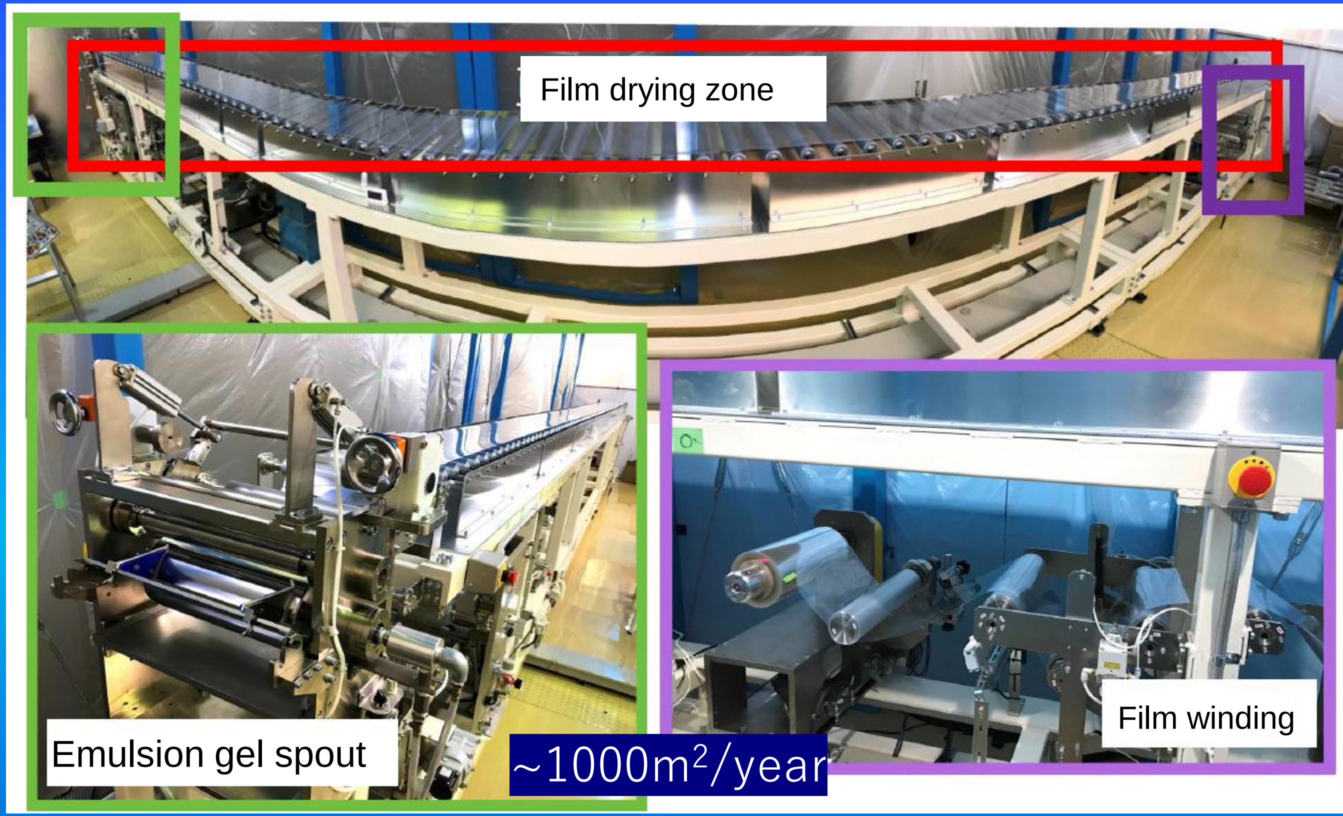
Nuclear emulsion film is made at Nagoya U.

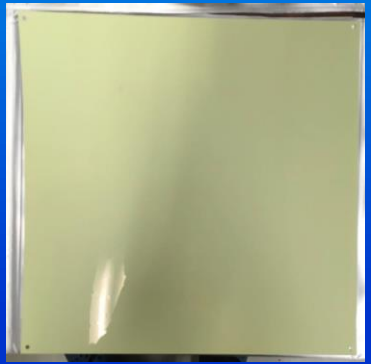


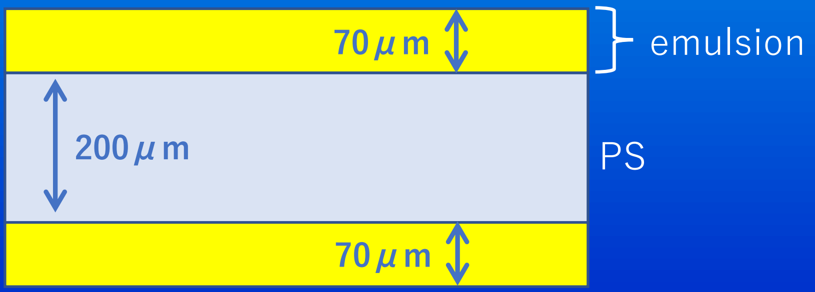
Gelatin + crystal

- Preparing liquid
- Gel production
- Gel melting
- Gel Coating
- Drying

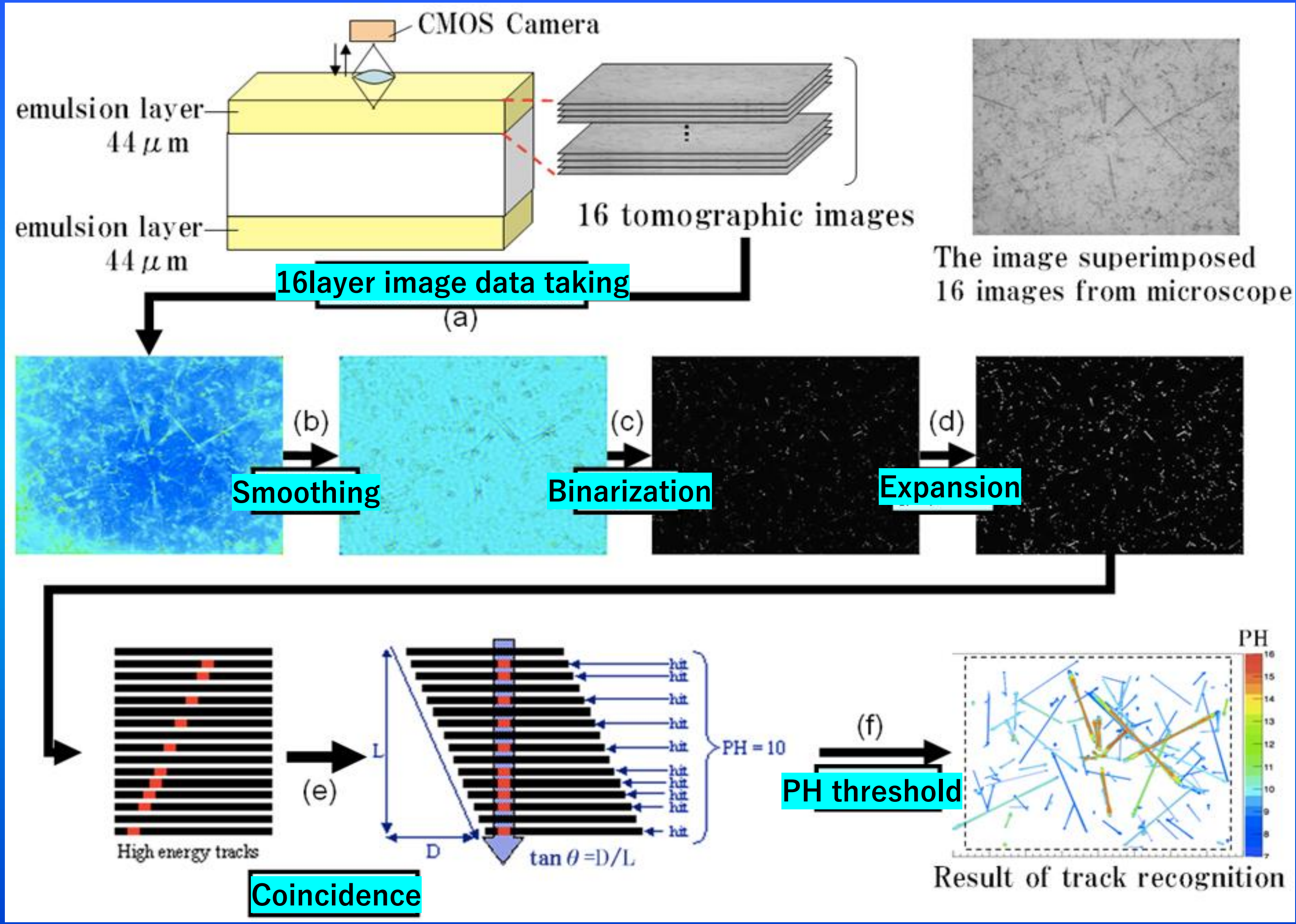
Automatic emulsion coating system at Nagoya U.

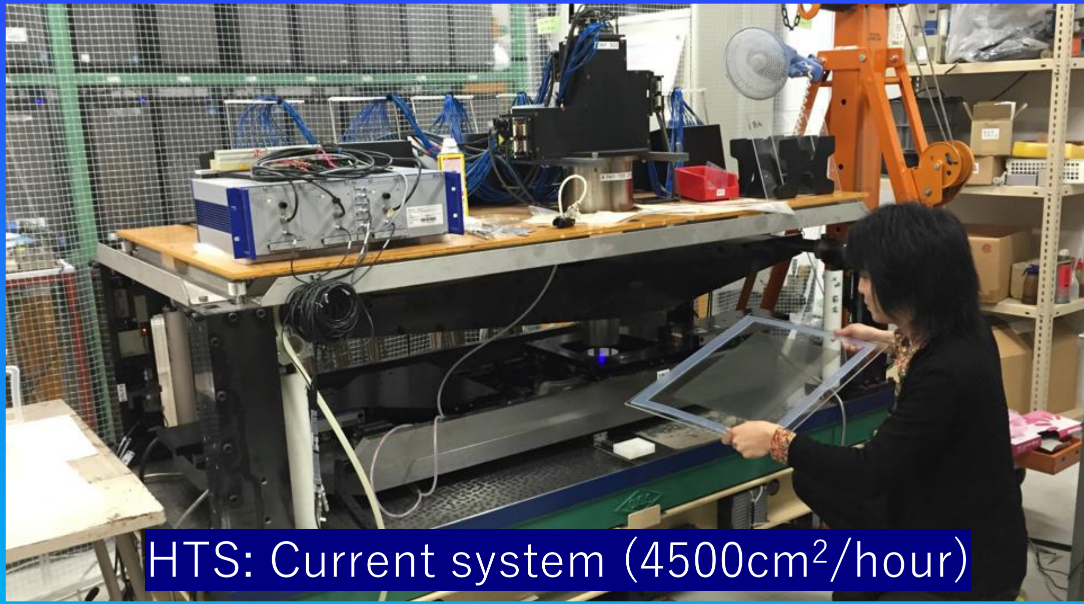


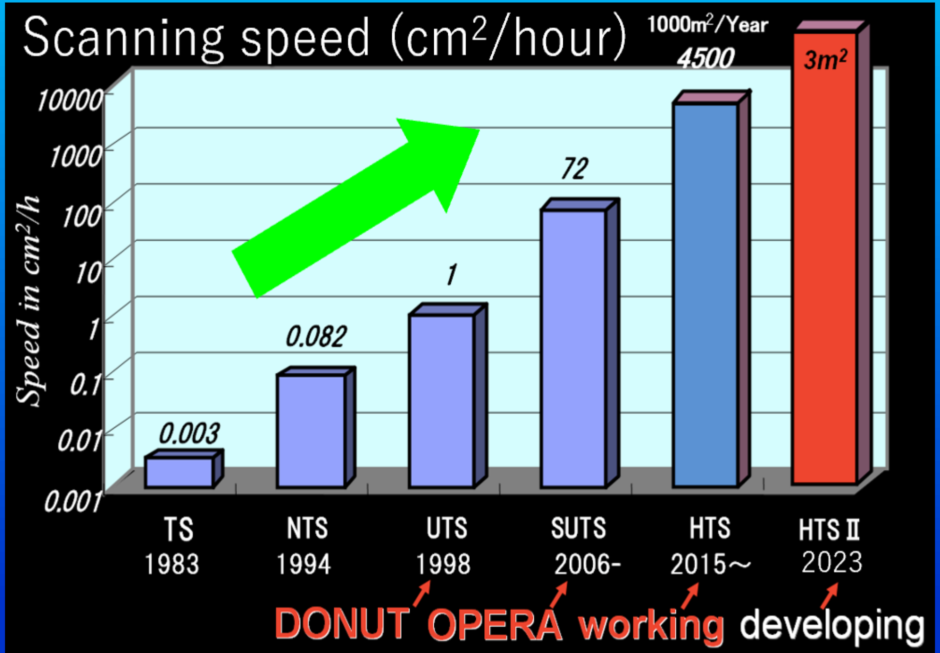




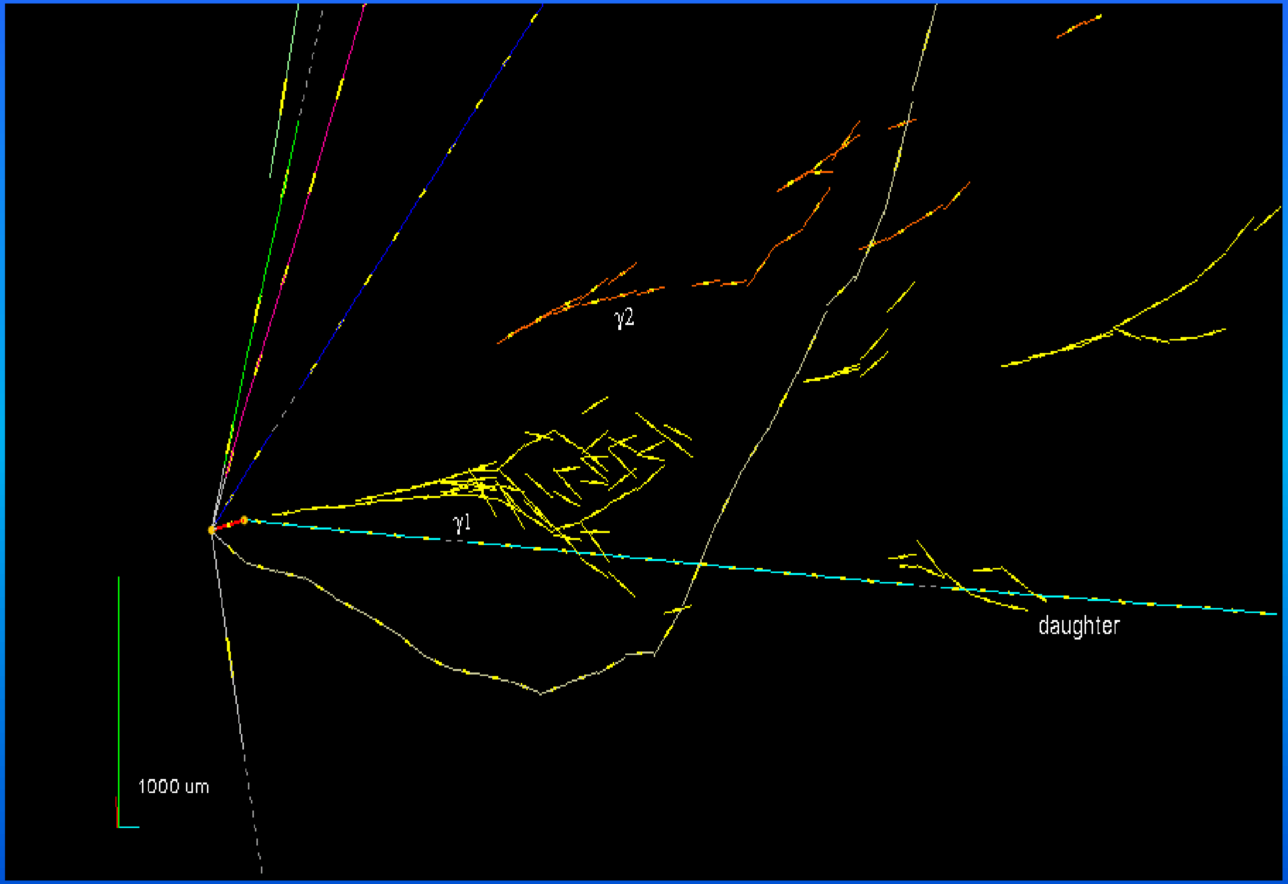
Emulsion film data taking



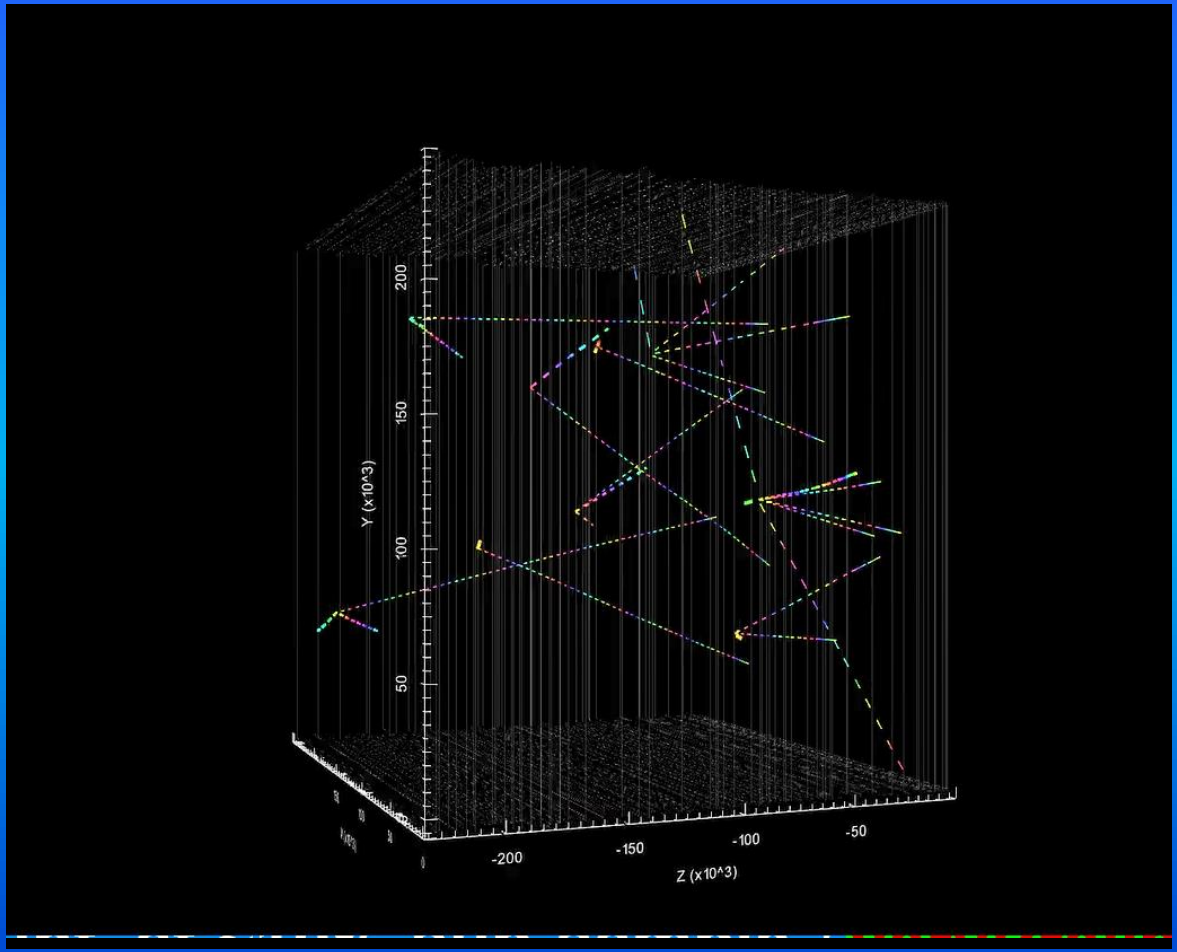




Neutrino events in emulsion



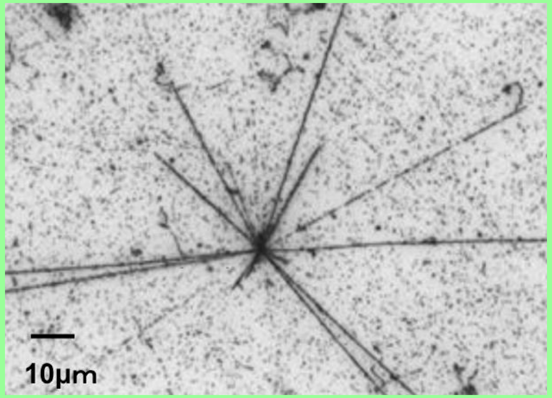
OPERA ν_τ event

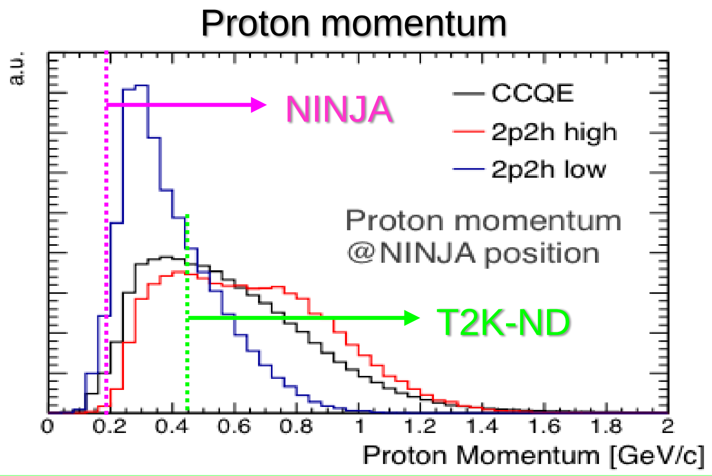


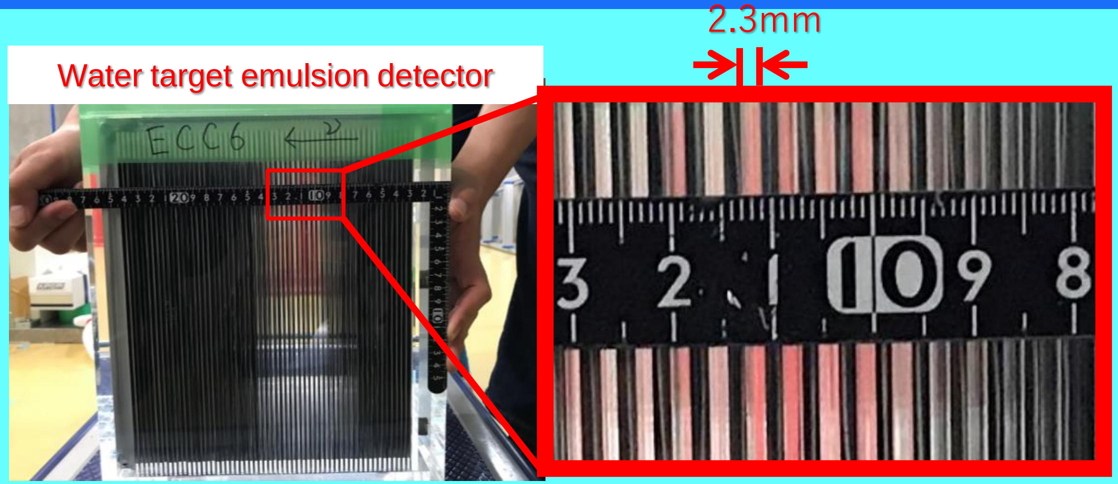
NINJA ν_μ events

Merits using emulsion detector

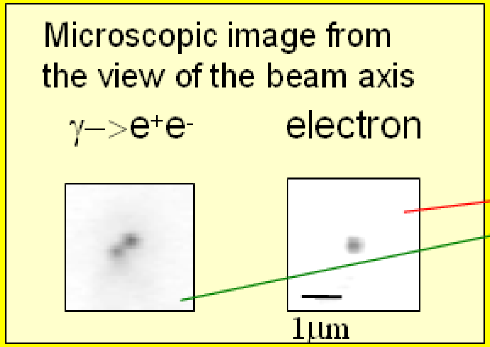
- Low energy hadron measurement ← difficult to measure so far
- Neutrino-water interactions ← same target as the large water Cherenkov detector
- Low background for ν_e measurement ← clear verification of sterile neutrino

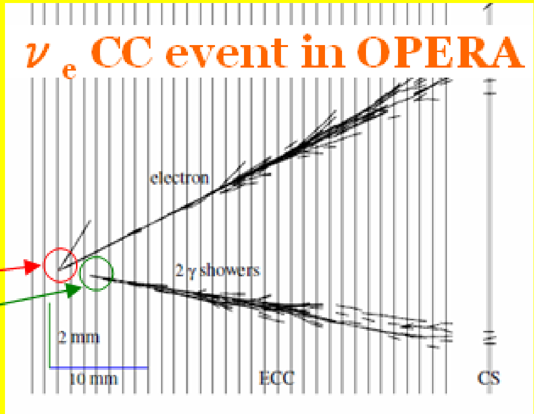






γ / electron ID



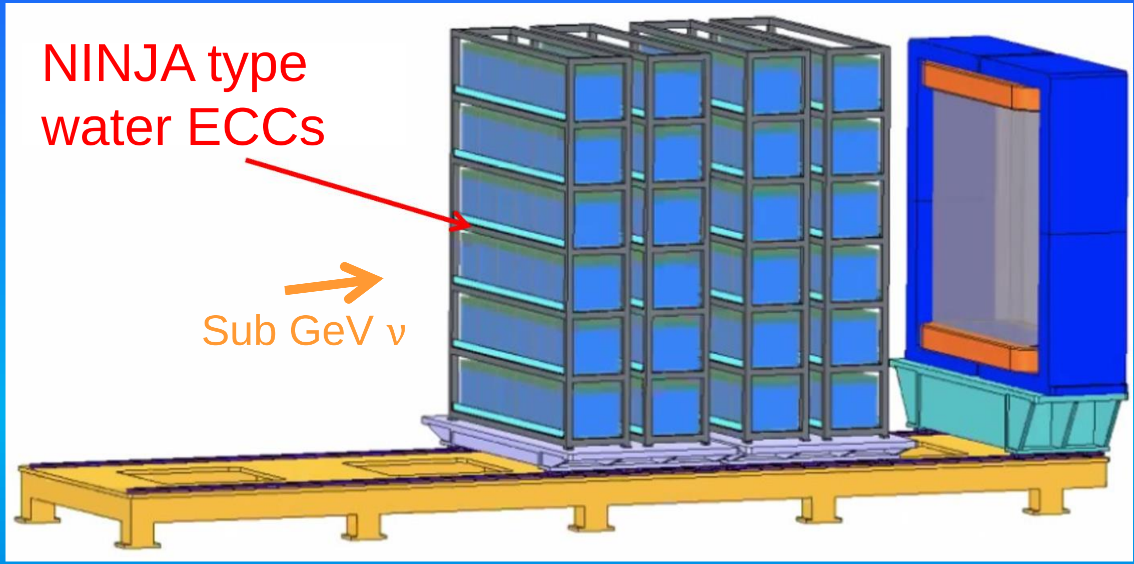


Low BG from ν_μ NC π^0 production

The nuclear emulsion has all the essential elements for low energy neutrino study.

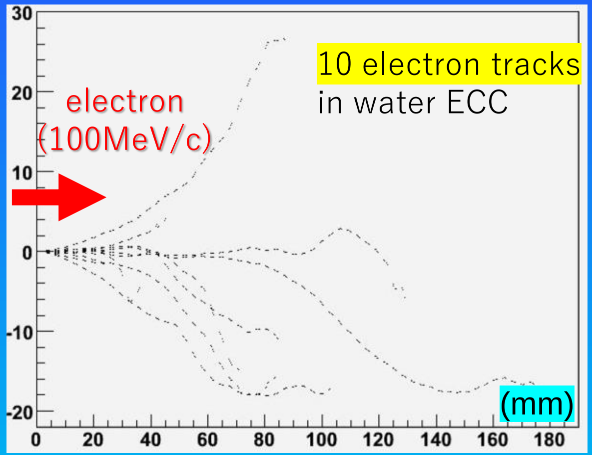
viking detector at ESSnuSB

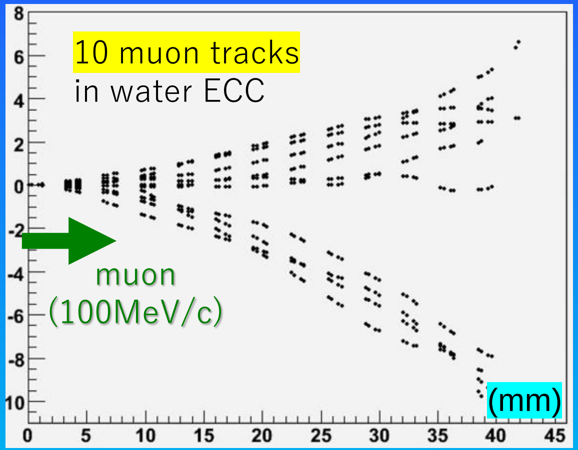
1ton water emulsion detector

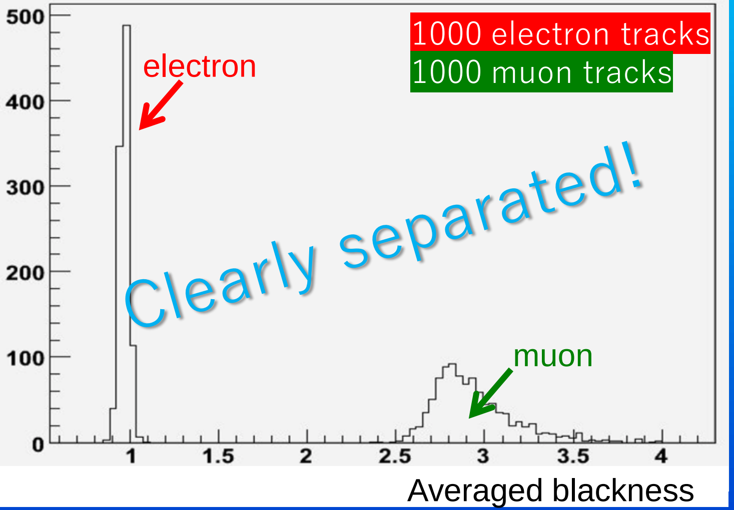


Low energy e/μ separation in water ECC GEANT4

Need to be confirmed experimentally



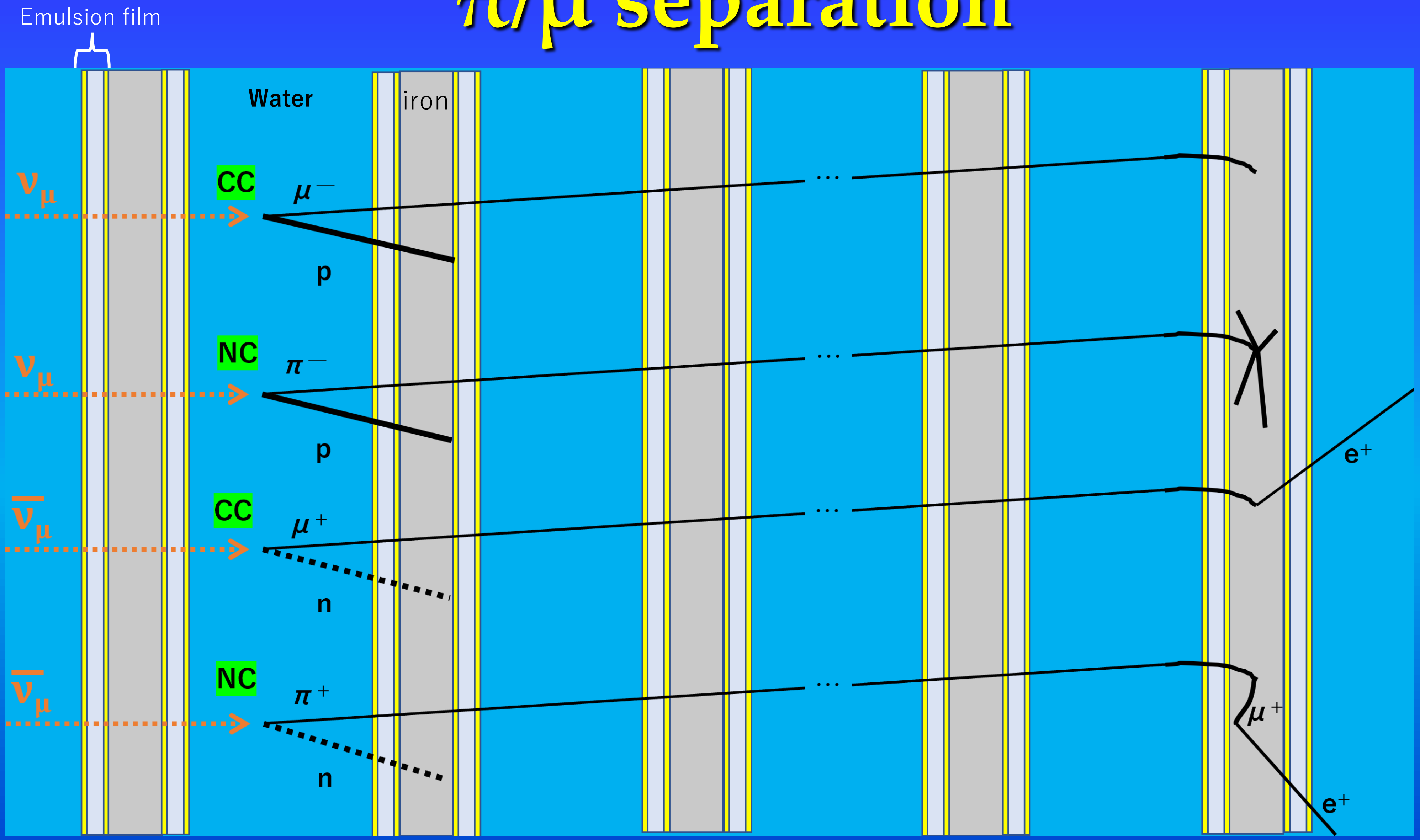




- 140 NINJA type water ECCs are installed.（6 x 6 x 4 walls）
- Detector size is 2m x 2m x 2m. The detectors should be installed a cooling shelter because the temperature need to be keep at 5-10℃ for emulsion films.
- Total apparatus mass include cooling shelter and detector racks is ~8 ton.

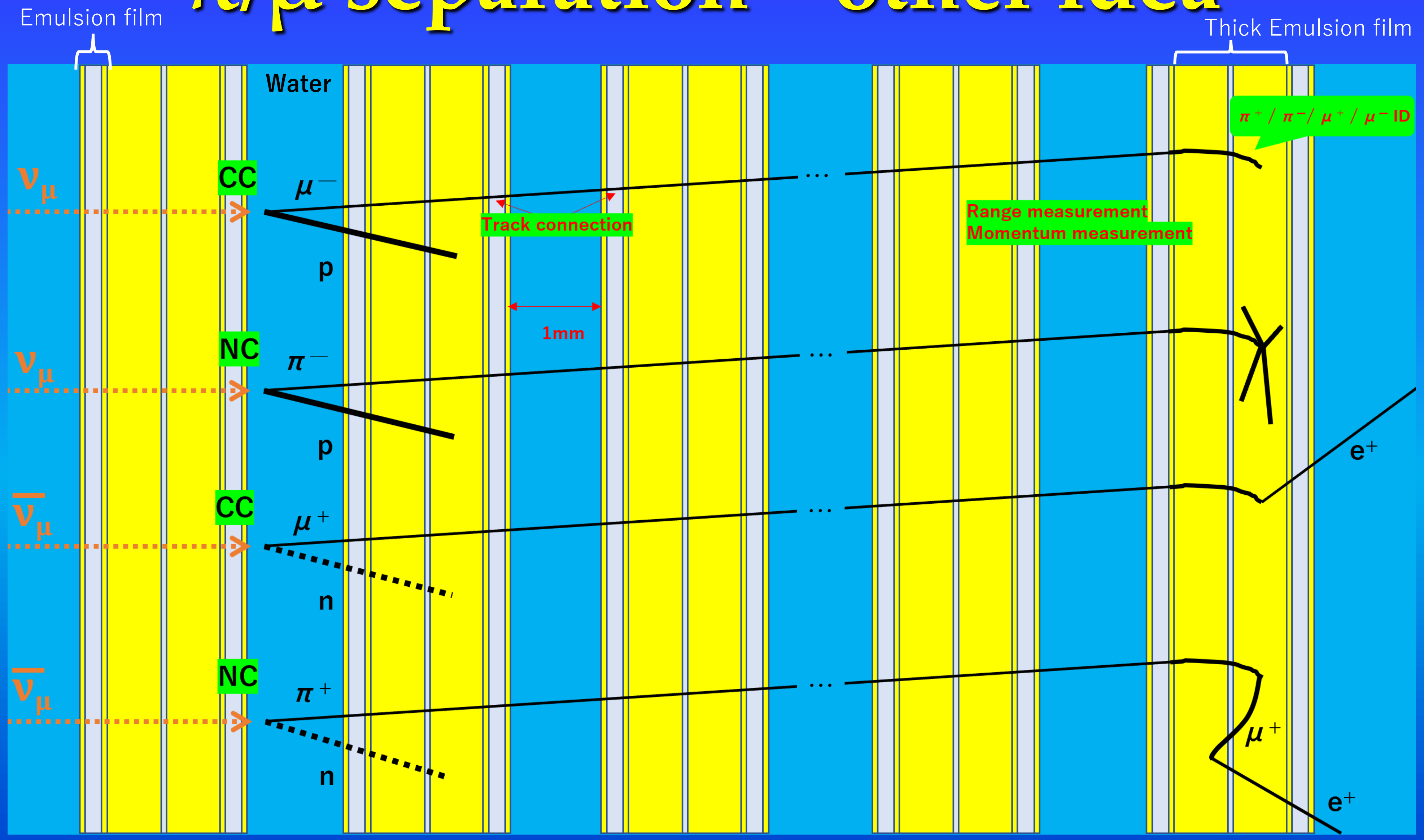
How about π/μ separation?

π/μ separation



In principle, π and μ can be separated by using Range-dE/dx information.
But need to be confirmed by MC and experiment.

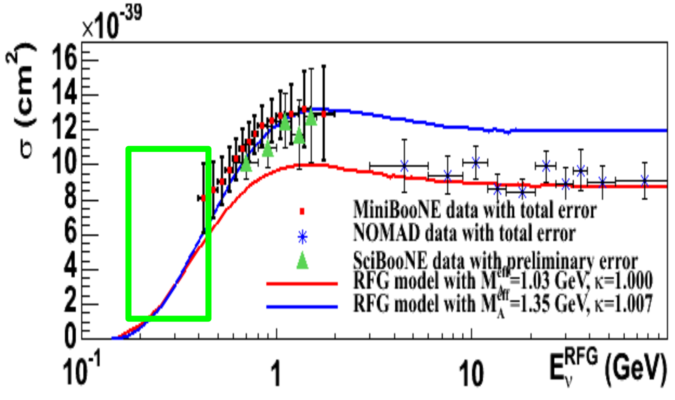
π/μ separation – other idea –



Using thick emulsion sheets instead of iron plates,
π and μ is identified by image analysis at each stop point.

ν cross-section measurement

Energy region with no neutrino interaction data



Number of selected events

$$\sigma = \frac{N_{sel} - N_{bkg}}{\varphi \; T \; \varepsilon}$$

calculated based on the data

Evaluated using the MC

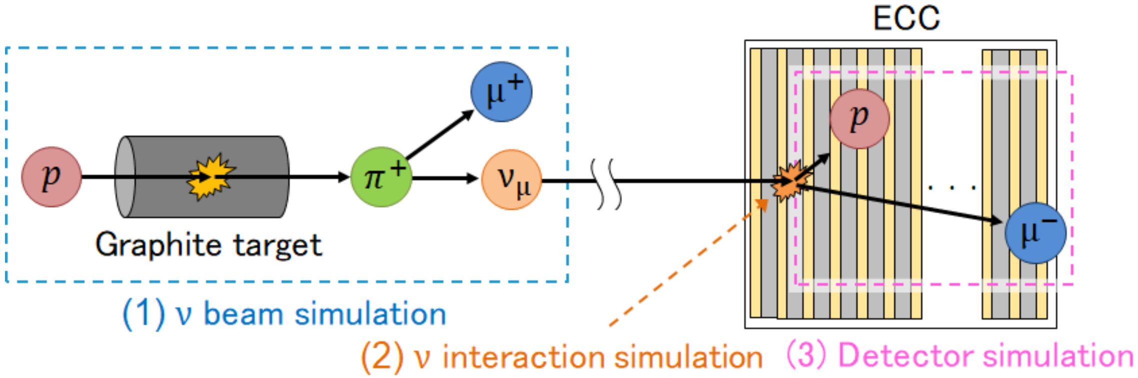
N_{sel}	Number of selected events
N_{bkg}	Number of background events
φ	Integrated neutrino flux
T	Number of target nucleons
ε	Selection efficiency

NINJA case

(1) Neutrino beam:
JNUBEAM 13av6.1

(2) Neutrino interaction:
NEUT 5.4.0

(3) Detector response:
GEANT4 (QGSP BERT physics list) (normalize : POT value & target mass)



Systematic uncertainties

Item	$\sigma_{\mathrm{CC}}^{\mathrm{Fe}}$	$\sigma_{\mathrm{CC\ phase\,space}}^{\mathrm{Fe}}$
Neutrino flux	−5.8% +6.6%	−5.9% +6.5%
$M_{\mathrm{A}}^{\mathrm{QE}}$	−0.0% +1.5%	−0.0% +0.9%
$M_{\mathrm{A}}^{\mathrm{RES}}$	−0.0% +0.1%	−0.3% +0.2%
$C_5^{\mathrm{A}}(0)$	−1.2% +1.1%	−0.7% +0.6%
Isospin $\frac{1}{2}$BG	−0.9% +0.8%	−0.3% +0.3%
CC other shape	−0.6% +0.5%	−0.3% +0.2%
CC coherent normalization	−1.5% +1.6%	−0.7% +0.7%
NC other normalization	−1.0% +1.0%	−0.4% +0.4%
NC coherent normalization	−0.8% +0.0%	−0.2% +0.0%
2p2h normalization	−2.5% +2.8%	−1.1% +1.2%
Fermi momentum P_{F}	−1.1% +1.0%	−0.5% +0.4%
Binding energy E_{b}	−0.9% +0.0%	−0.3% +0.2%
Pion absorption normalization	−0.9% +1.0%	−0.4% +0.5%
Pion charge exchange normalization ($p_\pi < 500\,\mathrm{MeV}/c$)	−0.0% +0.8%	−0.0% +0.2%
Pion charge exchange normalization ($p_\pi > 500\,\mathrm{MeV}/c$)	−0.0% +0.8%	−0.0% +0.2%
Pion quasi elastic normalization ($p_\pi < 500\,\mathrm{MeV}/c$)	−0.8% +0.7%	−0.3% +0.2%
Pion quasi elastic normalization ($p_\pi > 500\,\mathrm{MeV}/c$)	−0.0% +0.8%	−0.2% +0.2%
Pion inelastic normalization	−0.8% +0.7%	−0.3% +0.2%
Wall backgrounds	−1.1% +1.1%	−0.2% +0.2%
ECC–Shifter–INGRID misconnection backgrounds	−1.4% +2.2%	−1.1% +1.7%
Base track detection efficiency	−0.3% +0.1%	−0.3% +0.1%
ECC track reconstruction	−0.1% +0.1%	−0.1% +0.1%
ECC bricks track connection	−0.1% +0.1%	−0.1% +0.1%
ECC–Shifter track connection	−2.3% +2.4%	−2.3% +2.3%
ECC–INGRID track connection	−3.0% +3.2%	−3.1% +3.2%
INGRID track reconstruction	−0.7% +0.8%	−0.7% +0.8%
Kink event cut	−0.6% +0.5%	−0.2% +0.1%
Momentum consistency check	−1.3% +1.3%	−0.8% +0.8%
Target mass	−0.6% +0.6%	−0.7% +0.7%
Difference between iron and the stainless steel	−0.3% +0.3%	−0.3% +0.3%
Total	−8.5% +9.4%	−7.5% +8.2%

Full (Restricted) phase space

Flux :
-5.8% / +6.6%
(-5.9% / +6.5%)

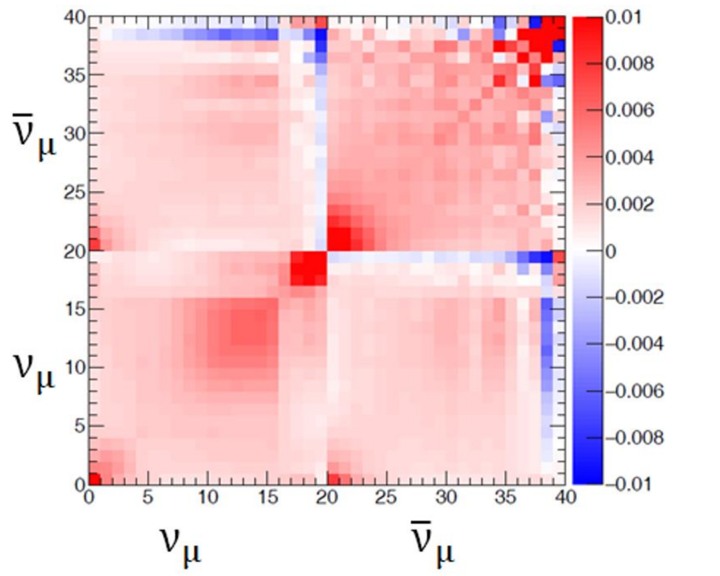
Neutrino interaction model :
-4.1% / +4.6%
(-1.9% / +2.0%)

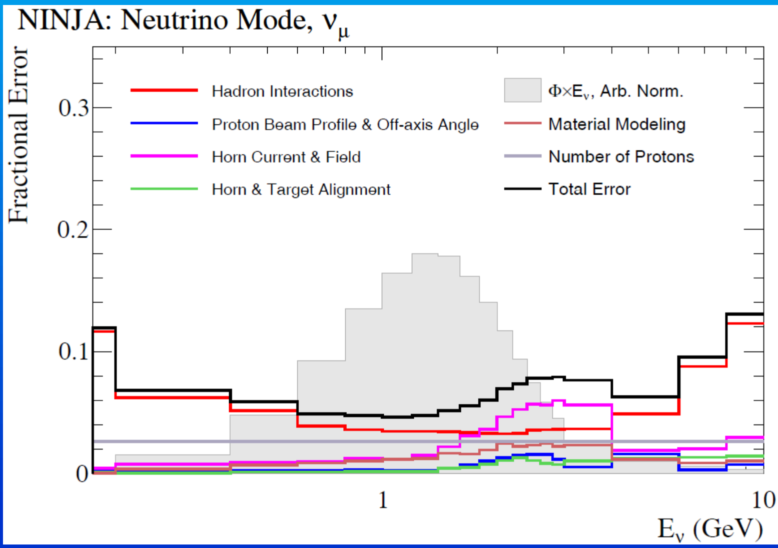
Background estimation :
-1.8% / +2.4%
(-1.1% / +1.7%)

Detector response :
-4.2% / +4.4%
(-4.1% / +4.2%)

Need to update

Covariance matrix of flux uncertainty



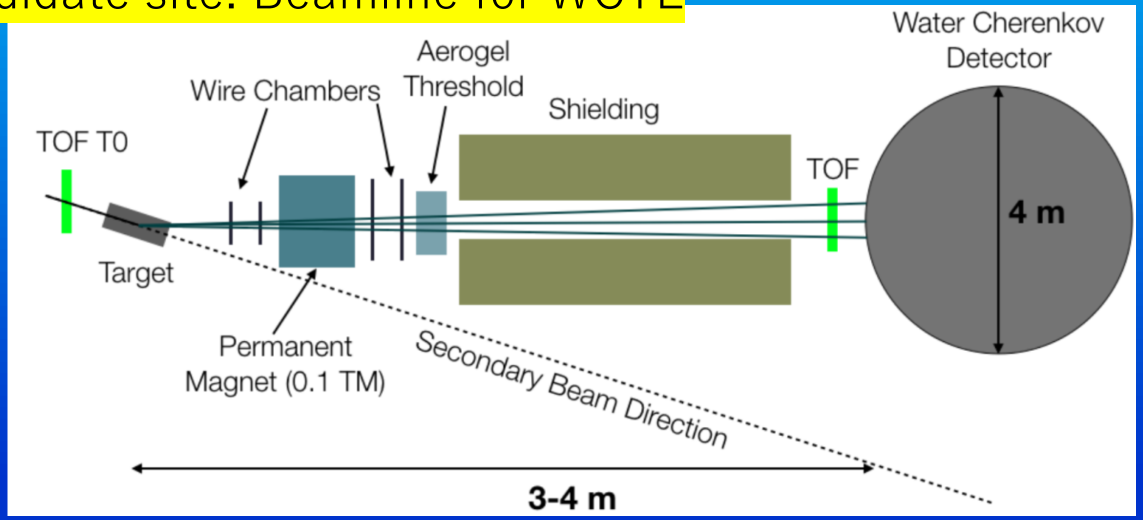


To do

1. Detector simulation using GEANT4 to analyze PID.
2. Check MC PID works for neutrino interactions in ESSnuSB energy.
3. Full MC process of neutrino cross-section measurements.

4. Experimental verification of 1,2 and 3.
   - for 1, a test experiment by CERN?
   - for 2&3, a physics run in NINJA at J-PARC?

Candidate site: Beamline for WCTE

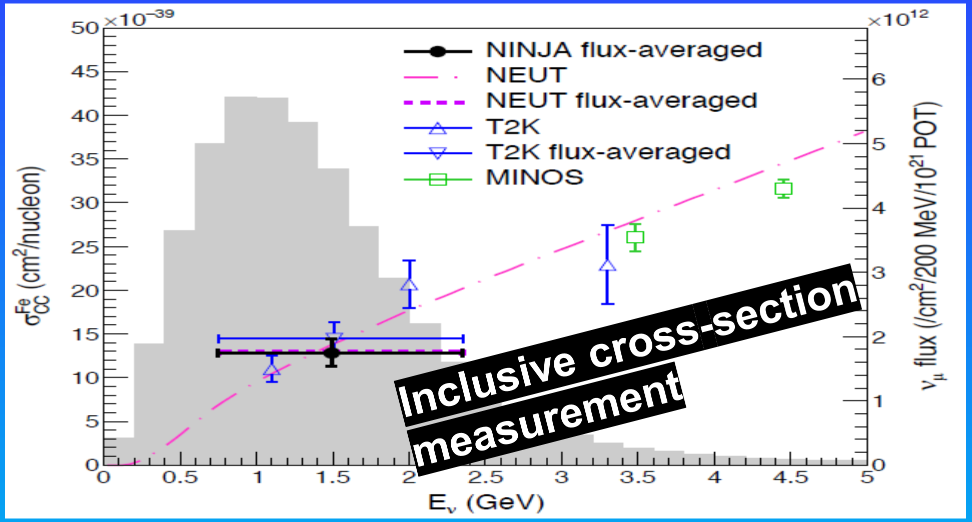


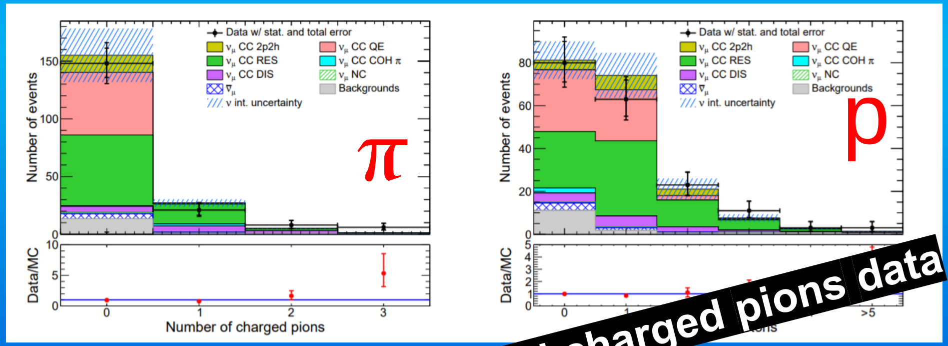
Current status of NINJA

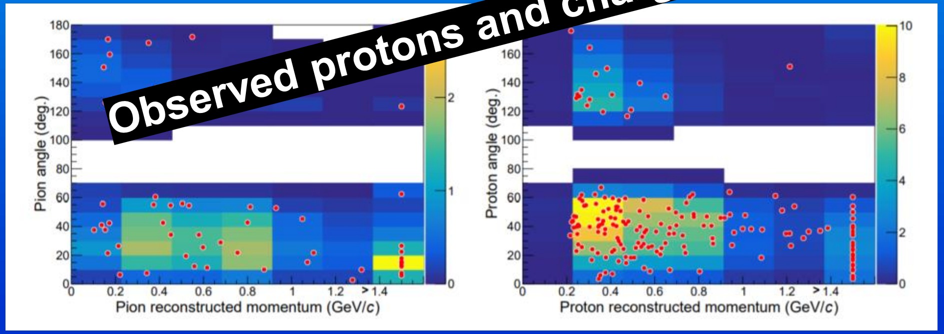
- The analysis of Detector Run using 60kg iron target was completed. In backward π production, significant discrepancy between data and simulation was found.
- The analysis of Physics Run using 75kg water target was going on.
- Second Physics Run using water target will be implemented this year.
- Large budget (1M€ for 5years:2023-2027) was obtained last month. So the discussion of new plan for next year and beyond is started.

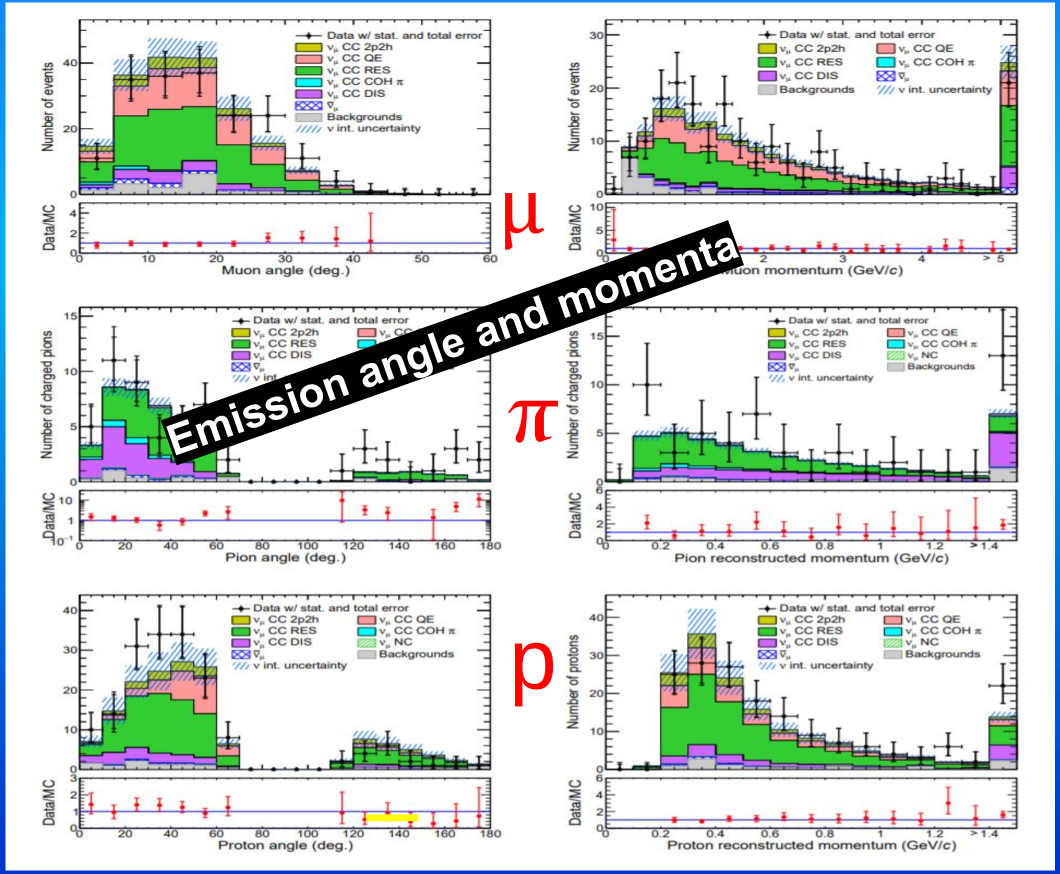
NINJA Results of Detector Run(1)

- 4.0 x 10^{19} POT @ Detector run
- Target: 65kg iron → ν-iron int.
- Momentum, emission angle and multiplicity of μ, π and p are measured for 183 CC events.









Results of Detector Run(2)

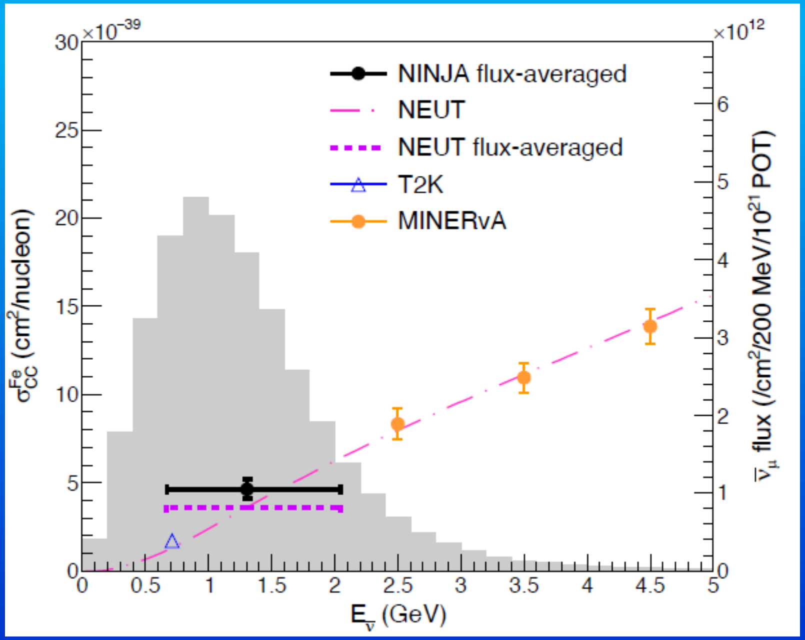
- 3.5 x 10^{20} POT @ Detector run
- Target: 65kg iron → $\bar{\nu}$-iron int.
- Momentum, emission angle and multiplicity of μ, π and p are measured for 770 CC events.

	Result $\times 10^{-39}$ $(cm^2/nucleon)$	MC $\times 10^{-38}$
σ_{CC}^{Fe}	$4.63 \pm 0.23(stat.)^{+0.53}_{-0.48}(syst.)$	3.57
$\sigma_{CC\ phase\ space}^{Fe}$	$3.85 \pm 0.20(stat.)^{+0.42}_{-0.40}(syst.)$	3.22

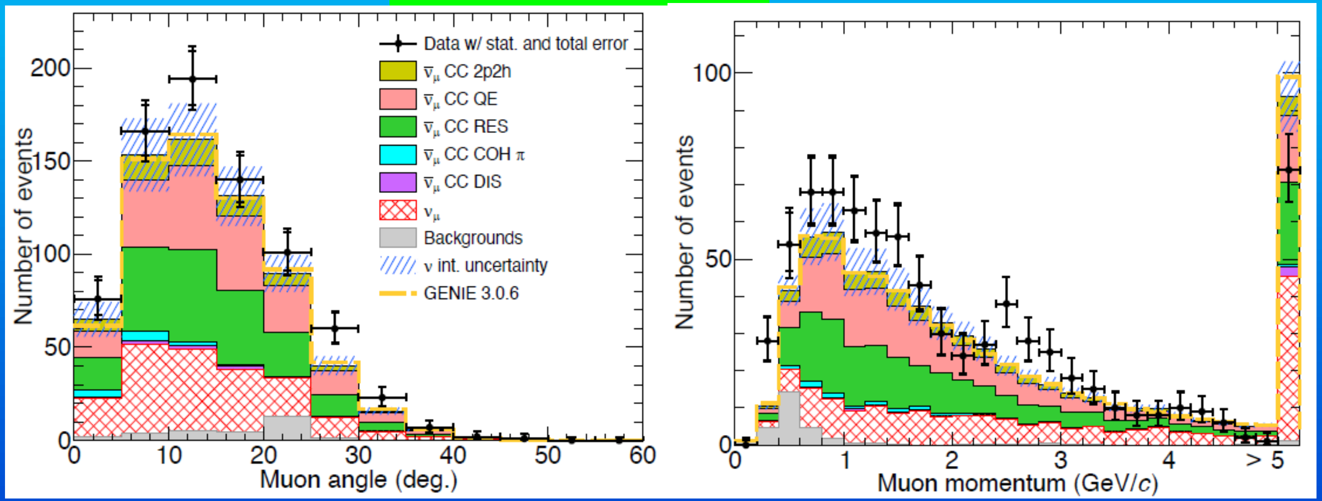
23% larger

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

Inclusive Cross-section measurement



Muon kinematics



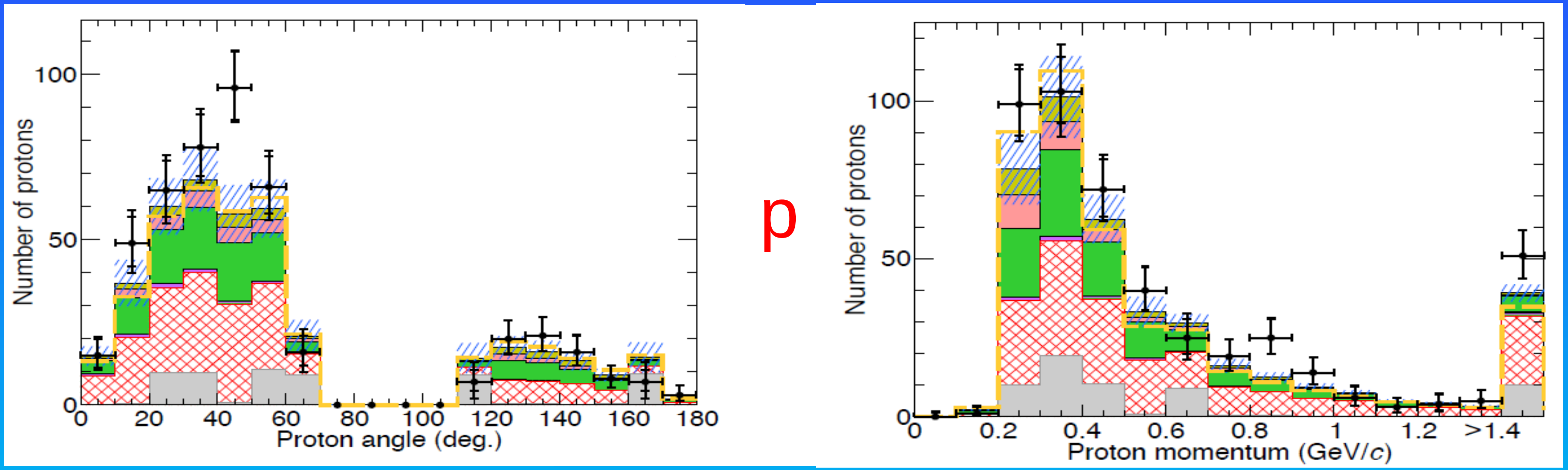
The results agree well with the MC prediction

NINJA

Results of Detector Run(2)′

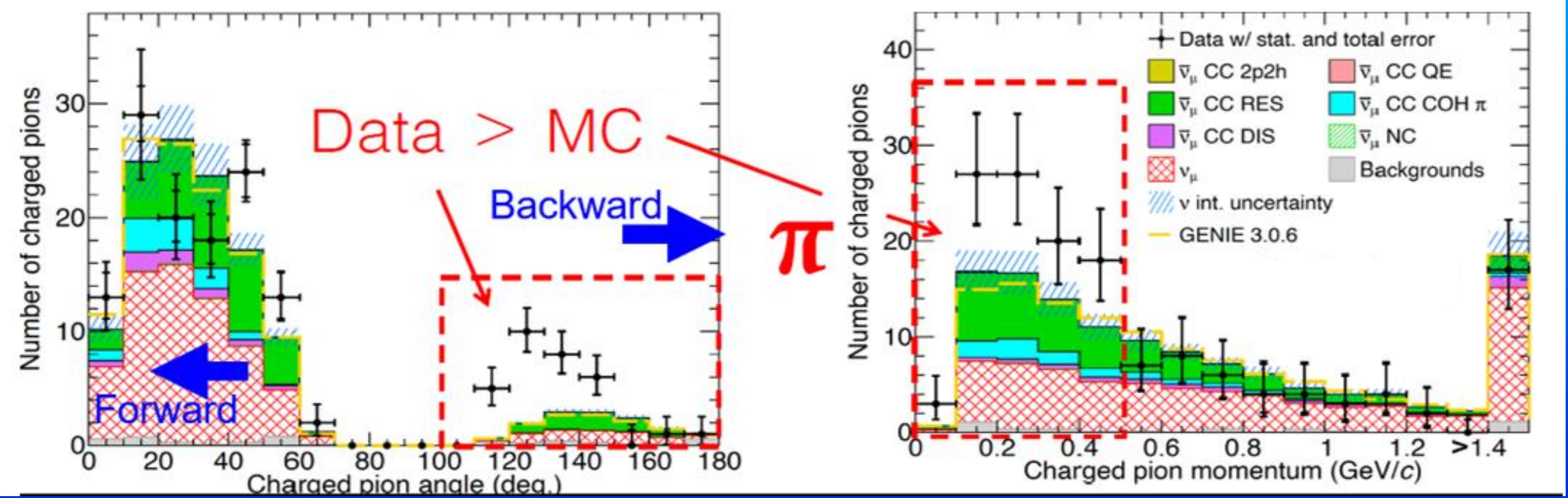
Proton kinematics

The results agree well with the MC prediction



Pion kinematics

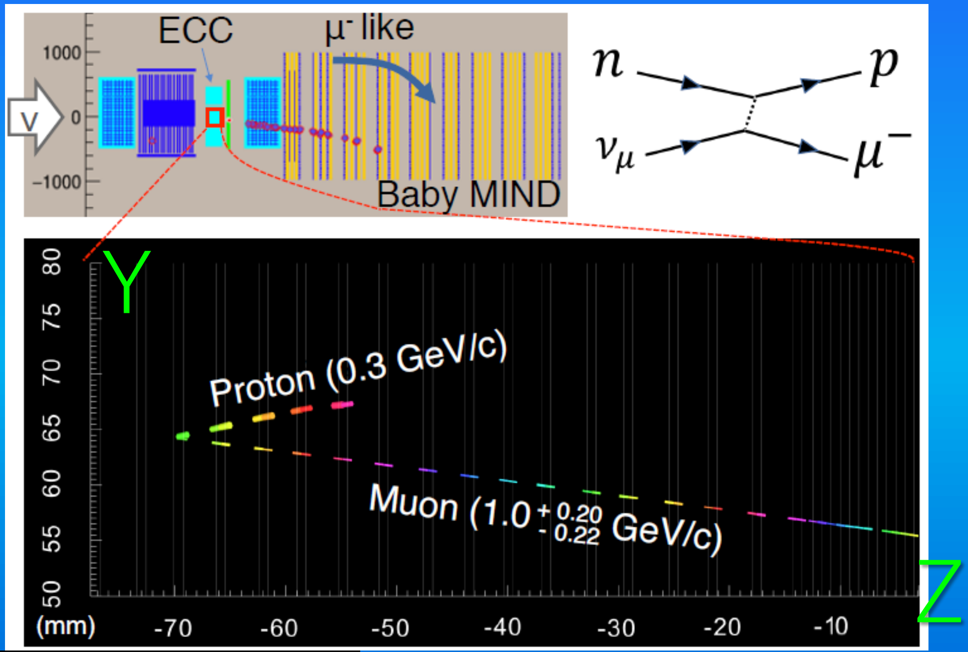
Data of charged pion production (backward) is larger than the MC prediction.



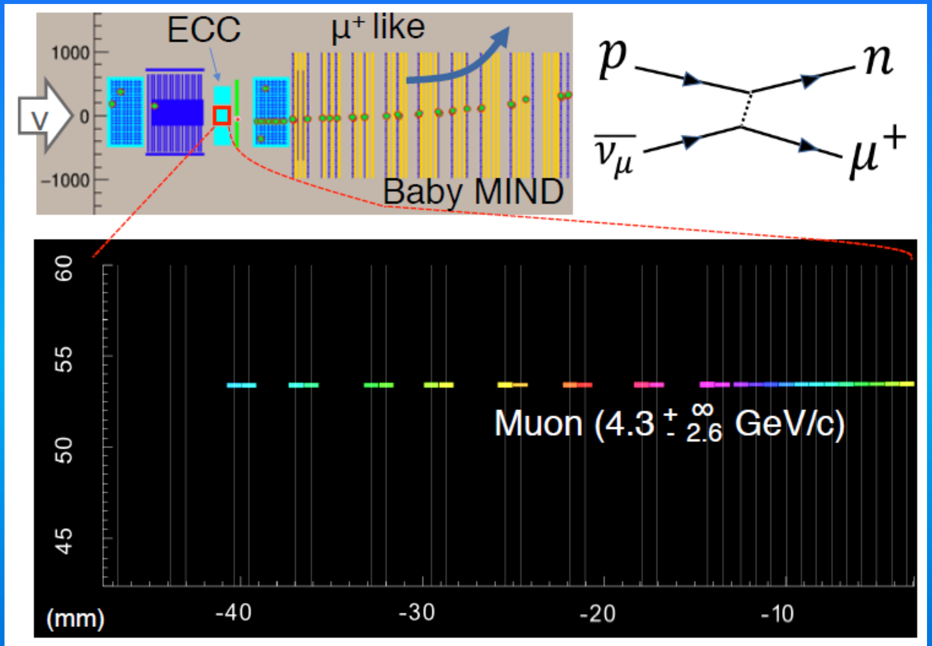
NINJA Detected neutrino events in Physics Run

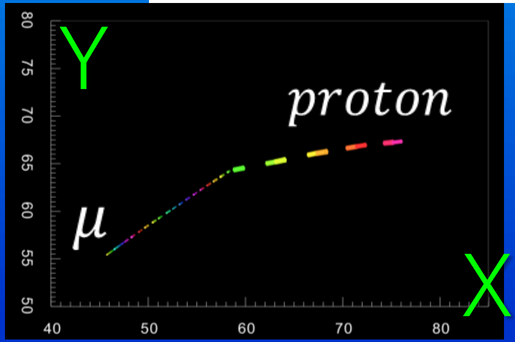
ECC – Emulsion Shifter – Scintillation Tracker – Baby MIND worked well and succeeded in μ ID and measuring their charge.

Typical Neutrino CC event



Typical Anti neutrino CC event





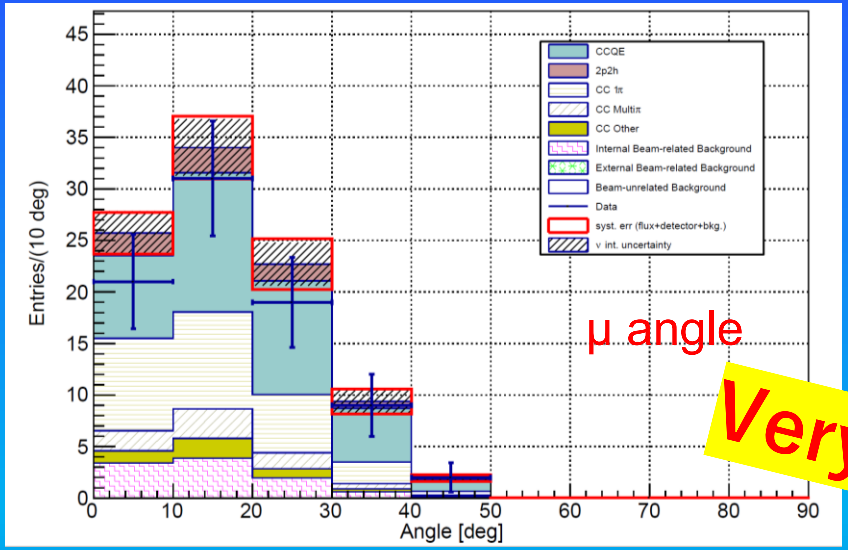
- The event pictures (number of protons) in ECC and the μ charge measured by Baby MIND are consistent.
- To finalized data set, we are checking the muon connections and analysis in ECC, event by event carefully.

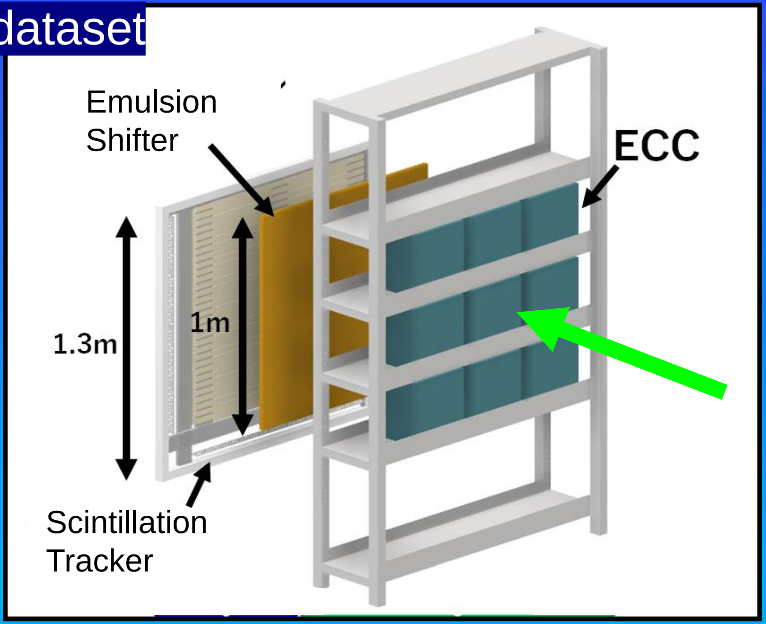
NINJA

Analysis status of Physics Run

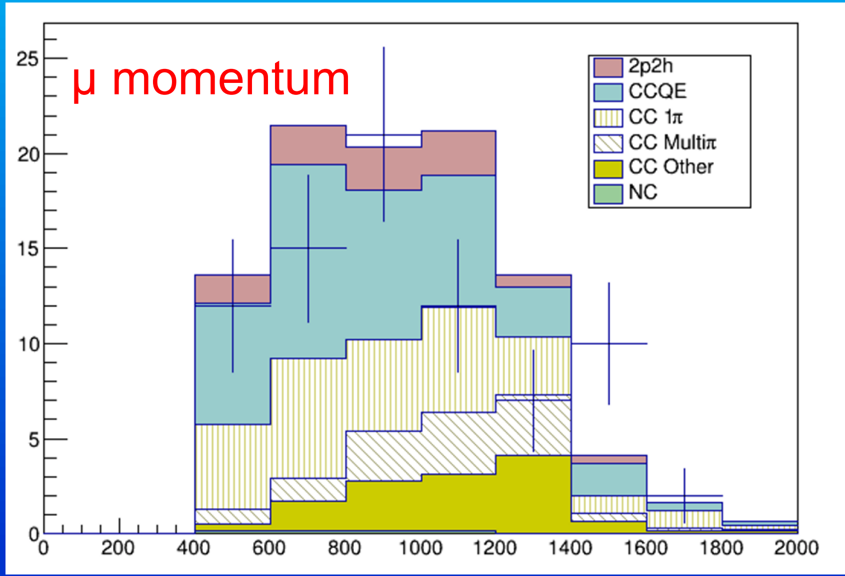
Detected muons and protons in ν-water int. at ~10% sub-sample

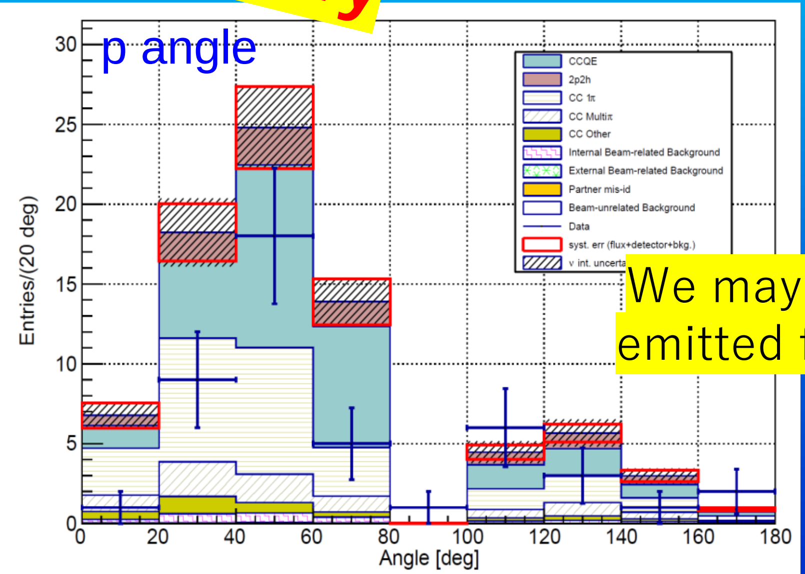
Performance check by sub-data set (the central ECC) before opening full dataset





Very Preliminary

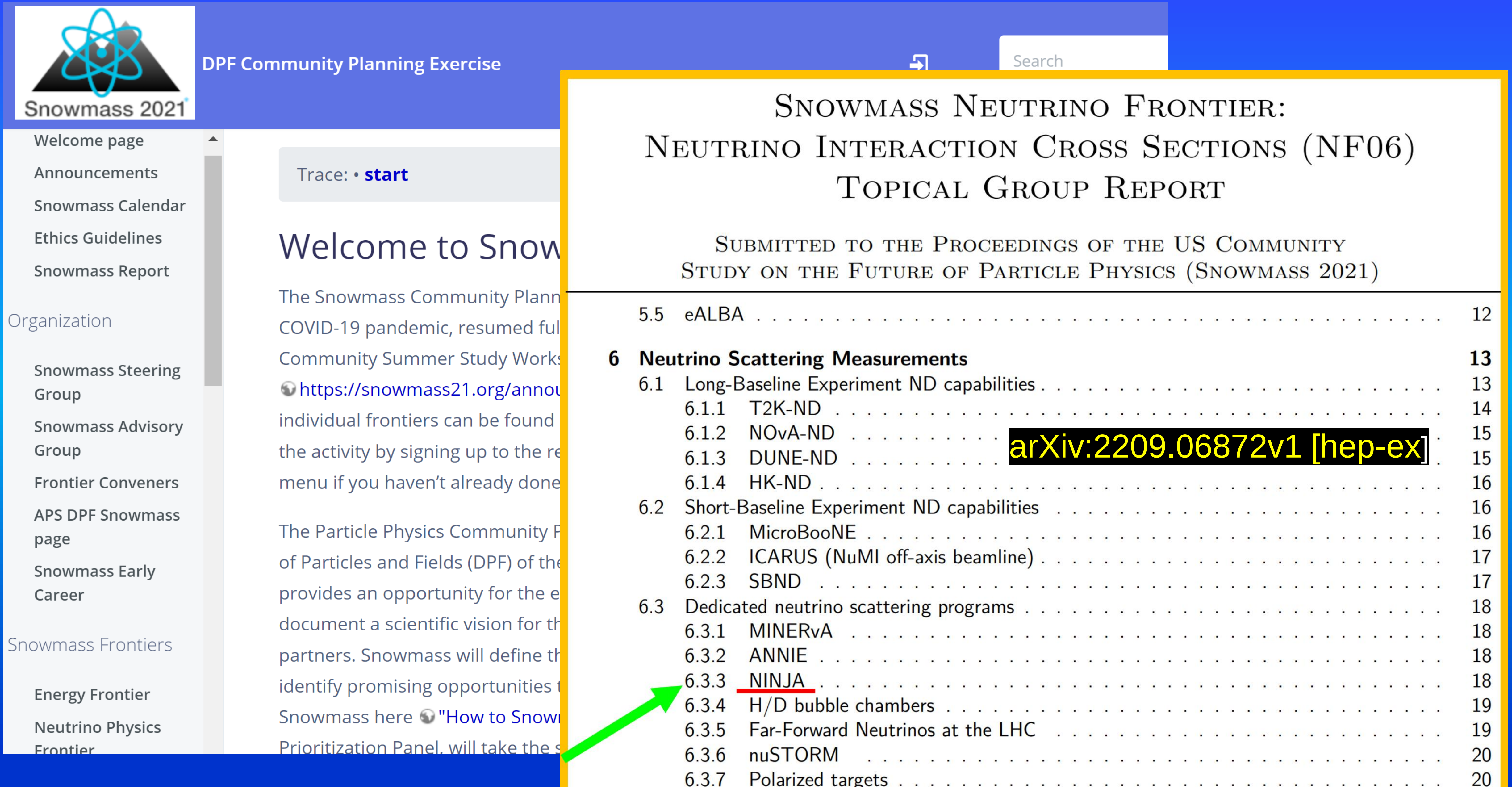




We may find that the number of protons emitted forward was less than expected?

→ Open full dataset near future!

Snowmass2021 process at US



Future prospect : D_2O

There is a discussion to further understand ν-nucleus interactions, the study of ν-nucleon interactions is important.


FERMILAB-CONF-22-149-ND,LA-UR-21-31459

Neutrino Scattering Measurements on Hydrogen and Deuterium: A Snowmass White Paper

Luis Alvarez-Ruso[1], Joshua L. Barrow[2,3], Leo Bellantoni[4], Minerba Betancourt[4], Alan Bross[4], Linda Cremonesi[5], Kirsty Duffy[6], Steven Dytman[7], Laura Fields[8], Tsutomu Fukuda[9], Diego González-Díaz[10], Mikhail Gorchtein[11], Richard J. Hill[12,4], Thomas Junk[4], Dustin Keller[13], Huey-Wen Lin[14], Xianguo Lu[15], Kendall Mahn[14], Aaron S. Meyer[16,17], Tanaz Mohayai[4], Jorge G. Morfín[4], Joseph Owens[18], Jonathan Paley[4], Vishvas Pandey[19], Gil Paz[20], Roberto Petti[21], Ryan Plestid[12,4], Bryan Ramson[4], Brooke Russell[17], Federico Sanchez Nieto[22], Oleksandr Tomalak[12,4,23], Callum Wilkinson[17], and Clarence Wret[24]

[1]*Instituto de Física Corpuscular (IFIC), Consejo Superior de Investigaciones Científicas (CSIC) and Universidad de Valencia (UV), E-46980, Valencia, Spain*
[2]*Massachusetts Institute of Technology, Cambridge, MA*
University College, London, London, WC1E 6BT, United Kingdom
[6]*University of Oxford, Oxford, OX1 3RH, United Kingdom*
[7]*University of Pittsburgh, Pittsburgh, PA 15260, USA*
[8]*University of Notre Dame, Notre Dame, IN 46556, USA*
[9]*IAR/Flab, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan*

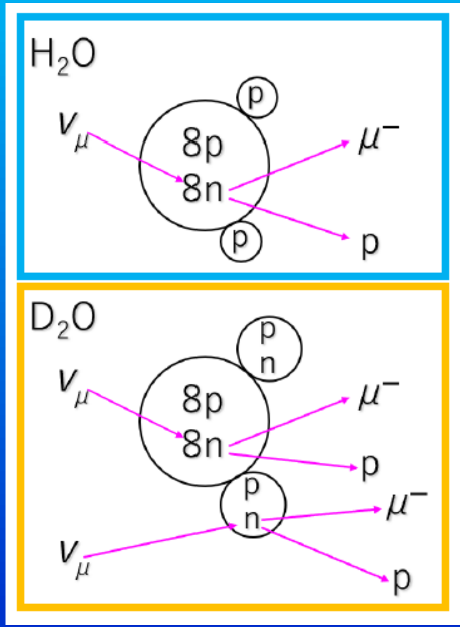
arXiv:2203.11298v2 [hep-ex] 1 Jun 2022

arXiv:2203.11298 [hep-ex].

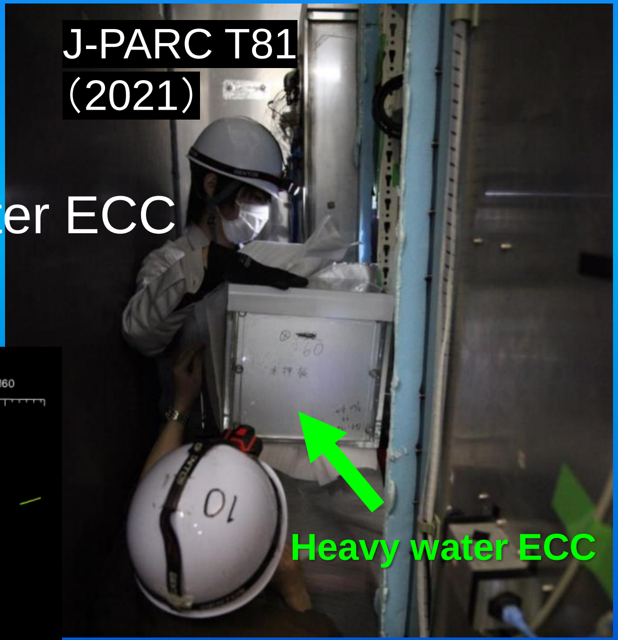
Development of a bubble chamber is being considered in US.

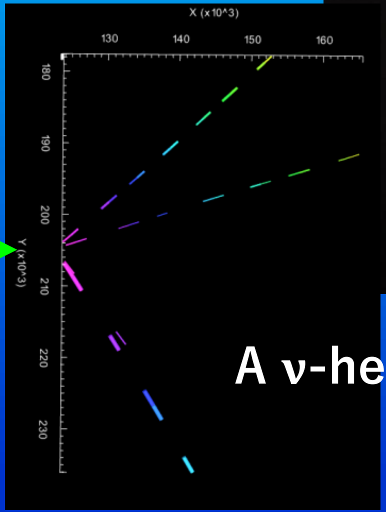
In NINJA, by introducing a heavy water target, we are developing a method to study ν-nucleon interactions by analyzing the subtraction between a heavy water events and a water events.

Conceptual principle:
$(\nu\text{-}D_2O) - (\nu\text{-}H_2O) \rightarrow (\nu\text{-}n)$



Actually, a heavy water ECC was installed in T81.





A ν-heavy water interaction

Summary

- Nuclear emulsion is 3D tracking detector with sub-micron spatial resolution. It allows us to analyze neutrino interactions on a variety of nucleus.
- We have been studying neutrino interactions around 1GeV through the NINJA experiment. It should be optimized to study neutrino interactions at even lower energies.
- In this talk, I have shown the items for consideration and the future direction of END emulsion detector (νiking).
- Your comments or inputs is very welcome and we would like to discuss it!

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