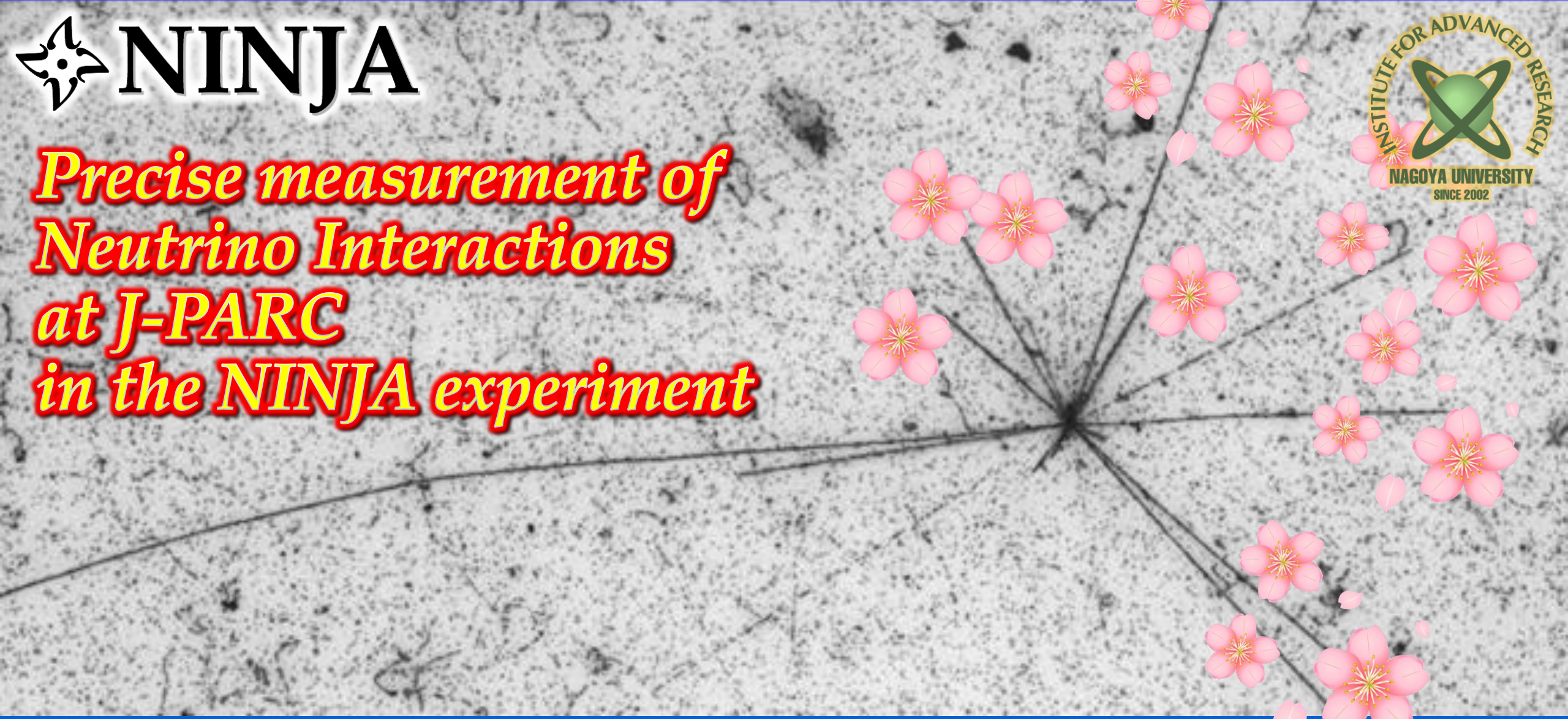
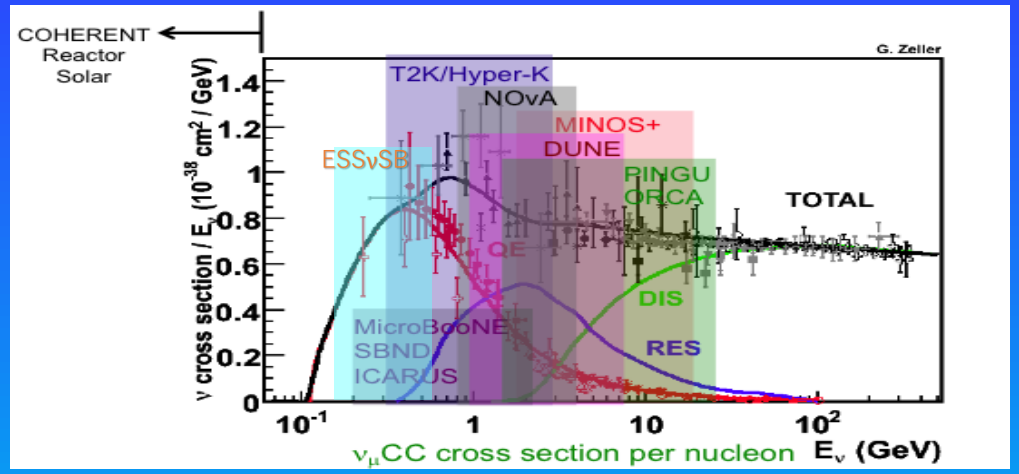
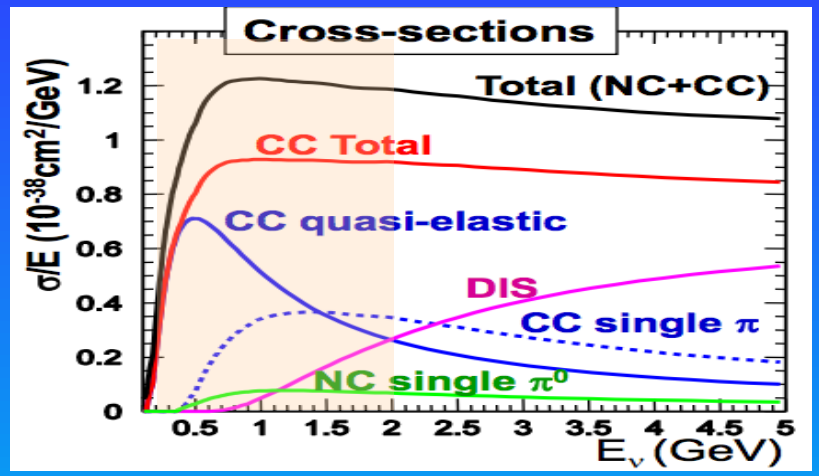


Tsutomu Fukuda (Institute for Advanced Research/F-lab. Nagoya Univ.)
on behalf of the NINJA Collaboration

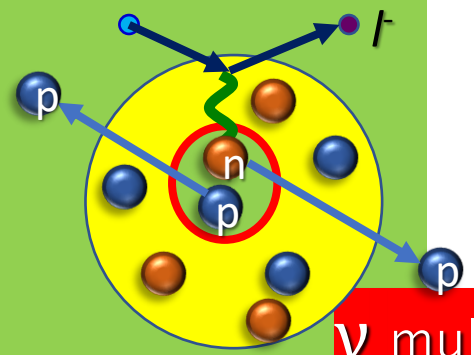
International Conference on the Physics of Two Infinities, Kyoto, 29th Mar. 2023

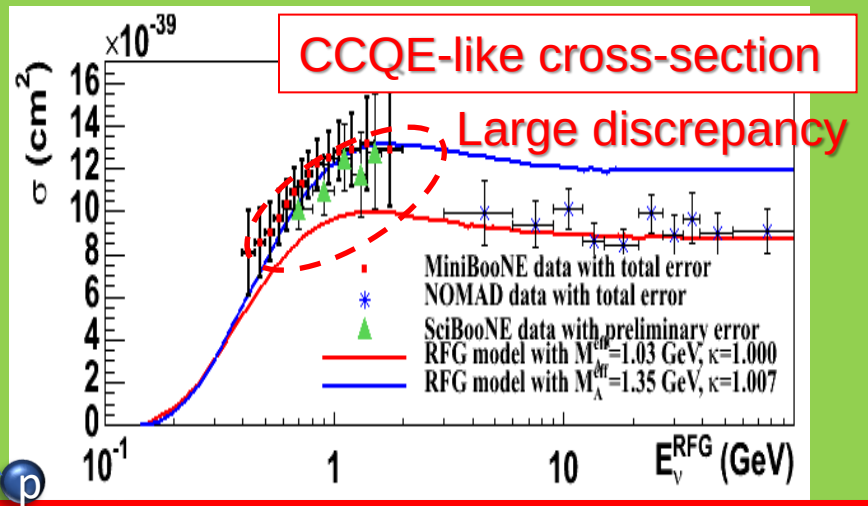
Neutrino physics on sub-multi GeV



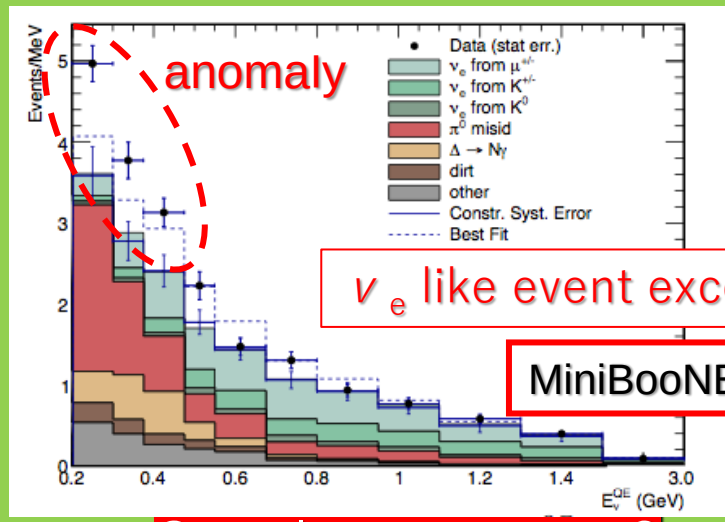


Most current and future neutrino oscillation experiments are in this energy region





ν multi-nucleon (CC2p2h) interaction?



ν e like event excess

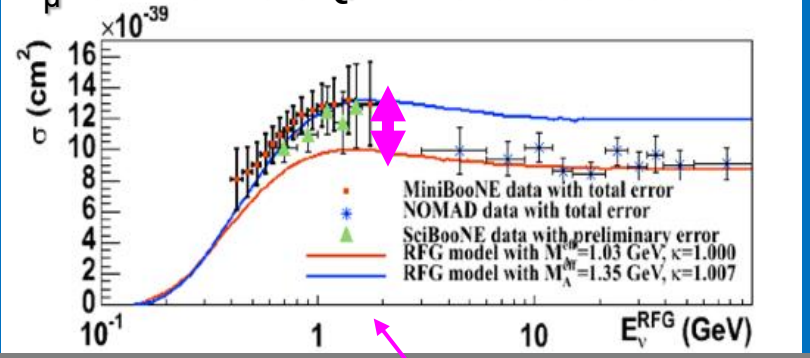
MiniBooNE

Sterile neutrino ?

A better understanding of ν-nucleus interactions is important for the precise measurement of ν oscillations.

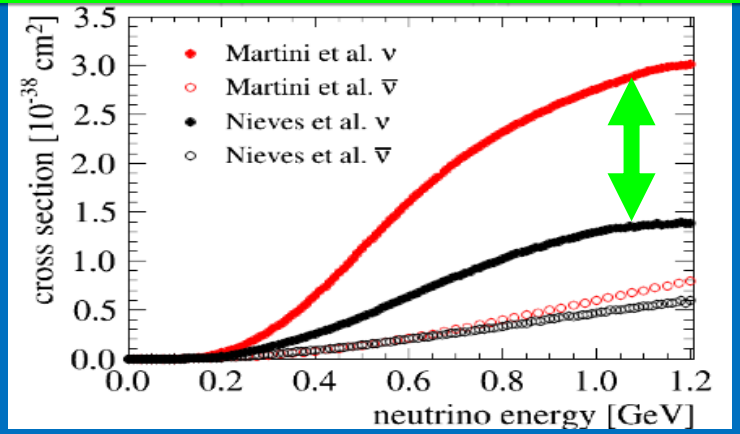
Neutrino multi-nucleon interaction

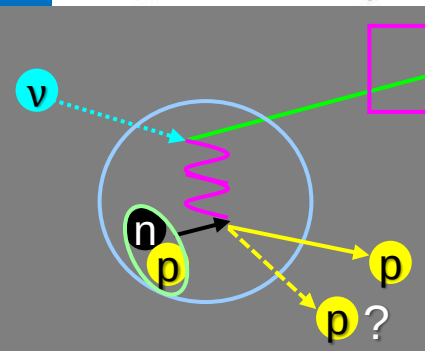
ν_μ-Carbon CCQE like cross-section



Detected in electron scattering experiment.
→ in case neutrino scattering?
Can explain the excess of CCQE-like event?

Theoretical prediction of cross-section of ν multi-nucleon interaction (2p2h)



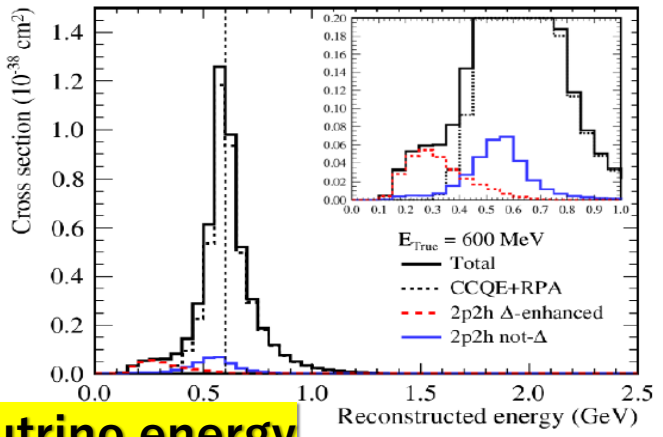


Only μ measurement

CCQE-like event is NOT CCQE event.
Contamination from unknown interaction?

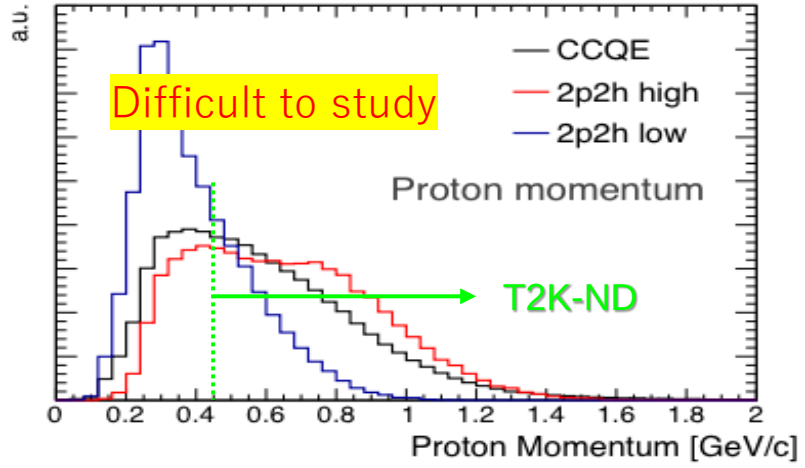
CCQE: $\nu_\mu + n \rightarrow \mu^- + p$
→ 2 body reaction

2p2h: 2proton emission
$\nu_\mu + (n, p) \rightarrow \mu^- + p + p$
→ 3 body reaction



→ **wrong reconstruction of neutrino energy**

Proton momentum

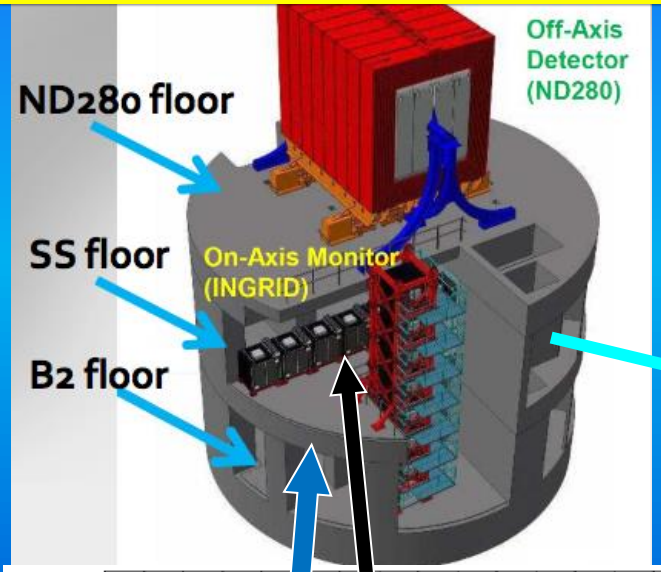


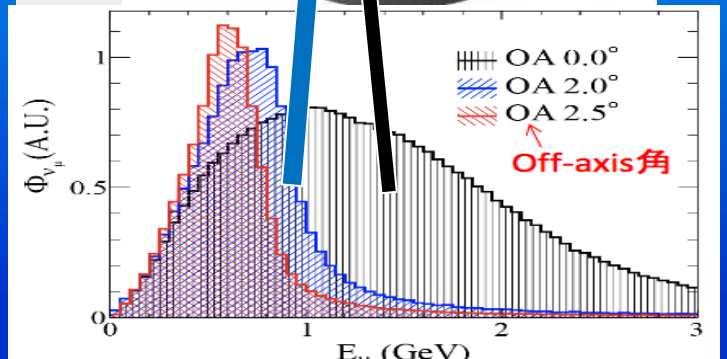
NINJA Experiment

Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

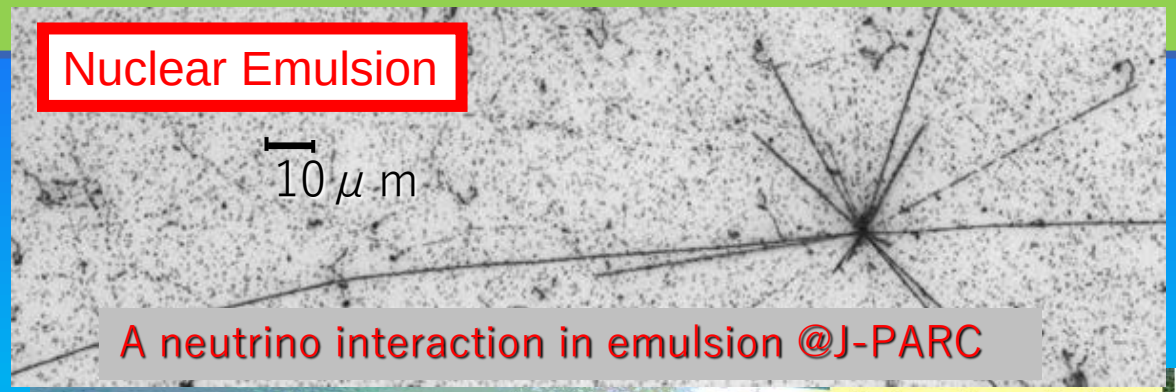
- Precise measurement of neutrino-nucleus cross-sections in Sub-Multi GeV neutrinos
- Electron neutrino cross-section measurement
- Sterile neutrino search

J-PARC Neutrino monitor building

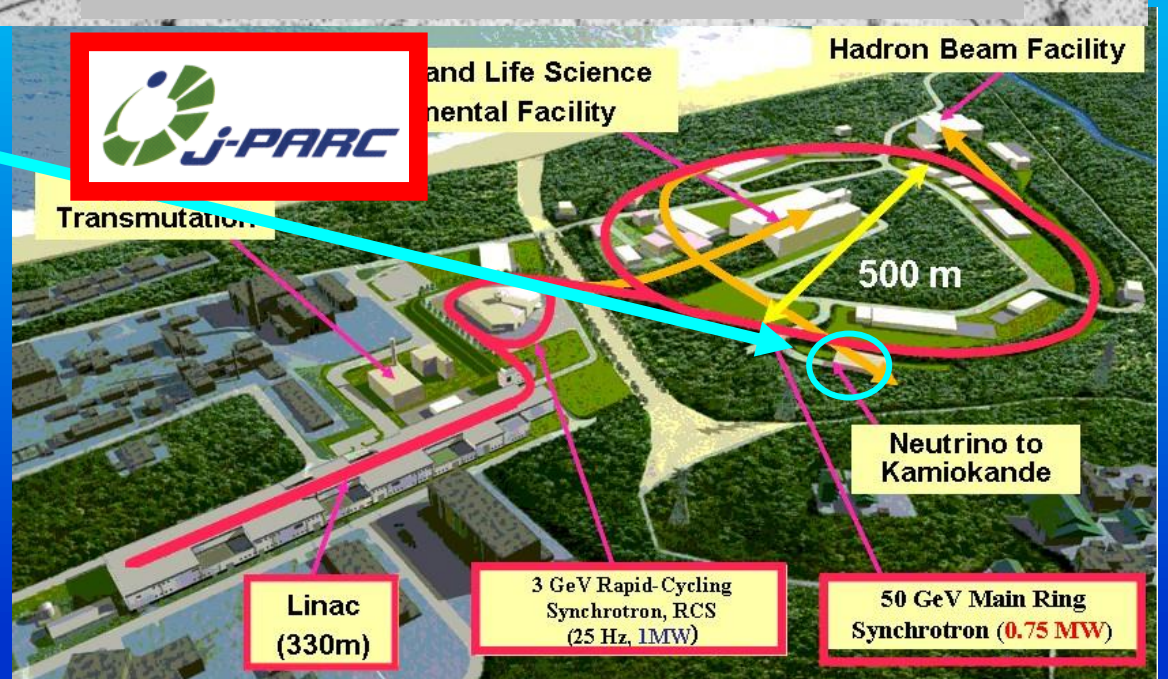




Nuclear Emulsion



A neutrino interaction in emulsion @J-PARC



NINJA Collaboration

(* Spokesperson)

Nihon University: S. Mikado

Nagoya University: T. Fukuda*, T. Hayakawa, Y. Hirobe, H. Inamoto, G. Iwamoto, A. Kasumi, H. Kawahara, T. Kawahara, T. Kawanago, H. Kobayashi, R. Komatani, M.Komatsu, A. Masuda, T. Matsuo, H. Minami, Y. Morimoto, K. Morishima, M. Nakamura, Y. Nakamura, T. Nakano, N. Naganawa, H. Rokujo, O. Sato, K. Sugimura, L. Suzui, Y. Suzuki, I. Usuda, M. Watanabe, S. Yamamoto

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RIKEN: M. Yoshimoto

Tohoku University: A. K. Ichikawa

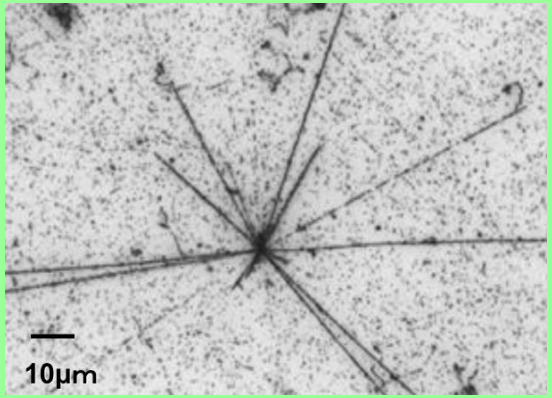
Ruđer Bošković Institute: M. Ghosh, L. Halić, B. Kliček

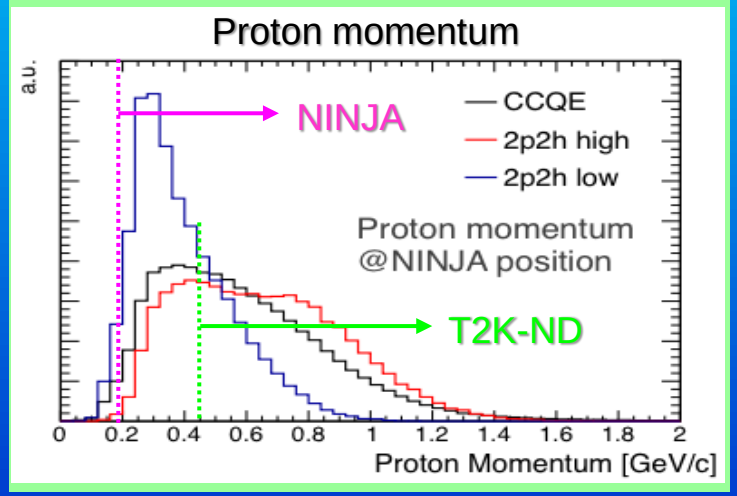
King's College London: T. Katori

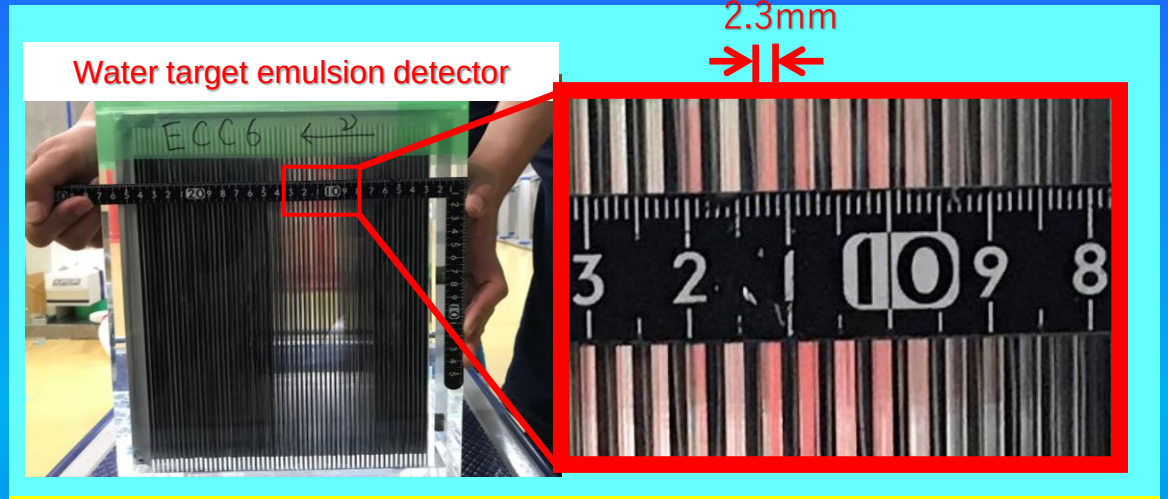
52 researchers from 13 Institutes from 3 countries

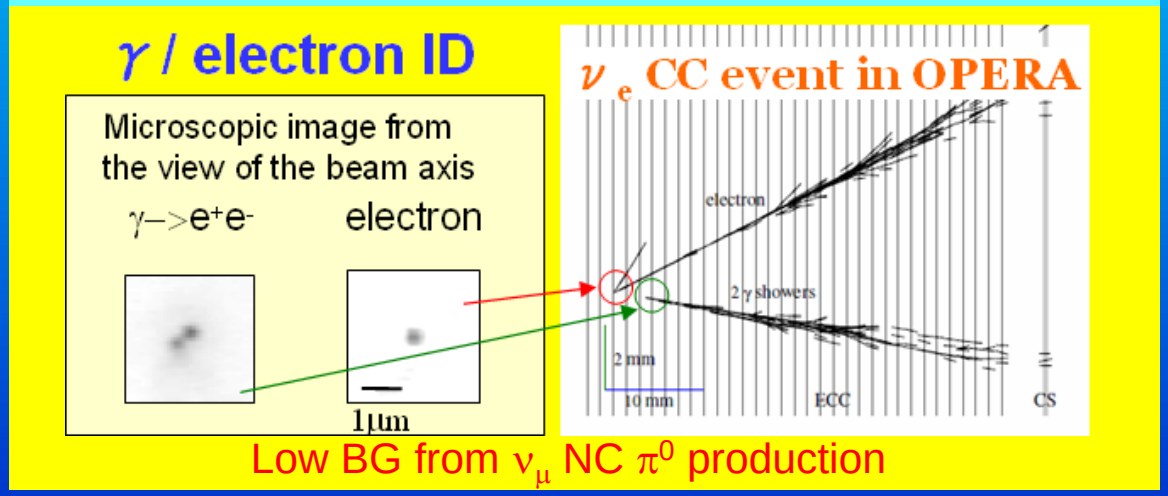
Merits using nuclear emulsion

- 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





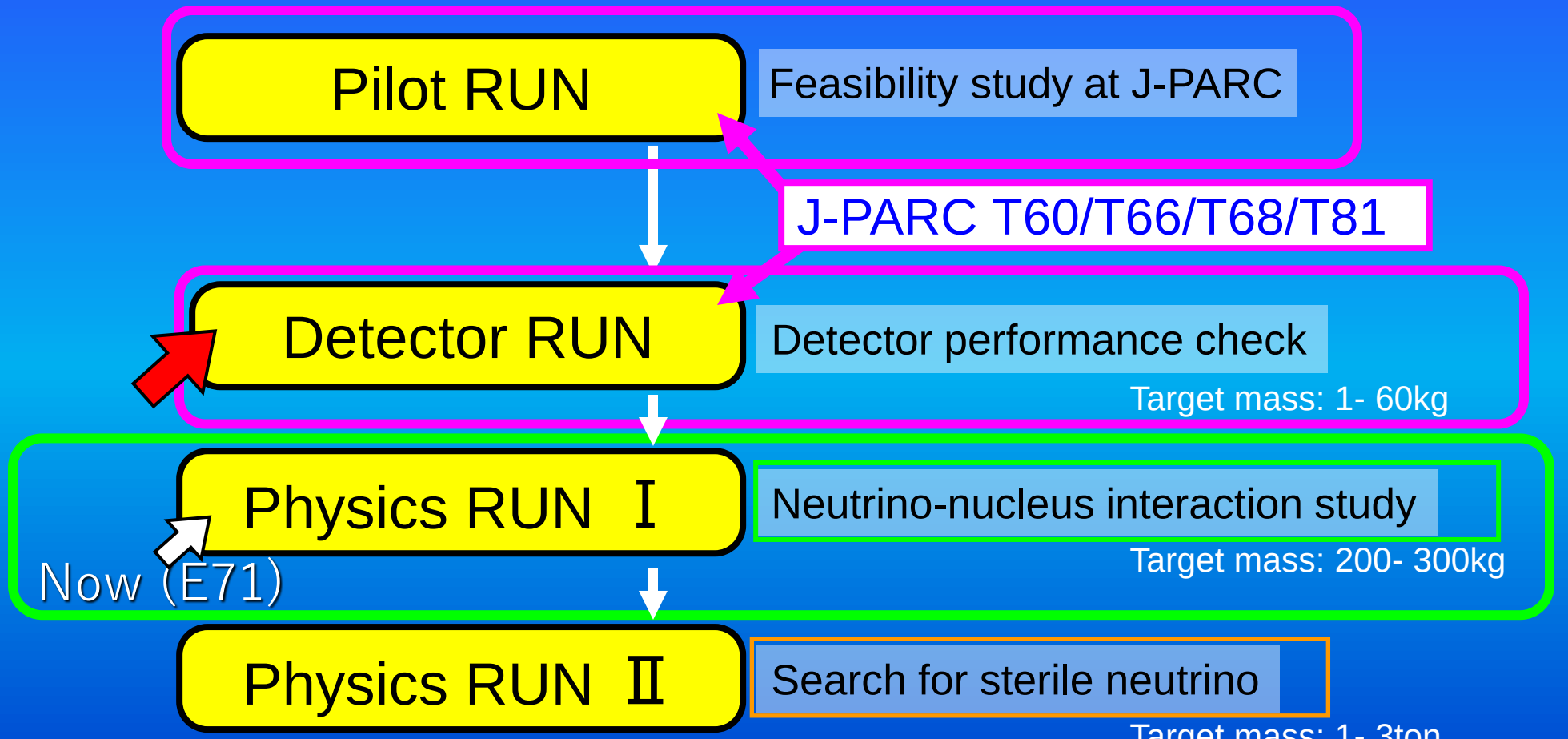




Low BG from ν_μ NC π^0 production

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

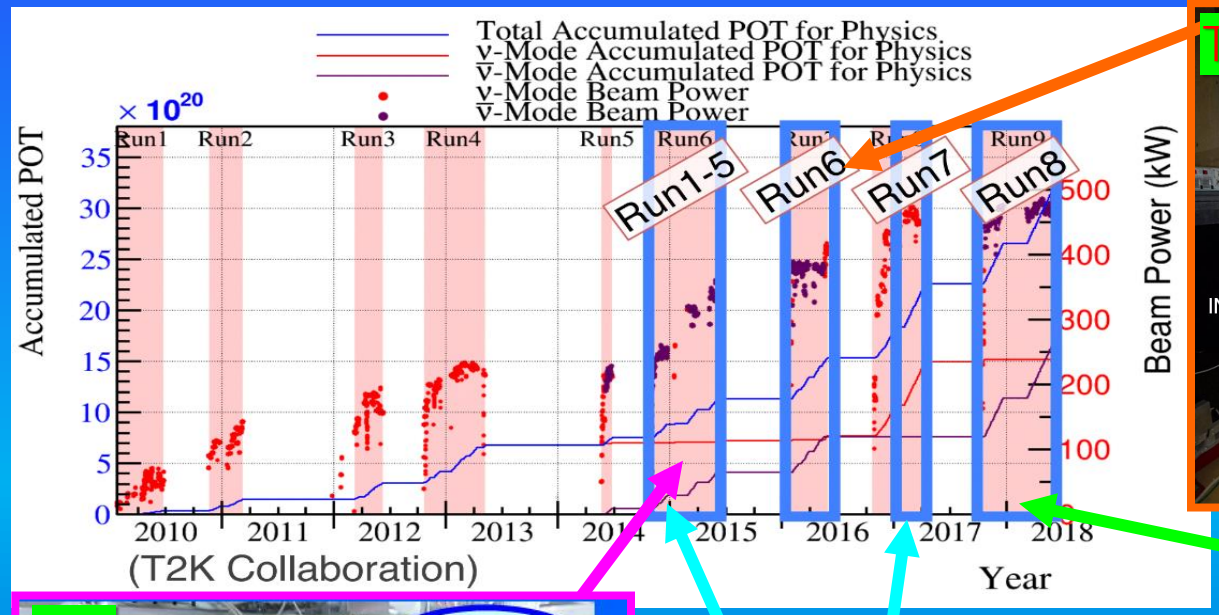
NINJA Roadmap



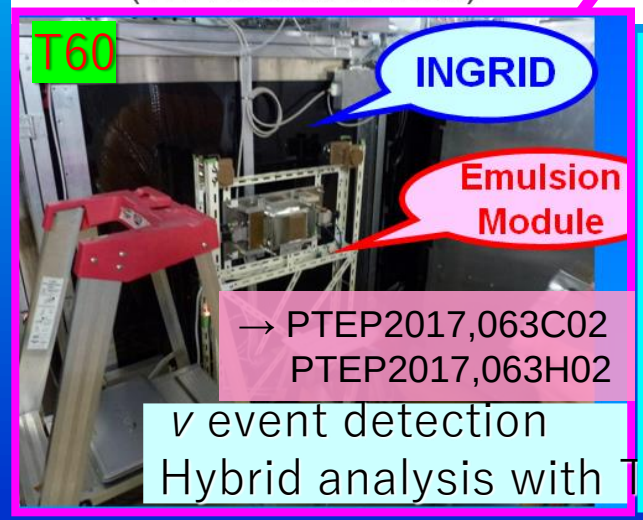
Currently, physics run is underway.

ν exposure of NINJA

Since the end of 2014, we started test experiments.

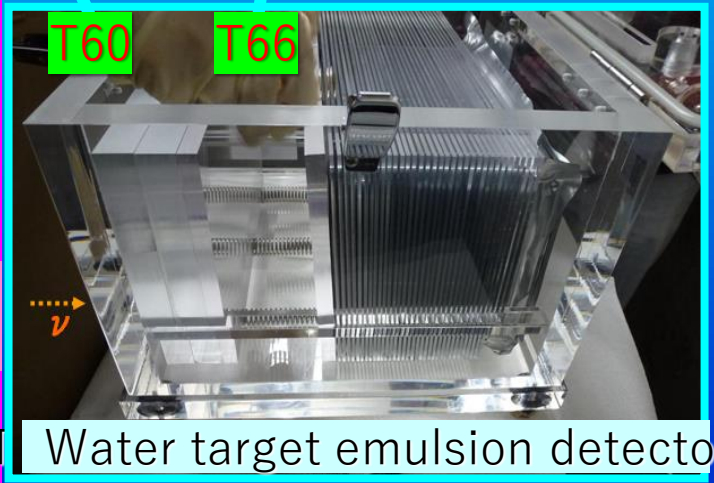


→ PTEP 2021, 033C01
PRD 106, 032016 (2022)



→ PTEP2017,063C02
PTEP2017,063H02

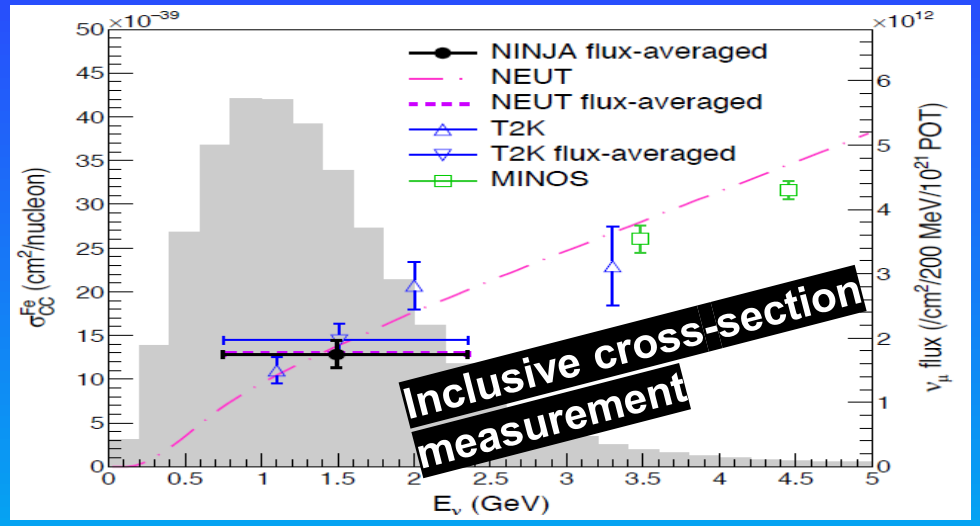
ν event detection
Hybrid analysis with T

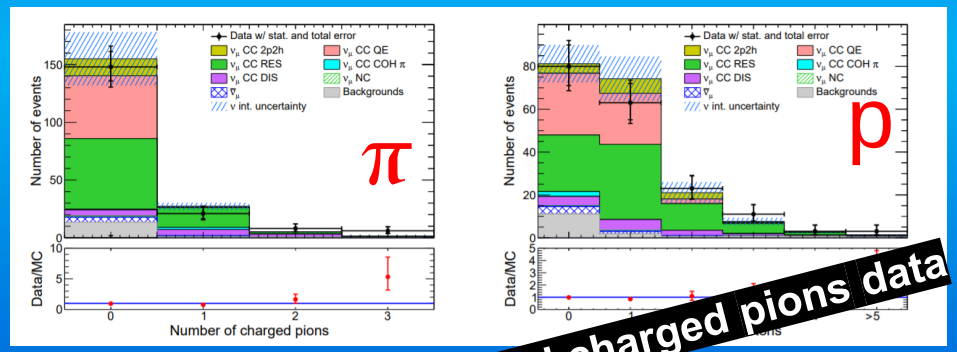


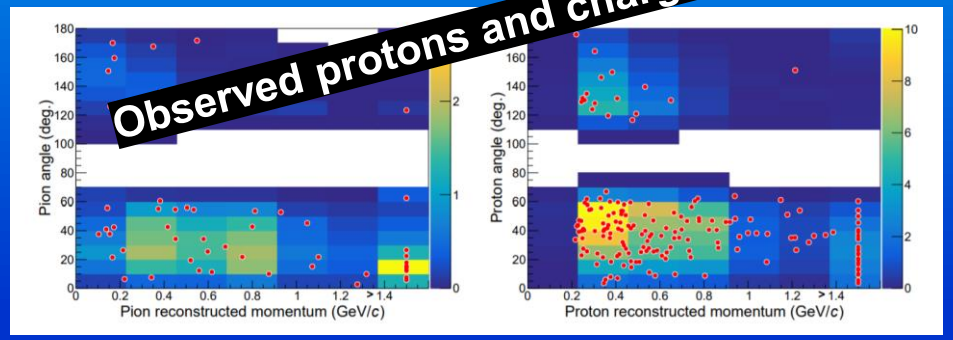
Water target emulsion detecto

→ PRD 102, 072006 (2020)

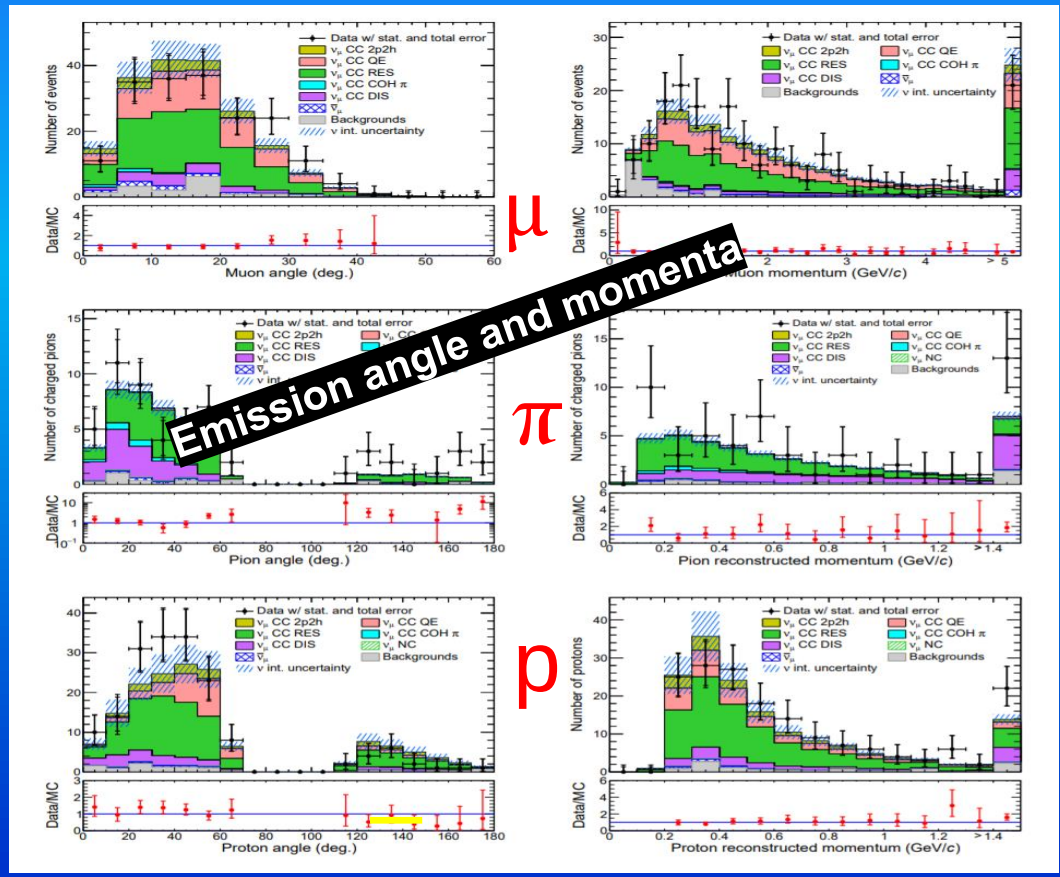
Results of Detector Run(1)







- 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)

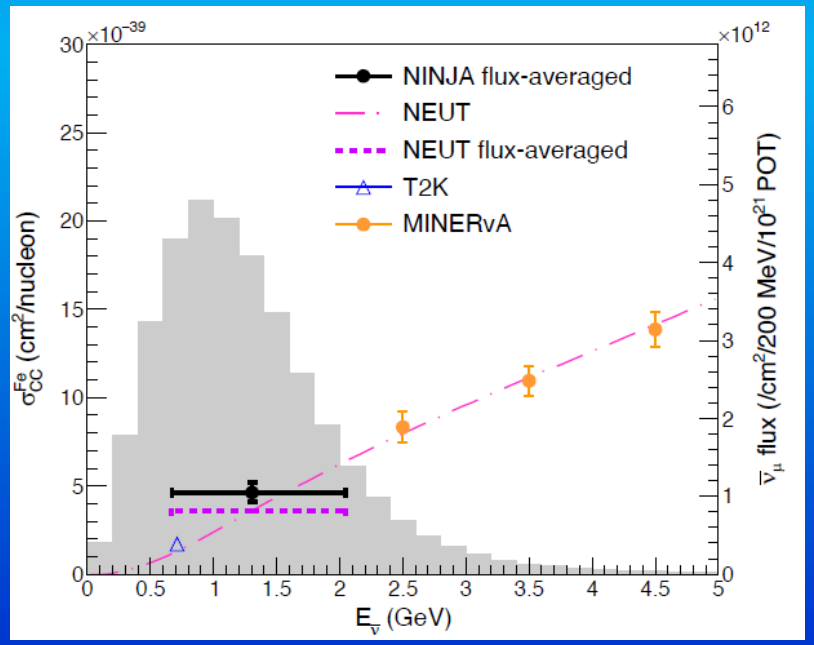
- 3.5 x 10^{20} POT @ Detector run
- Target: 65kg iron → $\overline{\nu}$-iron int.
- Momentum, emission angle and multiplicity of μ, π and p are measured for 770 CC events.

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

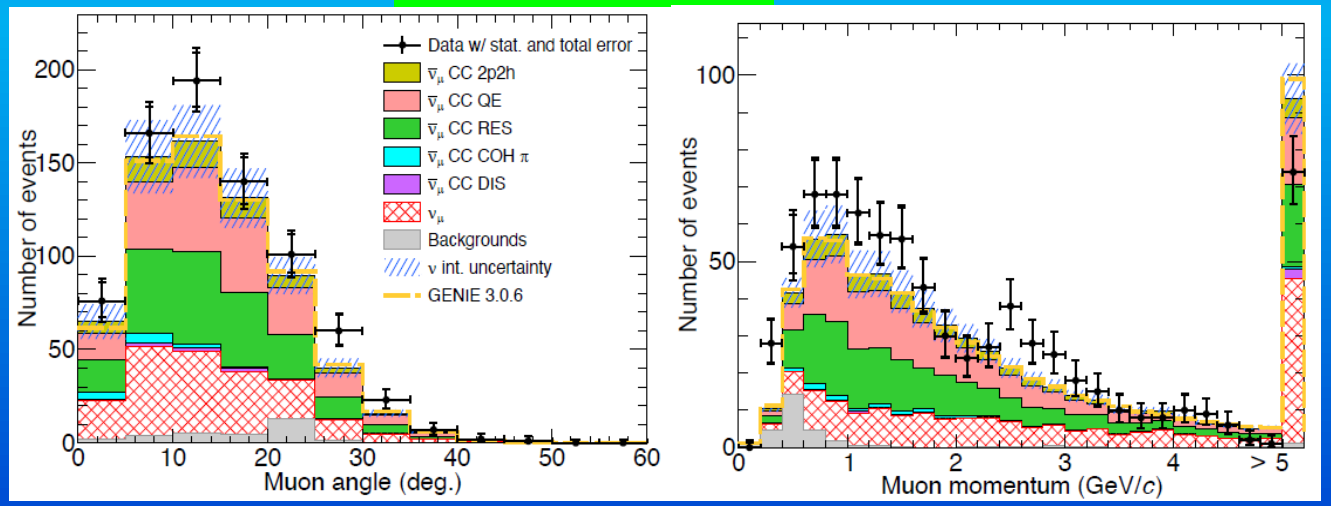
23% larger

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

Inclusive Cross-section measurement



Muon kinematics

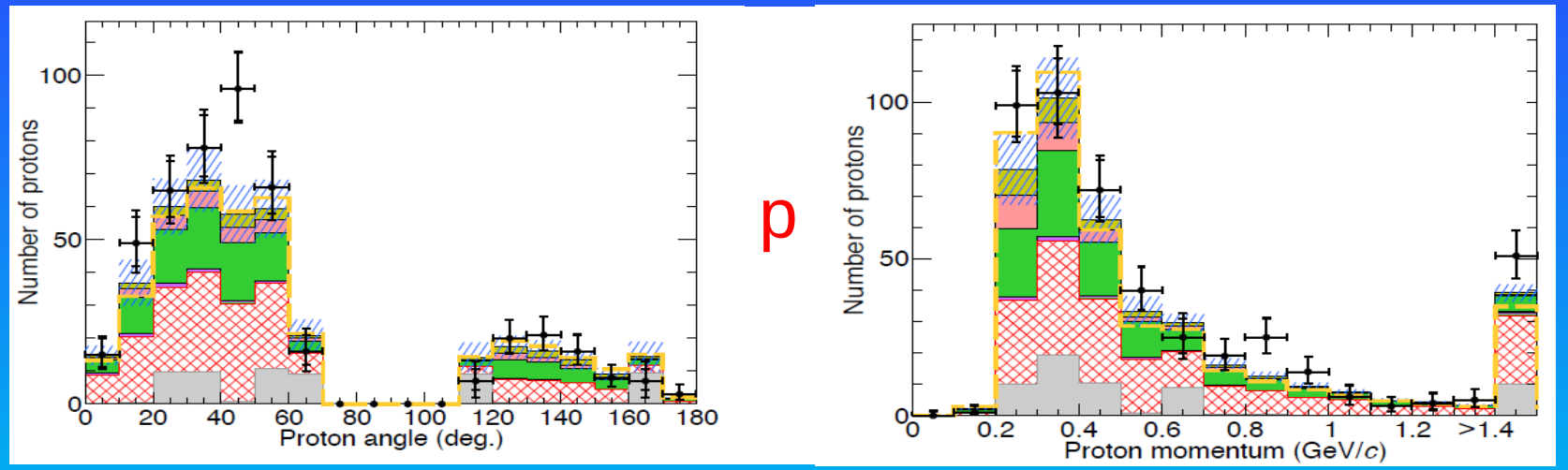


The results agree well with the MC prediction

Results of Detector Run(2)'

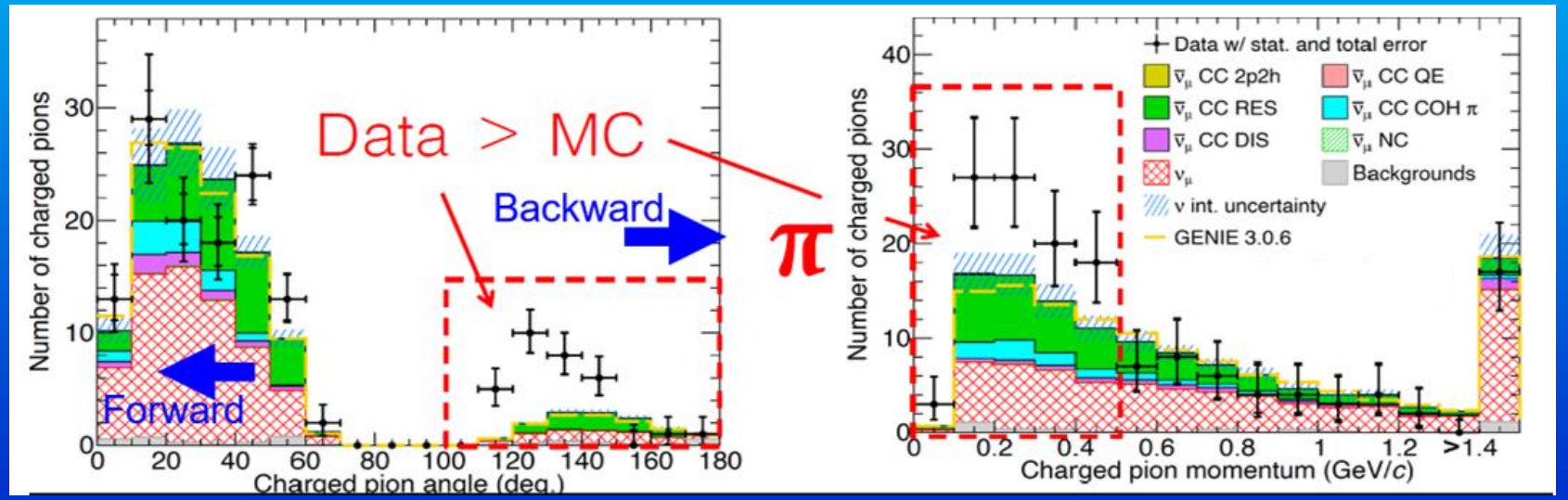
Proton kinematics

The results agree well with the MC prediction



Pion kinematics

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



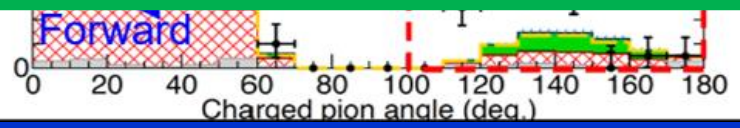
Results of Detector Run(2)′

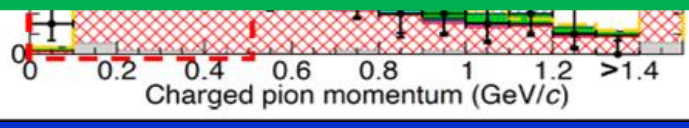
Proton kinematics The results agree well with the MC prediction

We are currently discussing what is causing this discrepancy（neutrino interaction model or generator）, in the meeting or the workshop with outside groups and theorists.

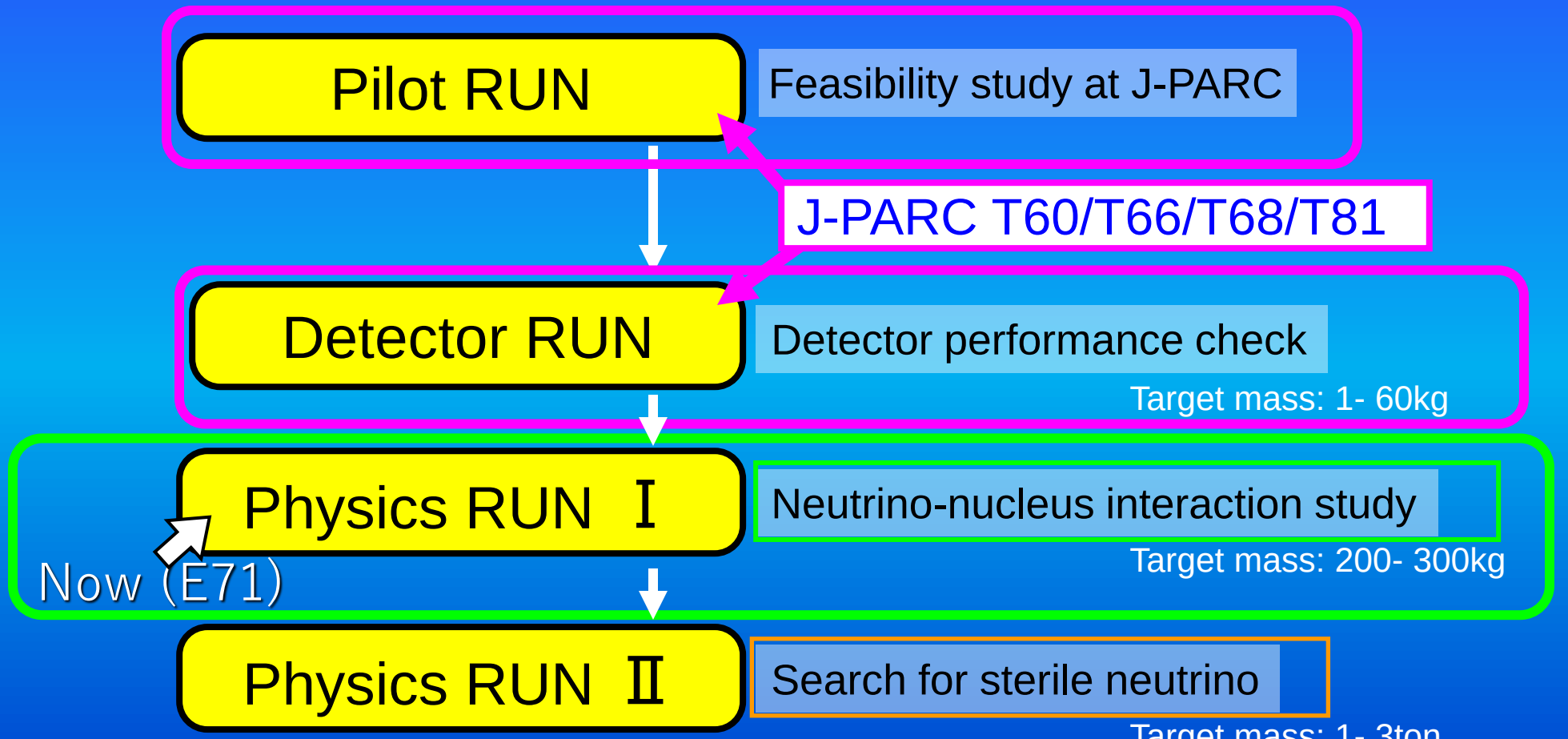
Oct. 24th	NuInt workshop	International workshop
Dec. 2nd	T2K NIWG meeting	with some experts in T2K
Dec. 22nd	NINJA mini workshop	with an invited theorist

Such new measurements of low energy hadrons will enhance our understanding of ν-nucleus interaction.





NINJA Roadmap

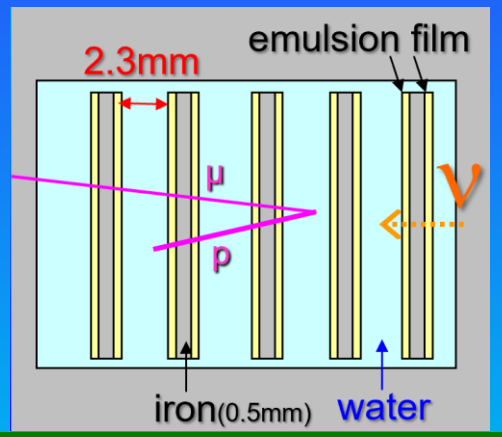


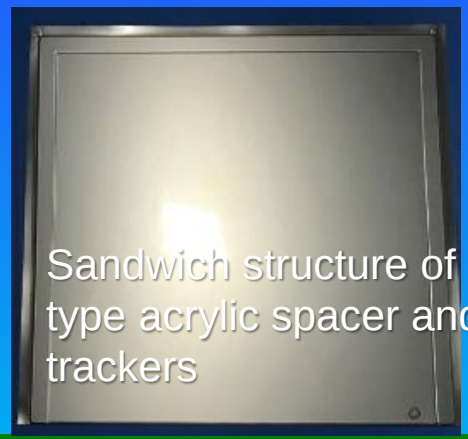
Currently, physics run is underway.

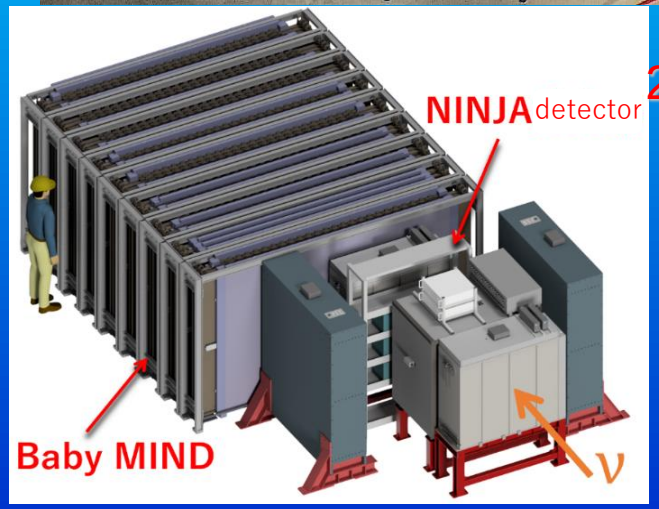
Physics Run (E71a)

- First measurement of ν-multi nucleon interactions
- Exclusive cross-section measurement of ν-water interactions

Neutrino beam:
Nov. 2019 – Feb. 2020
Total POT: 4.8 x 10^{20}







250kg Target

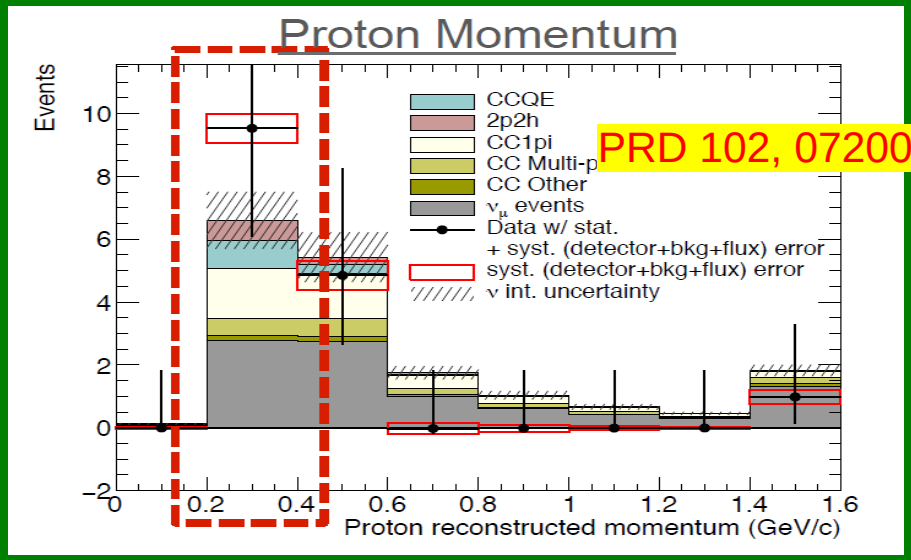
H_2O: 75kg
Fe: 130kg
CH: 15kg
em : 30kg

Film 130m^2

↓

5,000 events

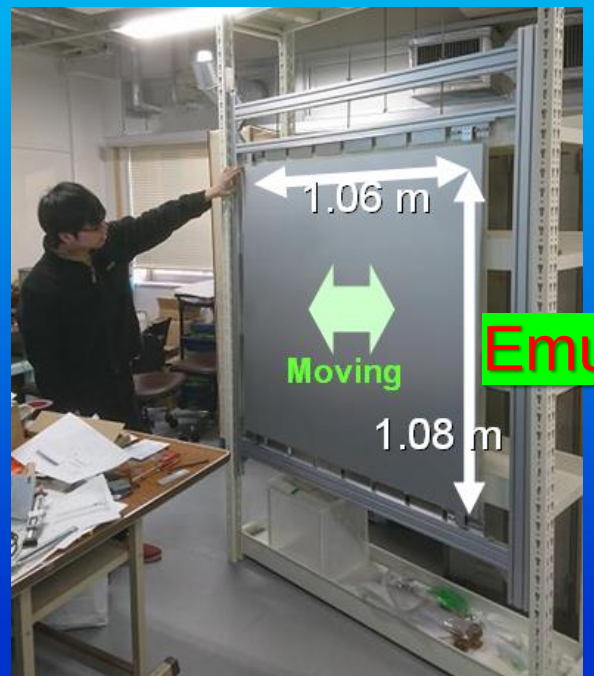
Detection of low energy protons from ν-water int. at Detector Run (T68)



PRD 102, 072006 (2020)

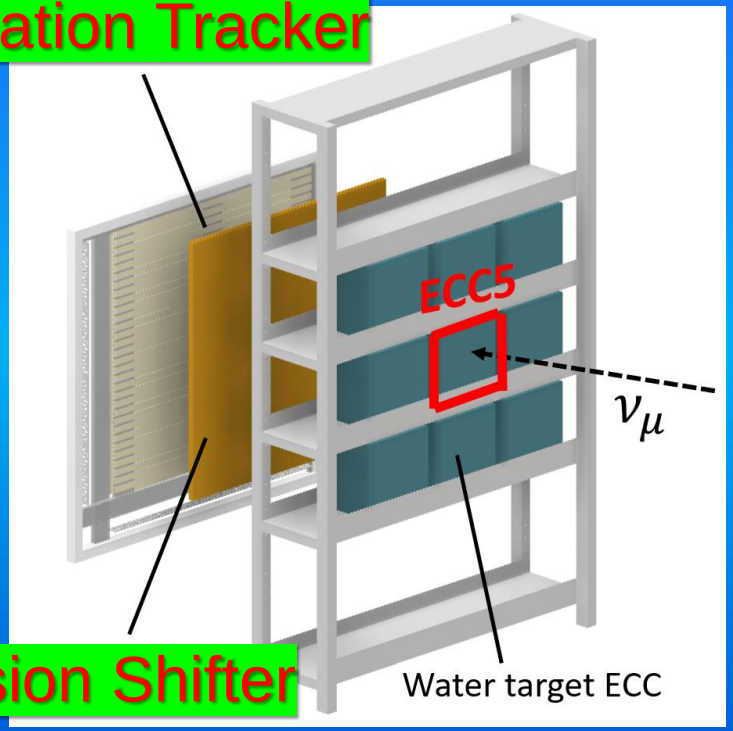
NINJA detector (E71a)

Emulsion Shifter and Scintillation Tracker give time stamps to emulsion track in ECC to identify μ with Baby MIND.



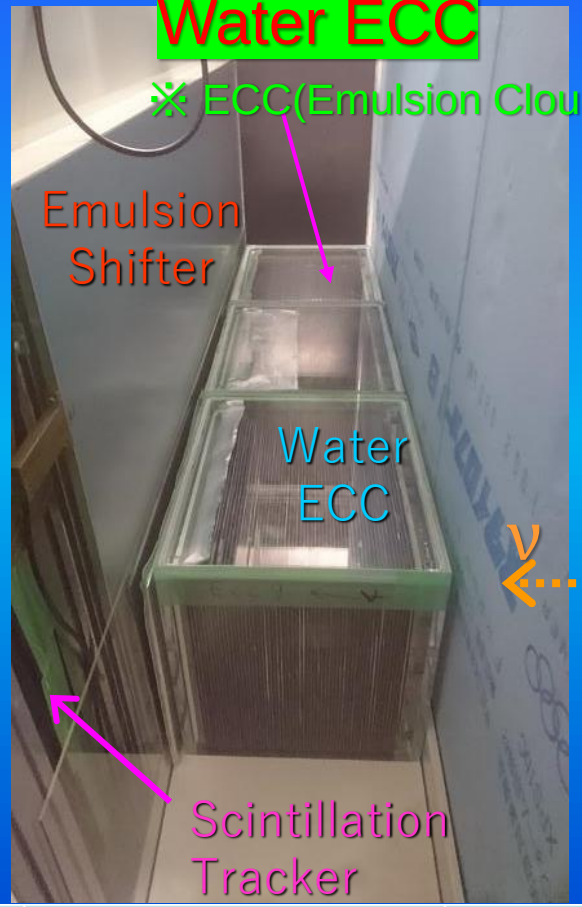
Scintillation Tracker

Emulsion Shifter



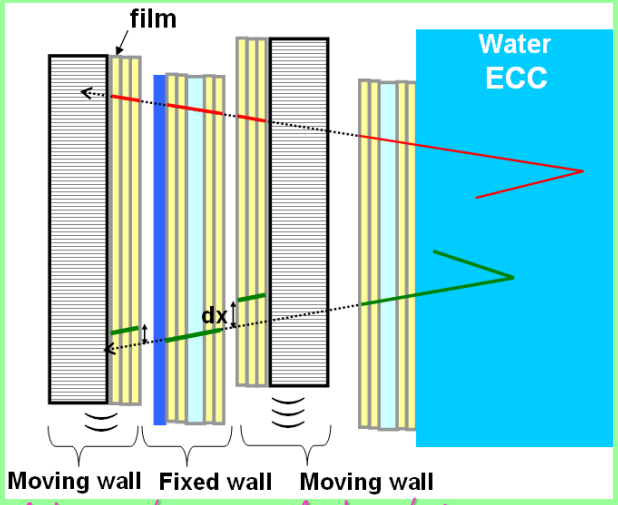
Water ECC

※ ECC(Emulsion Cloud Chamber)



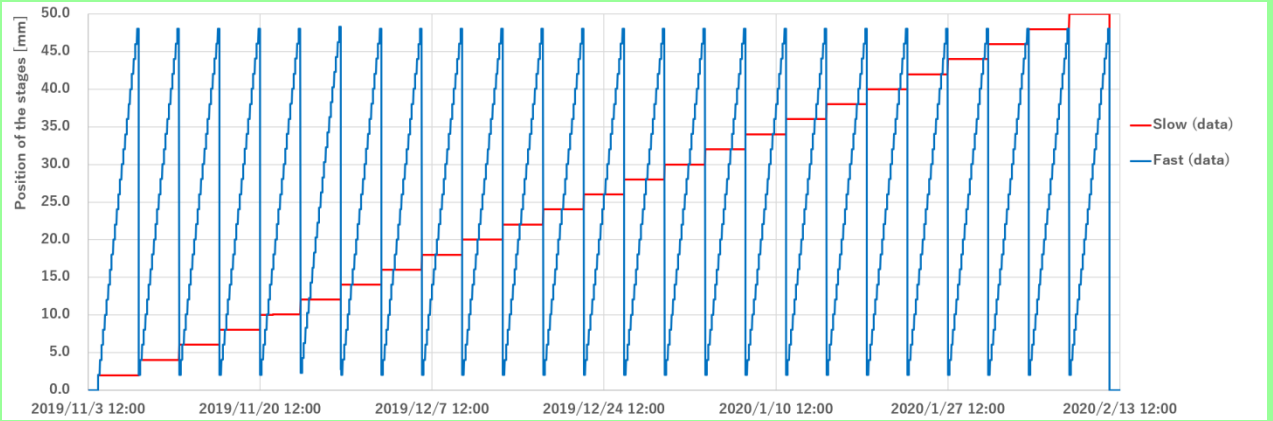
	Scintillation Tracker	Emulsion Shifter	Water ECC
Time resolution	10 nsec level	4 hour	--- (100 day)
Position resolution	2.1 mm	1 μm level	1 μm level

Emulsion Shifter

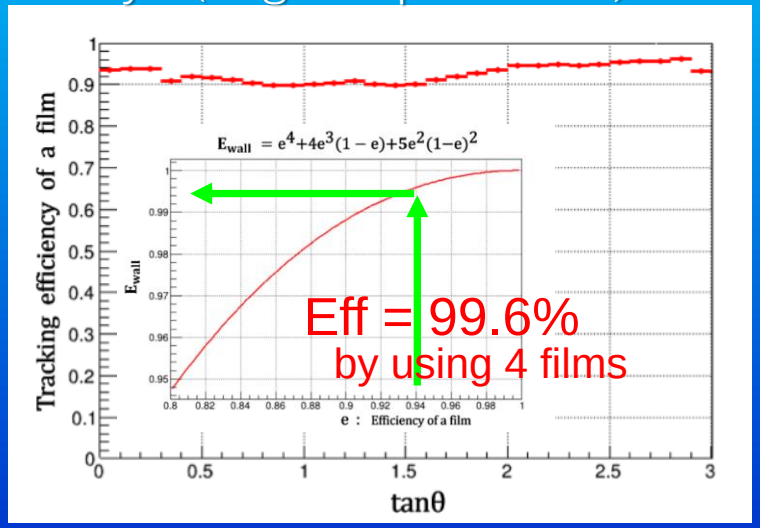


4 hour/step 4 day/step

Operation of the Emulsion Shifter → Stable

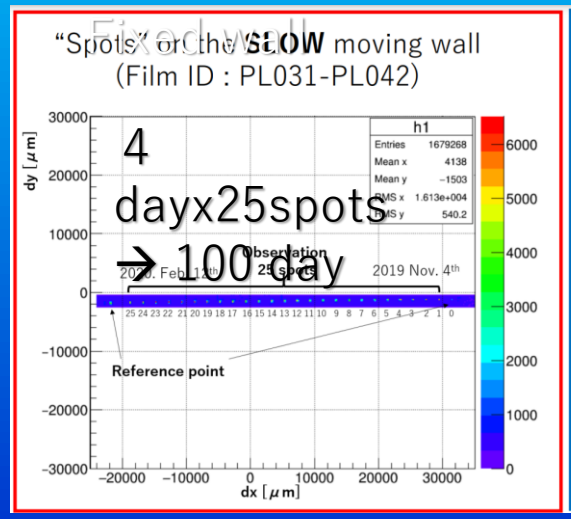


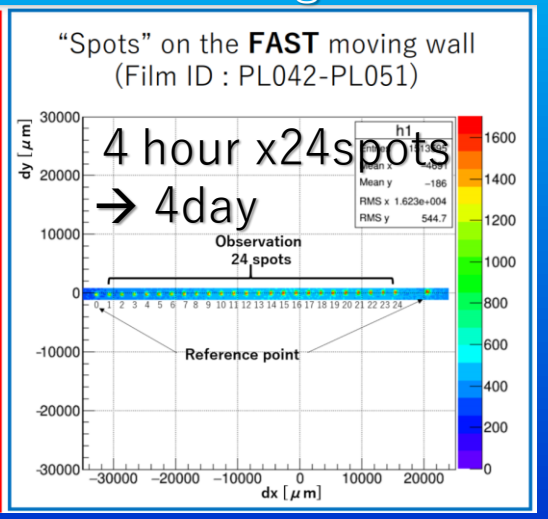
Tracking efficiency (angle dependence) for one film



4 films are used for a wall of emulsion shifter

Position difference between Moving wall and Fixed wall

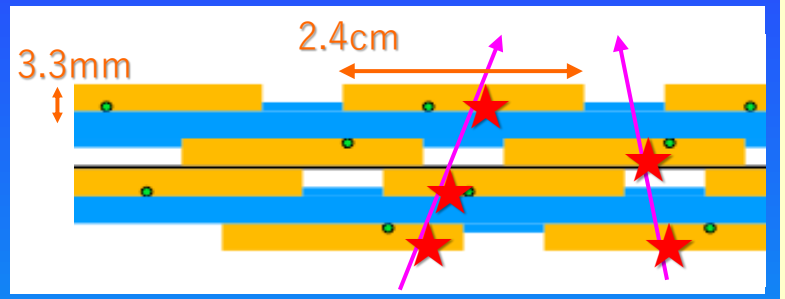


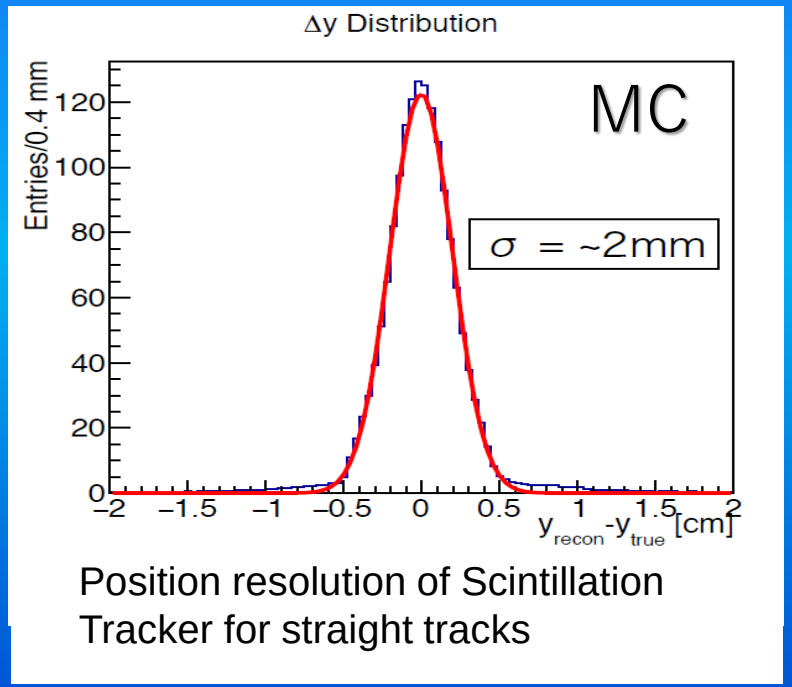


Each spot corresponds to the time information.

Scintillation Tracker

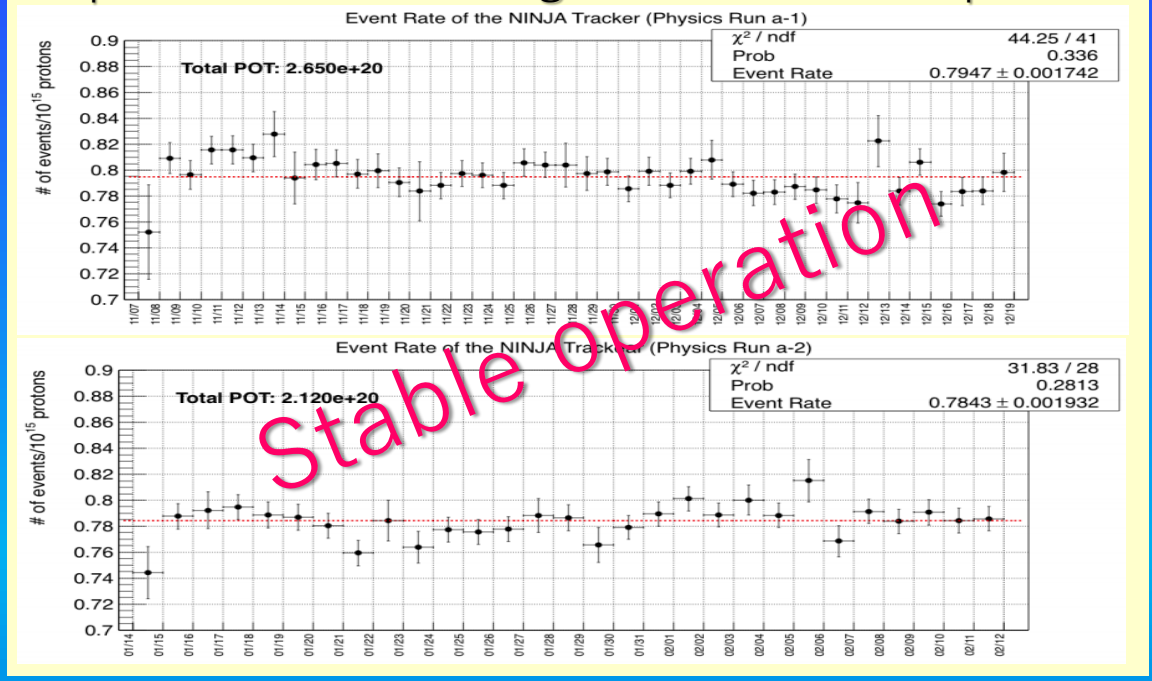
Structure of Scintillation Tracker



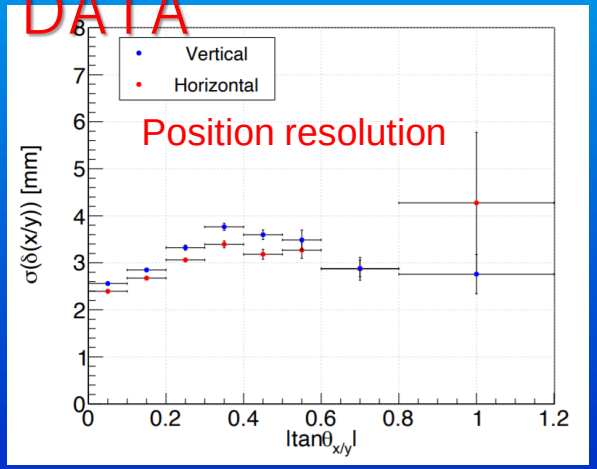


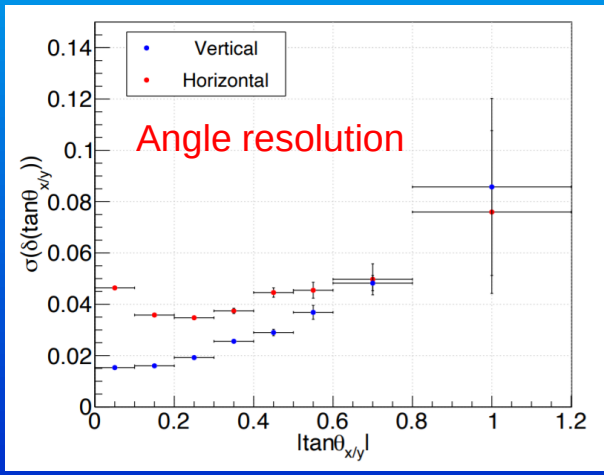
Position resolution of Scintillation Tracker for straight tracks

Operation result during neutrino beam exposure



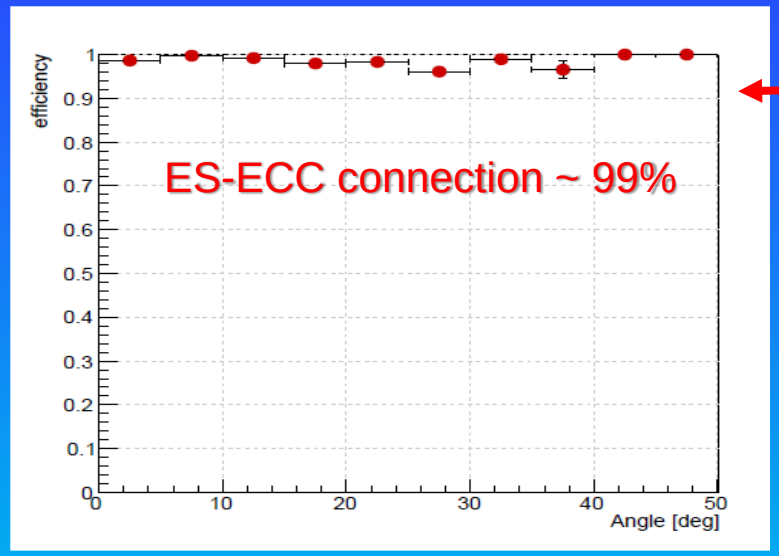
DATA

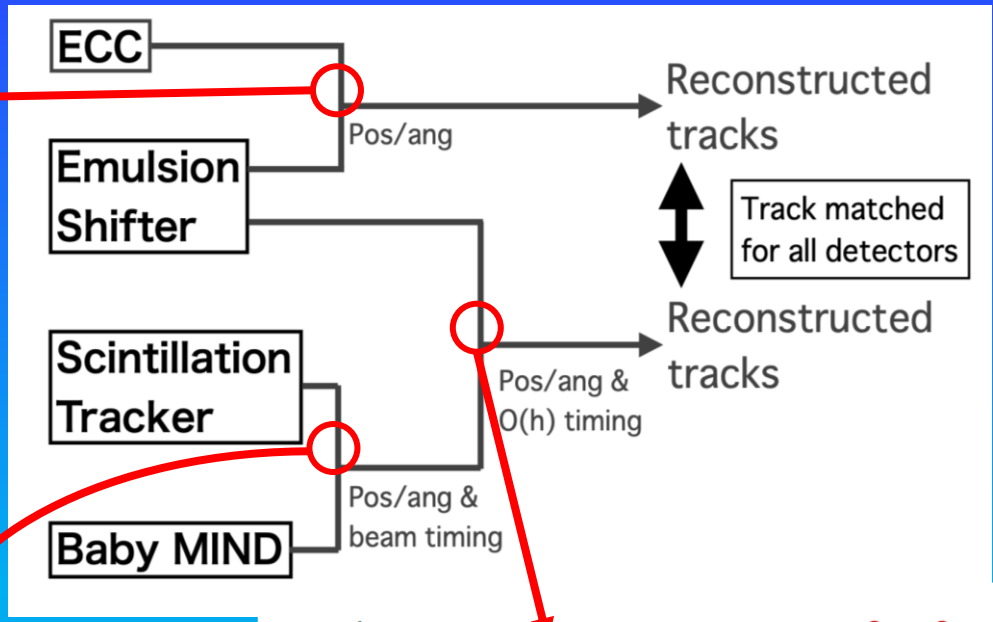


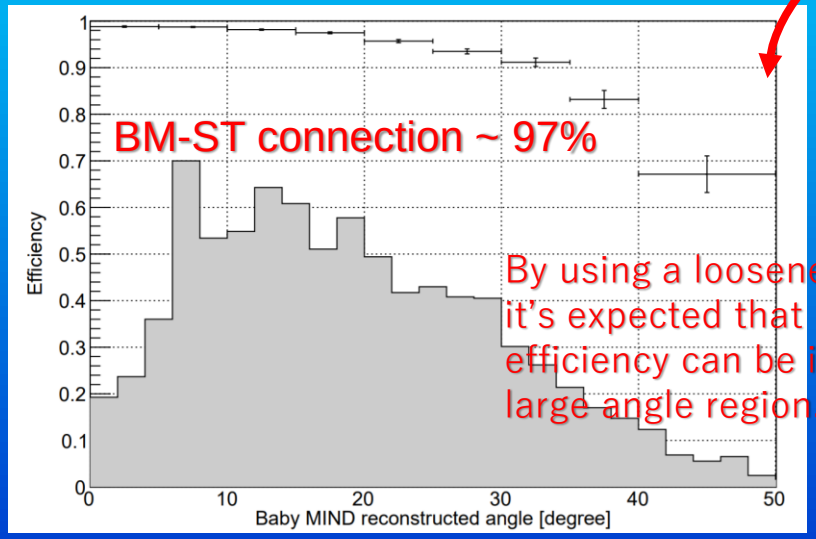


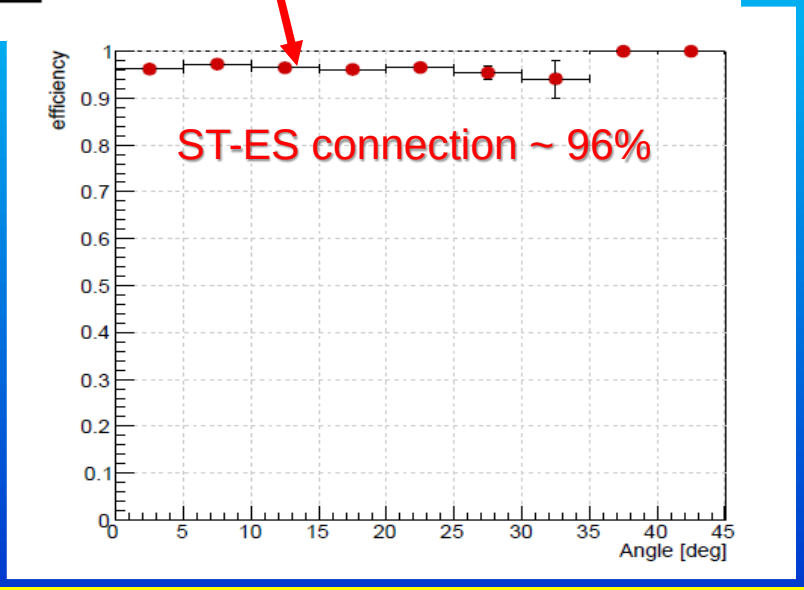
The performance (position and angle resolution) of the Scintillation Tracker was as expected.

Track connection btw ECC and BM



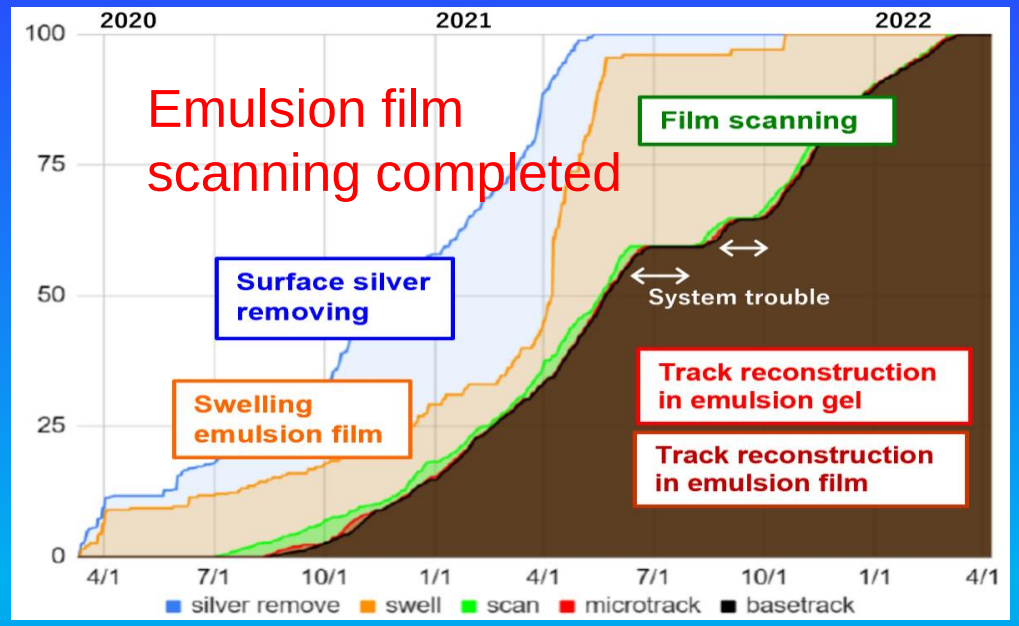




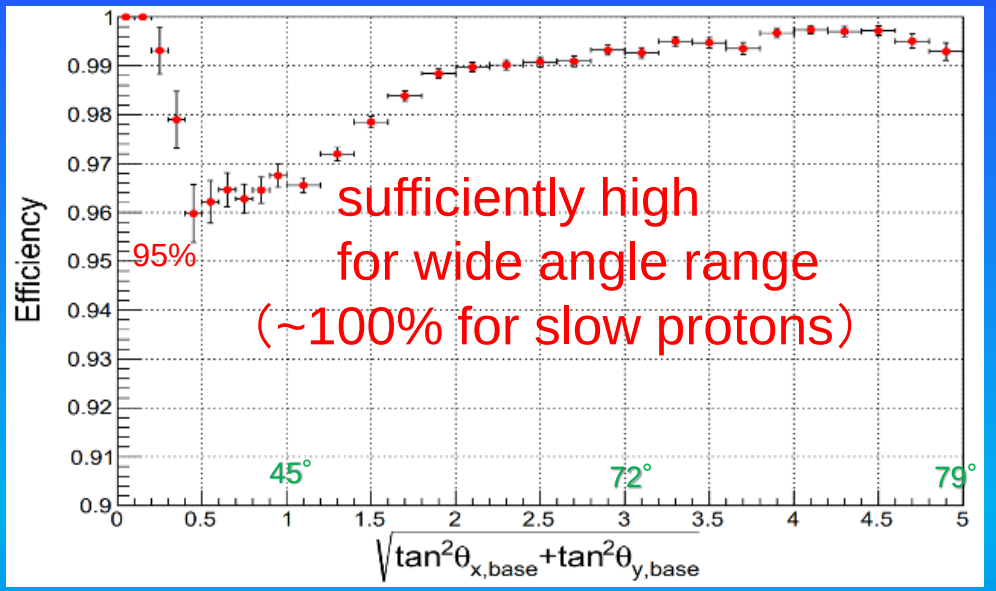


High detection and connection efficiencies have been achieved at each process.

Emulsion scanning and analysis

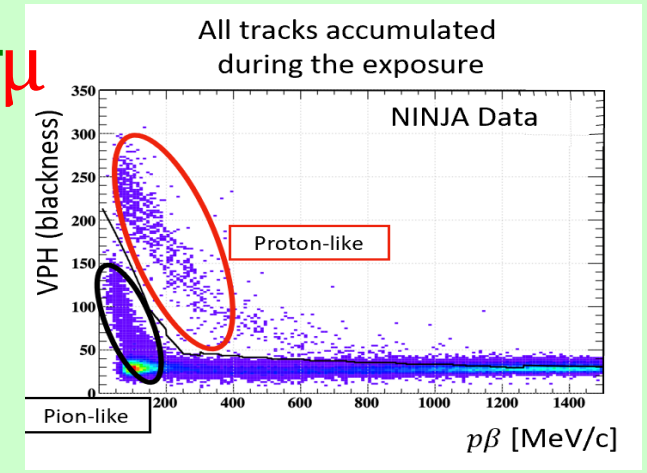


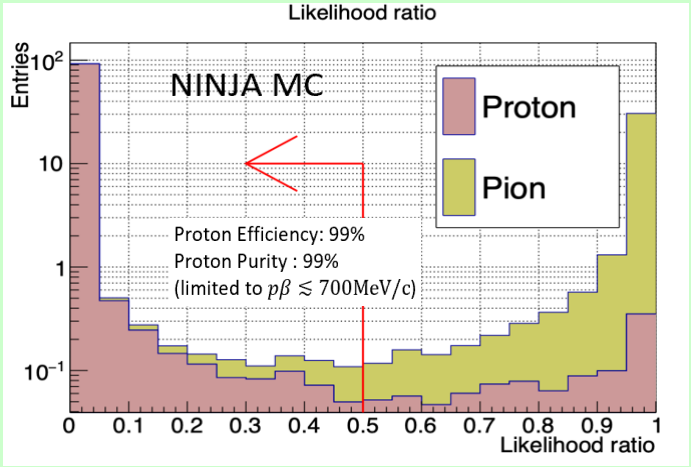
Tracking efficiency for MIP

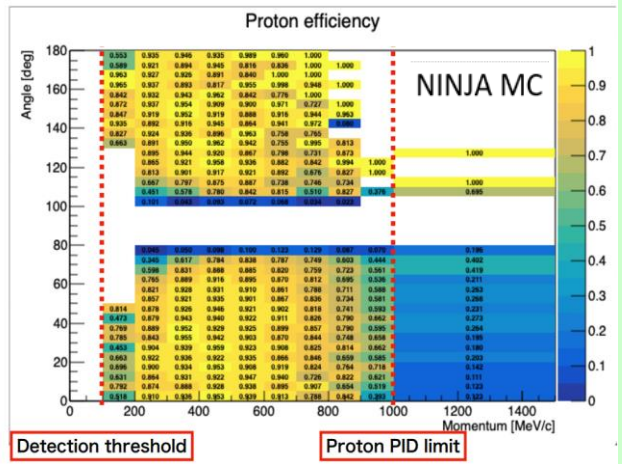


Particle identification

$p/\pi\mu$



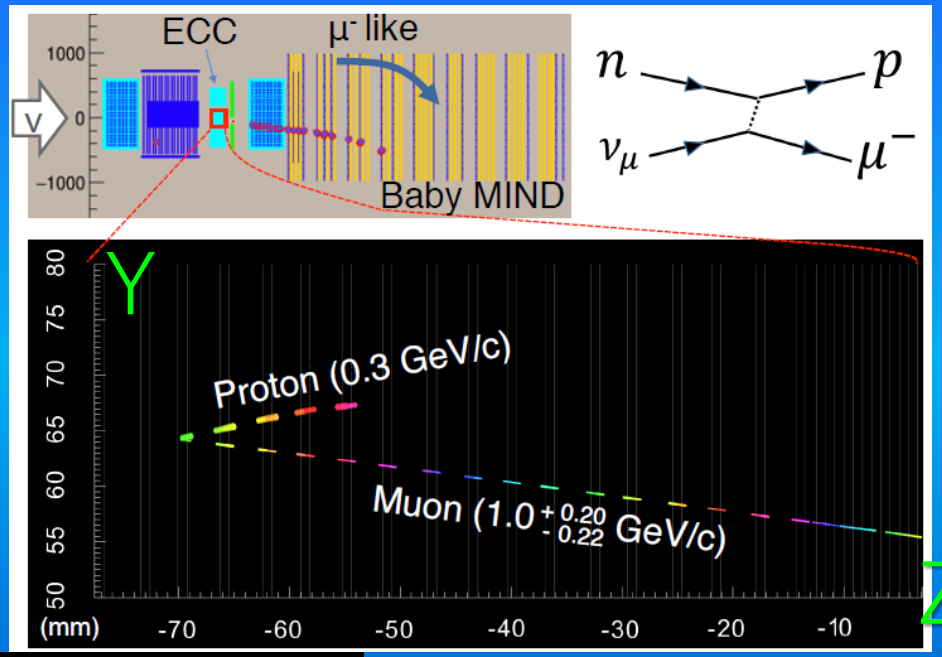




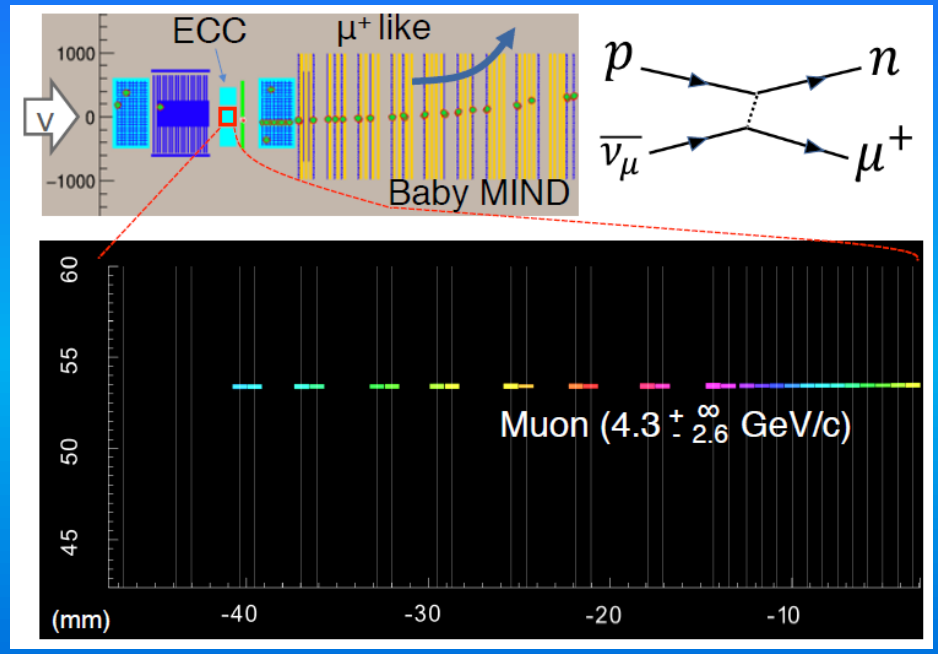
Detected neutrino events

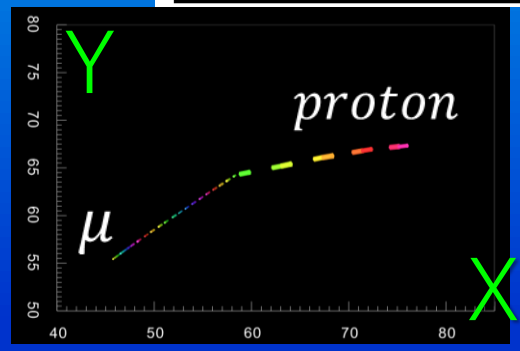
ECC – Emulsion Shifter – Scintillation Tracker – Baby MIND worked well and succeeded in μ ID and measuring their charge.

Typical Neutrino CC event



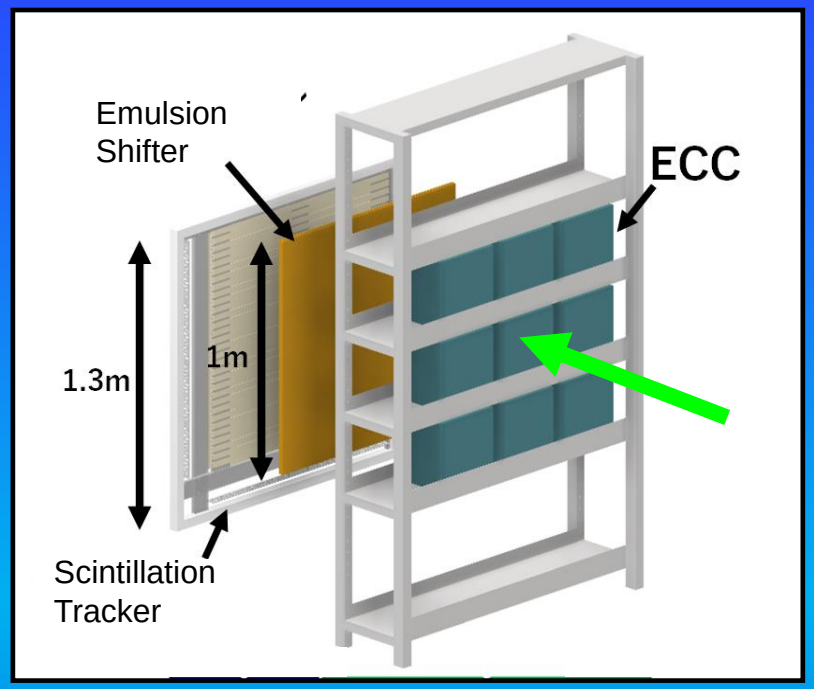
Typical Anti neutrino CC event



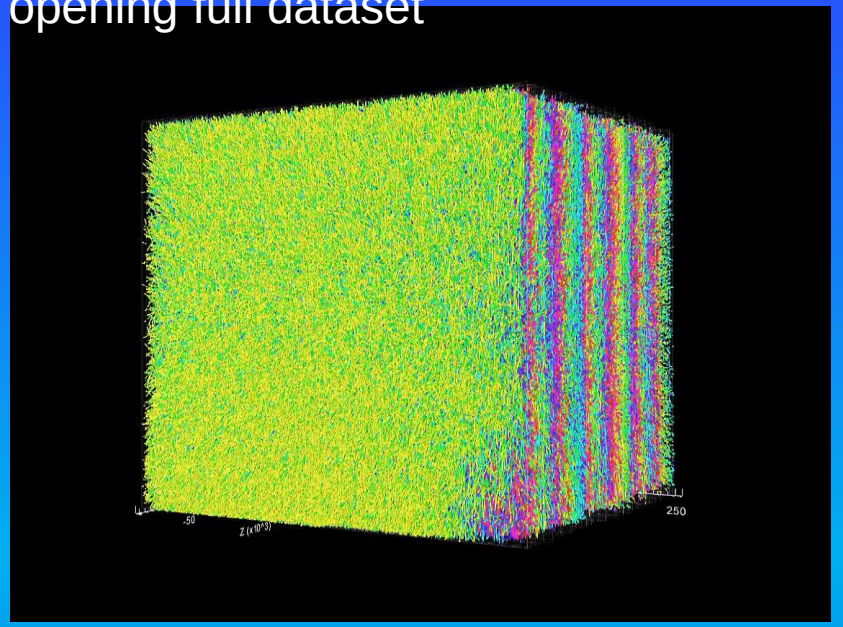


- The event pictures (number of protons) in ECC and the μ charge measured by Baby MIND are consistent.
- To finalized data set, we are checking the muon connections and analysis in ECC, event by event carefully.

Analysis status



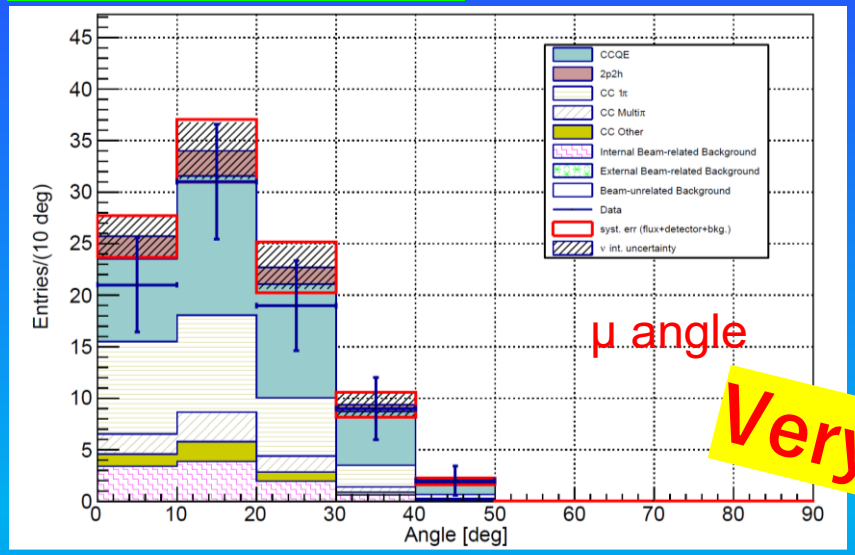
Performance check by sub-data set (the central ECC) before opening full dataset



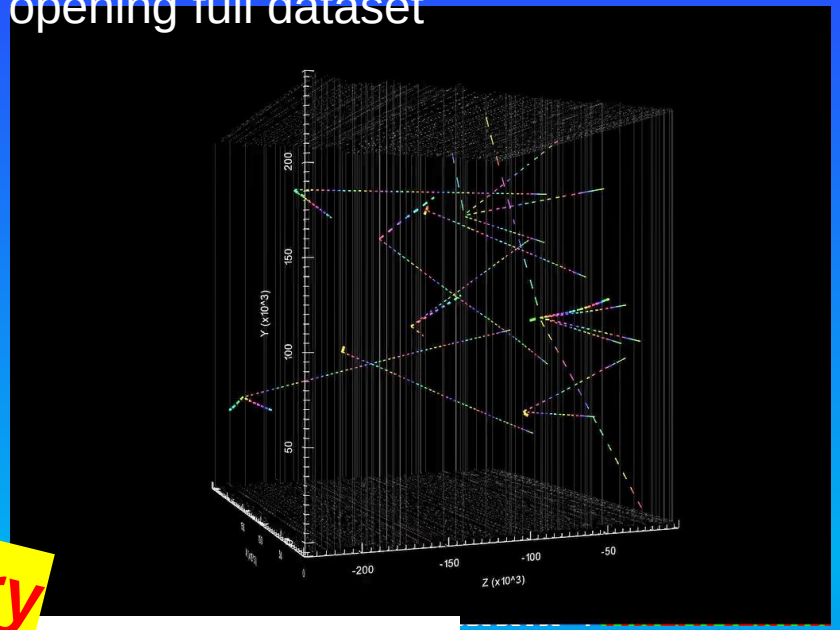
Analysis status

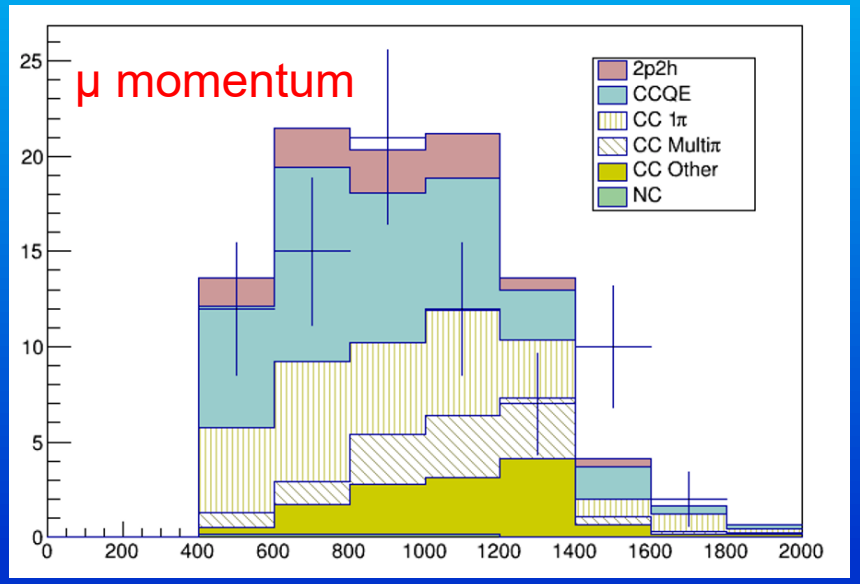
Detected muons and protons in ν-water int. at ~10% sub-sample

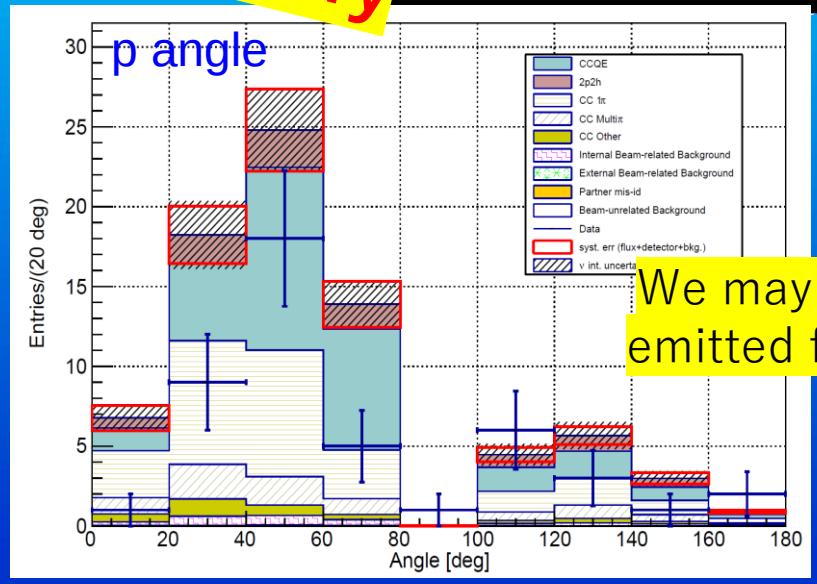
Performance check by sub-data set (the central ECC) before opening full dataset



Very Preliminary







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

→ Open full dataset near future!

Future prospect ①：E71b

Next Physics Run

Requested POT	10 x 10^{20}
E71a	4.8 x 10^{20}
E71b	5.2 x 10^{20}

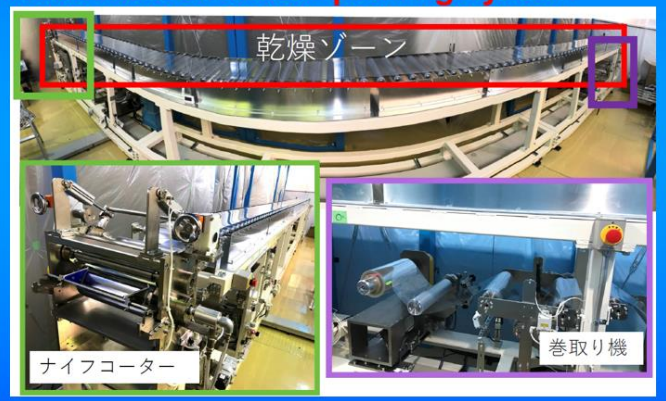
Exposure done → analysis ongoing

Plan to be implemented after fall 2023.

Preparation is ongoing.

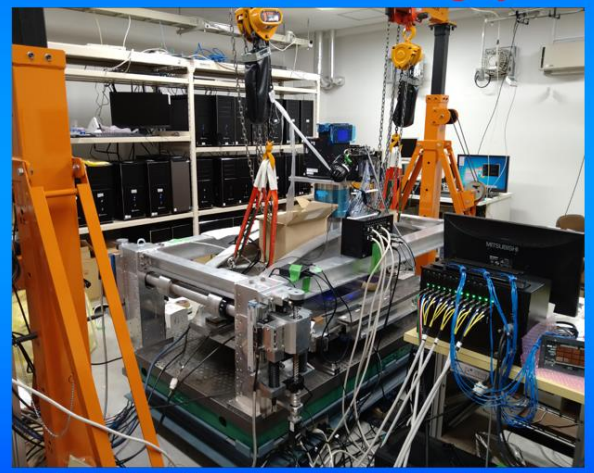
We have developed an automatic emulsion pouring system and a new higher speed emulsion scanning system in Nagoya U.

Automatic emulsion pouring system



x10 faster than hand made

New automatic emulsion scanning system

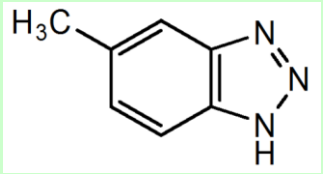


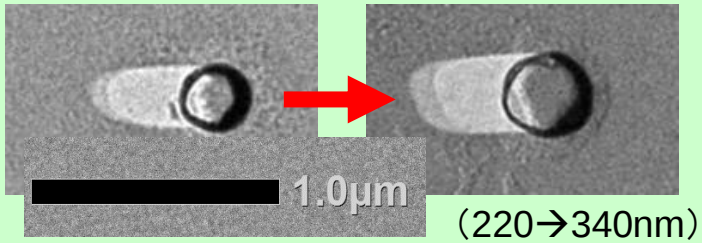
x5 faster than current system

Large scale of emulsion facilities allows us to conduct the high statistics experiment.

New emulsion film

Refreshable Large size AgBr crystal Nuclear Emulsion





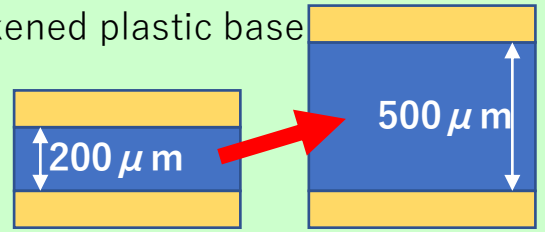
(220→340nm)

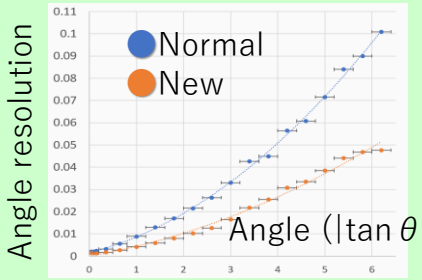
Refreshable
→ erasing accumulated noise track before beam exposure

Large size crystal
→ optimized for new high speed scanning system

Thicker base Emulsion film → Improve angle resolution

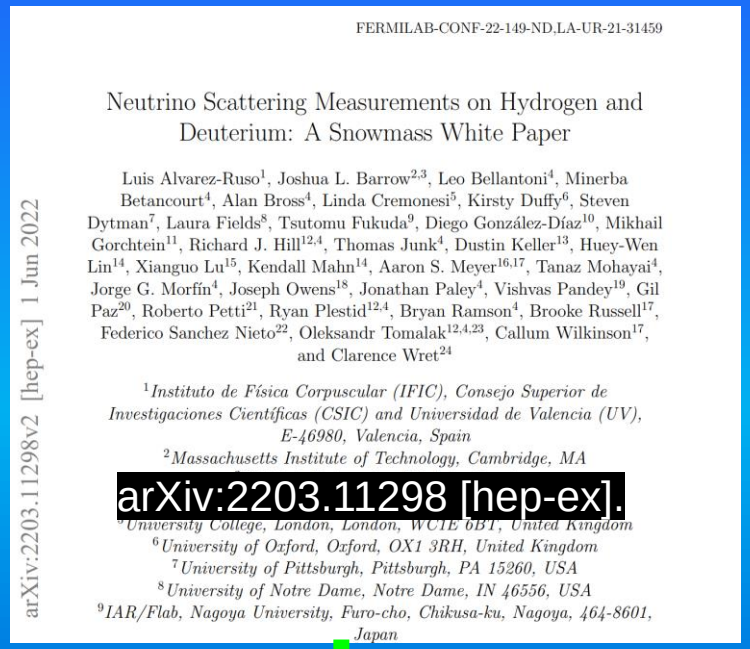
Thickened plastic base





Future prospect ② : 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*
[5]*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*

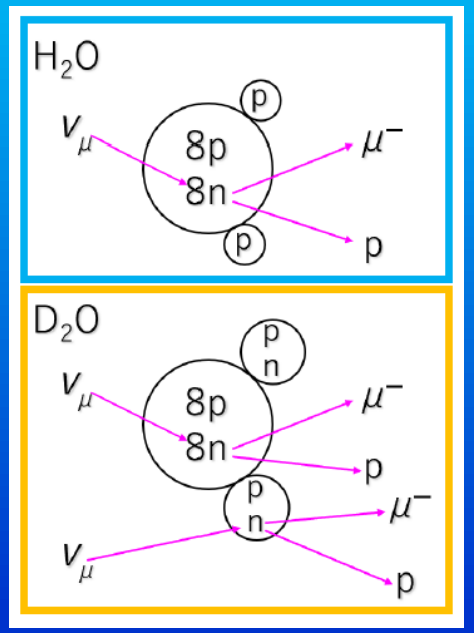
arXiv:2203.11298v2 [hep-ex] 1 Jun 2022

arXiv:2203.11298 [hep-ex].

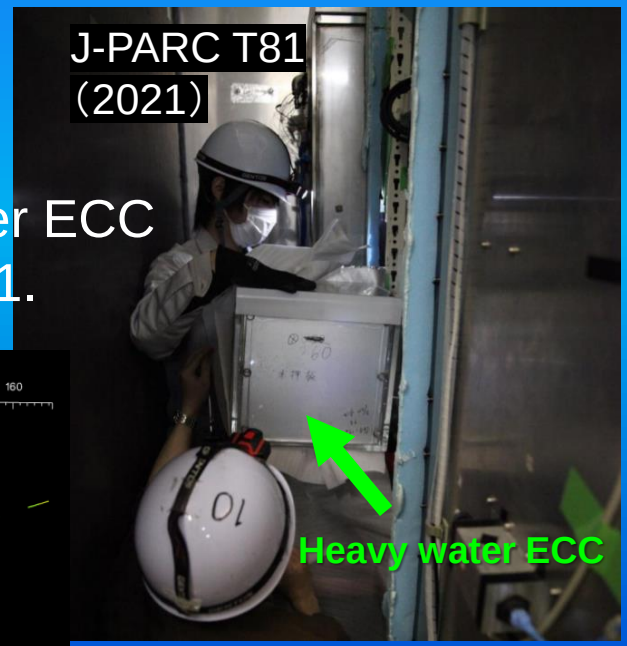
Development of a bubble chamber is being considered in US.

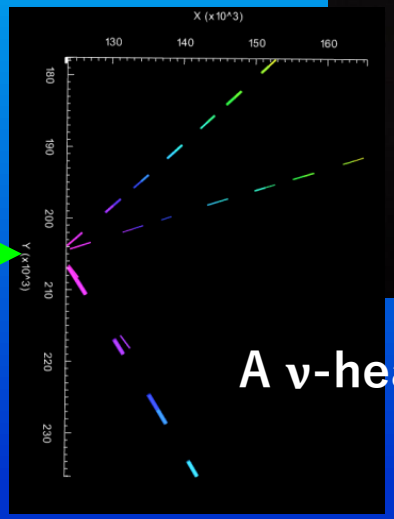
In NINJA, by introducing a heavy water target, we are developing a method to study ν-nucleon interactions by analyzing the subtraction between a heavy water events and a water events.

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



Actually, heavy water ECC was produced in T81.





A ν-heavy water interaction

Snowmass2021 process at US

DPF Community Planning Exercise

Search

- Welcome page
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Organization

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- Frontier Conveners
- APS DPF Snowmass page
- Snowmass Early Career

Snowmass Frontiers

- Energy Frontier
- Neutrino Physics Frontier

Trace: • **start**

Welcome to Snow

The Snowmass Community Plann
COVID-19 pandemic, resumed ful
Community Summer Study Work
https://snowmass21.org/annou
individual frontiers can be found
the activity by signing up to the re
menu if you haven't already done

The Particle Physics Community P
of Particles and Fields (DPF) of the
provides an opportunity for the e
document a scientific vision for th
partners. Snowmass will define th
identify promising opportunities
Snowmass here "How to Snow
Prioritization Panel, will take the s

Snowmass Neutrino Frontier: Neutrino Interaction Cross Sections (NF06) Topical Group Report

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

arXiv:2209.06872v1 [hep-ex]

NINJA

Summary

- Precise measurement of neutrino-water interactions is important for future neutrino oscillation analysis (especially, CC2p2h and ν_eCC) and proton information is key to improving the neutrino-nucleus interaction model.
- NINJA has introduced nuclear emulsion to study low-energy neutrino interactions for this purpose.
- The results of neutrino and anti neutrino-iron interactions were reported. We found a discrepancy between data and MC in backward pion production.
- The analysis of the physics run (E71a) is ongoing and we will open the full data set, corresponding to 4.8×10^{20} POT near future.
- The next physics run (E71b) is scheduled in JFY2023.
- A new experiment using heavy water ECC is being considered.

New data is being released one after another! We welcome you to join NINJA!

Back up