NINJA

Neutrino cross-section measurements in the NINJA Experiment

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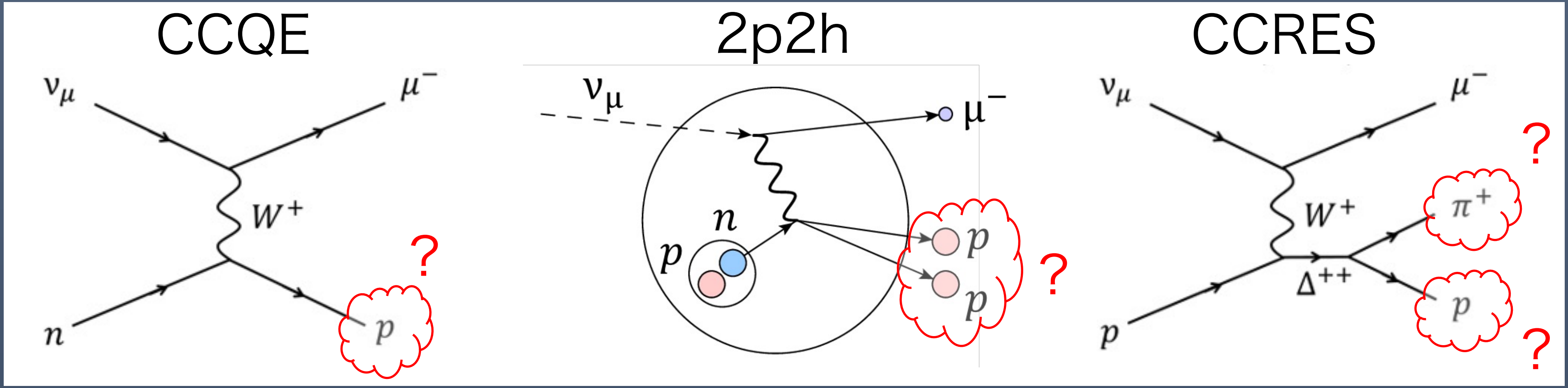
Introduction : Neutrino – Nucleus interactions

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



➡ It is hard to separate each interaction mode because the FSIs generate or hide the particles.

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

NINJA Experiment

Country: Japan · Croatia · the UK (13 Institutes, ~50 researchers)

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

→ Various targets (H_2O, D_2O, Fe, C, etc.)

→ Low momentum thresholds ~ 200 (50) MeV/c for protons (pions)

NINJA Run

A) 2kg iron target run @ SS (2015, $\bar{\nu}$: 1.38×10^{20} POT)

B-1) 65kg iron target run @ SS (2016, ν : 0.4×10^{20} POT, $\bar{\nu}$: 3.5×10^{20} POT)

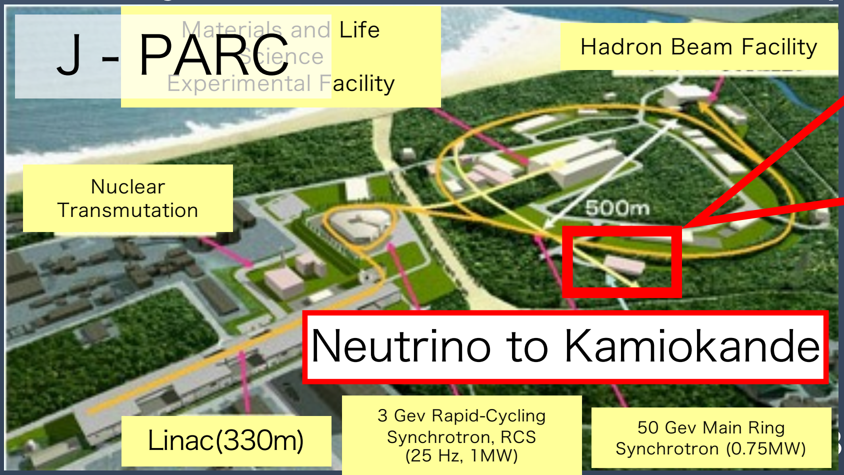
B-2) 3kg water target run @ SS (2017-2018, $\bar{\nu}$: 7.0×10^{20} POT)

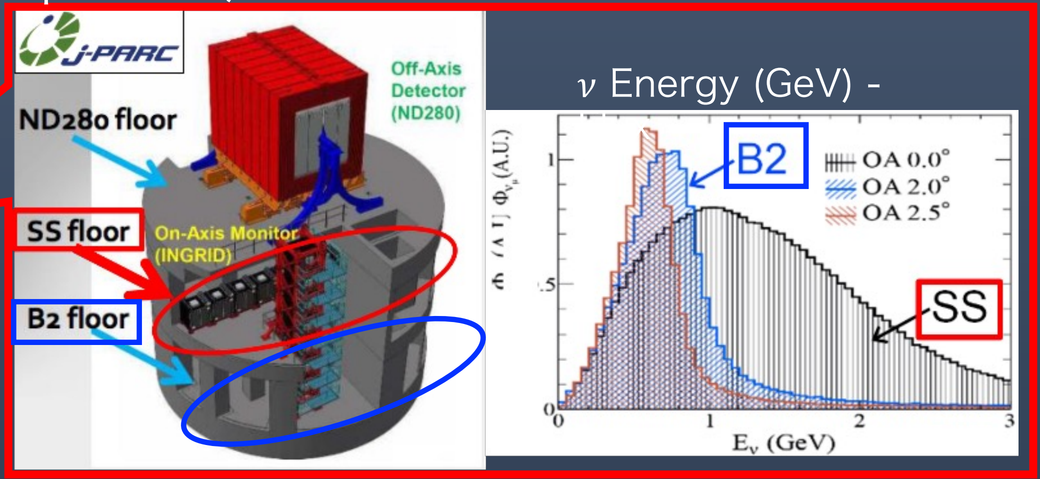
B-3) 9kg heavy water target run @ B2 (2021, ν : 1.8×10^{20} POT)

C) Physics run E71-a @ B2 (2019-2020, ν : 4.8×10^{20} POT)

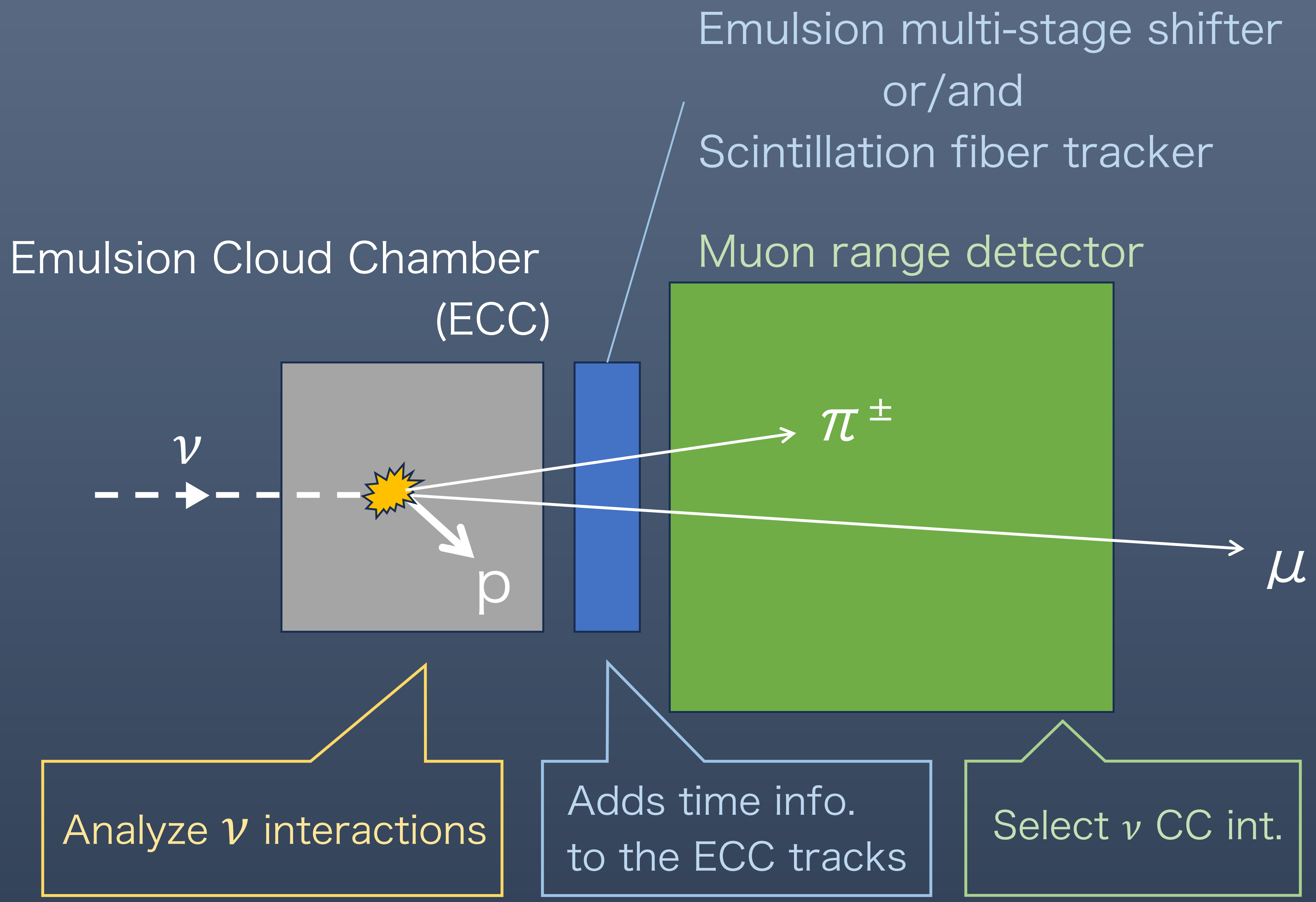
(75kg H_2O, 130kg Fe, and 15kg CH targets)

Physics run E71-b @ B2 (Under preparation)





NINJA Experiment : Detector concept



Emulsion multi-stage shifter
or/and
Scintillation fiber tracker

Muon range detector

Emulsion Cloud Chamber
(ECC)

Analyze ν interactions

Adds time info.
to the ECC tracks

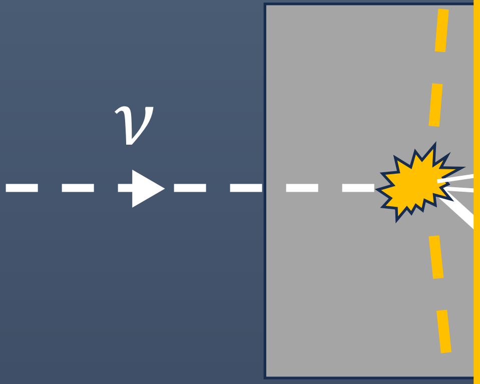
Select ν CC int.

NINJA Experiment : Detector concept

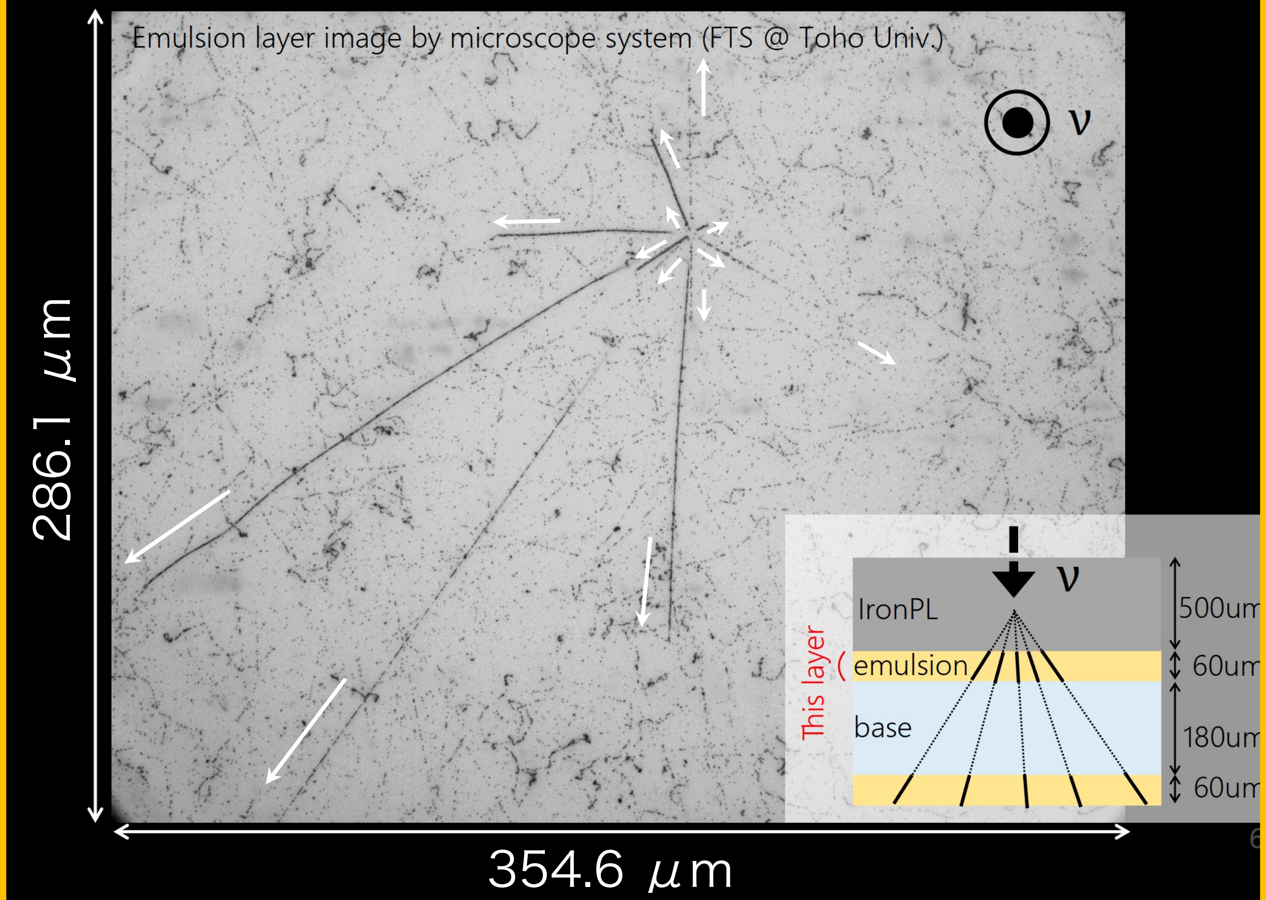
Emulsion multi-stage shifter

or/and

Emulsion Cloud Cha



An example of ν – iron interaction (NINJA iron target run in 2016)



Analyze ν interactions

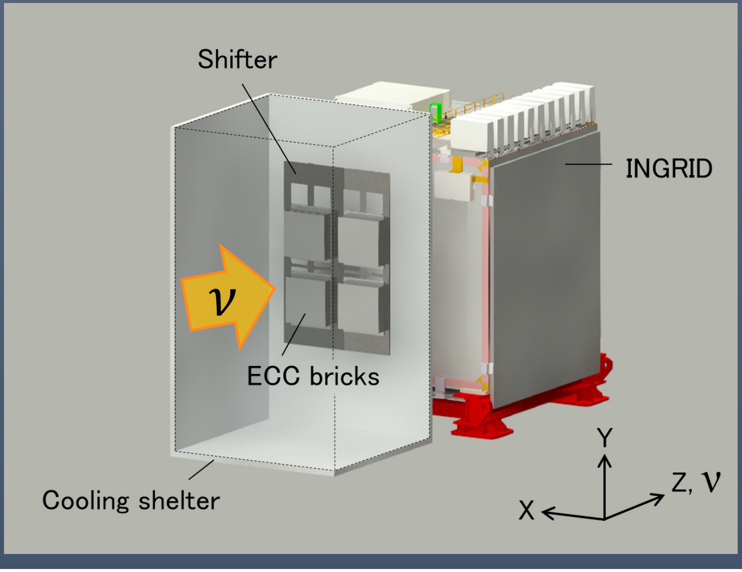
to the ECC tracks

Select ν CC int.

NINJA Pilot runs：Detector

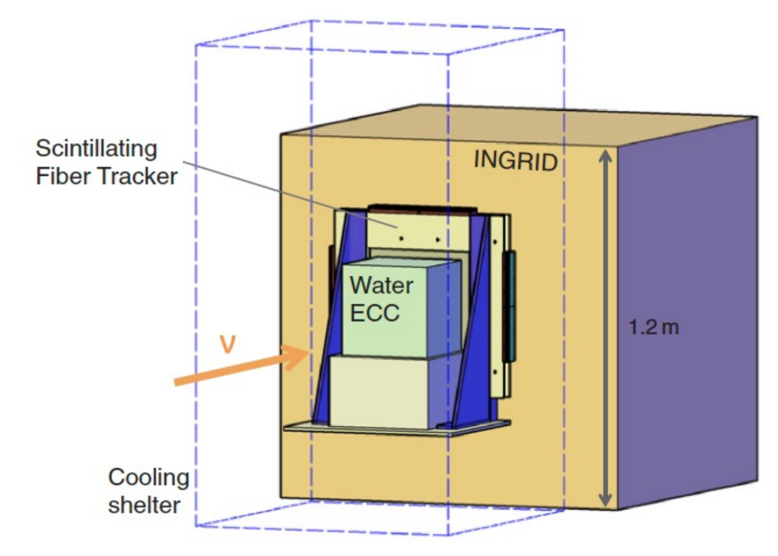
65 kg Iron target run (2016)

Iron ECC + Shifter + INGRID

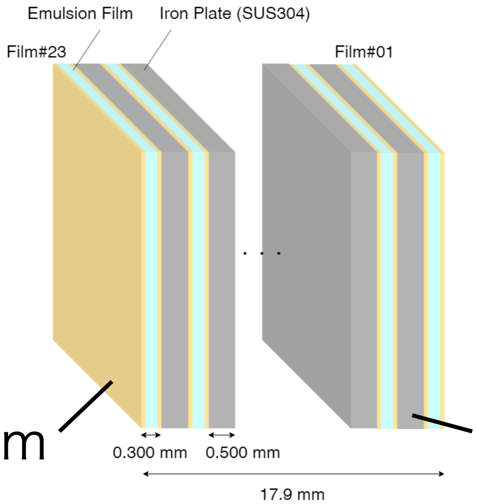


3 kg Water target run (2017–2018)

Water ECC + SFT + INGRID



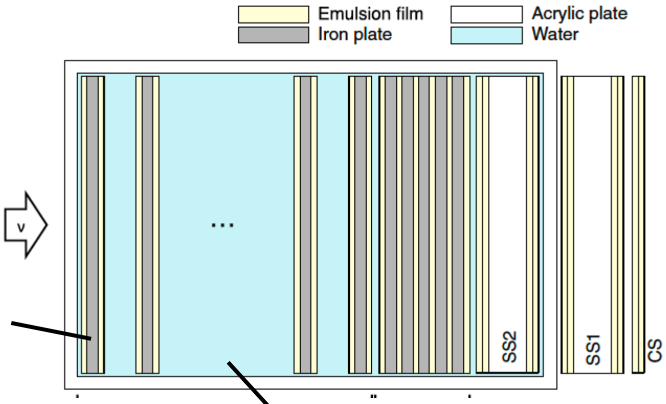
Iron ECC



Emulsion film

Iron plate

Water ECC



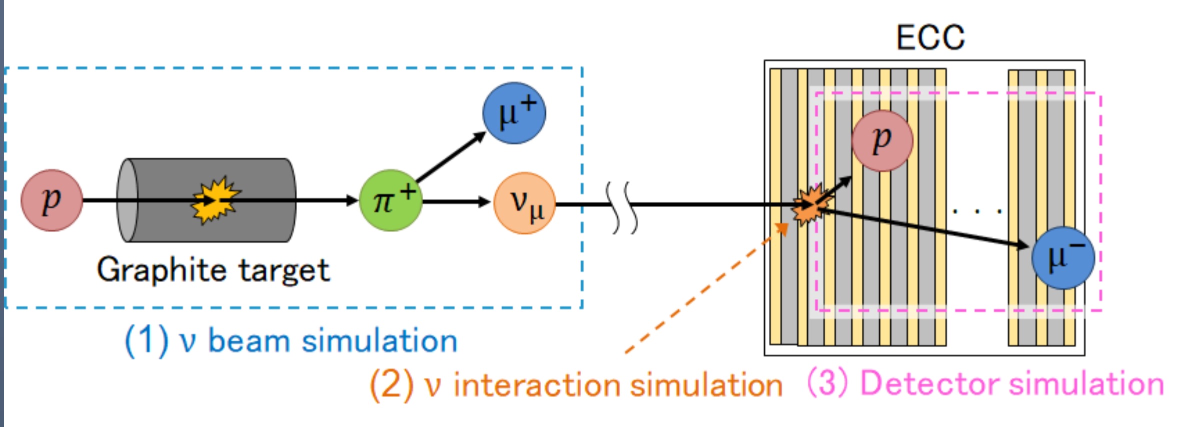
Emulsion film
+ Iron plate

Water

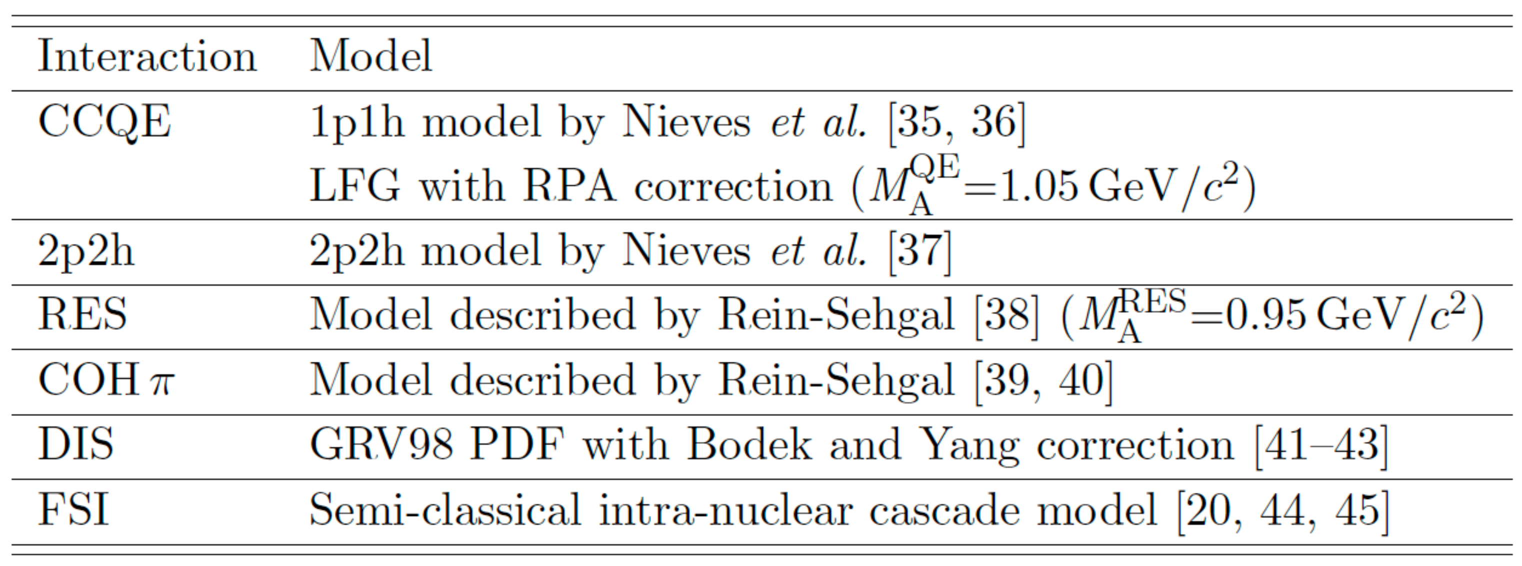
Monte Carlo simulation

- Neutrino beam :
  JNUBEAM 13av6.1
- Event generation :
  NEUT 5.4.0
- Detector response :
  Geant4 (QGSP BERT physics list)

（normalize : POT value & target mass）



Neutrino interaction models used in the nominal MC simulation.

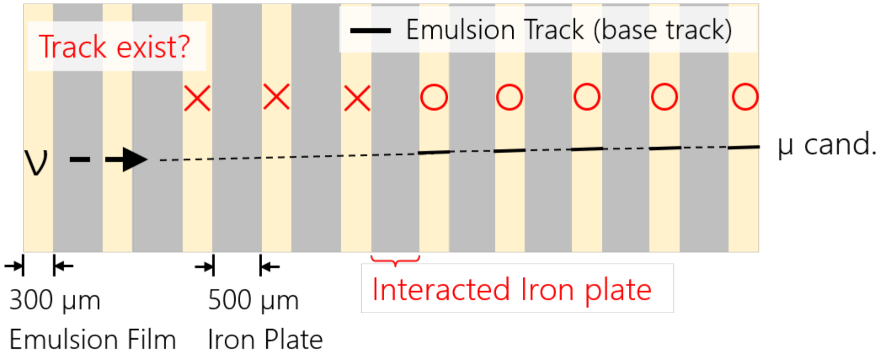


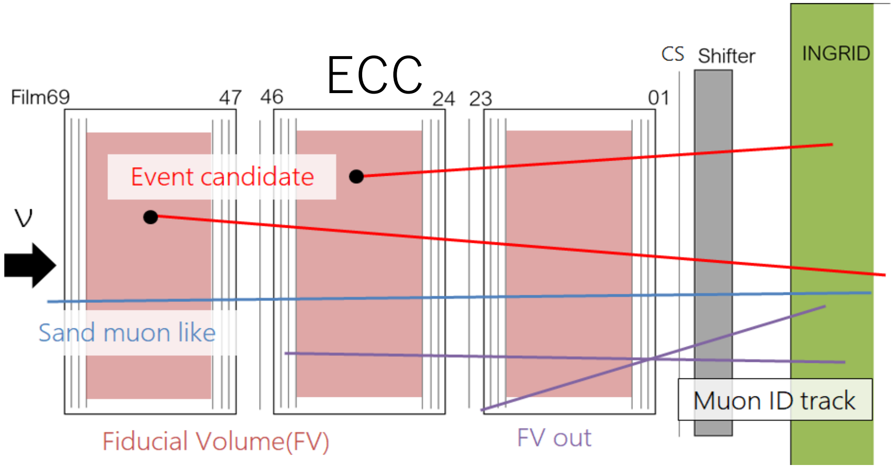
Interaction	Model
CCQE	1p1h model by Nieves *et al.* [35, 36] LFG with RPA correction (M_A^{QE}=1.05 GeV/c^2)
2p2h	2p2h model by Nieves *et al.* [37]
RES	Model described by Rein-Sehgal [38] (M_A^{RES}=0.95 GeV/c^2)
COH π	Model described by Rein-Sehgal [39, 40]
DIS	GRV98 PDF with Bodek and Yang correction [41–43]
FSI	Semi-classical intra-nuclear cascade model [20, 44, 45]

/ DCC

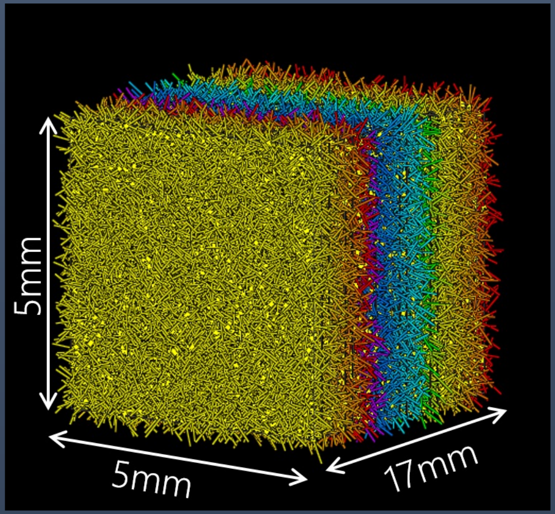
Event reconstruction and the selection of neutrino interactions

Scanback method : The muon candidates were traced back from INGRID to the interaction vertices. If no tracks with connection are found in three consecutive films, the retracing is finished.

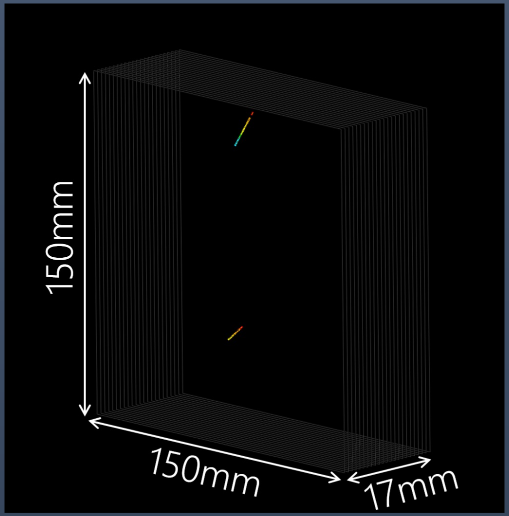




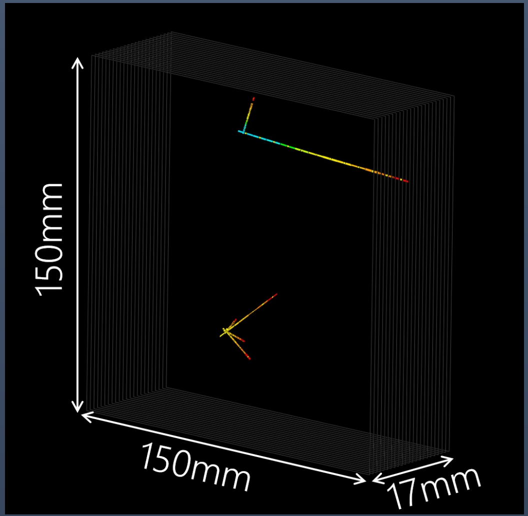
ν + $\bar{\nu}$ int.(CC+NC) + cosmic-ray



ν CC int. μ cand.



ν CC int. events



Detection of ν CC interactions
Muon selection (Shifter & INGRID)

Event reconstruction (ECC)
Proton and pion track search

Selection efficiency (FHC)

The efficiency is mainly determined by the following factors:

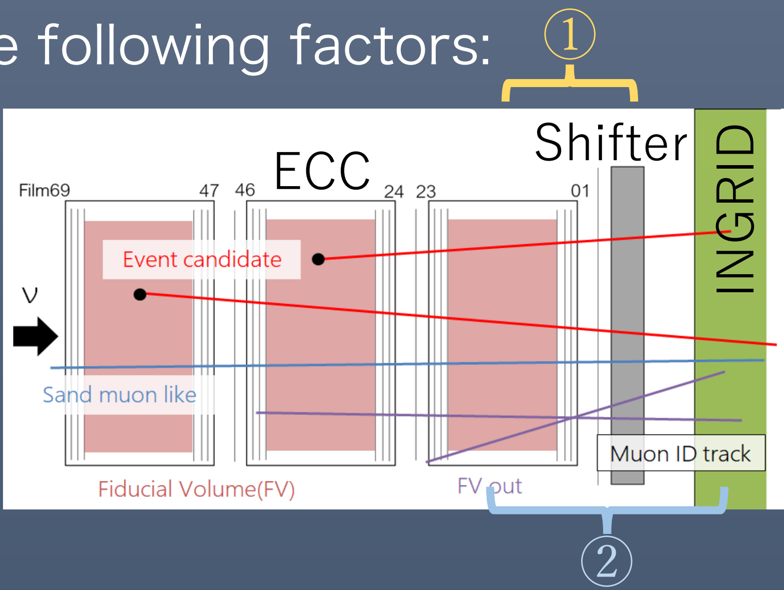
① ECC-Shifter connection

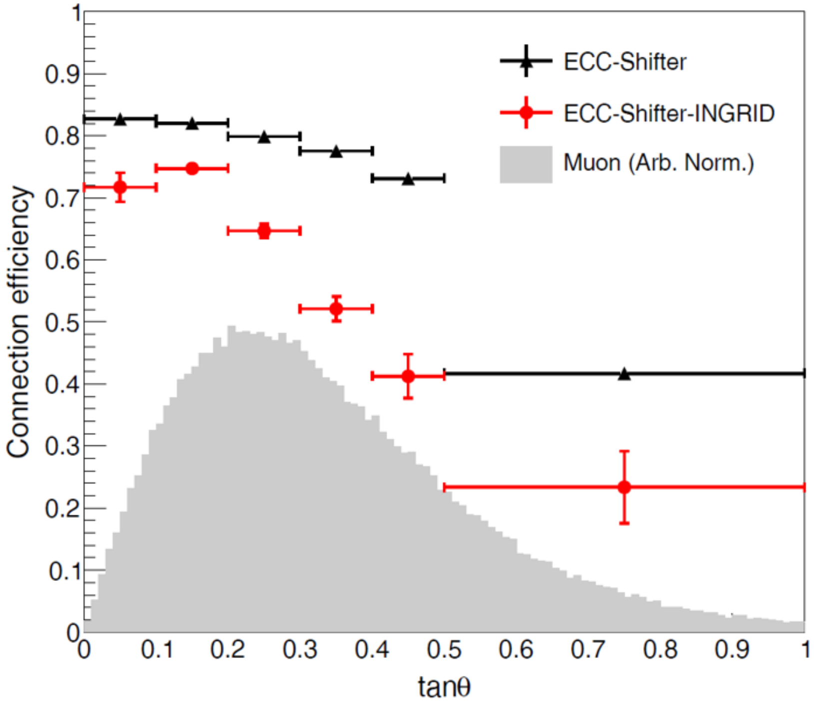
② ECC-INGRID connection

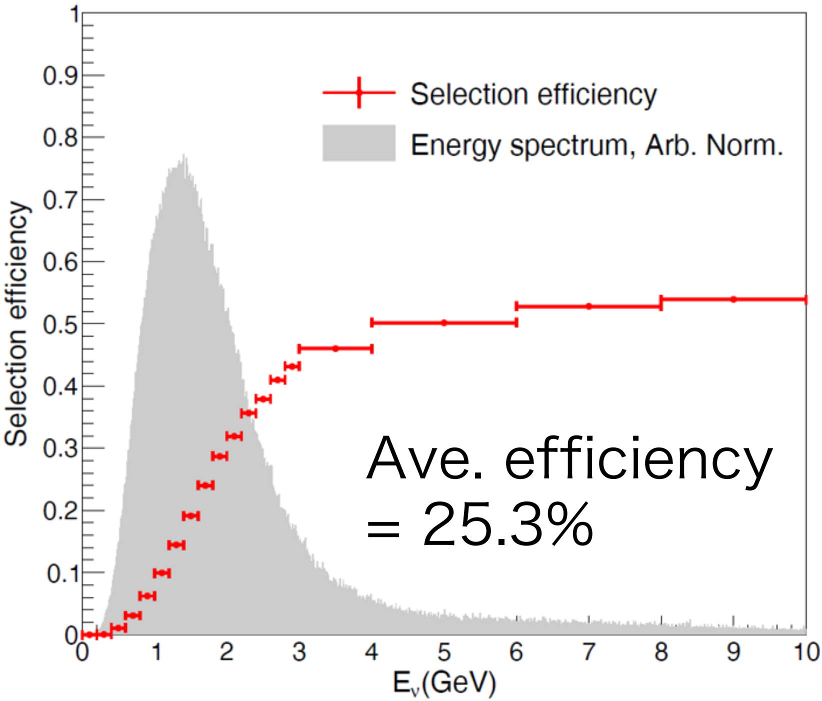
↑

Muon detection threshold is determined by the track connection among the ECC and INGRID.

$$\theta_{\mu} < \sim 45°, P_{\mu} > \sim 300\ \mathrm{MeV}/c$$

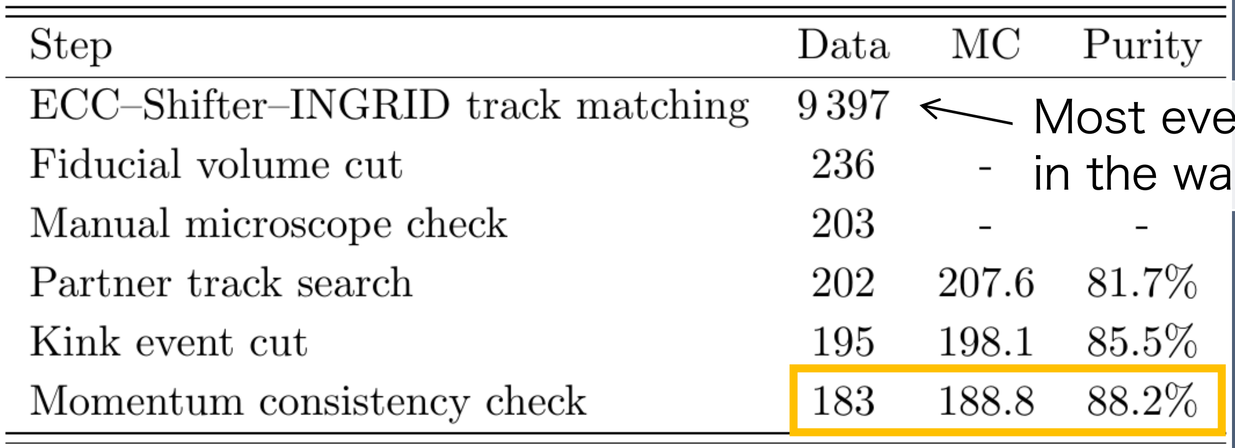






Ave. efficiency
= 25.3%

Number of selected events and fractions (FHC)



Step	Data	MC	Purity
ECC–Shifter–INGRID track matching	9 397		
Fiducial volume cut	236	-	
Manual microscope check	203	-	-
Partner track search	202	207.6	81.7%
Kink event cut	195	198.1	85.5%
Momentum consistency check	183	188.8	88.2%

← Most events are muons of ν int. in the wall of the detector hall

← ν_μ-iron CC int. candidates

Signal and background source	Fraction
ν_μ CC	88.2%
ECC-Shifter-INGRID mismatching (neutrino events, cosmic-ray events)	4.8%
Upstream wall and INGRID vertical module (neutron, proton, pion)	3.4%
Anti-ν_μ	2.7%
ν_μ NC	0.8%
INGRID horizontal module (back scatter muon, charged hadron)	< 0.1%
ν_e and anti-ν_e	< 0.1%

← Signal events

Background events

Muon phase space in cross-section measurement

(1) *Full* phase space of induced muons

Merit : easy to compare several measurements and
neutrino interaction models

Demerit : the prediction of the events out of acceptance
depends on the MC models

➡ the systematic uncertainties of models are large!

(2) *Restricted* kinematic phase space of induced muons

Merit : the systematic uncertainties of neutrino interaction
models can be reduced

Demerit : the result can be compared to the only same phase space

➡ In this analysis, we measured cross sections in *full-* and *restricted-* muon phase spaces, $\theta_{\mu} < 45°, P_{\mu} > 400\ \mathrm{MeV}/c$, respectively.

Cross-section measurement (FHC)

In this analysis, we measured cross sections in full phase space and limited kinematic phase space, $\theta_{\mu} < 45°, P_{\mu} > 400\ \mathrm{MeV}/c$, respectively.

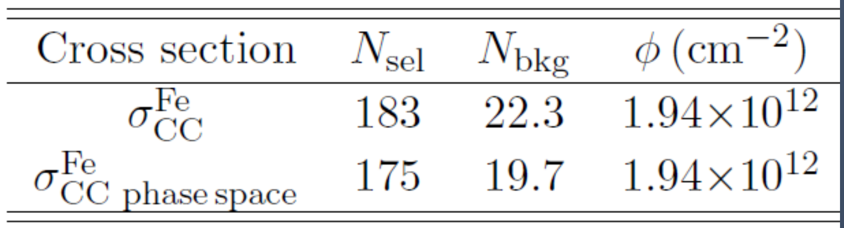
Number of selected events

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

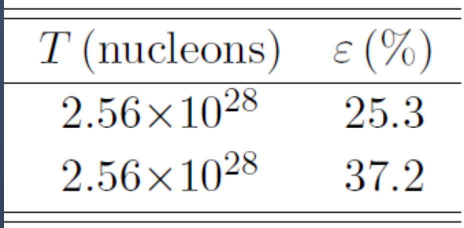
Calculated based on the data

Evaluated using the MC

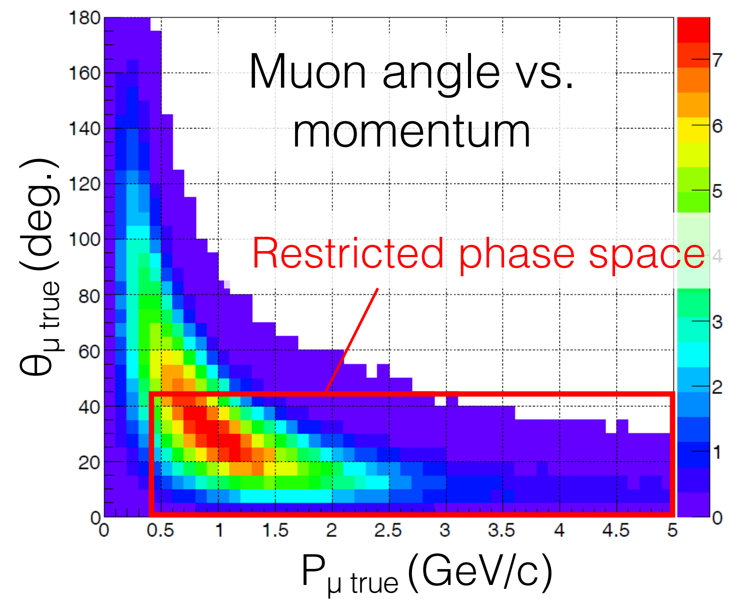
$\mathrm{N_{sel}}$	Number of selected events
$\mathrm{N_{bkg}}$	Number of background events
φ	Integrated neutrino flux
T	Number of target nucleons
ε	Detection efficiency



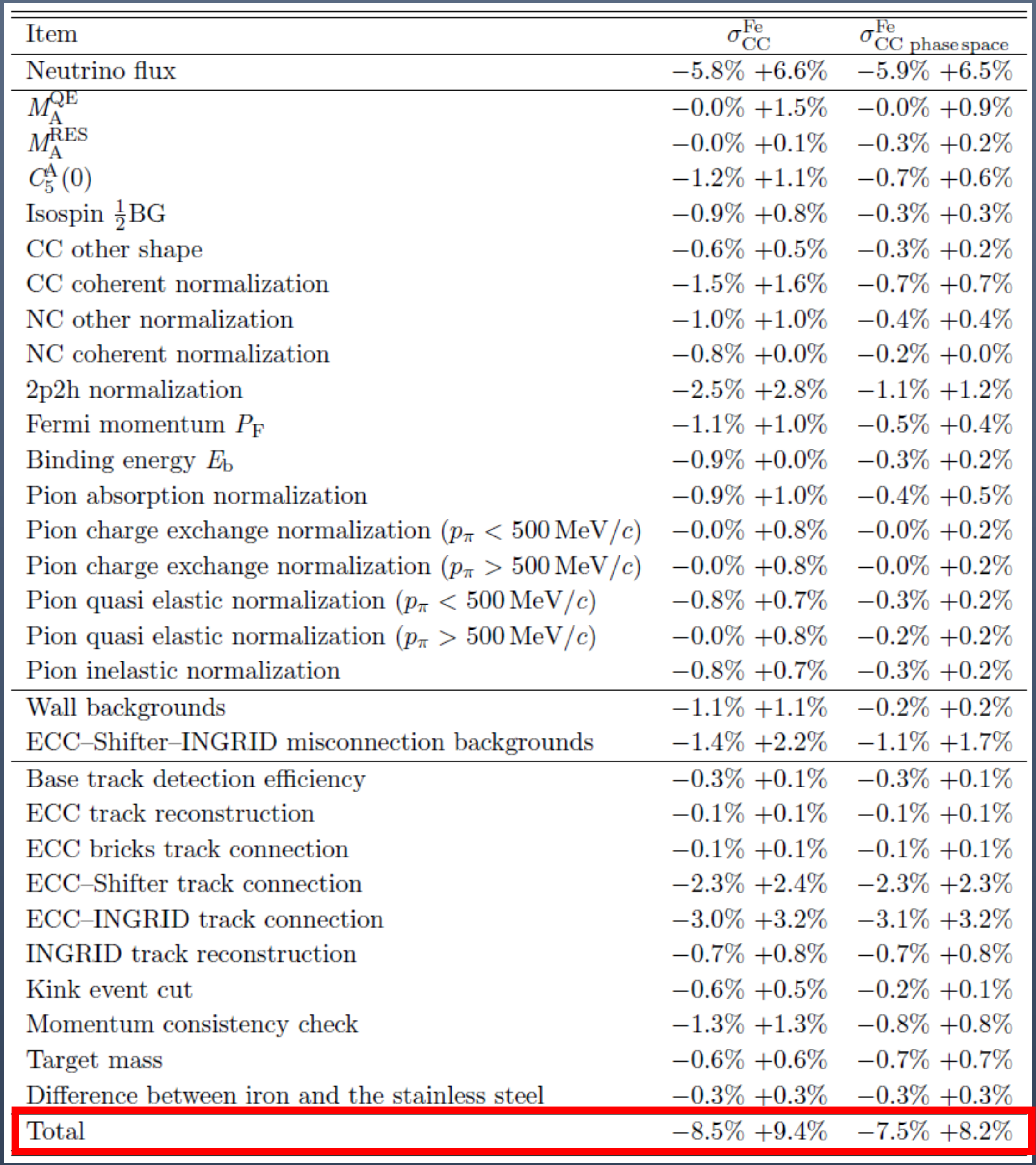
Cross section	N_{sel}	N_{bkg}	$\phi\ (\mathrm{cm}^{-2})$
$\sigma^{\mathrm{Fe}}_{\mathrm{CC}}$	183	22.3	1.94×10^{12}
$\sigma^{\mathrm{Fe}}_{\mathrm{CC\ phase\ space}}$	175	19.7	1.94×10^{12}



T (nucleons)	ε (%)
2.56×10^{28}	25.3
2.56×10^{28}	37.2



Summary of the systematic uncertainties (FHC)



Item	$\sigma^{\mathrm{Fe}}_{\mathrm{CC}}$	$\sigma^{\mathrm{Fe}}_{\mathrm{CC\ phase\ space}}$
Neutrino flux	−5.8% +6.6%	−5.9% +6.5%
M_A^{QE}	−0.0% +1.5%	−0.0% +0.9%
M_A^{RES}	−0.0% +0.1%	−0.3% +0.2%
$C_5^A(0)$	−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 phase space
(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%)

ν_μ CC Cross section (FHC)

Data release

Iron int.: 183 events

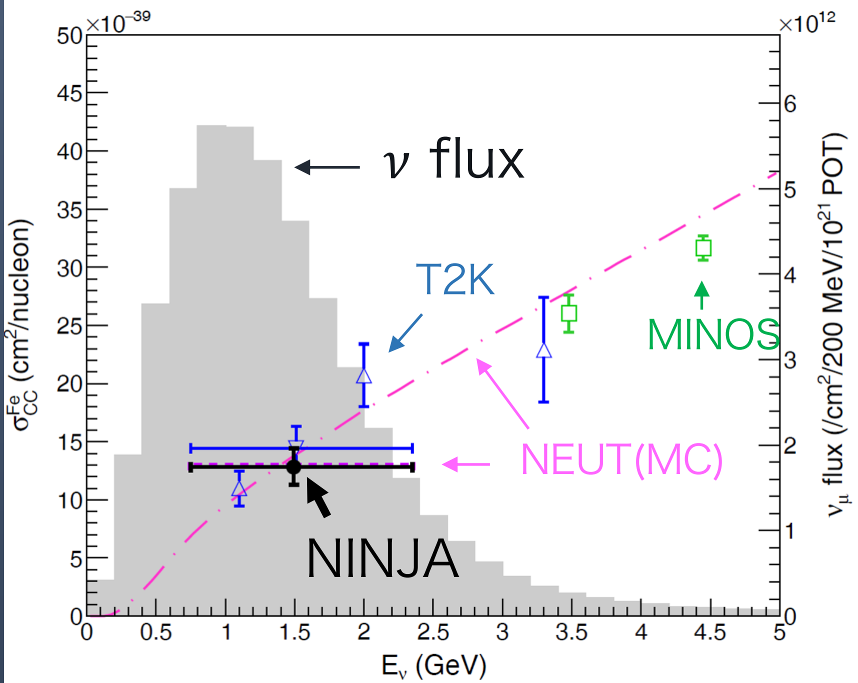
PTEP 2021, 033C01 (2021).
PRD 106, 032016 (2022).

Flux averaged CC inclusive cross section:

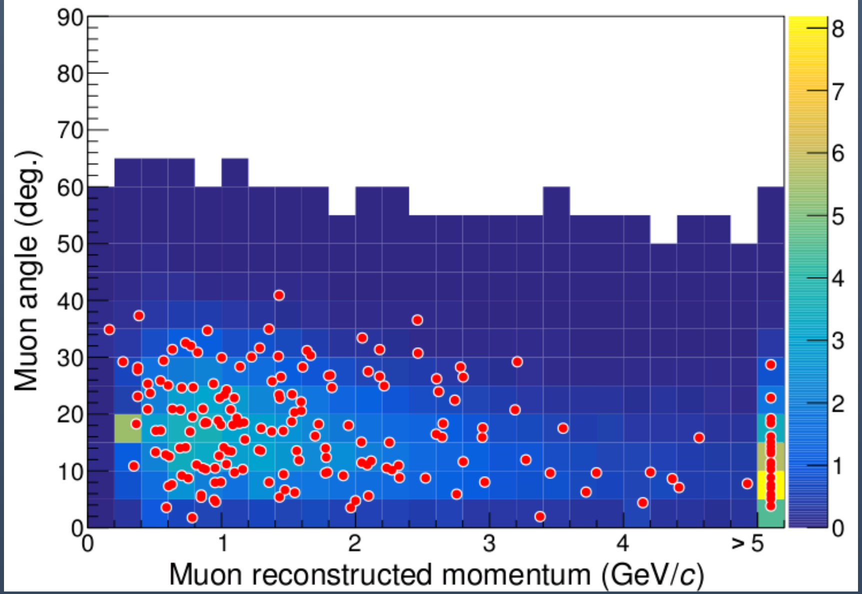
	Result $\times 10^{-38}$ (cm^2/nucleon)	MC $\times 10^{-38}$	T2K(INGRID) $\times 10^{-38}$
$\sigma_{\mathrm{CC}}^{\mathrm{Fe}}$	$1.28 \pm 0.11(\mathrm{stat.})^{+0.12}_{-0.11}(\mathrm{syst.})$	1.30	$1.444 \pm 0.002(\mathrm{stat.})^{+0.189}_{-0.157}(\mathrm{syst.})$
$\sigma_{\mathrm{CC\ phase\ space}}^{\mathrm{Fe}}$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

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

Cross section



Muon emission angle vs. momentum



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

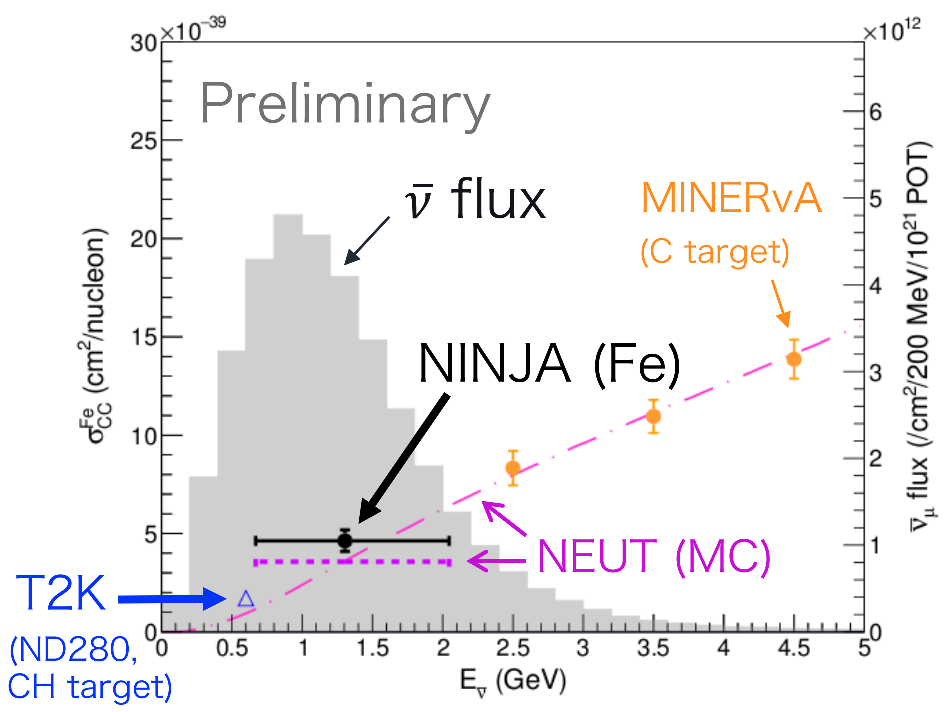
$\bar{\nu}_\mu$ CC Cross section (RHC)

Preliminary

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 $\times 10^{-39}$
$\sigma_{\mathrm{CC}}^{\mathrm{Fe}}$	$4.63 \pm 0.23(\mathrm{stat.})^{+0.53}_{-0.48}(\mathrm{syst.})$	3.57
$\sigma_{\mathrm{CC\ phase\ space}}^{\mathrm{Fe}}$	$3.85 \pm 0.20(\mathrm{stat.})^{+0.42}_{-0.40}(\mathrm{syst.})$	3.22

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



<u>NINJA (Fe target):</u>
(MC – DATA)/DATA
= (3.57 – 4.63)/4.63 = – 23%

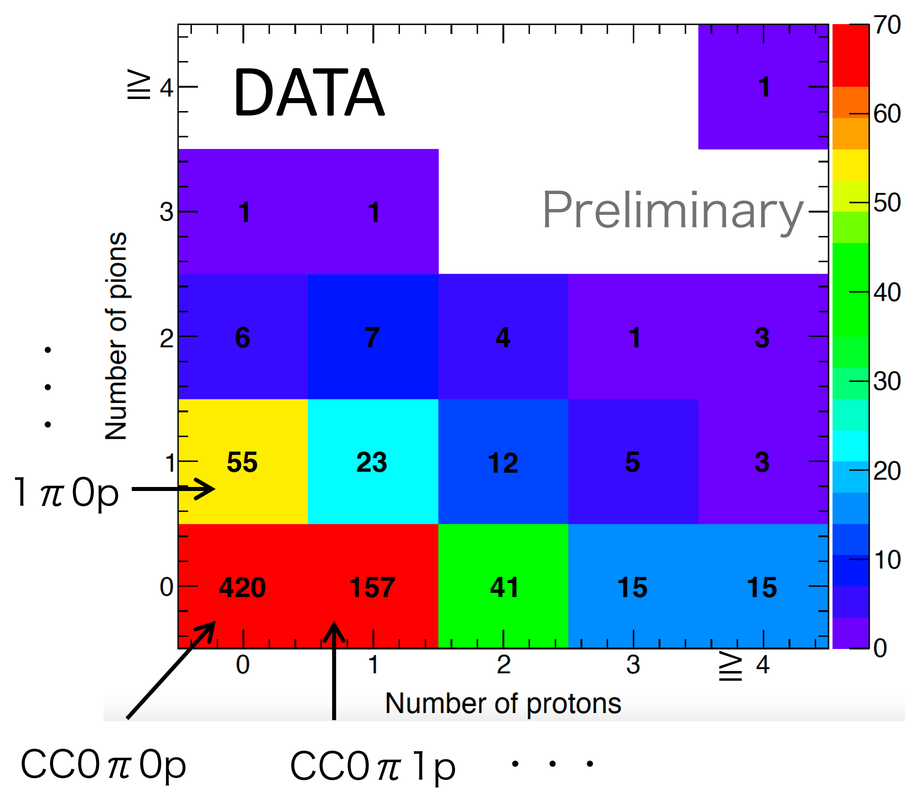
<u>T2K (ND280, CH target):</u>
(MC – DATA)/DATA
= (1.31 – 1.71)/1.71 = – 23%

➡ 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.

Multiplicity distributions (RHC mode)

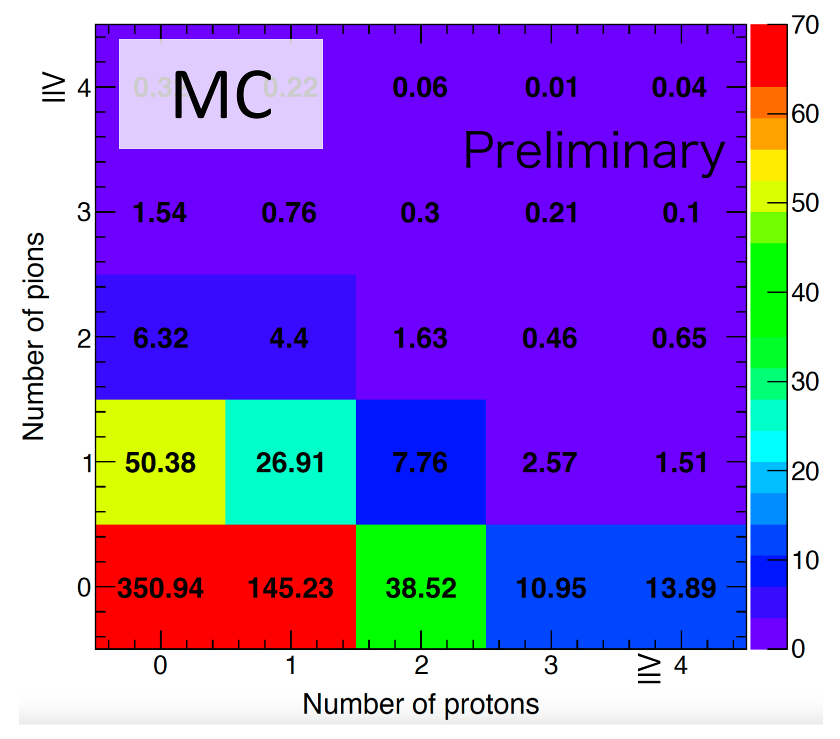
Iron int.: 770 events



1 π 0p

CC0 π 0p

CC0 π 1p ・・・



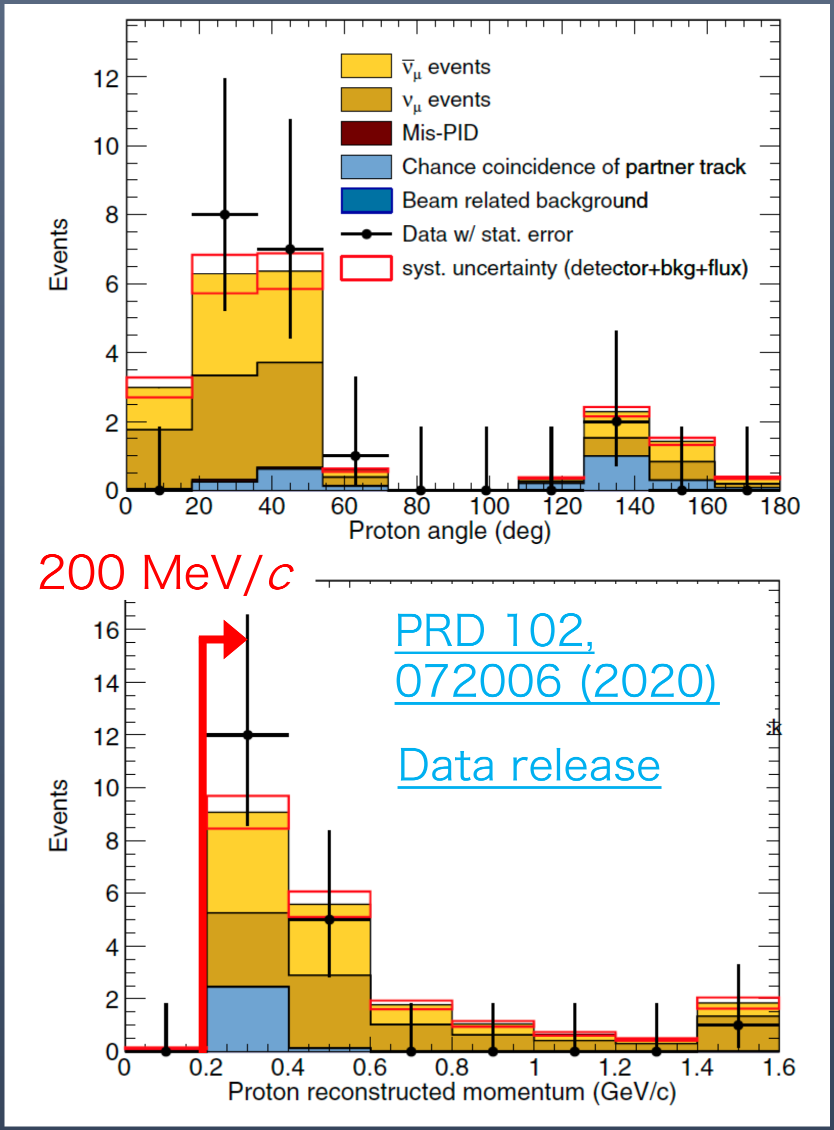
This is one of the analyses that take advantage of the sub-μm positional resolution of the emulsion detector.

We aim to measure CC*Nπ N'p* cross sections based on the measurement of multiplicity in the final state.

Proton results (RHC mode)

Water int.: 86 events

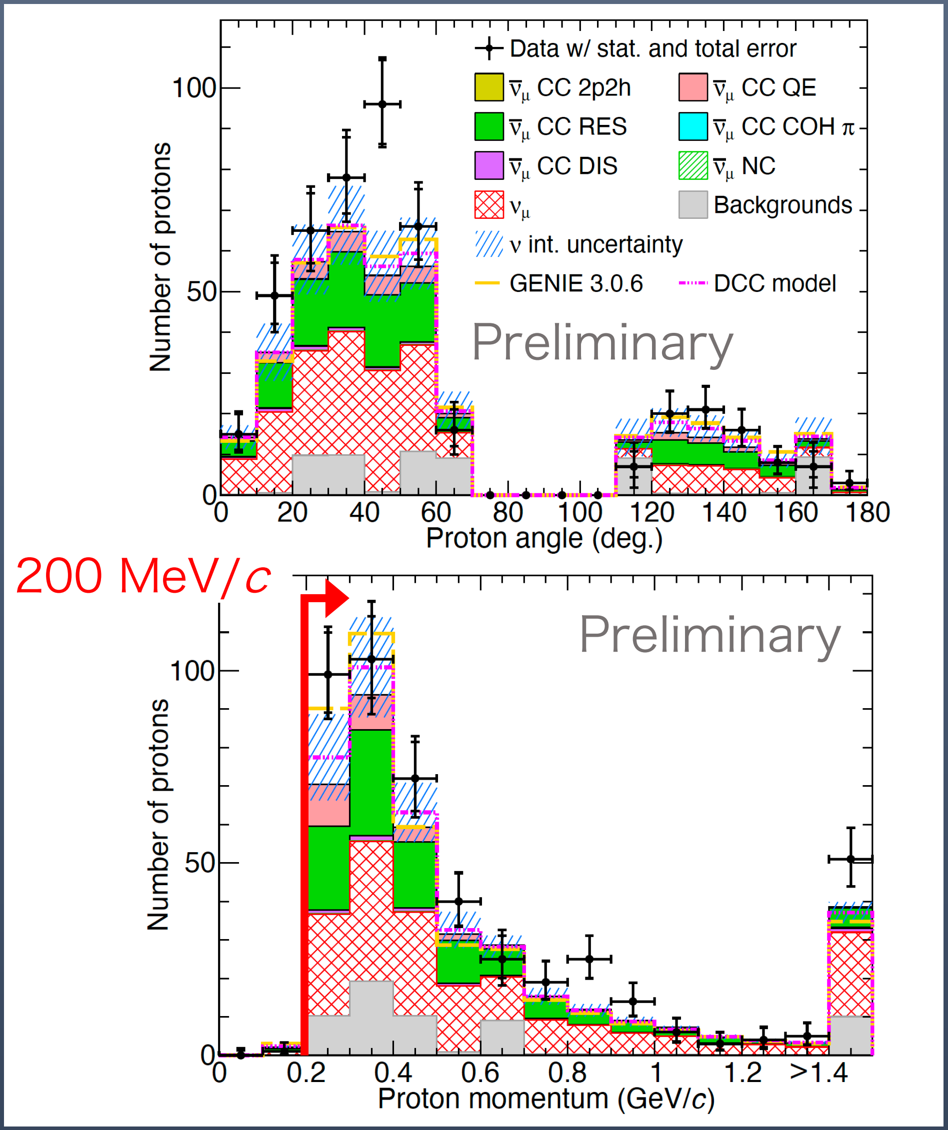
Iron int.: 770 events



200 MeV/*c*

PRD 102, 072006 (2020)

Data release

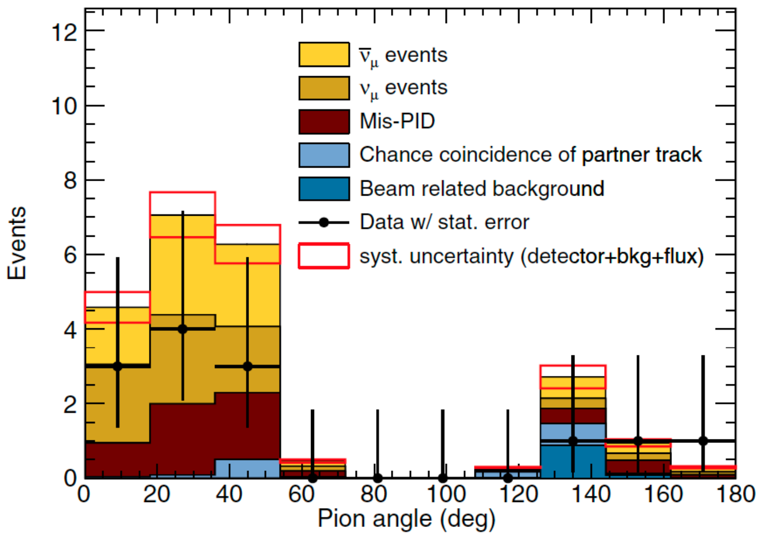


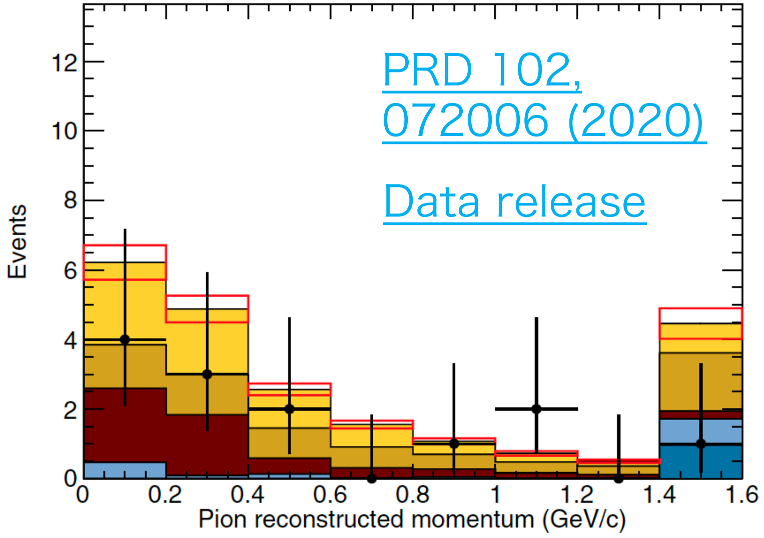
200 MeV/*c*

Data are generally consistent with the MC prediction.

Pion results (RHC mode)

Water int.: 86 events



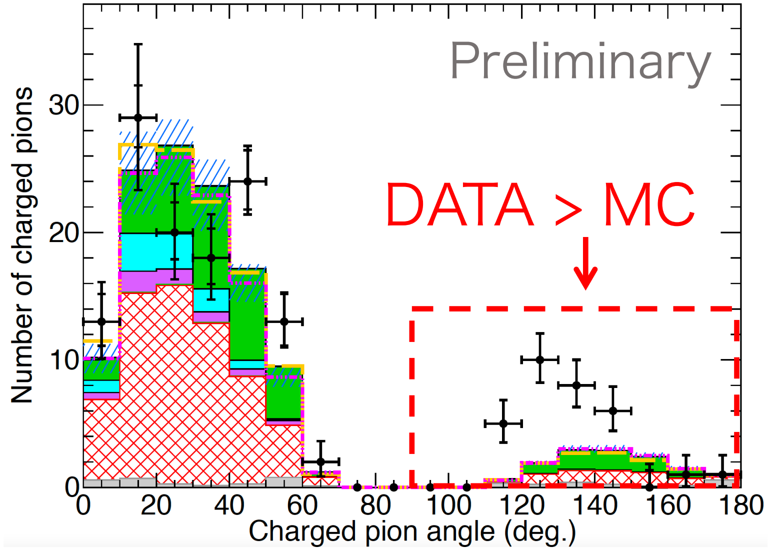


PRD 102, 072006 (2020)

Data release

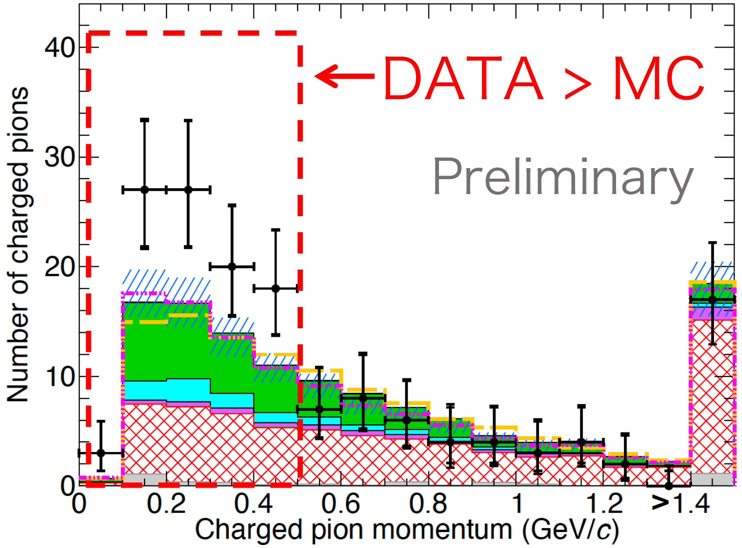
Number of pions of the data is less than that of the MC simulation.

Iron int.: 770 events



Preliminary

DATA > MC



← DATA > MC

Preliminary

NEUT (Rein-Sehgal, DCC) and GENIE cannot reproduce the data.
→ Problems of π production or FSI models?

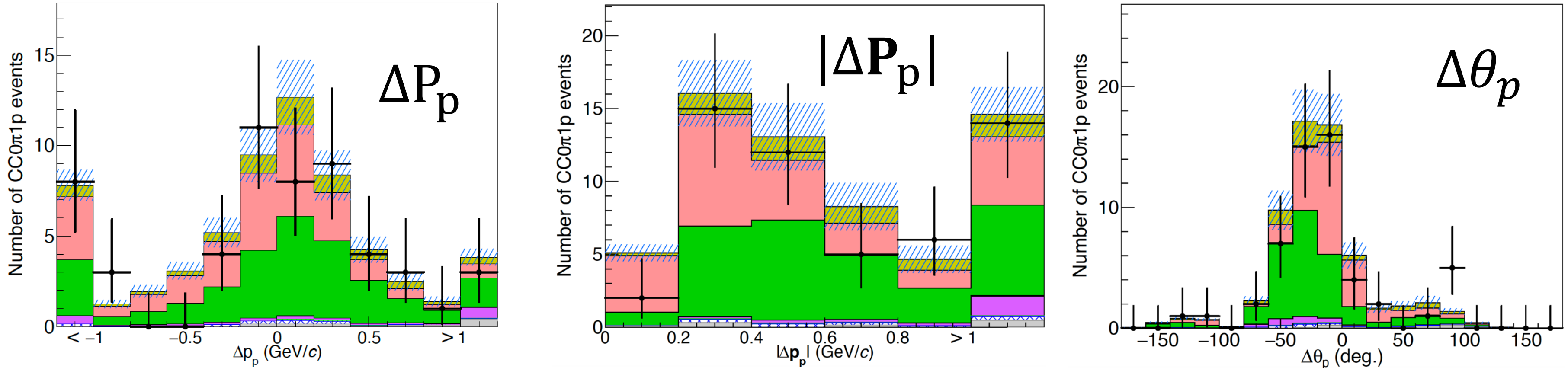
CC0π1p: Proton results (FHC mode)

Iron int. (CC0π1p): 54 events

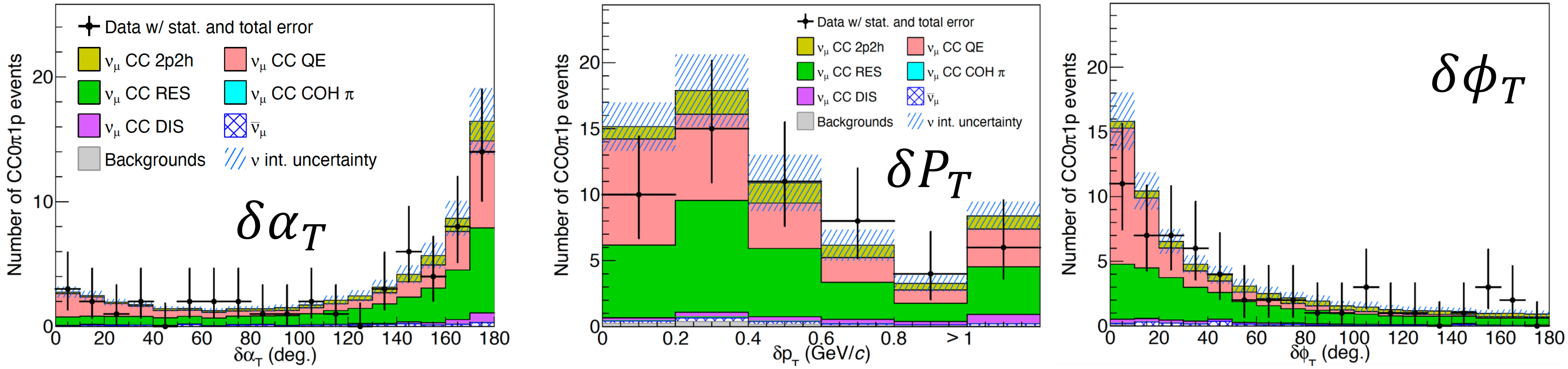
Data release

PRD 106, 032016 (2022).

Transverse Kinematic Imbalance



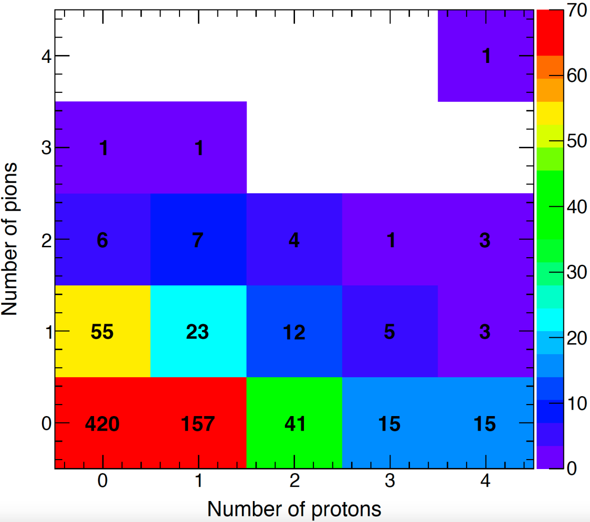
Inferred Proton Kinematics



We also measured kinematic correlations between muons & protons. (PRD 106, 032016 (2022).)

Toward a differential cross-section measurement

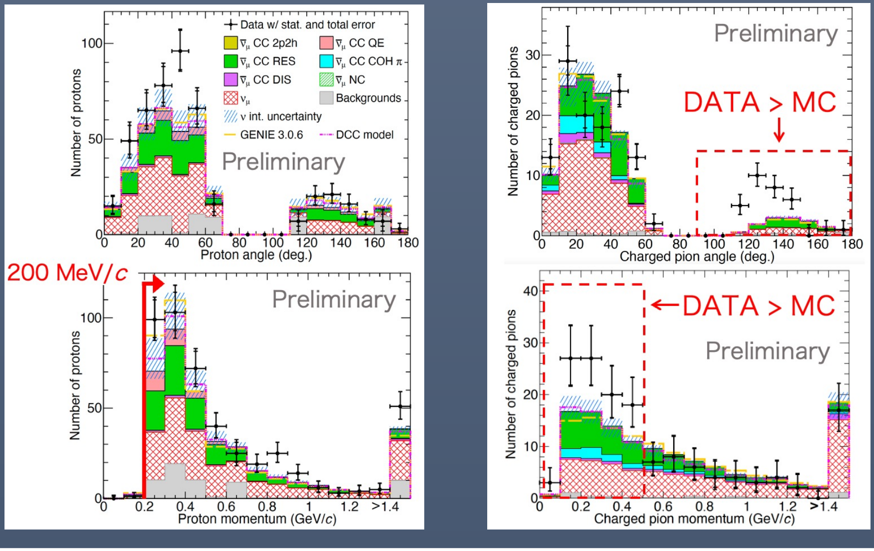
Proton & Pion Multiplicities



Number of pions \ Number of protons	0	1	2	3	4
4					1
3	1	1			
2	6	7	4	1	3
1	55	23	12	5	3
0	420	157	41	15	15

+

Proton & Pion Kinematics



DATA for CC$N\pi N'p$

- Background subtraction
- Unfolding
- Efficiency correction

Differential cross section

Analysis with more statistics for the differential cross section measurements is on-going!

Data release

ν_{μ} - iron interactions (FHC): 183 events

$\bar{\nu}_{\mu}$ and ν_{μ} - water interactions (RHC): 86 events

May 31, 2022

Dataset Open Access

Data release for the paper "Measurements of protons and charged pions emitted from the ν_{μ} charged-current interactions on iron at a mean neutrino energy of 1.49 GeV using a nuclear emulsion detector"

The NINJA experiment

This data release is associated with the paper "Measurements of protons and charged pions emitted from the ν_{μ} charged-current interactions on iron at a mean neutrino energy of 1.49 GeV using a nuclear emulsion detector". It is currently available on arXiv:2203.08367 and to be submitted to Phys. Rev. D.

When citing this data release, please cite as well the paper.

The provided zip file contains the data as below.

1. event.root: Event by event information of 183 iron-target interactions.
2. plot.root: Plot information as shown in the paper.
3. detector_efficiency.root: Detectrion efficiencies for muons, charged pions, and protons.
4. momentum_resolution.root: Relation between true and reconstructed momentum for muons, charged pions, and protons.
5. misPID.root: Mis-PID rates of protons and pions.
6. syscov.root: Covariance matrices of systematic uncertainties.
7. flux.root: The neutrino flux and the covariance matrix of the flux error.

The zip file also contains a README.pdf file with detailed information on the included files. Please read it.

Preview

ninja_data_release_2022a.zip

ninja_data_release_2022a

README.pdf	24.6 kB
detector_efficiency.root	12.0 kB
detector_efficiency.txt	7.9 kB
event.root	17.7 kB
event.txt	23.0 kB
flux.root	14.5 kB
flux.txt	12.4 kB
misPID.root	9.4 kB
misPID.txt	7.9 kB
momentum_resolution.root	189.2 kB
plot.root	22.9 kB
plot.txt	14.5 kB
syscov.root	34.0 kB
syscov.txt	20.8 kB

159 views

20 downloads

See more details...

Indexed in OpenAIRE

Publication date:
May 31, 2022

DOI:
DOI 10.5281/zenodo.6597038

Communities:
NINJA Experiment

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Versions

Version 2 10.5281/zenodo.6597038	May 31, 2022
Version 1 10.5281/zenodo.6355555	Mar 16, 2022

Cite all versions? You can cite all versions by using the DOI 10.5281/zenodo.6355554. This DOI represents all versions, and will always resolve to the latest one. Read more.

Share

Cite as

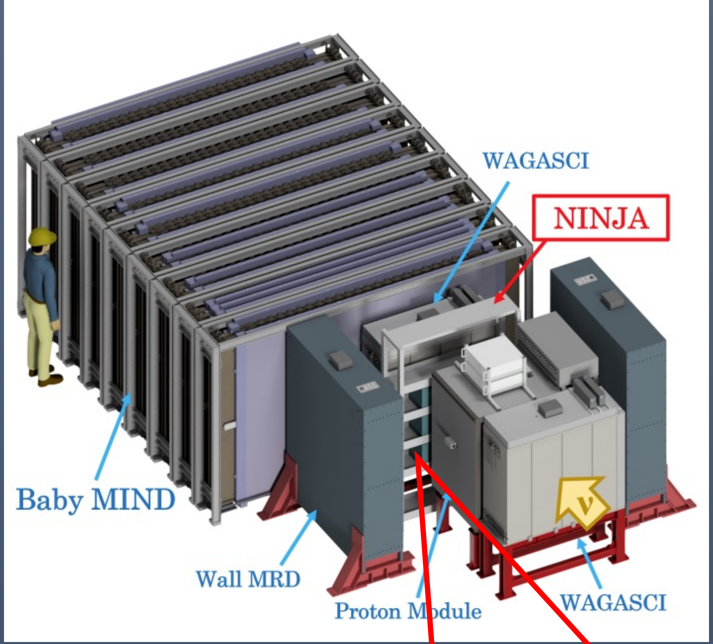
The NINJA experiment. (2022). Data release for the paper "Measurements of protons and charged pions

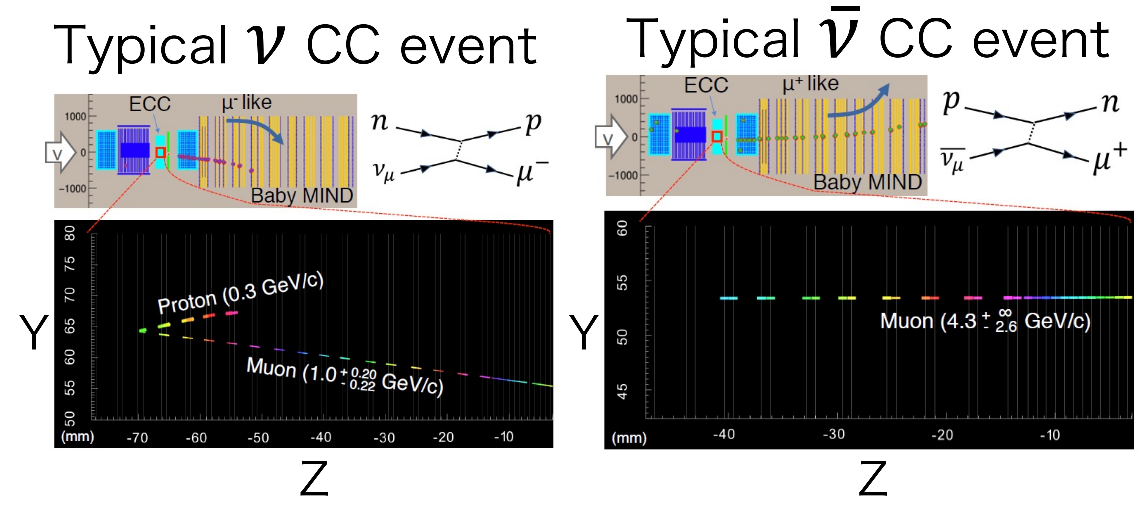
- Event information
- Detection efficiency
- Detector resolution
- Mis-PID rates
- Covariance matrices
- ν flux and cov. matrix

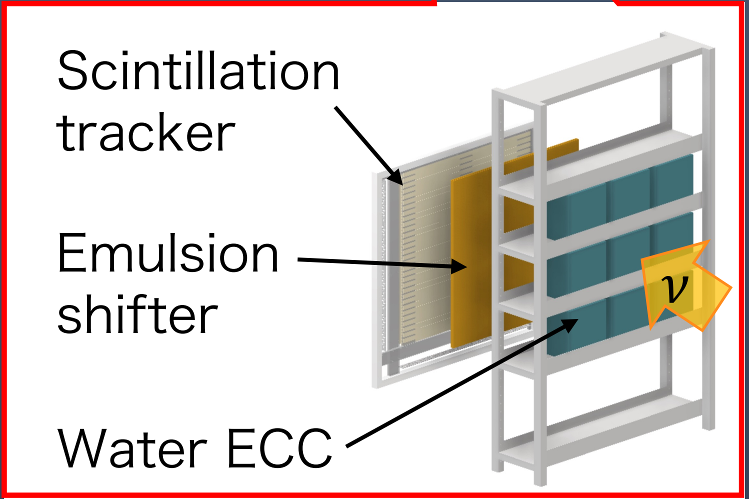
ROOT file format
& Text file format

Physics run E71a : Detector

E71a : 75 kg Water + 130 kg Iron targets run (2019–2020)







ECC : Analyze ν interactions

Shifter /

Scintillation tracker : Adds time info. to the ECC tracks

BabyMIND : Muon range detector w/ magnet

→ Selects $\nu/\bar{\nu}$ events via μ^-/μ^+separation

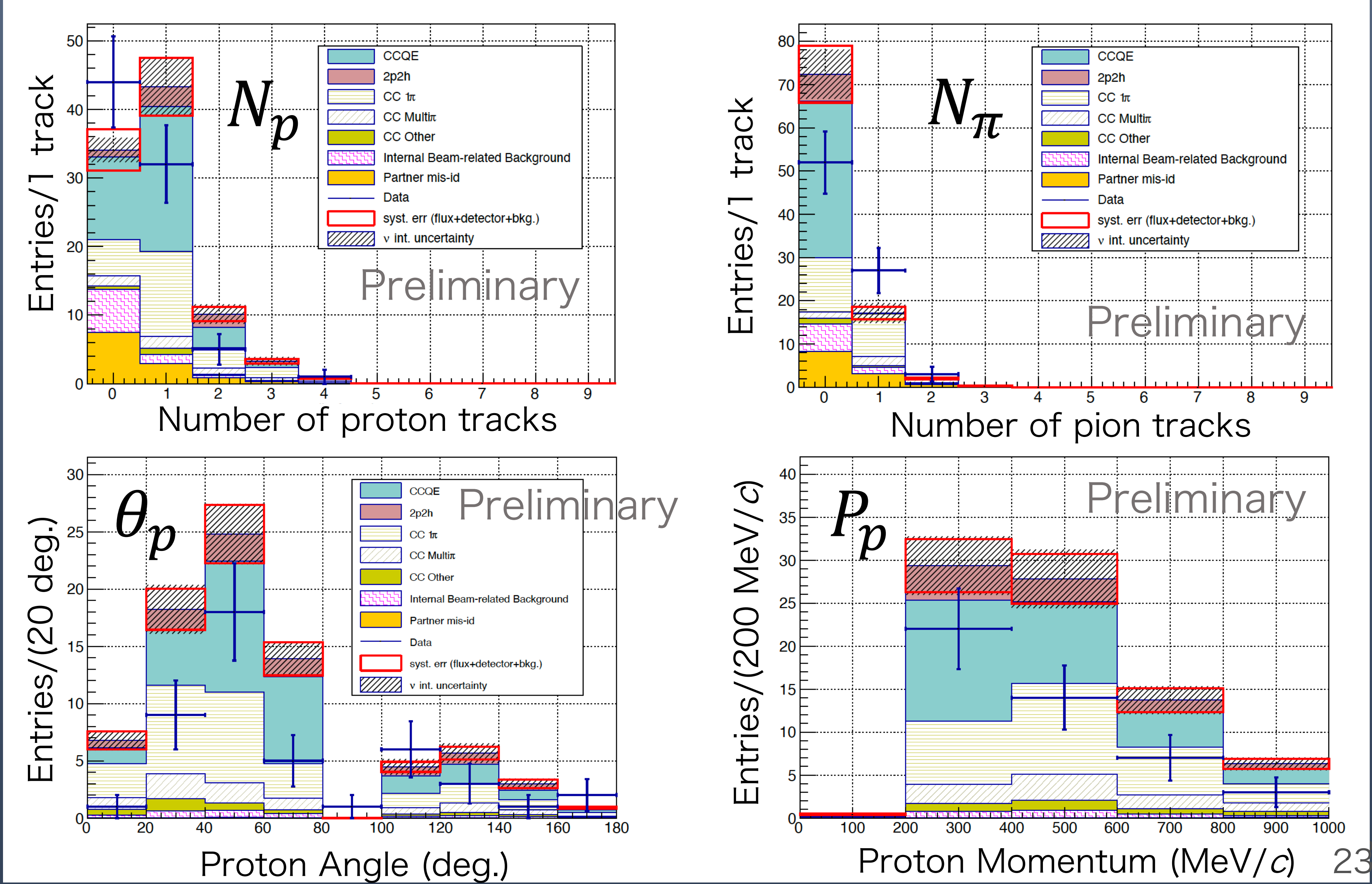
- We conducted an expanded detector scale based on the pilot runs.
- We expect 15 times more neutrino events than that of pilot runs.

Physics run E71a : Proton & Pion results (ν–water int.)

- Results using ~10% sub-sample of the total

Y. Suzuki, Ph.D. thesis, Nagoya Univ., 2023.
T. Odagawa, Ph.D. thesis, Kyoto Univ., 2023.

- Preparation of the full-dataset and the analysis is on-going.

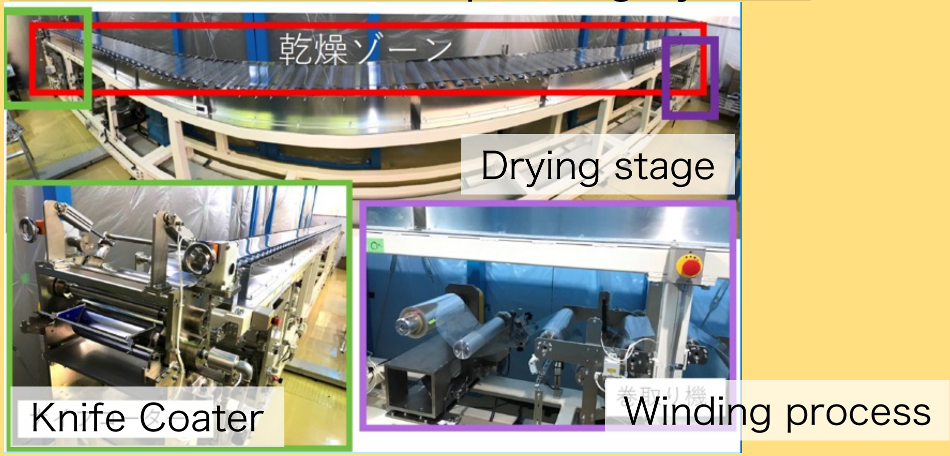


Future prospects ① : Next physics run (E71b)

Next physics run is planned for FY2023 and the detector is being prepared.

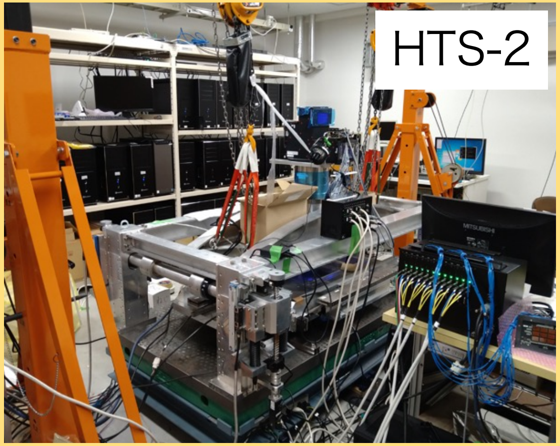
Equipment developments

Automatic emulsion pouring system



→ ×10 faster than hand made

New high speed emulsion scanning system

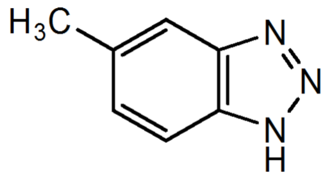


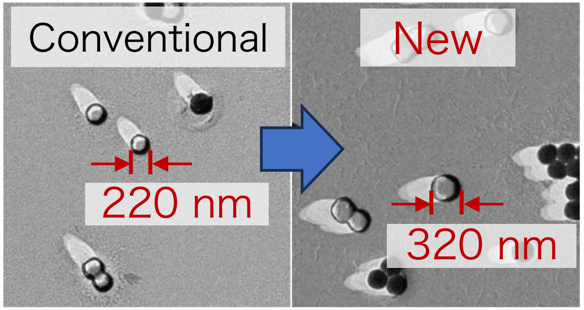
→ ×5 faster than current system

Detector upgrades

Refreshable large AgBr crystal size gel

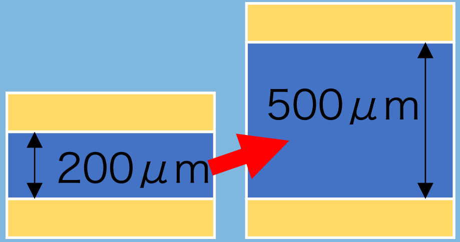
5-methyl benzotriazole

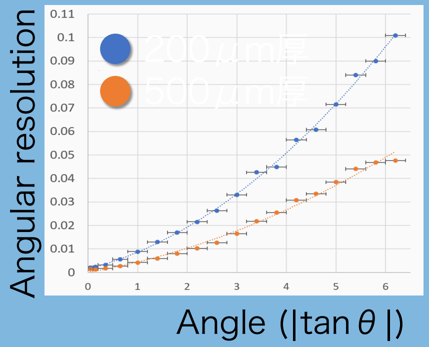




→ necessary for HTS2 to scan tracks
with fast & high efficiency.

Thicker-base emulsion film



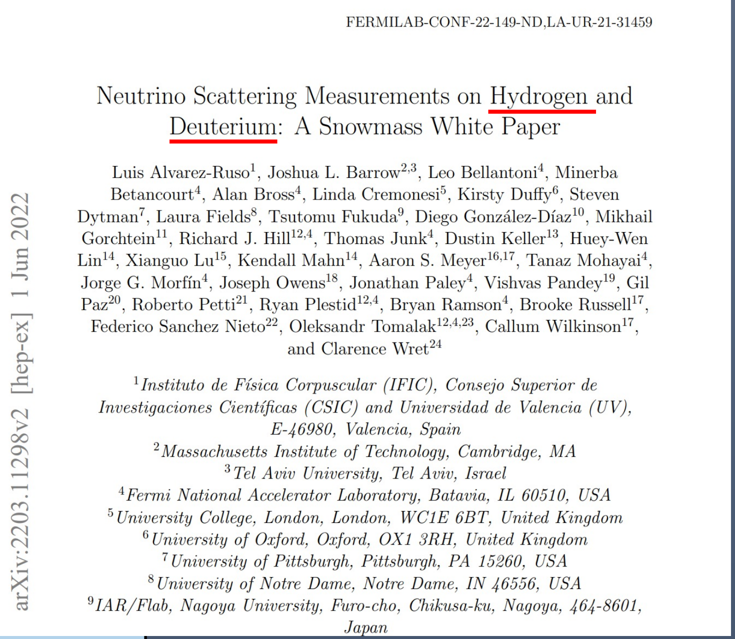


→ Improve angular resolution

Future prospects ② : Heavy water target run

ν-nucleon int. measurement using Hydrogen & Deuterium is brought back into the spotlight.

→ Using a "Bubble chamber" is considered to measure **ν-nucleon** interactions in US.



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*

[3] *Tel Aviv University, Tel Aviv, Israel*

[4] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*

[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*

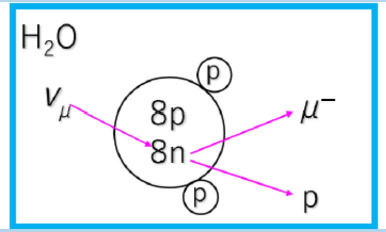
[9] *IAR/Flab, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan*

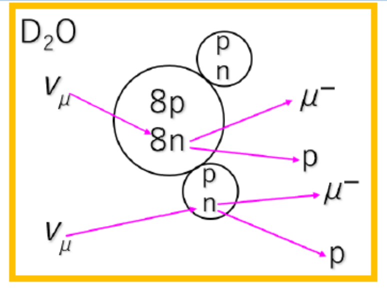
arXiv:2203.11298v2 [hep-ex] 1 Jun 2022

We plan to measure **ν-nucleon** int. using a "Water ECC" & a "Heavy water ECC."

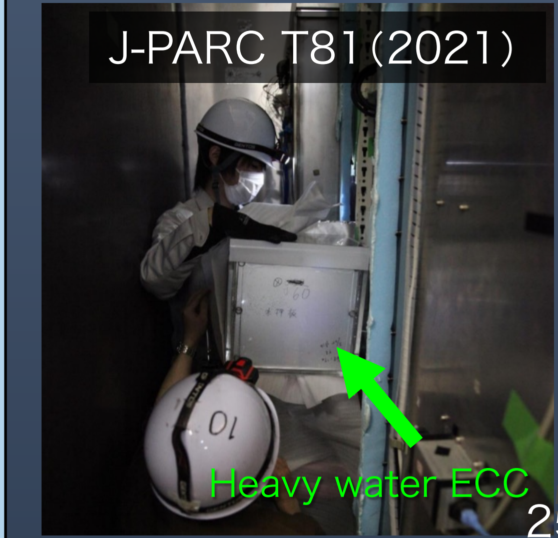
Experimental concept

$$(\nu \cdot \mathrm{D_2O}) - (\nu \cdot \mathrm{H_2O}) \rightarrow (\nu \cdot n)$$





Pilot "Heavy water" target run was already conducted. We will conduct a large-scale "Heavy water" run in near future.


J-PARC T81 (2021)

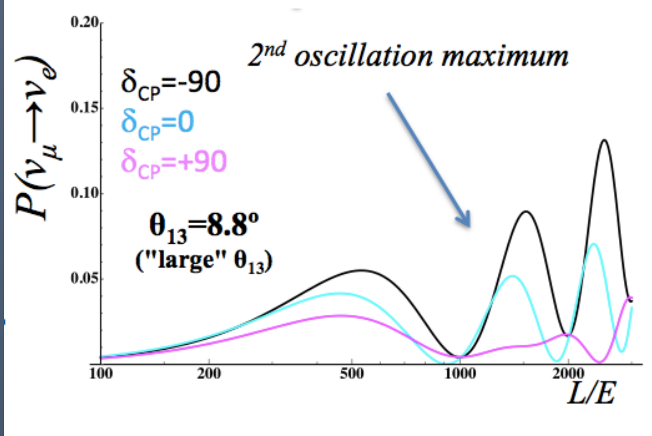
Future prospects ③ : ESS ν SB project (2037~)

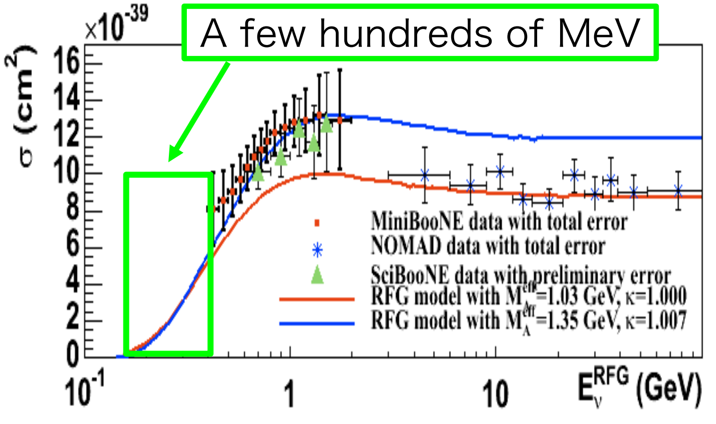
The ESS neutrino superbeam project (ESSnuSB)

Measure ν oscillations at the 2nd oscillation maximum, which is sensitive to CP violation.

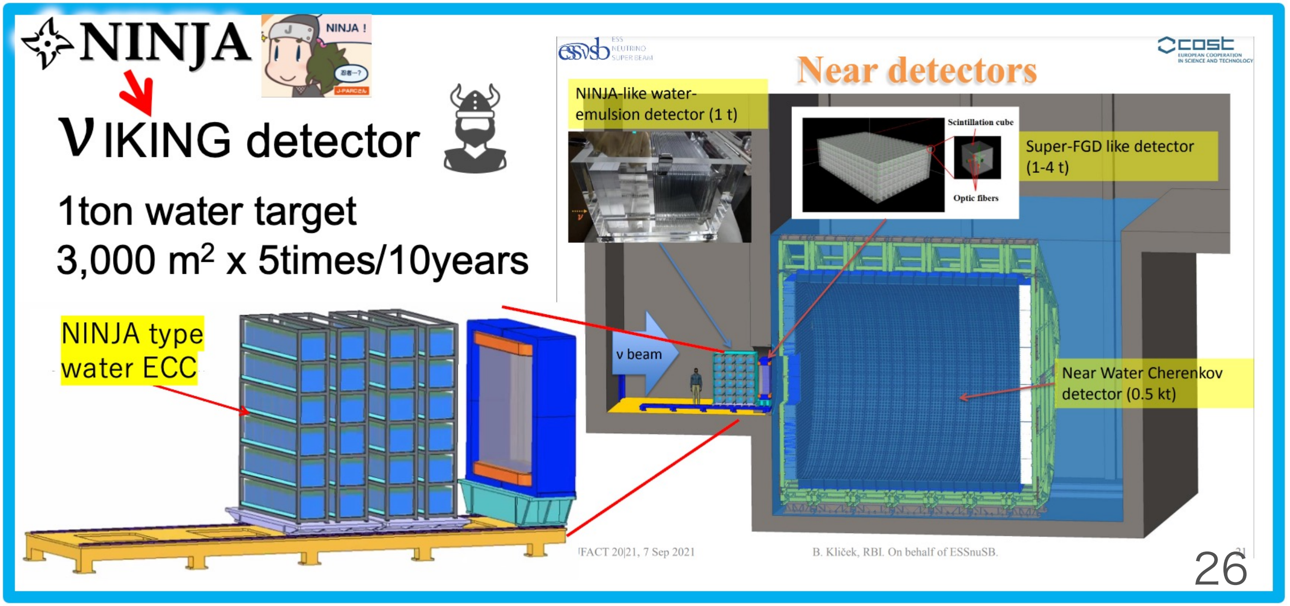
There is less data for ν int. in the energy region of interest.

→ It is essential to understand the ν int. in this energy region.





NINJA's Water ECC is also planned to install as a near detector.



NINJA

VIKING detector

1ton water target

3,000 m² x 5times/10years

NINJA type water ECC

Near detectors

NINJA-like water-emulsion detector (1 t)

Scintillation cube

Optic fibers

Super-FGD like detector (1-4 t)

ν beam

Near Water Cherenkov detector (0.5 kt)

FACT 20|21, 7 Sep 2021

B. Kliček, RBI. On behalf of ESSnuSB.

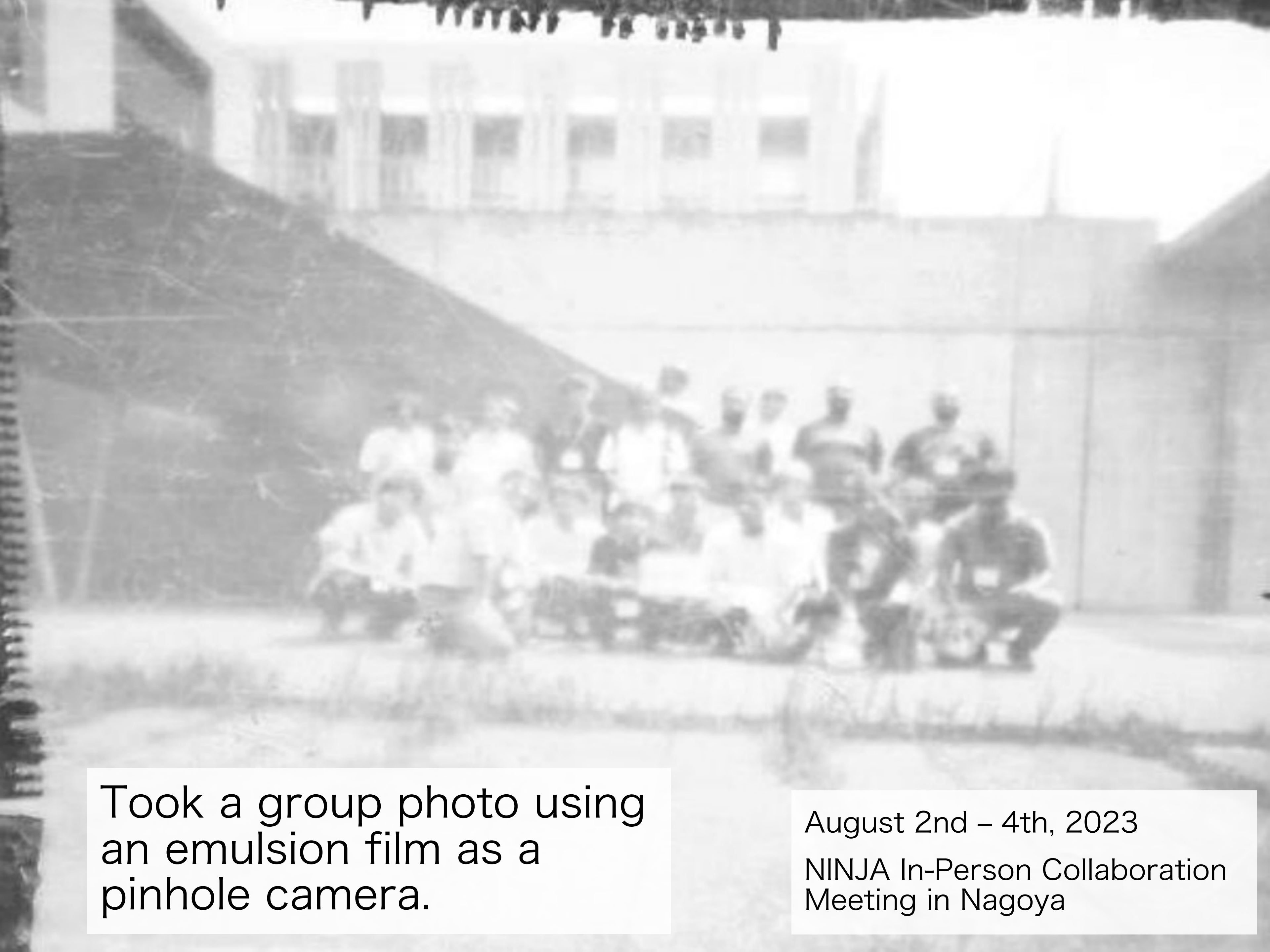
Summary

- NINJA aim to study ν - nucleus interactions using the emulsion detector.
- In the 65 kg iron & the 3 kg water target pilot runs, neutrino cross section and kinematics of muons, protons, and pions were measured.
- We aim to measure CCNπN'p cross sections and proton & pion differential cross sections each exclusive channels.
- To increase the statistics, we have performed Physics run E71a (2019-2020).
  We show the results using ~10% sub-sample of the total.
  Preparation of the full-dataset and the analysis is on-going.
- We also plan a next Physics run E71b in FY2023 and the preparation for emulsion detector is on-going.
- We also plan to conduct a large-scale "Heavy water" run in near future.
- In ESSνSB project, the NINJA Water ECC will be installed as a near detector.

Thank you for your attention!
Please enjoy our results and stay tuned for more!

August 2nd – 4th, 2023

NINJA In-Person Collaboration Meeting in Nagoya



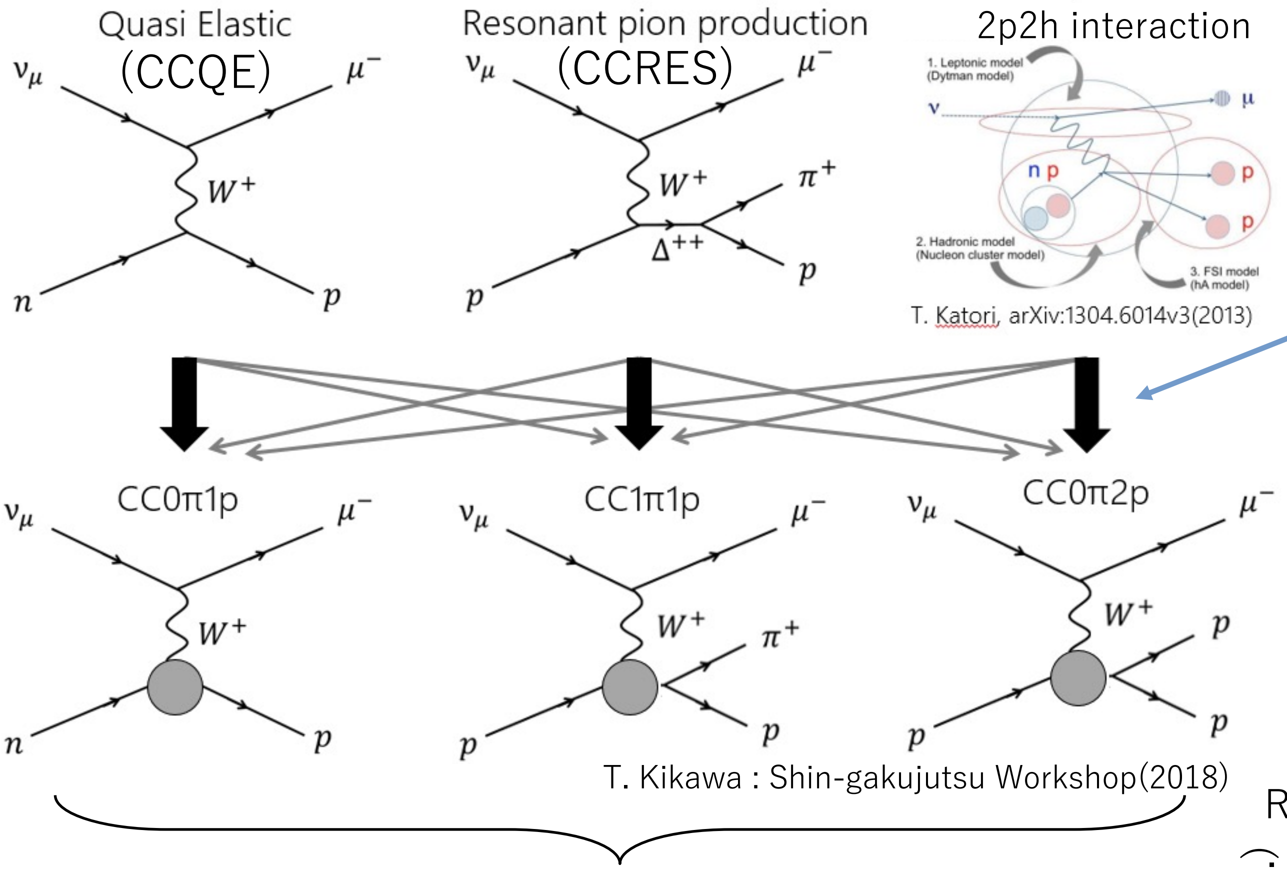
Took a group photo using an emulsion film as a pinhole camera.

August 2nd – 4th, 2023

NINJA In-Person Collaboration Meeting in Nagoya

Back up

Neutrino charged-current interactions in the 1 GeV energy region



T. Katori, arXiv:1304.6014v3(2013)

T. Kikawa : Shin-gakujutsu Workshop(2018)

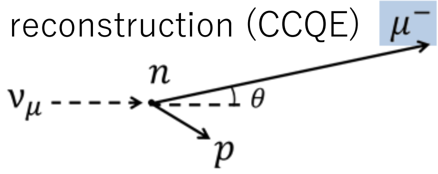
- hard to detect the low energy protons.
- pions can be re-scattered, charge exchanged or absorbed in nucleus.

Hard to separate interaction modes.

→ Neutrino energy reconstruction can be mistaken.

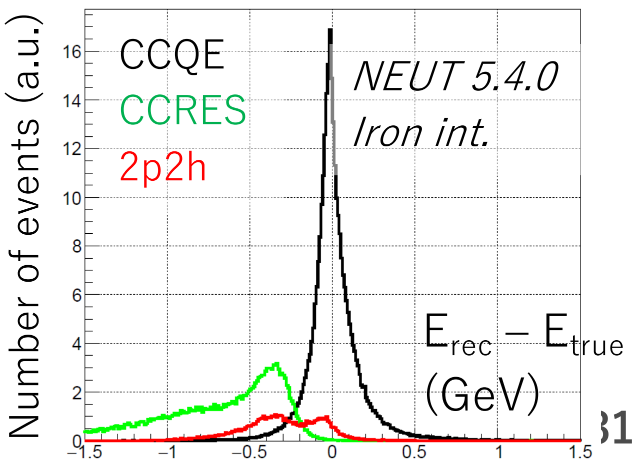
→ This is a major systematic uncertainty in neutrino oscillation experiments.

E_ν reconstruction (CCQE)



$$E_{\nu\ rec.} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu \cos\theta}$$

Residual of Neutrino Energy(MC)



What we can measure?

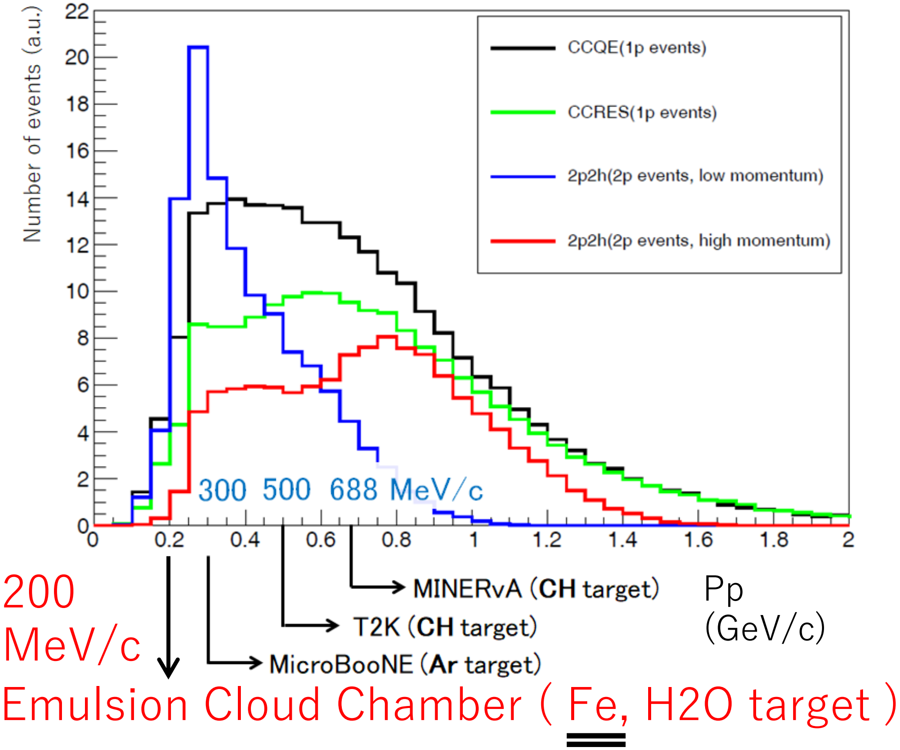
What we can measure to solve this problem :

- the number of charged hadrons
- their emission angles and momenta

with wide angle acceptance
and low energy threshold.

We use an emulsion-based detector, Emulsion Cloud Chamber(ECC), which has sub-micron position resolution with wide angle acceptance.

Proton momentum (MC)



It is a challenging task applying an emulsion detector techniques based on the high energy experiments!!

We report a measurement of the flux-averaged cross section of the ν_μ charged-current interaction using an emulsion detector.

Nuclear emulsion film

✔ A kind of silver halide photographic films.

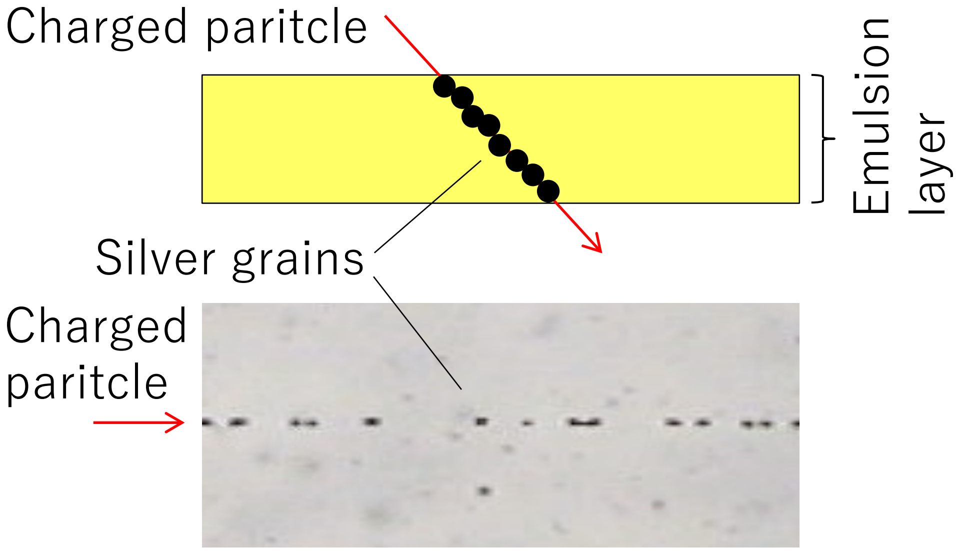
✔ Three-dimensional tracking detector for charged particles.

- Sub-μm spatial resolution
- No dead time

✔ It has been effective in detecting particles with short lifetimes.

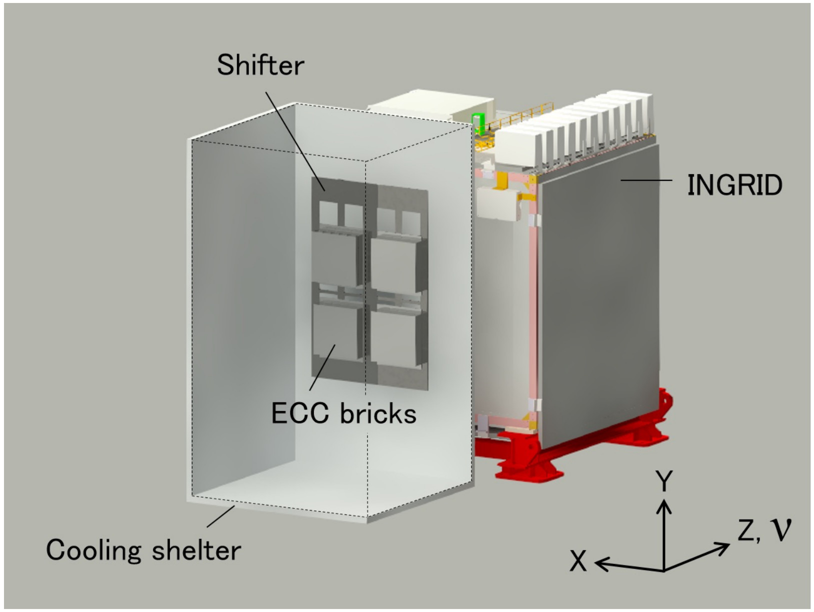
ex.) First observations of charm particles, tau-neutrinos,
and double-lambda hypernucleus.

Films (Yellow), Iron plates(Silver)



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

NINJA pilot experiment (65-kg iron target) : Detector

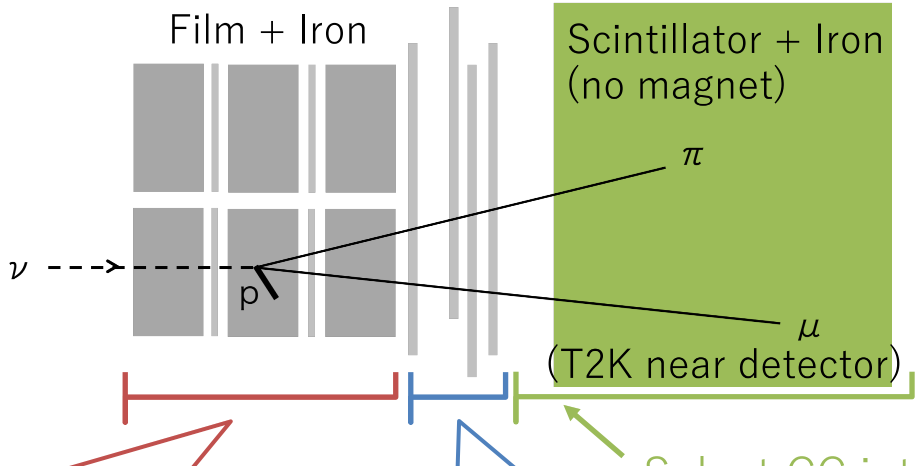


Side view

ECC

Shifter

INGRID
Muon range detector



Select CC int.

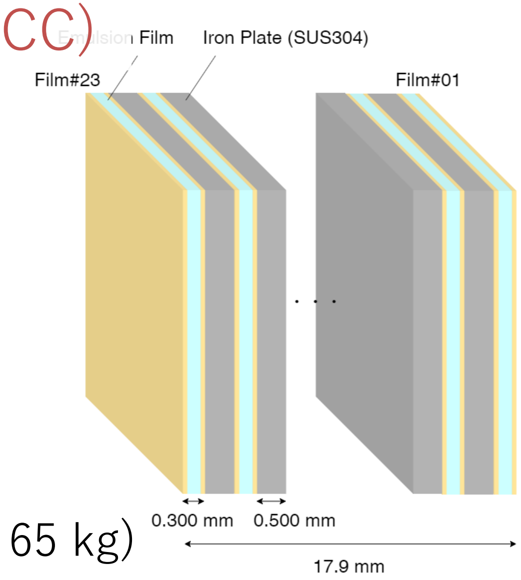
Emulsion Cloud Chamber (ECC)

Analyze ν -iron interactions

Emulsion film (iron plate) :
25cm× 25cm× 0.03 (0.05) cm

Each ECC brick :
23 films + 22 iron plates

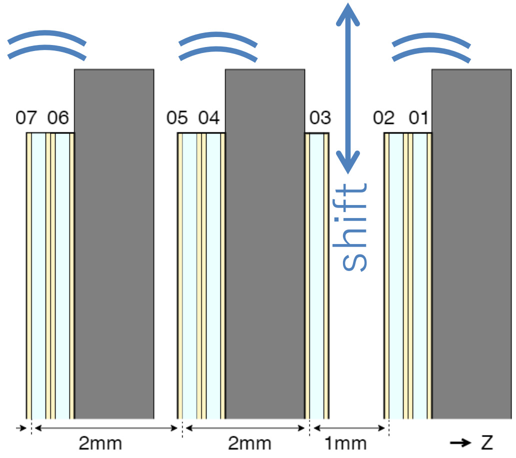
Total :
12 ECC bricks (264 iron plates, 65 kg)



Emulsion have no dead time, but do not have time resolution.

Shifter

Adds time information to the ECC tracks



Event reconstruction

(1) Track reconstruction in the ECC bricks

- Slope acceptance $|\tan\theta_{x(y)}| < 1.7$ ($|\theta_{x(y)}| < \sim 60^\circ$)
- Number of track segments > 2 segments.
- Detection efficiency of each film : 95-99%
- Track connection efficiency between films > 99%

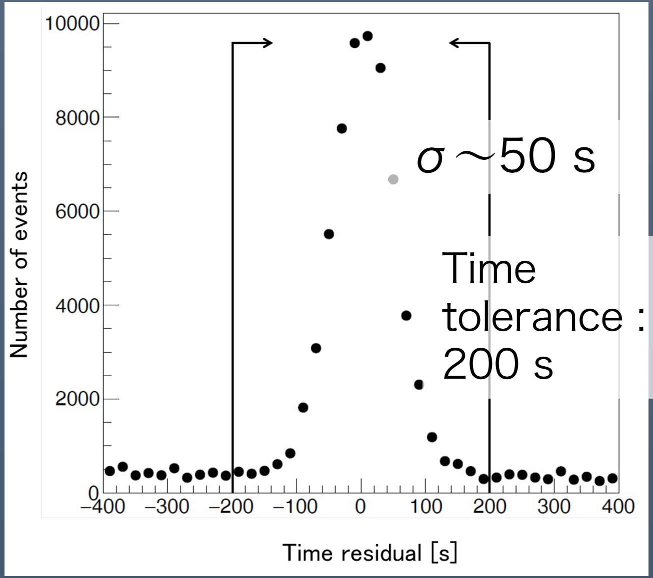
(2) Time-stamping to the ECC tracks

- Connection tolerances between stages:
  $|\Delta\tan\theta_{x(y)}| < 0.025, |\Delta x(y)| < 75\ \mu\mathrm{m}$
- Time resolution ~ 50 s (top figure)

(3) Track reconstruction in INGRID

- Events are required to have at least three active planes
  → muon momentum threshold ~ 300 MeV/c
- Tracks are required to start at the most upstream plane

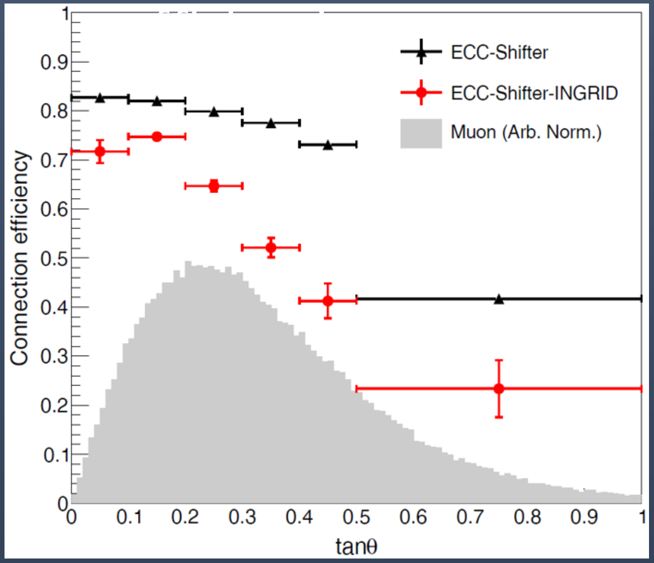
Time residuals between ECC events and INGRID



$\sigma \sim 50$ s

Time tolerance : 200 s

Connection



Event selection (1)

(1) ECC-Shifter-INGRID track matching

Muon candidates were selected by track matchings. Matching tolerances are below:

$|\Delta t| \leq 200\ \mathrm{s}, \left|\Delta \tan\theta_{x(y)}\right| < 0.100, |\Delta x(y)| < 5\ \mathrm{cm}$

(2) Scanback

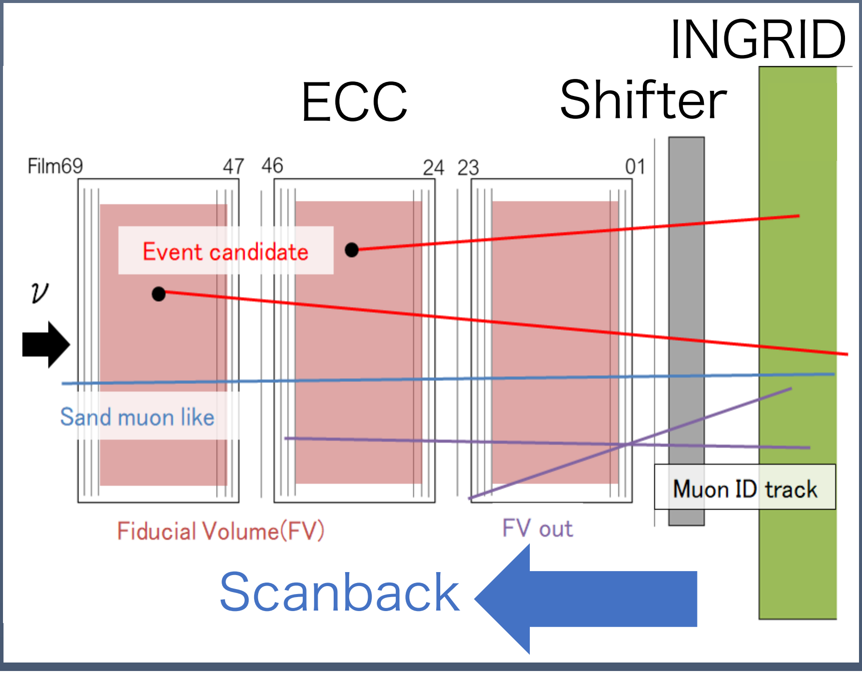
The muon candidates were traced back from INGRID to the interaction vertices. If no tracks with connection are fond in the three upstream films, the retracing is finished.

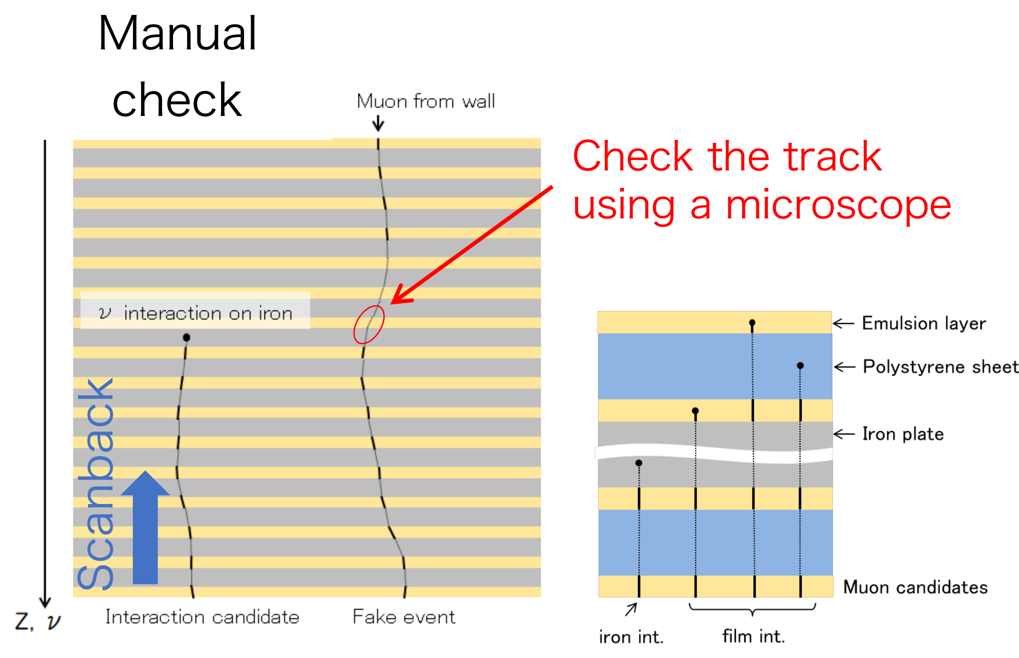
(3) FV cut

ν CC interactions in the FV were selected. Each average fiducial scanning area is 116mm×78mm.

(4) Manual microscope check

We check whether the muon tracks were present on the film using a microscope. ν-iron CC interactions in FV are selected.





Event selection (2)

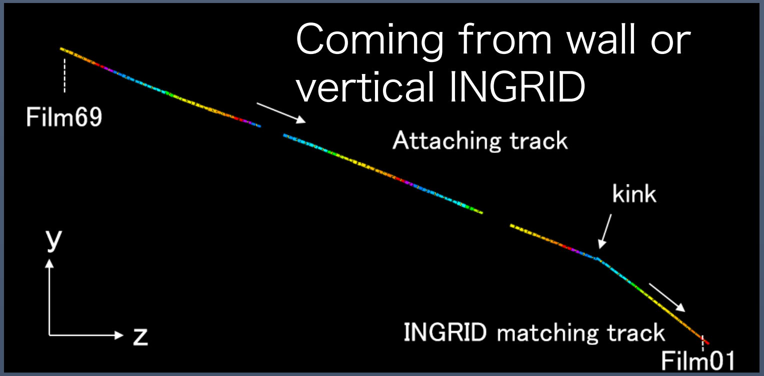
(5) Partner track search

p/π tracks were searched.
If multiple tracks for a particular event were connected to INGRID, the track with the highest momentum was assumed to be a muon candidate. Whereby two tracks were connected to INGRID, one of the events was discarded.

(6) Kink event cut

Two-track events consisting of a muon candidate and a pion-like track with an opening angle in the region of $\cos\theta_{op} < -0.96$ were assumed as kink events, and were discounted.

An event display of a kink event

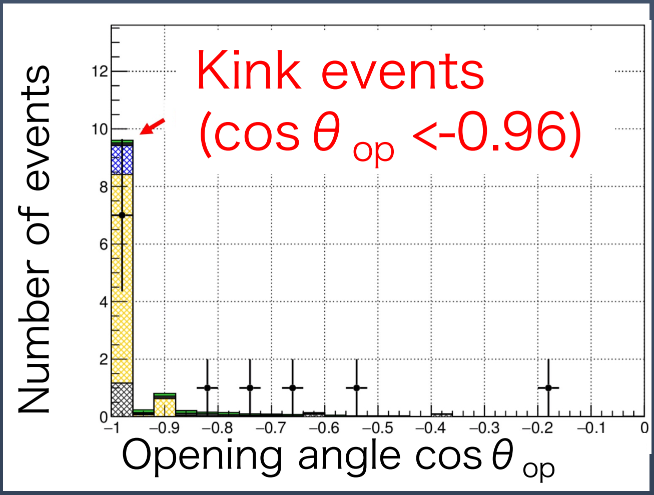


(7) Momentum consistency check

The muon momenta estimated by the MCS measurement in the ECC brick and the range-energy relation in the ECC and the INGRID module can be compared to exclude misconnected backgrounds.

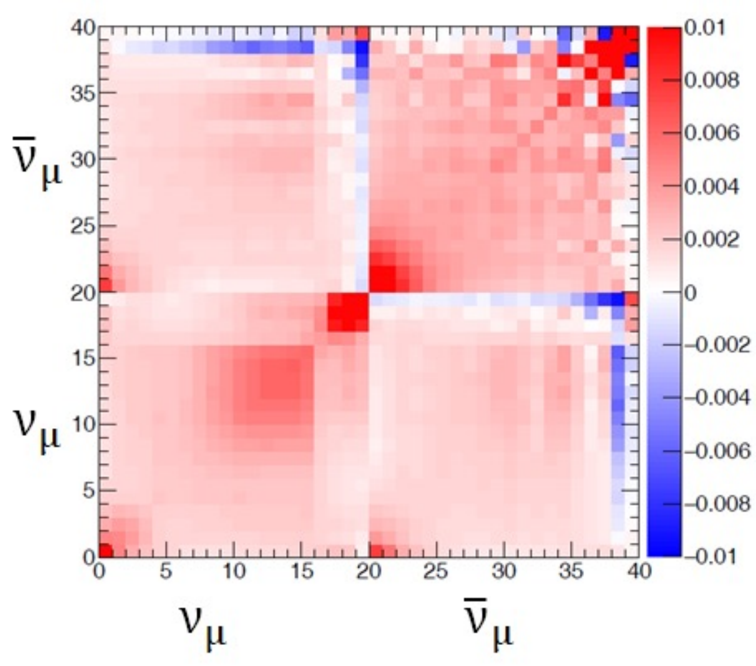
$p\beta_{MCS} > 2.18\ p\beta_{Range}$, $p\beta_{MCS} < 0.17\ p\beta_{Range}$
$p\beta_{MCS} > 3.52\ p\beta_{Range}$, $p\beta_{MCS} < 0.45\ p\beta_{Range}$

This criteria were based on the two-sigma confidenceinterval of the momentum measurement accuracy.



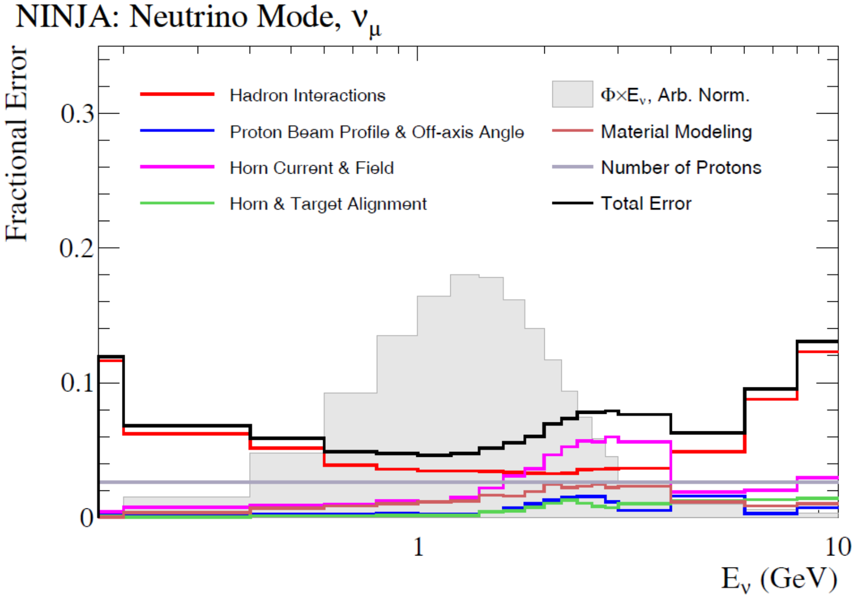
Covariance matrix of flux uncertainty (FHC)

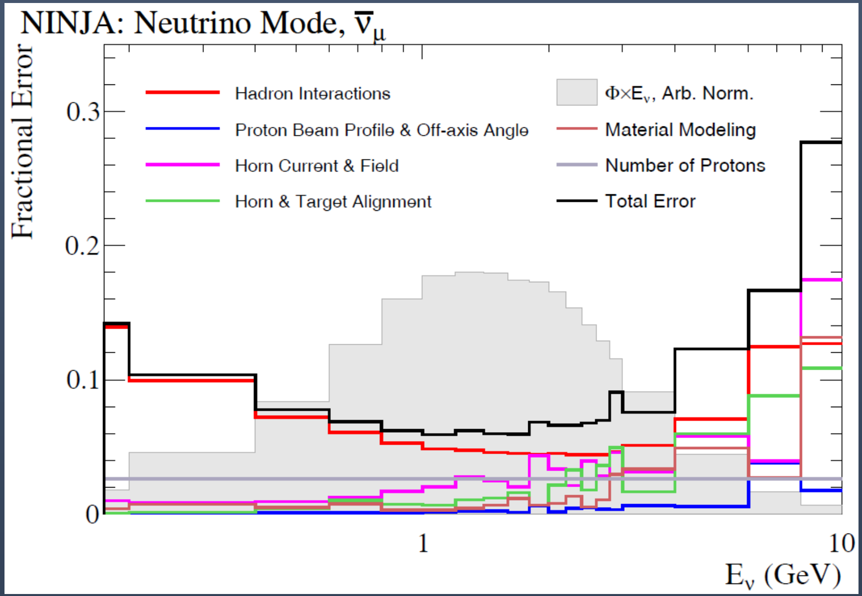
Covariance matrix



- Covariance matrix is calculated for INGRID module 4.
- Binning : [0.0,0.2,0.4,0.6,0.8,1.0,1.2,1.4,1.6,1.8,2.0,2.2,2.4, 2.6,2.8,3.0,4.0,6.0,8.0,10.0,30.0(GeV)]

Total uncertainties





Systematic uncertainty : Flux (FHC)

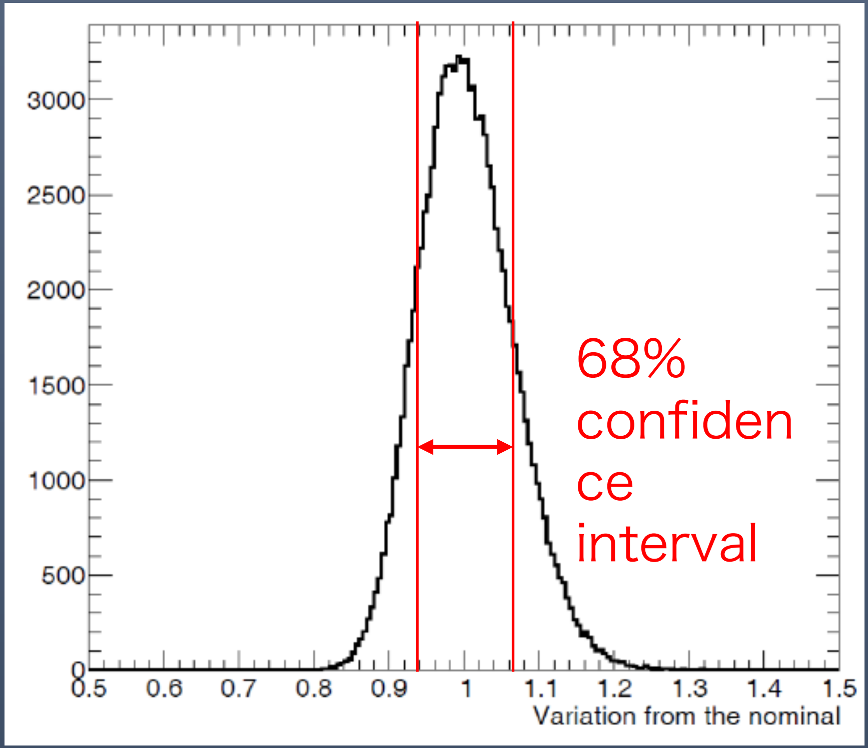
The neutrino flux fluctuates according to the covariance matrix 10^5 times and the ±1 σ change of the cross-section result is taken as systematic uncertainty.

Flux uncertainty of cross section is evaluated by fluctuating the number of backgrounds and the number of selected CC events.

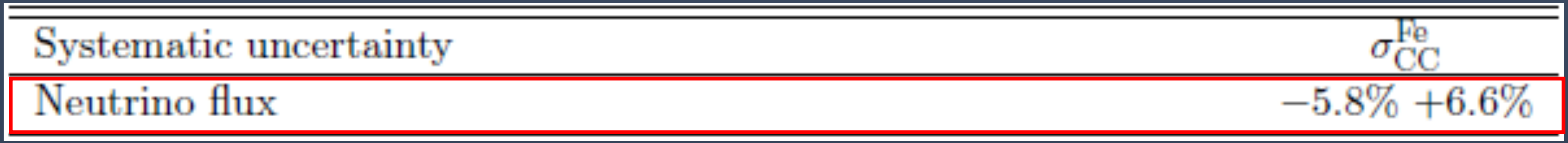
$$\sigma_{CC} = \frac{(N_{sel} - N_{bkg}) \times \sigma_{CC}^{MC}}{\sigma_{CC}^{MC} \times \varphi T \varepsilon} = \frac{(N_{sel} - N_{bkg}) \times \sigma_{CC}^{MC}}{N_{sel}^{MC}}$$

$$\frac{\sigma_{CC}^{variation}}{\sigma_{CC}^{nominal}} = \frac{(N_{sel} - N_{bkg}^{variation})/N_{sel}^{MC\ variation}}{(N_{sel} - N_{bkg}^{nominal})/N_{sel}^{MC\ nominal}}$$

Variation from the nominal.



The 68% confidence interval of the variation is defined as systematic uncertainty for cross-section result.



Systematic uncertainty	σ_{CC}^{Fe}
Neutrino flux	−5.8% +6.6%

Systematic uncertainties : Neutrino interaction models (FHC)

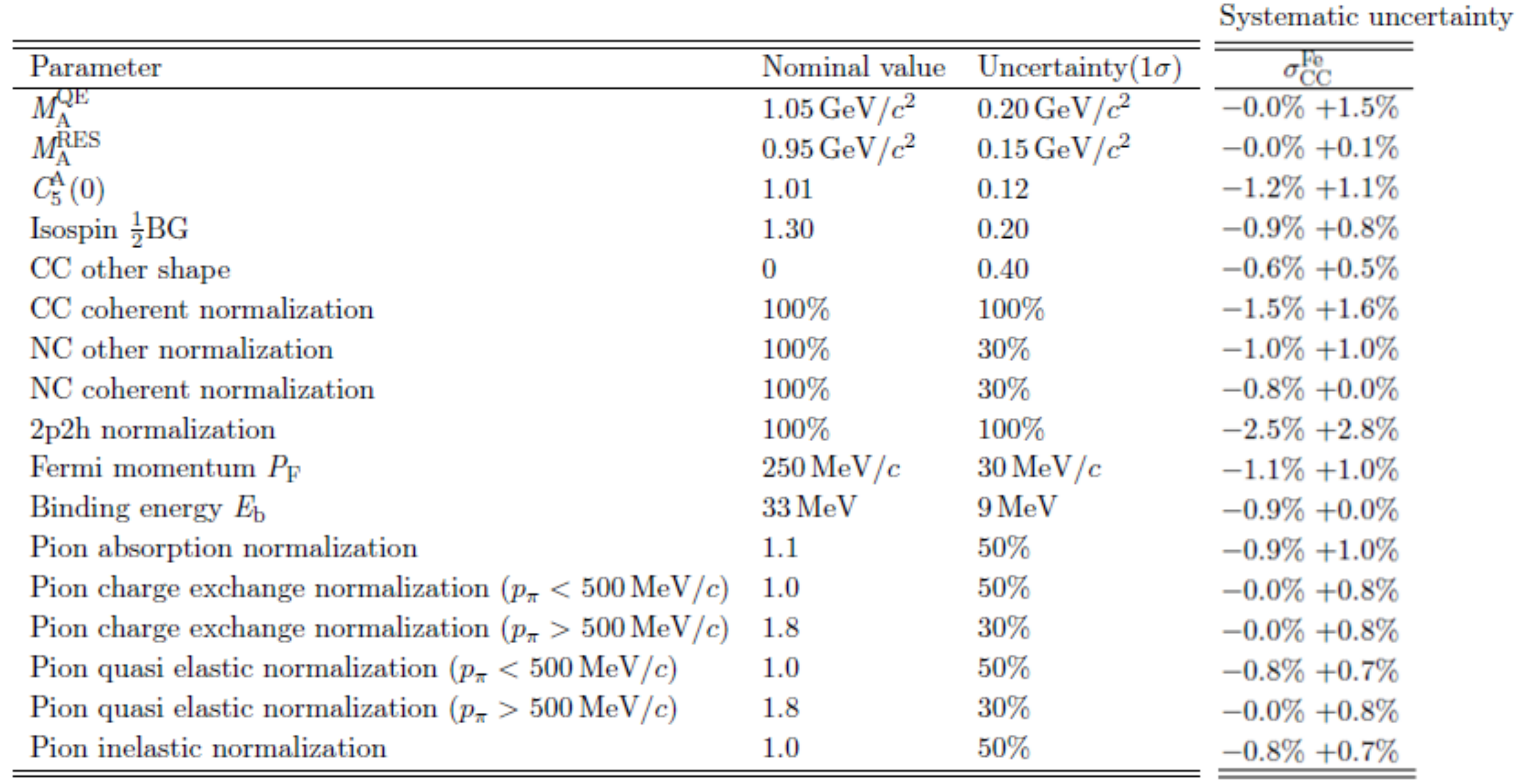
The variations of N_{bkg} and ε are evaluated by changing $\pm 1\sigma$ of each parameter.

$$\sigma_{CC} = \frac{N_{sel} - \boxed{N_{bkg}}}{\phi T \boxed{\varepsilon}}$$

The variation from the nominal is defined as uncertainties of cross-section result.

$$\delta\sigma_{CC} = \frac{\sigma_{CC}^{variation} - \sigma_{CC}^{nominal}}{\sigma_{CC}^{nominal}}$$

The nominal values and the 1σ uncertainties.



			Systematic uncertainty
Parameter	Nominal value	Uncertainty(1σ)	σ_{CC}^{Fe}
M_A^{QE}	$1.05\,\mathrm{GeV}/c^2$	$0.20\,\mathrm{GeV}/c^2$	−0.0% +1.5%
M_A^{RES}	$0.95\,\mathrm{GeV}/c^2$	$0.15\,\mathrm{GeV}/c^2$	−0.0% +0.1%
$C_5^A(0)$	1.01	0.12	−1.2% +1.1%
Isospin $\frac{1}{2}$BG	1.30	0.20	−0.9% +0.8%
CC other shape	0	0.40	−0.6% +0.5%
CC coherent normalization	100%	100%	−1.5% +1.6%
NC other normalization	100%	30%	−1.0% +1.0%
NC coherent normalization	100%	30%	−0.8% +0.0%
2p2h normalization	100%	100%	−2.5% +2.8%
Fermi momentum P_F	$250\,\mathrm{MeV}/c$	$30\,\mathrm{MeV}/c$	−1.1% +1.0%
Binding energy E_b	33 MeV	9 MeV	−0.9% +0.0%
Pion absorption normalization	1.1	50%	−0.9% +1.0%
Pion charge exchange normalization ($p_\pi < 500\,\mathrm{MeV}/c$)	1.0	50%	−0.0% +0.8%
Pion charge exchange normalization ($p_\pi > 500\,\mathrm{MeV}/c$)	1.8	30%	−0.0% +0.8%
Pion quasi elastic normalization ($p_\pi < 500\,\mathrm{MeV}/c$)	1.0	50%	−0.8% +0.7%
Pion quasi elastic normalization ($p_\pi > 500\,\mathrm{MeV}/c$)	1.8	30%	−0.0% +0.8%
Pion inelastic normalization	1.0	50%	−0.8% +0.7%

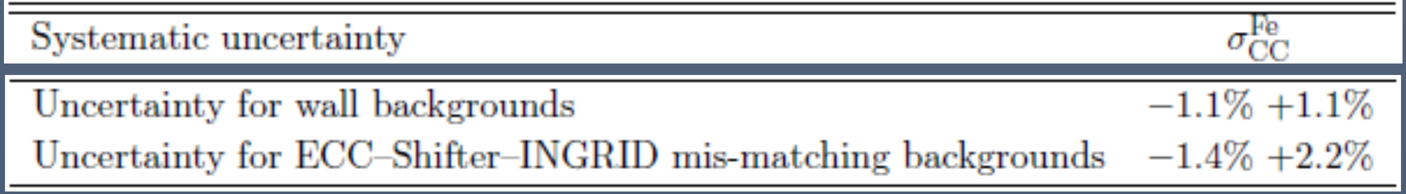
Total :
-4.1% / +4.6%

Systematic uncertainties : Background estimation (FHC)

The variations of N_{bkg} are evaluated, and the cross-section variations from the nominal are evaluated.

$$\sigma_{CC} = \frac{N_{\mathrm{sel}} - \boxed{N_{\mathrm{bkg}}}}{\phi T \varepsilon}$$

$$\delta\sigma_{CC} = \frac{\sigma_{CC}^{variation} - \sigma_{CC}^{nominal}}{\sigma_{CC}^{nominal}}$$



Systematic uncertainty	$\sigma_{\mathrm{CC}}^{\mathrm{Fe}}$
Uncertainty for wall backgrounds	−1.1% +1.1%
Uncertainty for ECC–Shifter–INGRID mis-matching backgrounds	−1.4% +2.2%

Total : -1.8% / +2.4%

Wall backgrounds

The number of sand muons in the MC simulation is normalized by the data.
The difference in the number of sand muons between the data and MC is 30%, which is defined as the syst. uncertainty.

ECC-Shifter-INGRID mis-matching background

The uncertainty attributed to misconnected events was evaluated using mock data, which are the combination of the nominal and fake data in which the time information of the ECC tracks is shifted.
The systematic uncertainty is -39% / +24%.

↑

asymmetric : because the misconnection rates between the beam-induced tracks and the cosmic-ray tracks are different.

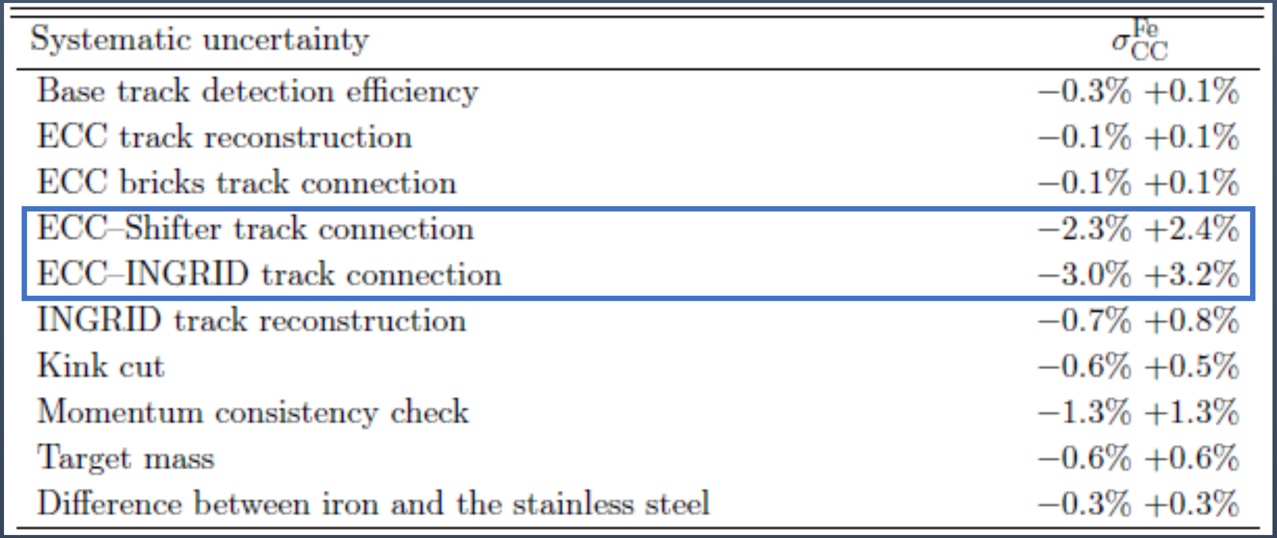
Systematic uncertainties : Detector response (FHC)

To evaluate the effect of the detector response uncertainties on the cross section, the MC simulations were run using each of the detector responses with their 1 σ uncertainty applied.

The variations of N_{bkg} and ε were evaluated, and the cross-section variations from the nominal were evaluated.

$$\sigma_{\mathrm{CC}} = \frac{N_{\mathrm{sel}} - \boxed{N_{\mathrm{bkg}}}}{\phi T \boxed{\varepsilon}}$$

$$\delta\sigma_{CC} = \frac{\sigma_{CC}^{variation} - \sigma_{CC}^{nominal}}{\sigma_{CC}^{nominal}}$$



Systematic uncertainty	$\sigma_{\mathrm{CC}}^{\mathrm{Fe}}$
Base track detection efficiency	-0.3% $+0.1\%$
ECC track reconstruction	-0.1% $+0.1\%$
ECC bricks track connection	-0.1% $+0.1\%$
ECC–Shifter track connection	-2.3% $+2.4\%$
ECC–INGRID track connection	-3.0% $+3.2\%$
INGRID track reconstruction	-0.7% $+0.8\%$
Kink cut	-0.6% $+0.5\%$
Momentum consistency check	-1.3% $+1.3\%$
Target mass	-0.6% $+0.6\%$
Difference between iron and the stainless steel	-0.3% $+0.3\%$

← Dominant error components

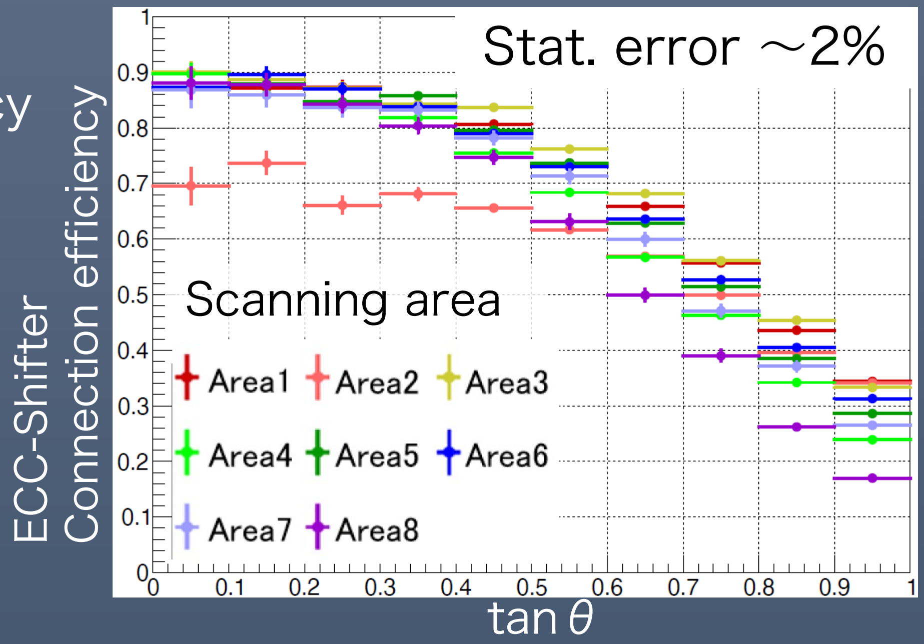
Total : -4.2% / +4.4%

Detector systematics : ECC-Shifter & ECC-INGRID connection

ECC-Shifter track connection

In the MC simulation, use the efficiency based on the data.

The statistical uncertainty of the data was defined as the syst. uncertainty.

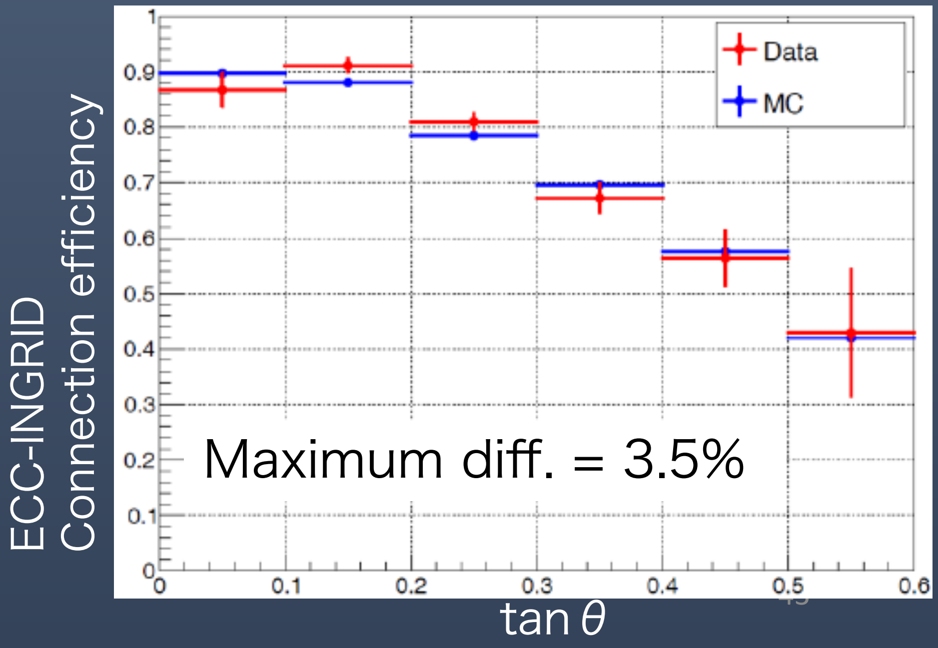


Stat. error ～2%

ECC-INGRID track connection

Same reconstruction processes were incorporated into the MC simulation.

Difference of the connection efficiency between the data and MC was defined as the syst. uncertainty.



Maximum diff. = 3.5%

Selection efficiency (RHC)

The efficiency is mainly determined by the following factors:

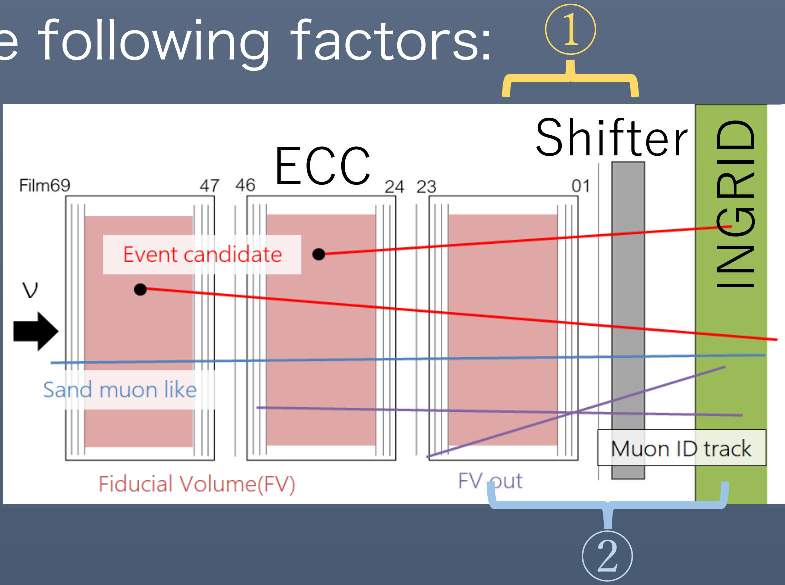
① ECC-Shifter connection

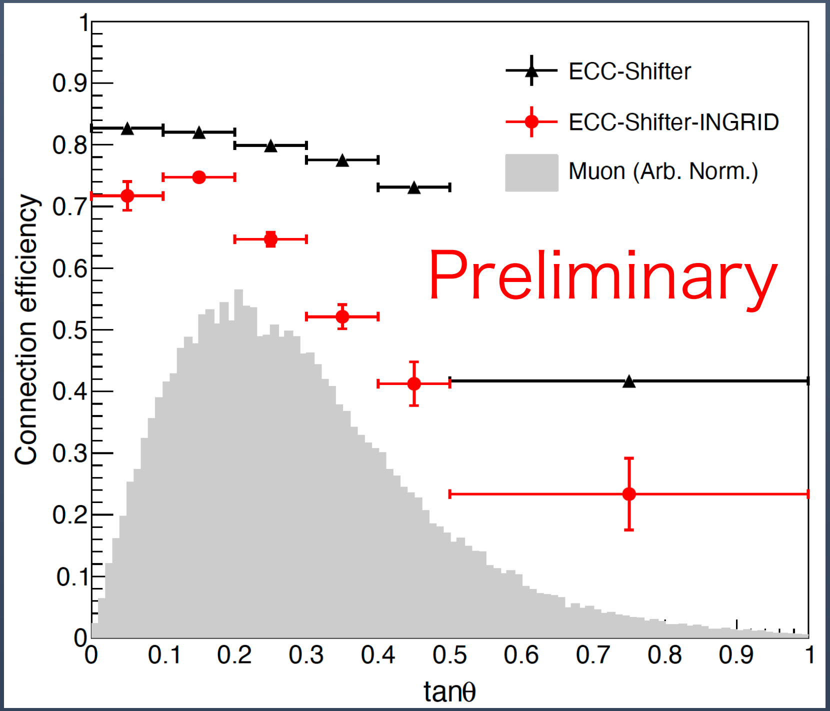
② ECC-INGRID connection

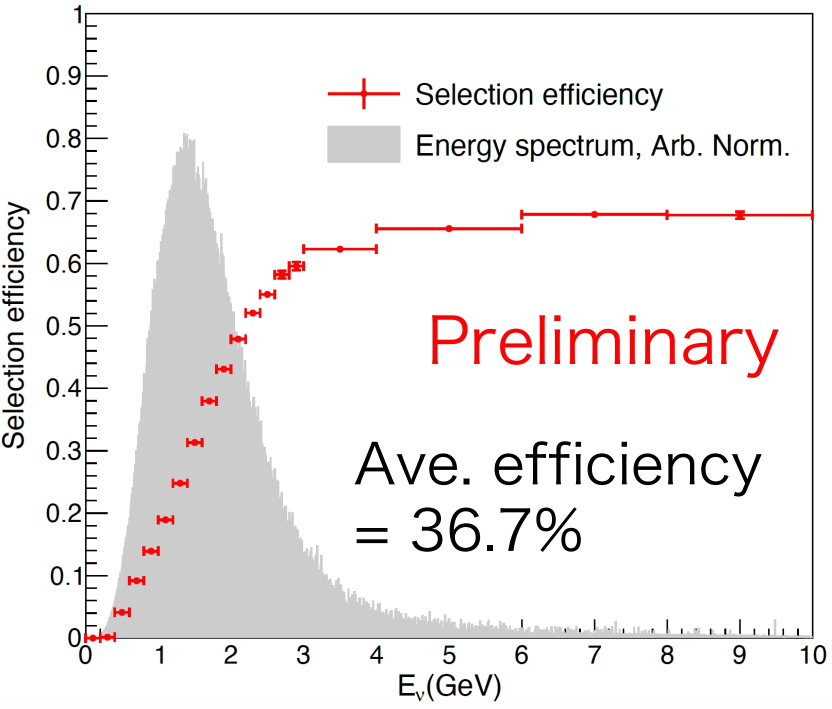
↑

Muon detection threshold is determined by the track connection among the ECC and INGRID.

$$\theta_\mu < \sim 45°, P_\mu > \sim 300\ \mathrm{MeV}/c$$







Ave. efficiency = 36.7%

Number of selected events and fractions (RHC)

Number of selected events remaining after each selection process.

Preliminary

Step	Data	MC	Purity
ECC–Shifter–INGRID track matching	38508		
Fiducial volume cut	926	-	
Manual microscope check	840	-	-
Partner track search	833	731.1	62.2%
Kink event cut	803	688.8	65.9%
Momentum consistency check	770	665.7	67.6%

Most events are muons of ν int. in the wall of the detector hall

$\bar{\nu}_\mu$-iron CC int. candidates

Signal and backgrounds	Fractions
$\bar{\nu}_\mu$ CC	67.6%
ν_μ	27.5%
Mis-matching events between ECC, Shifter, and INGRID (neutrino events, cosmic-ray events)	3.0%
Backgrounds from the wall of detector hall (neutron, proton, pion)	1.6%
$\bar{\nu}_\mu$ NC	0.2%
Others (INGRID module, ν_e and anti-ν_e)	< 0.1%

Signal events

Background events

Cross-section measurement (RHC)

In this analysis, we measured cross sections in full phase space and limited kinematic phase space, $\theta_\mu < 45°, P_\mu > 400\ \mathrm{MeV}/c$, respectively.

Number of selected events

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

Calculated based on the data

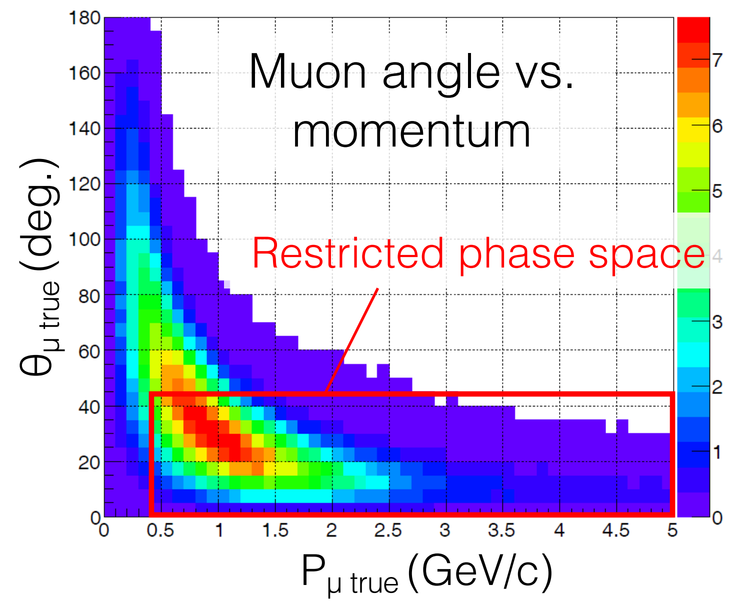
Evaluated using the MC

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

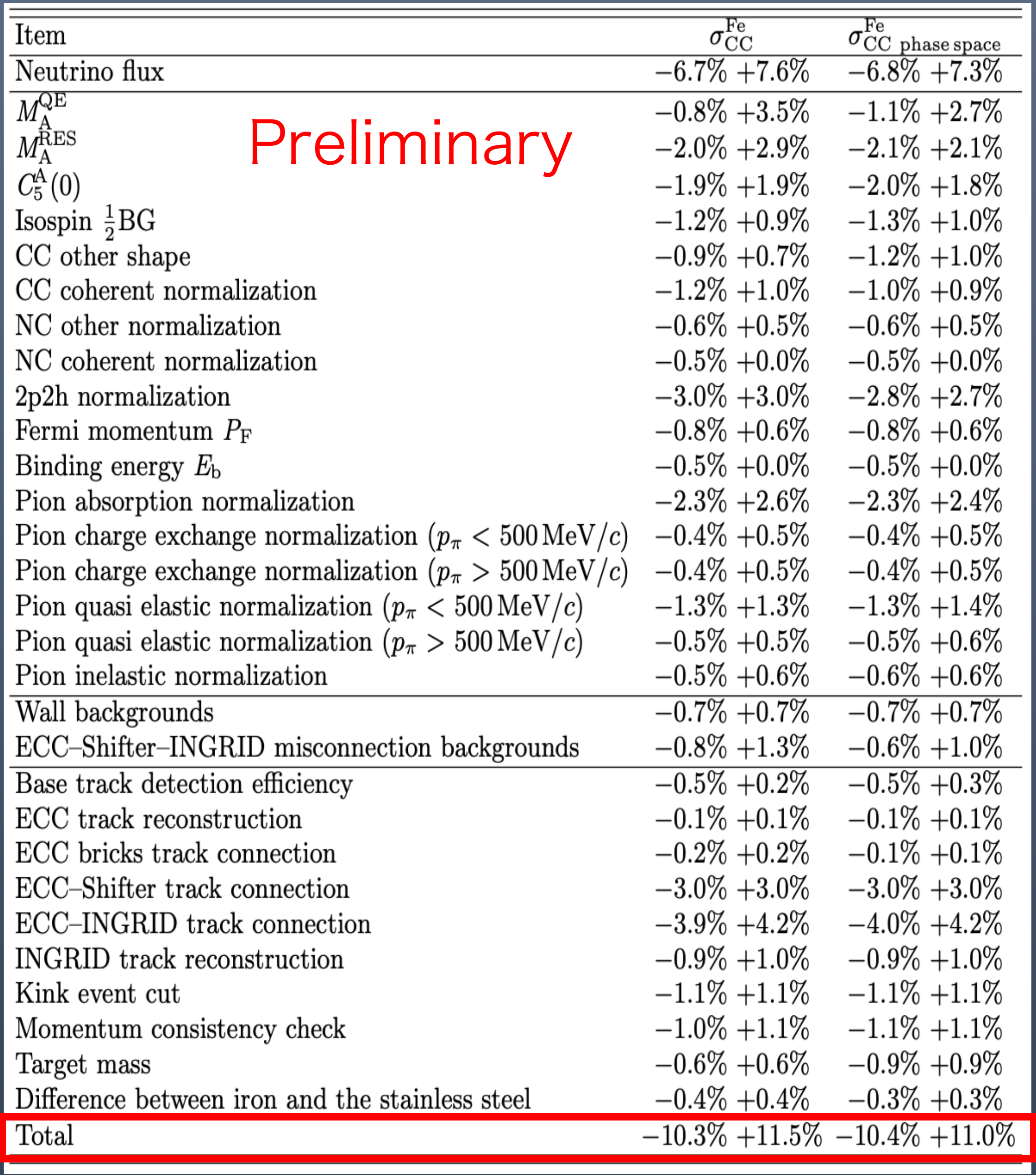
Cross section	N_{sel}	N_{bkg}	$\phi\ (\mathrm{cm}^{-2})$
σ^{Fe}_{CC}	770	215.9	1.27×10^{13}
$\sigma^{Fe}_{CC\ phase\ space}$	741	209.3	1.27×10^{13}

Preliminary

T (nucleons)	ε (%)
2.56×10^{28}	36.7
2.56×10^{28}	42.4



Summary of the systematic uncertainties (RHC)



Preliminary

Item	$\sigma^{\mathrm{Fe}}_{\mathrm{CC}}$	$\sigma^{\mathrm{Fe}}_{\mathrm{CC\ phase\ space}}$
Neutrino flux	−6.7% +7.6%	−6.8% +7.3%
$M_{\mathrm{A}}^{\mathrm{QE}}$	−0.8% +3.5%	−1.1% +2.7%
$M_{\mathrm{A}}^{\mathrm{RES}}$	−2.0% +2.9%	−2.1% +2.1%
$C_5^{\mathrm{A}}(0)$	−1.9% +1.9%	−2.0% +1.8%
Isospin $\frac{1}{2}$BG	−1.2% +0.9%	−1.3% +1.0%
CC other shape	−0.9% +0.7%	−1.2% +1.0%
CC coherent normalization	−1.2% +1.0%	−1.0% +0.9%
NC other normalization	−0.6% +0.5%	−0.6% +0.5%
NC coherent normalization	−0.5% +0.0%	−0.5% +0.0%
2p2h normalization	−3.0% +3.0%	−2.8% +2.7%
Fermi momentum P_{F}	−0.8% +0.6%	−0.8% +0.6%
Binding energy E_{b}	−0.5% +0.0%	−0.5% +0.0%
Pion absorption normalization	−2.3% +2.6%	−2.3% +2.4%
Pion charge exchange normalization ($p_\pi < 500\,\mathrm{MeV}/c$)	−0.4% +0.5%	−0.4% +0.5%
Pion charge exchange normalization ($p_\pi > 500\,\mathrm{MeV}/c$)	−0.4% +0.5%	−0.4% +0.5%
Pion quasi elastic normalization ($p_\pi < 500\,\mathrm{MeV}/c$)	−1.3% +1.3%	−1.3% +1.4%
Pion quasi elastic normalization ($p_\pi > 500\,\mathrm{MeV}/c$)	−0.5% +0.5%	−0.5% +0.6%
Pion inelastic normalization	−0.5% +0.6%	−0.6% +0.6%
Wall backgrounds	−0.7% +0.7%	−0.7% +0.7%
ECC–Shifter–INGRID misconnection backgrounds	−0.8% +1.3%	−0.6% +1.0%
Base track detection efficiency	−0.5% +0.2%	−0.5% +0.3%
ECC track reconstruction	−0.1% +0.1%	−0.1% +0.1%
ECC bricks track connection	−0.2% +0.2%	−0.1% +0.1%
ECC–Shifter track connection	−3.0% +3.0%	−3.0% +3.0%
ECC–INGRID track connection	−3.9% +4.2%	−4.0% +4.2%
INGRID track reconstruction	−0.9% +1.0%	−0.9% +1.0%
Kink event cut	−1.1% +1.1%	−1.1% +1.1%
Momentum consistency check	−1.0% +1.1%	−1.1% +1.1%
Target mass	−0.6% +0.6%	−0.9% +0.9%
Difference between iron and the stainless steel	−0.4% +0.4%	−0.3% +0.3%
Total	−10.3% +11.5%	−10.4% +11.0%

Full phase space
(Restricted phase space)

Flux :
–6.7% / +7.6%
(–6.8% / +7.3%)

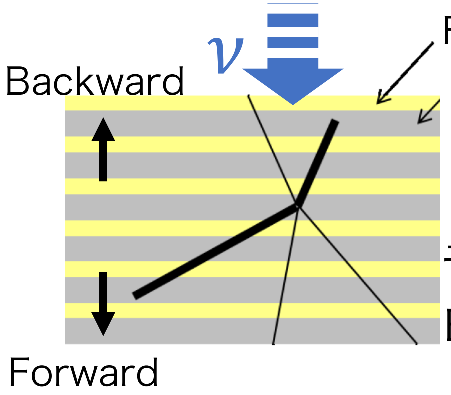
Neutrino interaction model :
–5.5% / +6.8%
(–5.6% / +5.9%)

Background estimation :
–1.0% / +1.4%
(–0.9% / +1.2%)

Detector response :
–5.3% / +5.5%
(–5.4% / +5.6%)

Proton / pion track search

- p/π tracks were searched using a minimum distance (MD) from the muon track.



MD allowance

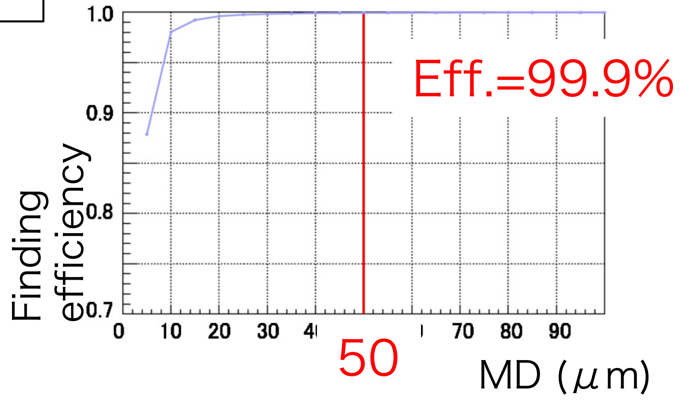
Thin track : 50 μm

Black track : 60 μm

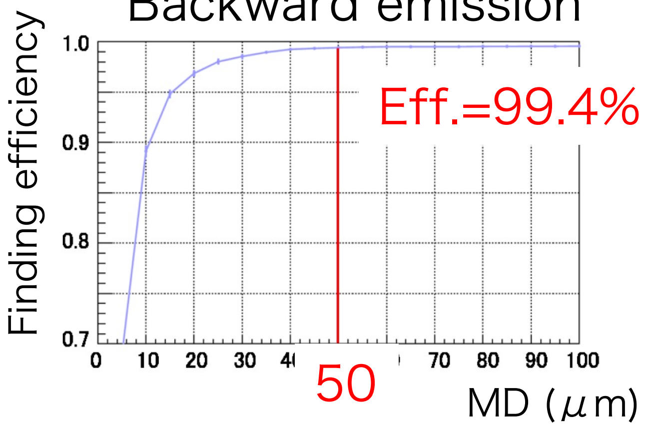
MC study

Thin tracks (MIPs)

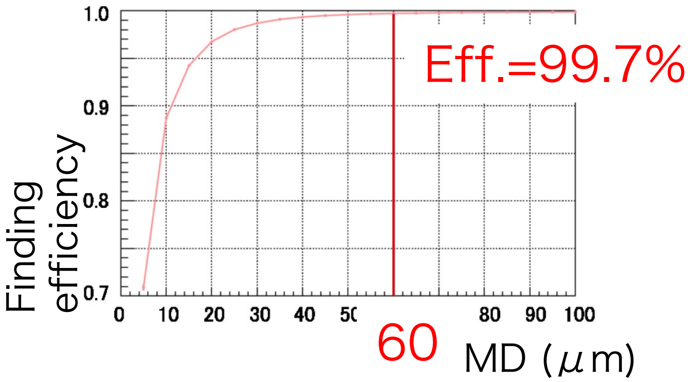
Forward emission

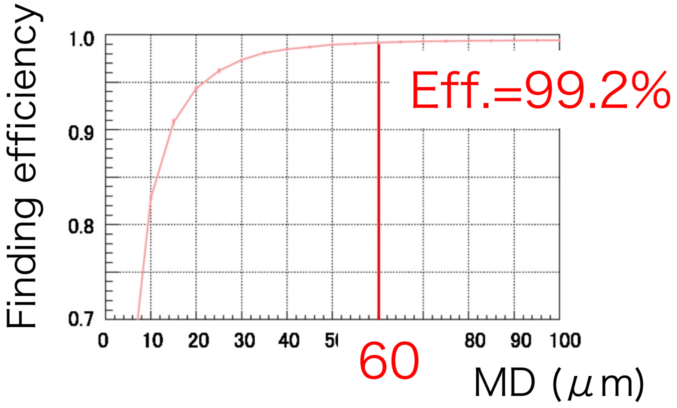


Backward emission



Black tracks (Heavily ionizing particles)



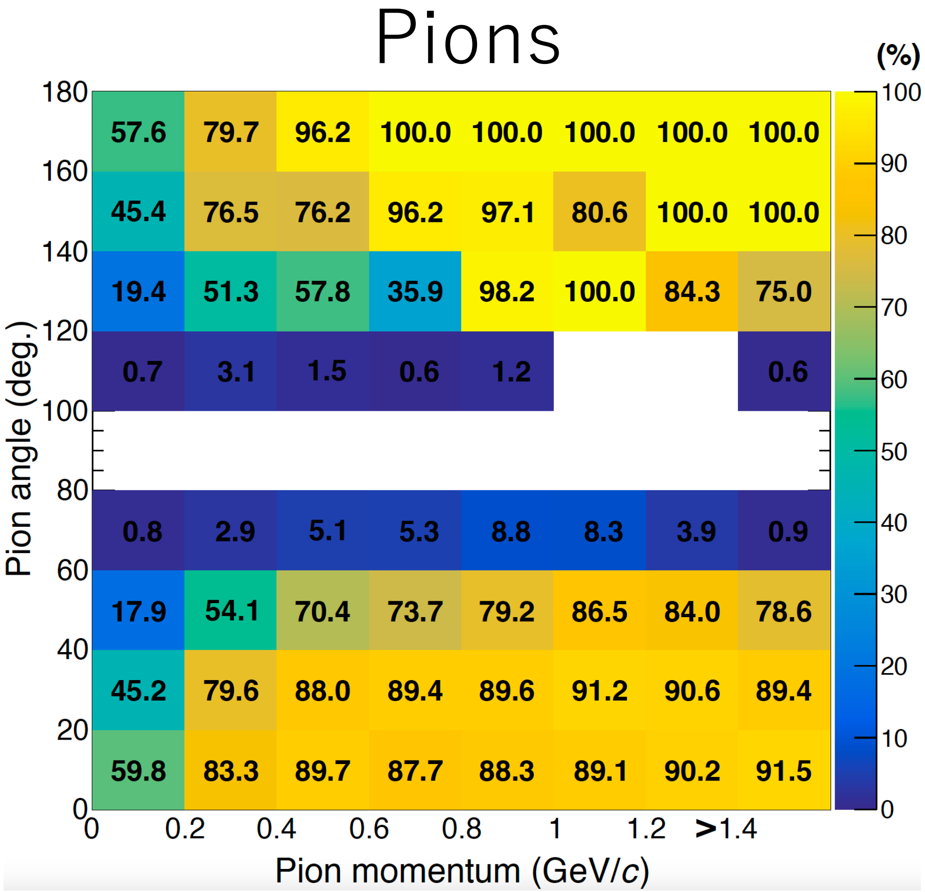


Detection efficiencies of pions and protons (FHC)

- Thin (Black) tracks are required to have at least three (two) track segments.

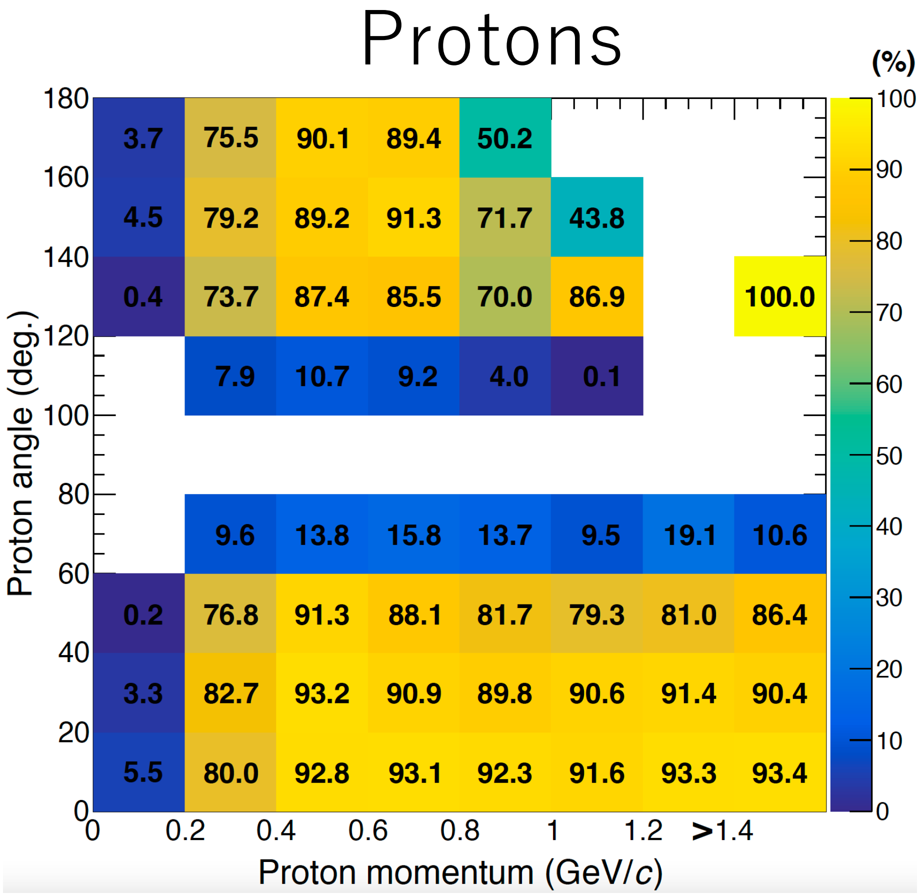
  → the momentum threshold for pions (protons) is 50 MeV/c (200 MeV/c).

- Angle acceptance: $|\theta_{x(y)}| < \sim 60°$



Pions

57.6	79.7	96.2	100.0	100.0	100.0	100.0	100.0
45.4	76.5	76.2	96.2	97.1	80.6	100.0	100.0
19.4	51.3	57.8	35.9	98.2	100.0	84.3	75.0
0.7	3.1	1.5	0.6	1.2			0.6
0.8	2.9	5.1	5.3	8.8	8.3	3.9	0.9
17.9	54.1	70.4	73.7	79.2	86.5	84.0	78.6
45.2	79.6	88.0	89.4	89.6	91.2	90.6	89.4
59.8	83.3	89.7	87.7	88.3	89.1	90.2	91.5



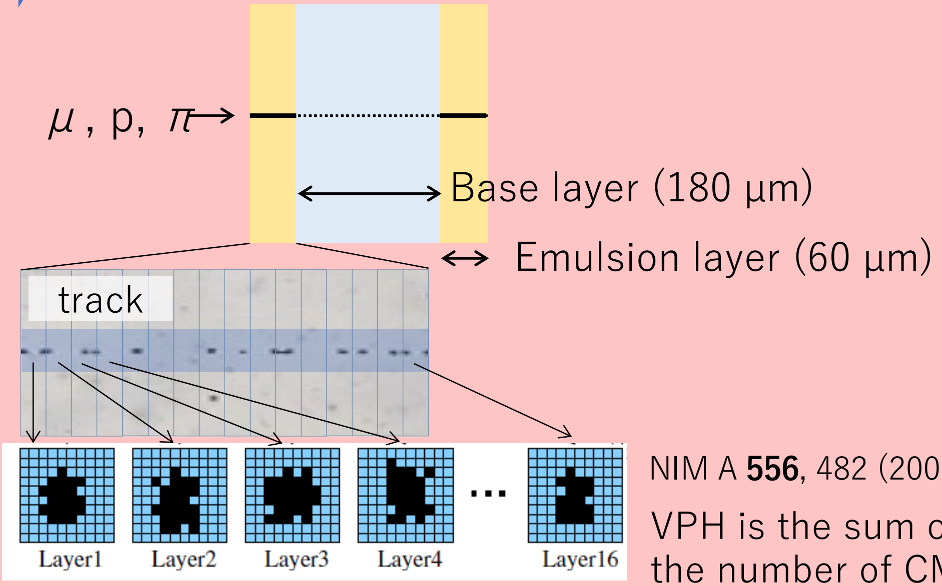
Protons

3.7	75.5	90.1	89.4	50.2			
4.5	79.2	89.2	91.3	71.7	43.8		
0.4	73.7	87.4	85.5	70.0	86.9		100.0
	7.9	10.7	9.2	4.0	0.1		
	9.6	13.8	15.8	13.7	9.5	19.1	10.6
0.2	76.8	91.3	88.1	81.7	79.3	81.0	86.4
3.3	82.7	93.2	90.9	89.8	90.6	91.4	90.4
5.5	80.0	92.8	93.1	92.3	91.6	93.3	93.4

dE/dx measurments in the ECC brick

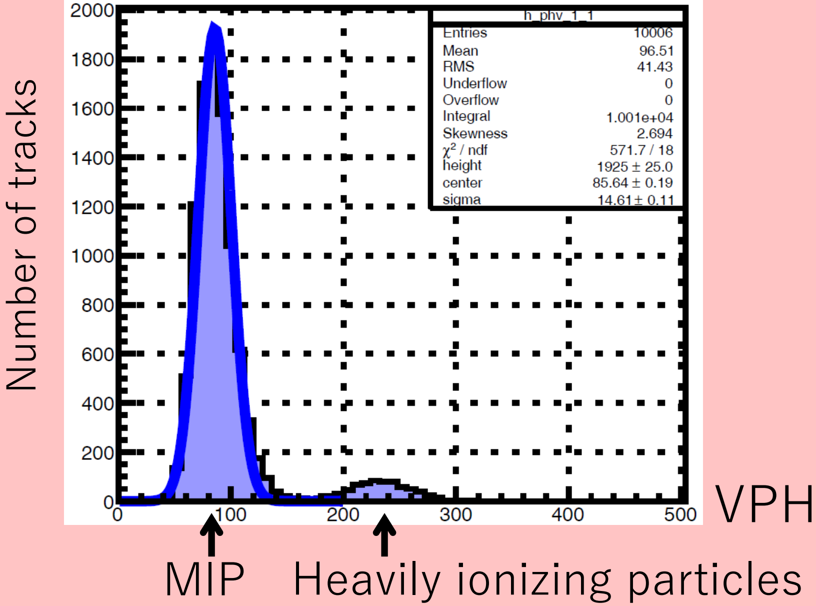
Volume Pulse Height (VPH)

- **VPH is a measure of dE/dx.**

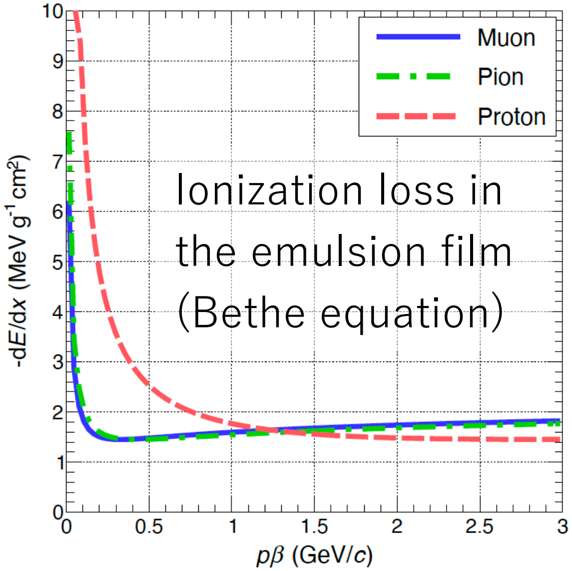


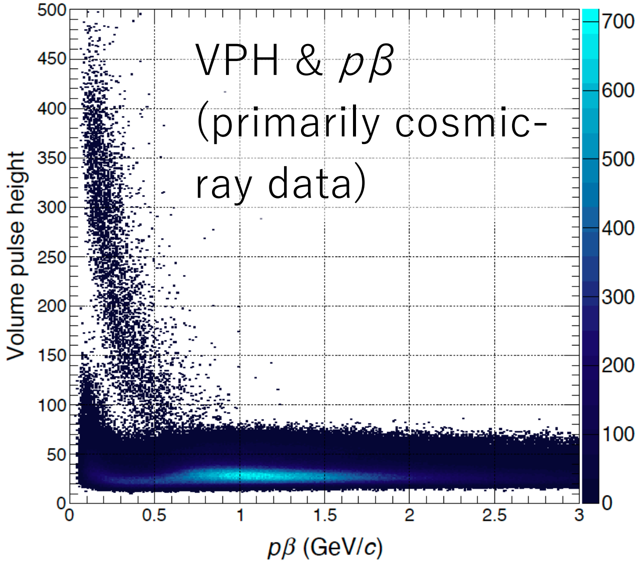
NIM A **556**, 482 (2006).

VPH distribution (ECC tracks)



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

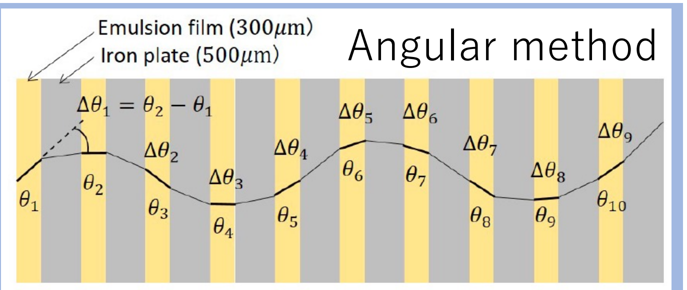




MIPs & HIPs can be well separated using the VPH & $p\beta$!

Momentum measurments in the ECC brick

- **Range – energy relation for a short track**
- **Measurement of Multiple Coulomb Scattering**
  - Angular method — Measurements of the angular difference.
  - Coordinate method — Measurements of the positional displacement.



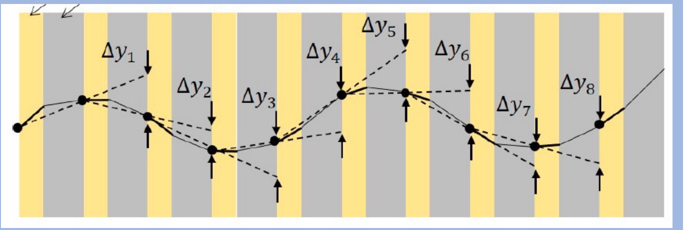
Momentum resolution	Muon	Pion	Proton
Angular method	43.0%	29.6%	36.0%
Coordinate method	25.9%	25.2%	30.7%
Range-energy relation	6.4%	-	3.8%

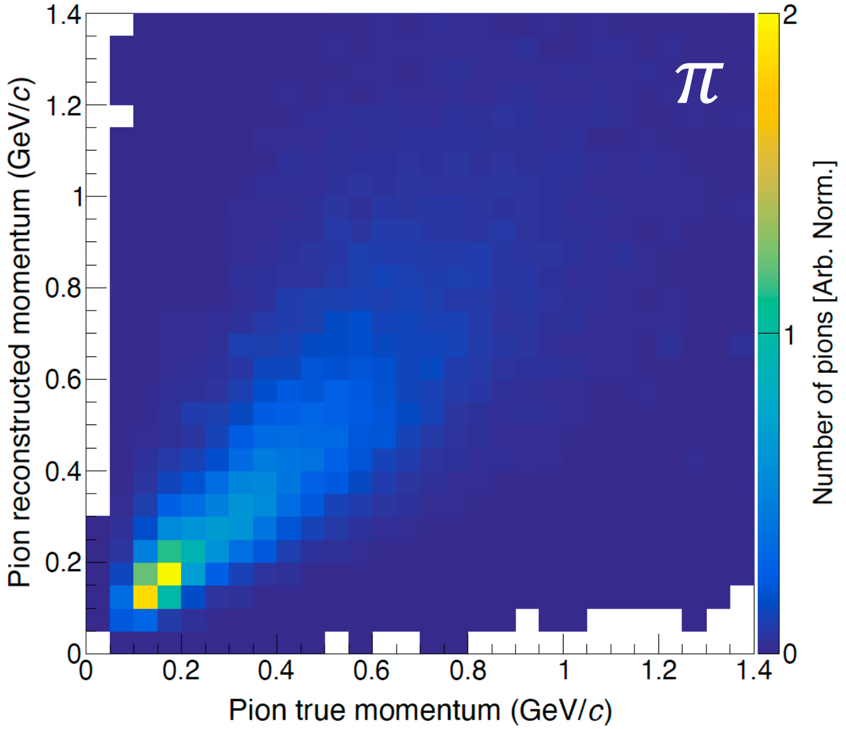
Angle & position meas. uncertainty

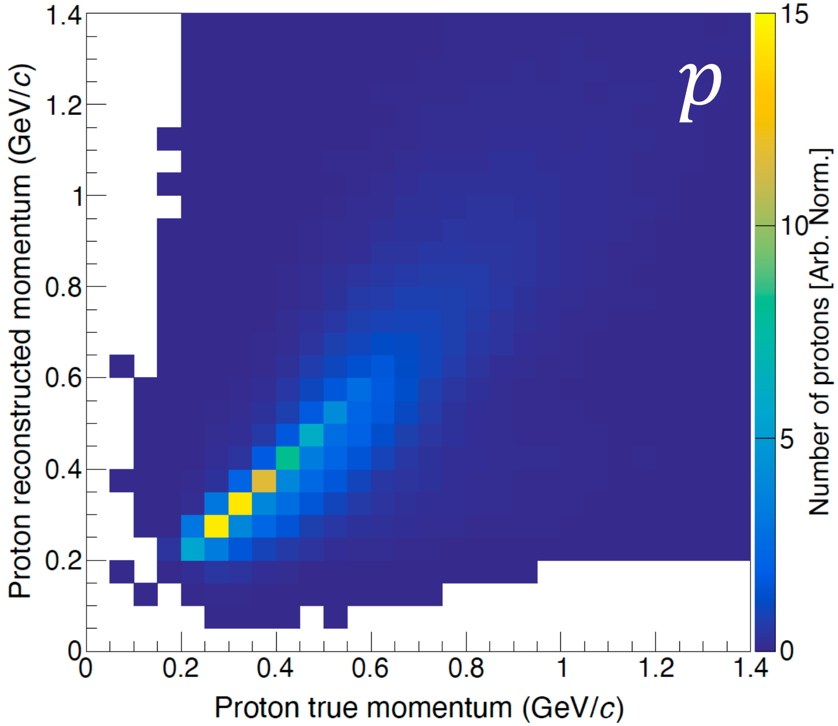
$\Delta\theta_{err} \sim 0.1^\circ$

$\Delta y_{err} \sim 3\ \mu m$

Coordinate method







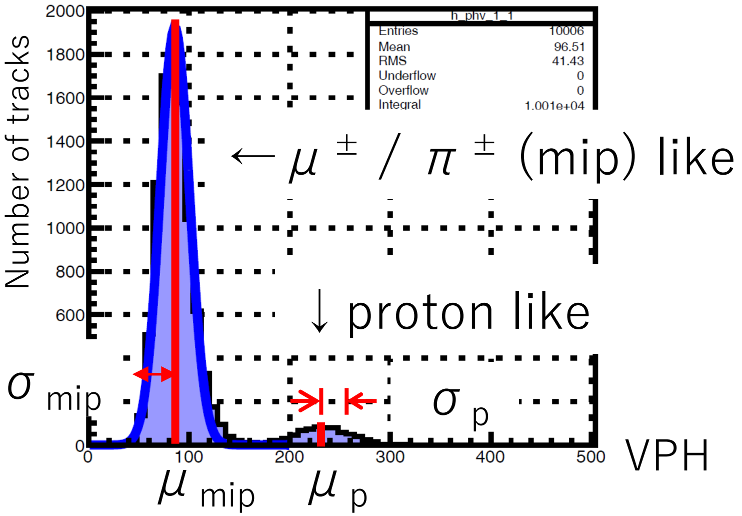
Particle identification of protons and pions (FHC)

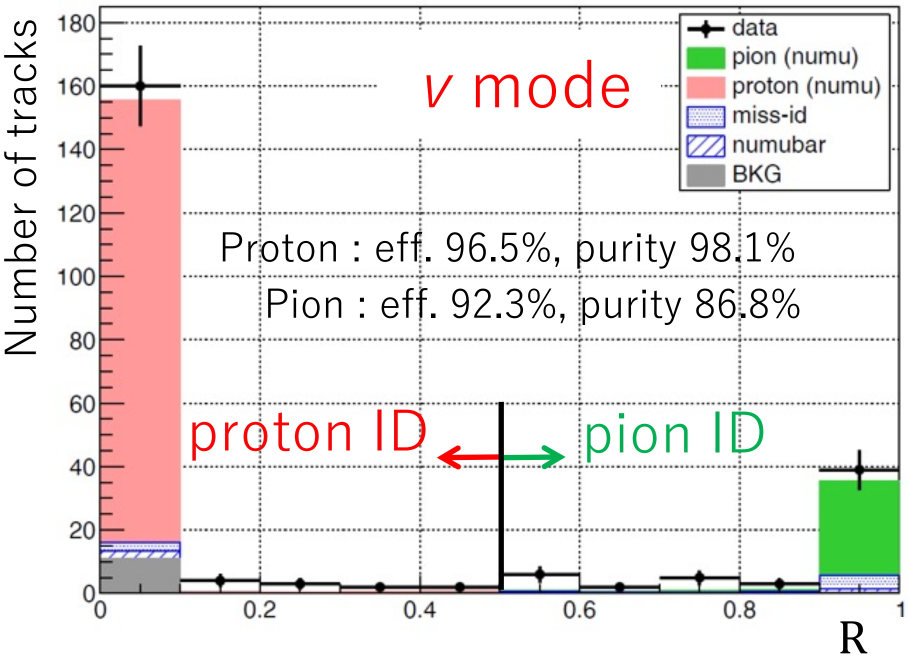
Likelihood function

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

Likelihood Ratio

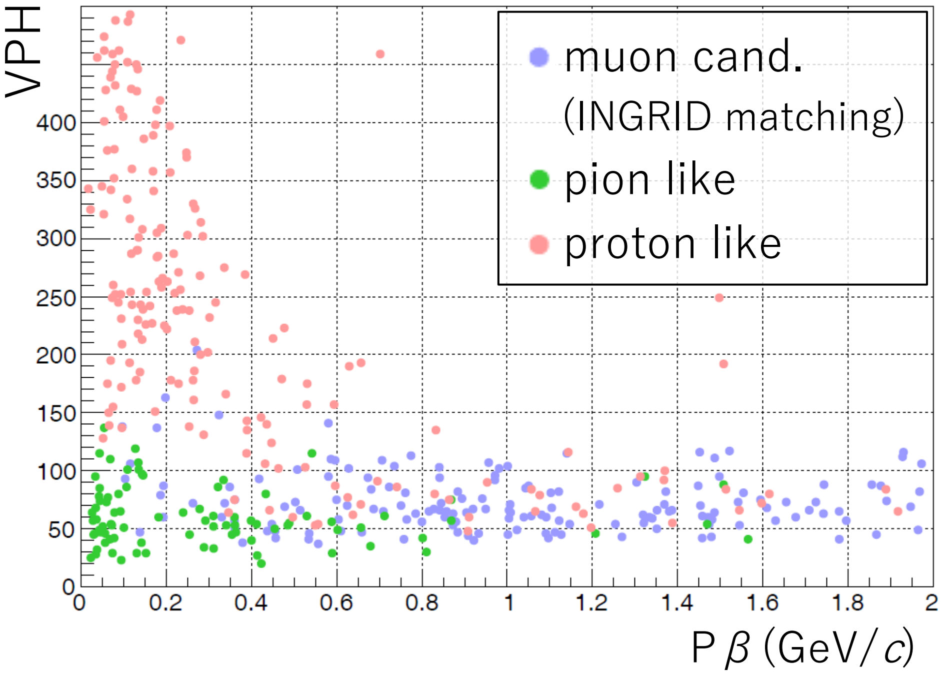
$$R = \frac{L_{mip\ like}}{L_{mip\ like}+L_{proton\ like}}$$





Proton : eff. 96.5%, purity 98.1%

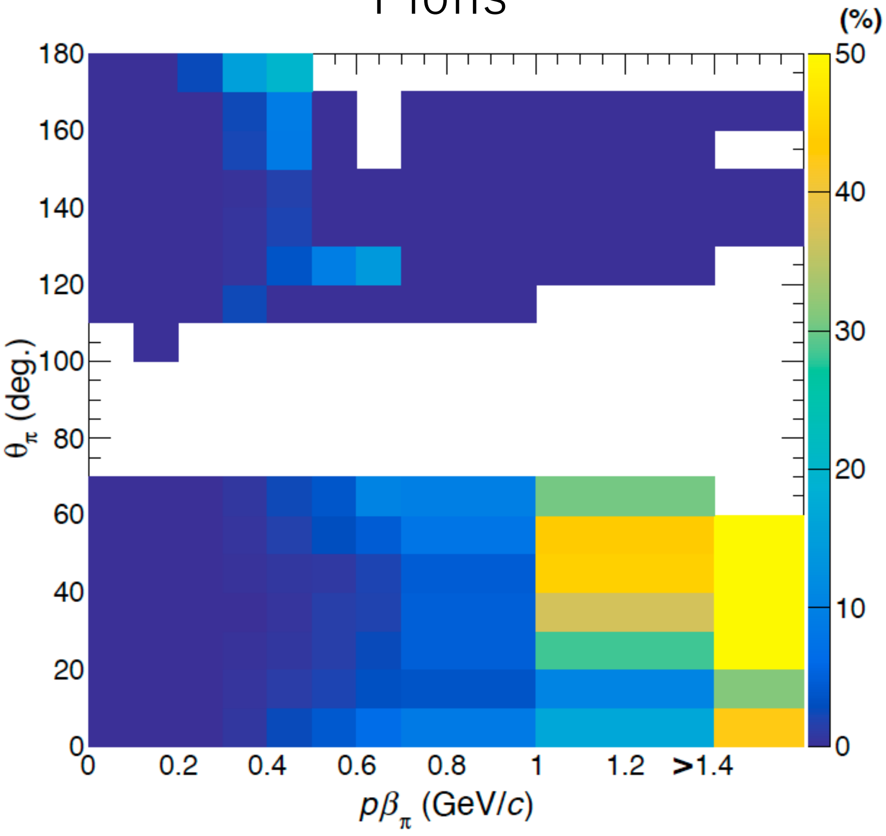
Pion : eff. 92.3%, purity 86.8%



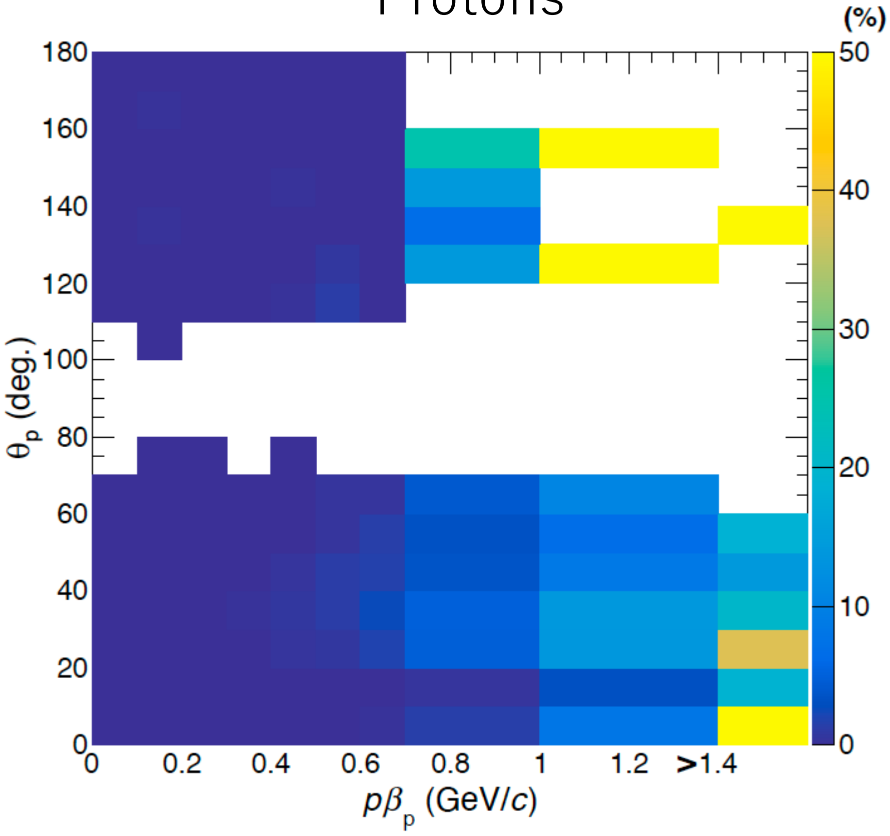
→ p / $\pi^{\pm}$ separation using VPH and momentum is good.

Mis-PID rates of pions and protons (FHC)

Pions



Protons



In the region of pβ below 0.5 GeV/c, the average mis-PID rates were 0.5% and 0.1% for pions and protons, respectively.

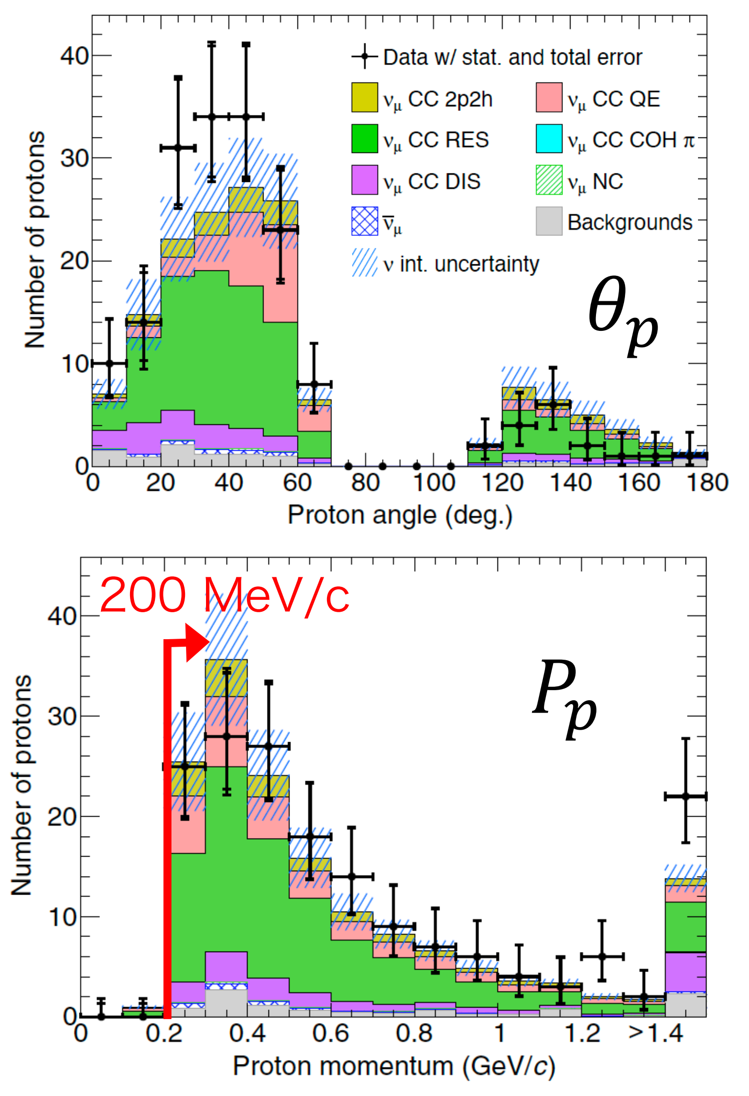
The mis-PID rates for pβ above 1.0 GeV/c are 19.3% and 15.7% for pions and protons, respectively.

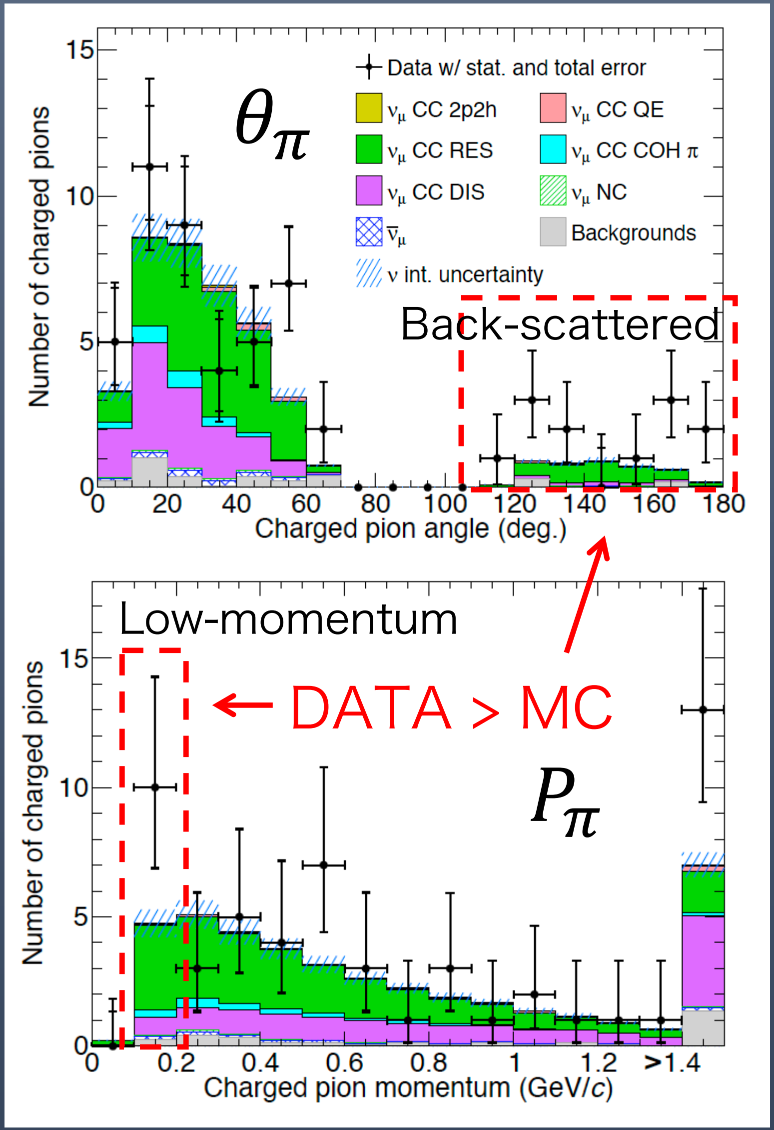
Proton & Pion results (FHC mode)

Data release

Iron int.: 183 events

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

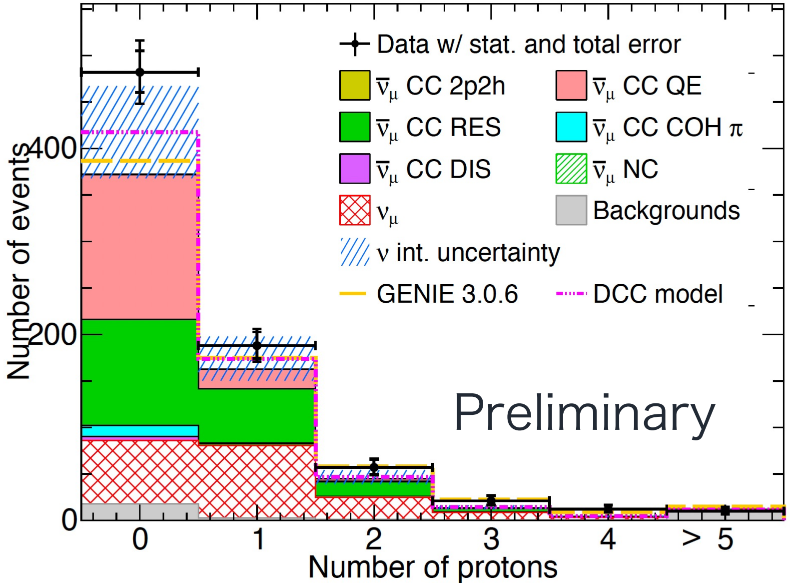


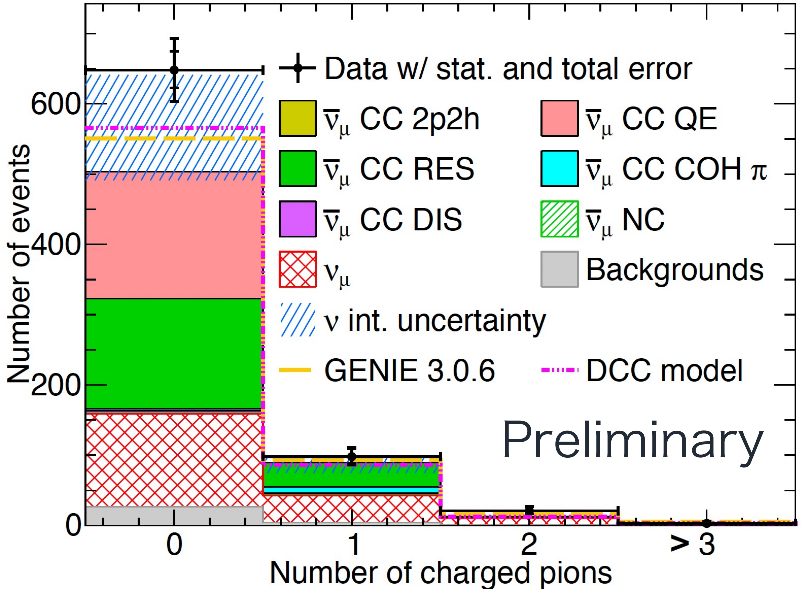


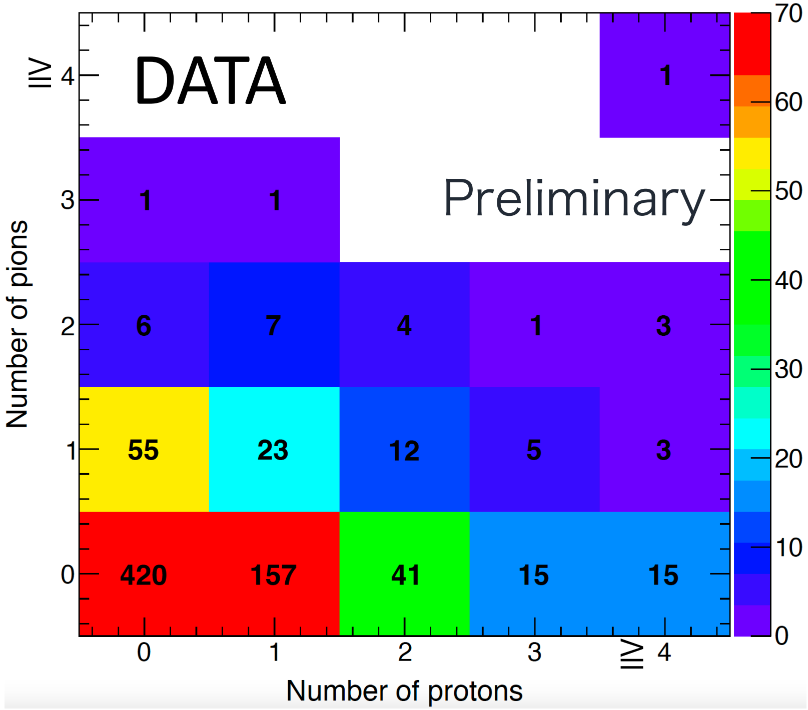
Data are generally consistent with the MC prediction.

Problems of π production or FSI models?

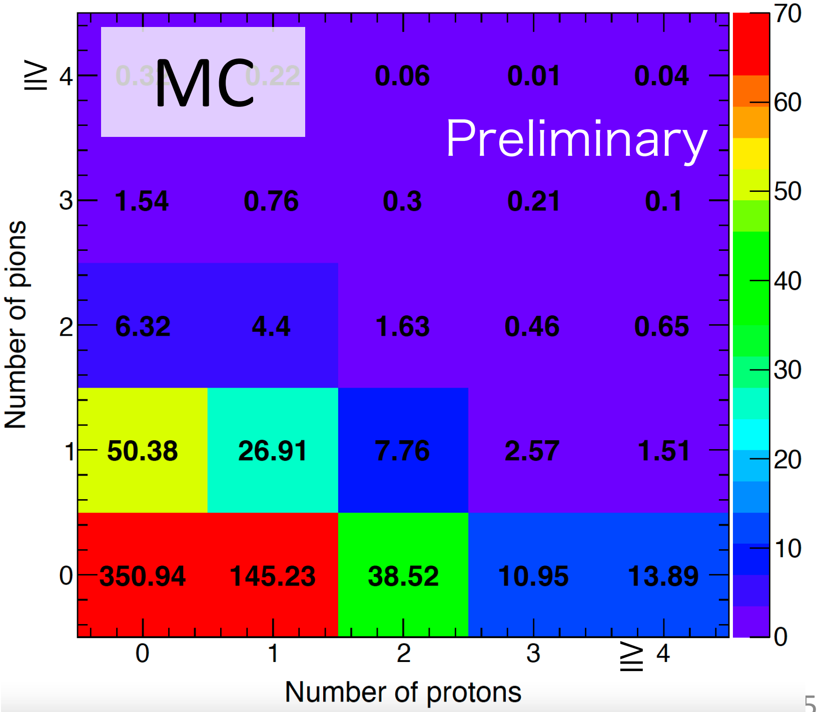
Multiplicity distibutions (RHC)





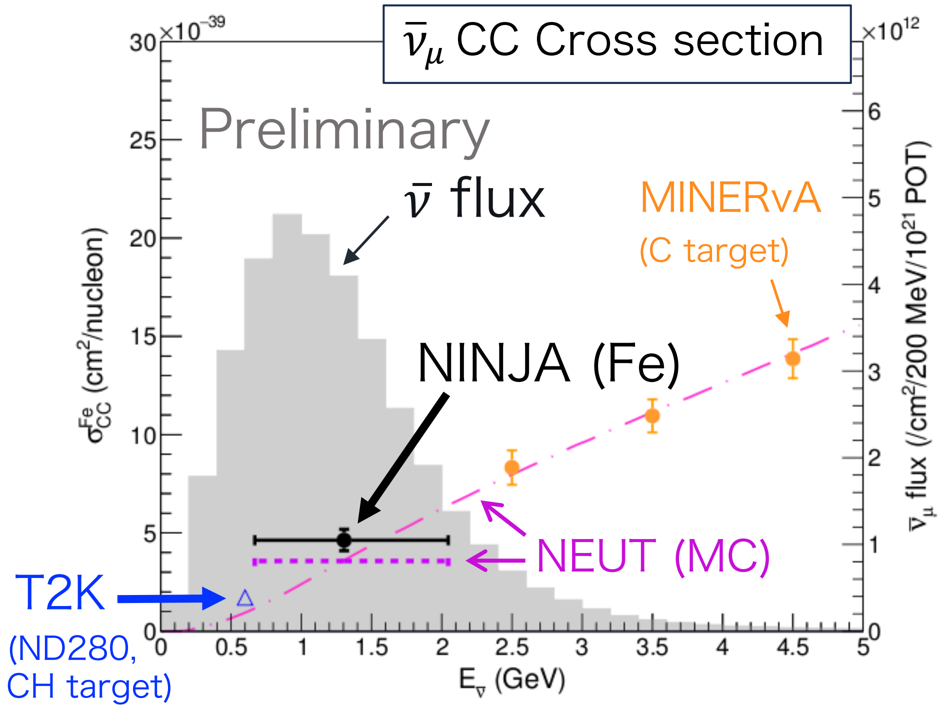


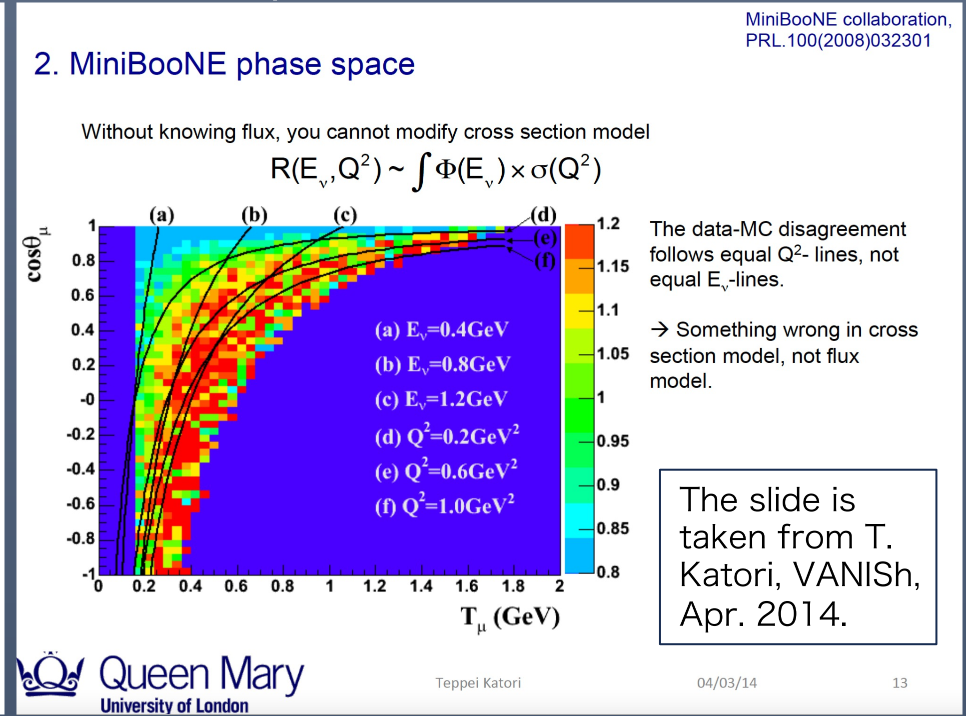
Number of pions \ Number of protons	0	1	2	3	≥ 4
≥ 4					1
3	1	1			
2	6	7	4	1	3
1	55	23	12	5	3
0	420	157	41	15	15



Number of pions \ Number of protons	0	1	2	3	≥ 4
≥ 4	0.3	0.22	0.06	0.01	0.04
3	1.54	0.76	0.3	0.21	0.1
2	6.32	4.4	1.63	0.46	0.65
1	50.38	26.91	7.76	2.57	1.51
0	350.94	145.23	38.52	10.95	13.89

Discussion for the result of $\bar{\nu}_\mu$ cross section





MiniBooNE collaboration,
PRL.100(2008)032301

2. MiniBooNE phase space

Without knowing flux, you cannot modify cross section model

$$R(E_\nu,Q^2) \sim \int \Phi(E_\nu) \times \sigma(Q^2)$$

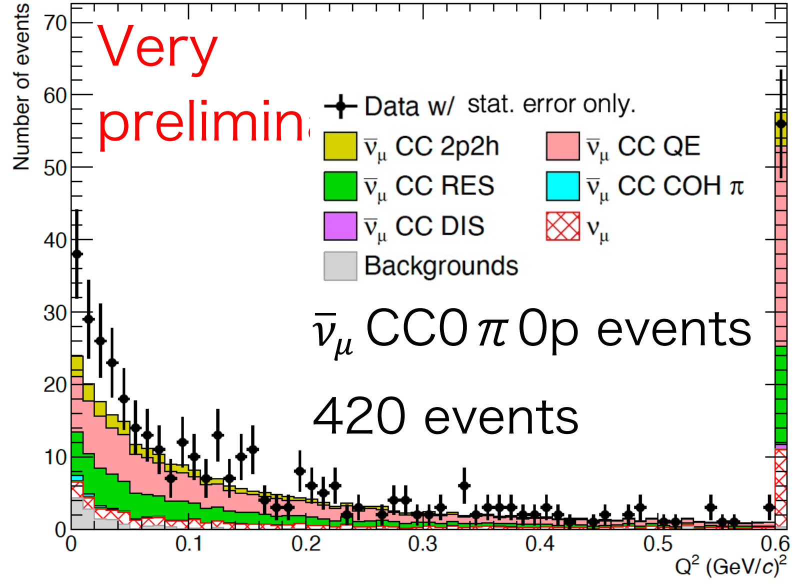
The data-MC disagreement follows equal Q^2- lines, not equal E_ν-lines.

→ Something wrong in cross section model, not flux model.

The slide is taken from T. Katori, VANISh, Apr. 2014.

Queen Mary
University of London

Teppei Katori 04/03/14 13



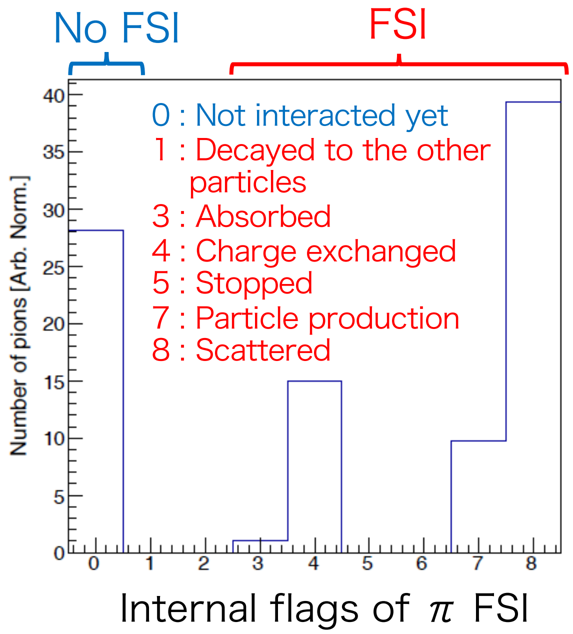
MC prediction of cross section is 23% lower than that of the data.
→ Problems of flux or cross section?

Flux: Energy dependent
Cross section: Q^2 dependent

Low-Q^2 data are not consistent with the MC prediction.
→ There is possibility that the cross section in low-Q^2 region may be strange.

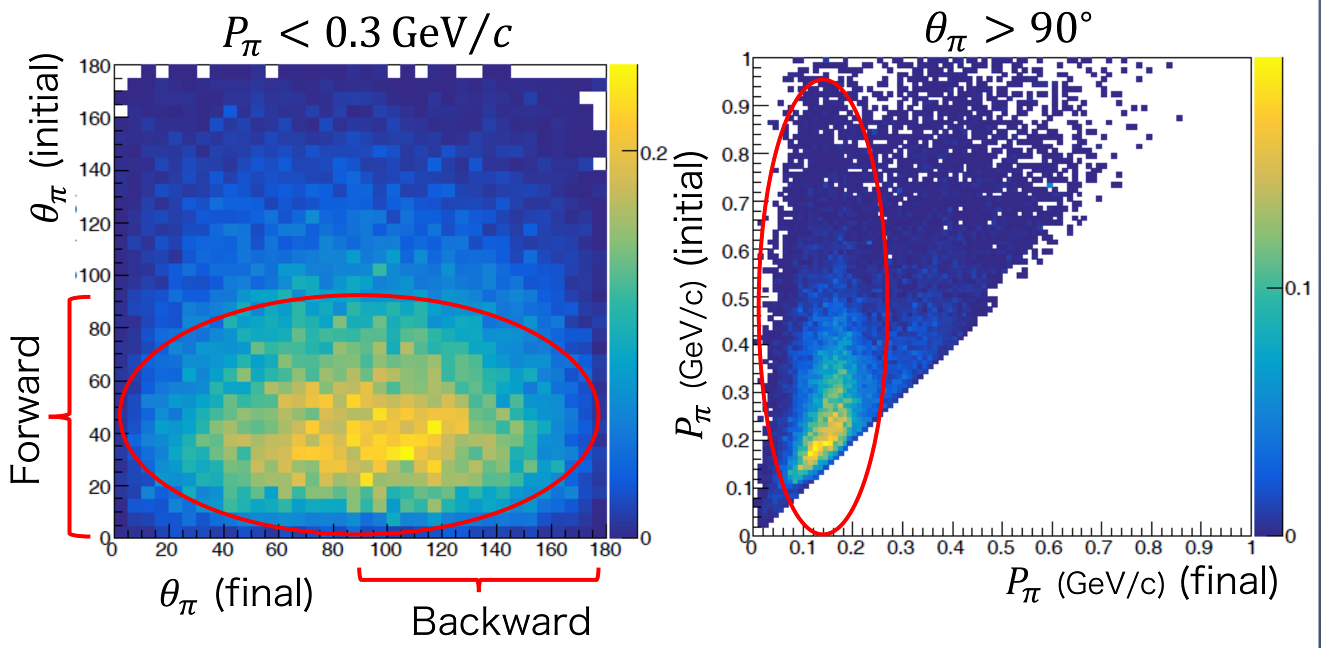
Pion FSIs ($P_\pi < 0.3\,\mathrm{GeV}/c\,, \theta_\pi > 90°$)

NEUT simulation



π may experience FSIs inside a target nucleus.

Scattered pions in a nucleus



Initial : Forward direction
Final : Backward direction

Initial : High momentum
Final : Low momentum

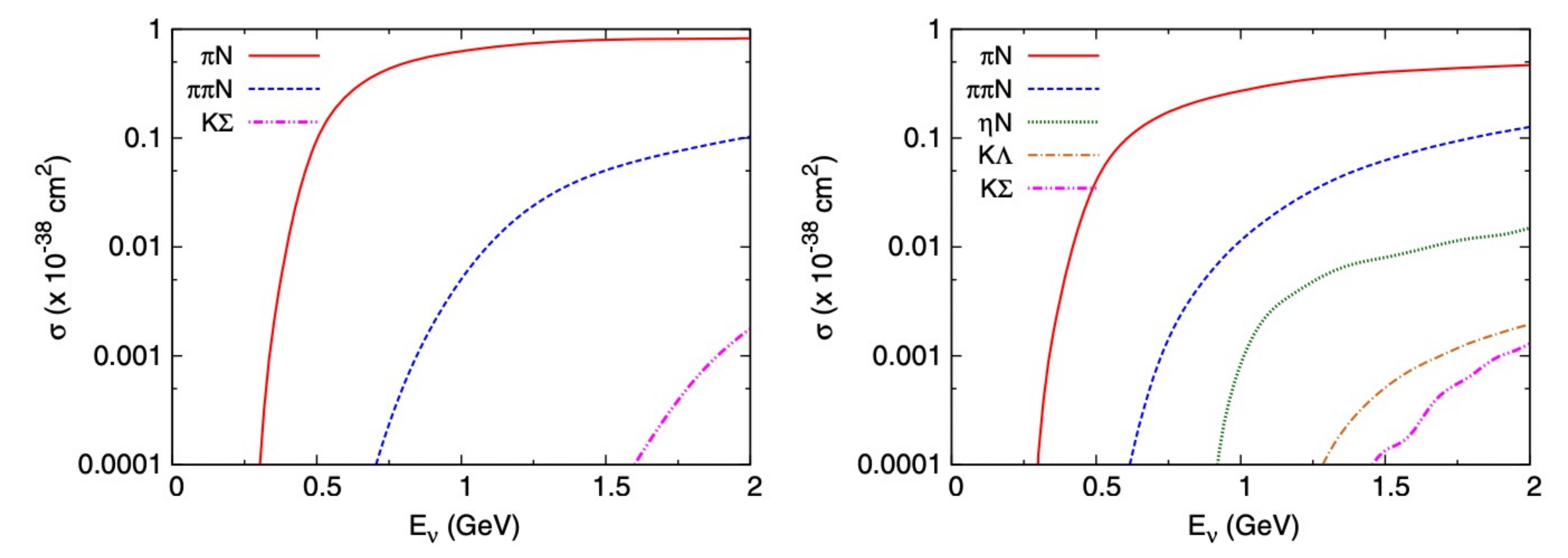
- Back-scattered and low-momentum pions are expected to reflect rescattering in the nucleus by FSI.
- These pion data will play an important role to improve pion production channels of neutrino interaction models.

Dynamical Coupled-Channel (DCC) model

- DCC approaches are a widely used tool in hadronic physics that allow to analyze different reactions and partial waves in a consistent way.
- The model is based on an energy independent Hamiltonian which is derived from a set of Lagrangians by using a unitary transformation method.

- DCC model for $\pi N, \gamma N \rightarrow \pi N, \eta n, K\Lambda, K\Sigma\ (W \leq 2.1\ \mathrm{GeV})$

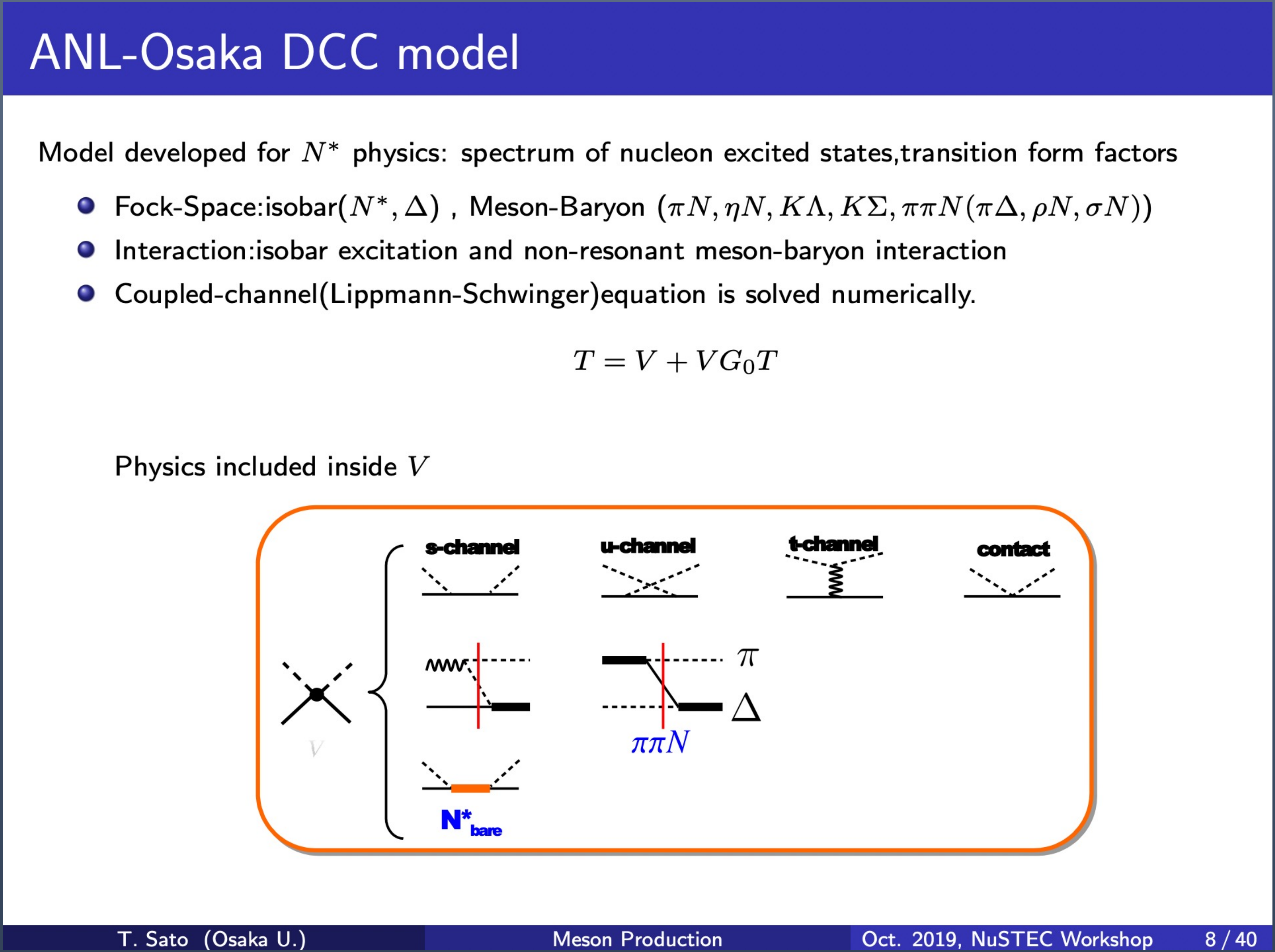
  → extension to $\nu N \rightarrow lX\ (X = \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma)\ (\mathrm{Q}^2 \leq 3.0\ (\mathrm{GeV}/c)^2)$ by analyzing electron-induced reaction data for both proton and neutron targets.



Total cross sections for the CC $\nu_\mu p$ (left) and $\nu_\mu n$ (right) reactions.

S. X. Nakamura, H. Kamano, and T. Sato, Phys. Rev. D 92, 074024 (2015).

The slide is taken from T. Sato, “Neutrino Induced Meson Production Reaction DCC(coupled channel) model,” NuSTEC Workshop, Oct. 2019.



ANL-Osaka DCC model

Model developed for N^* physics: spectrum of nucleon excited states,transition form factors

- Fock-Space:isobar(N^*, Δ) , Meson-Baryon $(\pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N(\pi\Delta, \rho N, \sigma N))$
- Interaction:isobar excitation and non-resonant meson-baryon interaction
- Coupled-channel(Lippmann-Schwinger)equation is solved numerically.

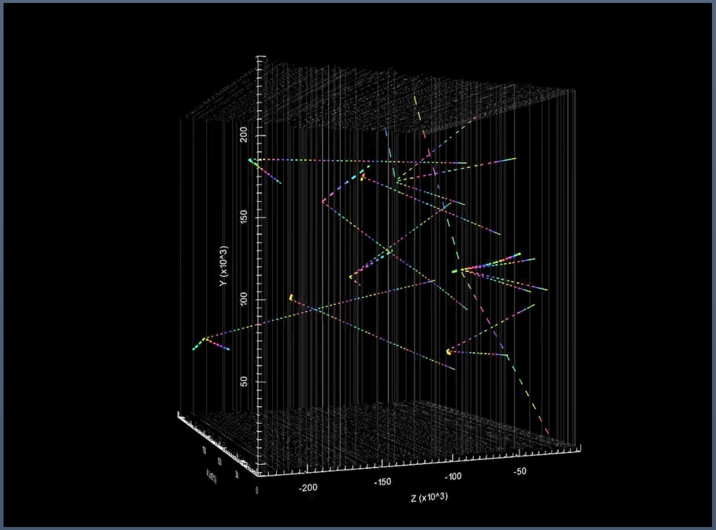
$$T = V + VG_0T$$

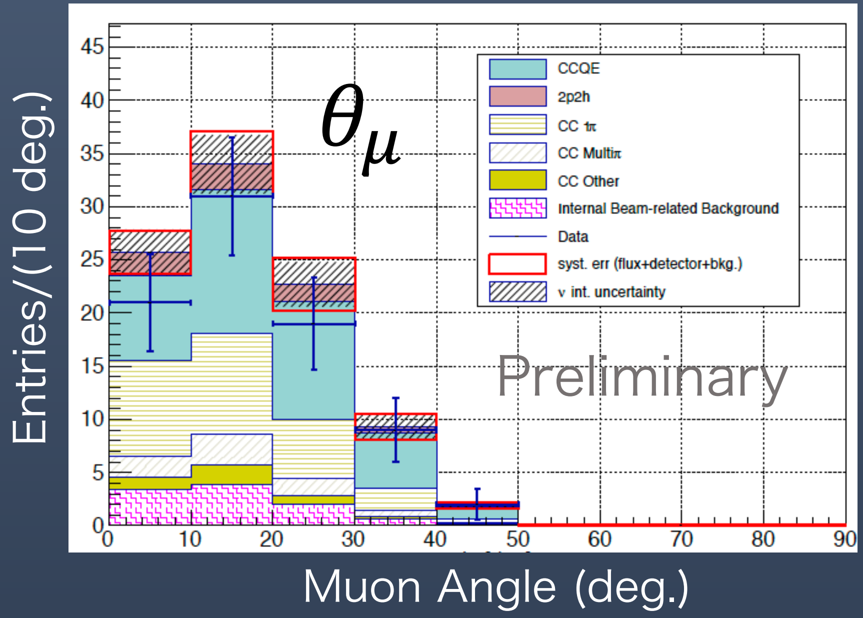
Physics included inside V

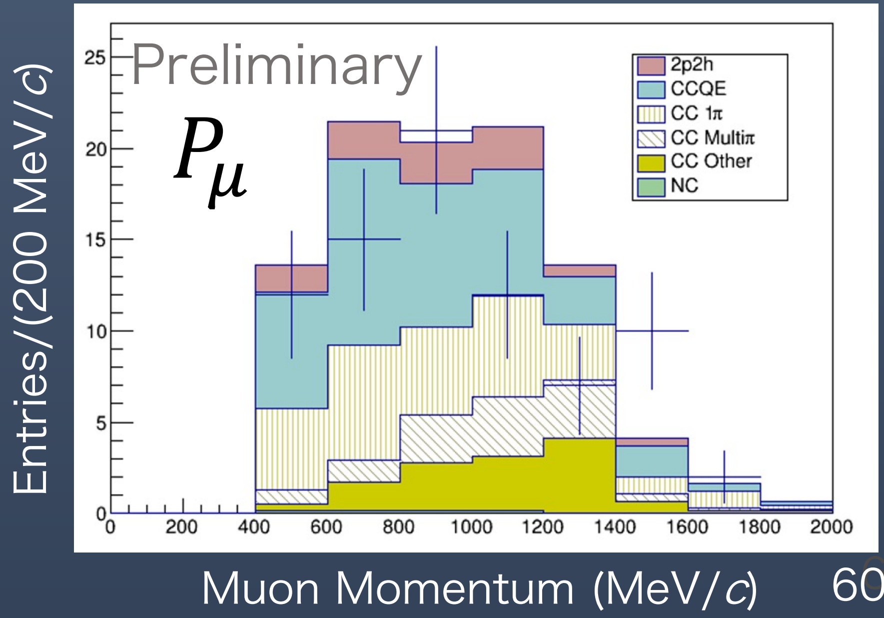
Physics run E71a : Muon results (ν–water int.)

- A sub-dataset was used to develop analysis methods.
- We show the preliminary results using ~10% sub-sample of the total.
- Preparation of the full-dataset and the analysis is on-going.

Y. Suzuki, Ph.D. thesis, Nagoya University, 2023.
T. Odagawa, Ph.D. thesis, Kyoto University, 2023.



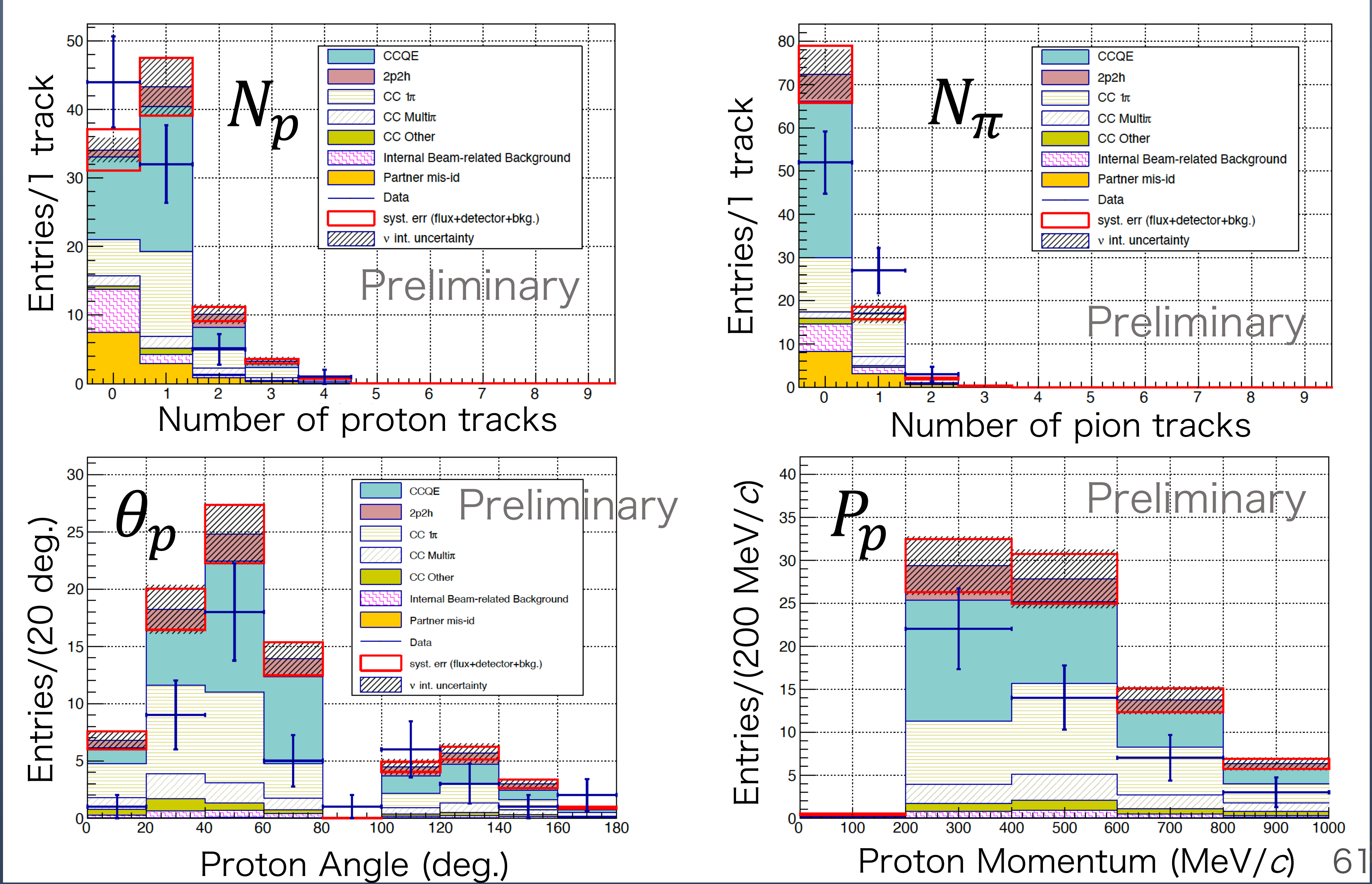




Physics run E71a : Proton & Pion results (ν–water int.)

- Results using ~10% sub-sample of the total
- Preparation of the full-dataset and the analysis is on-going.

Y. Suzuki, Ph.D. thesis, Nagoya Univ., 2023.
T. Odagawa, Ph.D. thesis, Kyoto Univ., 2023.



Neutrino flux @ ESSνSB