NINJA

Measurement of numu and numu-bar charged-current interactions on iron using a nuclear emulsion detector in the NINJA experiment

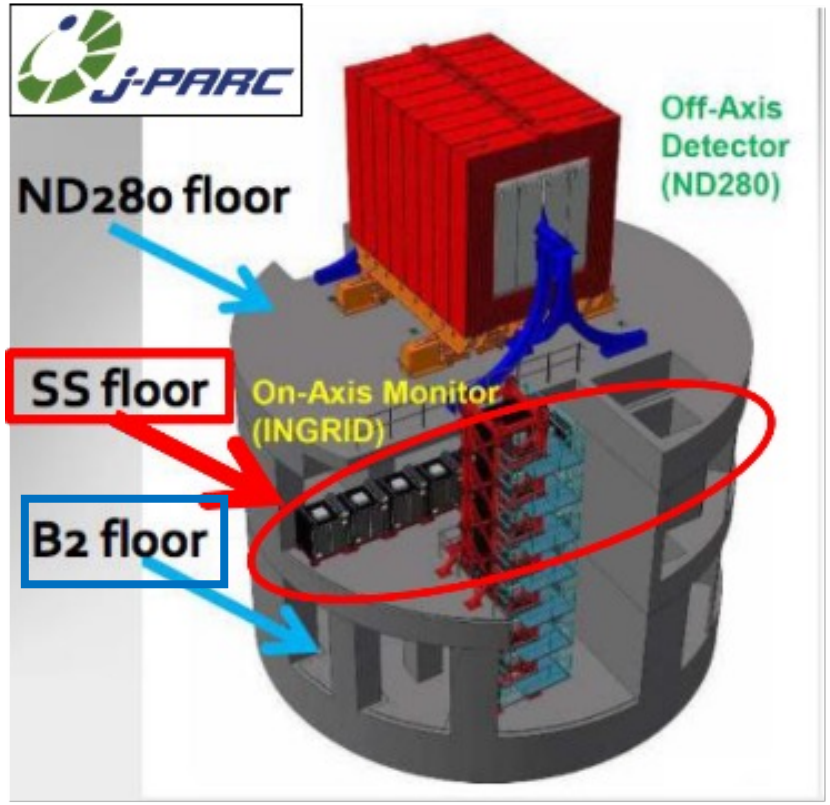
Akihiro Minamino (Yokohama National University)
for NINJA Collaboration

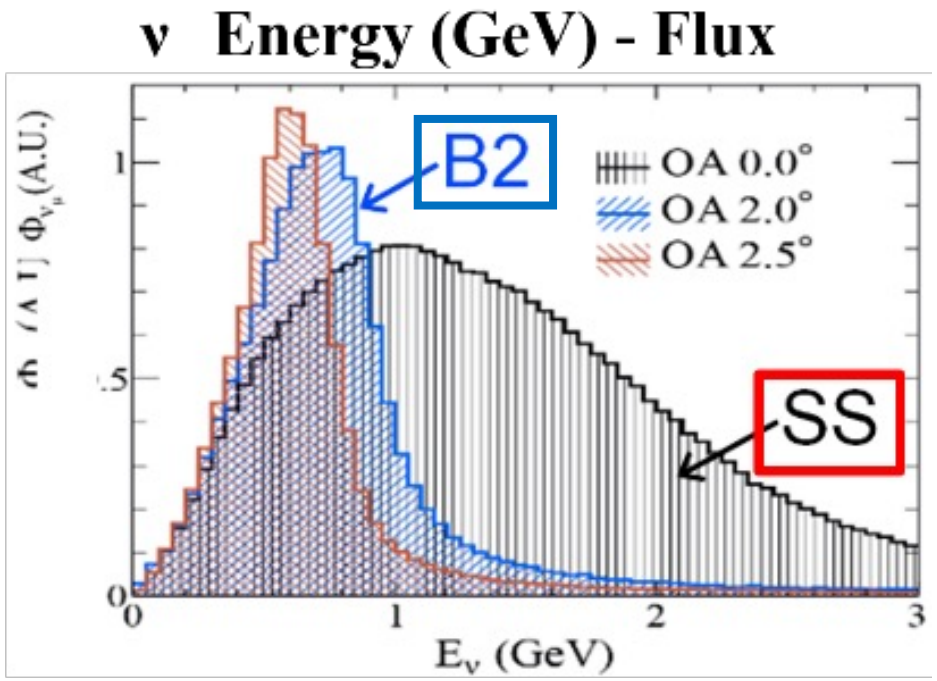
October 24, 2022
NuINT 2022 @ Seoul National University

NINJA experiment (J-PARC T60/T66/T68/T81 & E71)

Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

- The NINJA experiment is studying neutrino-nucleus interactions around 1 GeV using an emulsion-based detector and J-PARC neutrino beam.

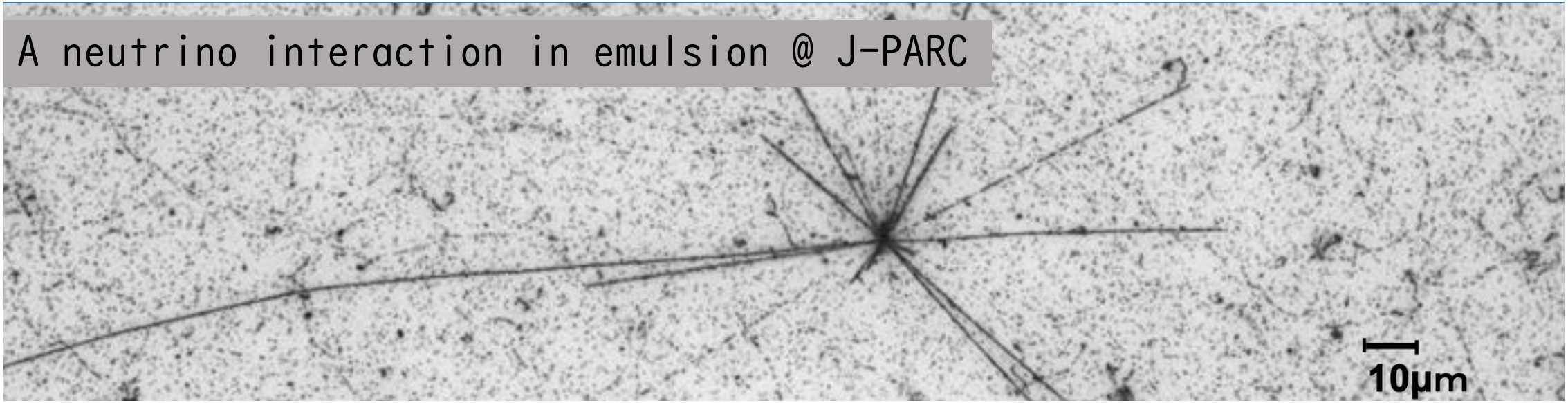




NINJA experiment (J-PARC T60/T66/T68/T81 & E71)

Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

- The sub-micron resolution allows us to detect short tracks of low-momentum charged particles.
  - Proton (Pion) tracks can be detected down to 200 (50) MeV/c.
  - Suitable to measure the nuclear effects.
  - Events such as 2p2h interactions can be selected with high purity.

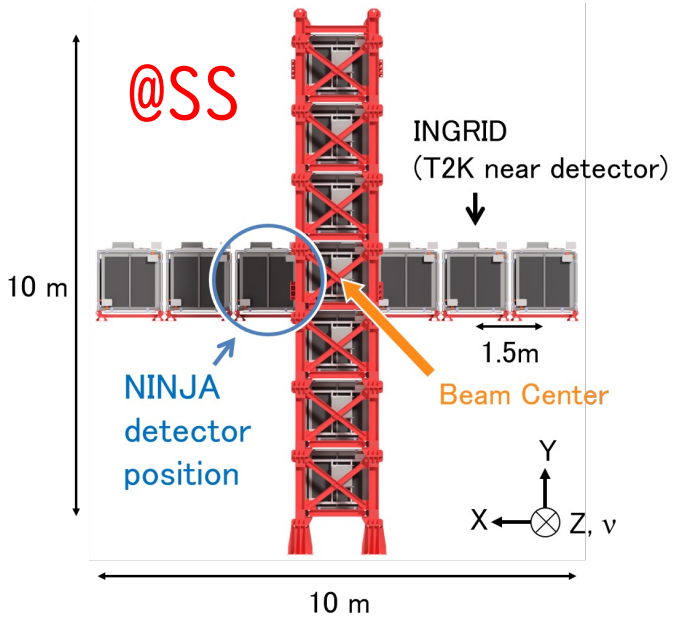


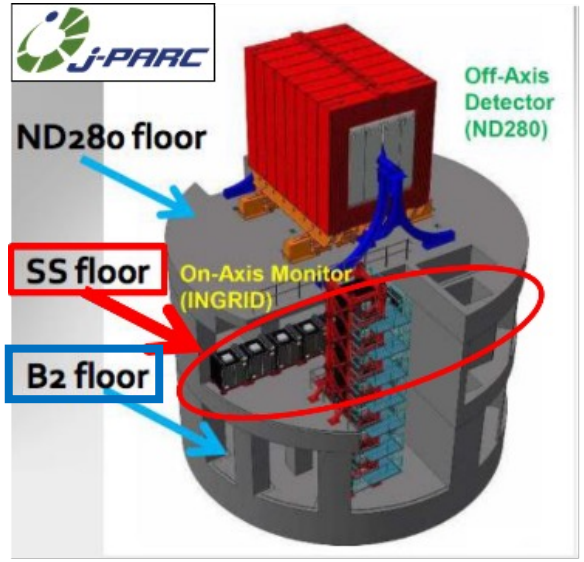
NINJA runs

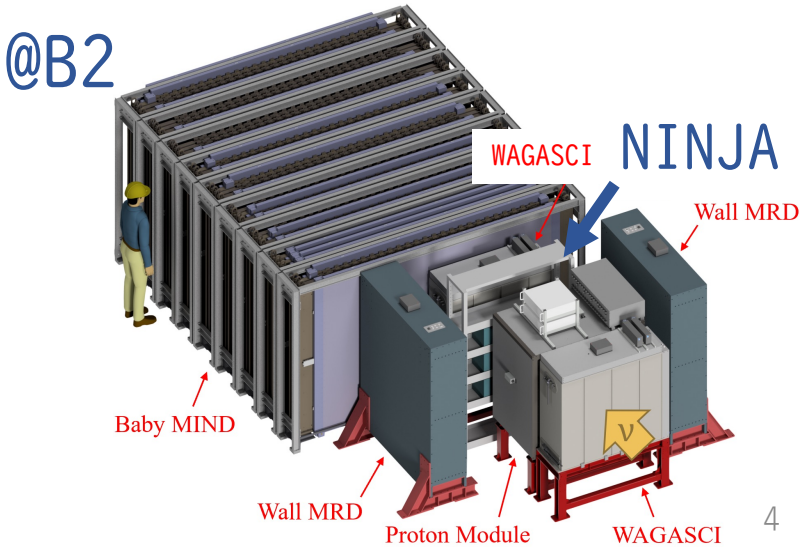
- **Pilot runs**
  - 2kg iron @SS (2015, $\bar{\nu}$: 1.38×10^{20} POT)
  - 65kg iron @SS (2016, ν: 0.4×10^{20} POT, $\bar{\nu}$: 3.5×10^{20} POT)
  - 3kg water @SS (2017-2018, $\bar{\nu}$: 7.0×10^{20} POT)
  - 9kg heavy water @B2 (2021, ν: 1.78×10^{20} POT)

Today

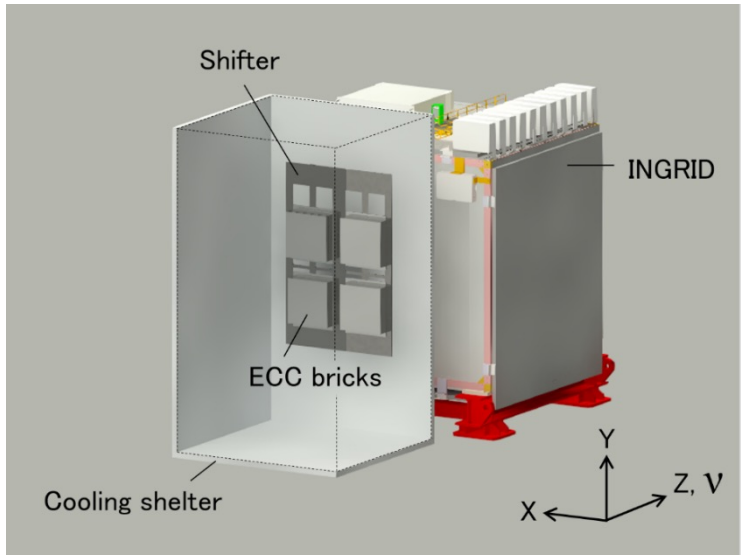
- **Physics run**
  - 75kg water, 130kg iron, CH 15kg @B2 (2019-2020, ν: 4.8×10^{20} POT)

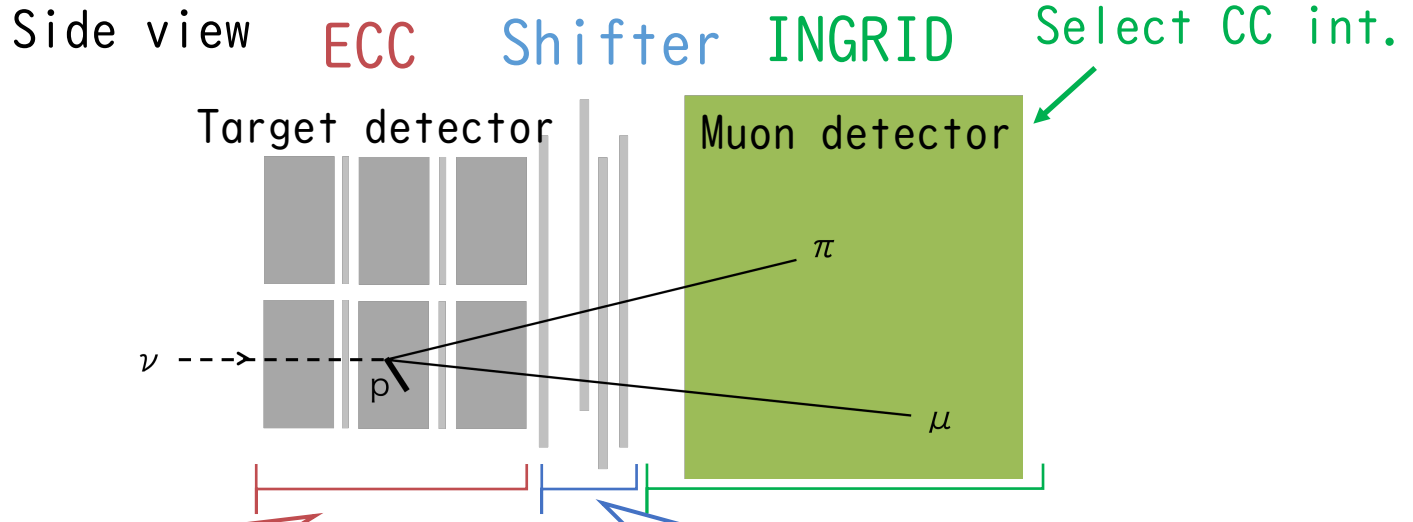






Detector setup (65 kg iron target run)

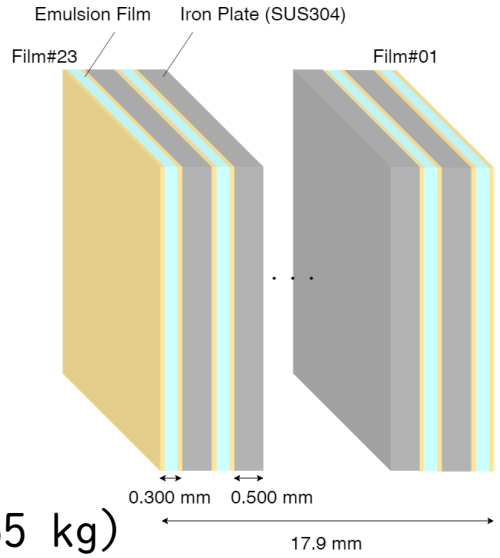




Emulsion Cloud Chamber (ECC)

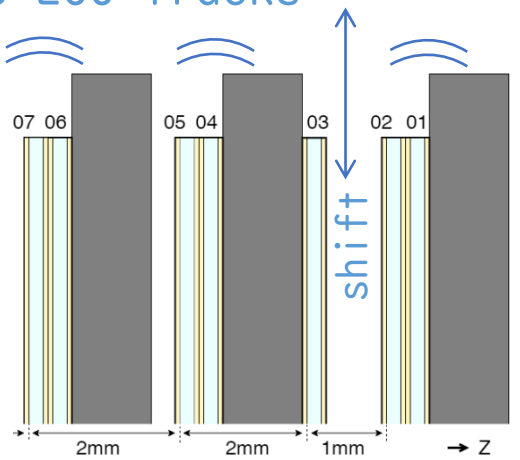
for ν-iron interaction

- Emulsion film :
  25 cm× 25 cm× 300 μm
- Iron plate:
  25 cm× 25 cm× 500 μm
- ECC brick :
  23 films + 22 iron plates
- Total :
  12 ECC bricks (264 iron plates = 65 kg)



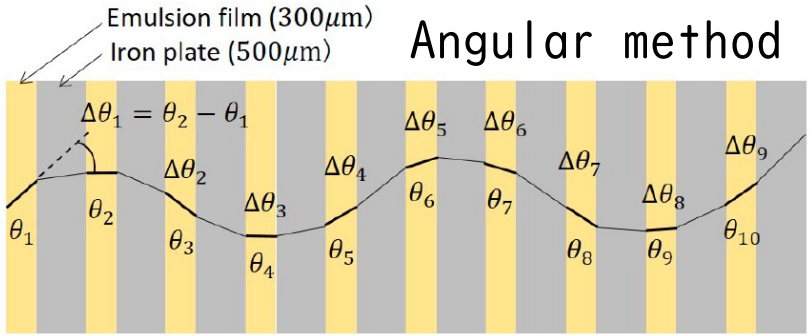
Emulsion Shifter

Adds time information to the ECC tracks

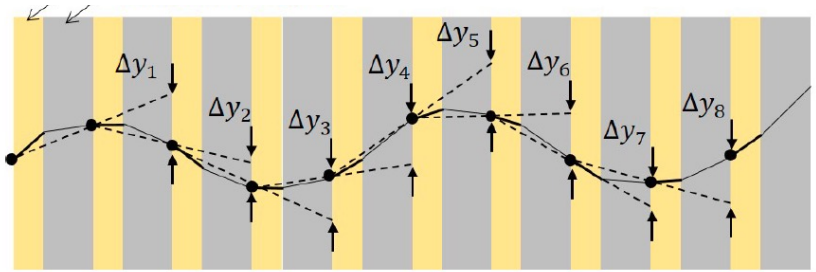


Momentum measurements in ECC

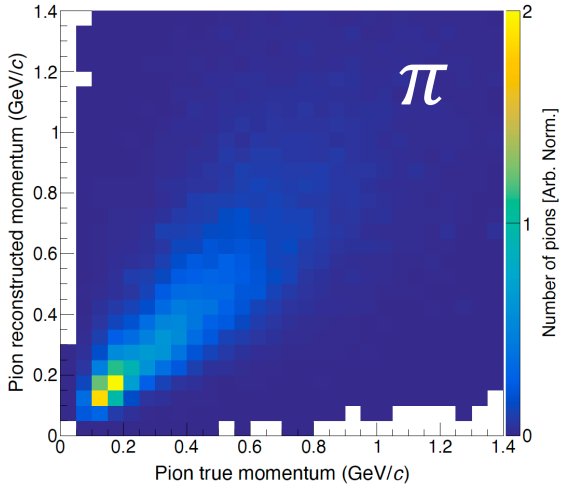
① Range-Energy relation
② Multiple Coulomb Scattering
  A) Angular method: angular difference
  B) Coordinate method: positional difference

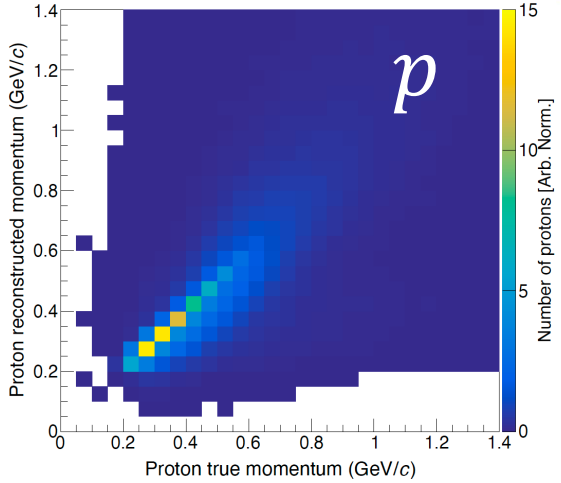


Coordinate method



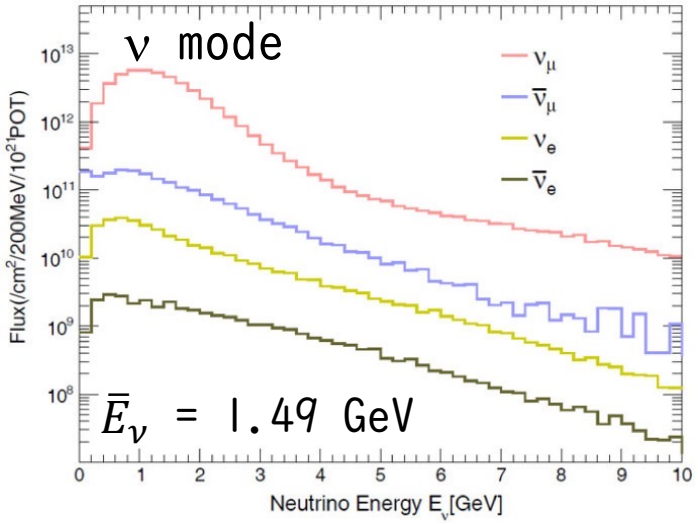
Momentum resolution	Muon	Pion	Proton
Angular method	43.0%	29.6%	36.0%
Coordinate method	25.9%	25.2%	30.7%
Range-energy relation	6.4%	-	3.8%

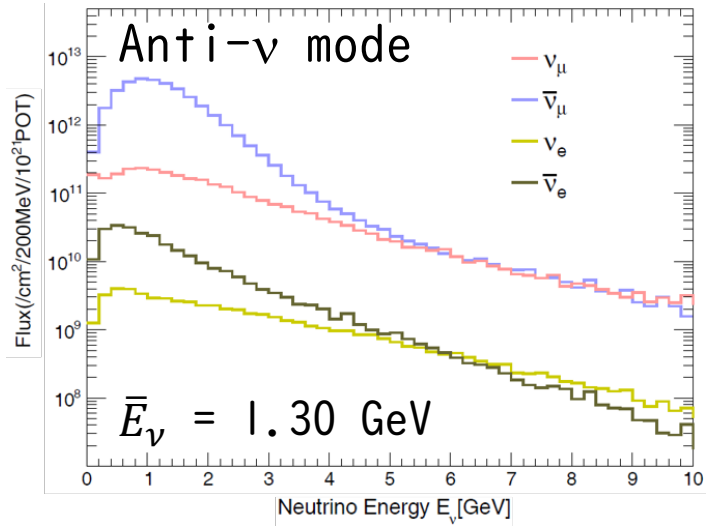


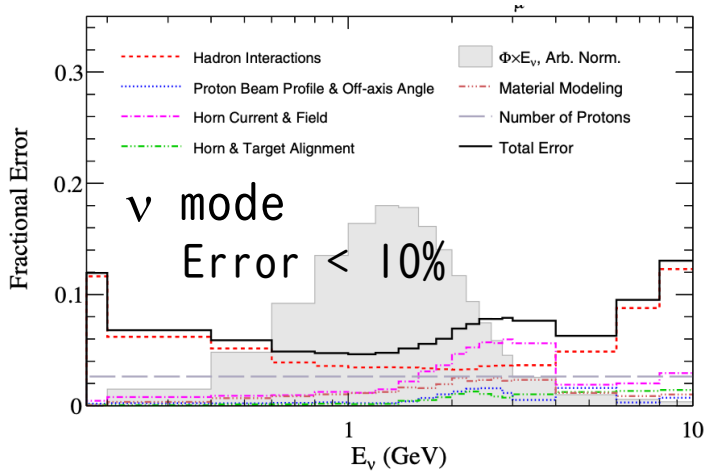


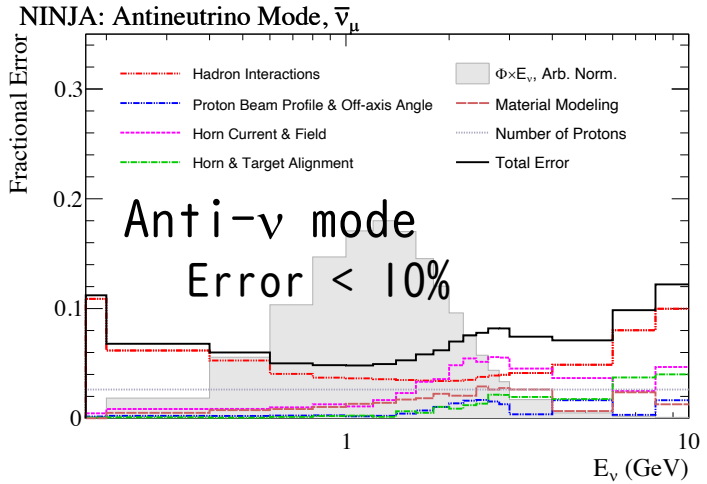
Neutrino beam simulation

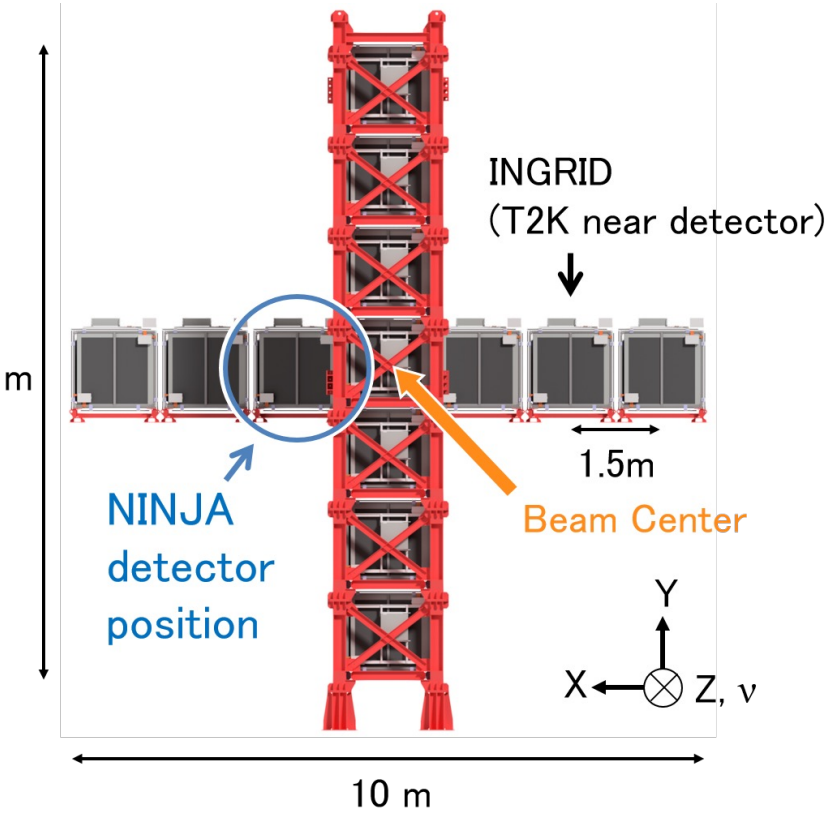
- JNUBEAM 13av6.1
  - FLUKA 2011.2 tuned with the NA61 replica-2009 data











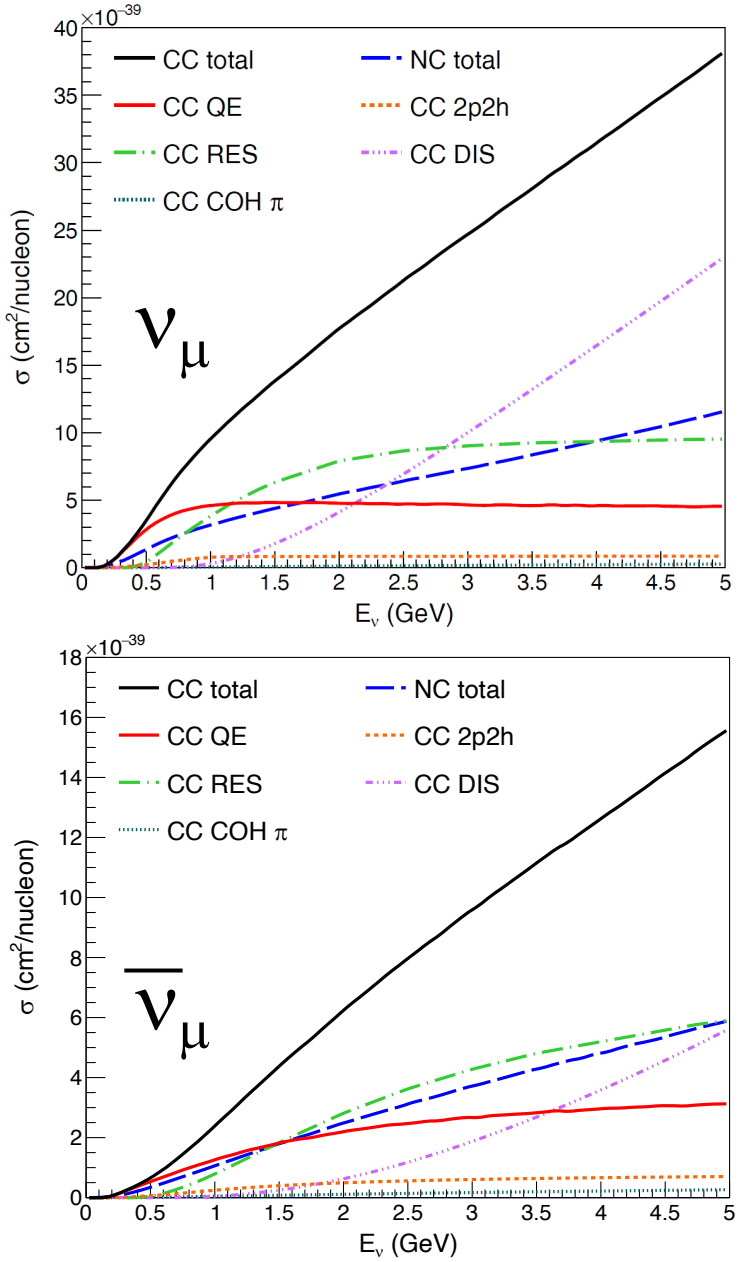
Neutrino Event generator

- NEUT 5.4.0

Interaction models used in the nominal MC

Interaction	Model
CCQE	Iplh model by Nieves et al. LFG with RPA correction (M_A^{QE}=1.05 GeV/c^2)
2p2h	2p2h model by Nieves et al.
RES	Model described by Rein-Sehgal (M_A^{RES}=0.95 GeV/c^2)
COHπ	Model described by Rein-Sehgal
DIS	GRV98 PDF with Bodek and Yang correction
FSI	Semi-classical intra-nuclear cascade model

cross sections on iron



Results (ν mode)

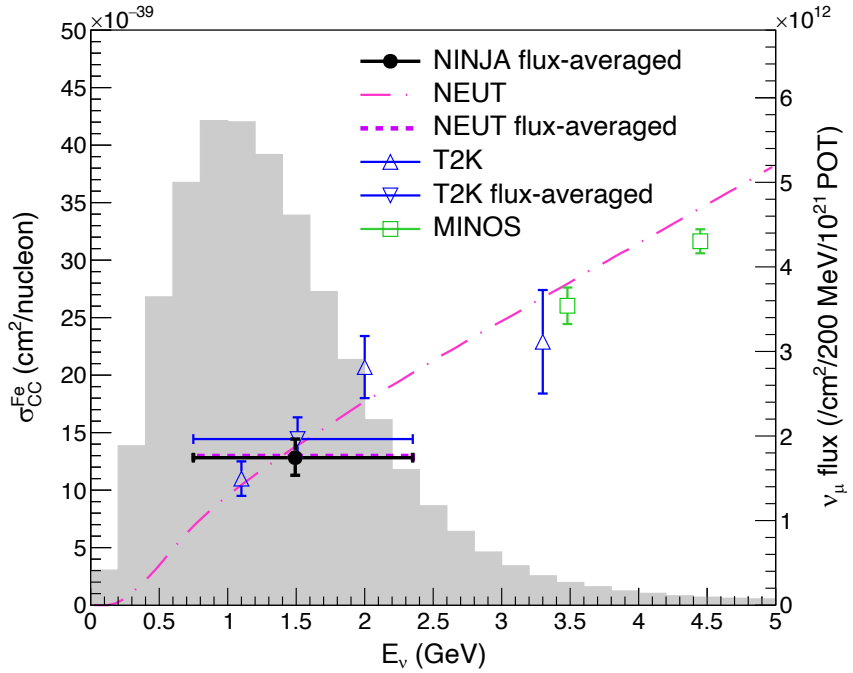
H. Oshima et al., Prog. Theor. Exp. Phys. 2021, 033C01 (2021)
H. Oshima et al., Phys. Rev. D 106, 032016 (2022)

Flux-averaged CC inclusive cross section on iron (ν mode, $\bar{E}_\nu$= 1.49 GeV)

- 183 events were selected as ν_μ CC interaction candidates.

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

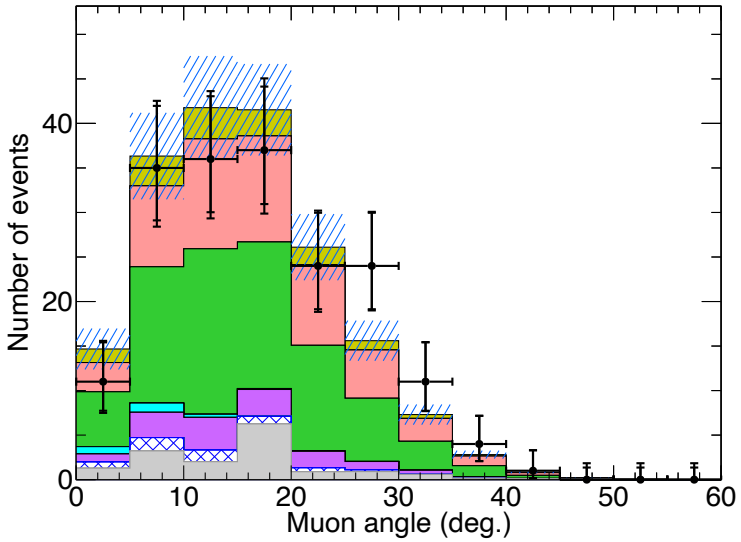
Phase space: $\theta_\mu < 45°, P_\mu > 400\ \text{MeV}/c$

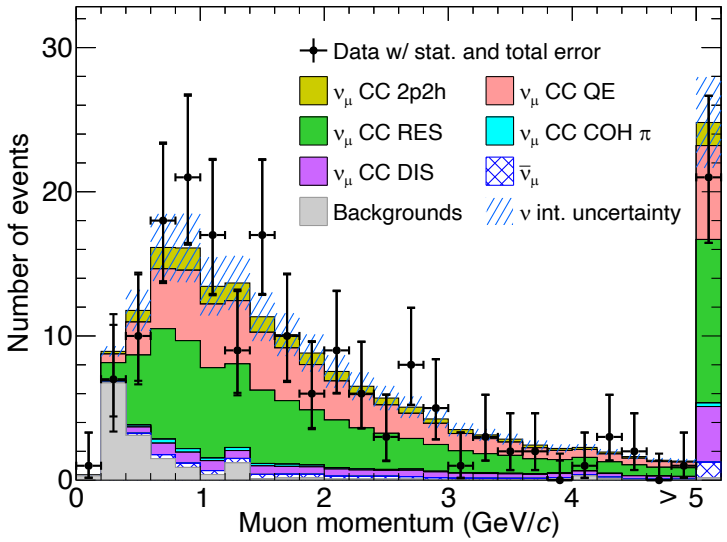


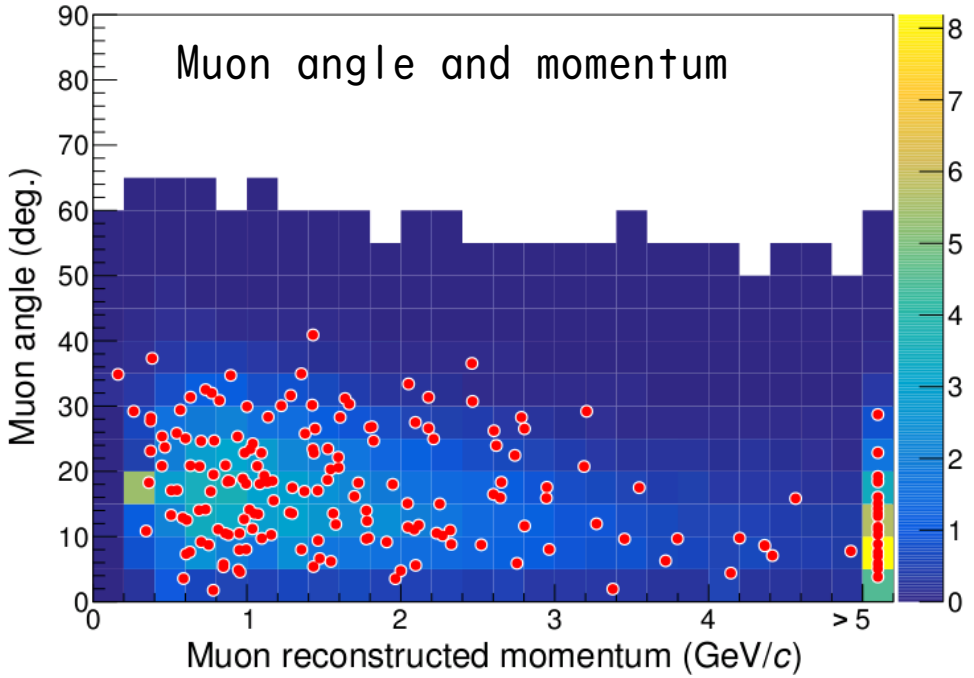
- The result is consistent with the T2K INGRID measurement on the same beamline.
- It also agrees well with the MC prediction.

* K. Abe et al. [T2K Collaboration], Phys. Rev. D **90**, 052010 (2014).

Muon kinematics of CC inclusive interaction on iron (183 events, ν mode, $\bar{E}_\nu$= 1.49 GeV)

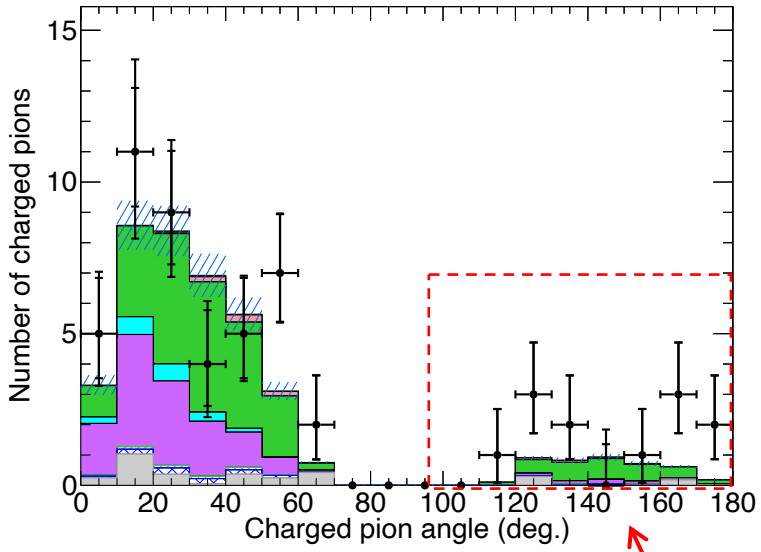


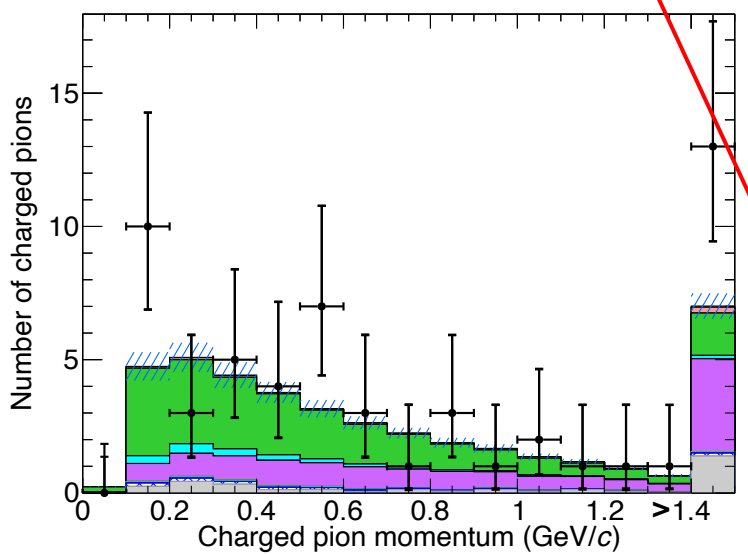


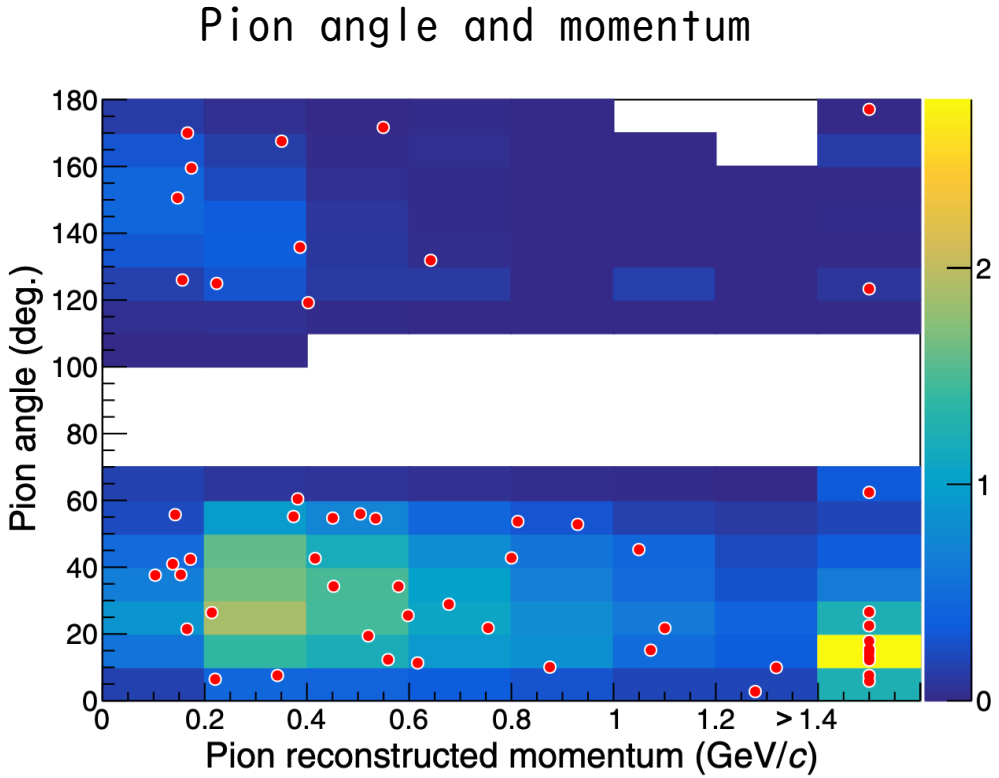


- The results agree well with the MC prediction.

Pion kinematics of CC inclusive interaction on iron (183 events, ν mode, $\bar{E}_\nu$= 1.49 GeV)

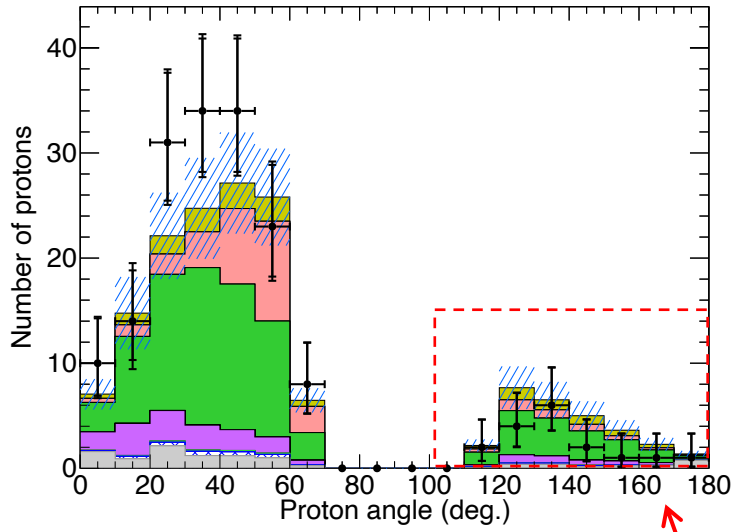


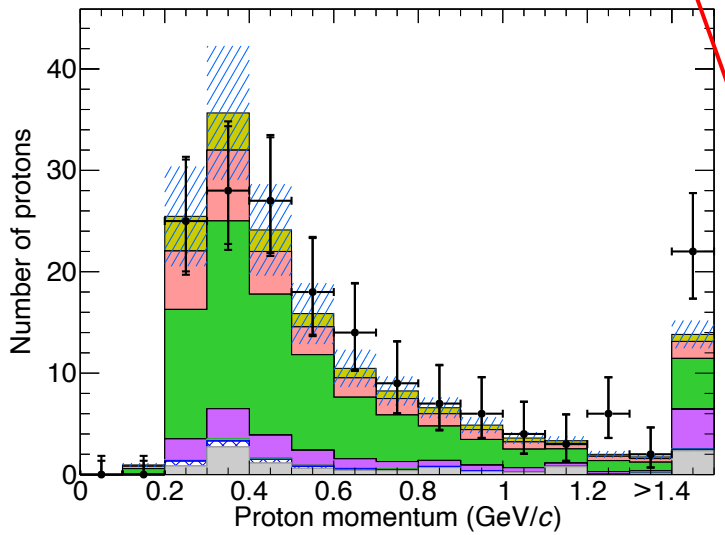


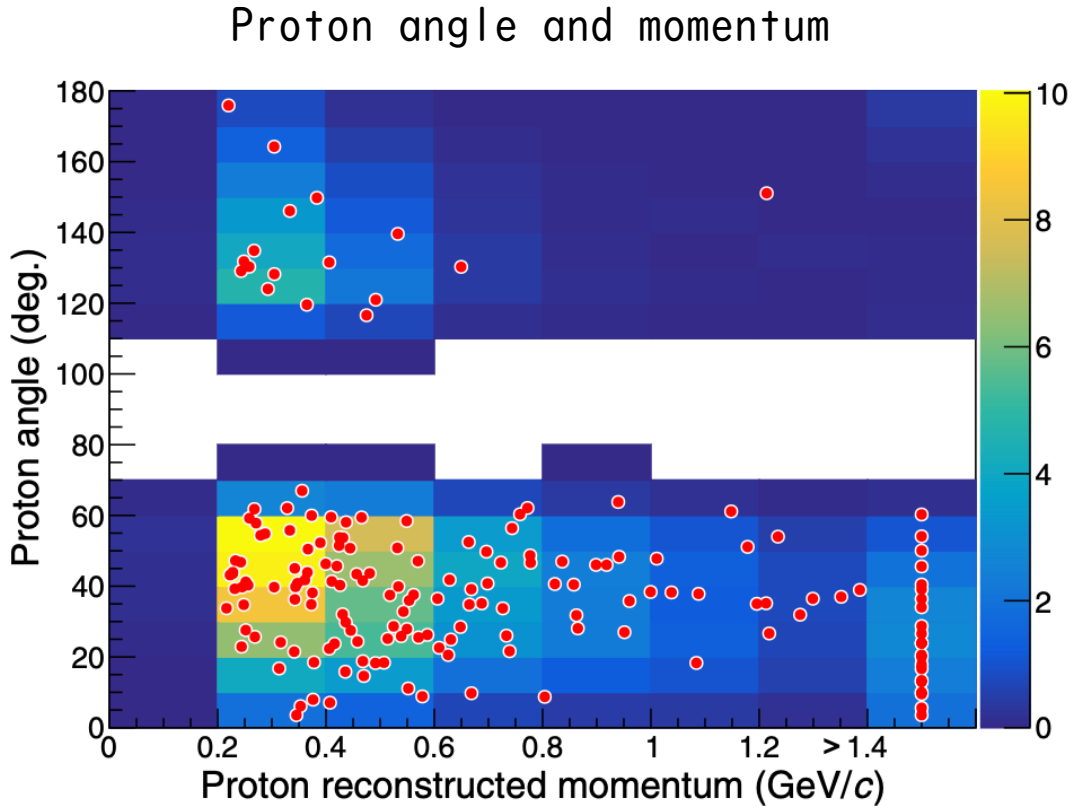


- # of back-scattered pions of Data are larger than that of MC prediction.

Proton kinematics of CC inclusive interaction on iron (183 events, ν mode, $\bar{E}_\nu$= 1.49 GeV)

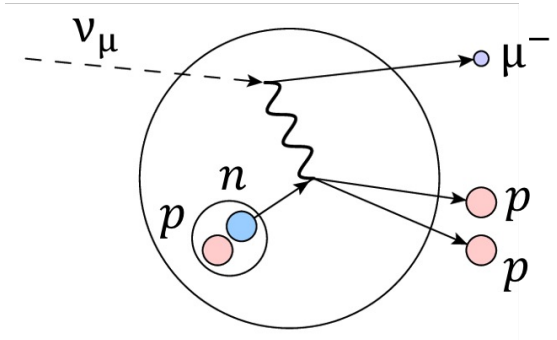


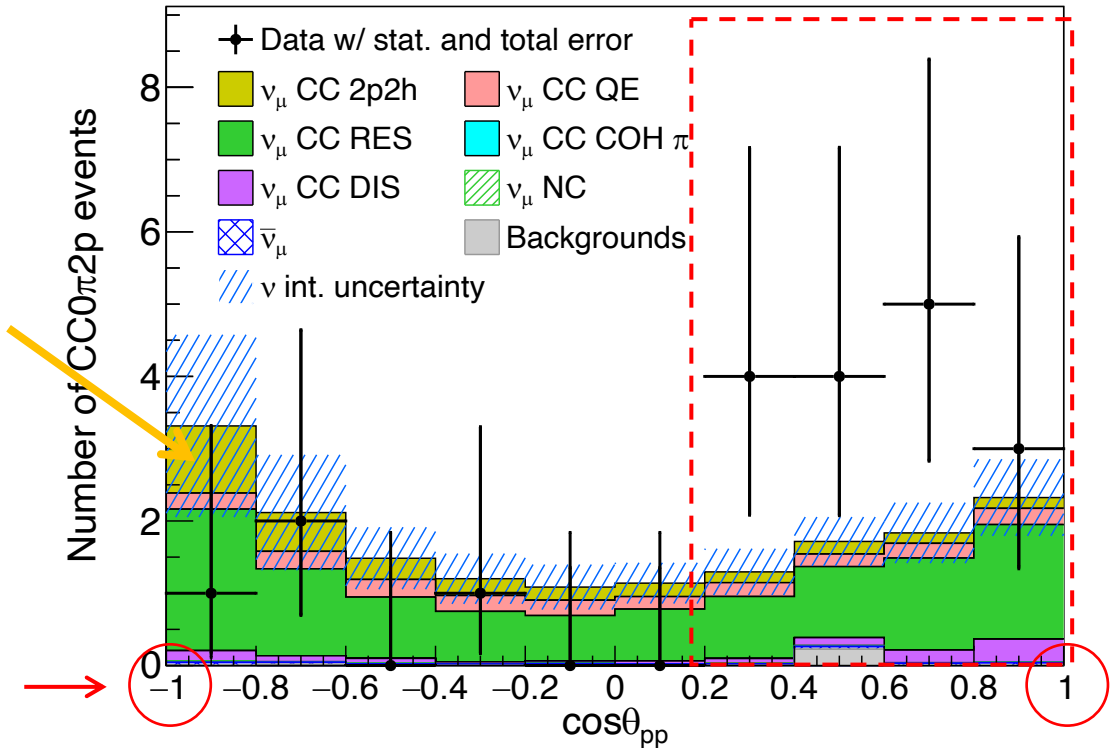




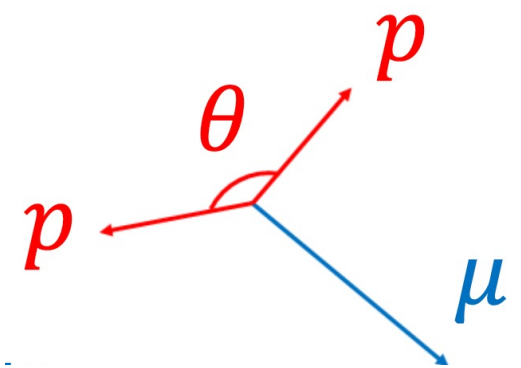
- # of back-scattered proton of Data are smaller than that of MC prediction.

Opening angle between two protons of CC0π2p on iron (20 events, ν mode, $\bar{E}_\nu$= 1.49 GeV)





Back-to-back ⟶ ⟵ Same-direction



- # of same-direction protons of Data are larger than that of MC prediction.

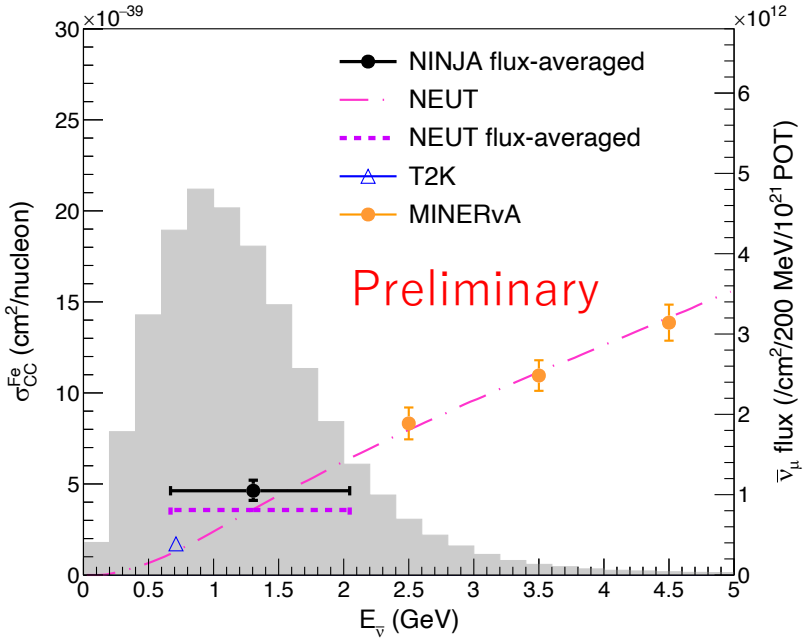
Results (Anti-ν mode)

Flux-averaged CC inclusive cross section on iron (anti-ν mode, $\bar{E}_\nu$= 1.30 GeV)

- 770 events were selected as $\overline{\nu_\mu}$ CC interaction candidates.

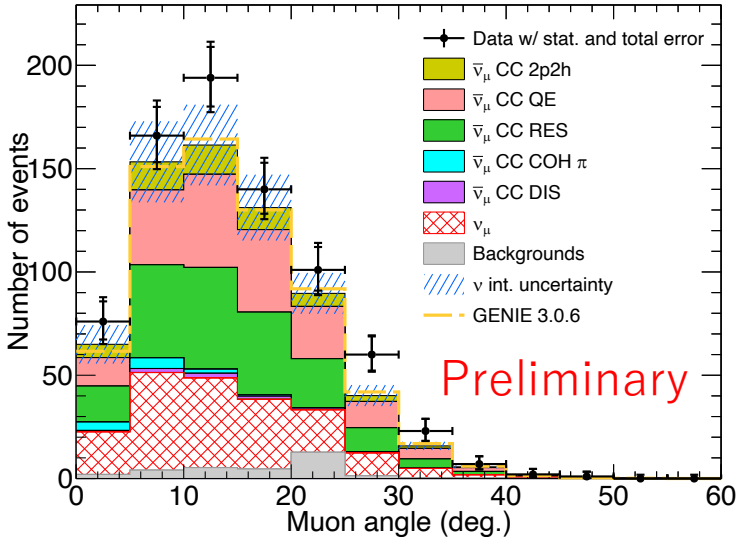
	Result $\times 10^{-39}$ (cm^2/nucleon)	MC $\times 10^{-39}$
$\sigma_{\mathrm{CC}}^{\mathrm{Fe}}$	$4.63 \pm 0.23(\mathrm{stat.})^{+0.53}_{-0.48}(\mathrm{syst.})$	3.57
$\sigma_{\mathrm{CC\ phase\ space}}^{\mathrm{Fe}}$	$3.85 \pm 0.20(\mathrm{stat.})^{+0.42}_{-0.40}(\mathrm{syst.})$	3.22

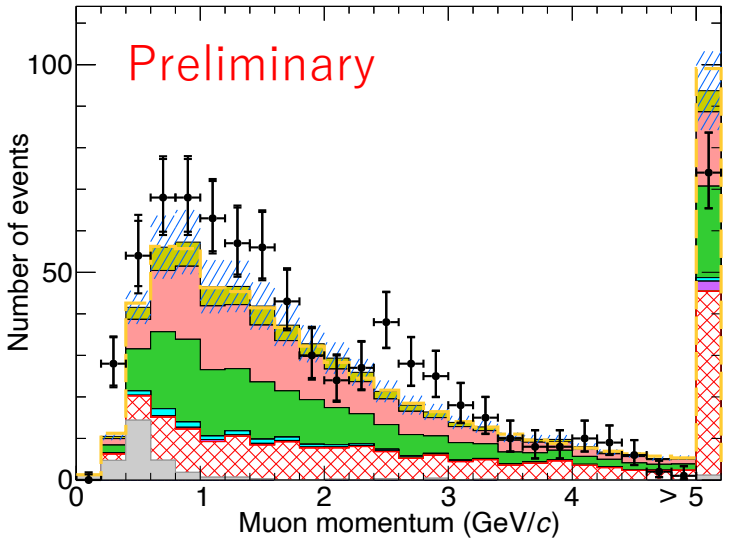
Phase space: $\theta_\mu < 45°, P_\mu > 400\ \mathrm{MeV}/c$

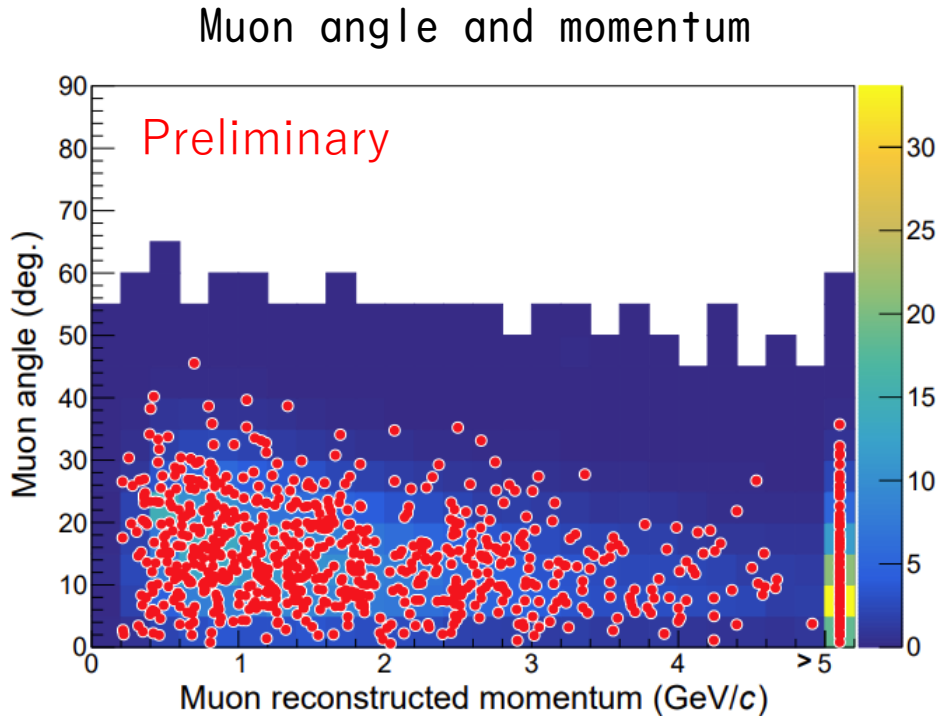


- Cross-section of Data is larger than that of the MC predictions. (23% difference)

Muon kinematics of CC inclusive interaction on iron (770 events, anti-ν mode, $\bar{E}_\nu$= 1.30 GeV)

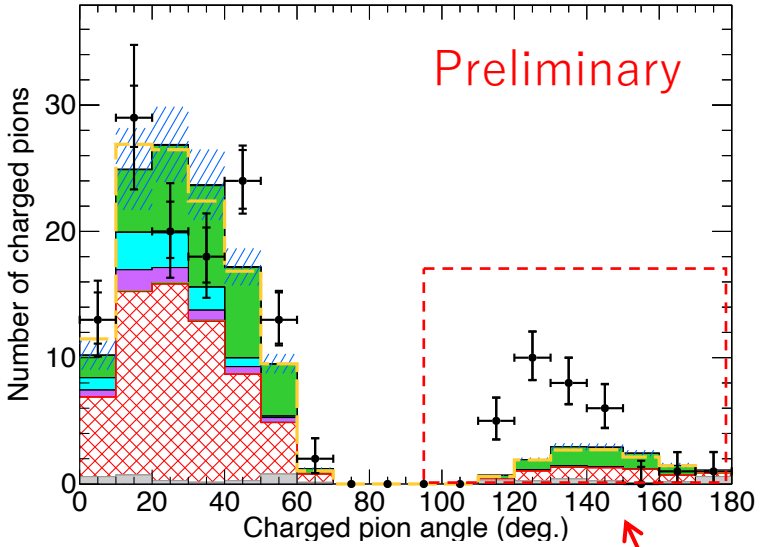


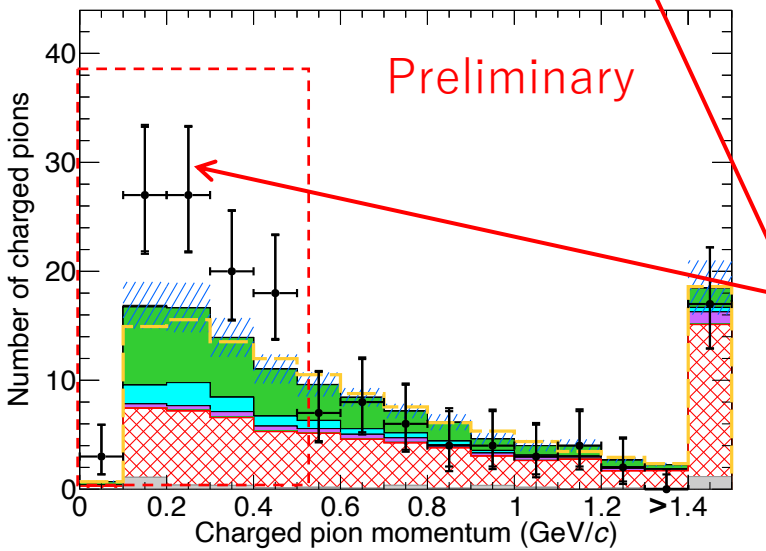




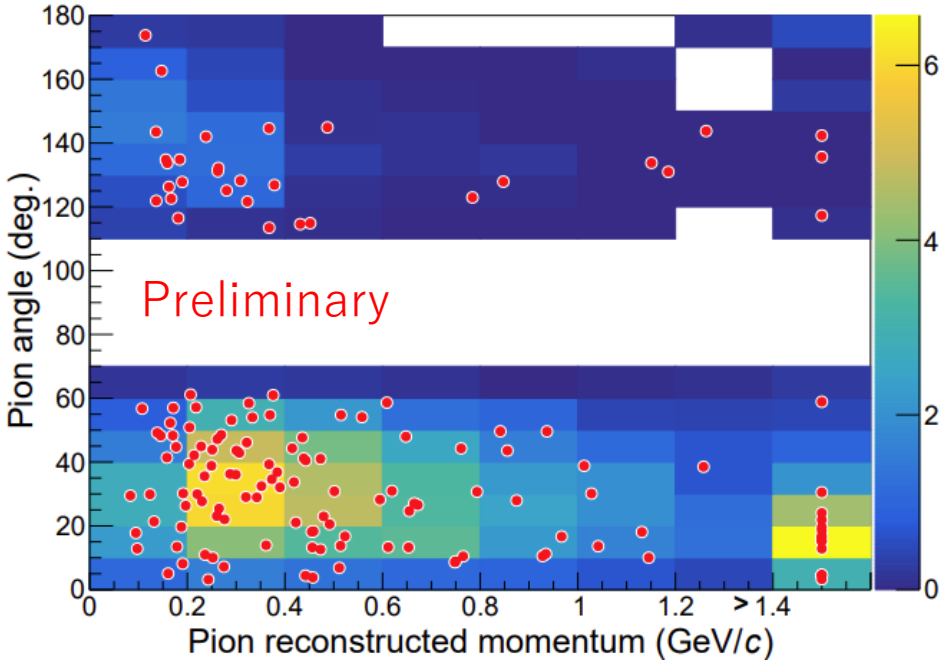
- The results agree well with the MC prediction.

Pion kinematics of CC inclusive interaction on iron (770 events, anti-ν mode, $\bar{E}_\nu$= 1.30 GeV)



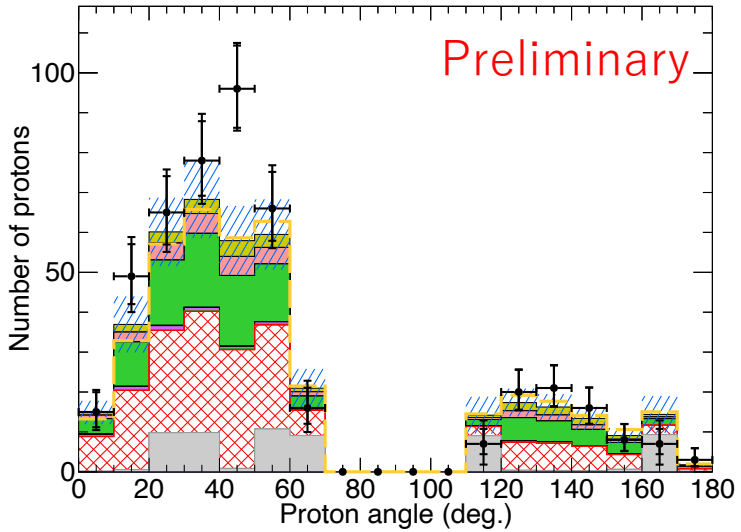


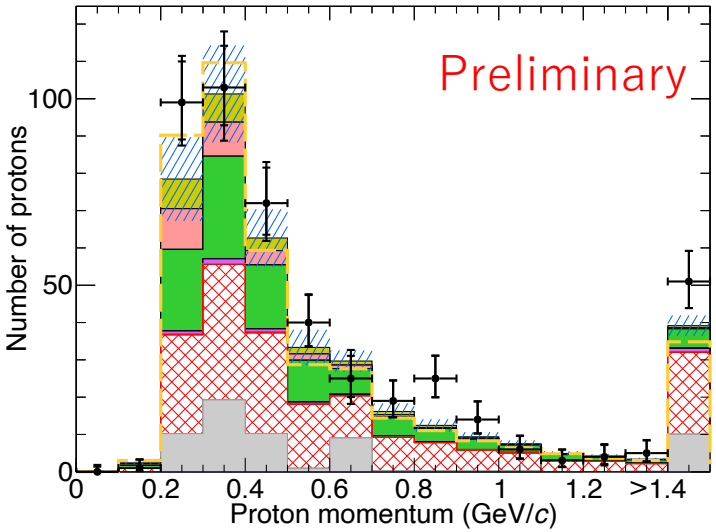
Pion angle and momentum



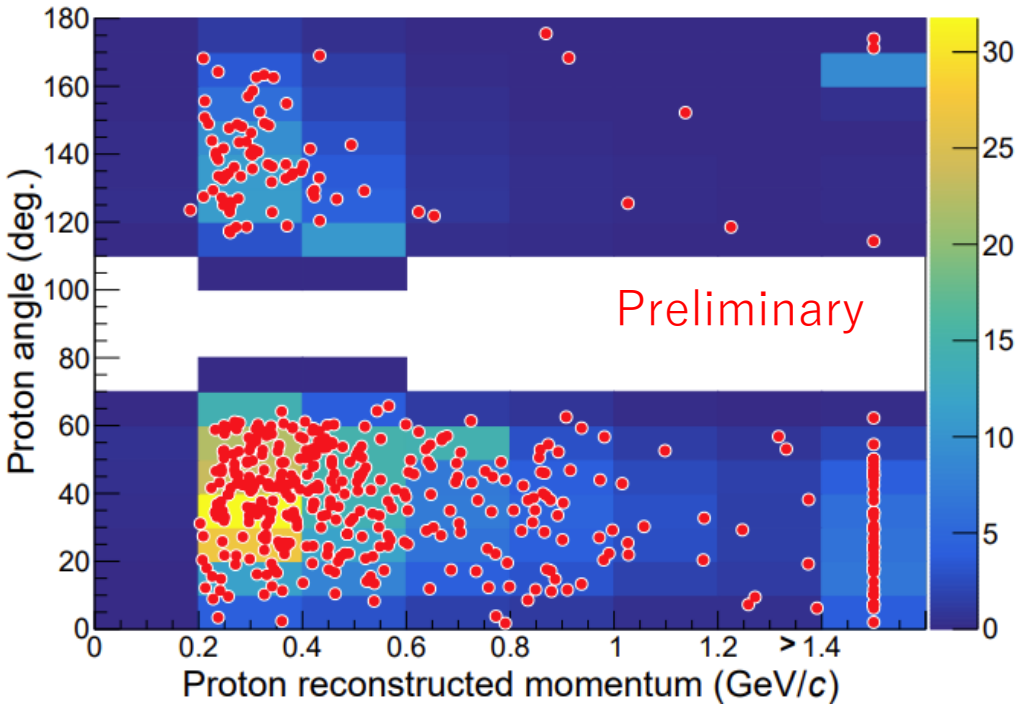
- # of back-scattered and low-momentum pions of Data are larger than that of MC prediction.

Proton kinematics of CC inclusive interaction on iron (770 events, anti-ν mode, $\bar{E}_\nu$= 1.30 GeV)





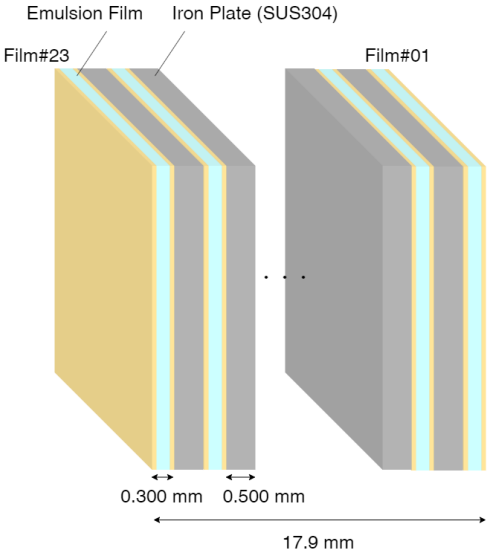
Proton angle and momentum



- The results agree well with the MC prediction.

Summary

65 kg iron target + emulsion films



- ν mode ($\bar{E}_\nu$= 1.49 GeV, 0.4×10^{20} POT)
  - The flux averaged CC-inclusive cross section is consistent with the T2K INGRID measurement and the MC prediction.
  - Differences in Data and MC were found below.
    - CC-inclusive: Angle distribution of pions.
    - CC-inclusive: Angle distribution of protons.
    - CC0π2p: Opening angle between two protons.
- Anti-ν mode ($\bar{E}_\nu$= 1.30 GeV, 3.5×10^{20} POT)
  - The flux averaged CC-inclusive cross section is larger than the MC prediction.
  - Differences in Data and MC were found below.
    - CC-inclusive: Angle and Momentum distribution of pions.

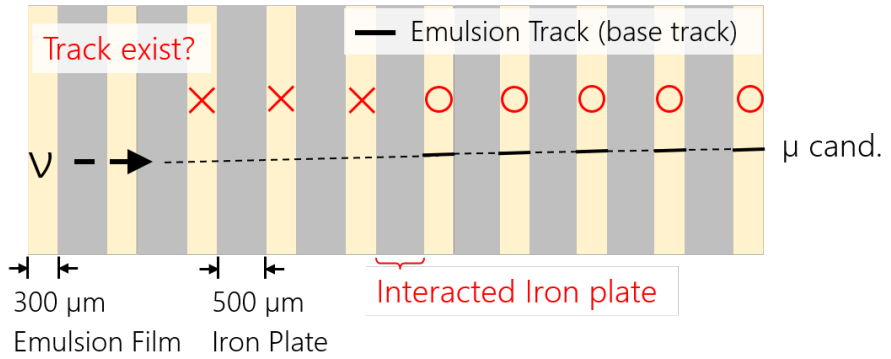
Backup

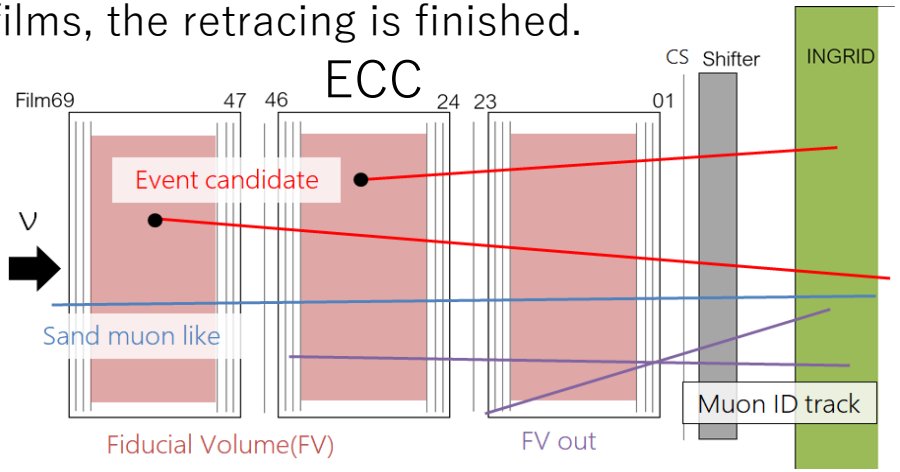
Monte Carlo simulations (65 kg iron target run)

- Neutrino beam simulation: JNUBEAM 13av6.1
- Neutrino Event generator: NEUT 5.4.0
- Detector simulation: Geant4 (QGSP BERT)

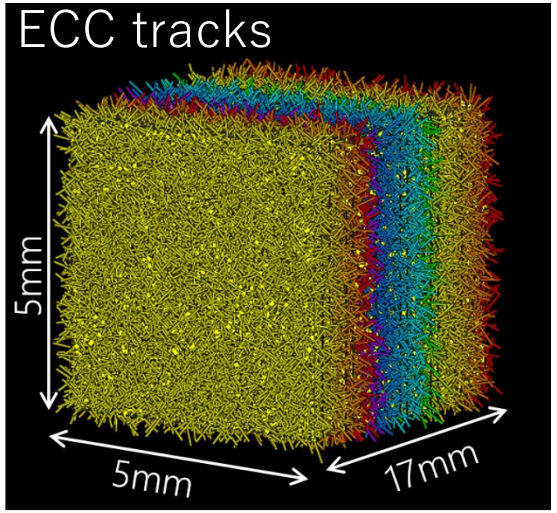
Event reconstruction and the selection of neutrino interactions

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

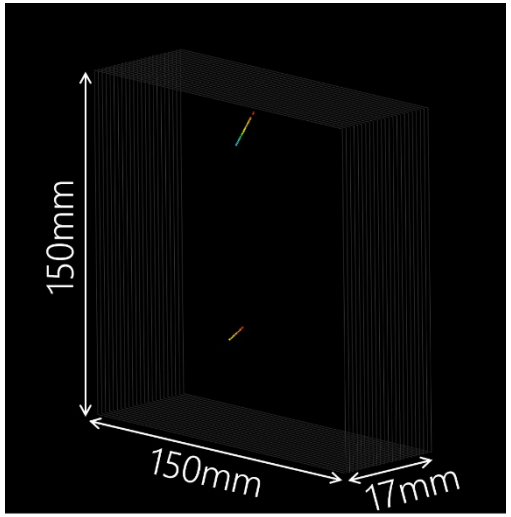




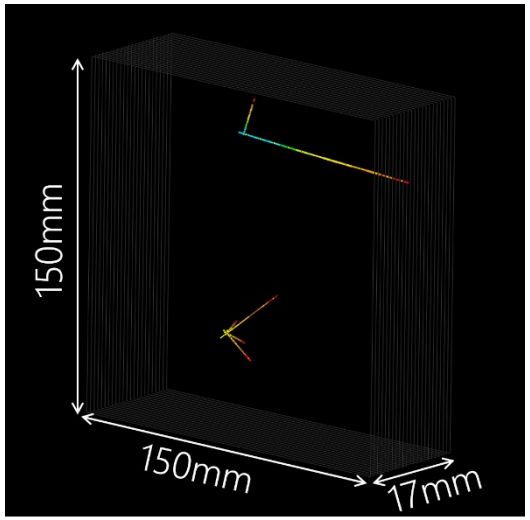
$\nu + \bar{\nu}$ int.(CC+NC) + cosmic-ray



$\nu + \bar{\nu}$ CC int. μ cand.



$\nu + \bar{\nu}$ CC int. events

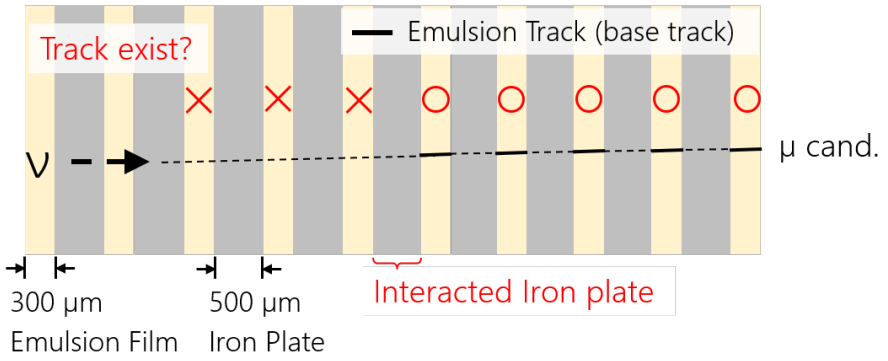


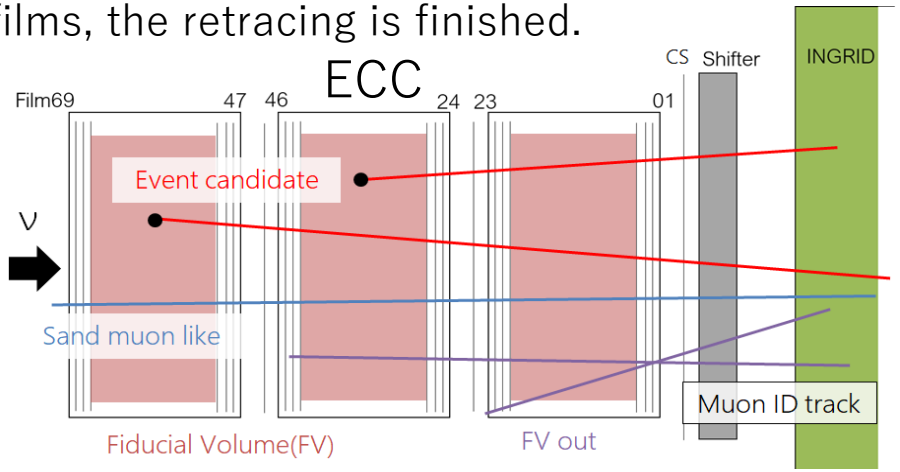
Detection of ν CC interactions
Muon selection (Shifter & INGRID)

Event reconstruction (ECC)
Proton and pion tracks search

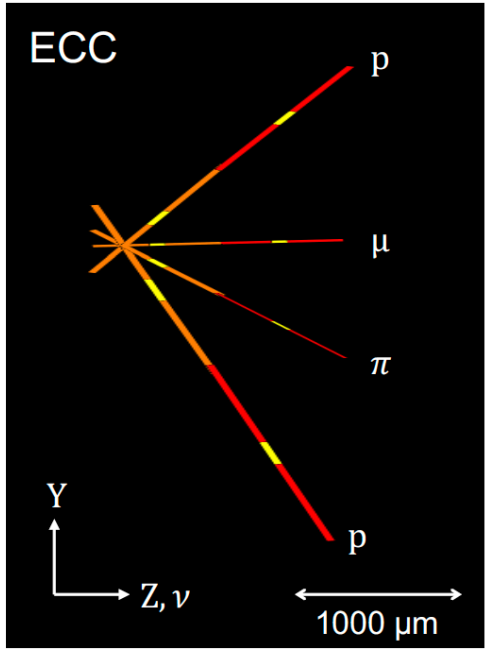
Event reconstruction and the selection of neutrino interactions

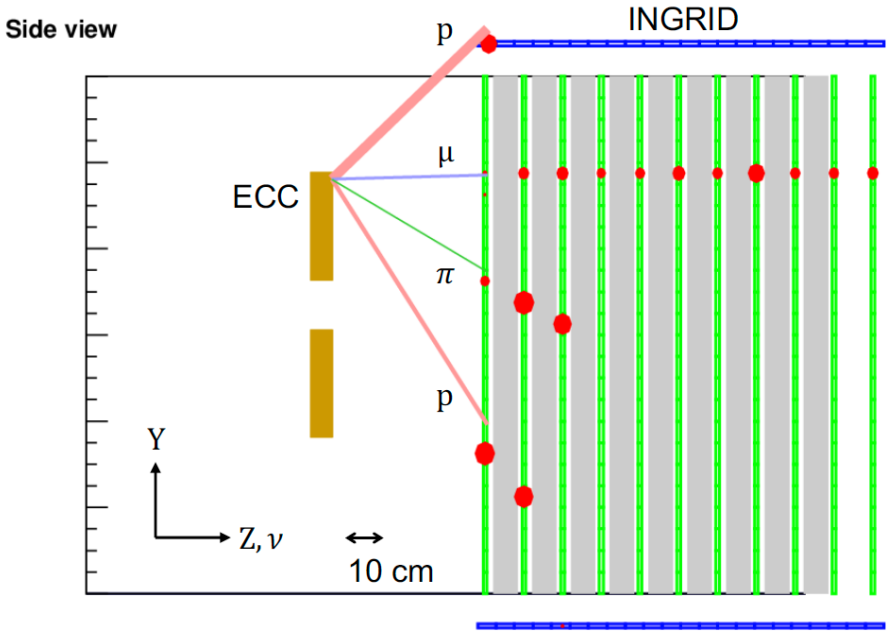
Scanback method :
The muon candidates were traced back from INGRID to the interaction vertices. If no tracks with connection are fond in the three upstream films, the retracing is finished.





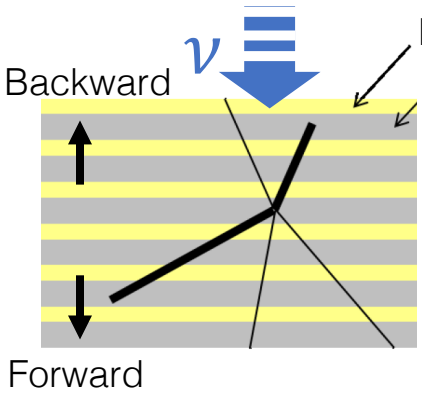
Event display (Data)





Proton / pion track search

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

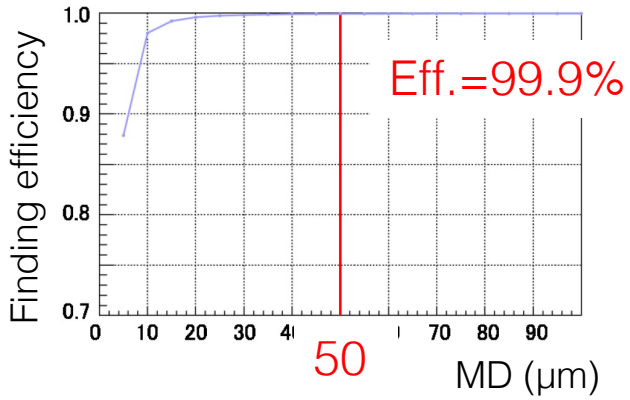


MD allowance
Thin track ：50 μm
Black track：60 μm

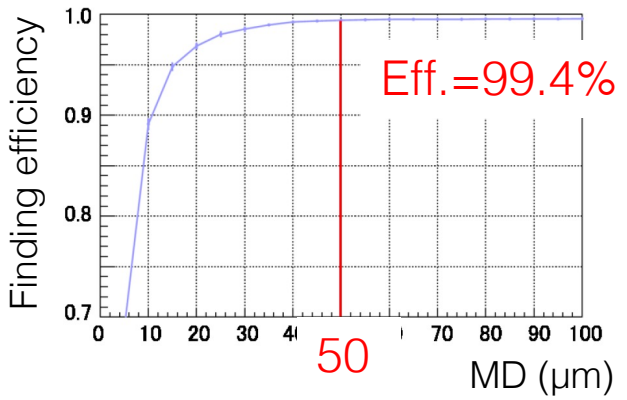
MC study

Thin tracks (MIPs)

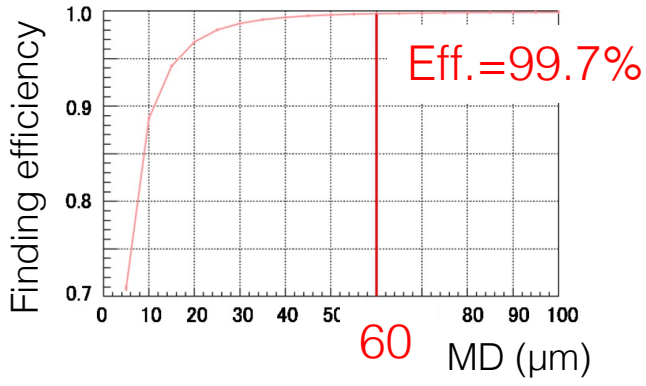
Forward emission

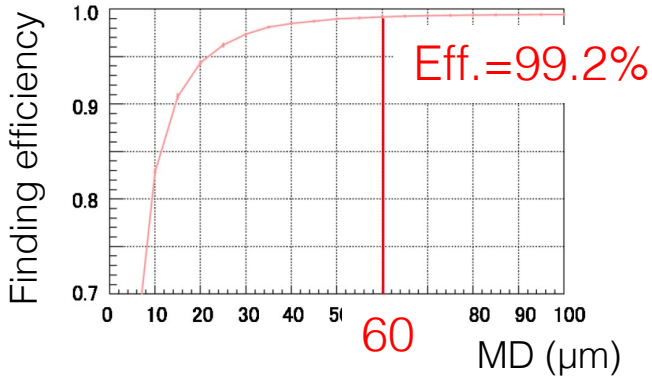


Backward emission



Black tracks (Heavily ionizing particles)



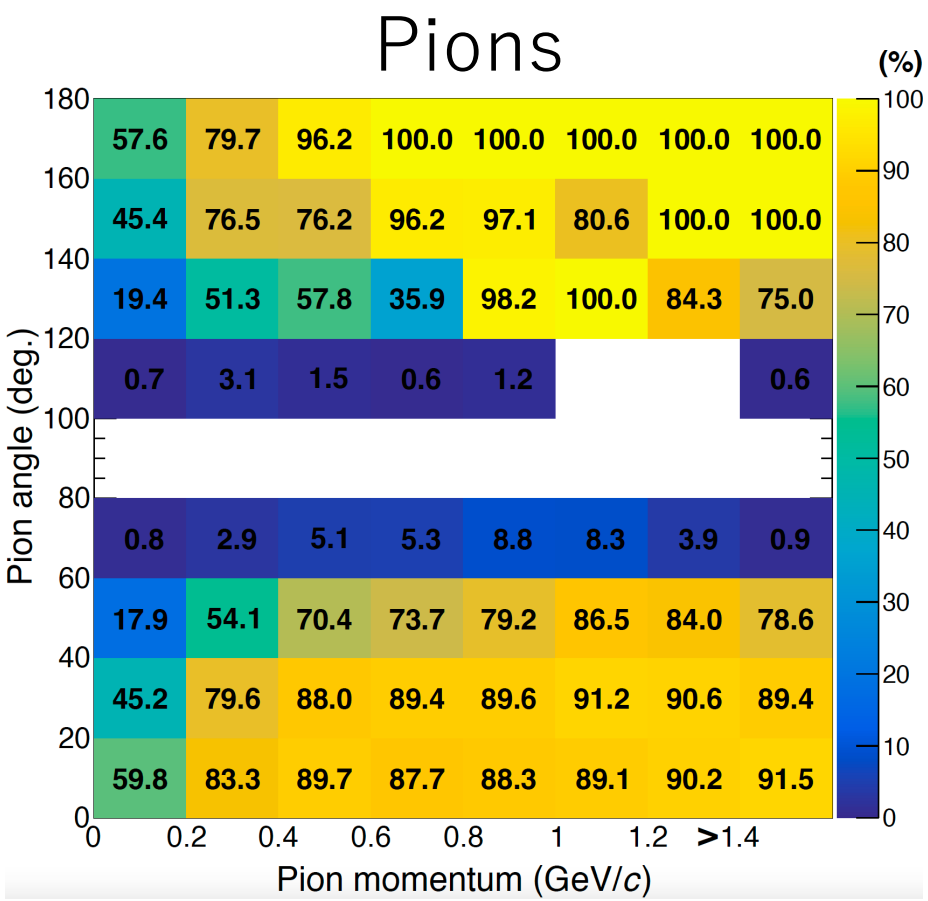


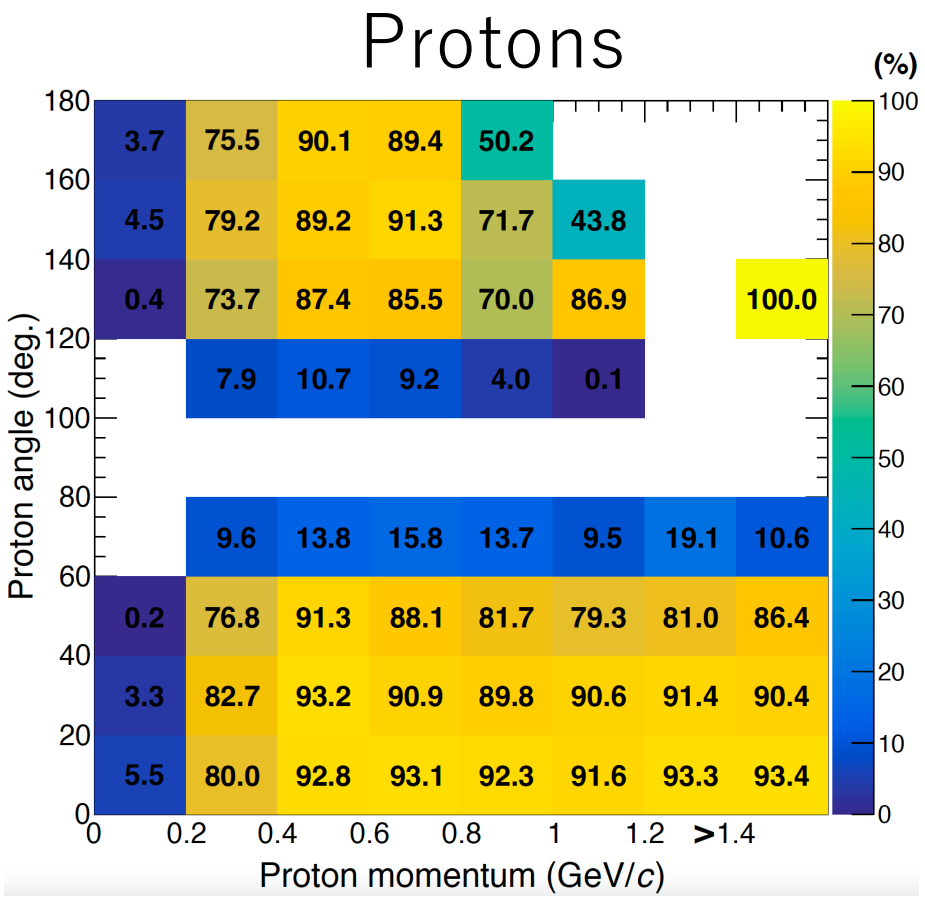
Detection efficiencies of pions and protons

- 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: $|\theta_{x(y)}| < \sim 60°$

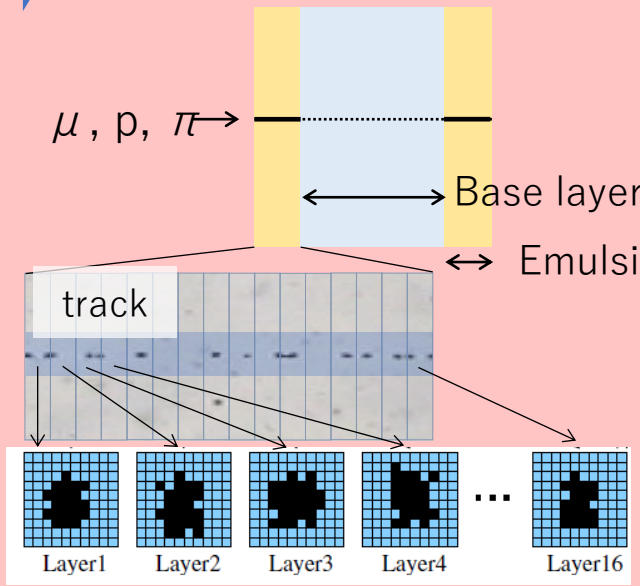




dE/dx measurments in the ECC brick

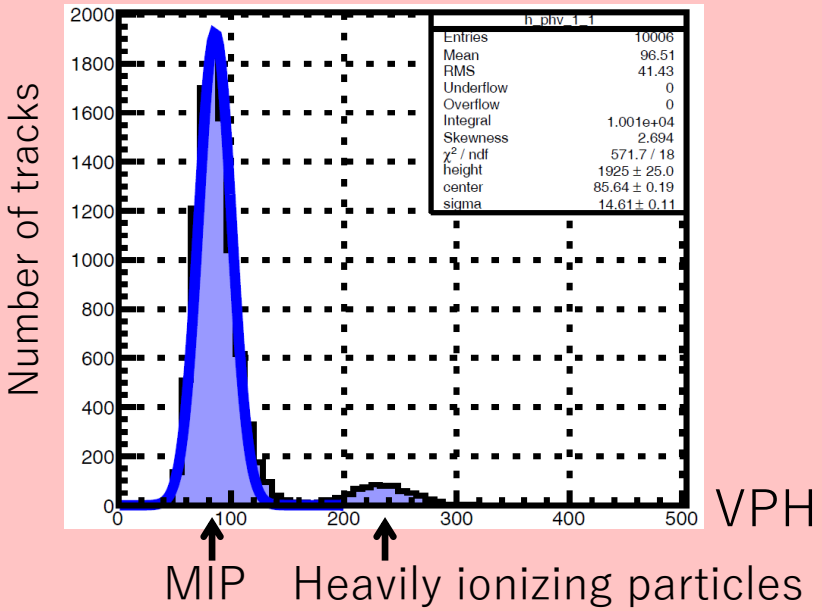
Volume Pulse Height (VPH)

VPH is a measure of dE/dx.

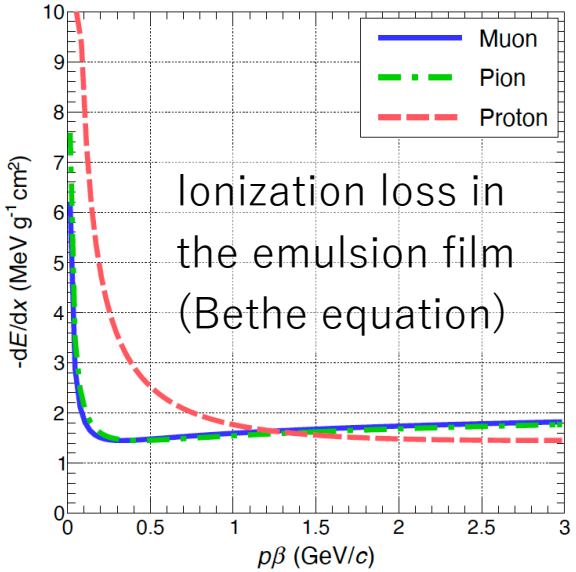


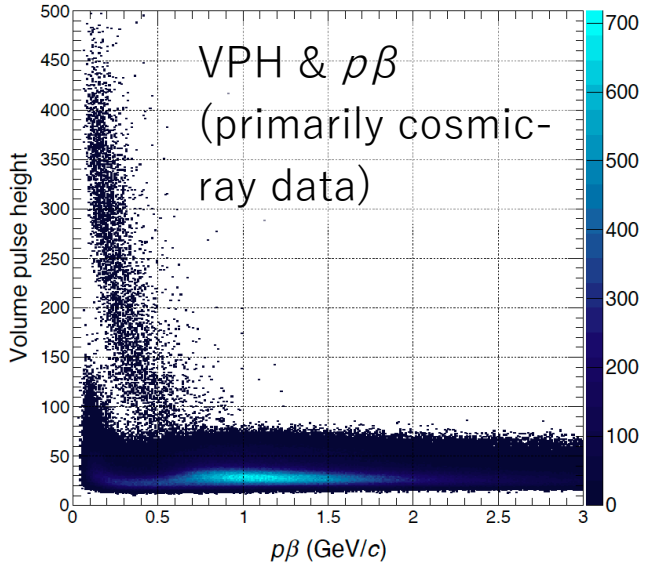
NIM A **556**, 482 (2006).

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 & $p\beta$!

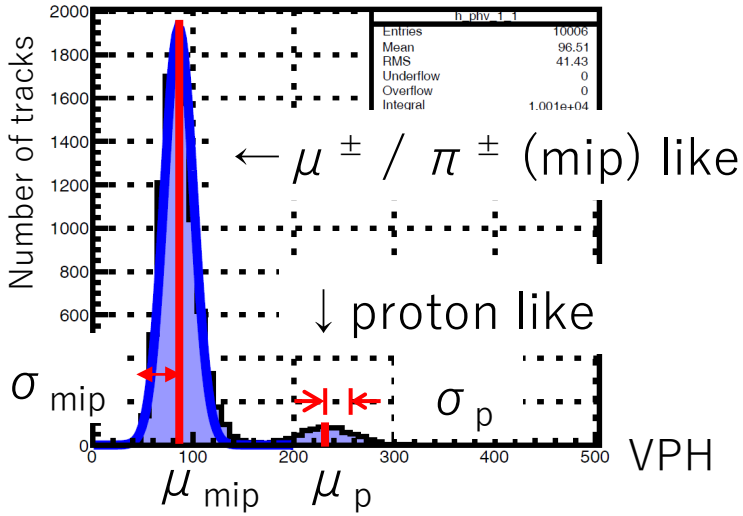
Particle identification of protons and pions

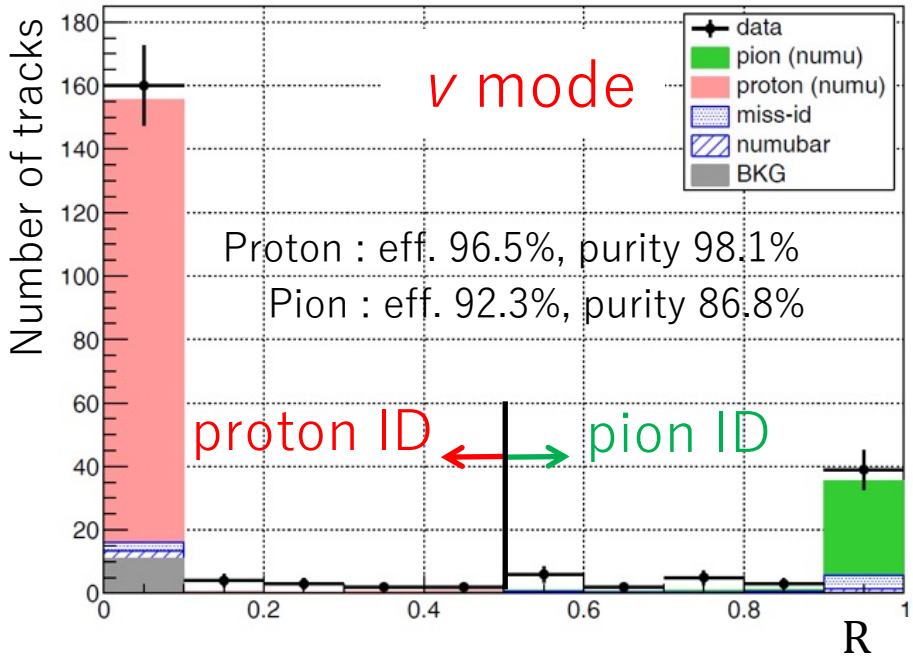
Likelihood function

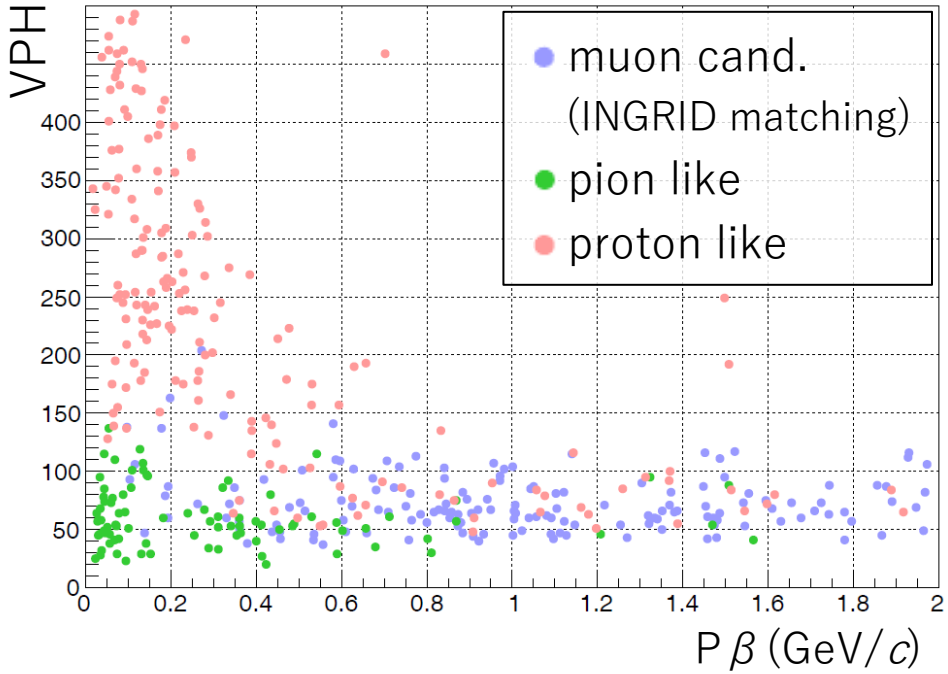
$$L = \frac{1}{\sqrt{2\pi}\sigma_{p\beta,angle}} \exp\left[\frac{-(VPH-\mu_{p\beta,angle})^2}{2\sigma^2_{p\beta,angle}}\right]$$

Likelihood Ratio

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

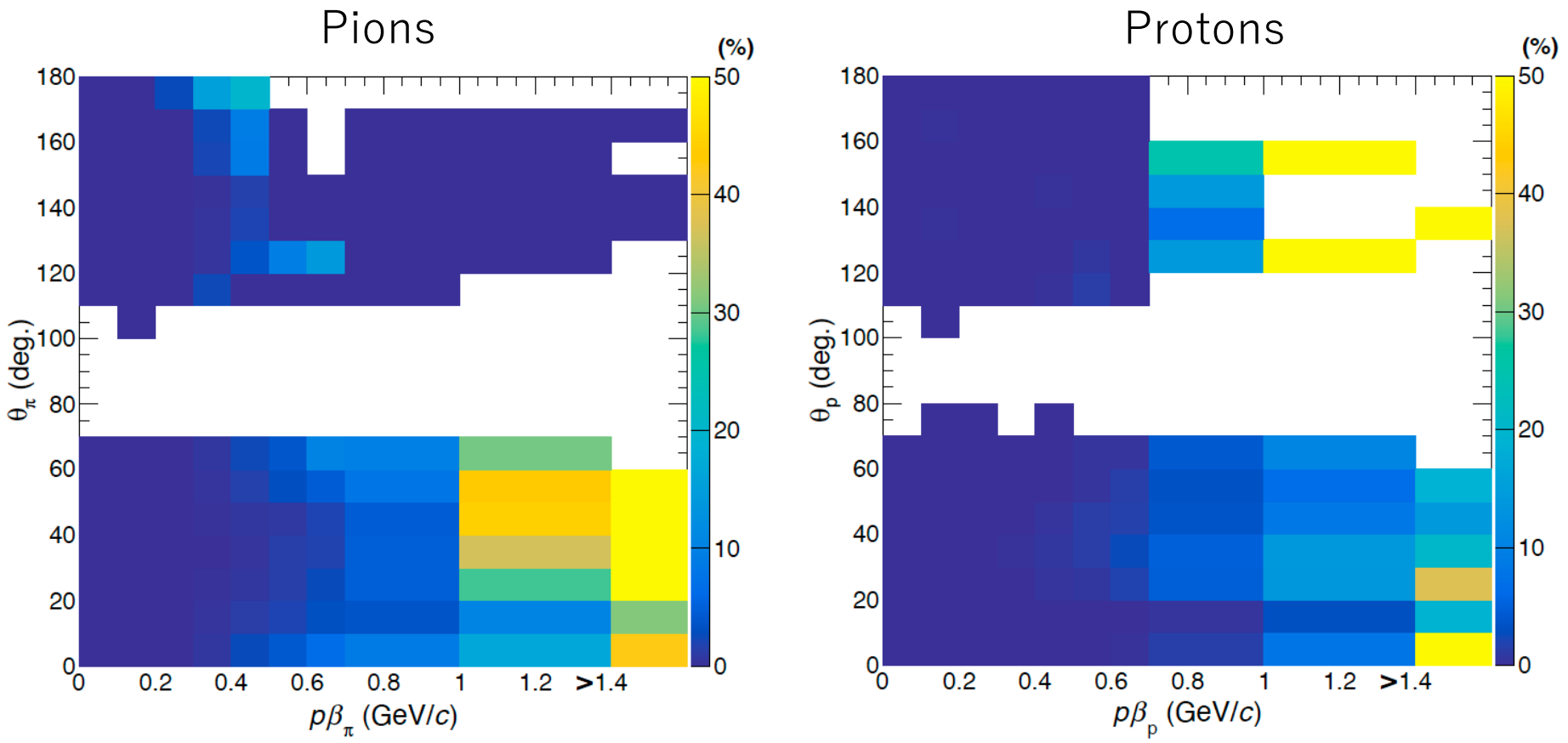






→ p / $\pi^{\pm}$ separation using VPH and momentum is good.

Mis-PID rates of pions and 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.