NINJA

First cross section measurement of neutrino charged current interactions in the iron ECC

Contents

- Introduction
- NINJA experiment
- Detector construction
- ν event analysis
- Outcomes
- Summary & Prospect

Toho Univ., Nagoya Univ., Kobe Univ., Nihon Univ., Kyoto Univ., Yokohama national Univ. ICRR and Univ. of Tokyo

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The 21st International Workshop on Neutrino from Accelerators (NUFACT2019)

Introduction : Neutrino Oscillation

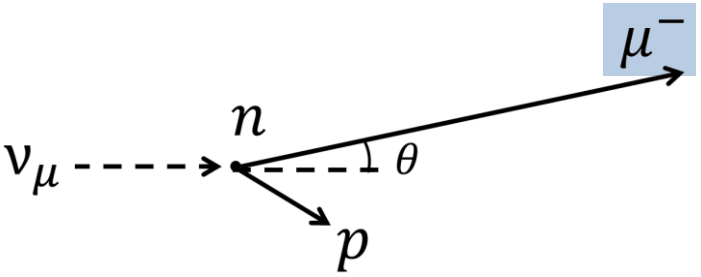
Oscillation Probability (2 flavor neutrino oscillation, for simplification)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \qquad \Delta m^2 = m_2^2 - m_1^2$$

Oscillation prob. is large in low E_ν region

Eν reconstruction

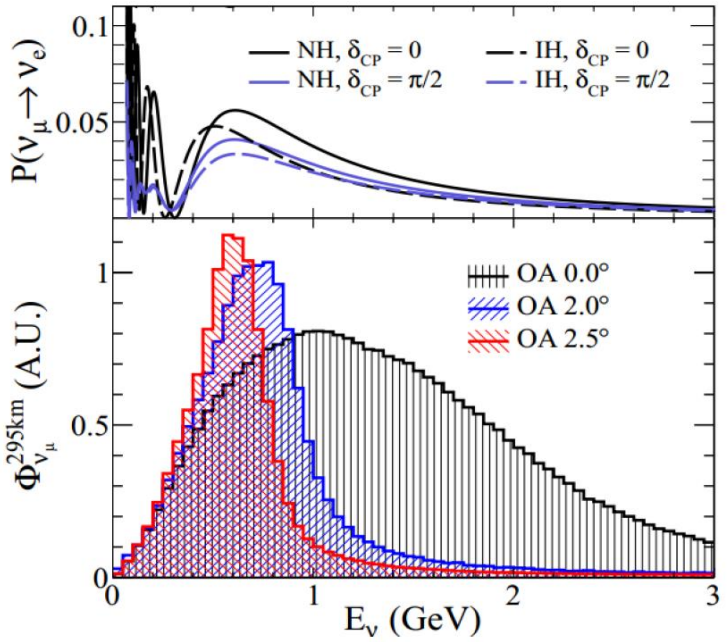
Charged Current Quasi Elastic Scattering



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

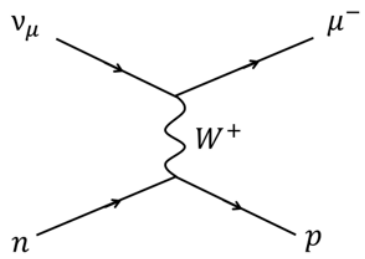
the neutrino energy can be easily reconstructed by the measurement of muon emission angle and momentum for the QES.

Eν vs. Osc. Prob. & ν Flux. (T2K FD(SK))

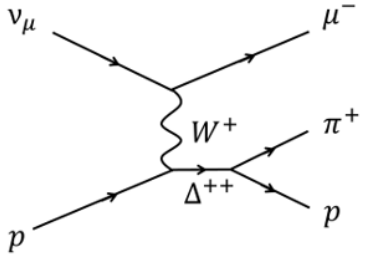


Introduction : Neutrino Interactions

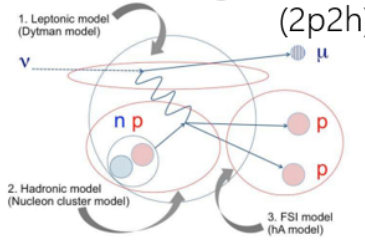
Quasi Elastic



Resonant pion production

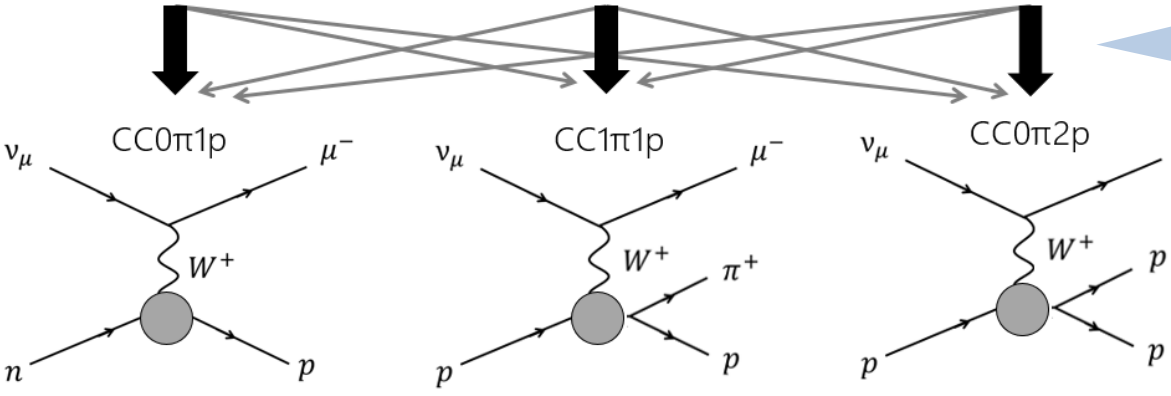


Meson Exchange Current (2p2h)



T. Katori, arXiv:1304.6014v3(2013)

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



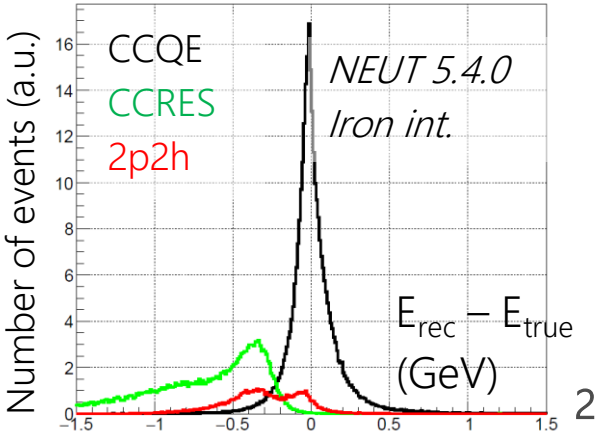
T. Kikawa : Shin-gakujutsu Workshop(2018)

Hard to separate interaction modes.

→ Neutrino energy reconstruction can be mistaken.

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

Residual of Neutrino Energy(MC)



Introduction : What we can measure

What we can measure to solve this problem :

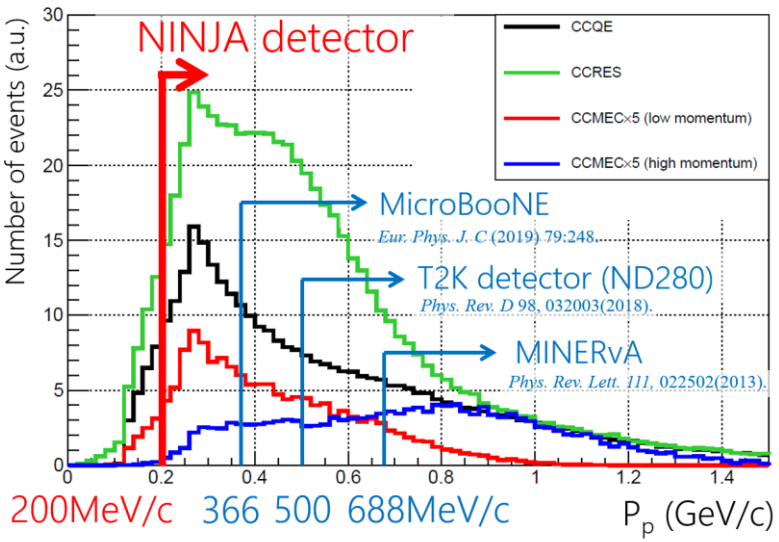
- the number of charged hadrons
- their emission angles and momenta

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.

We can measure charged hadron final states with low energy threshold.

Proton momentum (NEUT 5.4.0, ν-iron int.)



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

Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

The NINJA collaboration aims to study neutrino-nucleus interactions in the energy range of hundreds of MeV to a few GeV by using emulsion-based detector.

→ We can study ν–nucleus interactions with sub-micron accuracy.

→ We can use various target (Fe, H_2O, C, etc.)

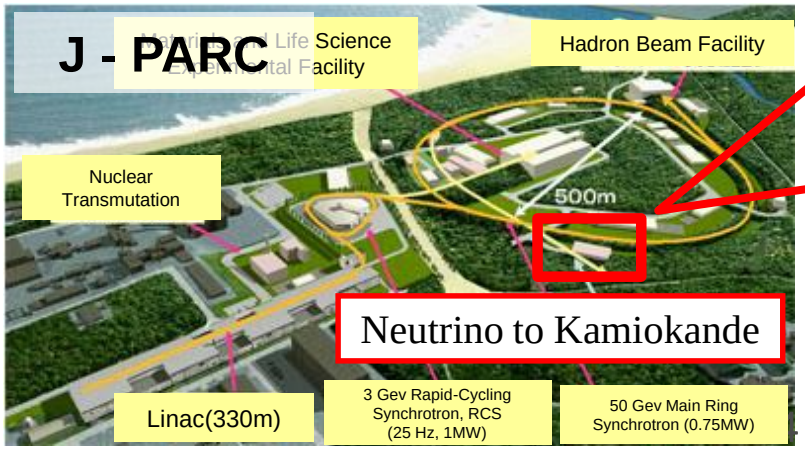
NINJA Run so far

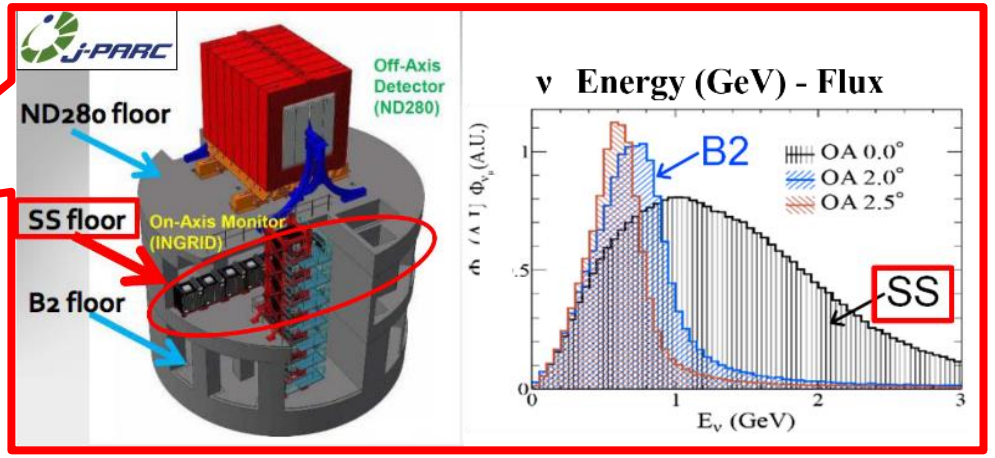
A) Detector test run with emulsion shifter → published — T. Fukuda, et al., PTEP, 063C02(2017); K. Yamada, et al., PTEP, 063H02 (2017)

B-1) 65kg iron target run (2016) → analysis on-going — This talk

B-2) 4kg water target run (2017-2018) → analysis on-going

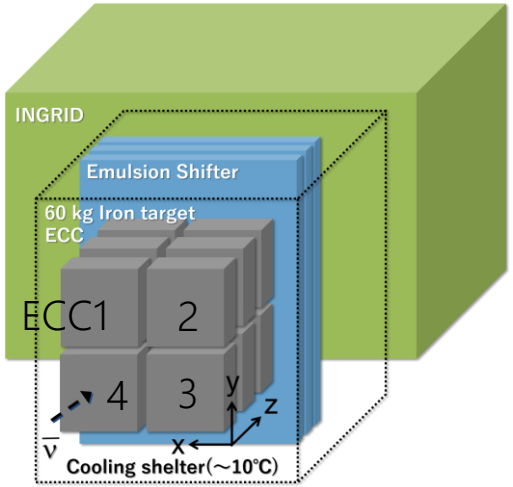
C) Physics run (75kg water target) → under preparation — T. Fukuda (oral, NUFACT2019, 29/08); T. Odagawa (poster, NUFACT2019, 26/08)



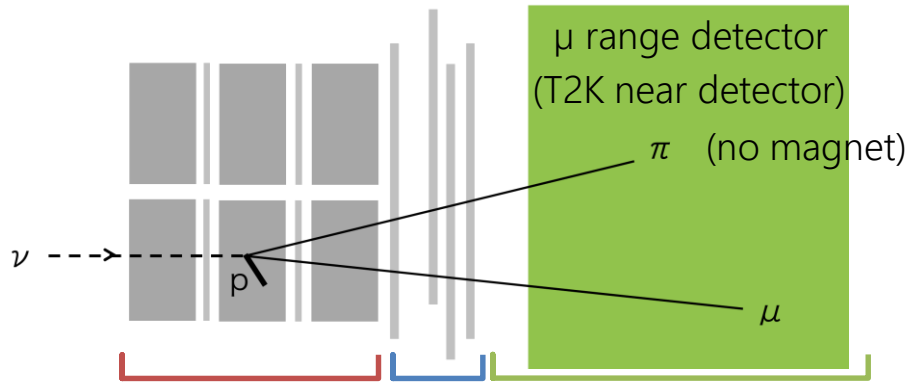


NINJA iron target run in 2016 : Detector construction

Detector : Overall view



Side view



muon ID
select CC int.

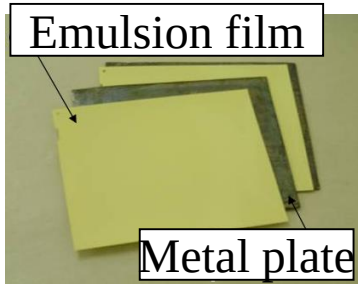
ECC (Emulsion Cloud Chamber)

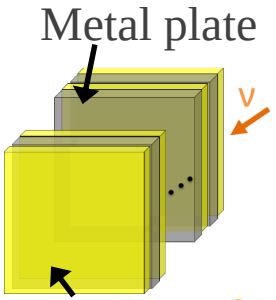
analyze a *Neutrino - Fe interaction*

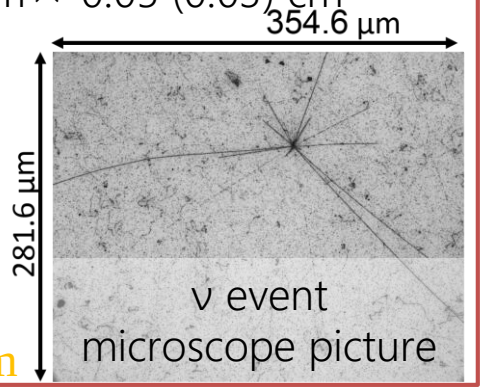
Total : 12 ECC (264 Iron PLs, 65kg)

Emulsion Film + Iron PL stacked chamber

Size of Iron Plate (Film) : 25cm× 25cm× 0.05 (0.03) cm

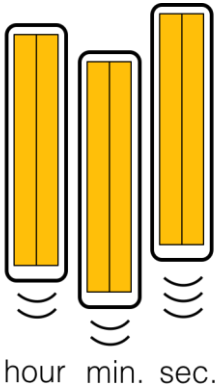




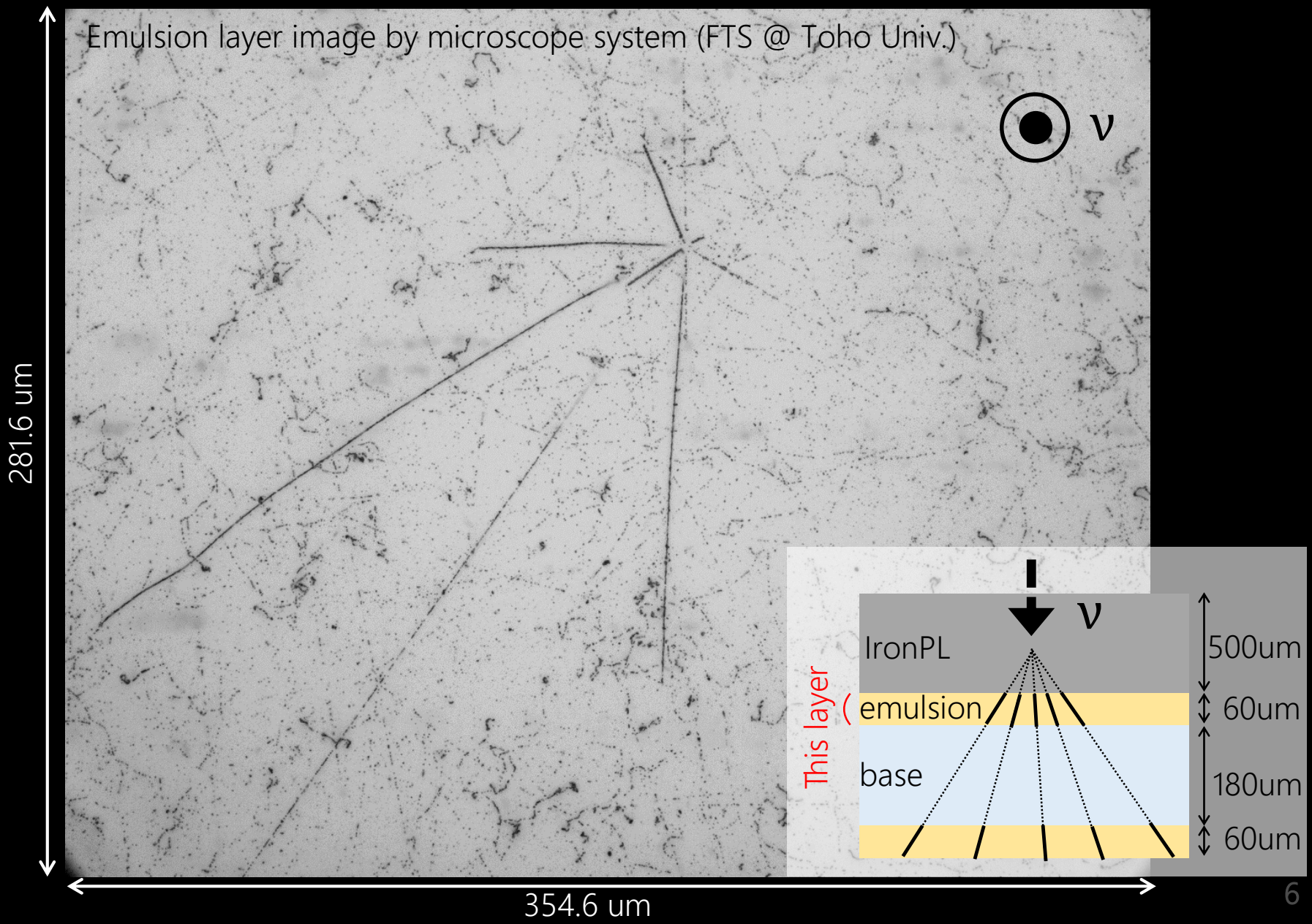


Emulsion multi-stage Shifter

Add timestamp for event tracks from ν int.



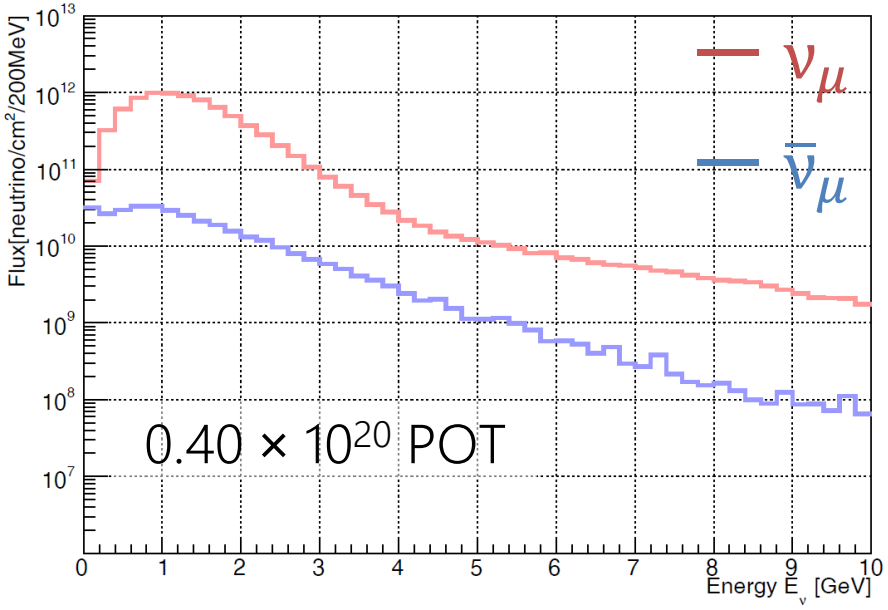
An example of ν – iron interaction (NINJA iron target run in 2016)



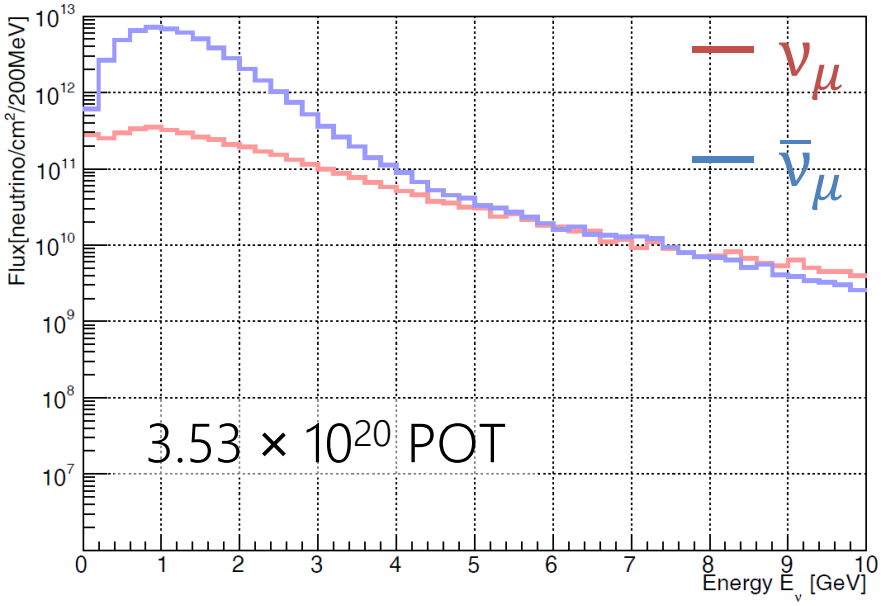
Expected Neutrino Flux @ ECCs

Beam Exposure @ SS floor, Feb. – May 2016

Neutrino Beam Mode



Anti-Neutrino Beam Mode

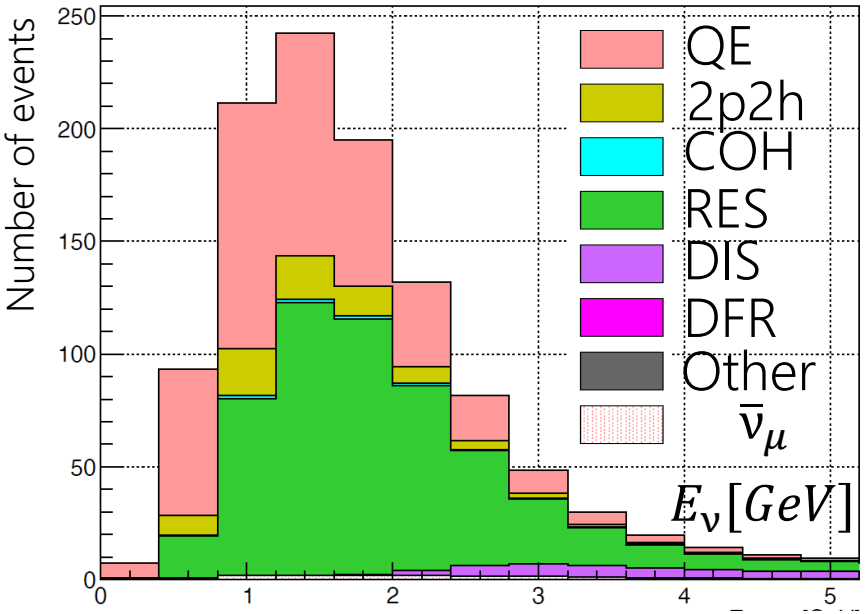


	Neutrino Beam Mode	Anti-Neutrino Beam Mode
ν_μ	95.9 %	7.8 %
$\bar{\nu}_\mu$	4.1 %	92.2 %
POT	0.40×10^{20}	3.53×10^{20}
E_ν average	ν : 1.49 GeV / anti-ν : 1.52 GeV	ν : 2.12 GeV / anti-ν : 1.30 GeV
E_ν peak	ν : 0.90 GeV / anti-ν : 0.70GeV	ν : 0.90 GeV / anti-ν : 0.90 GeV

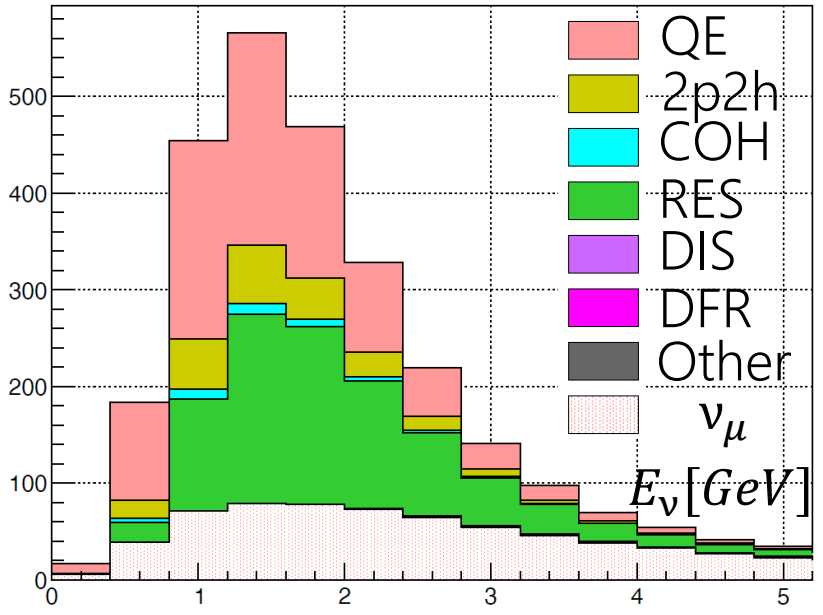
Expected CC Events in ECCs

NEUT 5.4.0, Iron CC int. (tuned flux)

Neutrino Beam Mode



Anti-Neutrino Beam Mode



	Neutrino Beam Mode	Anti-Neutrino Beam Mode
POT	0.40×10^{20}	3.53×10^{20}
ν_μ CC int.	98.6 %	28.2 %
$\bar{\nu}_\mu$ CC int.	1.4 %	71.8 %

Normalize factor :

- POT
- target mass

We can get the high purity ν – iron CC interactions by selecting ν beam mode events.

=> In this talk, we analyze these ν CC interactions.

Flow of event reconstruction

Detector preparation
@Nagoya Univ., Toho Univ.

↓

Beam exposure
@J-PARC SS floor

↓

Development, Swelling
@Nihon Univ.

↓

Track Scanning(HTS)
@ Nagoya Univ.

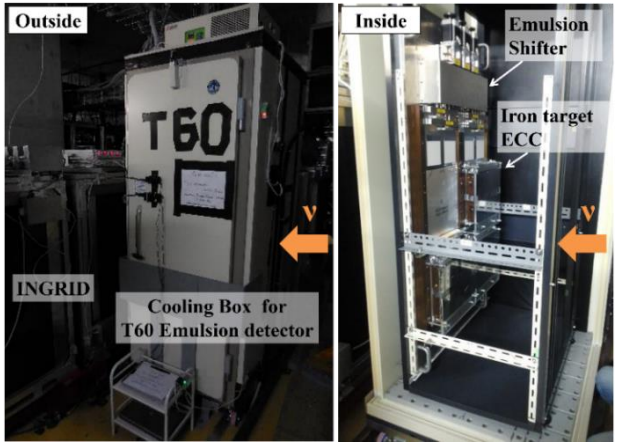
↓

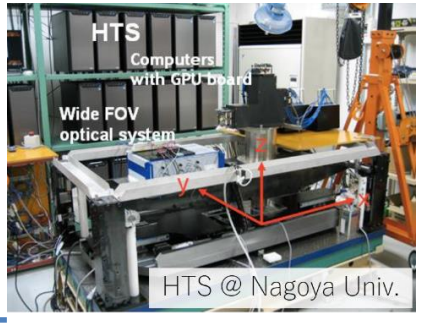
Track & Event reconstruction
@ Toho Univ., Nagoya Univ.

↓

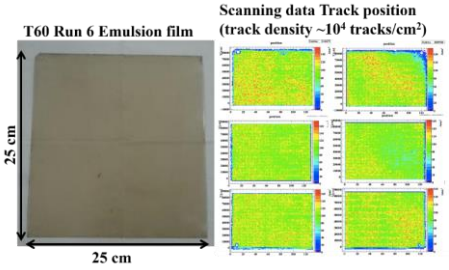
Event eye check (FTS)@ Toho Univ.

Overall view of detector (NINJA iron target run in 2016)

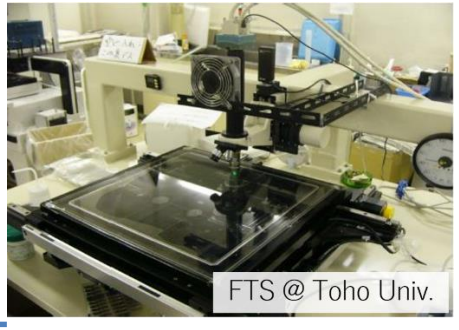


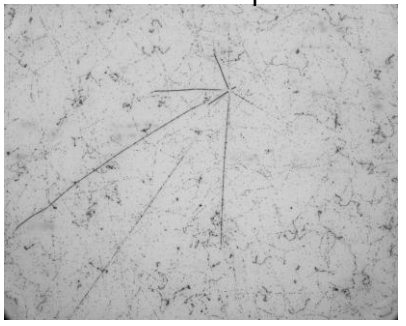


Track scanning



ν event FTS picture



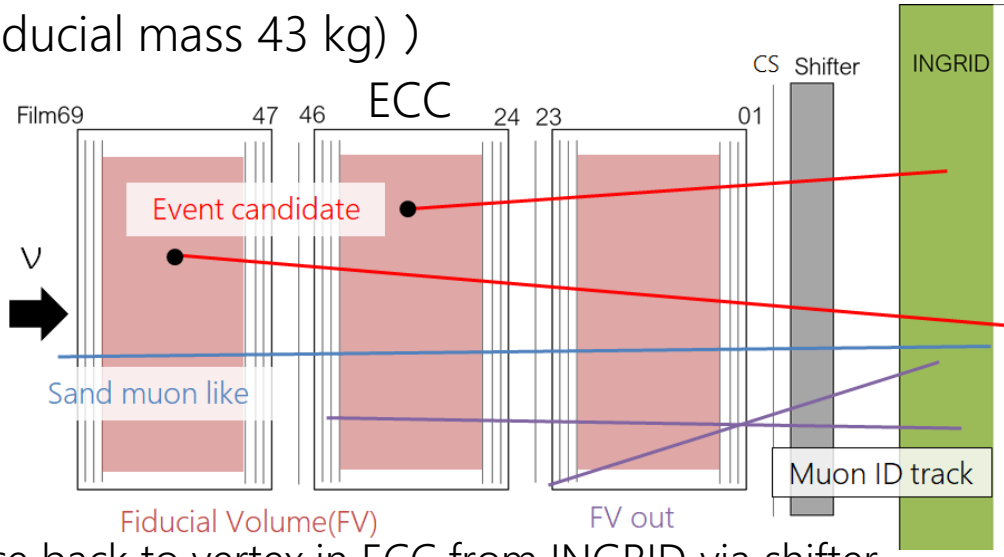


Extract ν CC interaction events by ScanBack method

Data : 12 ECCs (Target mass 65 kg (fiducial mass 43 kg))

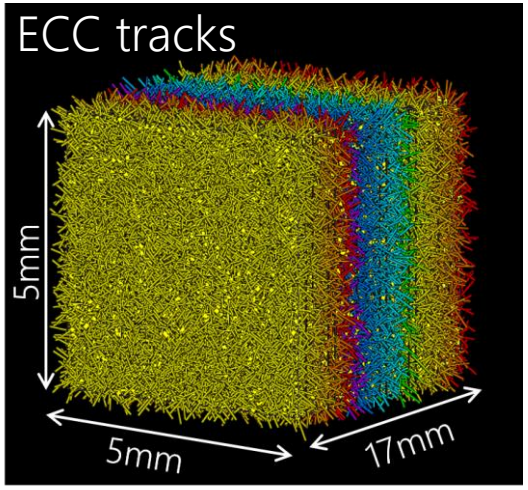
Muon ID track : 47,901 tracks

Muon ID track	# of Tracks
FV out	13,621 tracks
Wall (sand-μ, π, p)	3,2962 tracks
ν + ν̄ CC Event candidate	1,318 tracks

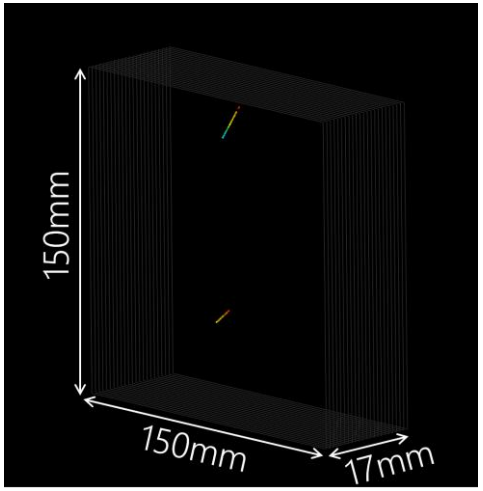


Trace back to vertex in ECC from INGRID via shifter.

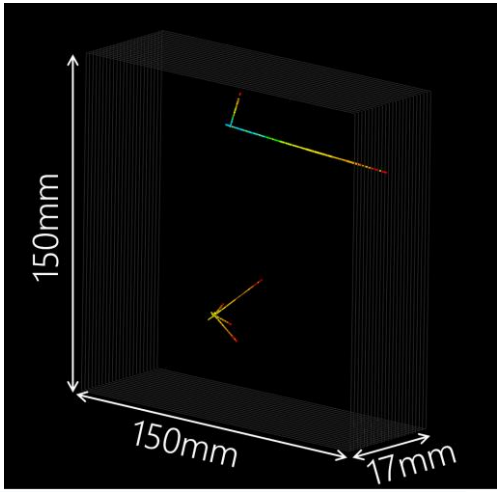
ν + ν̄ int.(CC+NC) + cosmic-ray



ν CC int. μ cand.



ν CC int. events



ν CC int. selection with shifter + INGRID :
Timestamp + Muon ID

Event reconstruction :
Attaching track search

Extract ν CC interaction events by ScanBack method

Data : 12 ECCs (Target mass 65 kg (fiducial mass 43 kg))

Muon ID track : 47,901 tracks

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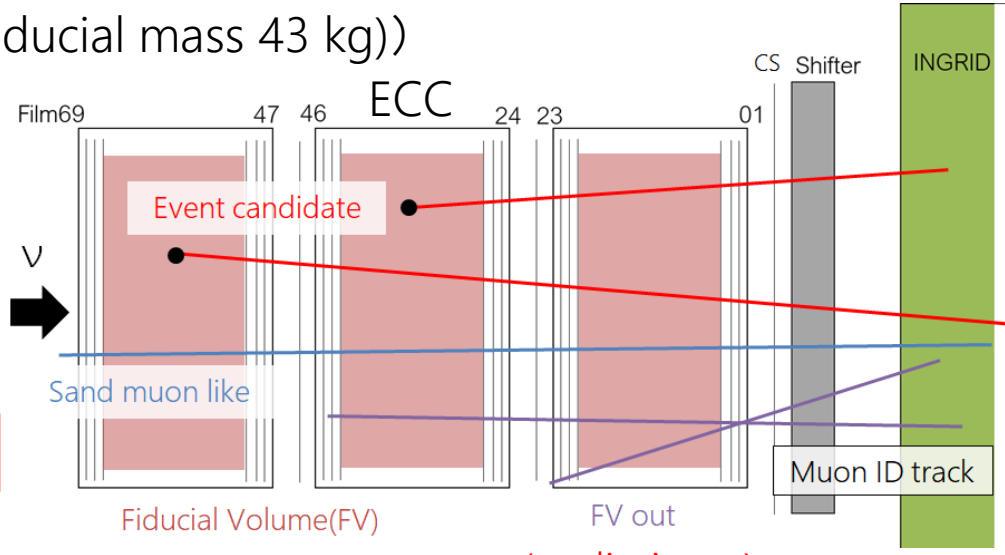


ν beam event selection efficiency : ~ 27 % (preliminary)

(NEUT 5.4.0 ν - iron int., Normalization : POT, Target mass)

ν beam : 221 events.

Iron int. :	**194 events.**
Emulsion int. :	13 events.
Base int. :	14 events.

We are analyzing the ν CC interactions.

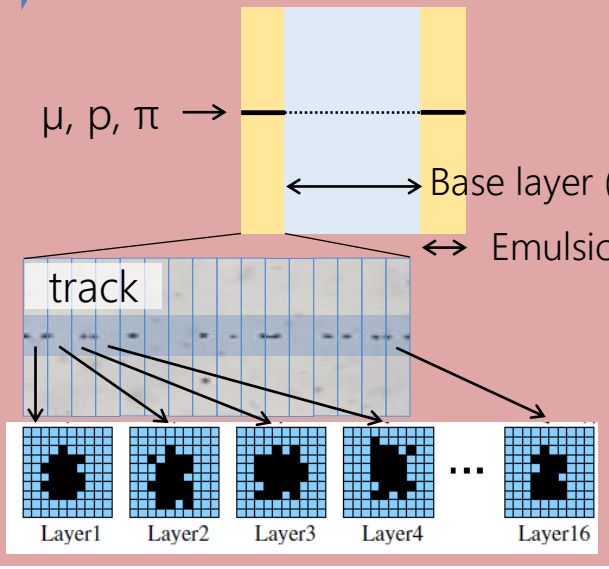
The results on the following slides are based on these 194 ν-iron Charged Current interactions.

ν̄ beam : 1,097 events. → Analysis on-going.

dE/dx & momentum measurments in iron ECC

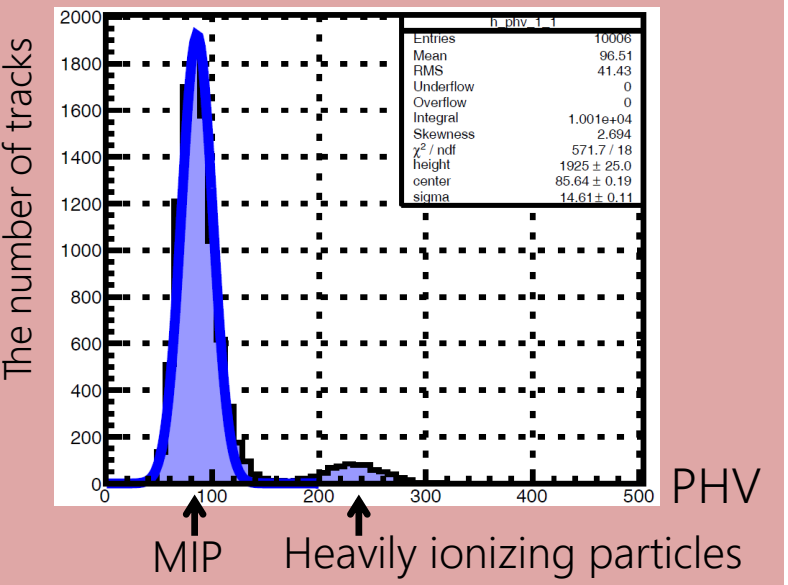
Pulse Height Volume (PHV)

➡ PHV is a measure of dE/dx.



T. Toshito Nucl. Instr. A, 556(2006) 482-489

PHV distribution (Iron ECC tracks)



PHV is the sum of the number of hit pixels in all 16 layers.

Momentum measurements in iron ECC

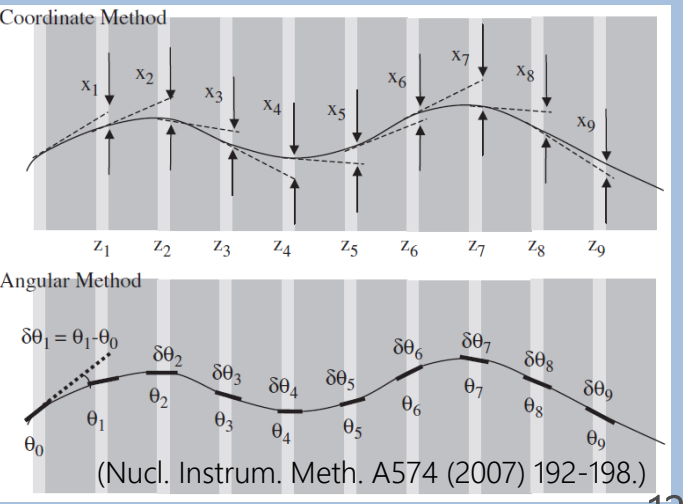
Measure momentum in three ways and use the best method for each track.

Range – energy relation for a short track

(P_μ err. ~ 16%, $P_{p/\pi}$ err. ~ 5%)

Measurement of Multiple Coulomb Scattering

- Coordinate method (1/pβ error sys. ~10%, stat. < ~45%)
- Angular method (1/pβ error sys. ~20%, stat. < ~50%)



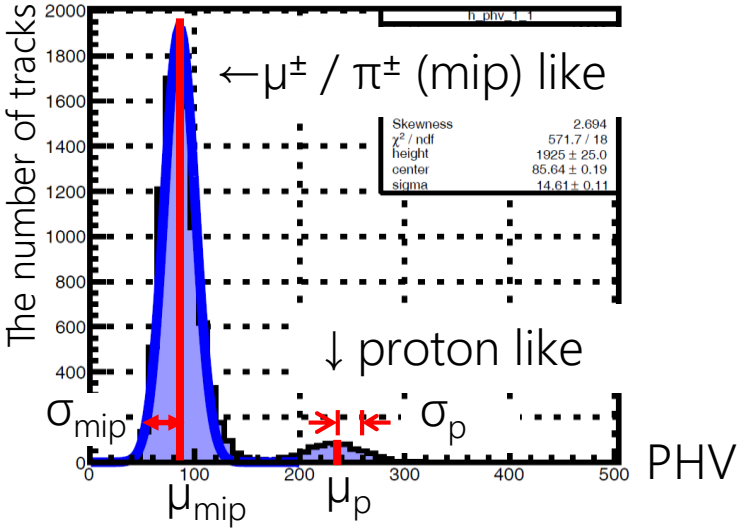
Proton and π± PID in ECC

Likelihood function

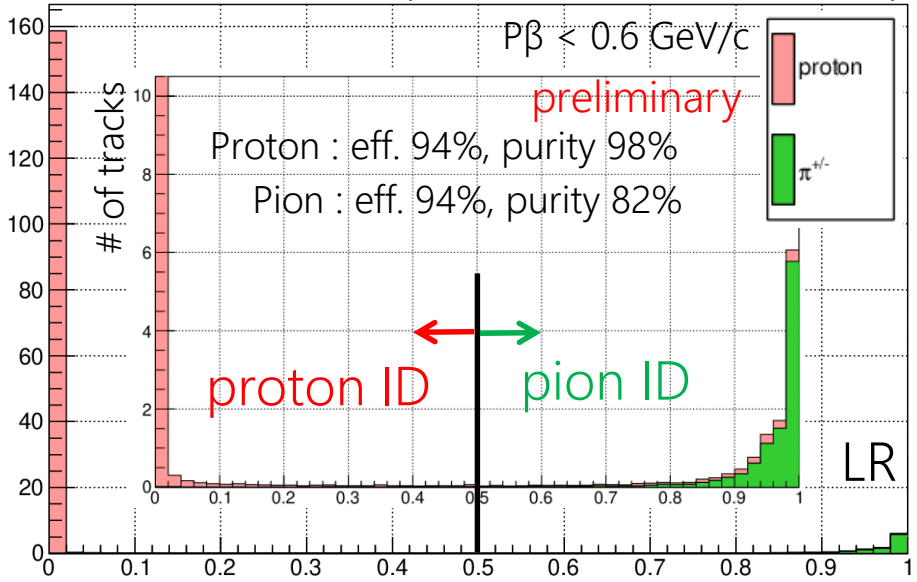
$$L = \frac{1}{\sqrt{2\pi}\sigma_{p\beta,angle}} \exp\left[\frac{-(PHV-\mu_{p\beta,angle})^2}{2\sigma^2_{p\beta,angle}}\right]$$

Likelihood Ratio

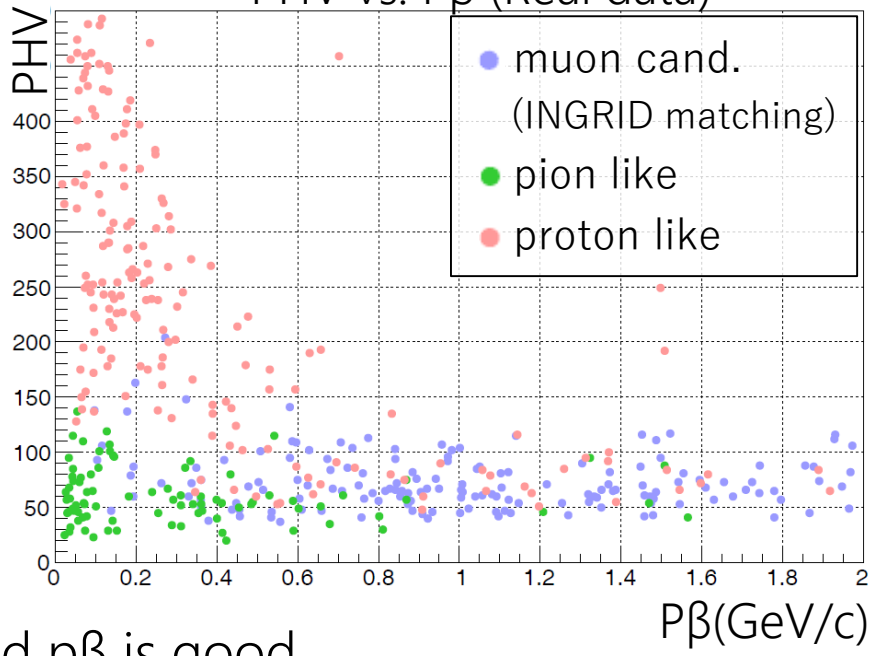
$$LR = \frac{L_{mip\ like}}{L_{mip\ like}+L_{proton\ like}}$$



Likelihood Ratio (NEUT 5.4.0, ν-Iron CC int.)



PHV vs. Pβ (Real data)



→ p / π± separation by using PHV and pβ is good.

Previous study Y. Morimoto (Toho Univ.), O. Sato (Nagoya Univ.), T. Toshito Nucl. Instr. A, 556(2006) 482-489.

Setup of Monte Carlo simulation

Event Generator :

NEUT 5.4.0

Used in Super-Kamiokande, T2K and the various experiments.
NEUT covers a wide energy range of neutrino from several tens of MeV to hundreds of TeV.

Y. Hayato, Nucl. Phys. B, Proc. Suppl. 112, 171 (2002), Y. Hayato, Acta Phys. Pol. B 40, 2477 (2009).

Normalization :

POT & target mass of NINJA 65kg iron target run in 2016.

Considered particle :

Muon, charged pion, proton

Detector response :

Angle … no smeared

Momentum … MCS $1/P\beta$ err. = 50%

Range P_{μ} err. = 16% (using ECC and INGRID iron plates(65mm))

$P_{p/\pi}$ err. = 5% (using ECC iron plates(0.5mm))

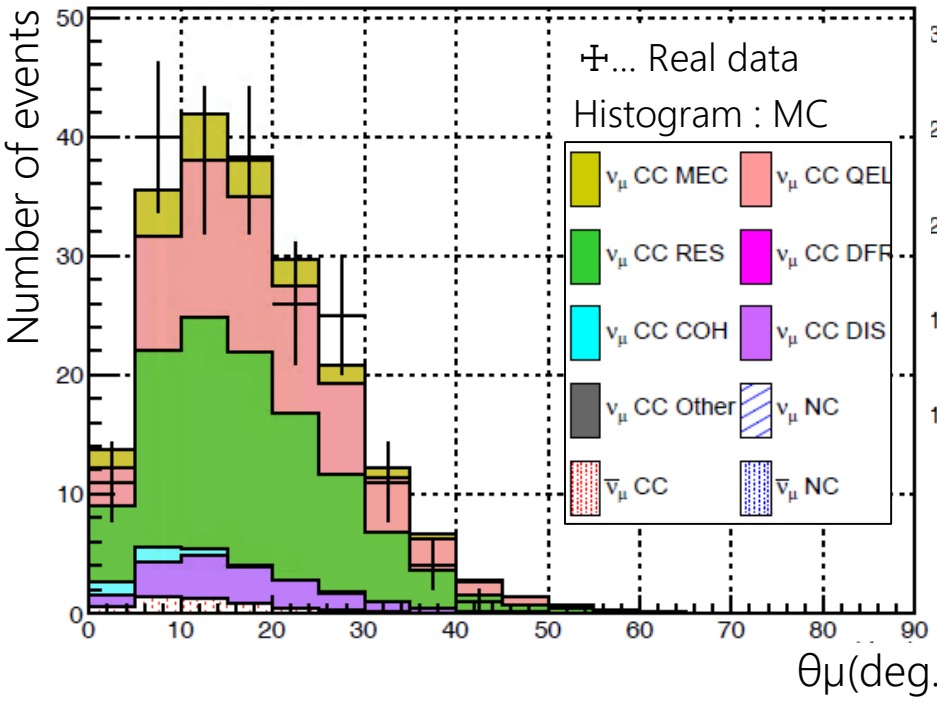
Muon angle & momentum distribution

preliminary

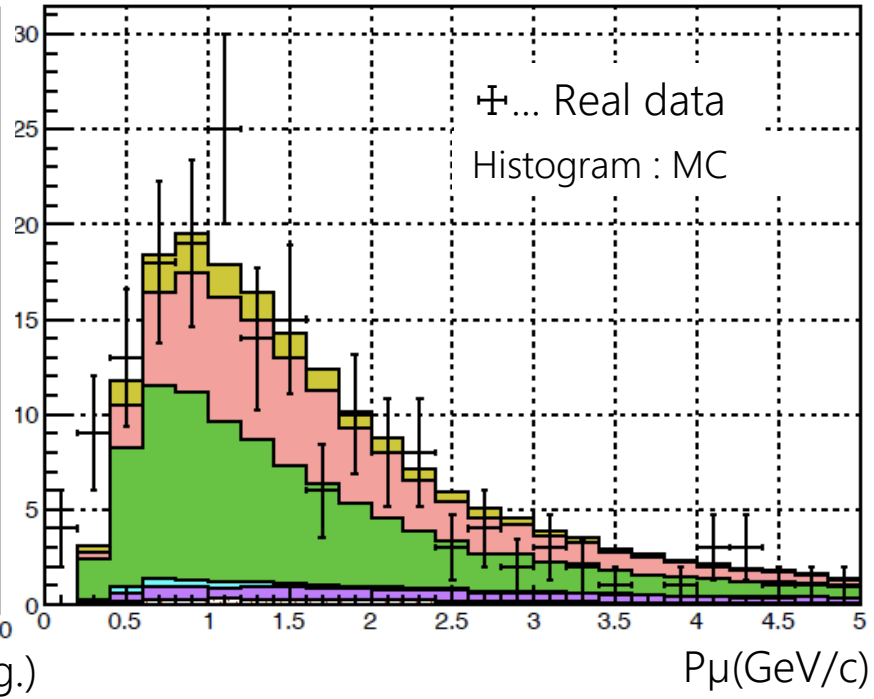
Detection condition

$|\tan\theta x| \leqq 1.7$, $|\tan\theta y| \leqq 1.7$, Nplane(Number of INGRID iron layers) $\geqq 2 \Rightarrow P_\mu >$ ~300 MeV/c

Muon angle



Muon momentum



- Angular distribution is limited to the forward direction because muon ID is performed by matching with ECC-Shifter-INGRID.
- Real Data and MC agree well.

The number of protons and $\pi^{\pm}$s from ν-iron interactions

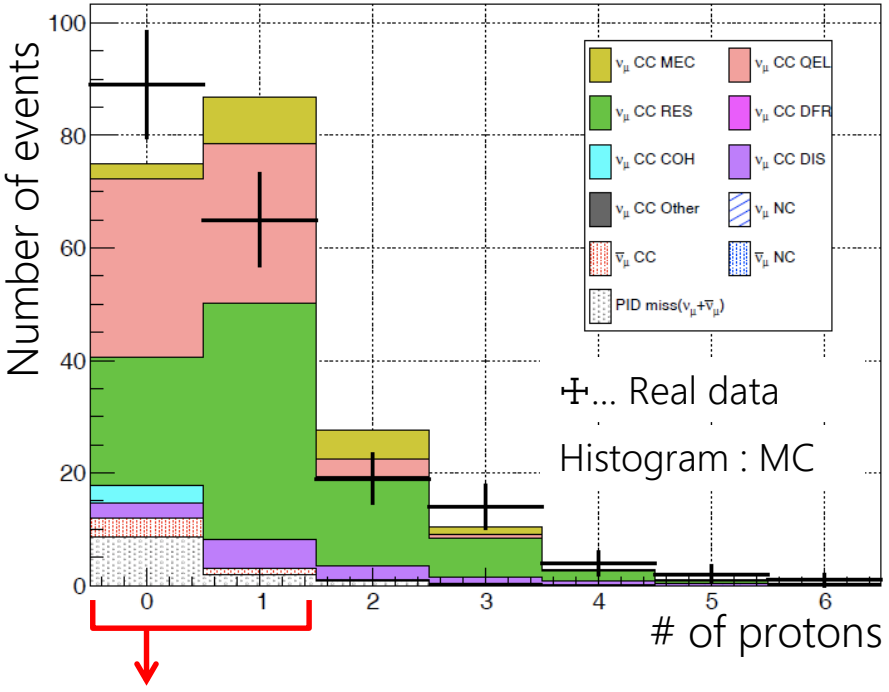
preliminary

Detection condition

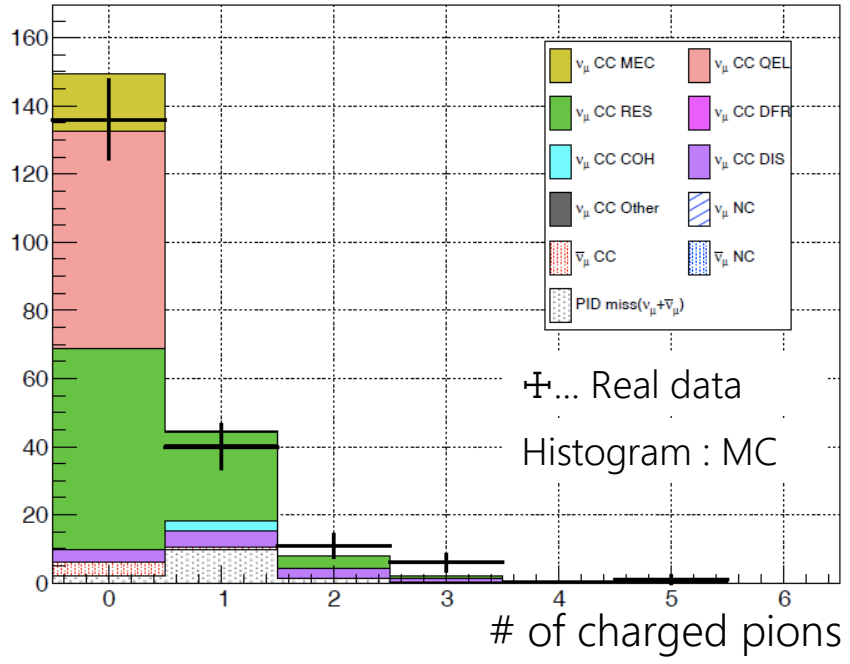
$|\tan\theta x| \leqq 1.7$, $|\tan\theta y| \leqq 1.7$, Nseg(Number of emulsion layers) $\geqq 2$

(If particle with angle $\tan\theta=0.0$ passed 2 iron plates. ⇒ P_{proton} > ~200 MeV/c, P_{π} > ~50 MeV/c)

The number of protons



The number of charged pions



0 p : The number of events in data are larger than that in MC.

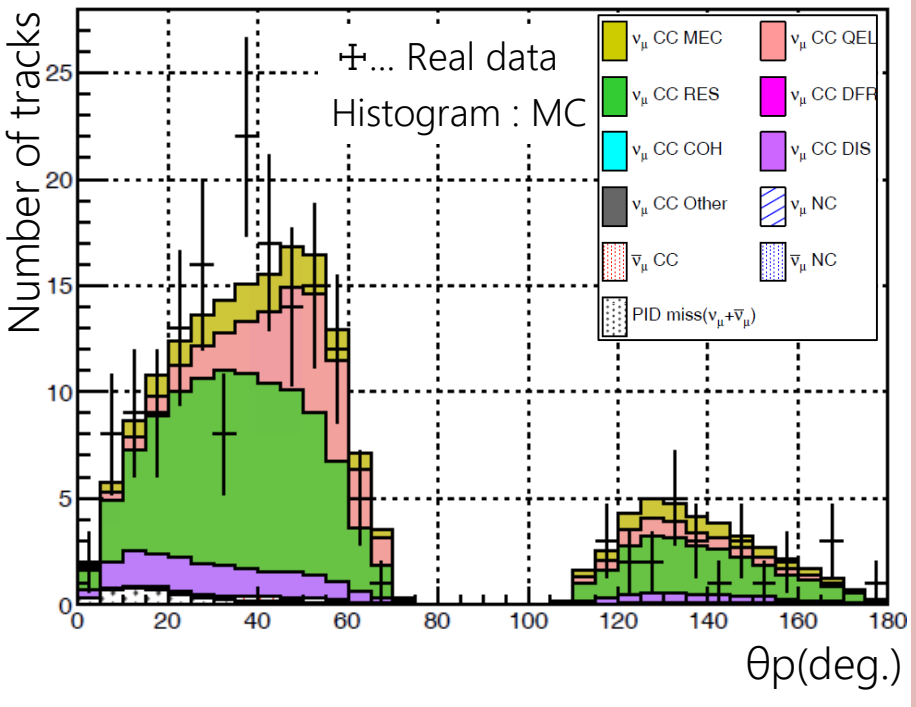
1 p : The number of events in data are smaller than that in MC.

→ Similar tendency was observed in a previous measurement, T2K. Phys. Rev. D 98, 032003(2018)

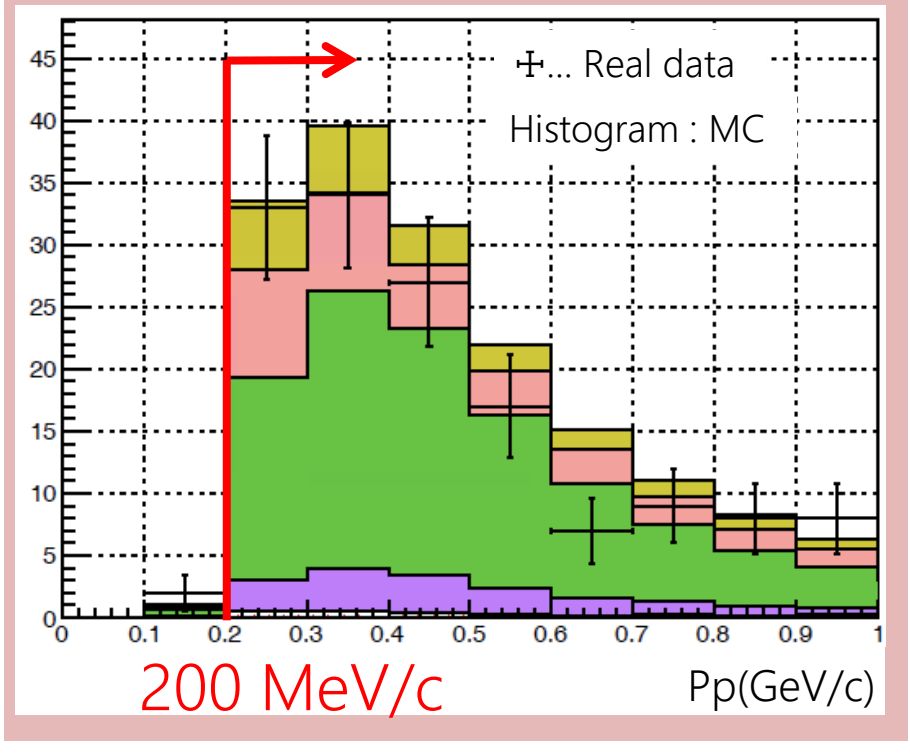
Proton angle & momentum distribution

preliminary

Proton angle



Proton momentum



MC Normalization : POT, Target mass

- Low momentum protons down to ~200 MeV/c were detected !

- The shape of Real Data is in good agreement with that of MC simulation.

The number of protons & charged pions

preliminary

The number of CCNπN'p events (N, N'=0, 1, 2, 3, ≧4)

Real Data (NEUT 5.4.0)

	$\pi^{\pm}$ \ p	$0\ p$	$1\ p$	$2\ p$	$3\ p$	$\geqq 4\ p$
CC0π	0 π	64(50.0)	45(66.6)	18(21.7)	7(8.1)	2(2.9)
CC1π	1 π	20(21.0)	14(16.3)	0(4.5)	4(1.7)	2(1.0)
CC2π	2 π	3(2.9)	4(3.1)	1(1.0)	1(0.5)	2(0.3)
CC3π	3 π	2(0.9)	1(0.6)	0(0.2)	2(0.1)	1(0.1)
	≧ 4 π	0(0.2)	1(0.2)	0(0.1)	0(0.0)	0(0.1)

This analysis is an advantage by using ECC.

We can measure charged hadron final states with low energy threshold.

We aim to measure cross section of CCNπN'p interactions.

Summary & Prospect

- Study of ν - nucleus interactions in sub-multi GeV energy region is very important for current & future neutrino oscillation experiments.

- A 65kg iron ECC target was exposed to the neutrino beam with a mean energy of 1.5 GeV at J-PARC in 2016.
  From this exposure of 0.40×10^{20} POT, 194 neutrino-iron CC interactions were located in the target.

- Charged hadrons in the final state were detected with low momentum thresholds, 200 MeV/c for protons and 50 MeV/c for charged pions.
  The number of protons and pions in the final state of each event, their emission angles and momenta were measured and compared with MC.

- We will measure the CCNπN'p (N,N'=0,1,2,…) cross section and differential cross section with the muon, proton and charged pion angle and momentum.

Thank you for your attention