Measurement of ν_μ CCQE cross section in the T2K on-axis neutrino beam

T. Kikawa (Kyoto University)
for the T2K collaboration

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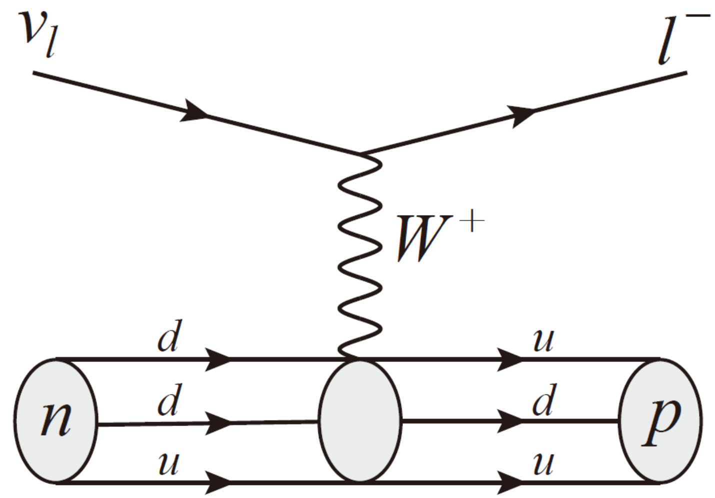
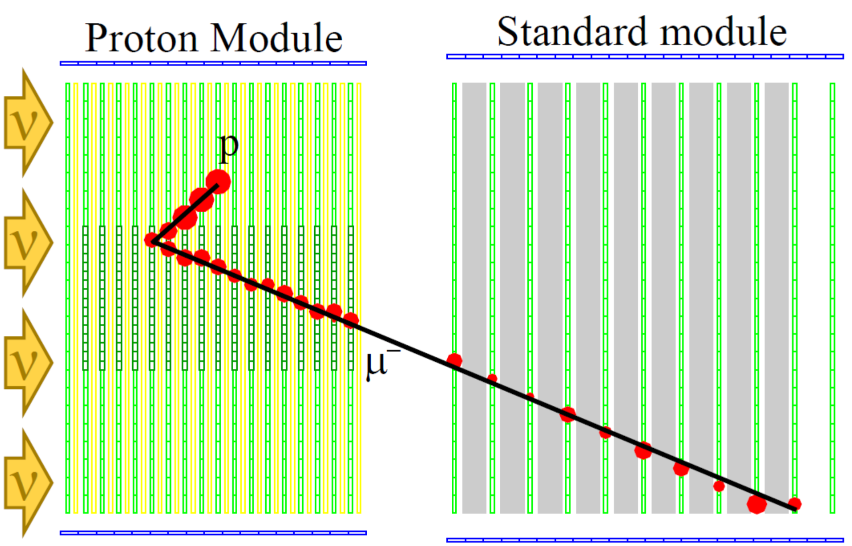
Overview

- The T2K experiment
- Introduction to CCQE cross section
- Event selection
- Analysis strategy
- Systematic errors
- Results

Feynman diagram of CCQE scattering



Event display of CCQE scattering

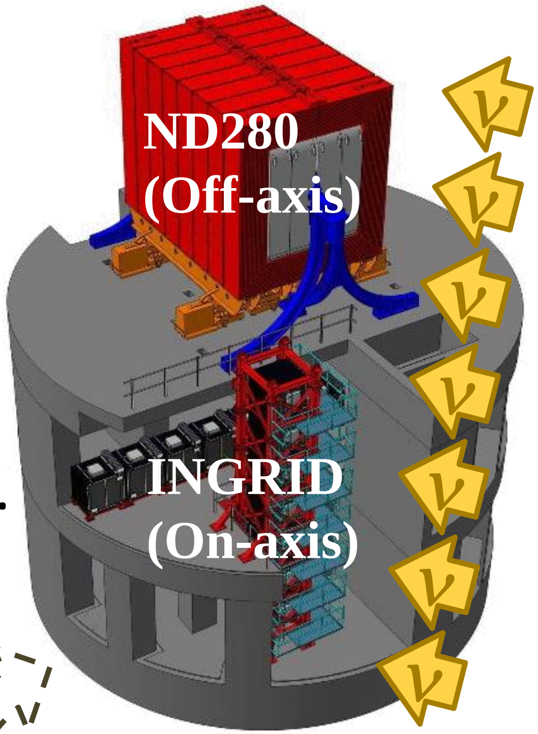


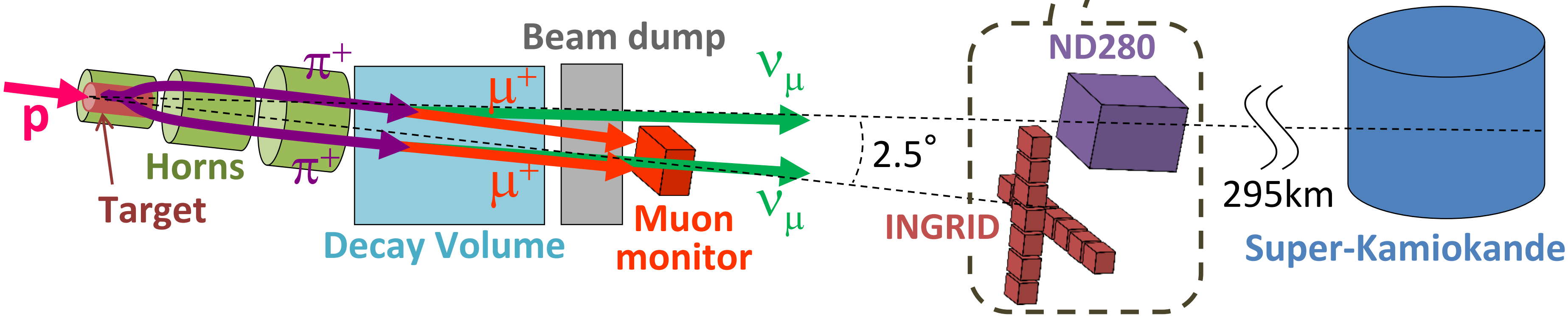
The T2K experiment

- High intensity neutrino beam from J-PARC.
- Super-Kamiokande, located 295km from neutrino generation point.
- ND280 (off-axis) and INGRID (on-axis) located 280m from neutrino generation point.

- Precise measurement of neutrino oscillations.
- <u>Precise measurement of neutrino nucleus interactions at E_ν~1GeV.</u>

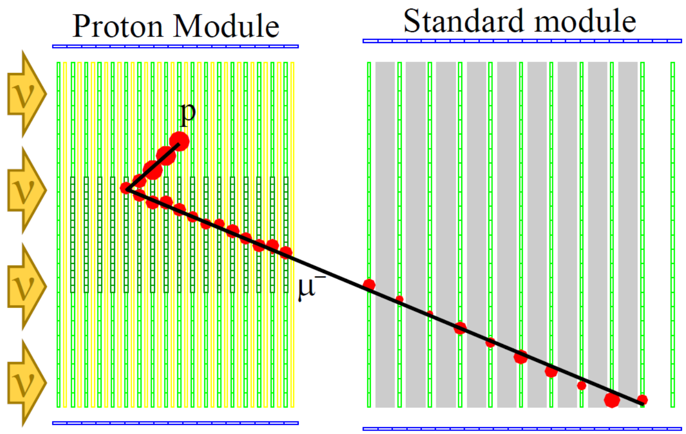
T2K Near detectors



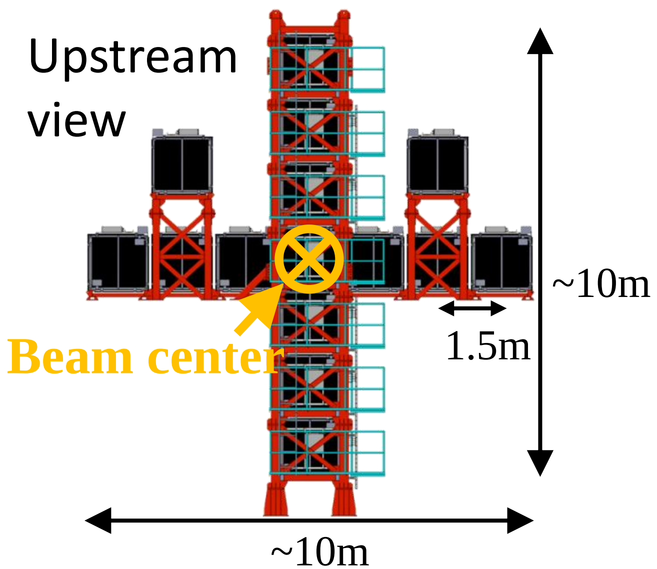


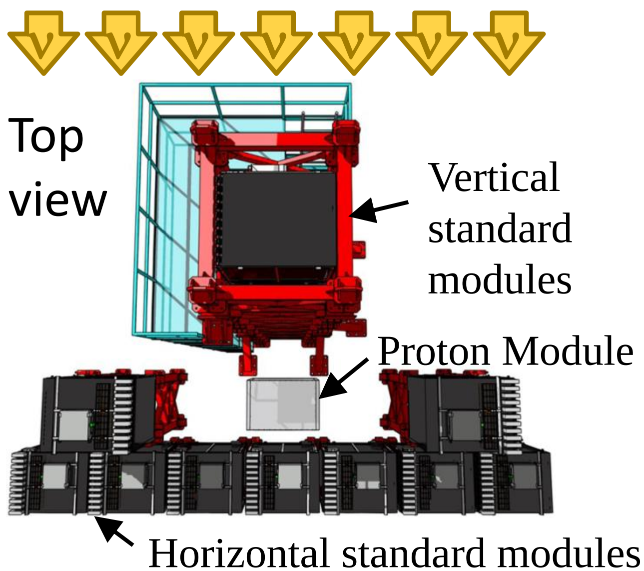
INGRID (on-axis near detector)

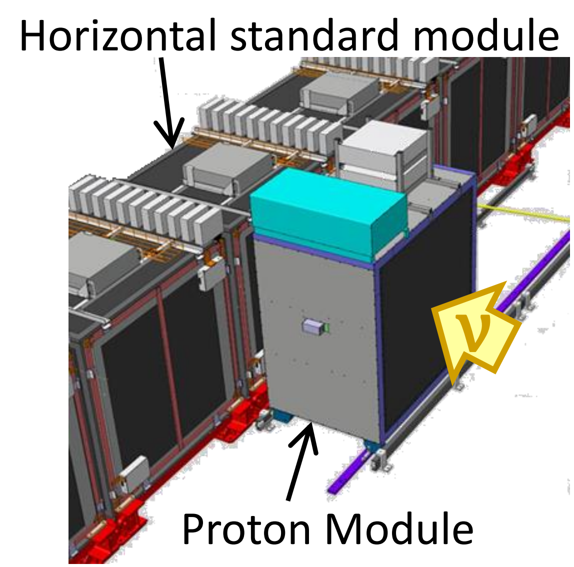
- 16 standard modules.
  - Sandwich structure of iron and scintillators.
  - Main purpose is beam monitoring.
- 1 extra module, (Proton Module).
  - Full scintillator module.
  - Developed for the cross section study.



- In this study, Proton Module is used as target, and standard module is used to identify muons from neutrino interactions.

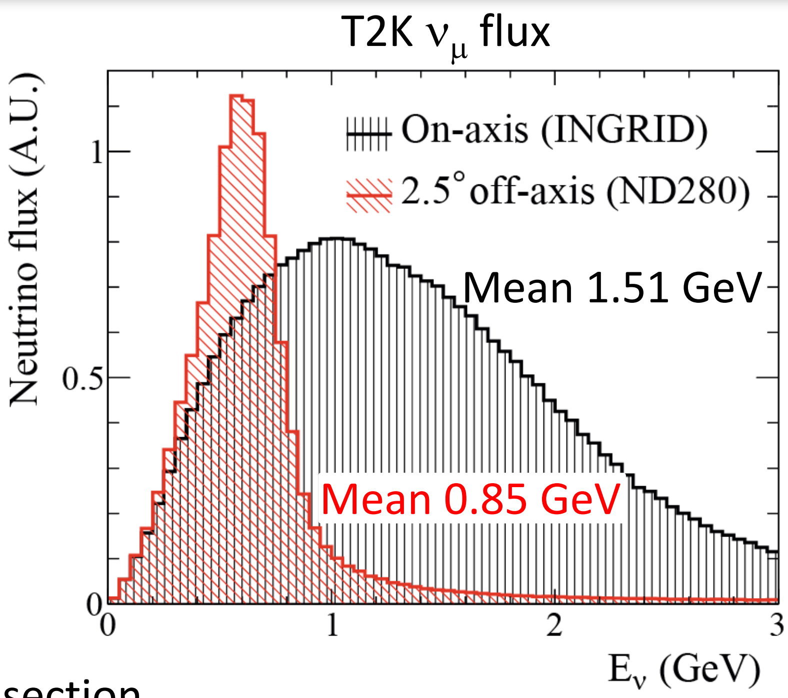


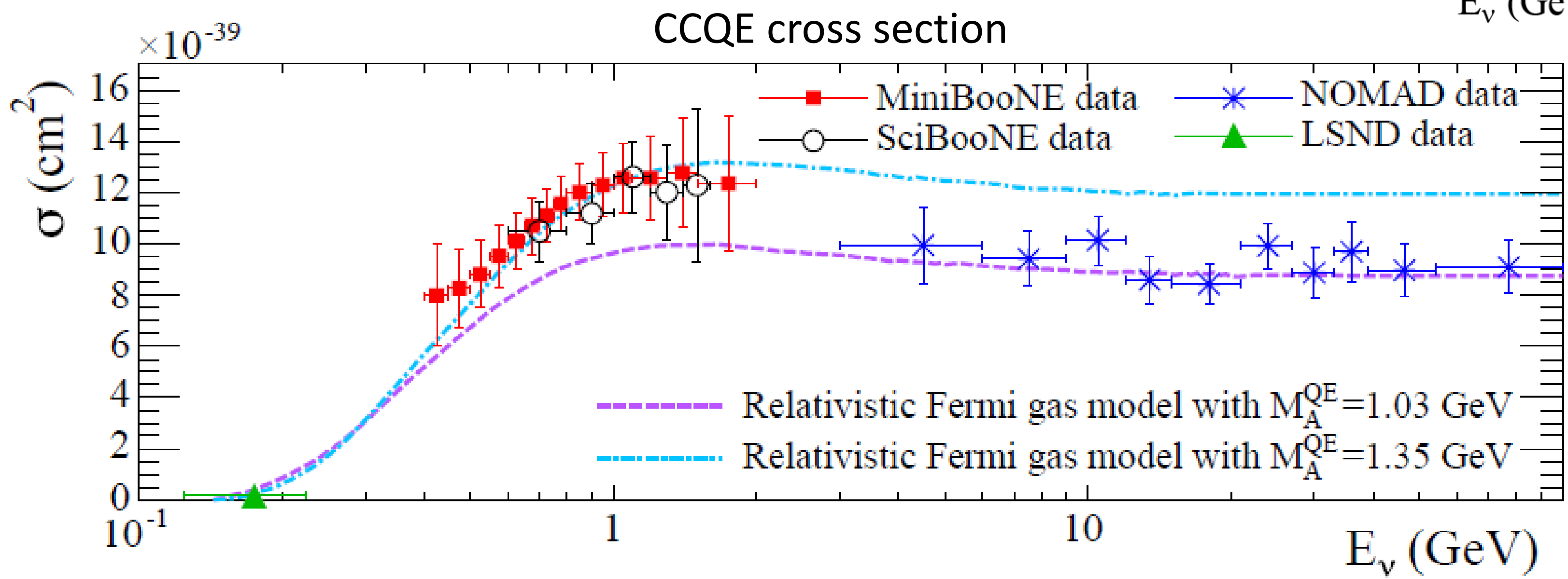




CCQE measurement using T2K on-axis neutrinos

- So far, both MiniBooNE and NOMAD CCQE results cannot be described by one neutrino interaction model.
- We measured CCQE cross section at 0~3GeV using T2K on-axis neutrinos and INGRID.





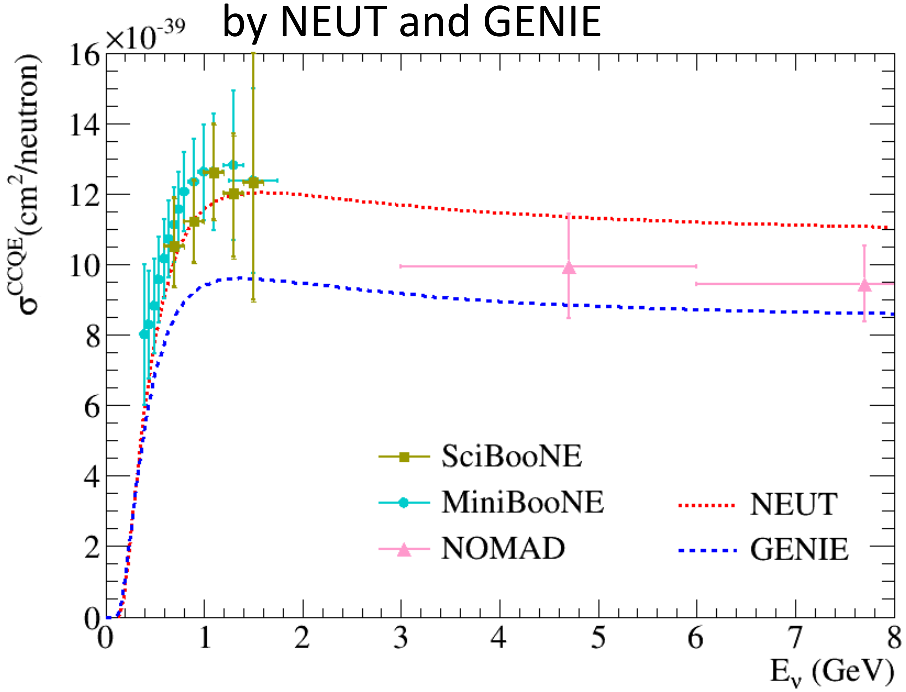
CCQE interaction models used in T2K

- NEUT and GENIE are used to generate neutrino interactions.
- Both NEUT and GENIE use Llewellyn Smith formalism for CCQE, and Fermi gas model as the nuclear model.
- Default axial vector mass (M_A^{QE}) is different.
- NEUT was used to estimate background and efficiency.
- GENIE was used for the comparison of cross section results in addition to NEUT.

Default M_A^{QE} value

NEUT	GENIE
1.21GeV/c^2	0.99GeV/c^2

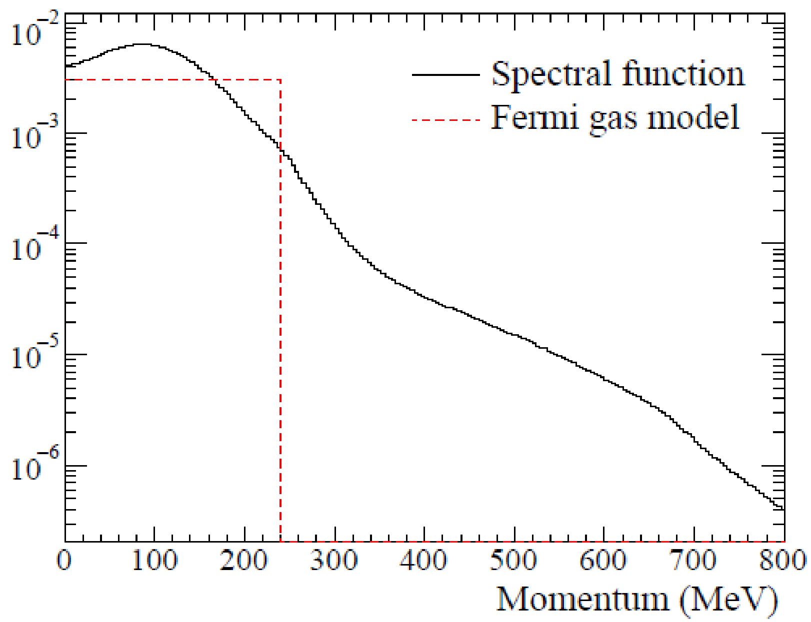
CCQE cross section predicted by NEUT and GENIE



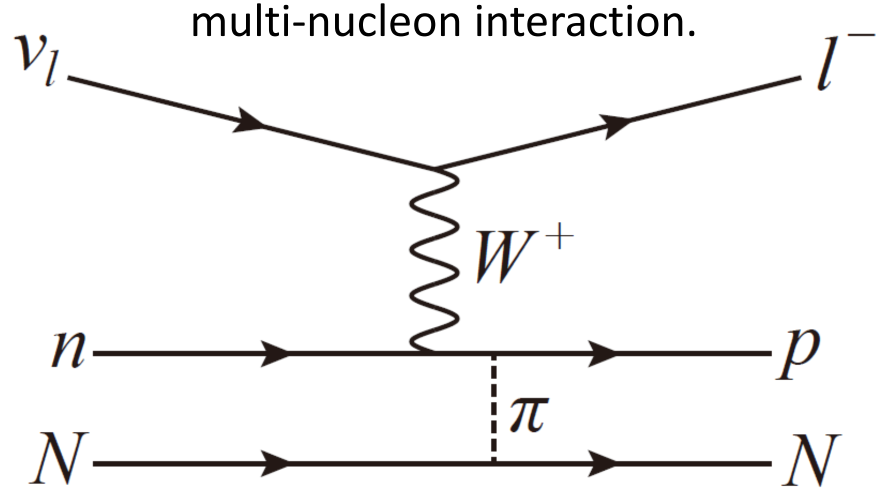
Various neutrino interaction models

- Spectral function is a more sophisticated nuclear model than the Fermi gas model.
- CCQE cross section measurement will be affected by MEC multi-nucleon interaction if it really exists.
- They can be causes of the discrepancy between MiniBooNE and NOMAD results.

Momentum distribution of nucleon in nucleus for Fermi gas model and spectral function.



Feynman diagram of MEC multi-nucleon interaction.



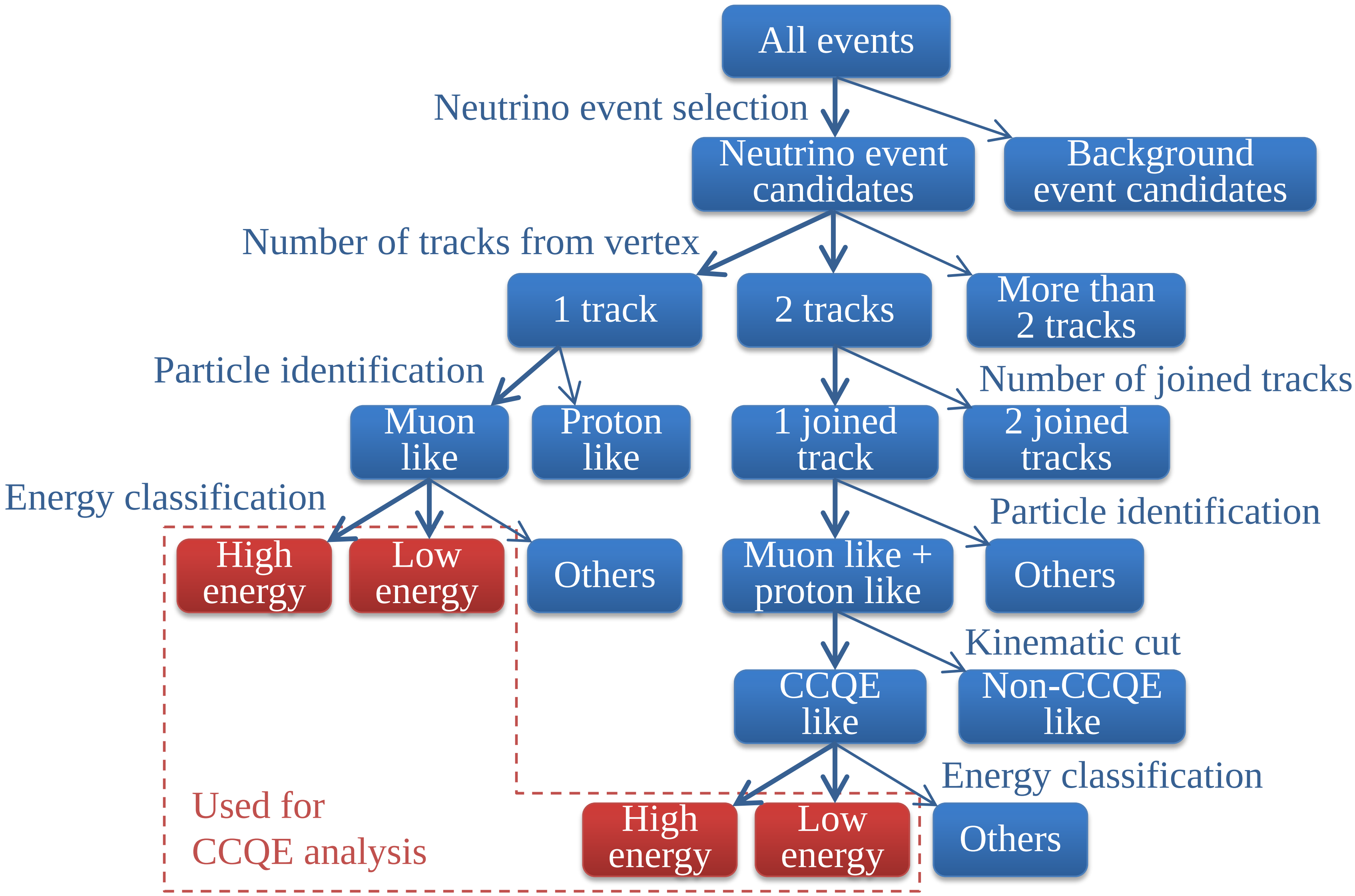
Various neutrino interaction models

- Recently, spectral function and MEC multi-nucleon interactions have been implemented in latest NEUT (v.5.3.2).
  - Spectral function : Benhar's model
  - MEC multi-nucleon interaction : Nieves' model
- Details will be explained in A. Furmanski's talk on Thursday.
- Cross section results assuming these models were also estimated in addition to the result with default NEUT. (Default NEUT was used unless otherwise noted.)
- Results are compared to each other.

Variety of the settings of NEUT

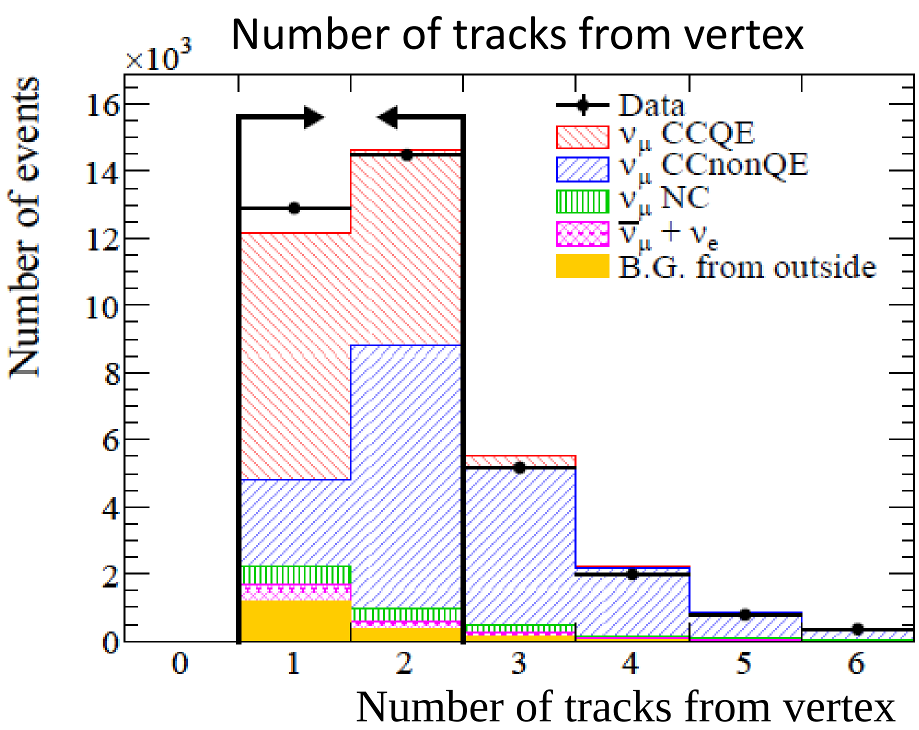
	Nuclear model	MEC multi-nucleon interaction
Default NEUT	Fermi gas model	Off
SF NEUT	Spectral function	Off
MEC NEUT	Fermi gas model	On

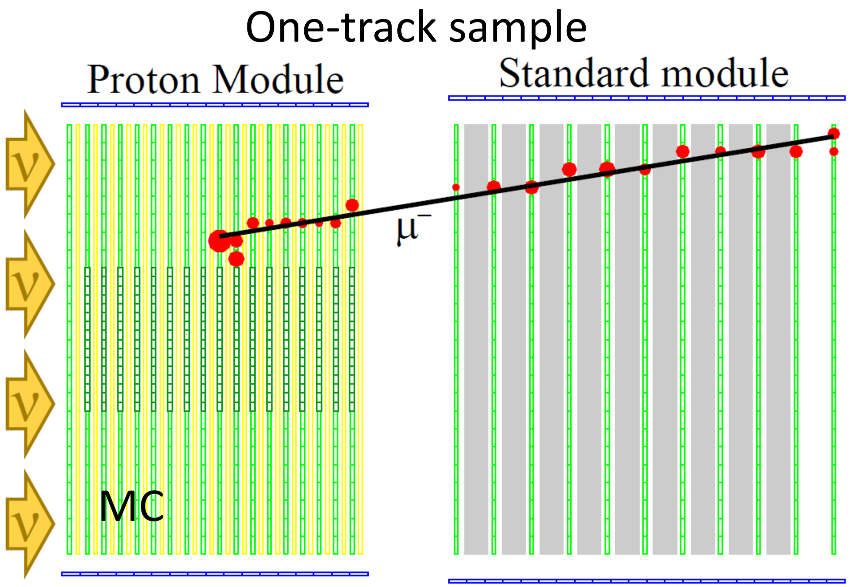
Event selection flow

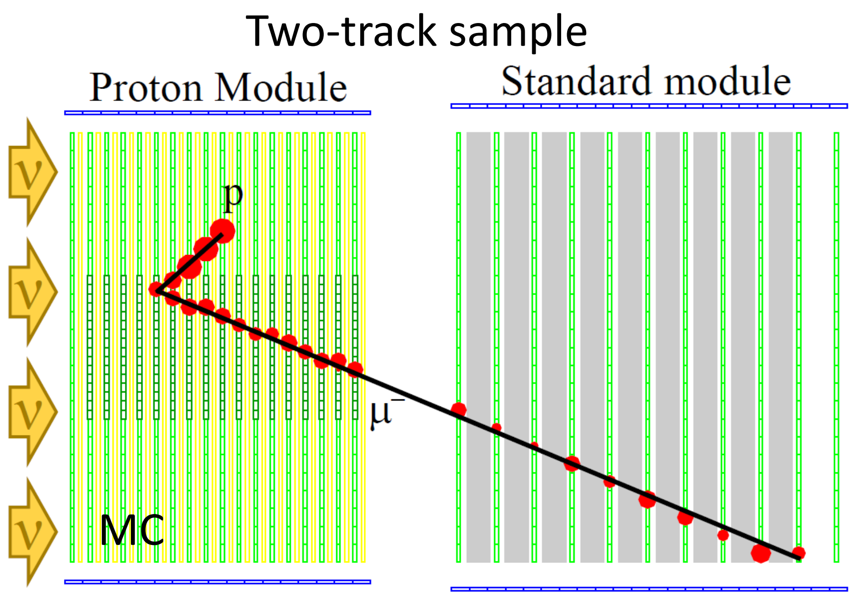


Number of tracks from vertex

- Final state particles from CCQE are a muon and a proton.
- Sometimes, proton from CCQE is not reconstructed.
- Select events with one or two tracks from vertex.

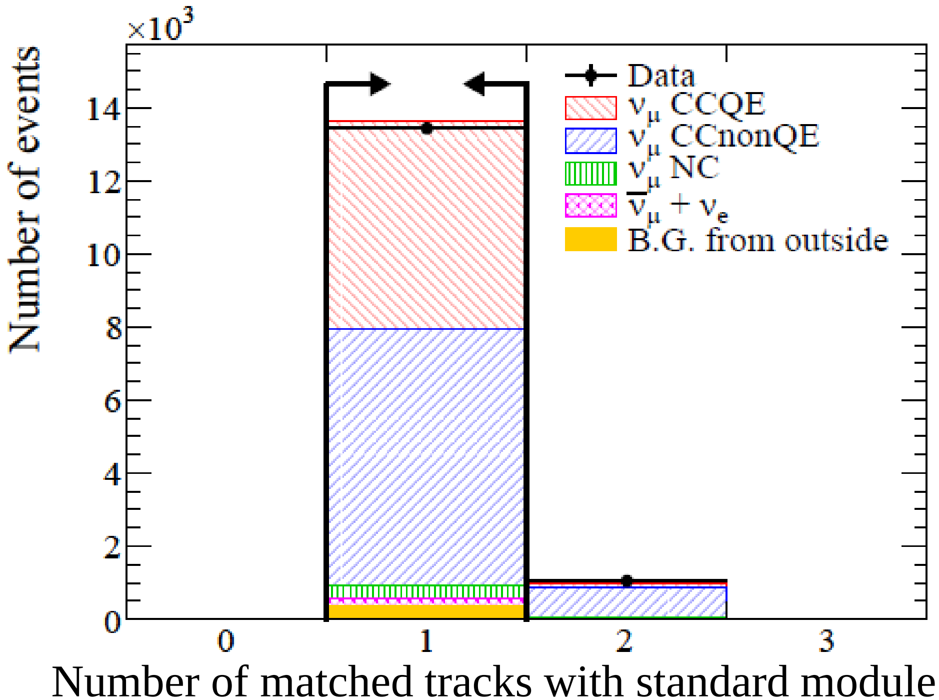


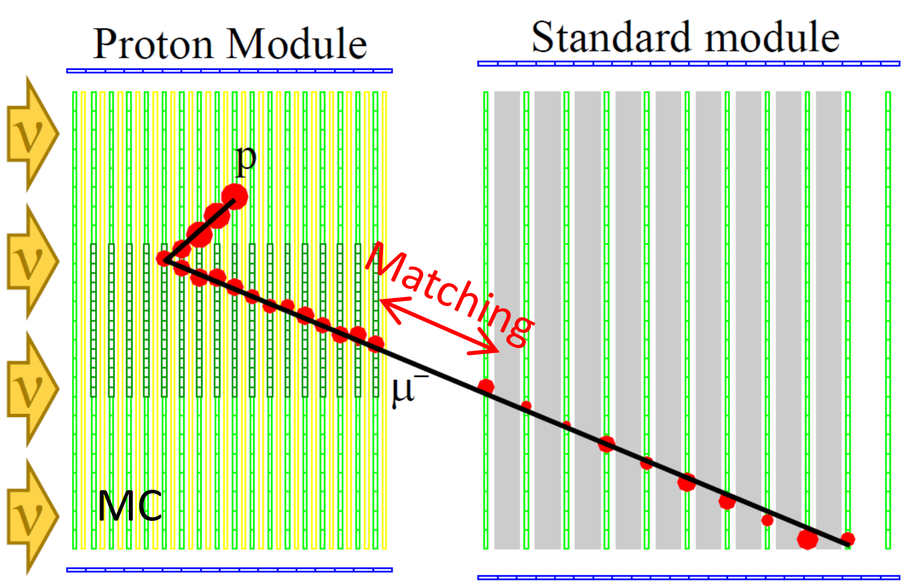




Number of tracks in standard module

- Muon generally goes through the Proton Module and the iron plates of the standard module.
- Proton is generally stopped in the Proton Module or the iron plates of the standard module.
- Select events with one matched track with the standard module track.

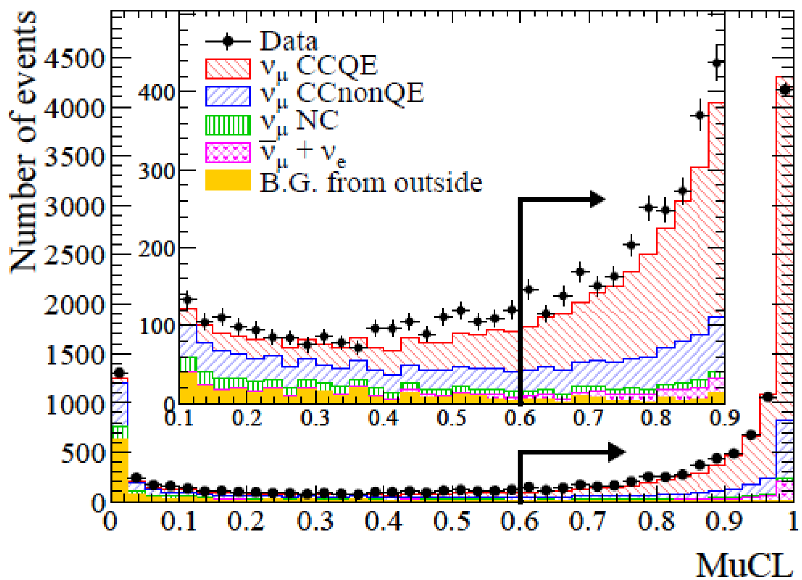




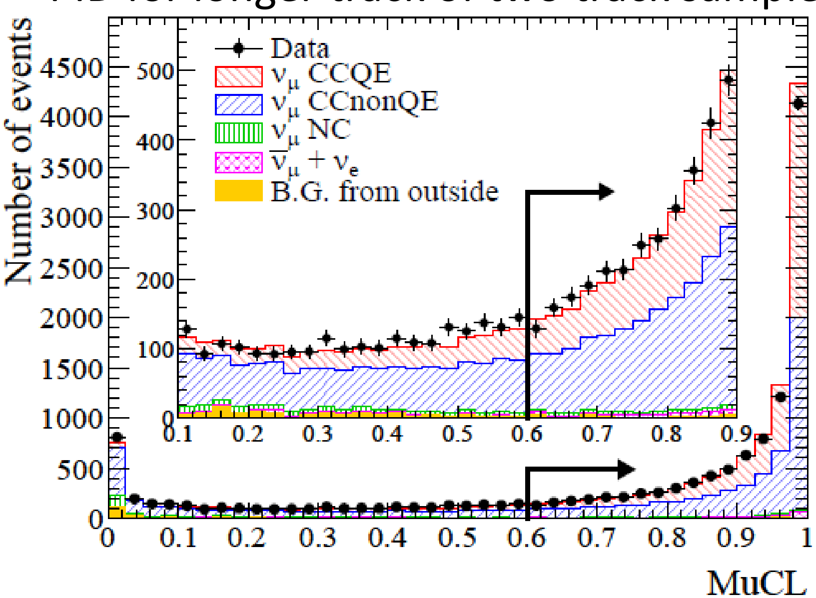
Particle identification

- Muon confidence level (MuCL) is defined with control muons.
  - MuCL≥0.6 : muon like
  - MuCL<0.6 : proton like
- Selection:
  - One-track sample: muon-like
  - Two-track sample:
    - Longer track: muon-like
    - Shorter track: proton-like

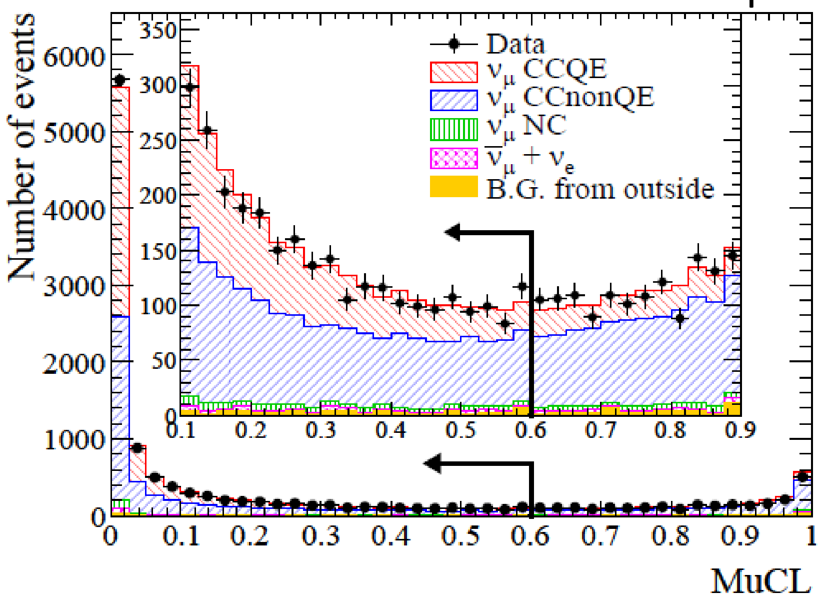
PID for one track sample



PID for longer track of two track sample

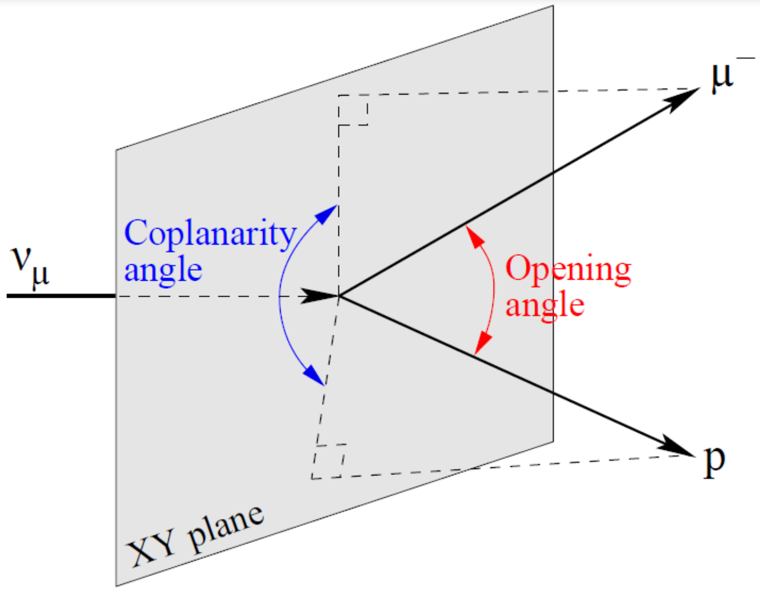


PID for shorter track of two track sample

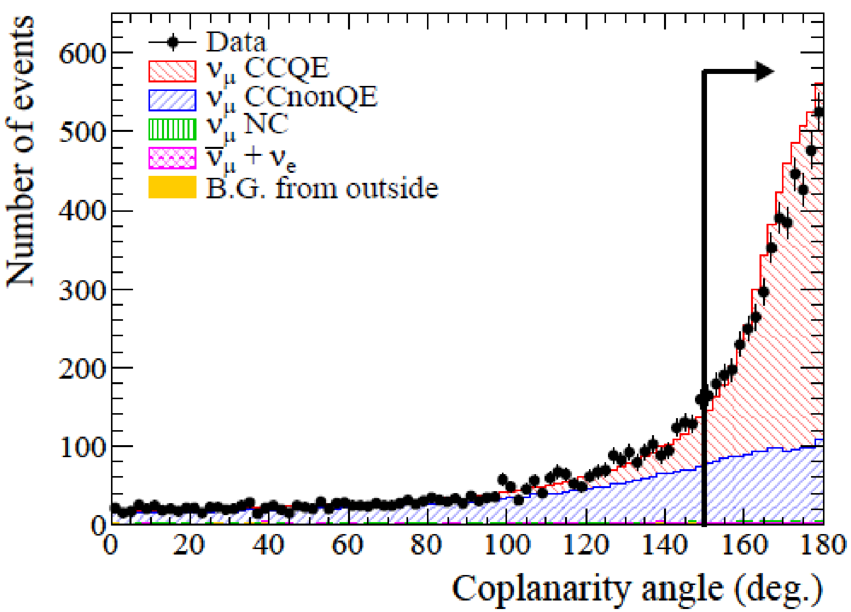


Kinematic cuts

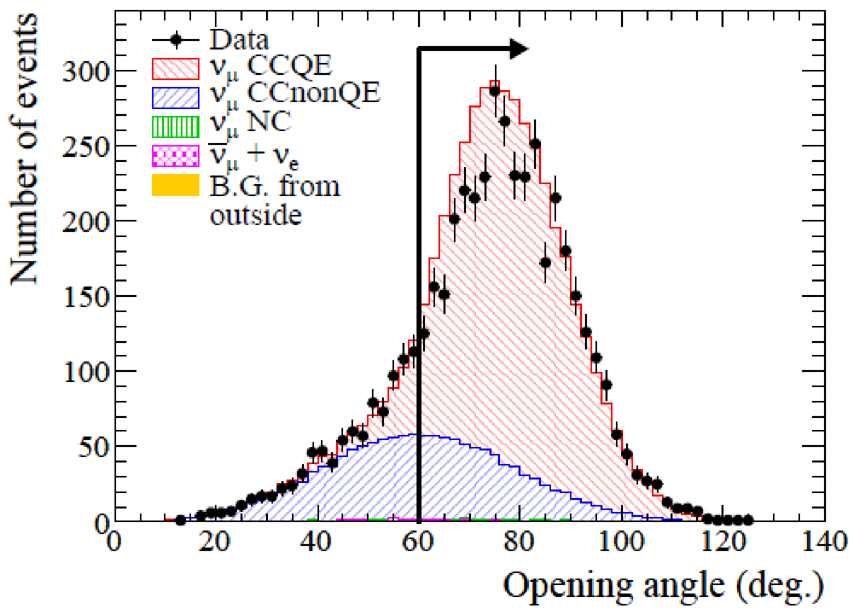
- Coplanarity angle
  - Angle between $\vec{\mu}$ and $\vec{p}$ projected to a plane which is perpendicular to $\vec{\nu}$.
  - Should be around 180 deg. for CCQE.
- Opening angle
  - Angle between $\vec{\mu}$ and $\vec{p}$.
  - Generally large for CCQE.



Coplanarity angle cut

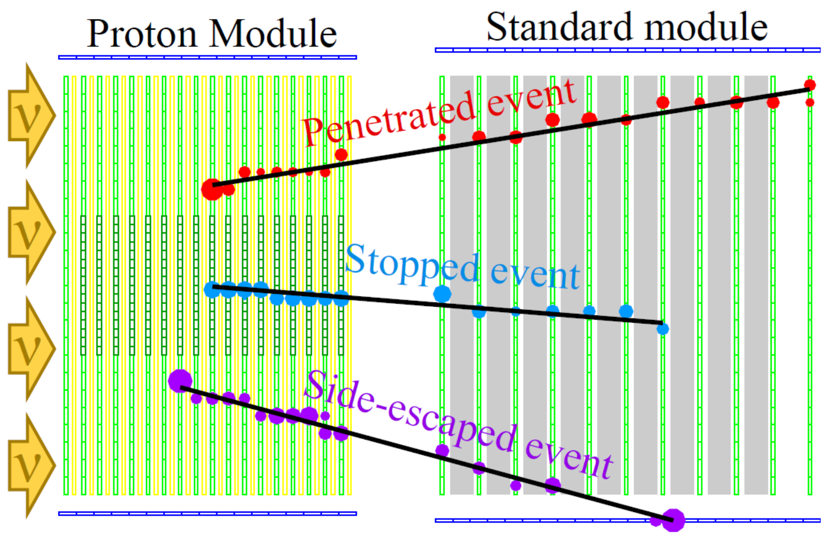


Opening angle cut

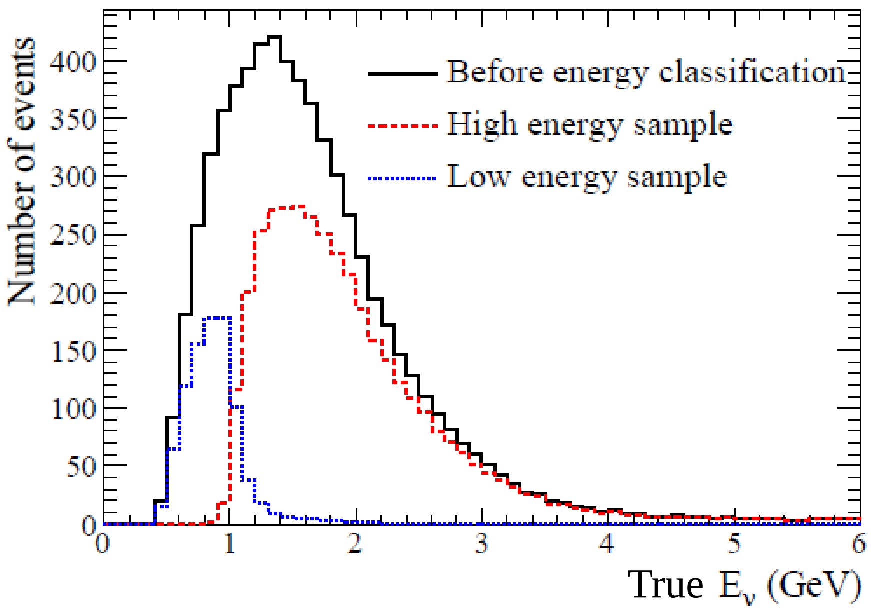


Energy classification

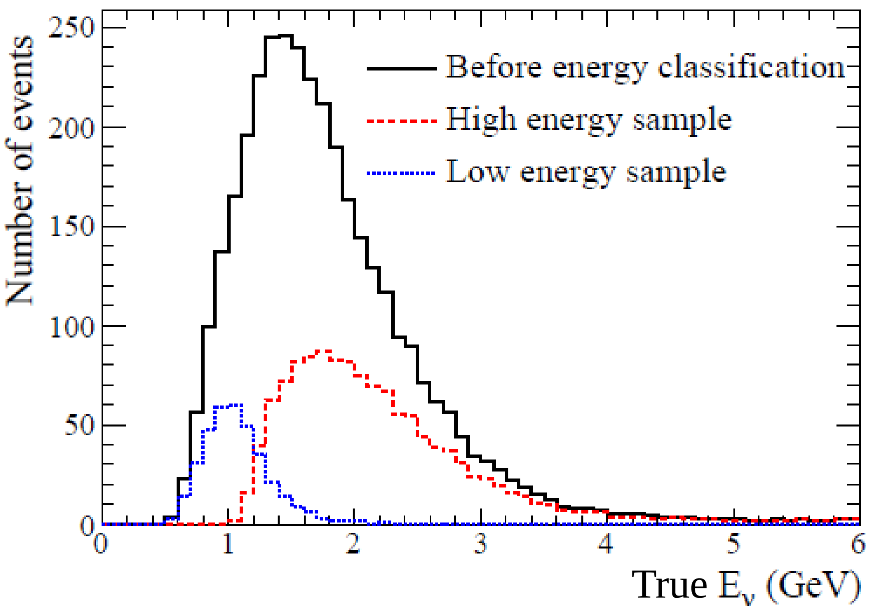
- Classify events by topology.
  - Muon penetrated events.
    → High energy sample.
  - Muon stopped events.
    → Low energy sample.
  - Muon side-escaped events.
    → Not used in this study.
- Cross section is measured in high and low energy regions.



Neutrino energy for one-track sample



Neutrino energy for two-track sample



Analysis strategy

- CCQE cross section is calculated with BG subtraction and efficiency correction.

$$\sigma_{CCQE} = \frac{N_{sel} - N_{BG}}{\Phi T \varepsilon_{CCQE}}$$

N_{sel}	: Number of selected events (data)
N_{BG}	: Number of selected BG events (MC)
Φ	: Integrated ν_μ flux (MC)
T	: Number of target neutrons
ε_{CCQE}	: Detection efficiency of CCQE events (MC)

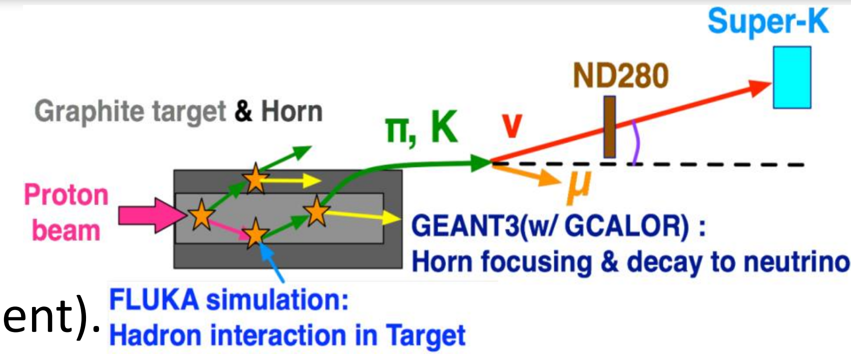
- It is measured
  - In high and low energy region regions, separately.
  - From one-track sample and two-track sample, separately.
- CCQE purity:~80%.
- CCQE efficiency:~30%.
- CC resonant pion events are dominant background events.

MC expected background ratio to all selected events

Source	High energy region		Low energy region	
	One track	Two track	One track	Two track
CC resonant pion	11.27%	11.92%	16.02%	18.73%
CC other	3.48%	3.15%	4.53%	6.05%
NC events	0.13%	0.04%	6.46%	1.30%
$\bar{\nu}_\mu$ events	5.64%	0.48%	2.78%	0.35%
ν_e events	0.00%	0.00%	0.34%	0.22%
Energy region	0.41%	0.01%	1.86%	5.20%
External	0.73%	0.00%	3.23%	0.00%

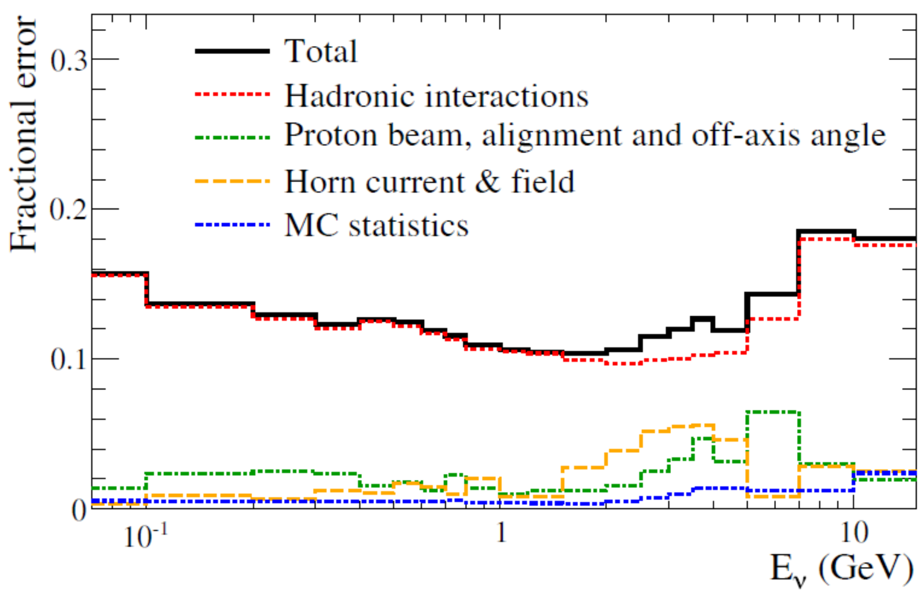
Systematic error from neutrino flux

- Source of the flux uncertainty:
  - Hadron interaction uncertainties.
  - T2K beamline uncertainties (proton beam position and intensity, beam direction, horn current, alignment).

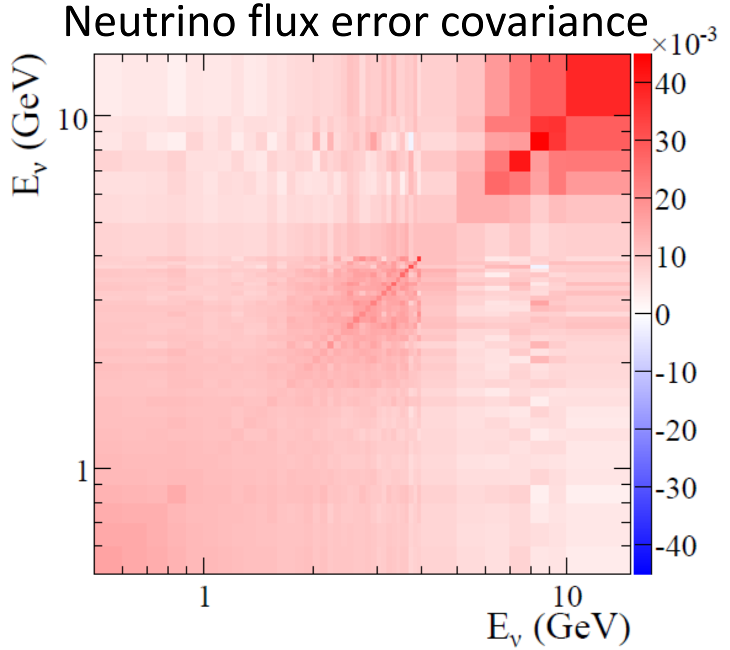


- Total neutrino flux uncertainty is ~10%.
- Hadron interaction uncertainty is dominant error source.
- Systematic error is evaluated by toy MC generated from the covariance matrix.

Fractional neutrino flux error



Neutrino flux error covariance



Systematic error from neutrino interaction

- Fit the external data with free model parameters in NEUT.
- Introduce ad hoc parameters to take into account remaining differences between data and NEUT.
- Estimate values and errors of the model and ad hoc parameters.
- Introduce, additional FSI uncertainties.

Neutrino interaction parameters

	Parameter	Value	Error
Model parameters	M_A^{QE}	1.21GeV	16.53%
	M_A^{RES}	1.21GeV	16.53%
	π-less Δ decay	0.2	20%
	Spectral function	0	100%
	Fermi momentum (CH)	217MeV/c	13.83%
	Binding energy (CH)	25MeV	36%
Ad hoc parameters	CC1π norm. ($E_\nu < 2.5$GeV)	1	21%
	CC1π norm. ($E_\nu > 2.5$GeV)	1	21%
	CC coherent π norm.	1	100%
	CC other shape	0	40%
	NC1π^0 norm.	1	31%
	NC coherent π norm.	1	30%
	NC1$\pi^\pm$ norm.	1	30%
	NC other norm	1	30%
	W shape	8.77MeV	52%
	CC1π^+ shape	0	50%

Systematic error

- Detector error:
  - Error sources: target mass, dark count, hit detection efficiency, light yield, event pileup.
  - Additional data-MC discrepancy in each event selection step is included as the detector error.
- Systematic error from neutrino flux is dominant.

Summary of systematic errors

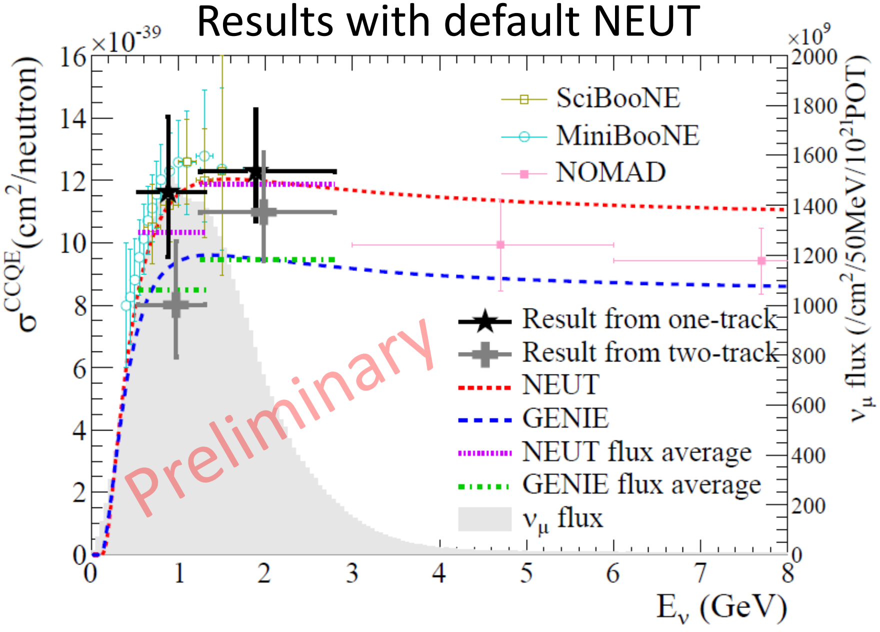
Source	High energy region		Low energy region	
	One track	Two track	One track	Two track
Neutrino flux	−11.00%+13.57%	−11.26%+13.93%	−13.58%+17.12%	−14.10%+17.62%
Neutrino interaction + FSI	−5.61%+7.42%	−7.05%+8.73%	−10.21%+10.43%	−11.45%+15.44%
Detector	±4.02%	±4.65%	±4.01%	±6.68%
Total	−12.98%+15.98%	−14.07%+17.08%	−17.46%+20.44%	−19.35%+24.36%

CCQE cross section result

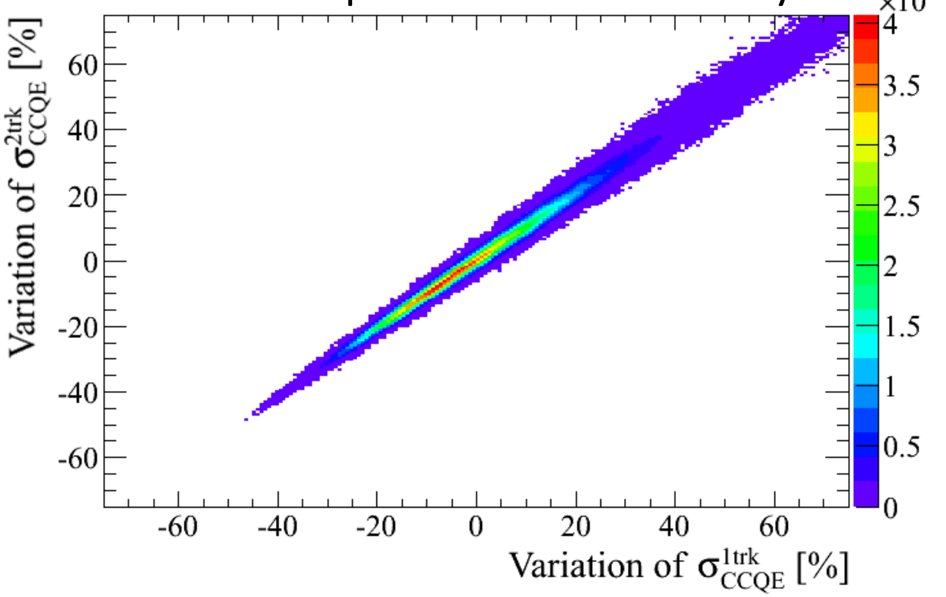
- Our CCQE cross section results are compatible with predictions.
- Result from one-track sample differs from that from two-track sample in low energy.
  (Actual difference is more significant than the error bars due to the large correlation between results from one and two track samples.)
- Ratio of results in the low energy region is

$$\frac{\sigma_{CCQE}^{1track}}{\sigma_{CCQE}^{2track}} = 1.45 \pm 0.09(stat.)^{+0.24}_{-0.29}\,(syst.)$$

Results with default NEUT



Correlation between results from one and two track samples from flux error toy MC



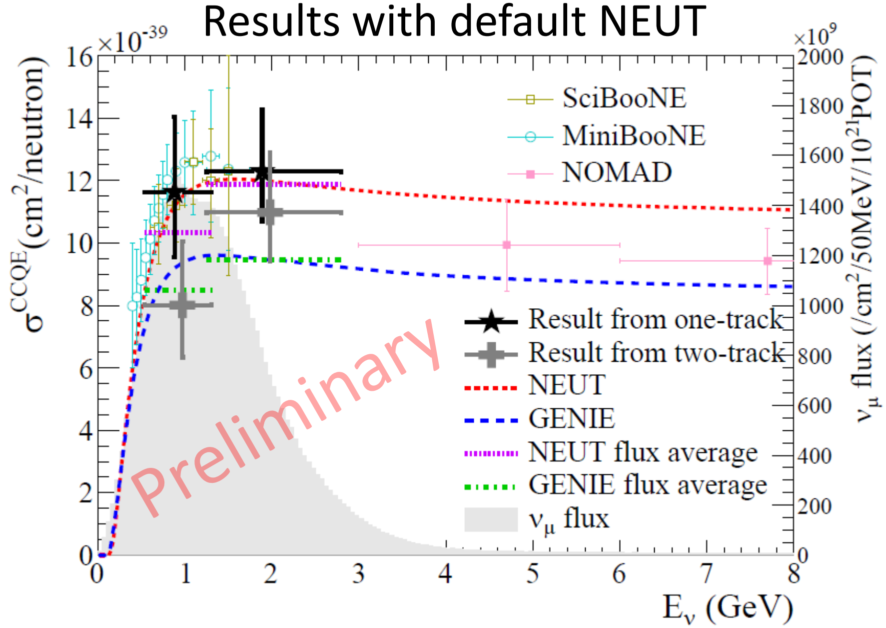
CCQE cross section result with spectral function

- When the SF NEUT is used for the efficiency correction, the difference becomes smaller.

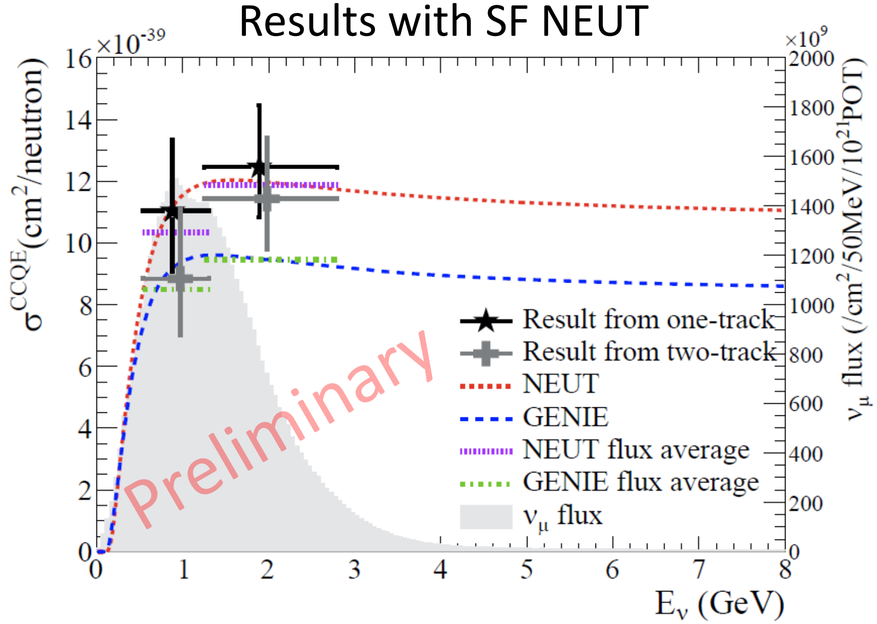
$$\frac{\sigma_{CCQE}^{1track}}{\sigma_{CCQE}^{2track}} = 1.25 \pm 0.08(stat.)^{+0.22}_{-0.26}\,(syst.)$$

- Change comes from the difference in the final state proton kinematics between Fermi gas model and spectral function.
- It may indicate the spectral function is a better representation of the nuclear model.

Results with default NEUT



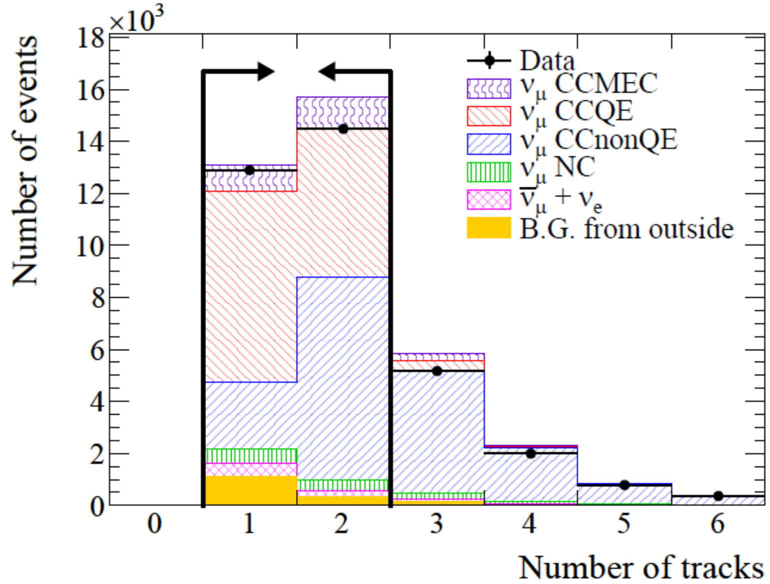
Results with SF NEUT



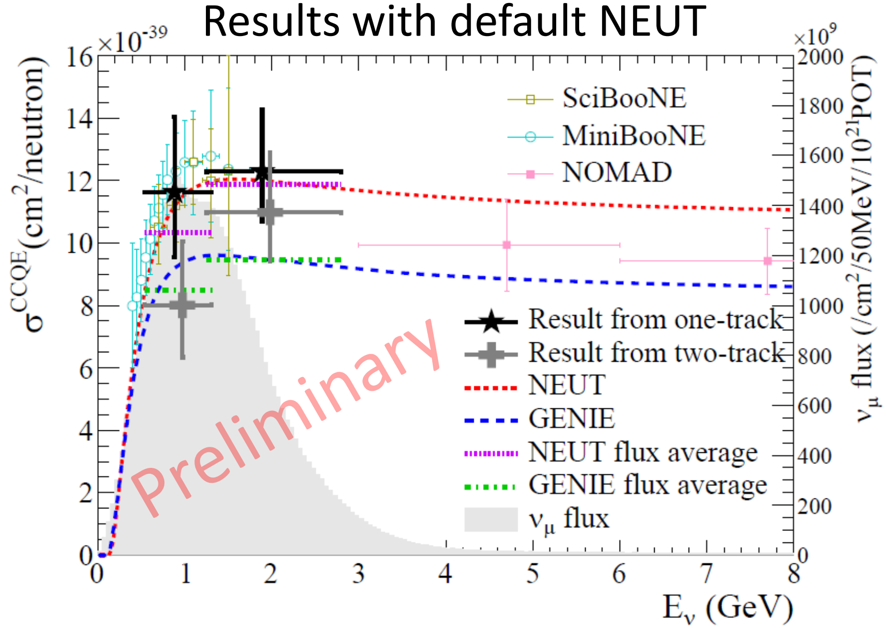
CCQE cross section result with MEC

- Cross section result with MEC is estimated by subtracting the MEC events as background events.
- Result with MEC still agree with predictions.
- No definite conclusions about the MEC from our results.

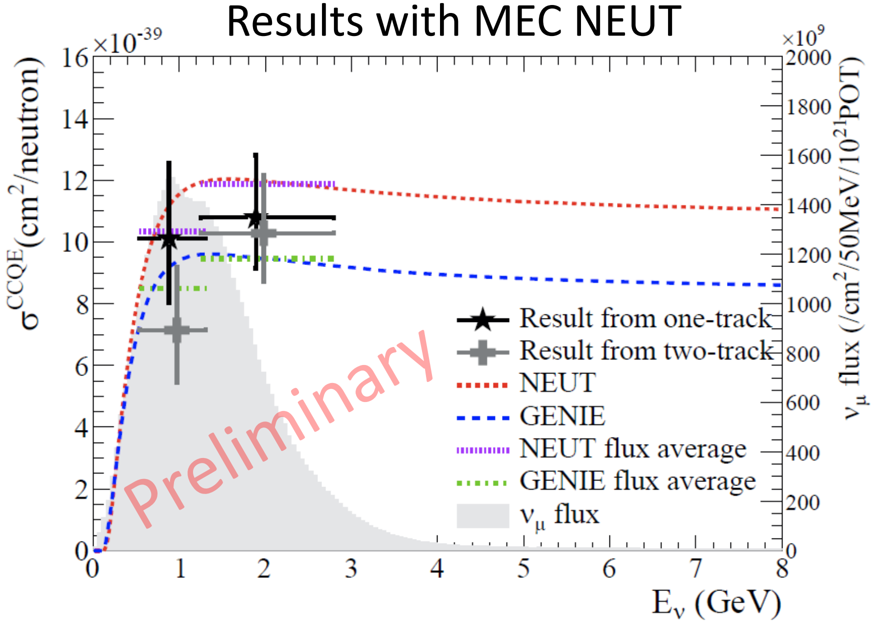
Number of tracks with MEC NEUT



Results with default NEUT



Results with MEC NEUT



Summary

- CCQE cross section was measured using T2K on-axis neutrino detector, INGRID.
- Cross section results agree with model predictions.
- Result assuming spectral function is preferred.
- Cross section result assuming MEC is also consistent with model predictions.
- Differential cross section measurement is ongoing.

Backup

Particle identification

- Muon confidence level (MuCL) is defined with muons from surrounding material.
  - The dE/dx distribution of muons obtained by muons from the walls.
  - The cumulative distribution function of the muon dE/dx distribution corresponds to the confidence level.
  - Combine the confidence levels obtained from all the planes.

$$\mathrm{MuCL} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!}, \quad P = \prod_{i=1}^{n} CL_i$$

Confidence level of i^{th} plane

dE/dx distribution of muons

cumulative distribution function of the muon dE/dx distribution