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

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for the T2K collaboration

NuInt14 @Surrey

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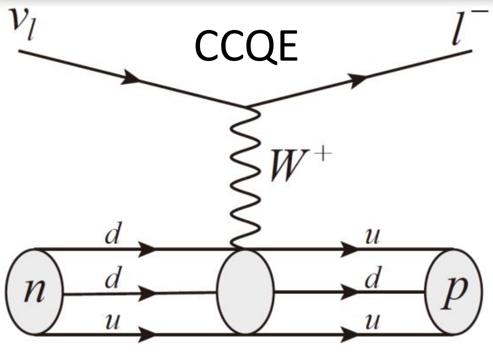
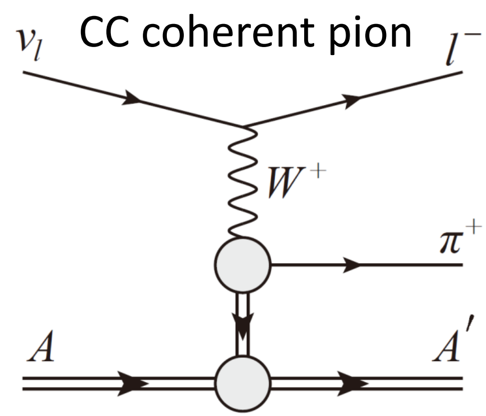
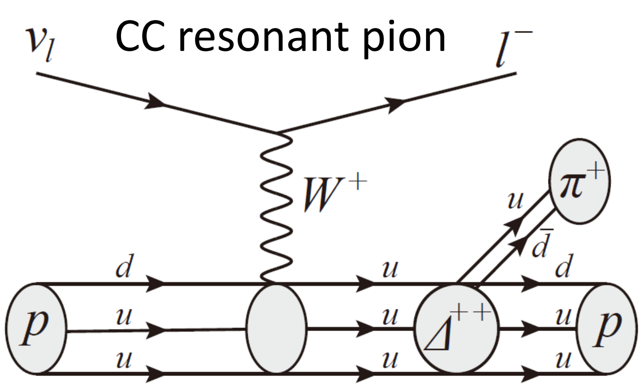
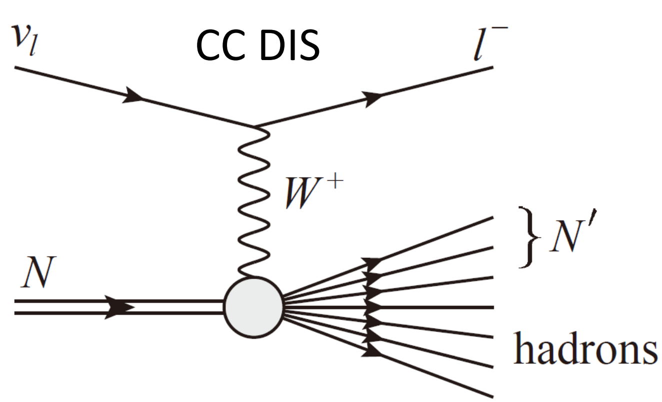
Overview

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







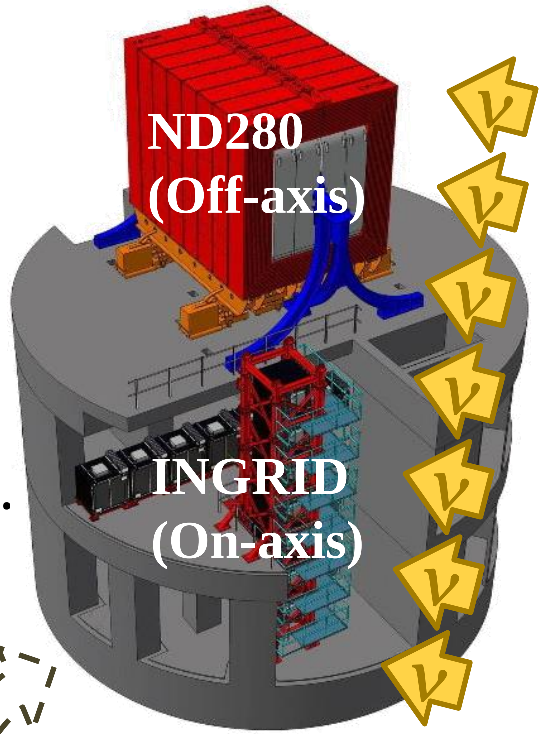


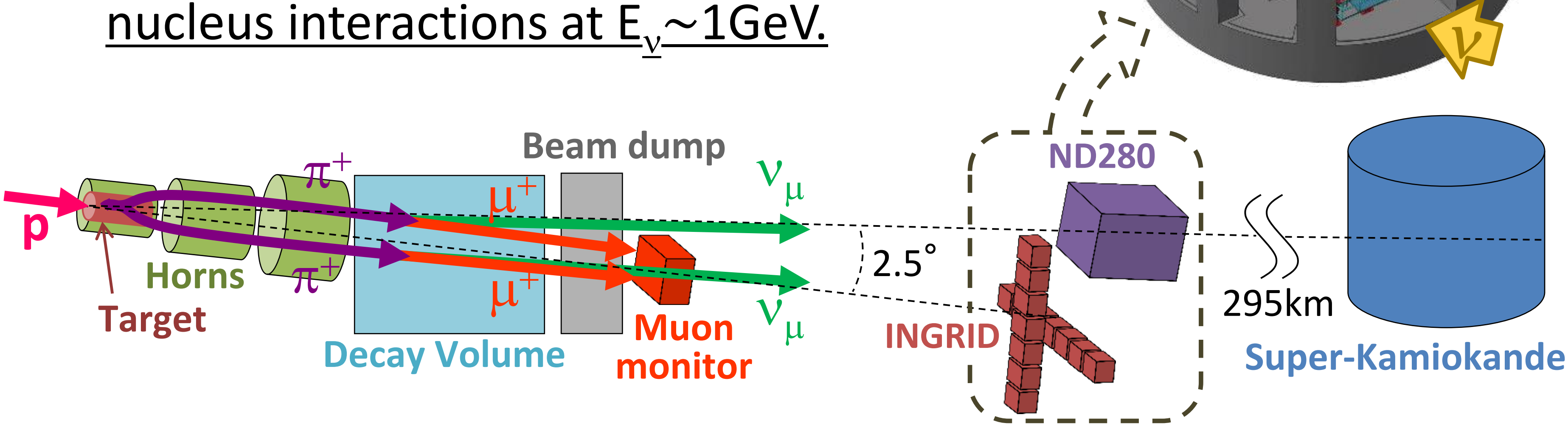
The T2K experiment

- 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.
- Precise measurement of neutrino nucleus interactions at $E_\nu \sim 1$GeV.

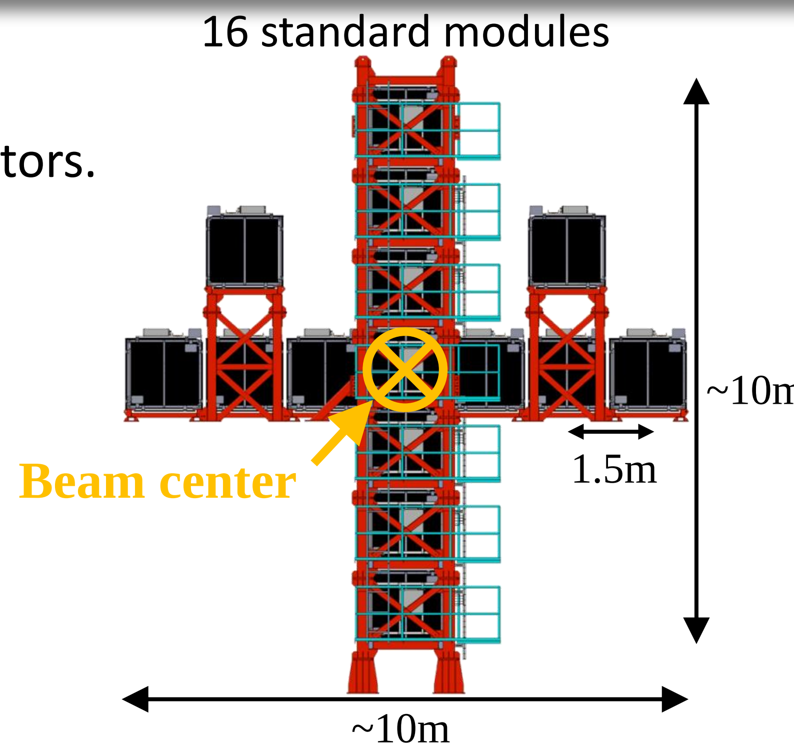
T2K Near detectors

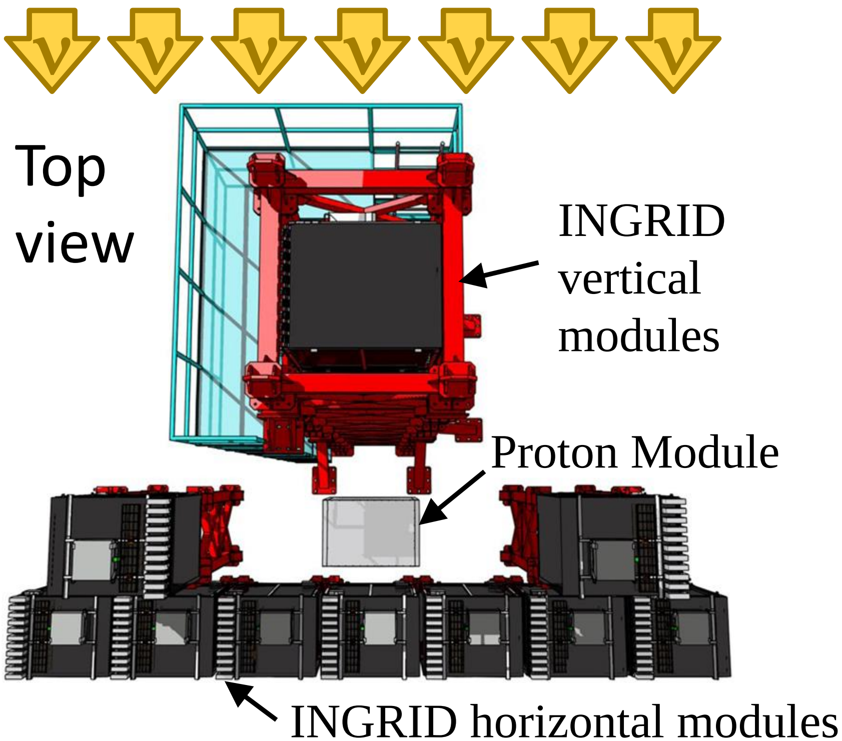


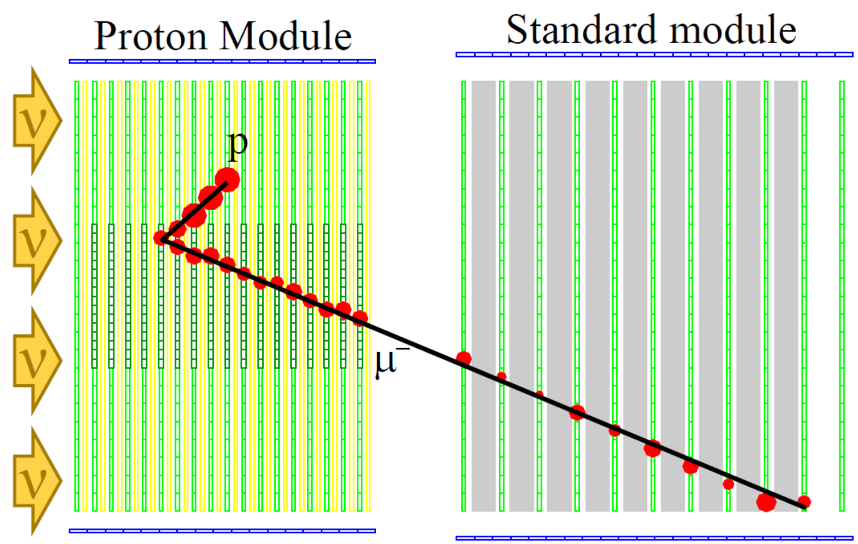


INGRID (on-axis near detector)

- 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.



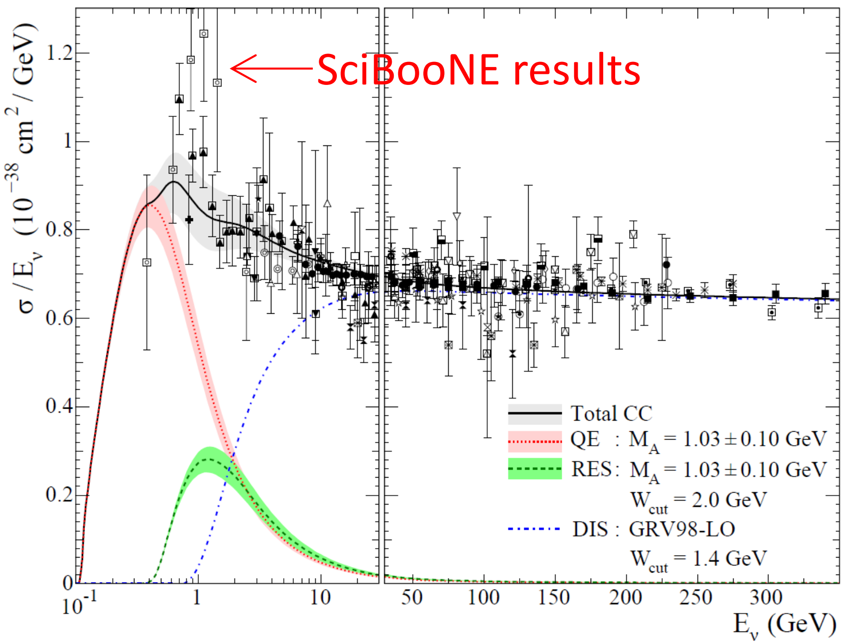




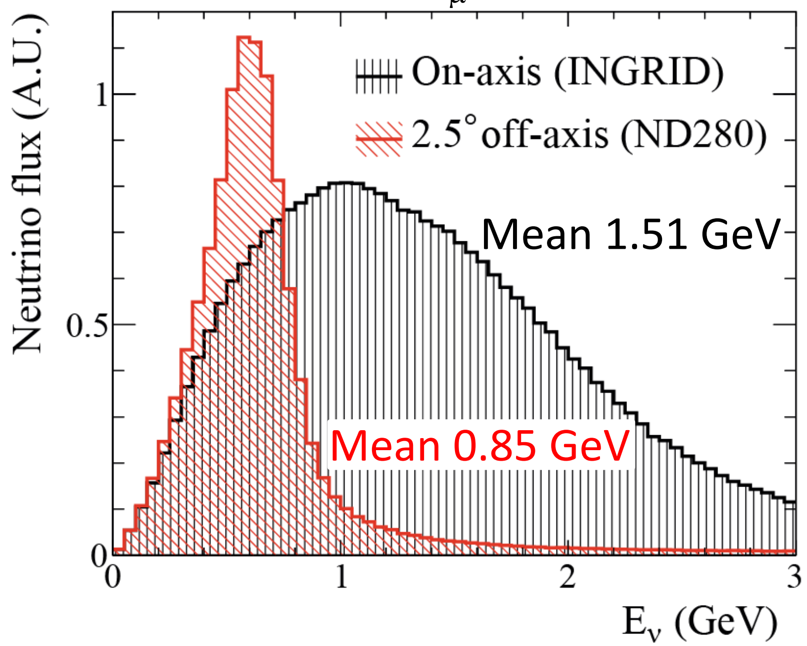
CC inclusive cross section

- CC inclusive cross section at a few GeV isn't well understood.
  - Nuclear effects of the neutrino target material is significant.
  - SciBooNE observed higher cross section than predictions.
- Cross section measurement for various target is important.
- We measured the flux averaged CC inclusive cross section on Fe and CH in a few GeV region with T2K on-axis neutrino beam.

CC inclusive cross section

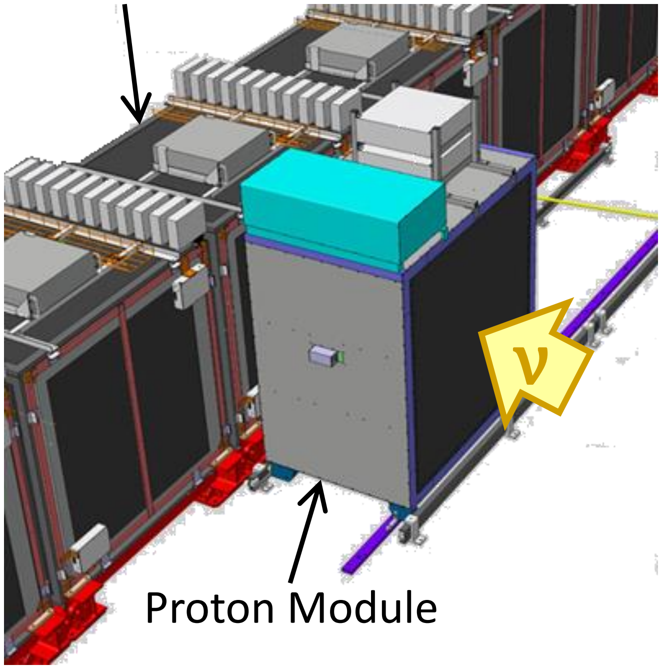


T2K ν_μ flux



CC inclusive cross section on Fe and CH

- Fe makes up 96.23% of the standard module by weight.
- CH makes up 98.57% of the Proton Module by weight.
- CC inclusive cross section on Fe and CH is measured from number of CC events in the central standard module and the Proton Module.
- CC inclusive cross section ratio on Fe to CH is measured using two detectors.
  → Large part of the systematic error is cancelled between two detectors on the same beam axis.



Elemental composition of neutrino target material by weight.

	H	C	N	O	Ti	Fe
Standard module	0.29%	3.42%	0.003%	0.03%	0.03%	96.23%
Proton Module	7.61%	90.96%	0.07%	0.59%	0.76%	0

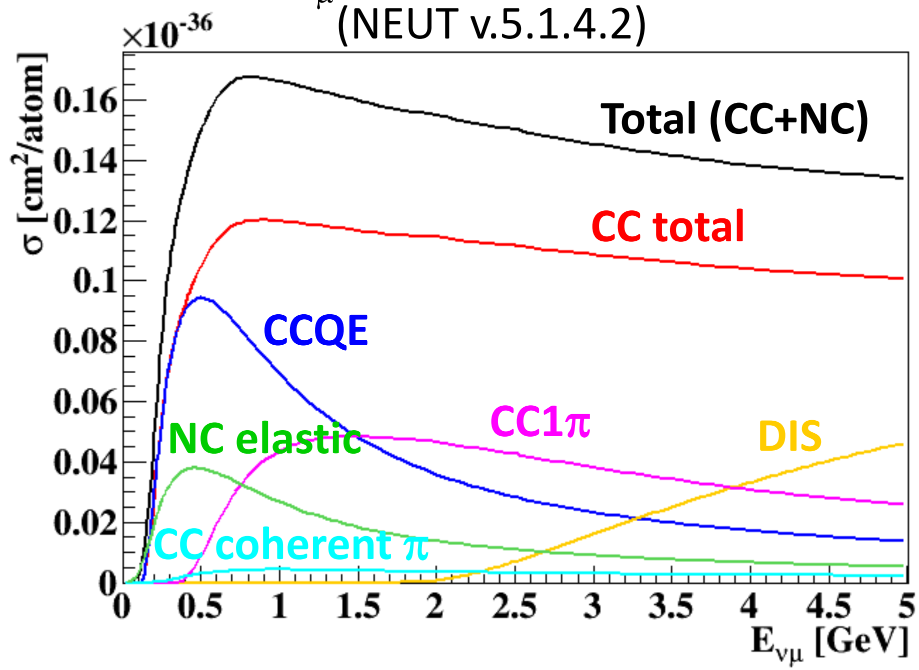
Neutrino interaction models used in T2K

- NEUT and GENIE are used to generate neutrino interactions.
- Common models used in NEUT and GENIE:
  - Quasi-elastic scattering : Llewellyn Smith formalism
  - Resonant pion production : Rein-Sehgal model
  - Coherent pion production : Rein-Sehgal model
  - Deep inelastic scattering : GRV98 PDF
- Differences between NEUT and GENIE:
  - Default values of M_A.
  - Treatment of nuclear effect.
  - Non-resonant process at low W.
  - Lepton mass term in coherent pion production.
- NEUT was used to estimate background and efficiency.
- GENIE was used only for the comparison of cross section results in addition to NEUT.

Default values of M_A

	NEUT	GENIE
M_A^{QE}	1.21GeV/c^2	0.99GeV/c^2
M_A^{RES}	1.21GeV/c^2	1.12GeV/c^2

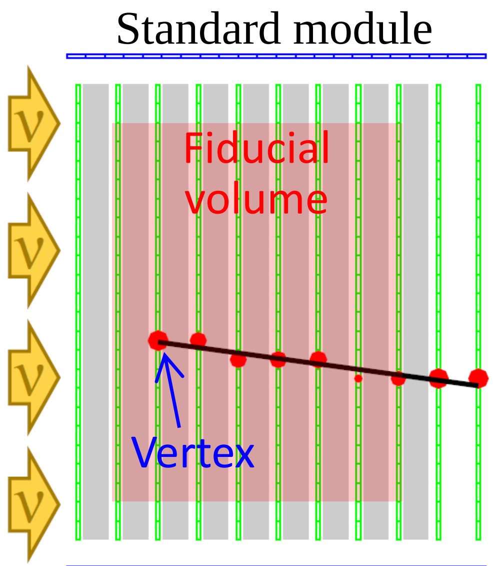
ν_μ cross section on C (NEUT v.5.1.4.2)



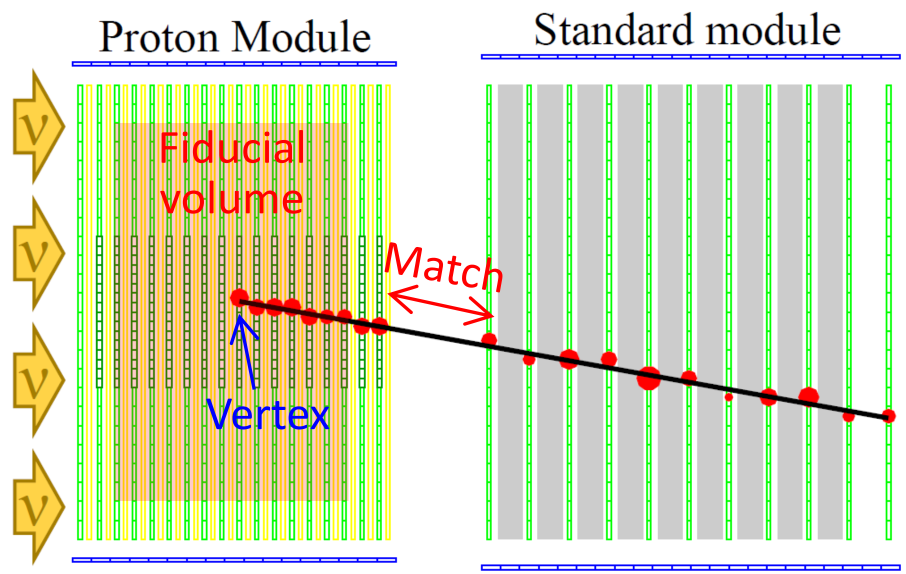
Event selection

- Reconstruct tracks and vertices.
- Select the events whose vertices are in the fiducial volume.
- Additionally, require the Proton Module track to be matched with standard module track.→ Select long muon track from CC.
- After the event selection,
  - Purity of CC interactions on Fe is 86.6% for standard module.
  - Purity of CC interactions on CH is 89.4% for the Proton Module.

Selected event in standard module



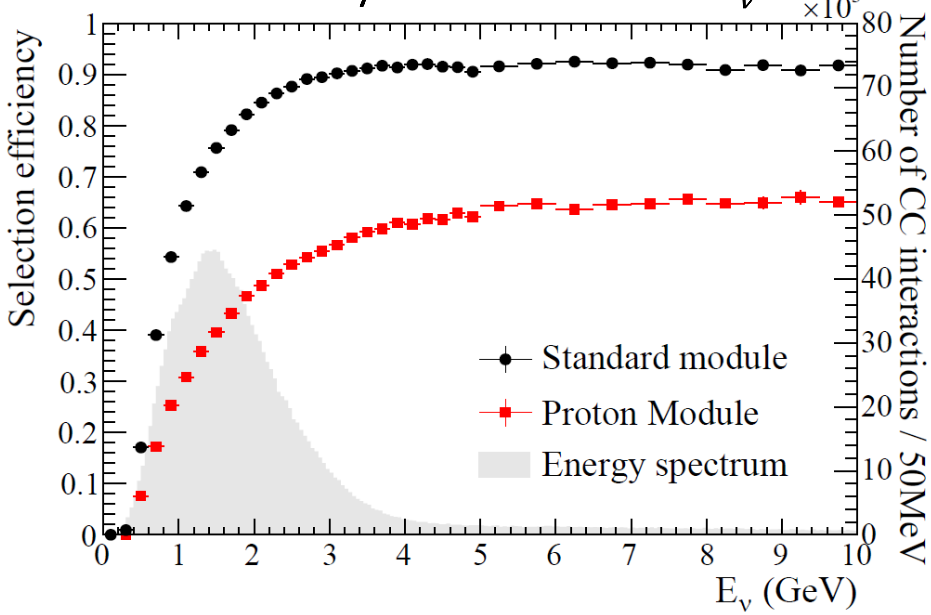
Selected event in Proton Module



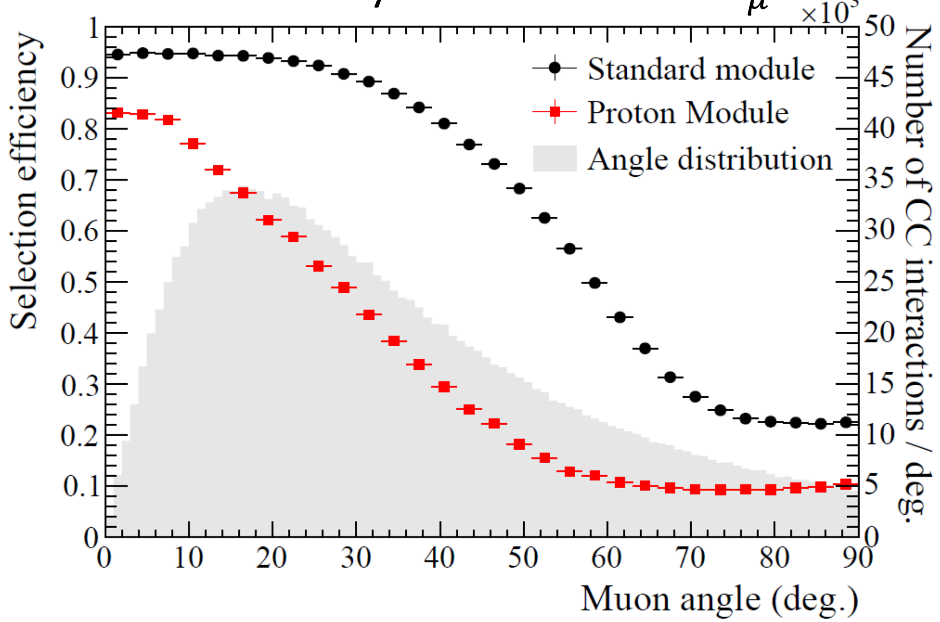
Difference in selection efficiency

- Selection efficiency for standard module is largely different from that for the Proton Module.
- It comes from the difference in acceptance due to the track matching required for the Proton Module.
- The difference should be reduced for the precise measurement of the CC inclusive cross section ratio on Fe to CH.

Efficiency as a function of E_ν



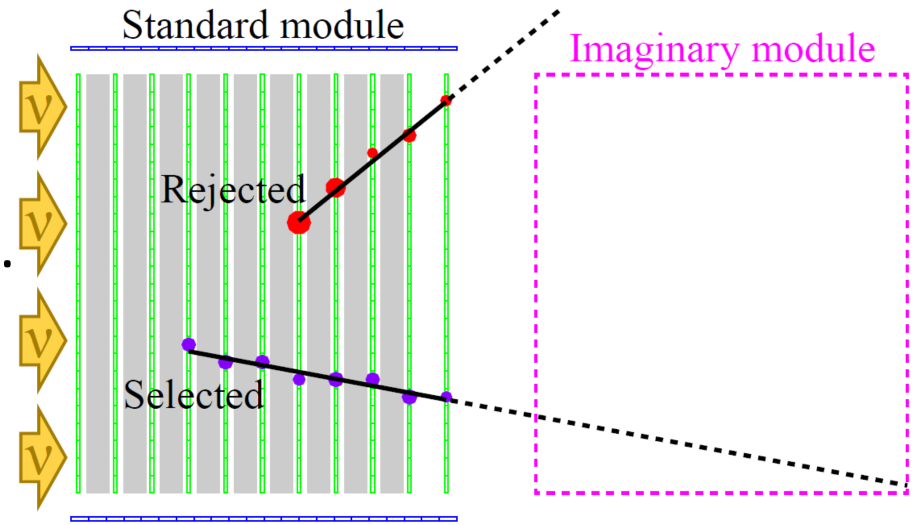
Efficiency as a function of θ_μ



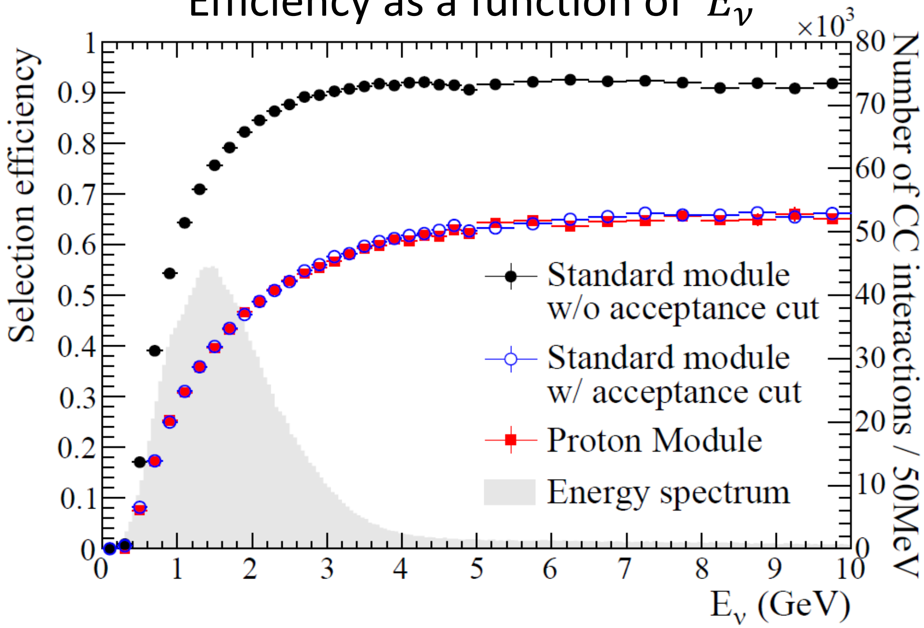
Difference in selection efficiency

- Define an imaginary module behind the standard module.
- Require standard module track to reach the imaginary module.
- After this acceptance cut, difference in selection efficiency becomes smaller.

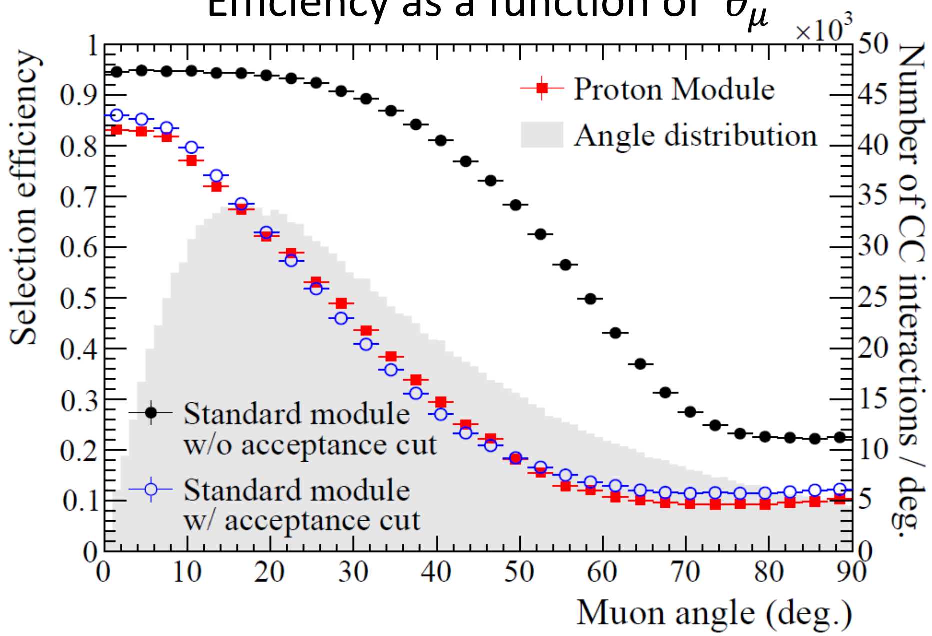
Acceptance cut for standard module



Efficiency as a function of E_ν



Efficiency as a function of θ_μ



Analysis strategy

- Flux averaged CC-inclusive cross section is calculated with background subtraction and efficiency correction.

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

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 nucleons
ε_{CC} : Detection efficiency of CC events (MC)

- This calculation is applied to the standard module and the Proton Module to estimate σ_{CC}^{Fe} and σ_{CC}^{CH}.
- Then $\sigma_{CC}^{Fe}/\sigma_{CC}^{CH}$ is calculated.

Neutrino interactions on scintillator(CH) of the standard module or those on reflector(TiO_2) of the Proton Module.

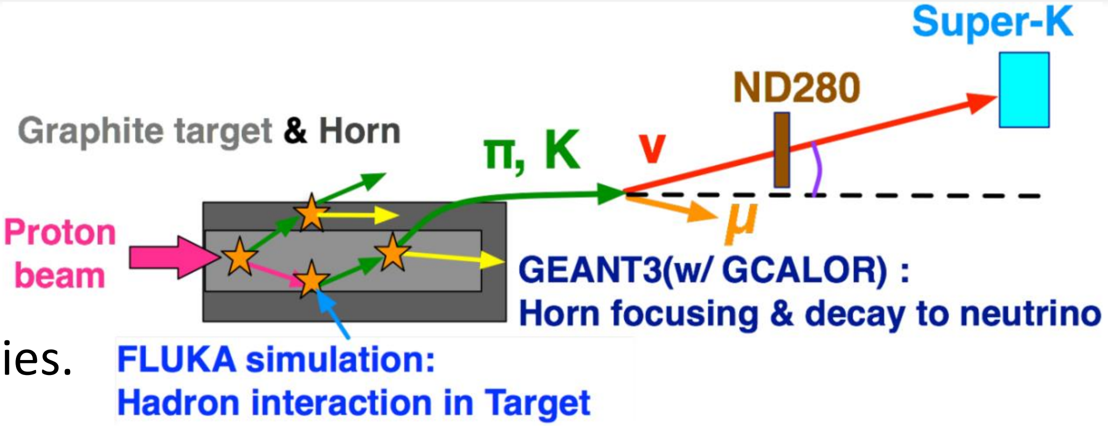
Caused by particles generated by neutrino interactions on surrounding materials.

MC expected background ratio to all selected events

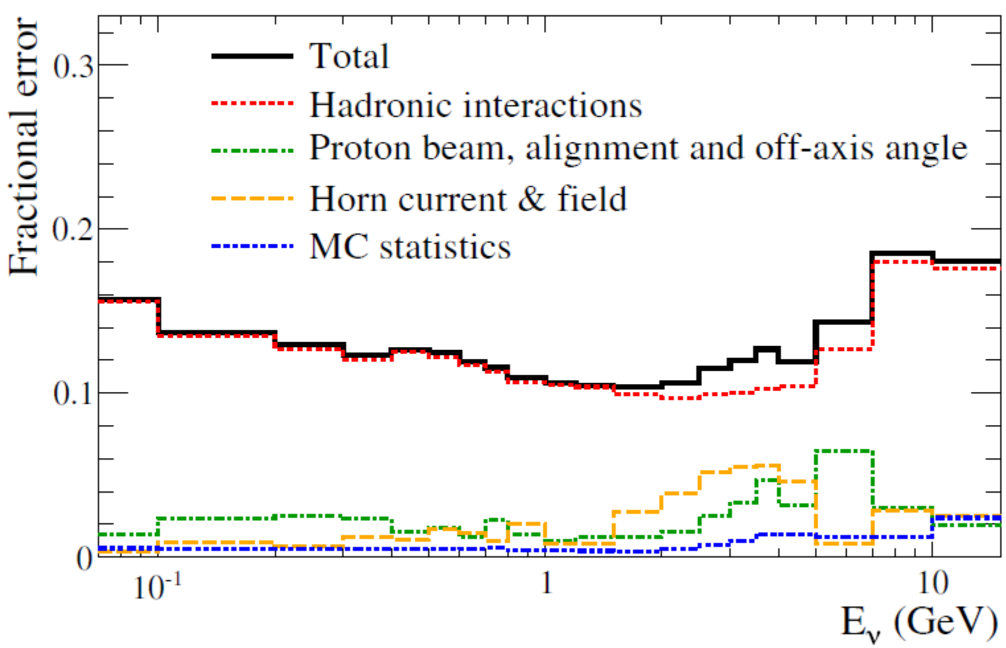
	σ_{CC}^{Fe}	σ_{CC}^{CH}
NC events	6.44%	4.19%
$\bar{\nu}_\mu$ events	2.04%	2.39%
ν_e events	0.99%	0.73%
Target element	2.67%	1.39%
External	0.82%	5.87%

Neutrino flux uncertainty

- Source of the flux uncertainty:
  - Hadron interaction uncertainties.
  - T2K beamline uncertainties. (proton beam position, proton beam intensity, neutrino beam direction, horn current, alignment).
- Total neutrino flux uncertainty is ∼10%.
- Hadron interaction uncertainty is dominant error source.



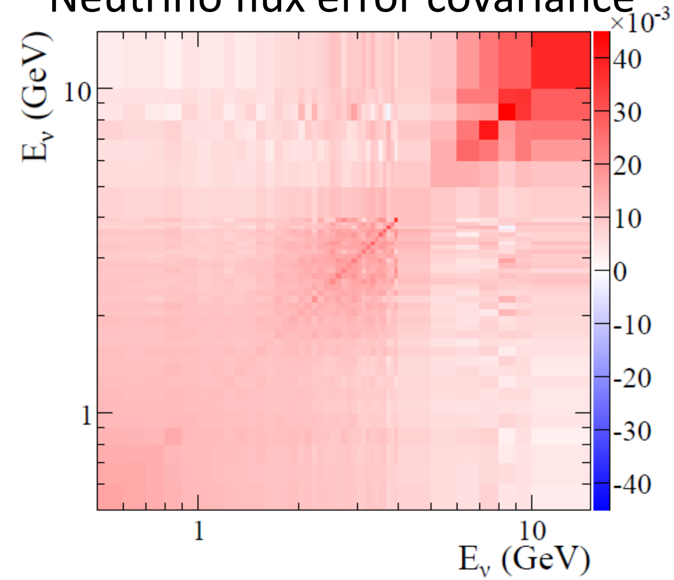
Fractional neutrino flux error



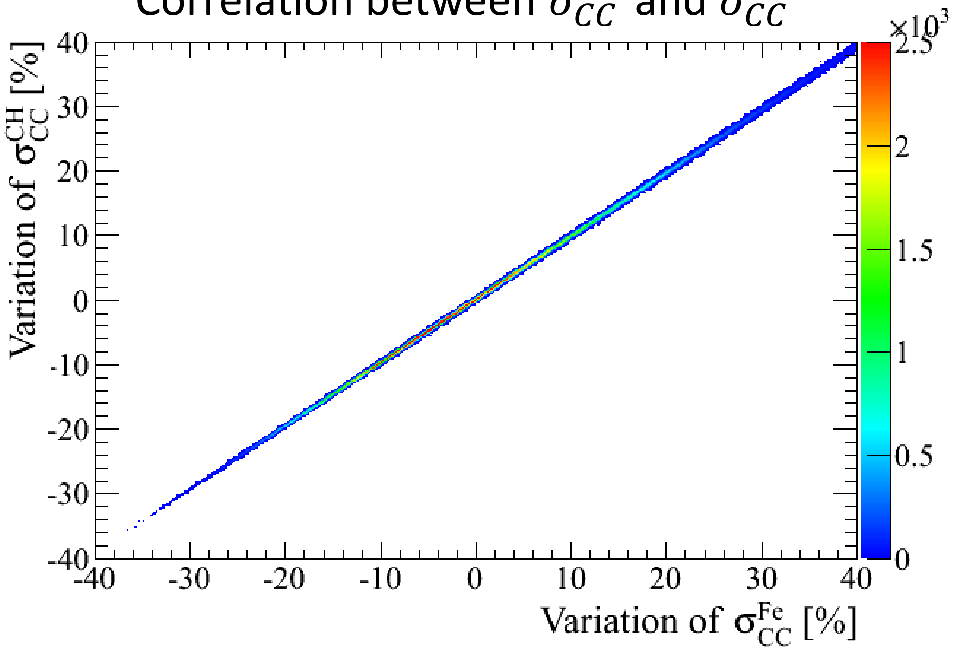
Systematic error from neutrino flux

- Systematic error is evaluated by toy MC generated from the covariance matrix.
- Systematic error from flux for σ_{CC}^{Fe} and σ_{CC}^{CH} is ~10%.
- That for $\sigma_{CC}^{Fe}/\sigma_{CC}^{CH}$ is about ~0.3% thanks to the large correlation between the variations of σ_{CC}^{Fe} and σ_{CC}^{CH}.

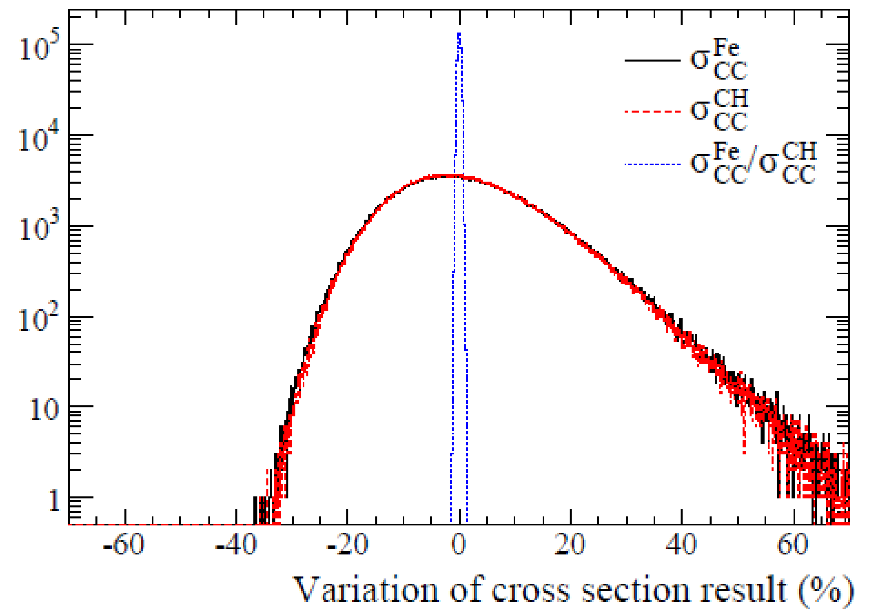
Neutrino flux error covariance



Correlation between σ_{CC}^{Fe} and σ_{CC}^{CH}



Variation of the cross section results



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 (final state interaction) uncertainties.

	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	CCQE norm. ($E_\nu < 1.5$GeV)	1	11%
	CCQE norm. ($1.5 < E_\nu < 3.5$GeV)	1	30%
	CCQE norm. ($E_\nu > 3.5$GeV)	1	30%
	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 summary

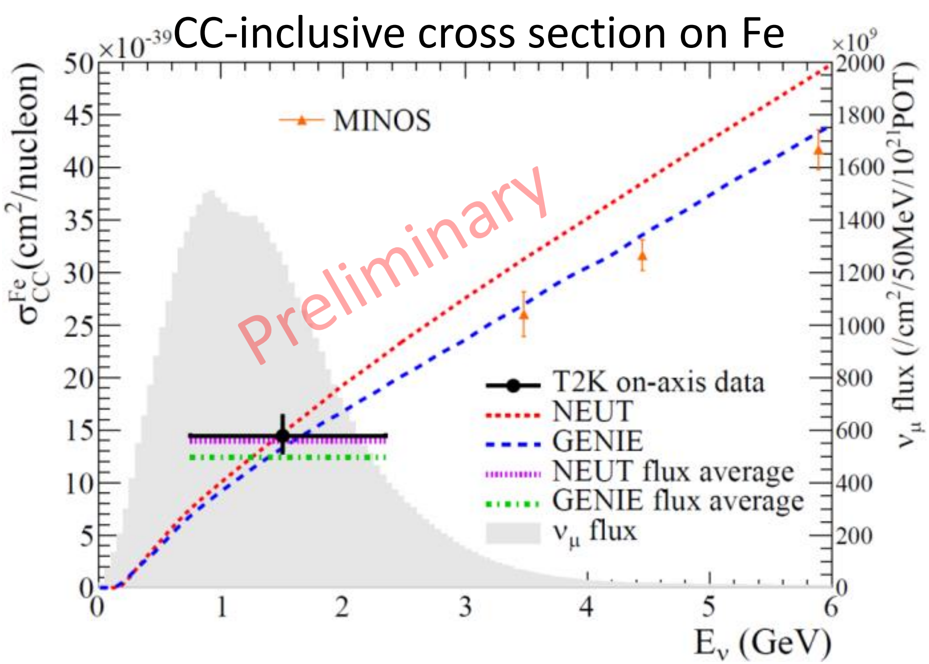
- Detector error:
  - Error sources: target mass, dark count, hit detection efficiency, event pileup.
  - Additional data-MC discrepancy in each event selection step is included as the detector error.
- Flux error is dominant for the absolute CC inclusive cross section measurement.
- Systematic error for the cross section ratio on Fe to CH is very small.

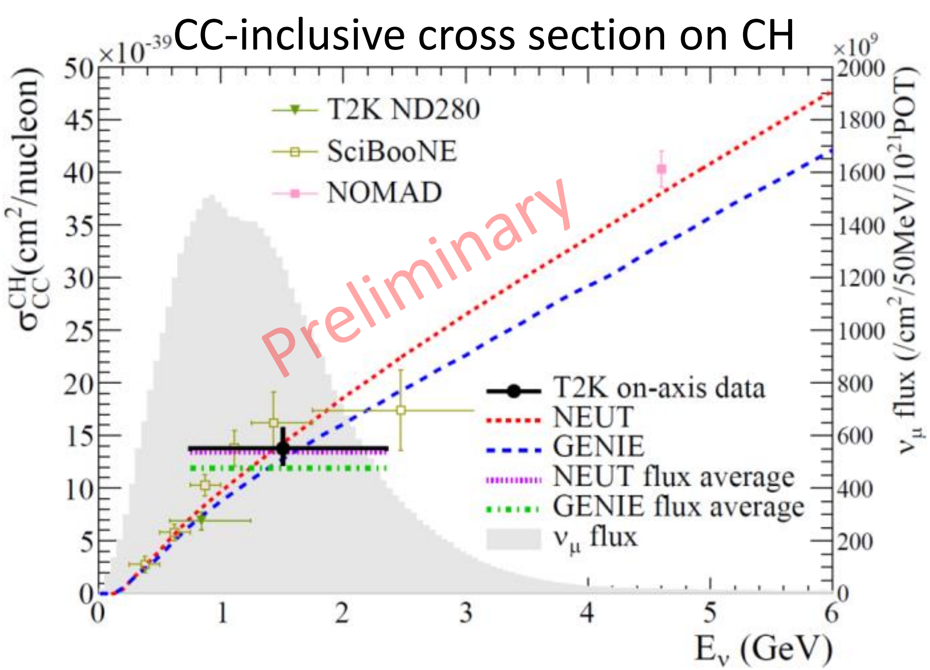
Summary of systematic errors

	σ_{CC}^{Fe}	σ_{CC}^{CH}	$\sigma_{CC}^{Fe}/\sigma_{CC}^{CH}$
Neutrino flux	$-10.34\%+12.74\%$	$-10.12\%+12.48\%$	$\underline{-0.31\%+0.31\%}$
Neutrino interaction + FSI	$-3.50\%+3.42\%$	$-3.67\%+3.68\%$	$-1.56\%+1.63\%$
Detector response	$\pm1.11\%$	$\pm1.71\%$	$\pm2.04\%$
Total	$-10.97\%+13.24\%$	$-10.90\%+13.12\%$	$\underline{-2.59\%+2.63\%}$

Flux averaged CC inclusive cross section result

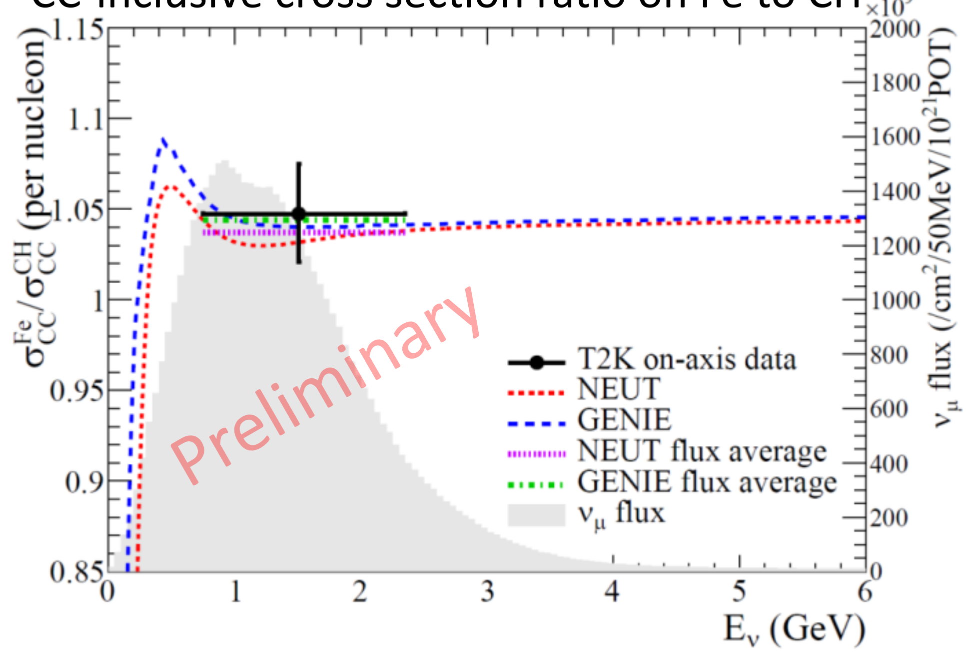
- Flux averaged CC inclusive cross sections on Fe and CH are
  $\sigma_{CC}^{Fe} = (1.444 \pm 0.002(stat.)^{+0.191}_{-0.159}(syst.)) \times 10^{-38}$ cm²/nucleon
  $\sigma_{CC}^{CH} = (1.379 \pm 0.009(stat.)^{+0.181}_{-0.150}(syst.)) \times 10^{-38}$ cm²/nucleon
  at mean energy of 1.51GeV.
- They agree well with predictions.
- Our result on Fe is the first result on Fe in a few GeV region.
- Our result on CH is smaller than the SciBooNE result.





CC inclusive cross section ratio result

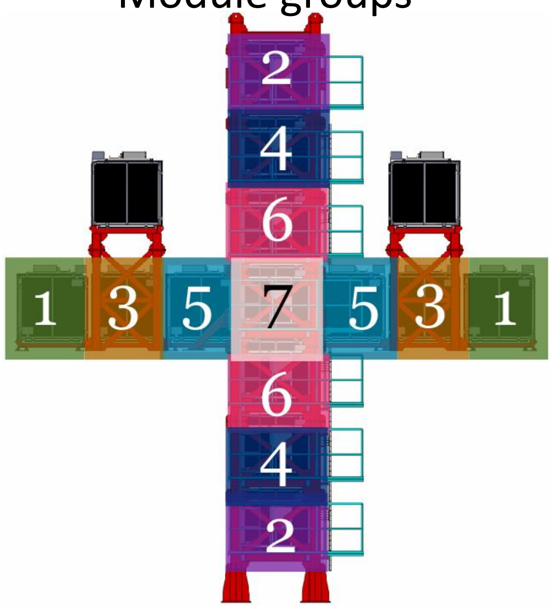
- CC inclusive cross section ratio on Fe to CH is
$$\frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{CH}} = 1.047 \pm 0.007(stat.)^{+0.028}_{-0.027}(syst.)$$
at mean energy of 1.51GeV.
- It agrees well with prediction.
- Target dependence is understood and controlled at the ~2% level.



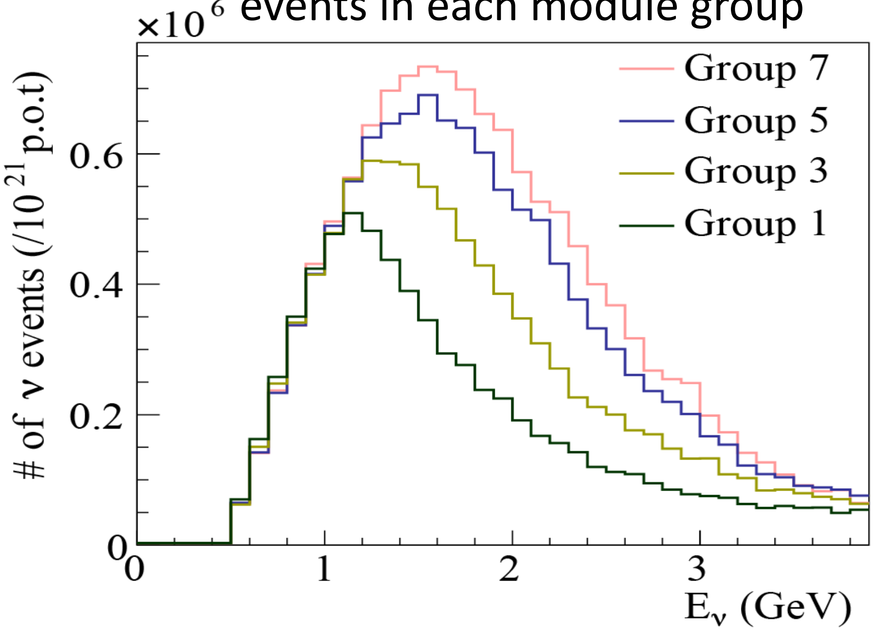
Energy dependent CC-inclusive cross section with INGRID

- Additional ongoing study using INGRID.
- Neutrino energy spectrum on each INGRID module is different.
- Categorize events by module group.
- In addition, categorize events by topology group.
- Fit the MC model to the numbers of events in the groups to extract CC-inclusive cross section in bins of E_ν.
- Result coming soon.

Module groups



Energy spectrum of neutrino events in each module group



Summary

- Flux averaged CC inclusive cross section on Fe and CH and their cross section ratio at mean energy of 1.51GeV were measured using T2K on-axis neutrino detector, INGRID.
- Cross section results agree well with model predictions.
- Our result on Fe is the first result on Fe in a few GeV region.
- Our result on CH is smaller than the SciBooNE result.
- Target dependence is understood and controlled in ~2% level.
- Paper will be submitted to Physical Review D soon.
- Energy dependent measurement is ongoing.
- Other results from T2K INGRID.
  - CCQE (May 21).
  - CC coherent pion (May 23).