T2K latest results on neutrino-nucleus cross sections

Marcela Batkiewicz-Kwaśniak
The H. Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences, Cracow

for the T2K Collaboration

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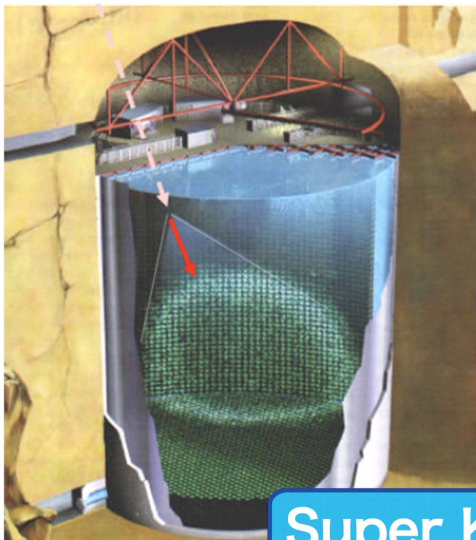
Content

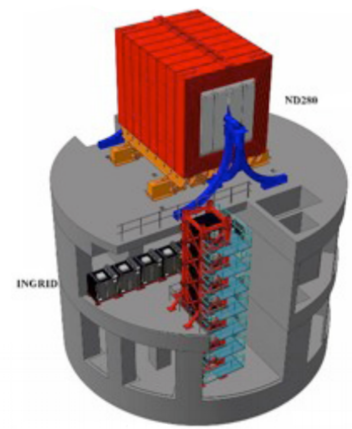
- T2K experiment overview
- Motivation
- Recent measurements:
  - On axis: Inclusive ν_μ CC on water, CH and iron
  - 1.5° off-axis: $\bar{\nu}_\mu$ CC0π0p on water and CH
  - 2.5° off-axis: ν_μ CC0π on oxygen and O/C
- Other cross-section measurements
- Summary

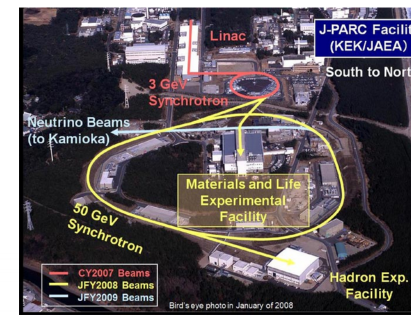
T2K experiment

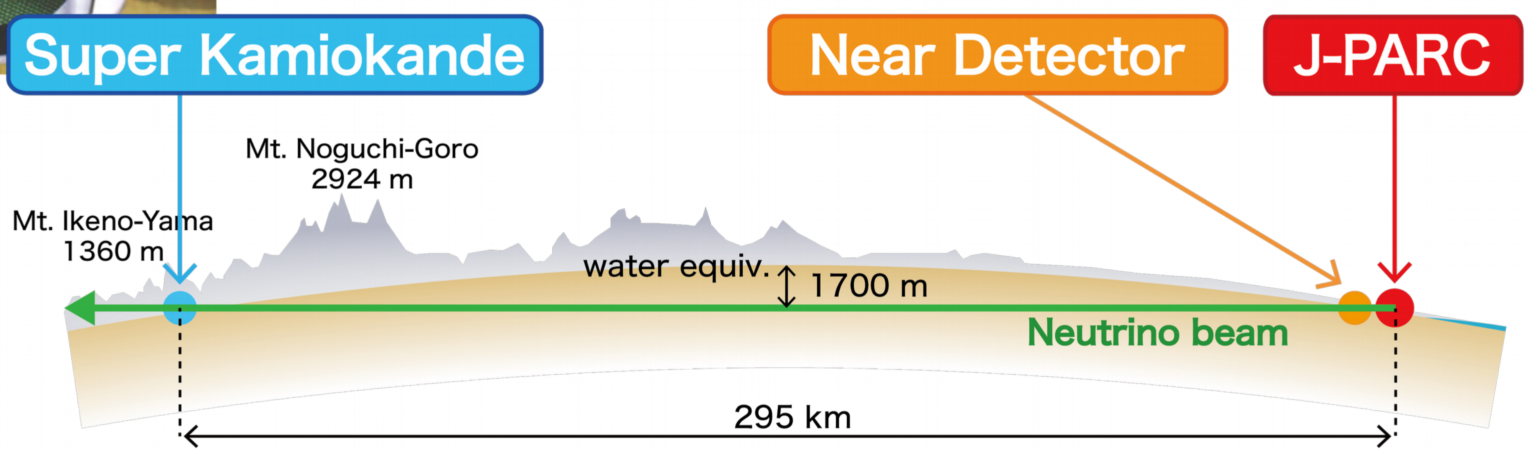
Far detector
in Kamioka



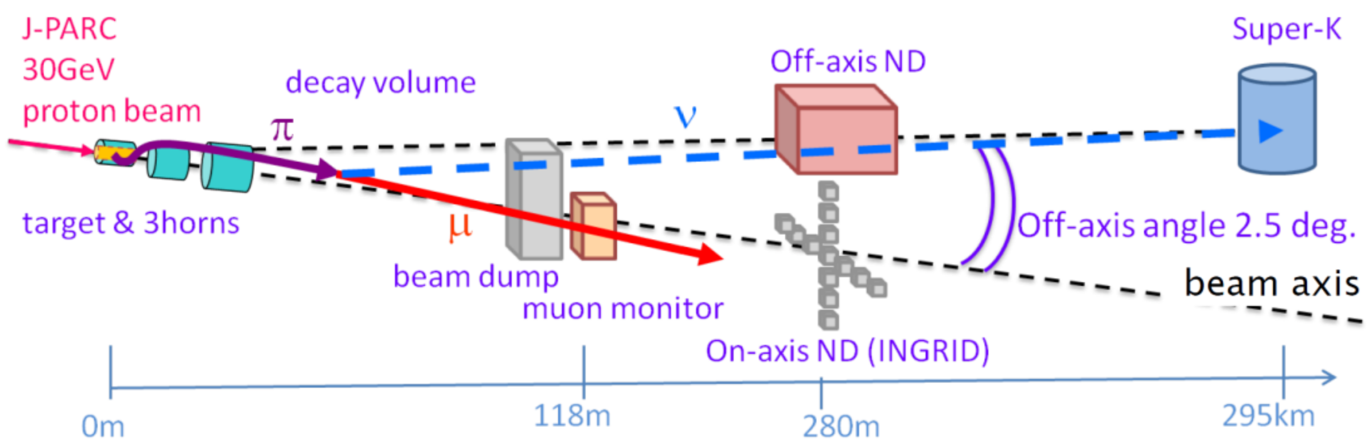
Accelerator complex and
near detectors in Tokai



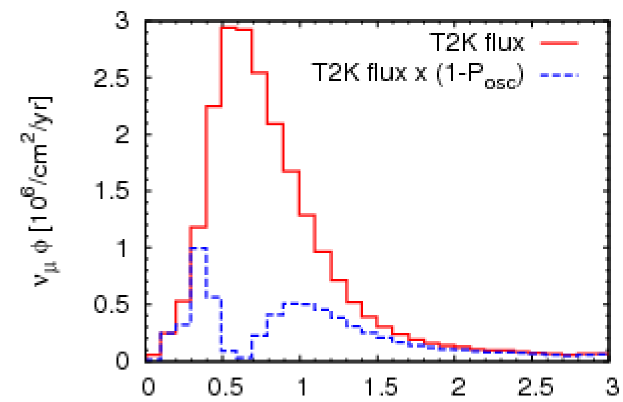


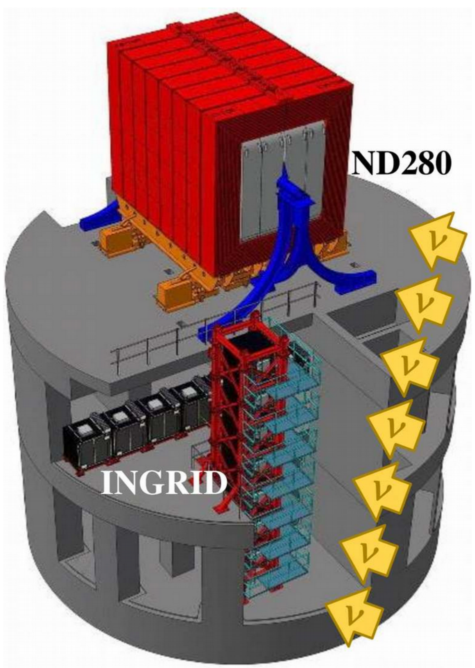


Beam-line and near detectors

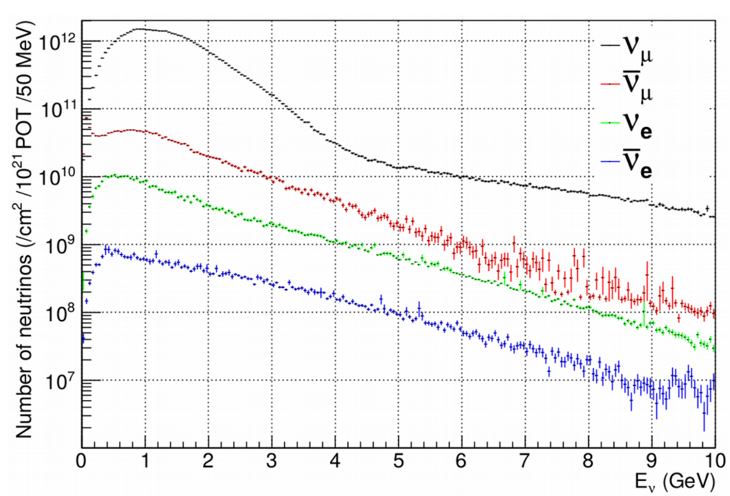


Flux at Super-K

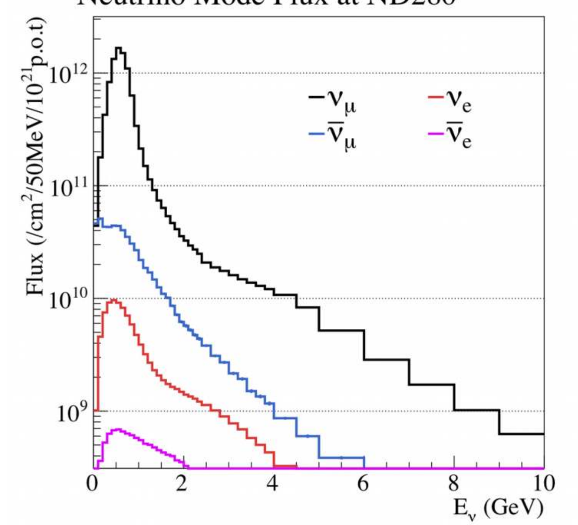




Neutrino Mode Flux at INGRID



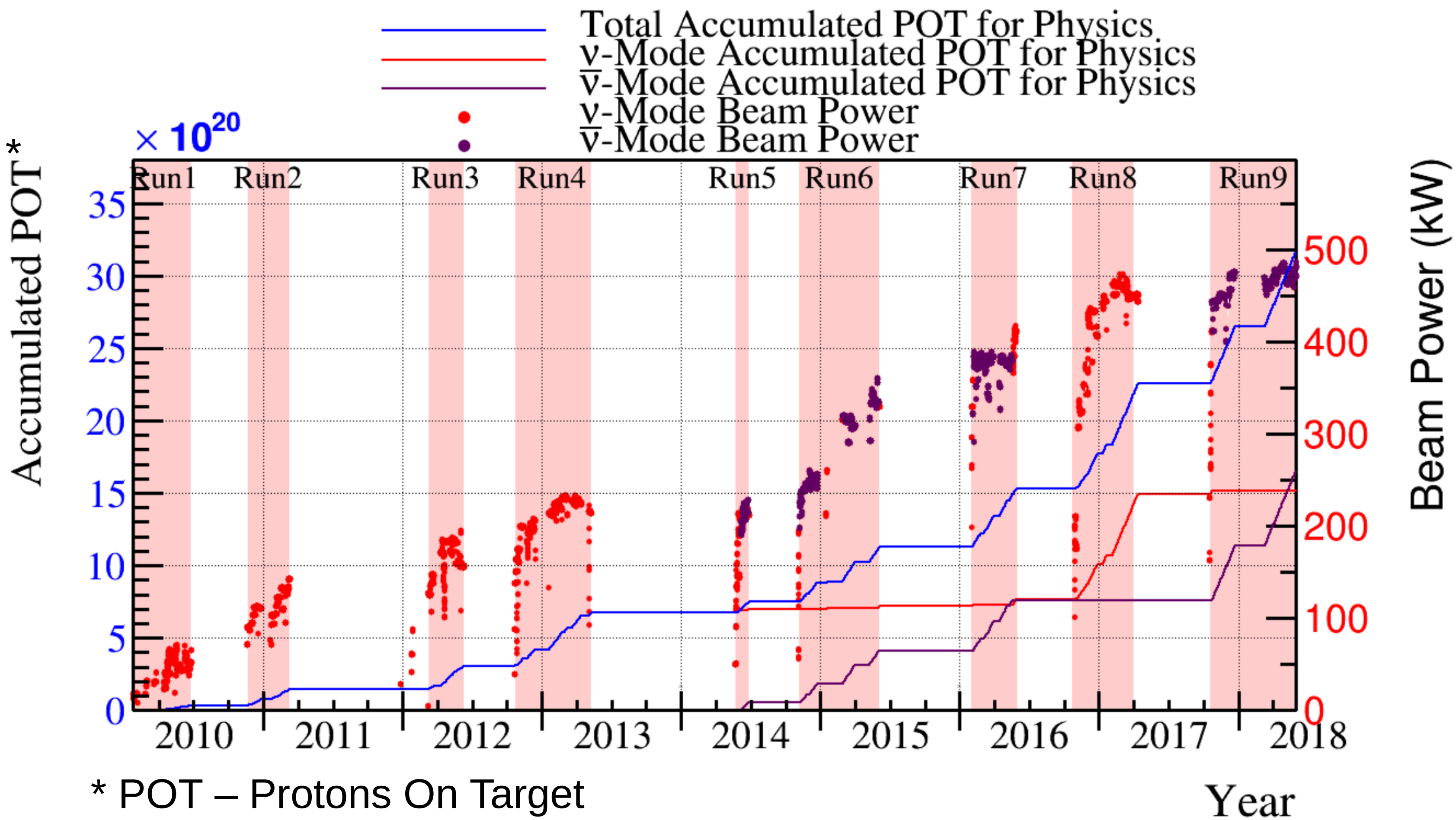
Neutrino Mode Flux at ND280



On-axis beam: wide, mean energy ~1.5 GeV

2.5° off-axis beam: narrow, mean energy ~0.6 GeV

T2K data-taking summary



* POT – Protons On Target

23 Jan. 2010 – 31 May 2018

POT total: 3.16×10^{21}

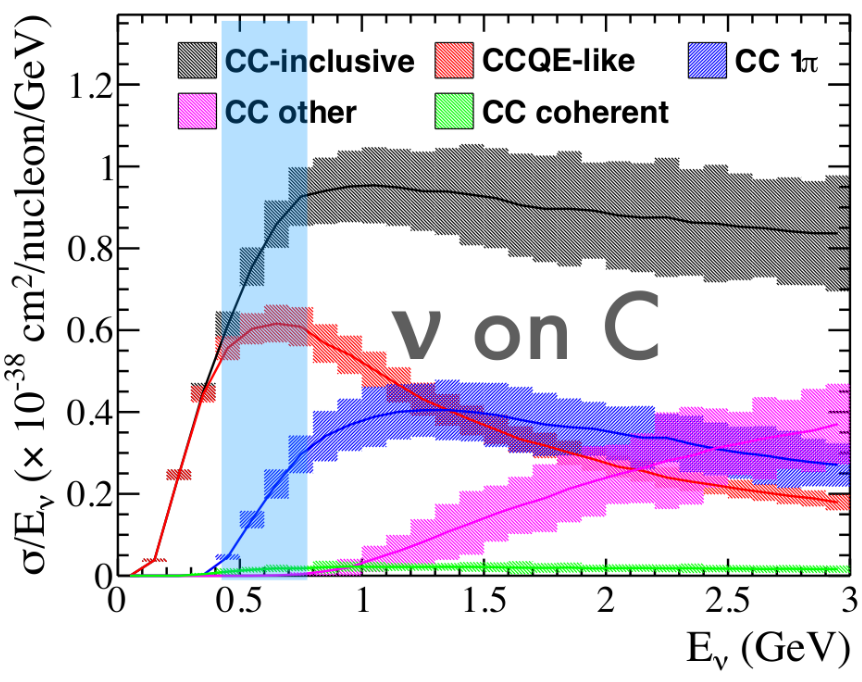
ν-mode 1.51×10^{21} (47.83%)

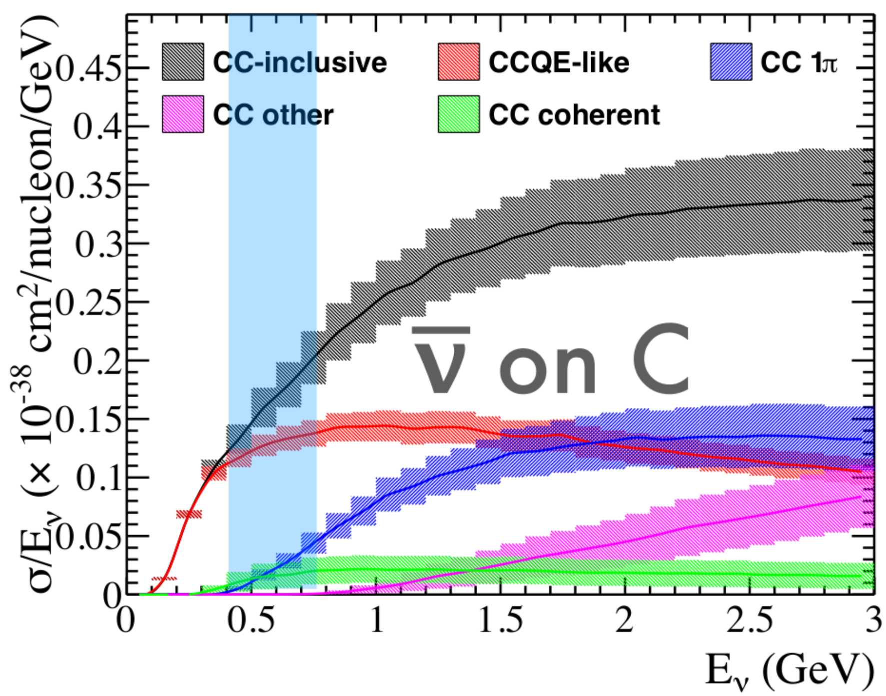
$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

Motivation

- Good neutrino interaction model is essential to decrease systematic errors in oscillation analysis, because of differences between near and far detectors:
  - angular acceptance
  - target material
  - neutrino energy spectra

⇒ Need of measurements of diverse type of interaction on different target materials at various range of neutrino energies and flavours





T2K systematics

FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

from M.Friend, KEK Physics Seminar, Jan 10, 2019

% Errors on Predicted Event Rates

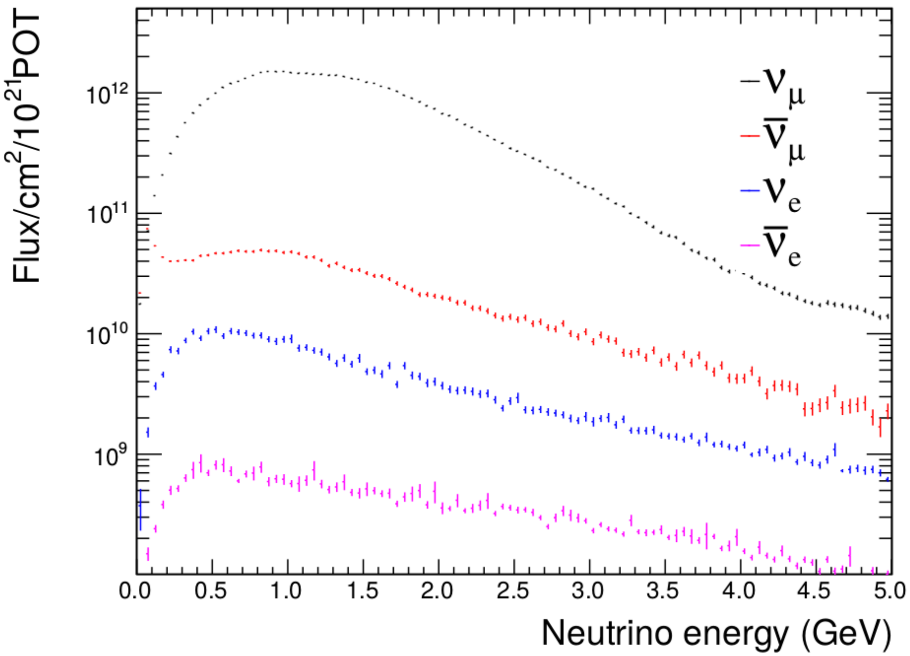
	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
$\rightarrow$ Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09	2.67
E_b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc	0.03	0.03	2.69	2.49	2.63	0.77
All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
All with osc	5.12	4.45	9.19	7.57	18.51	6.03

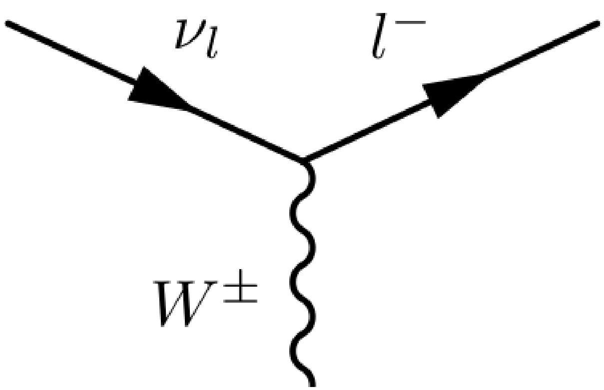
- Flux and cross section errors constrained by ND280 from ~15% to ~5%

Inclusive ν_μ CC on water, CH and iron cross sections and their ratios at on-axis T2K beam

https://arxiv.org/abs/1904.09611

On-axis neutrino beam

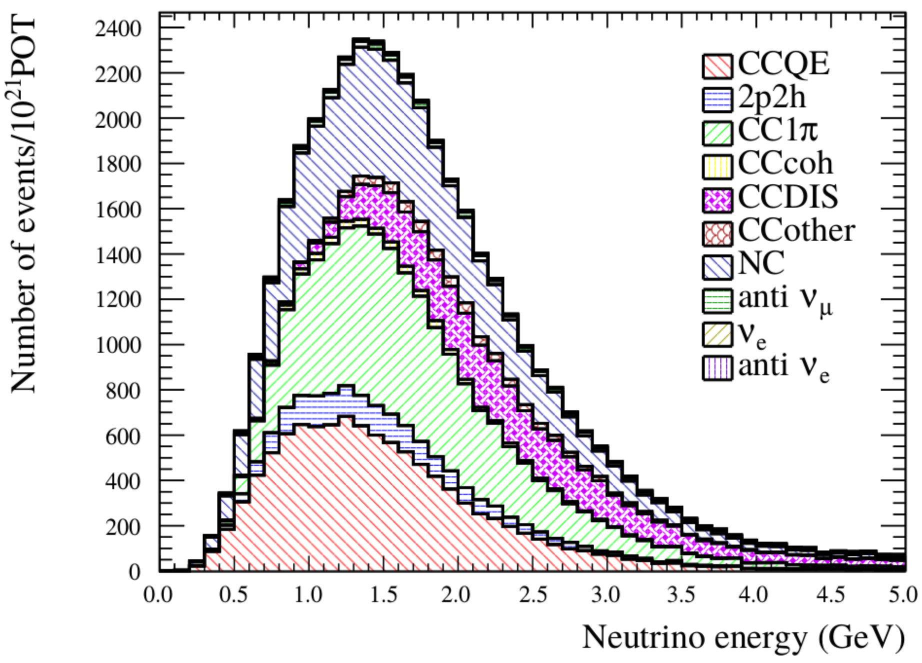




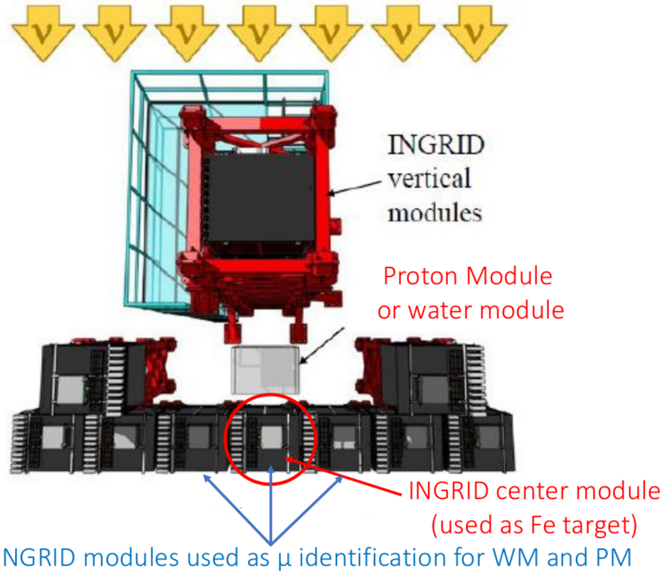
Mean energy: 1.5 GeV

ν beam mode data used:

- 5.89×10^{20} POT for Proton Module collected from Nov 2010 till May 2013
- 7.25×10^{20} POT for Water Module collected from Oct 2016 till Apr 2017



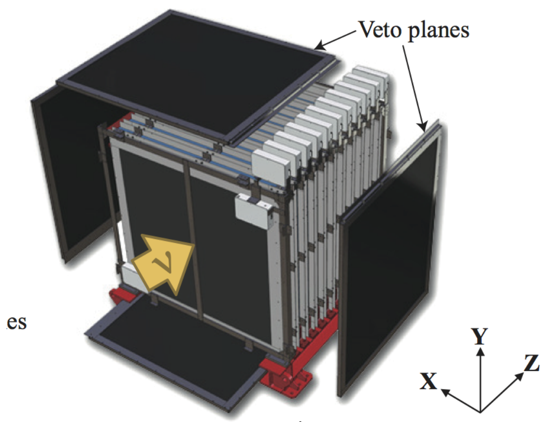
Detectors

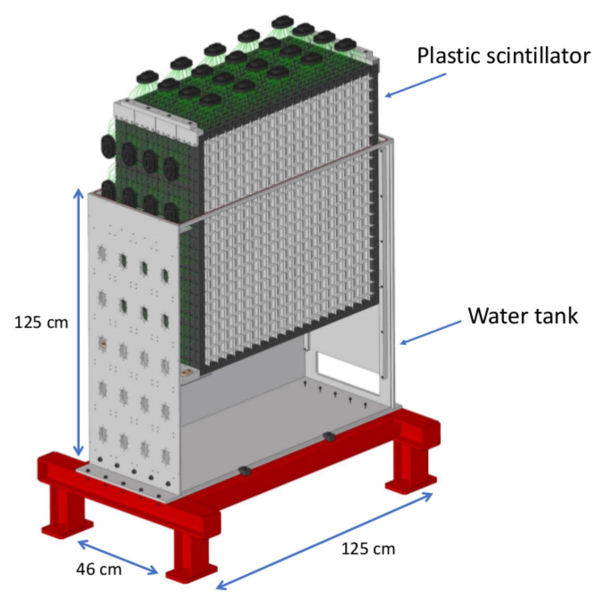


Non-magnetised detectors (momentum measurement possible only for stopping particles):

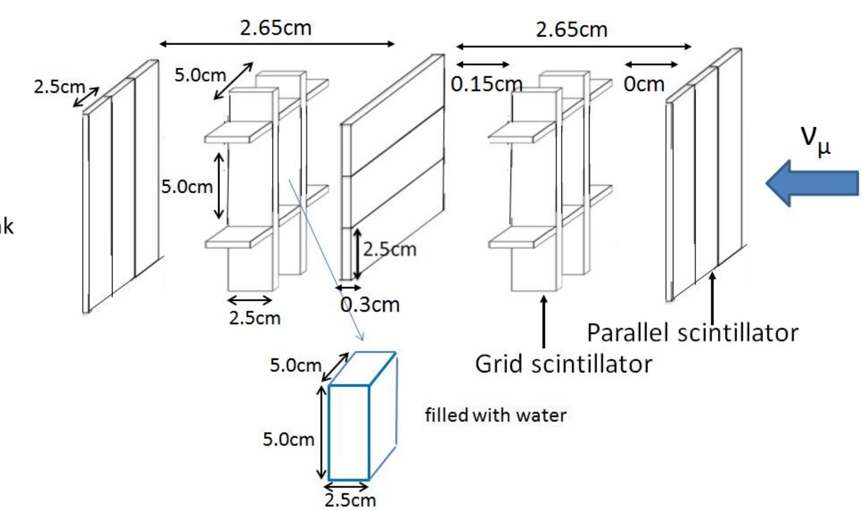
- INGRID (2.1 tons) – iron (96%), CH
- Proton module (0.16 tons) – CH (98%)
- Water Module/Wagasci (0.10 tons) – water(80%), CH (20%)

INGRID Module/ Proton Module



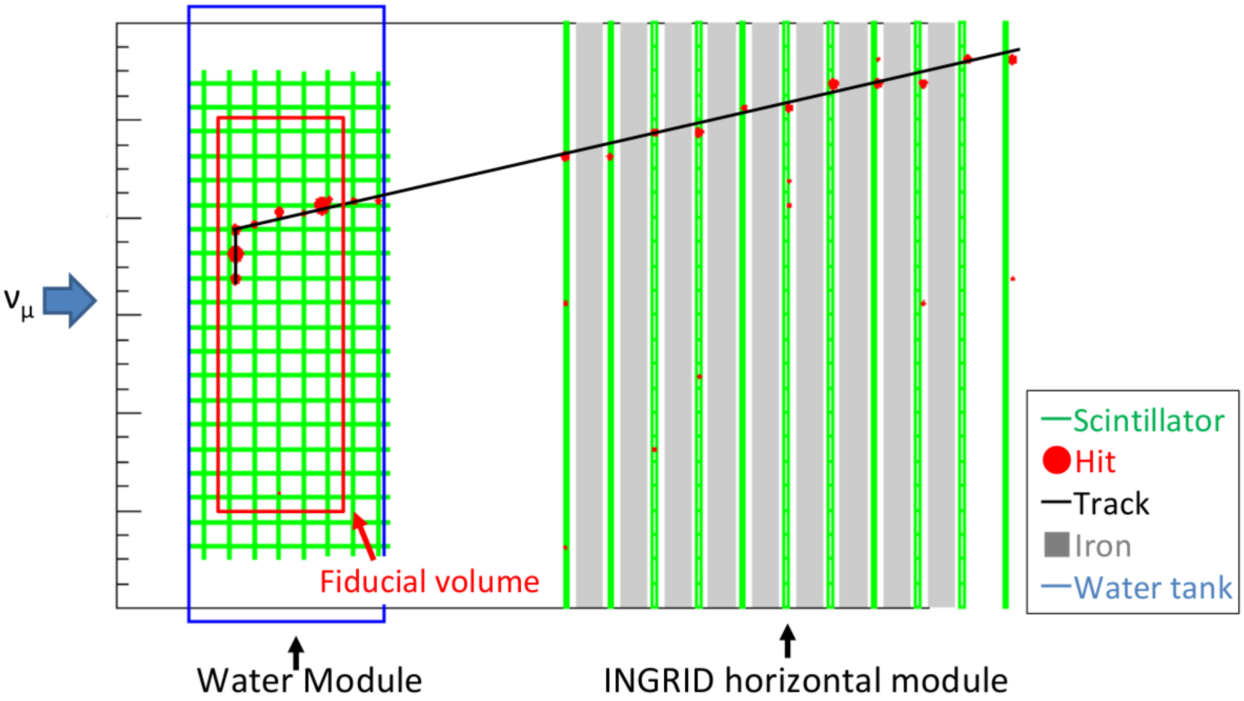


Water Module



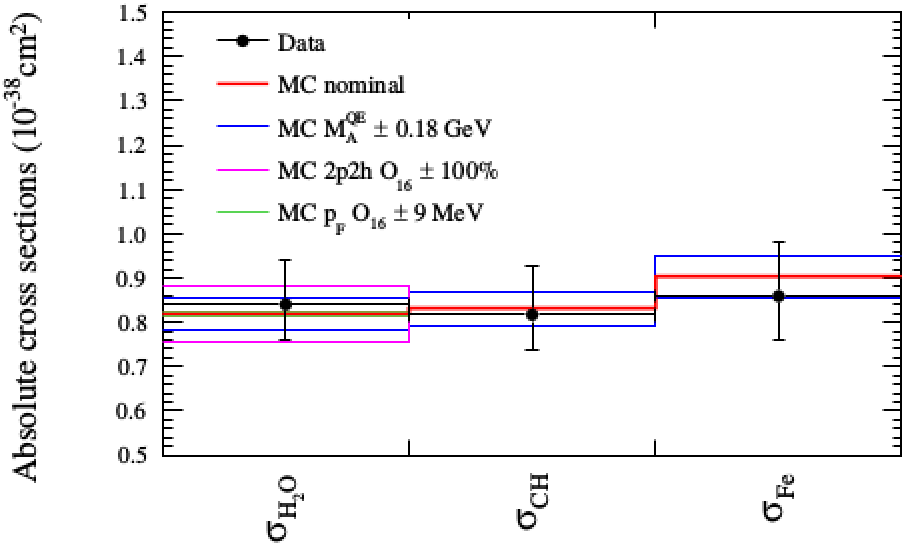
Event reconstruction

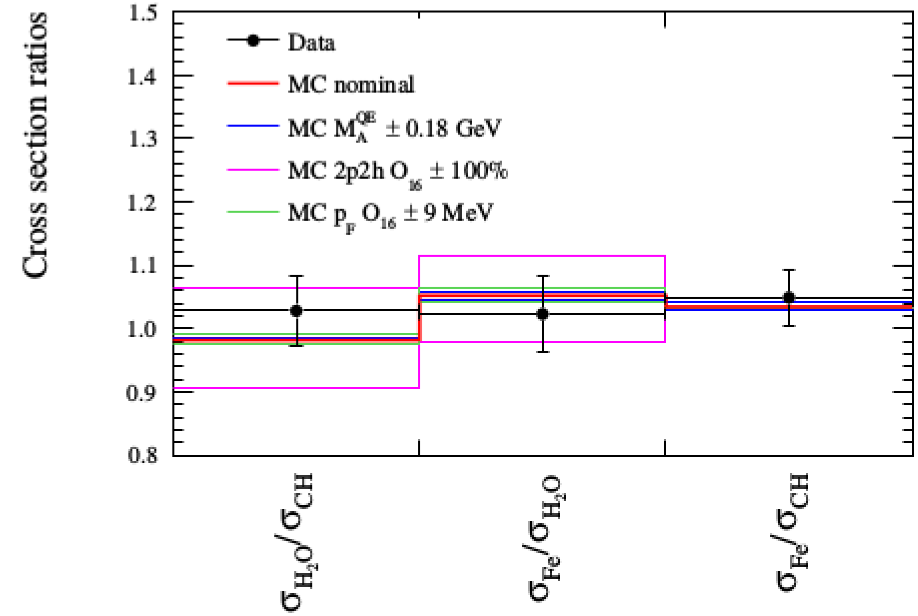
- Phase space restrictions for muon kinematics:
  - $p_\mu > 400$ MeV/c
  - $\theta_\mu < 45°$



Results

MC nominal model is NEUT v5.3.3 – for model details see backup slides





- The most precise measurement of neutrino cross section on water for this energy region (on-axis neutrino beam, with 1.5 GeV mean energy)
- The first measurement of neutrino cross-section ratios of water/CH and water/iron
- The results agree with the model used in the T2K oscillation analysis

Results

NEUT v5.3.3 prediction – for model details see backup slides

Cross section	NEUT expectation with RPA	NEUT expectation without RPA
$\sigma_{\mathrm{H_2O}}$	0.819×10^{-38} cm^2	0.860×10^{-38} cm^2
σ_{CH}	0.832×10^{-38} cm^2	0.875×10^{-38} cm^2
σ_{Fe}	not available	0.904×10^{-38} cm^2
$\sigma_{\mathrm{H_2O}}/\sigma_{\mathrm{CH}}$	0.984	0.983
$\sigma_{\mathrm{Fe}}/\sigma_{\mathrm{H_2O}}$	not available	1.051
$\sigma_{\mathrm{Fe}}/\sigma_{\mathrm{CH}}$	not available	1.033

T2K measurements

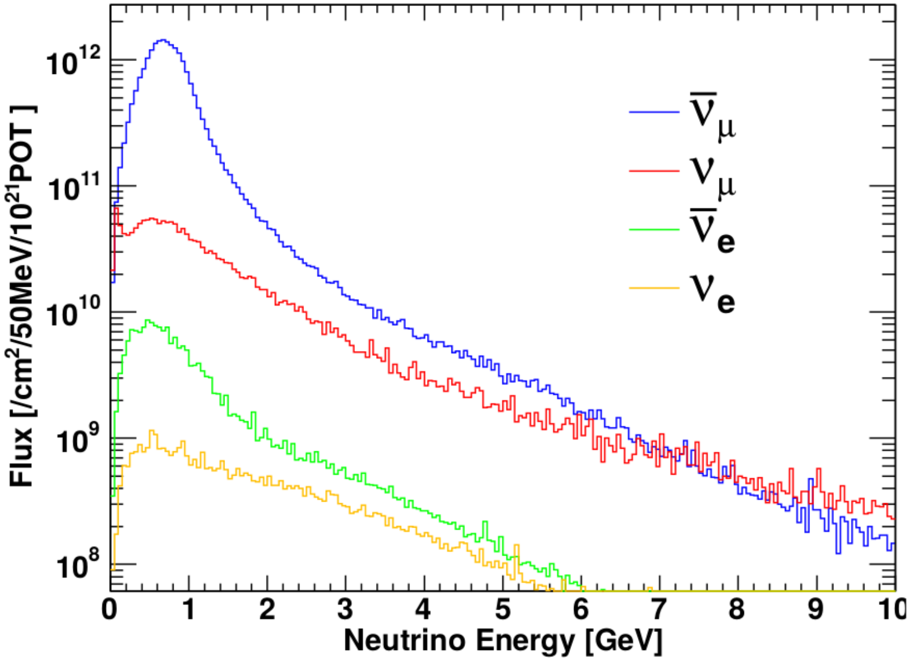
$$\sigma_{\mathrm{CC}}^{\mathrm{H_2O}} = (0.840 \pm 0.010(\mathrm{stat.})^{+0.10}_{-0.08}(\mathrm{syst.})) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon}, \qquad \frac{\sigma_{\mathrm{CC}}^{\mathrm{H_2O}}}{\sigma_{\mathrm{CC}}^{\mathrm{CH}}} = 1.028 \pm 0.016(\mathrm{stat.}) \pm 0.053(\mathrm{syst.}),$$

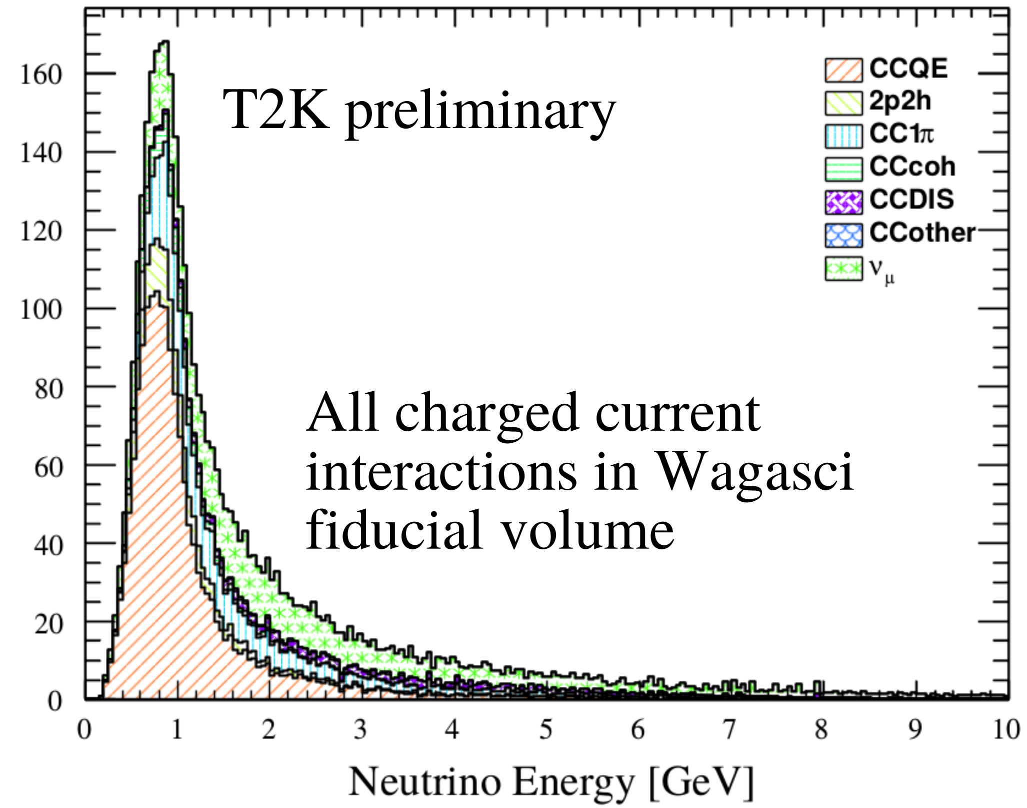
$$\sigma_{\mathrm{CC}}^{\mathrm{CH}} = (0.817 \pm 0.007(\mathrm{stat.})^{+0.11}_{-0.08}(\mathrm{syst.})) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon}, \qquad \frac{\sigma_{\mathrm{CC}}^{\mathrm{Fe}}}{\sigma_{\mathrm{CC}}^{\mathrm{H_2O}}} = 1.023 \pm 0.012(\mathrm{stat.}) \pm 0.058(\mathrm{syst.}),$$

$$\sigma_{\mathrm{CC}}^{\mathrm{Fe}} = (0.859 \pm 0.003(\mathrm{stat.})^{+0.12}_{-0.10}(\mathrm{syst.})) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon}. \qquad \frac{\sigma_{\mathrm{CC}}^{\mathrm{Fe}}}{\sigma_{\mathrm{CC}}^{\mathrm{CH}}} = 1.049 \pm 0.010(\mathrm{stat.}) \pm 0.043(\mathrm{syst.}).$$

$\bar{\nu}_\mu$ CC0π0p with limited acceptance on water and CH cross sections and their ratio at 1.5° off-axis T2K beam

1.5° off-axis neutrino beam





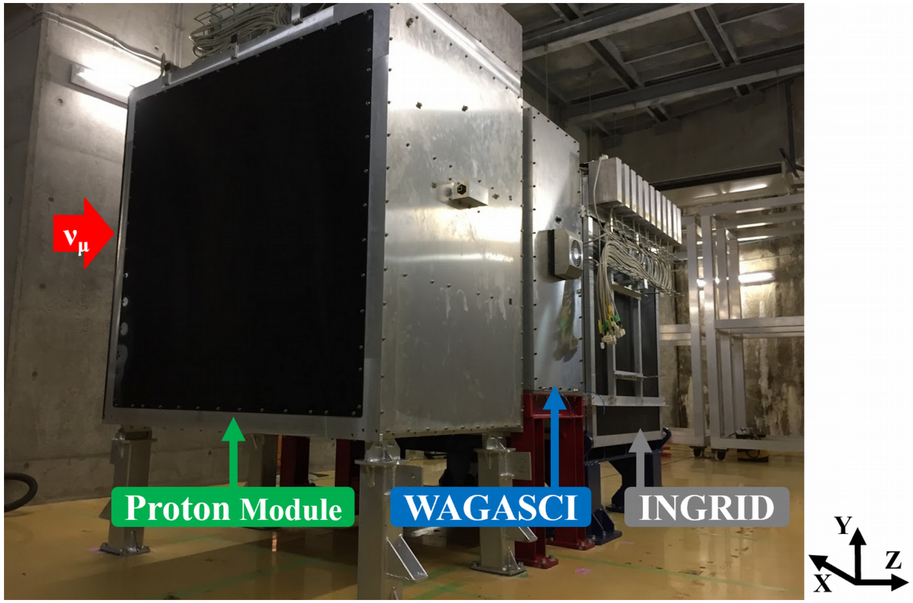
Mean energy: 0.86 GeV

7.91x10^20 POT in $\bar{\nu}$ beam mode
collected from Dec 2017 till May 2018

Detectors

Interaction vertices in:

- Proton module – CH (98%)
- Water Module/Wagasci – water(80%), CH (20%)
- INGRID used only for muon tracking



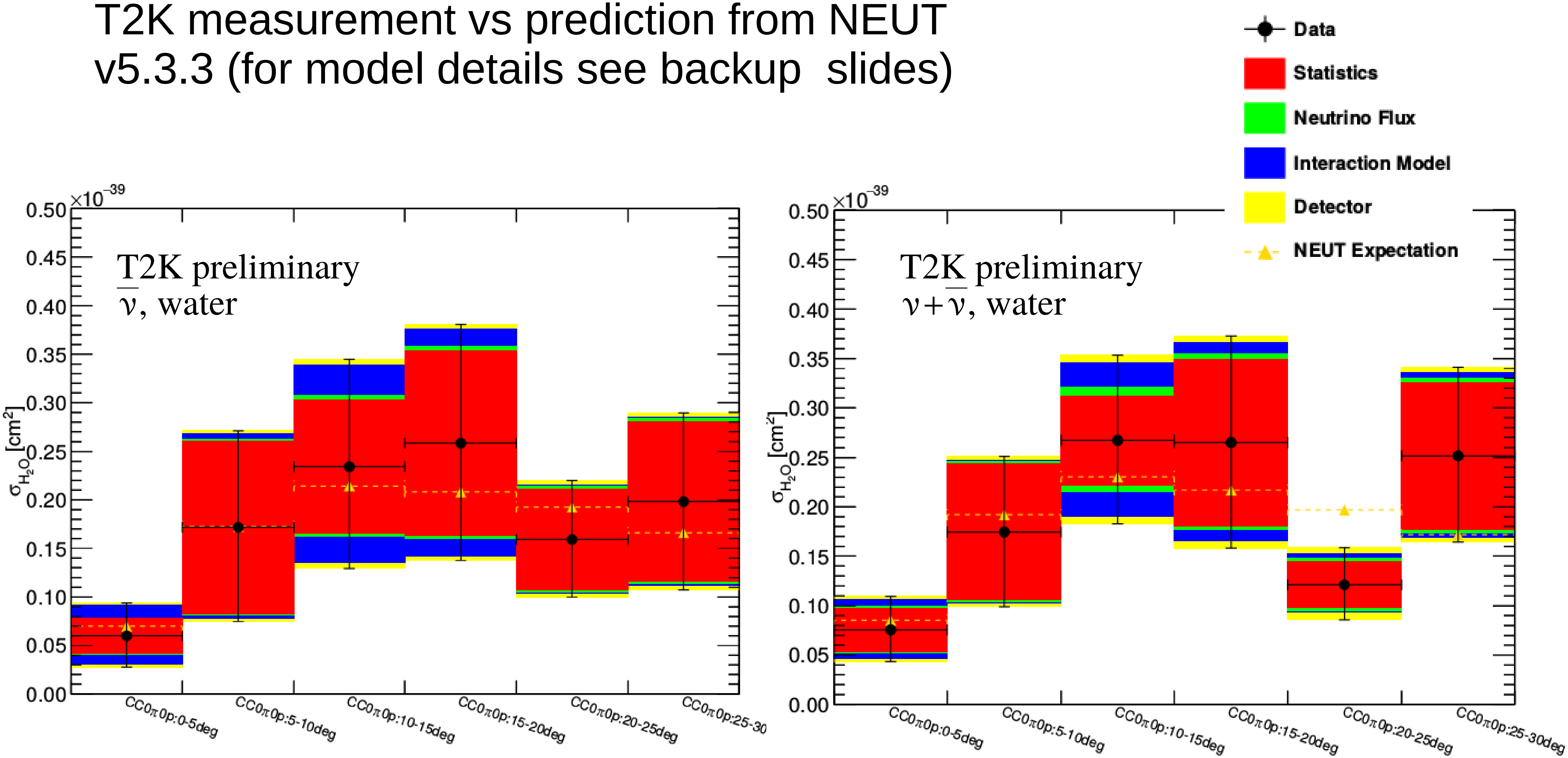
- Detector not magnetised $\Rightarrow$ no distinction between neutrinos and anti-neutrinos
- Significant ν_μ background in $\bar{\nu}_\mu$ beam mode (less pure beam, higher cross section for neutrinos)

  $\Rightarrow$ Measurement for $\bar{\nu}_\mu$, as well as for $\nu_\mu+\bar{\nu}_\mu$ (higher purity, smaller errors)

- Phase space restriction and thresholds
  - muon: $p_\mu > 400$ MeV/c, $\theta_\mu < 30°$
  - no proton: $p_p > 600$ MeV/c, $\theta_p < 70°$
  - no pion: $p_\pi > 200$ MeV/c, $\theta_\pi < 70°$

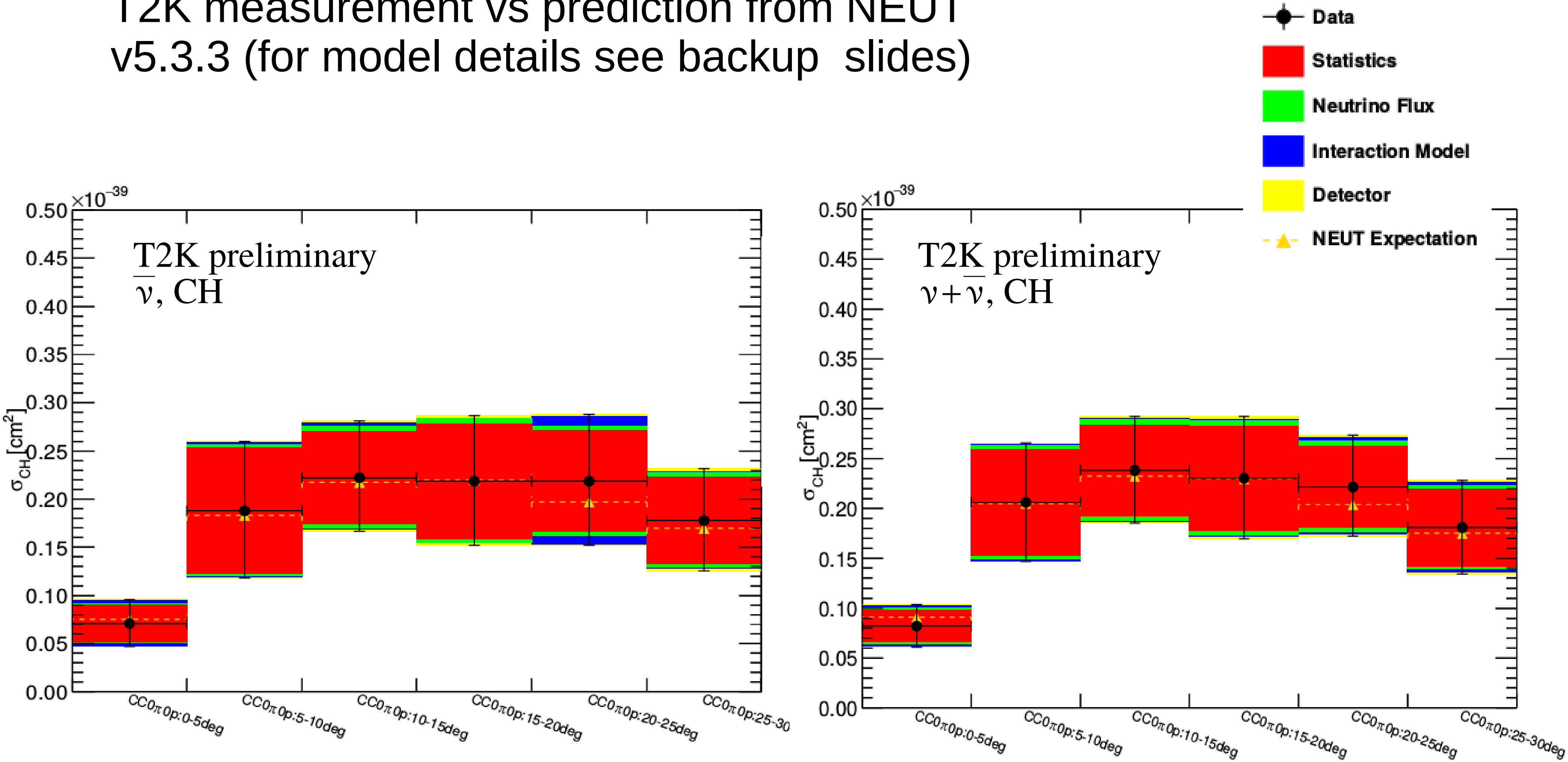
Cross sections on water

T2K measurement vs prediction from NEUT v5.3.3 (for model details see backup slides)



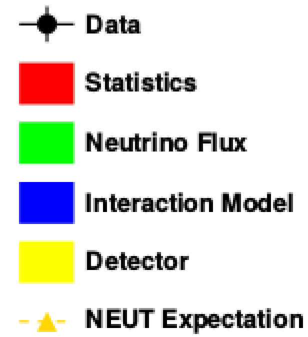
Cross sections on CH

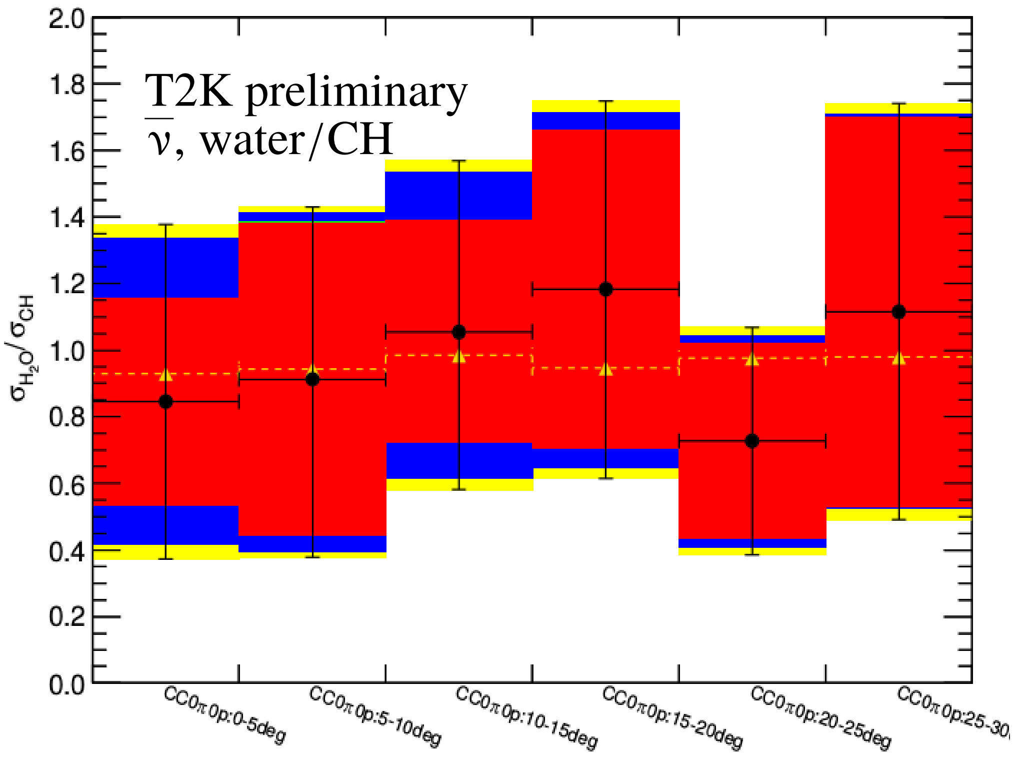
T2K measurement vs prediction from NEUT v5.3.3 (for model details see backup slides)

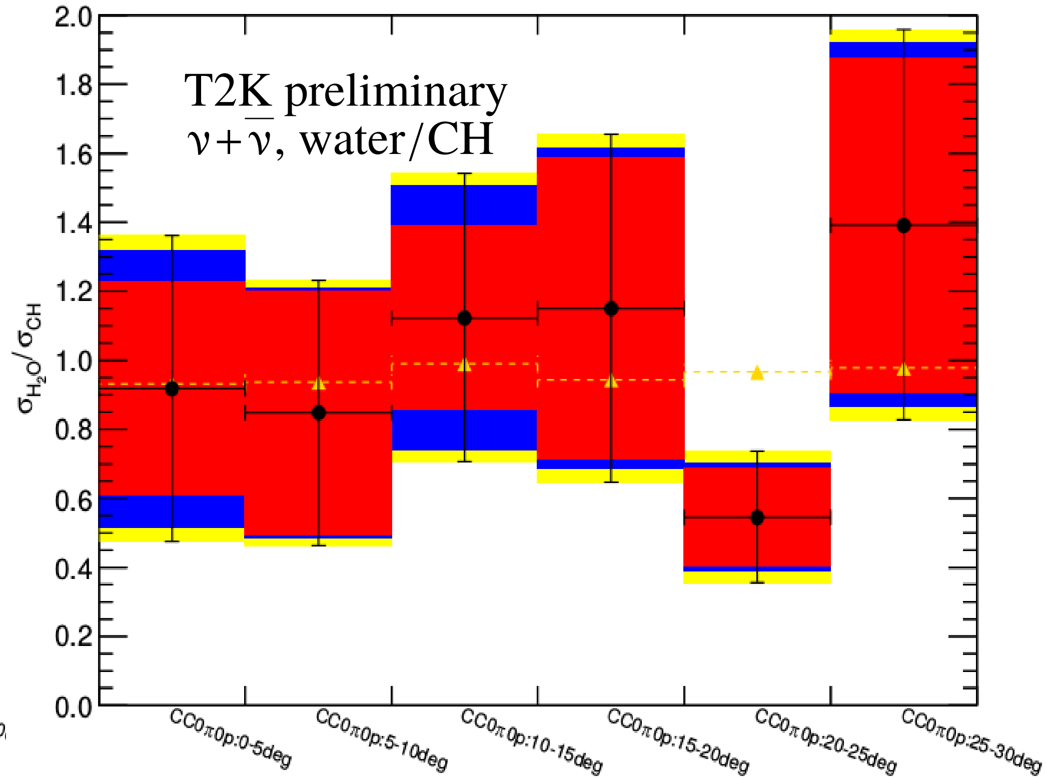


Cross-sections ratio water/CH

T2K measurement vs prediction from NEUT v5.3.3 (for model details see backup slides)







Results

- All integrated cross sections are consistent within 1σ level with NEUT v5.3.3 prediction:

$$\sigma^{\overline{\nu}_\mu}_{\mathrm{H_2O}} = \left[1.082 \pm 0.068(\mathrm{stat.})^{+0.145}_{-0.128}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \cdot \mathrm{nucleon}^{-1}$$

$$\sigma^{\overline{\nu}_\mu}_{\mathrm{CH}} = \left[1.096 \pm 0.054(\mathrm{stat.})^{+0.132}_{-0.117}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \cdot \mathrm{nucleon}^{-1}$$

$$\sigma^{\overline{\nu}_\mu}_{\mathrm{H_2O}}/\sigma^{\overline{\nu}_\mu}_{\mathrm{CH}} = 0.987 \pm 0.078(\mathrm{stat.})^{+0.093}_{-0.090}(\mathrm{syst.})$$

$$\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{H_2O}} = \left[1.155 \pm 0.064(\mathrm{stat.})^{+0.148}_{-0.129}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \cdot \mathrm{nucleon}^{-1}$$

$$\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{CH}} = \left[1.159 \pm 0.049(\mathrm{stat.})^{+0.129}_{-0.115}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \cdot \mathrm{nucleon}^{-1}$$

$$\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{H_2O}}/\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{CH}} = 0.996 \pm 0.069(\mathrm{stat.})^{+0.083}_{-0.078}(\mathrm{syst.})$$

Absolute χ^2 for $\overline{\nu}$ measurement

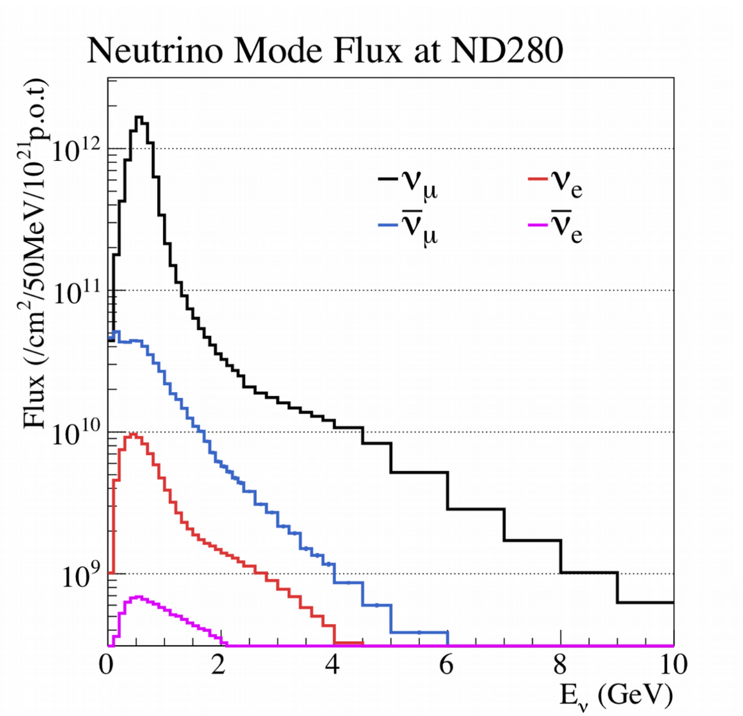
	σ_{H_2O}	σ_{CH}	$\sigma_{H_2O}/\sigma_{CH}$
NEUT	0.74	0.16	0.81
GENIE	0.72	0.54	0.89

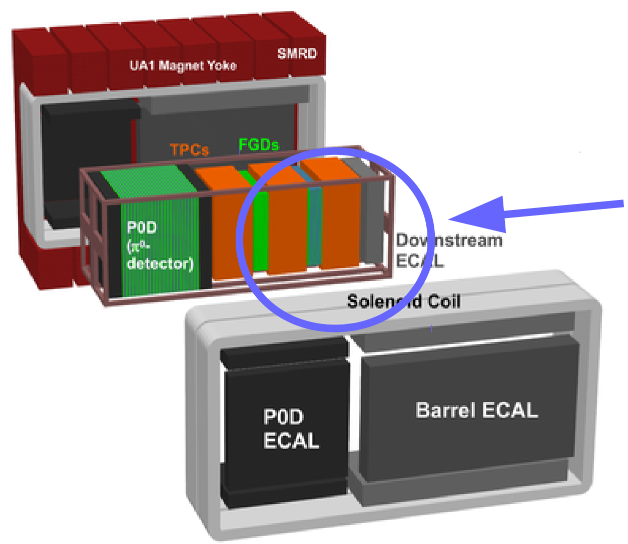
Absolute χ^2 for $\nu+\overline{\nu}$ measurement

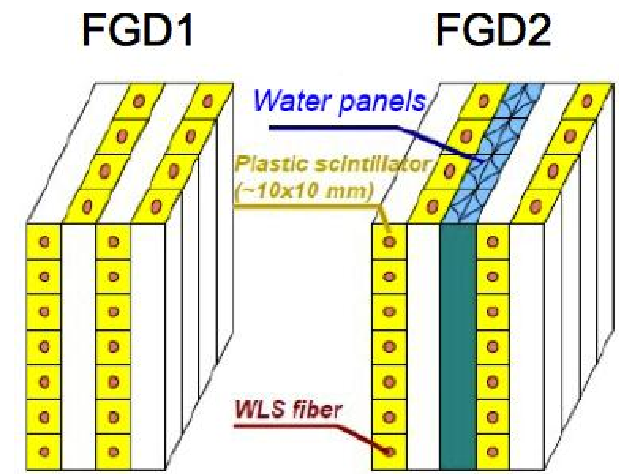
	σ_{H_2O}	σ_{CH}	$\sigma_{H_2O}/\sigma_{CH}$
NEUT	5.93	0.33	5.76
GENIE	5.98	0.57	6.35

ν_μ CC0π
double differential cross sections on oxygen and carbon and their ratio at 2.5° off-axis T2K beam

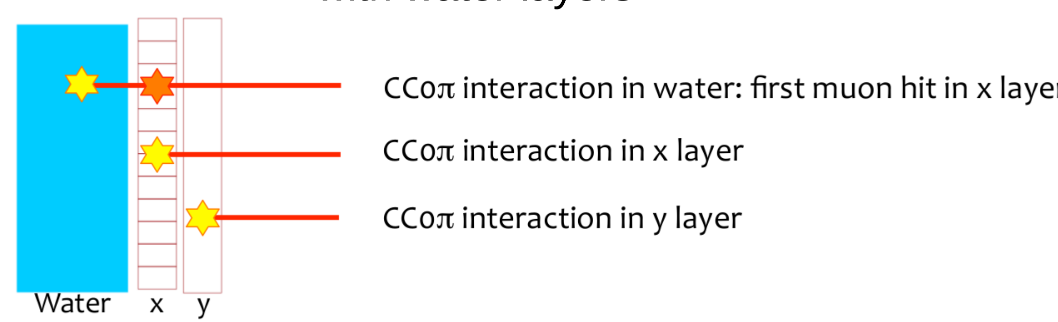
2.5° off-axis beam
FGD1 and FGD2 sub-detectors







- FGD1: plastic scintillator
- FGD2: plastic scintillator sandwiched with water layers

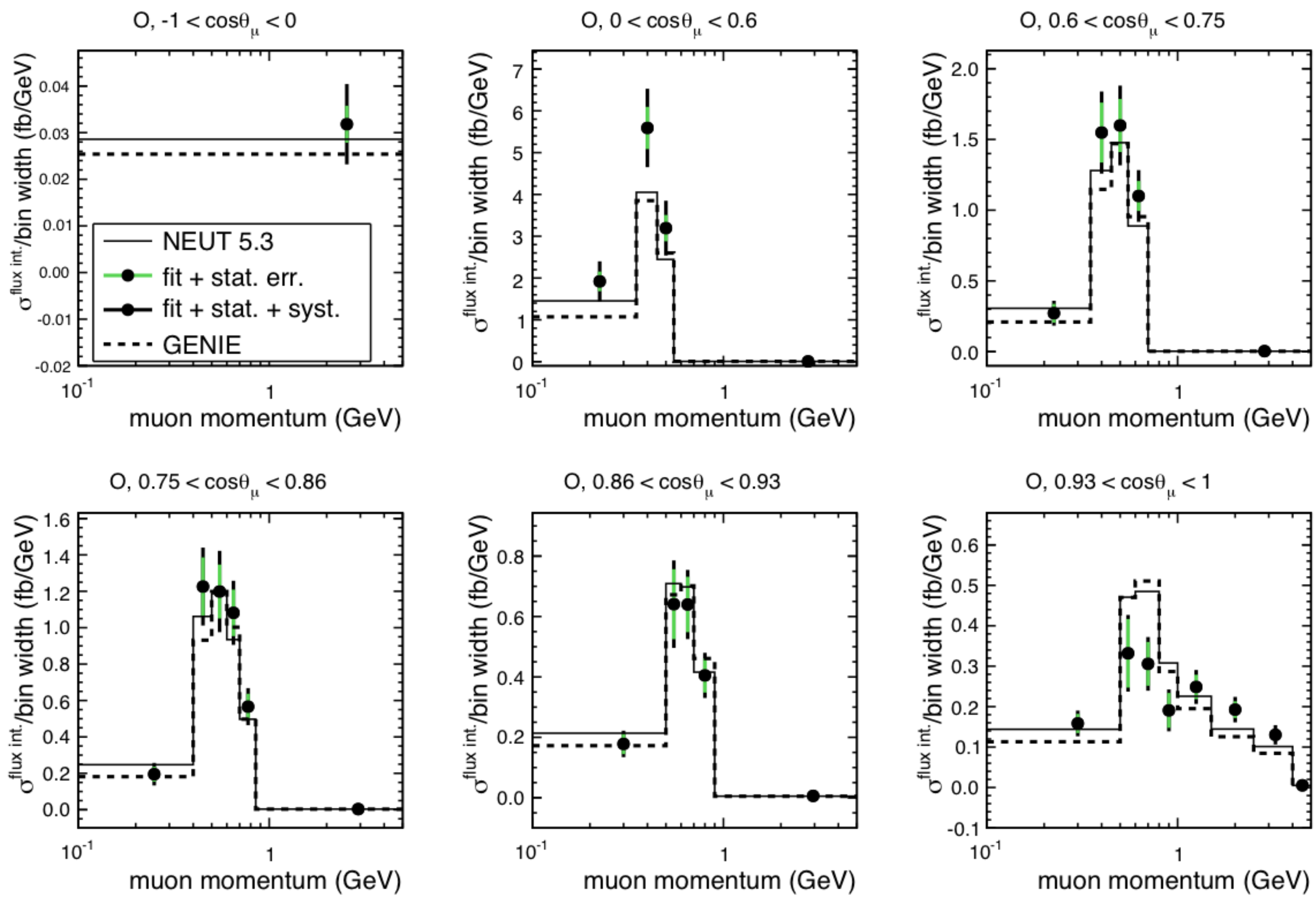


Mean energy: 0.6 GeV

5.734×10^{20} POT in ν beam mode collected from Nov 2010 till May 2013

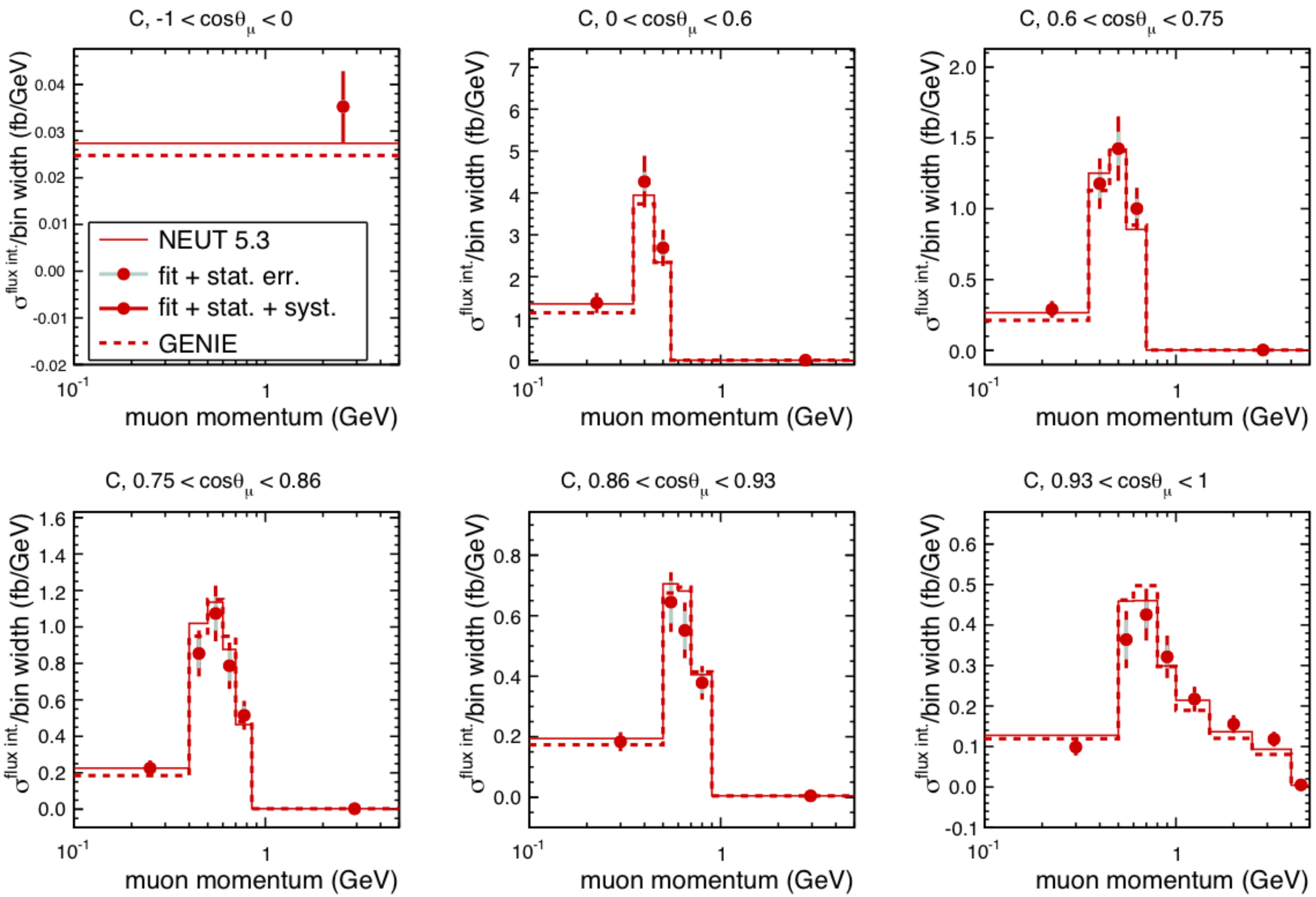
Double differential cross section on oxygen

T2K preliminary



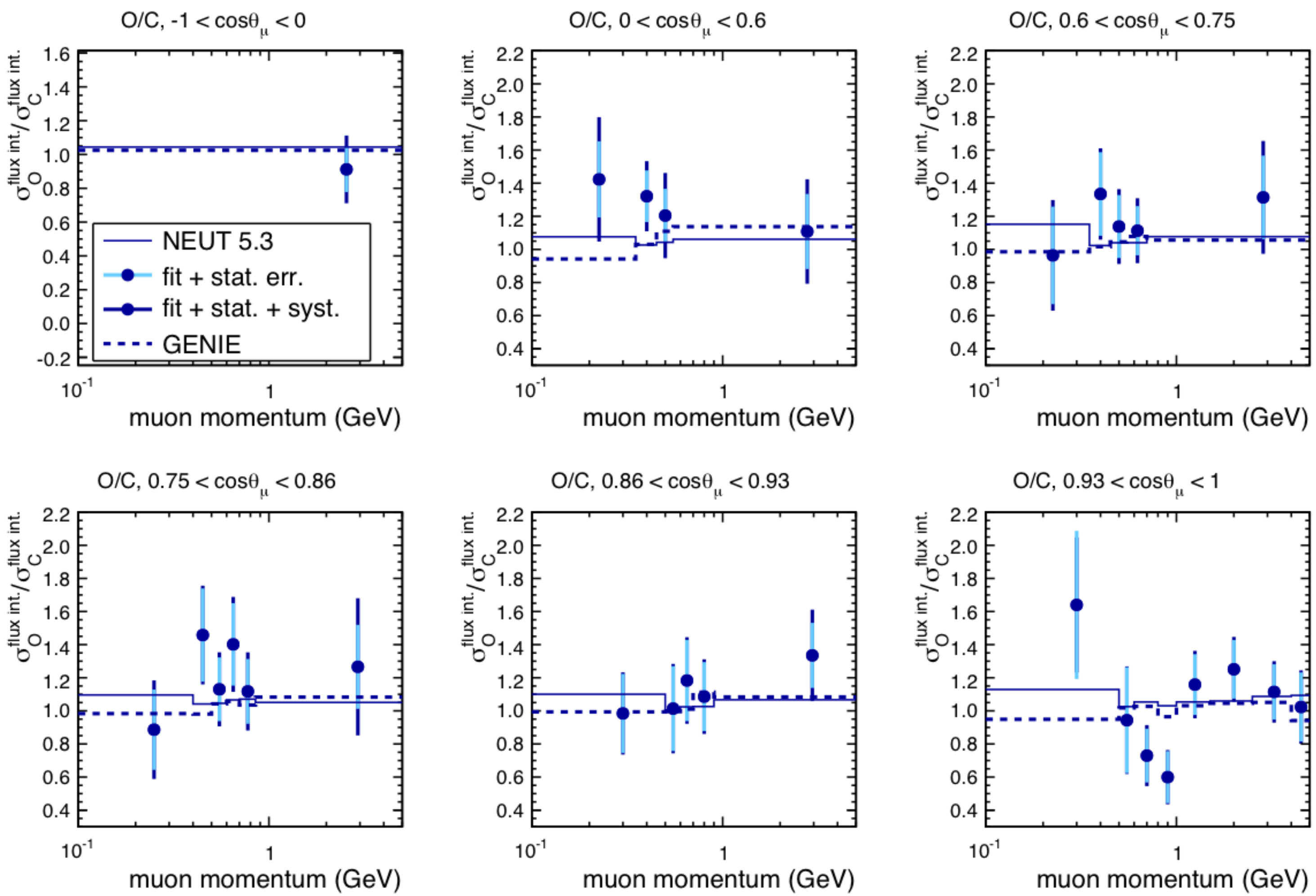
Double differential cross section on carbon

T2K preliminary



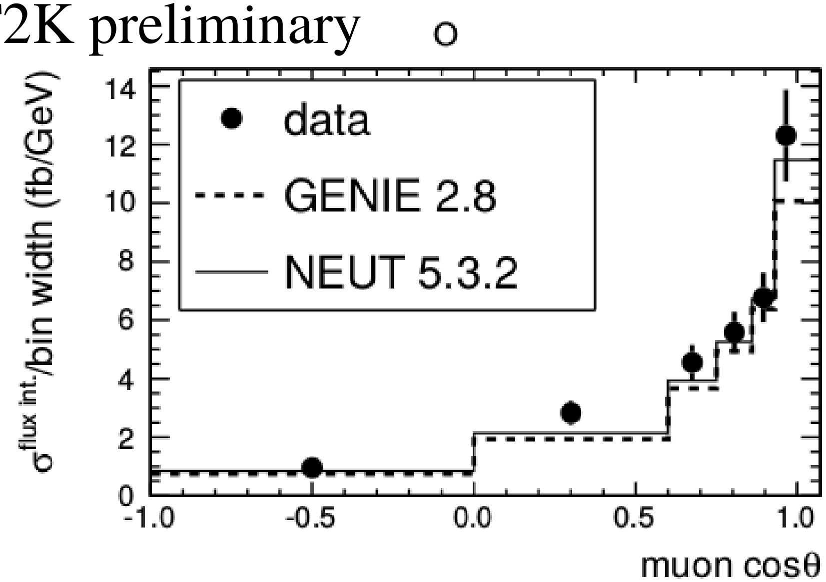
Double differential cross-section ratio O/C

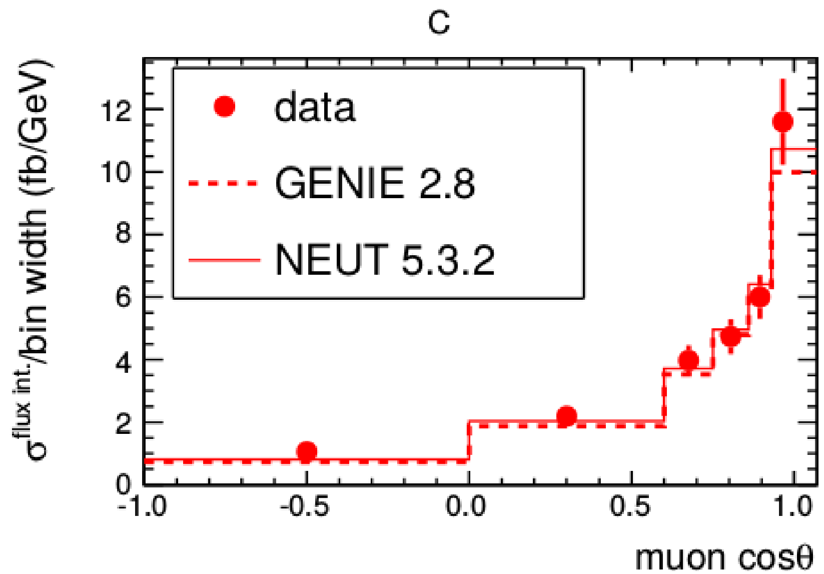
T2K preliminary

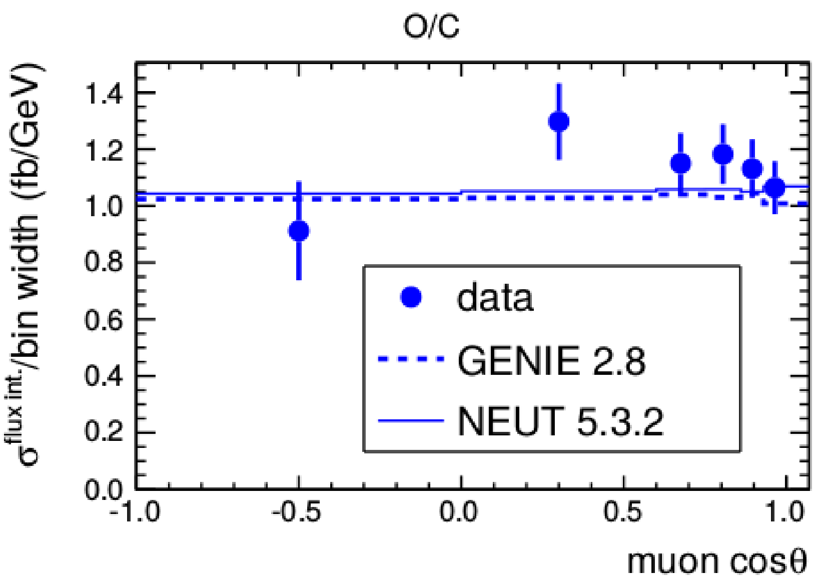


1D integrated cross sections

T2K preliminary







For the first time FGD1 and FGD2 samples treated together to extract cross section on oxygen.

Agreement within uncertainties for cross section on carbon
Some discrepancies in high-angle region for oxygen.

Comparisons with other models coming soon!

χ^2 goodness of fit

Goodness of fit for 58 bins (29 for carbon and 29 for oxygen):

- NEUT v5.3.2 (CCQE – Spectral Function, 2p2h – Nieves, MAQE=1.21) generator slightly better than GENIE v2.8
- However, both reproduce the data

Num. toys	NEUT unreg.	GENIE unreg.	NEUT reg.	GENIE reg.
1000	113.2	148.2	105.7	145.9
1000 w. pFSI syst.	101.9	136.8	93.6	134.4
1000 w. pFSI and bkw migr. (100% err.)	79.8	106.8	74.3	106.5
1000 w. pFSI and bkw migr. (30% err.)	81.4	108.0	76.3	108.2

Other T2K cross-section measurements

Previous measurements presented here:

- NOW 2018 - http://www.ba.infn.it/~now/now2018/program.html
  - M.Buizza, T2K ν-nucleus cross-section results

- NuInt 2018 - https://indico.cern.ch/event/703880/
  - C.Riccio, ν_μ and $\bar{\nu}_\mu$ CC0π cross-section measurements at T2K
  - D.Cherdack, ν_μ CC1π+ in the P0D sub-detector of ND280
  - B.Quilain, ν_μ CC1π cross section on carbon and water using T2K on-axis detectors
  - D.Fukuda, ν-oxygen NC scattering measurement in the T2K far detector

Some upcoming measurements:

- CC inclusive: $\bar{\nu}_\mu$, on Ar
- CC0π on C,C,Pb off-axis, C on/off axis
- Vertex activity for CC0π1p
- ν_μ CC1π+, CC1π0 and NC1π0 on H2O and C
- NC1γ

+ many others

Summary

- Good understanding of neutrino interaction mechanisms and reliable interaction model are essential in oscillation analysis
- T2K studies done for various channels of neutrino interactions on different material targets, neutrino energies and types
- Combine measurement of cross sections at different angles w.r.t. neutrino beam (different energy spectra on one beam)
- Ongoing works to make measurements less model-dependent, increase angular acceptance and lower particle reconstruction threshold
- Future T2K upgrade will allow us to produce even better results

Backup slides

On axis measurement of inclusive ν_μ CC cross sections on water, CH and iron

NEUT v5.3.3 - MC model details

Mode	Nominal model	Parameter
CCQE-like	Dipole type axial form factor	$M_A^{QE} = 1.15$ GeV$/c^2$.
	RFG model by Smith-Moniz [25] with binding energy (E_b) and Fermi surface momentum (p_F)	E_b= 25, 27, 33 MeV and p_F= 217, 225, 250 MeV/c for ^{12}C , ^{16}O, and ^{56}Fe, respectively.
	RPA model by Nieves *et al.* [26]	RPA is applied for ^{12}O and ^{16}C. RPA is not applied for ^{56}Fe.
	2p2h model by Nieves *et al.* [27]	Normalization
1π	Model by Rein-Sehgal [30]	$C_5^A(0) = 1.01$, $M_A^{RES} = 0.95$ GeV$/c^2$, Isospin$\frac{1}{2}$bg $= 1.30$.
DIS	PYTHIA [31], Parton distribution function by GRV98 with Bodek and Yang correction [32] [33] [34]	Energy dependent normalization
Coherent	Model by Berger-Sehgal [35]	Normalization

1.5° off-axis measurement of ν_μ CC0π0p on water and CH

NEUT v5.3.3 - MC model details

	NEUT 5.3.3 with NIWG2014 tuning
CCQE	RFG Llewellyn-Smith with rel. RPA BBBA05 $M_A^{QE} = 1.15$ GeV/c^2
2p2h	Nieves *et al.*
FSI	Intra-nuclear cascade