T2K experiment neutrino cross section results

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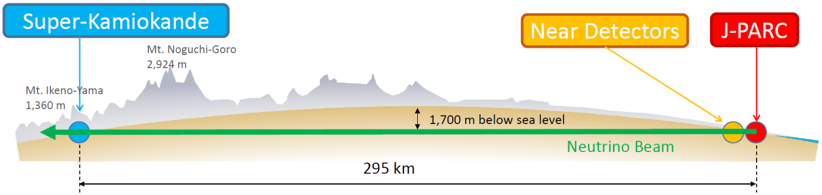
Outline

1. The T2K Experiment
2. Motivation
3. T2K cross-section results
   - on-axis
   - 1.5° off-axis
   - 2.5° off-axis
4. Summary

T2K overview

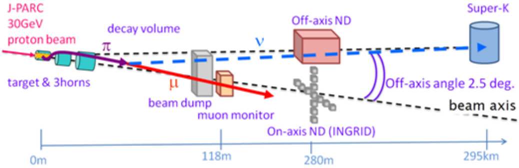


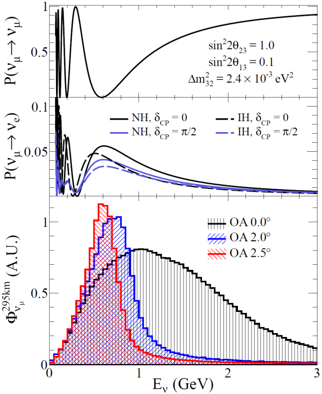
- ~500 people from 12 countries, 66 institutes
- high intensity beam produced at J-PARC with ν_μ and $\bar{\nu}_\mu$ mode
- off-axis technique to get narrower energy spectrum

main goals:

- estimate δ_{CP} through ν_e appearance
- measure θ_{23}, $|\Delta m^2_{32}|$, through ν_μ disappearance

Off-axis beam properties

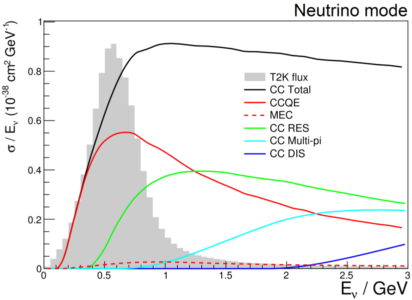


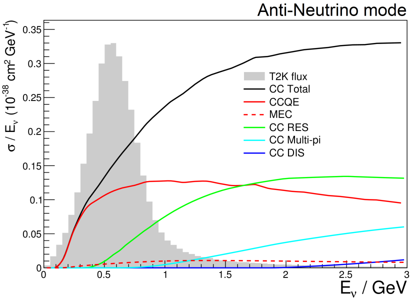


- narrowed energy spectrum peaks at 0.6 GeV
- ν_μ flux peaked at maximum disappearance and appearance
- off-axis technique used in the experiment for the first time

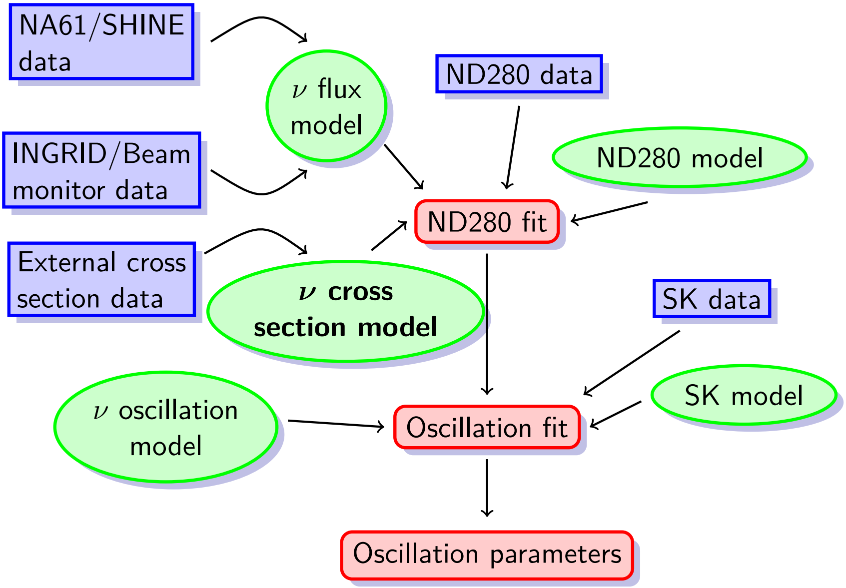
Motivation

- Difference between near and far detector
  - angular acceptance
  - target
  - flux
- requirement of proper interaction model to decrease the systematic errors in OA
- demand of different cross section measurements on different targets and for all $\overset{(-)}{\nu}$ flavours





Oscillation analysis prescription



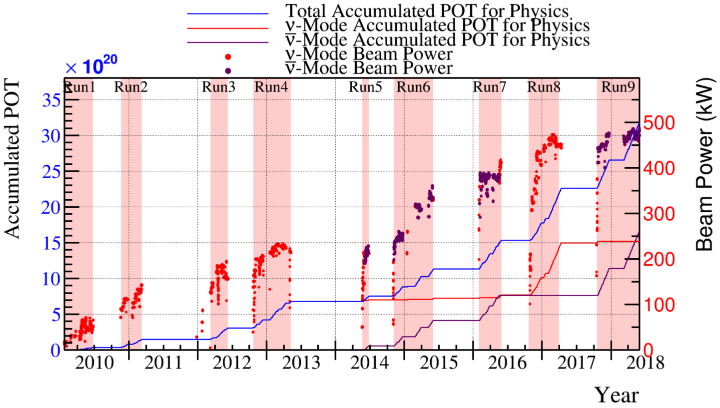
Near detector fit

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interaction	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

- Errors on SK reduced from:
  $\sim 15\%$ to $\sim 5\%$

Phys. Rev. Lett. 121, 171802, 2018
arXiv:1807.07891

T2K Data-Taking status



23 Jan. 2010 – 31 May 2018

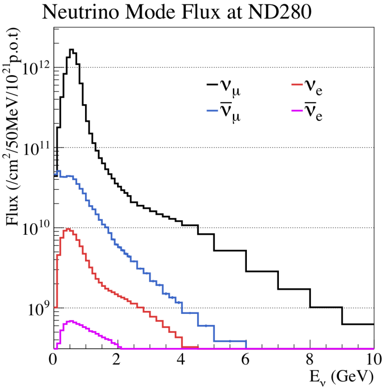
POT total: 3.16 x 10^{21}

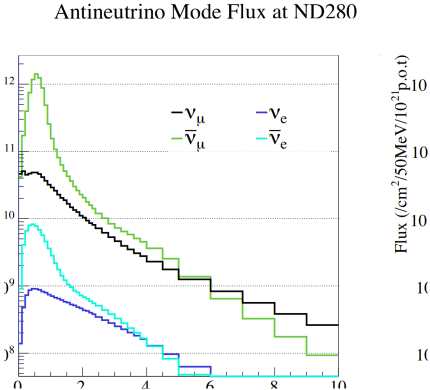
ν-mode 1.51 x 10^{21} (47.83%)

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

- 3.16×10^{21} Protons On Target (POT)

2.5° off-axis properties



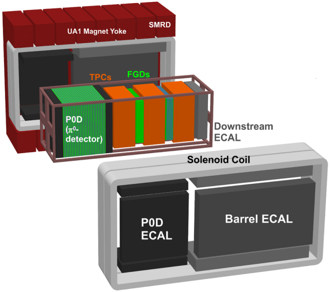


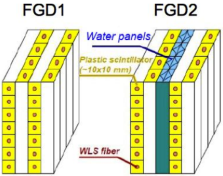
- peak energy at 0.6 GeV
- wrong-sign component greater in anti-neutrino mode

ND280

Off-axis beam detector:

- sub-detectors in $0.2T$ field:
  - P0D - π^0,
  - TPC - PID, track particles,
  - FGD - target, vertex info.,
  - ECAL - PID for particles exiting ND280 (γ's, π^0's)
- measure $\overset{(-)}{\nu}$ event spectrum before oscillation occurs
- $\overset{(-)}{\nu}$ cross-section measurements
- measure $\overset{(-)}{\nu}_e$ contamination in the beam



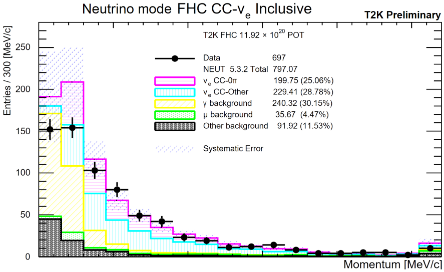


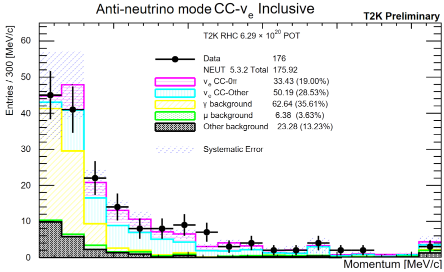
Nucl. Instrum. Meth. A 659, 106 (2011)
arXiv:1106.1238

ν_eCC and $\bar{\nu}_e$CC inclusive cross-sections on plastic

Motivation - measurement of intrinsic ν_e and $\bar{\nu}_e$

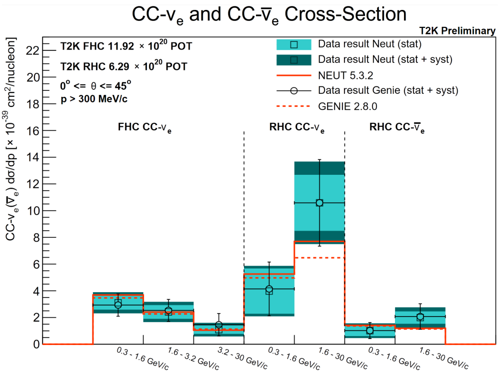
- Challenging - small sample
- background contamination in low momentum region
- discrepancy between data and MC
- $0^\circ \leq \theta_\mu \leq 45^\circ$
- $p_\mu > 0.3$ MeV/c





ν_eCC and $\bar{\nu}_e$CC inclusive cross-sections on plastic

- limited phase-space
- three channels & γ sidebands fitted simultaneously
- agrees with NEUT and Genie MC
- first $\bar{\nu}_e$CC result since Gargamelle measurement (1979)

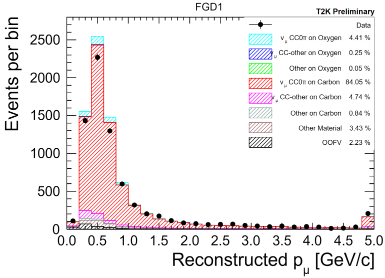


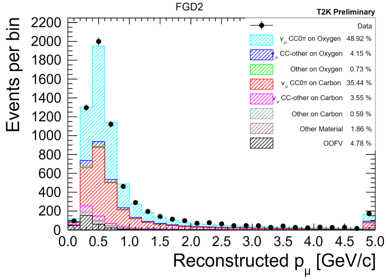
ν_μCC0π flux integrated cross-section (O, C O/C)

Motivation: important for proper ν energy reconstruction

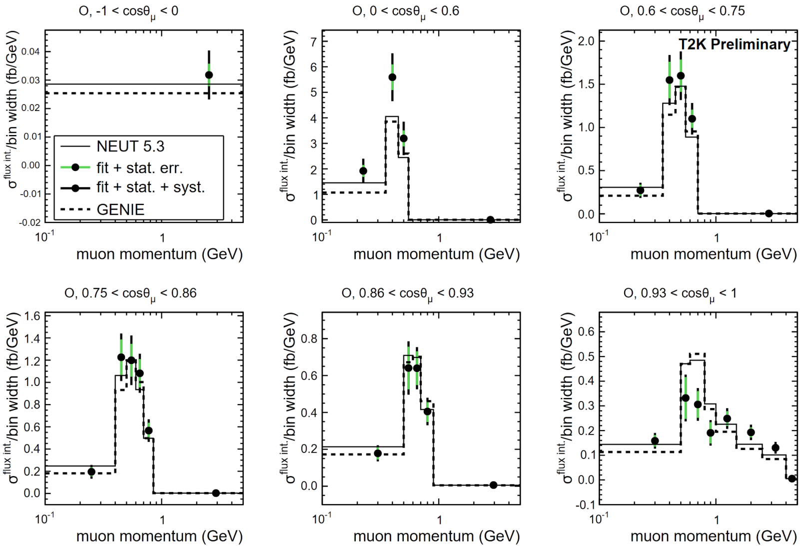
Selection:

- five samples & two sidebands
- vertices in FGD1 / FGD2
- different targets (C, O)
- data/MC disagreement

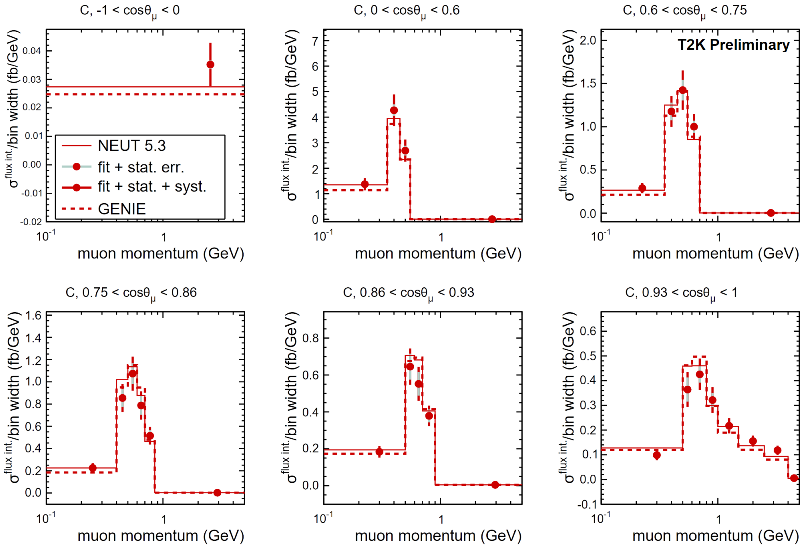




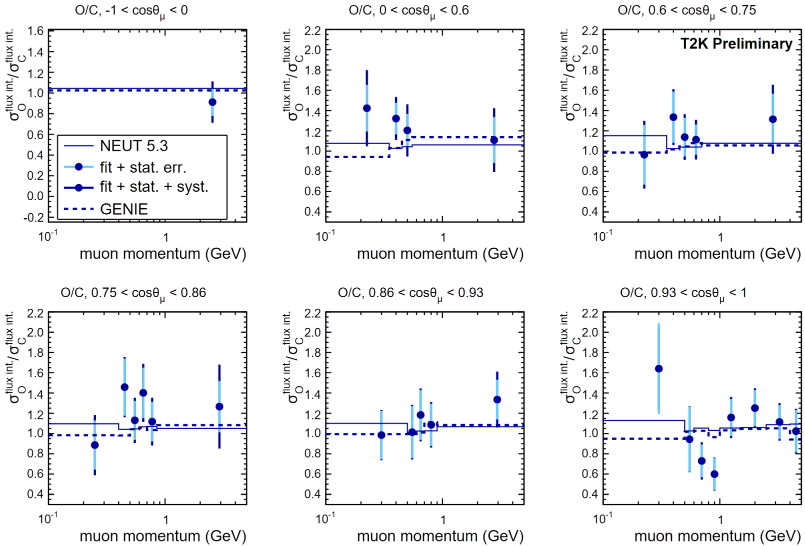
Double differential cross section on Oxygen



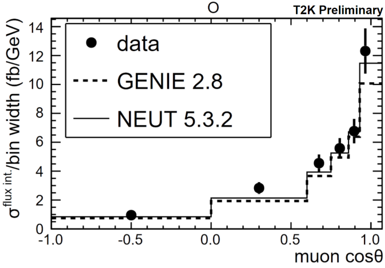
Double differential cross section on Carbon

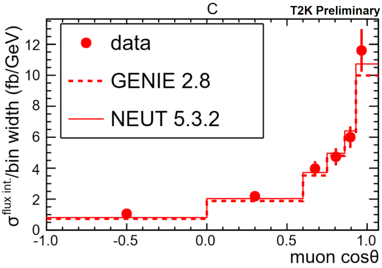


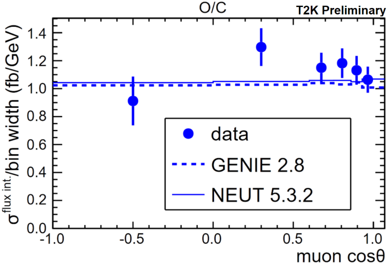
Double differential cross section ratio



1D integrated cross sections

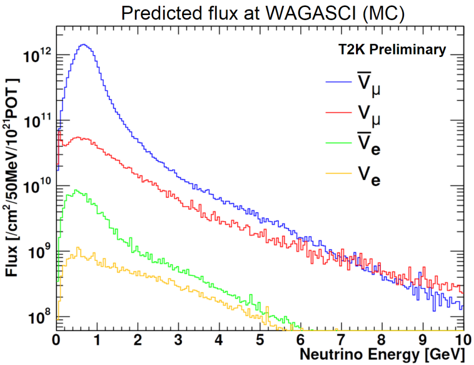






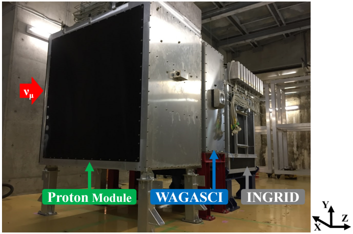
- First FGD1 & FGD2 joint measurement
- reduction of correlated systematics errors
- simultaneous fit to all samples

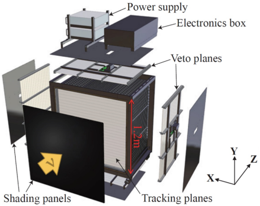
1.5° off-axis properties



- peak energy at 0.66 GeV
- mean energy 0.86 GeV

PM, WAGASCI, INGRID





Phys. Rev. D 90, 052010, 2014

- Detectors are not magnetized!
- INGRID used for μ tracking

Proton Module:

- fully active tracking
- 1088 scinitlllator bars
- 98% CH

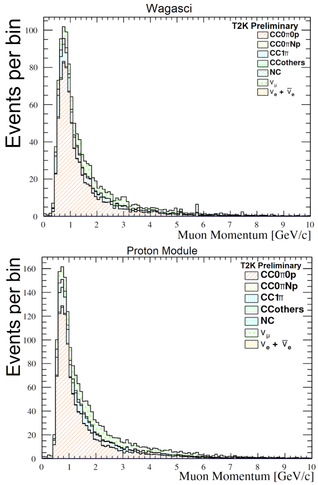
WAGASCI:

- 0.6 tons of water (80%)
- 1280 plastic scintillator bars
- 3D-grid like structure

$CC0\pi0p^+$ cross section (H_2O & CH)

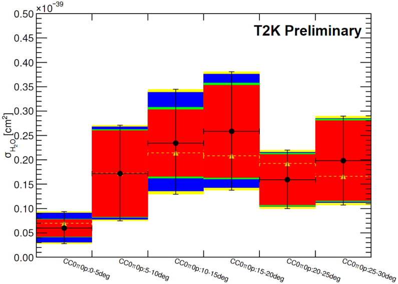
Motivation: increase the number of water target cross sections measurements

- Vertex in WAGASCI or PM
- $\theta_\mu > 30°$ & $p_\mu > 0.4$ GeV/c
- Detectable phase-spaces for π's and p^+'s:
- $\theta_\pi < 70°$ & $p_\pi > 0.2$ GeV/c
- $\theta_p < 70°$ & $p_p > 0.6$ GeV/c
- measure $\bar{\nu}_\mu$ and $(\bar{\nu}_\mu + \nu_\mu)$

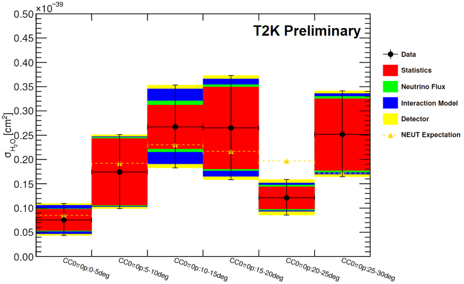


$CC0\pi 0p^+$ cross section on water

$\bar{\nu}_\mu$

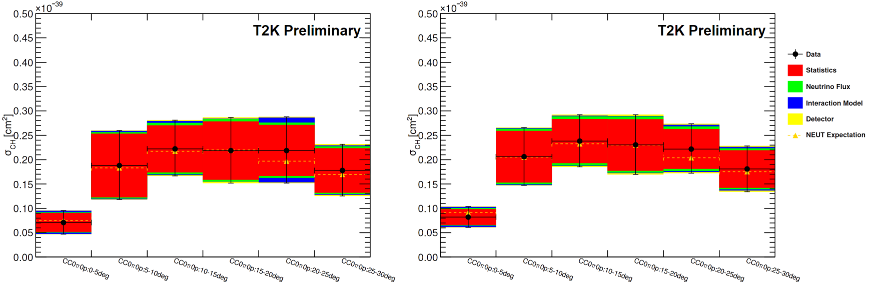


$(\bar{\nu}_\mu + \nu_\mu)$



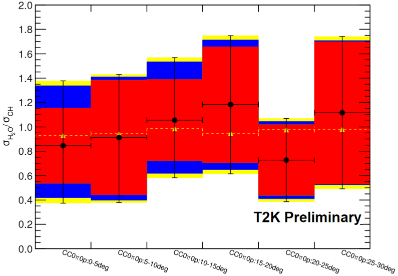
CC0π0p^+ cross section on plastic

$\bar{\nu}_\mu$ $\qquad$ $(\bar{\nu}_\mu + \nu_\mu)$

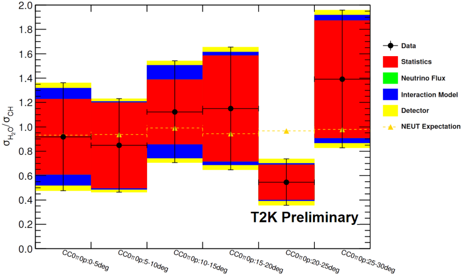


CC0π0p^{+} cross section ratio

$\bar{\nu}_\mu$



$(\bar{\nu}_\mu + \nu_\mu)$

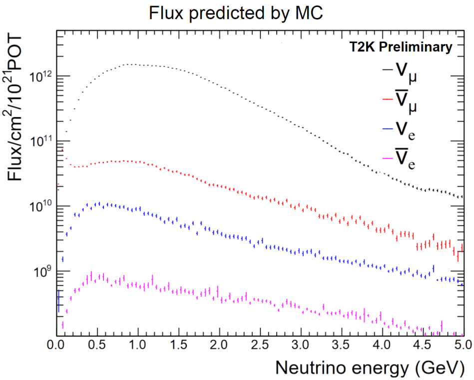


$CC0\pi0p^+$ cross section (H_2O & CH)

	$\sigma \times 10^{-39}$ cm^2/nucleon	stat. error	syst. error
$\sigma^{\bar{\nu}_\mu}_{H_2O}$	1.082	± 0.068	$^{+0.145}_{-0.128}$
$\sigma^{\bar{\nu}_\mu}_{CH}$	1.096	± 0.054	$^{+0.132}_{-0.117}$
$\sigma^{\bar{\nu}_\mu}_{H_2O} / \sigma^{\bar{\nu}_\mu}_{CH}$	0.987	± 0.078	$^{+0.093}_{-0.090}$
$\sigma^{\bar{\nu}_\mu+\nu_\mu}_{H_2O}$	1.155	± 0.064	$^{+0.148}_{-0.129}$
$\sigma^{\bar{\nu}_\mu+\nu_\mu}_{CH}$	1.159	± 0.049	$^{+0.129}_{-0.115}$
$\sigma^{\bar{\nu}_\mu+\nu_\mu}_{H_2O} / \sigma^{\bar{\nu}_\mu+\nu_\mu}_{CH}$	0.996	± 0.069	$^{+0.083}_{-0.078}$

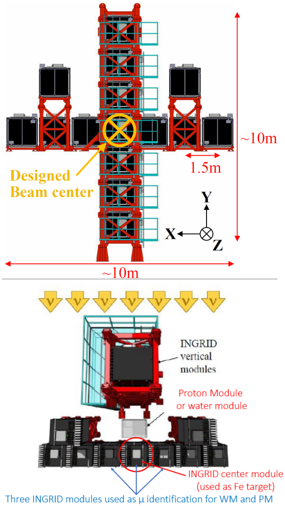
T2K Preliminary

On-axis properties



- peak energy at 0.66 GeV
- mean energy 1.5 GeV

INGRID, PM & WM



JPS Conf. Proc.8, 023003, 2015

INGRID:

- 16 modules (iron/scintillator sandwich)
- additional module with scintillators only
- 96% Fe
- monitor beam rate, direction and stability

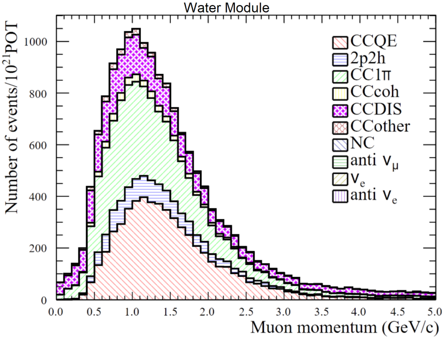
Water Module:

- 0.10 tons
- 80% water
- 20% CH

Inclusive $\nu_\mu CC$ H_2O, Fe, CH & ratios

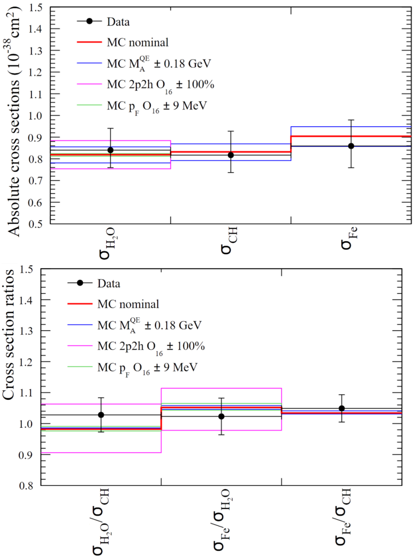
Motivation: test of an interaction model at various targets material and energies

- $\theta_\mu < 45^\circ$
- $p_\nu > 0.4$ GeV/c
- main background from ν interaction on scintillators



Inclusive $\nu_\mu CC$ H_2O, Fe, CH & ratios

- Most precise for such energy region
- first measurement of ratios H_2O/CH & H_2O/Fe
- agrees with model used by T2K



arXiv:1904.09611

Inclusive $\nu_\mu CC$ H_2O, Fe, CH & ratios

	$\sigma \times 10^{-38}$ cm^2/nucleon	stat. error	syst. error
$\sigma_{CC}^{H_2O}$	0.840	± 0.010	$^{+0.10}_{-0.08}$
σ_{CC}^{CH}	0.817	± 0.007	$^{+0.11}_{-0.08}$
σ_{CC}^{Fe}	0.859	± 0.003	$^{+0.12}_{-0.10}$
$\sigma_{CC}^{H_2O}/\sigma_{CC}^{CH}$	1.028	± 0.016	± 0.053
$\sigma_{CC}^{Fe}/\sigma_{CC}^{H_2O}$	1.023	± 0.012	± 0.058
$\sigma_{CC}^{Fe}/\sigma_{CC}^{CH}$	1.049	± 0.010	± 0.043

arXiv:1904.09611

Previous T2K cross sections measurements

- Measurement of the ν_μ charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam
  Phys.Rev. D91, 112002, 2015
- Measurement of double-differential muon neutrino charged-current interactions on C_8H_8 without pions in the final state using the T2K off-axis beam
  Phys. Rev. D 93, 112012, 2016
- Measurement of $\bar{\nu}_\mu$ and ν_μ charged current inclusive cross sections and their ratio with the T2K off-axis near detector
  Phys. Rev. D 96, 052001, 2017
- Measurement of inclusive double-differential ν_μ charged-current cross section with improved acceptance in the T2K off-axis near detector
  Phys. Rev. D 98, 012004, 2018
- Characterization of nuclear effects in muon-neutrino scattering on hydrocarbon with a measurement of final-state kinematics and correlations in charged-current pionless interactions at T2K
  Phys. Rev. D 98, 032003, 2018
- First measurement of the ν_μ charged-current cross section on a water target without pions in the final state
  Phys. Rev. D 97, 012001, 2018
- + many to come...

Summary

- Good understanding of neutrino interaction mechanisms and reliable interaction model are essential in oscillation analysis
- Rich and unique neutrino cross section program
- Combine measurement of cross sections at different angles w.r.t. neutrino beam
- Ongoing works to make measurements less model-dependent, increase angular acceptance and lower particle reconstruction threshold
- Vital to reduce systematic uncertainties for the neutrino oscillation measurements and CP-violation searches

Thank You!

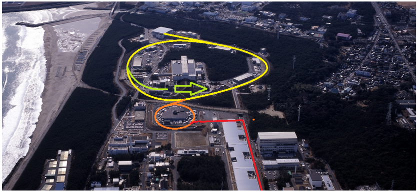
WM, PM, INGRID details

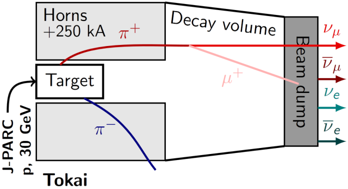
Parameter	Water Module	Proton Module	INGRID module
Target mass in fiducial volume (ton)	0.10	0.16	2.1
Main target materials and fraction	H_2O (80%), CH (19%)	CH (98%)	Fe (96%)
Dimension of a scintillator (cm^3)	100×2.5×0.3	120×2.5×1.3 (SciBar-type), 120×5×1 (INGRID-type)	120×5×1
Dimension of an iron plane (cm^3)	-	-	124×124×6.5
The number of readout channels	1280	1204	616
MPPC serial number	S13660	S10362-13-050C	S10362-13-050C
MPPC gain stability	10%	10%	10%
MPPC dark noise rate (hits/module/bunch)	0.2	12	6
Mean scintillator light yield for MIP (p.e. per scintillator thickness)	16	56 (SciBar-type), 23 (INGRID-type)	23
Angular acceptance respect to beam axis	$0°$ to $90°$	$0°$ to $75°$	$0°$ to $60°$
Period located at on-axis position	July 2016-	November 2010-May 2016	2009-

Inclusive $\nu_\mu CC$ NEUT MC 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 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.*	RPA is applied for ^{12}O and ^{16}C. RPA is not applied for ^{56}Fe.
	2p2h model by Nieves *et al.*	Normalization
1π	Model by Rein-Sehgal	$C_5^A(0) = 1.01$, $M_A^{RES} = 0.95$ GeV/c^2, Isospin$\frac{1}{2}$bg $= 1.30$.
DIS	PYTHIA [31], Parton distribution function by GRV98 with Bodek and Yang correction	Energy dependent normalization
Coherent	Model by Berger-Sehgal	Normalization

Beam production





- 30 *GeV* proton beam delivered by Linac→RCS→MR
- High intensity p^+ beam hits the carbon target,
- magnetic horns focusing outgoing hadrons,
- $\pi^\pm$ decays to $\mu^\pm$ and $\overset{(-)}{\nu}_\mu$ in 100m long decay volume,
- beam dump stops almost all μ particles,
- number of $\overset{(-)}{\nu}$'s is proportional to number of p^+
  ($\nearrow$ beam power $\sim$ $\nearrow$ $\overset{(-)}{\nu}$ flux)