Recent results from T2K and future plans

ICPPA 2016

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on behalf of the T2K collaboration

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Introduction

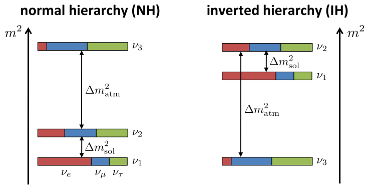
Open questions in neutrino physics

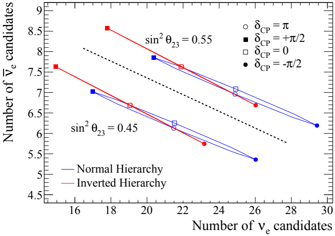
Discovery of neutrino oscillations in 1998
$\Rightarrow$ neutrinos are massive.

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij},$

$\Delta m^2_{ij} = m^2_i - m^2_j$





Questions:

- What is the neutrino mass hierarchy?
  $\Delta m^2_{31} \gtrless 0$?
- Is θ_{23} mixing angle maximal?
  $\theta_{23} = 45°, \gtrless 45°$? (octant)
  hint for flavour symmetries?
- What are the precise values of mixing angles θ_{ij}?
  is PMNS matrix (U) unitary?
- CP violation in leptonic sector?
  $\delta \neq 0, \pi$?
  hint for leptogenesis?

Measurements at a muon neutrino beam

Muon neutrino disappearance

$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\widehat{\Delta}_{31}$

$\Rightarrow$ sensitive to θ_{23} and Δm^2_{31} ($\widehat{\Delta}_{31} = \frac{\Delta m^2_{31} L}{4E}$)

Electron neutrino appearance (first order in $\alpha = |\Delta m^2_{21}/\Delta m^2_{31}|$)

$$\begin{aligned} P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} & \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\widehat{\Delta}_{31}]}{(1-x)^2} \\ - \alpha\sin\delta & \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\widehat{\Delta}_{31}\frac{\sin x\widehat{\Delta}_{31}}{x}\frac{\sin[(1-x)\widehat{\Delta}_{31}]}{1-x} \\ + \alpha\cos\delta & \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\widehat{\Delta}_{31}\frac{\sin x\widehat{\Delta}_{31}}{x}\frac{\sin[(1-x)\widehat{\Delta}_{31}]}{1-x} \end{aligned}$$

for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$, just replace δ by $-\delta$ and x by $-x$

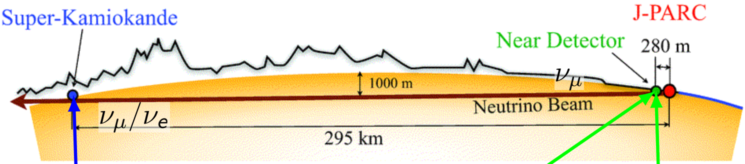
- Dependence on θ_{13} in leading term and θ_{23} octant ($\lessgtr 45°$)
- CP-violating phase $\delta \Rightarrow P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$
- Matter effect through $x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$: sensitivity to mass hierarchy ($x \lessgtr 0$)

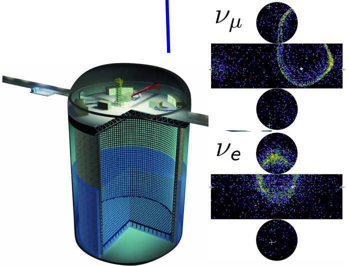
T2K experiment

T2K experiment

Off-axis beam (2.5°)
Neutrino flux peaks at 0.6 GeV
Less than 1% ν_e under the peak

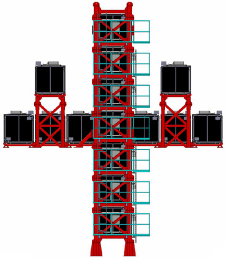
Two production modes:
- Neutrino mode
- Antineutrino mode

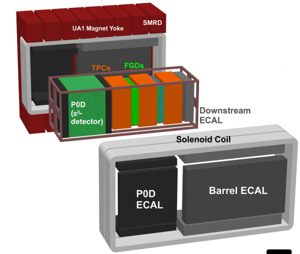




Super-Kamiokande (SK)
50 kt water (22.5 kt fiducial)

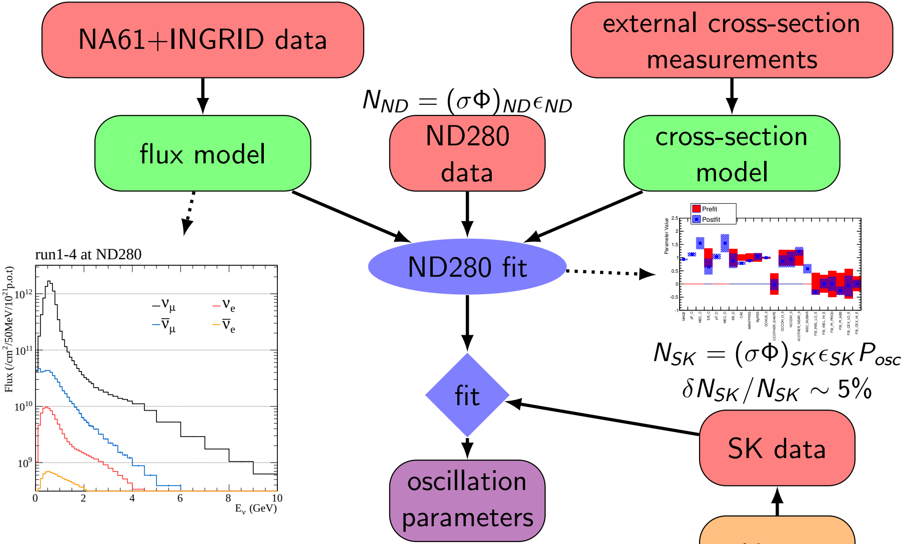
INGRID





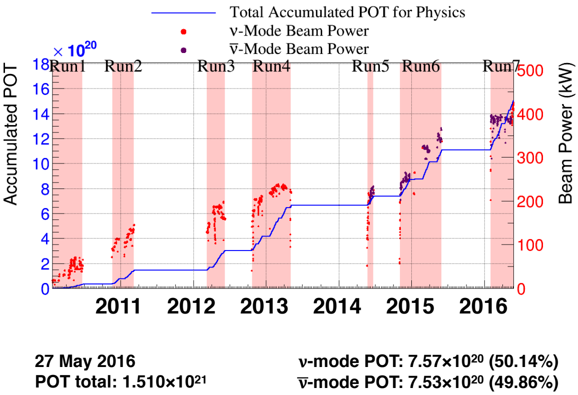
ND280

T2K analysis method



$(\theta_{13}, \theta_{23}, \Delta m^2_{31/32}, \delta_{CP})$ fitted,
$(\theta_{12}, \Delta m^2_{21})$ fixed from other exp.

T2K data so far



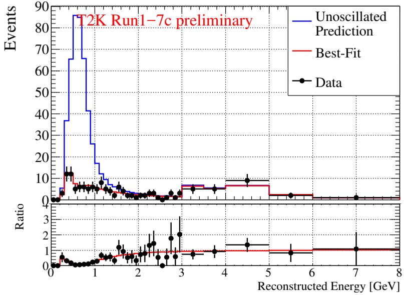
- Results with full "good-quality" data up to May 27
  - ν-mode: 7.48×10^{20} POT[1]
  - $\overline{\nu}$-mode: 7.47×10^{20} POT

[1] protons on target

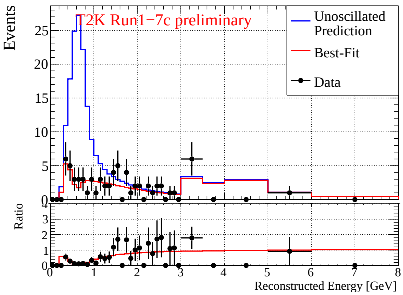
Results

$\nu_\mu - \overline{\nu}_\mu$ disappearance

Neutrino mode



Anti-neutrino mode

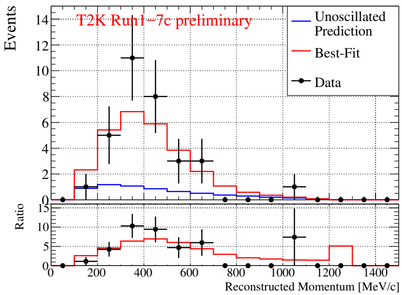


Beam mode	Sample	Exp. Not Osc	Exp. $\delta_{CP} = 0$ (NH)	Observed
neutrino	μ-like	521.8	135.5	135
antineutrino	μ-like	184.8	64.1	66

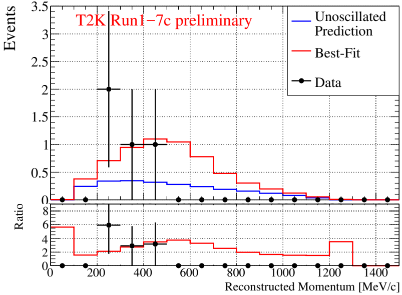
2015 paper: [arXiv: 1502.01550], 10.1103/PhysRevD.91.072010

$\nu_e - \overline{\nu}_e$ appearance

Neutrino mode



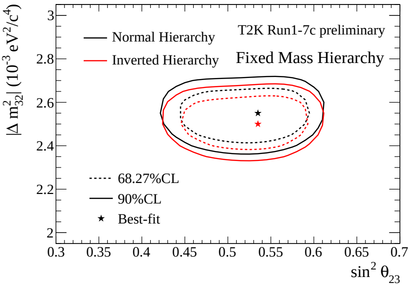
Anti-neutrino mode

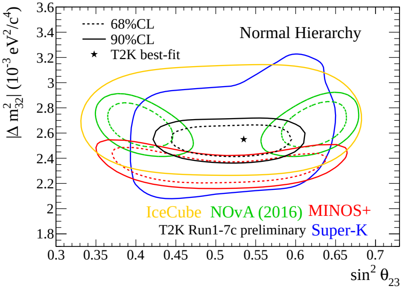


Beam mode	Sample	Exp. Not Osc	Exp. $\delta_{CP} = 0$ (NH)	Observed
neutrino	*e*-like	6.1	24.2	32
antineutrino	*e*-like	2.3	6.9	4

2015 paper: [arXiv: 1512.02495], 10.1103/PhysRevLett.116.181801

θ_{23} and Δm^2_{32}

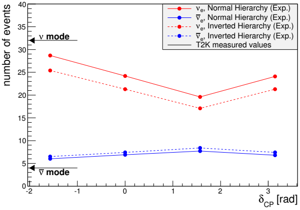




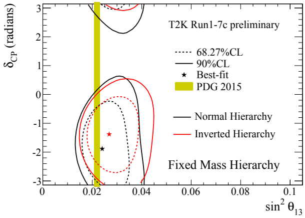
	Normal Hierarchy		Inverted Hierarchy	
Parameter	Best fit	$\pm 1\sigma$	Best fit	$\pm 1\sigma$
$\sin^2\theta_{23}$	0.532	[0.464; 0.578]	0.534	[0.468; 0.577]
$\Delta m^2_{32}(10^{-3}eV^2)$	2.545	[2.461; 2.626]	2.510	[2.427; 2.591]

θ_{13} and δ_{CP}

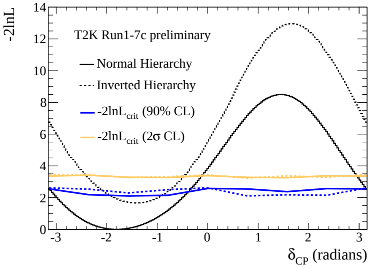
δ_{CP} effect[1]



T2K fit



T2K + reactor constraint



- θ_{13} in agreement with reactor exp.
- T2K begins to probe δ_{CP}
- T2K disfavors $\{\delta_{CP} = 0\}$ at 2σ
  $\{\delta_{CP} = 0, \pi\}$ at 90%

[1] Expectations computed using $\sin^2\theta_{13} = 0.0217$, $\sin^2\theta_{23} = 0.528$, $\sin^2\theta_{12} = 0.846$, $\Delta m^2_{32}(\Delta m^2_{13}) = 2.509 \times 10^{-3} eV^2/c^4$, $\Delta m^2_{21} = 7.53 \times 10^{-5} eV^2/c^4$

Prospects

T2K II

- **original T2K:** expected to end around 2020 with 7.8×10^{21} POT
- **T2K phase II:** extends up to 2026 for 20×10^{21} POT
- **J-PARC upgrade:** beam power $\nearrow$ 1.3 MW (currently $\sim$ 400 kW)

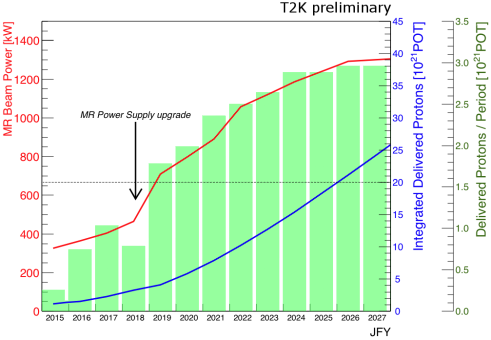
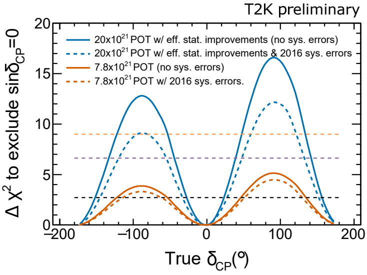
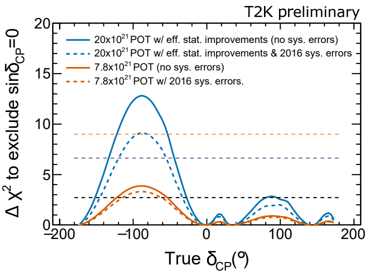


Figure: Targeted scenario

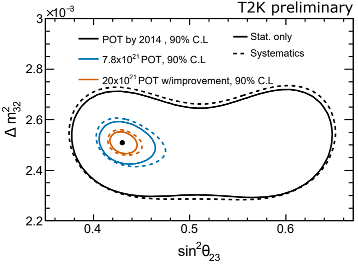
Physics potential of T2K-II



(a) δ_{CP} if hierarchy is normal



(c) δ_{CP} if hierarchy is unknown



(b) Sensitivity for $\sin^2\theta_{23} = 0.43$

- Sensitivity to CP violation up to 3σ with full T2K-II statistics
- Sensitivity to θ_{23} octant

Conclusion

Conclusion

- Since 2010, T2K has accumulated $\sim 1.5 \times 10^{21}$ POT, equally split in neutrino and anti-neutrino mode.

- Joint analysis across all modes ($\nu_\mu/\overline{\nu}_\mu$ disappearance, $\nu_e/\overline{\nu}_e$ appearance) gives leading results for θ_{23} and Δm^2_{32}.

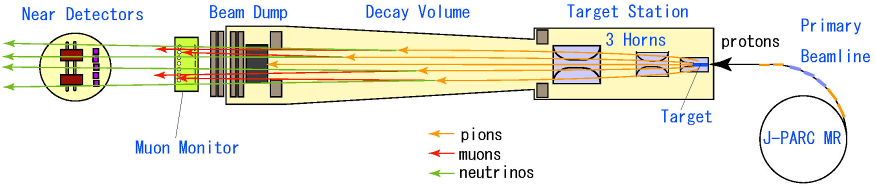
- First constraints on CP violation: T2K data prefer $\delta_{CP} = -\frac{\pi}{2}$ and normal hierarchy.

  T2K disfavors $\{\delta_{CP} = 0\}$ at 2σ
  $\{\delta_{CP} = 0, \pi\}$ (no CP violation) at 90% CL.

- Extension to T2K-II was proposed:
  - to achieve 20×10^{21} POT in 2026
  - to reach $> 3\sigma$ sensitivity to CP violation in leptonic sector

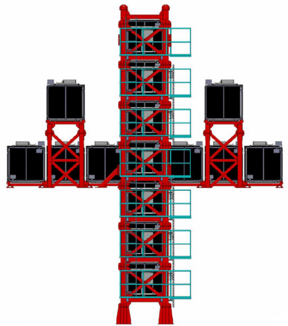
Backups

Neutrino beamline

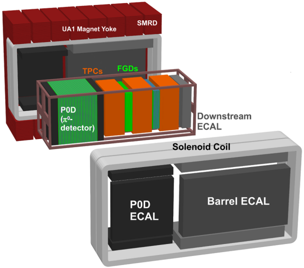


- 30 GeV proton beam from J-PARC Main Ring (MR)
- Protons directed on a thick graphite target
- Pions and kaons from the interaction are focused by magnetic horns
  Two possible modes:
  - Forward horn current (FHC): π^+ and K^+ are collected
  - Reverse horn current (RHC): π^- and K^- are collected
- Decay volume ($\sim$ 96 m long) in which mesons decay:
  - FHC: $\boxed{\pi^+ \to \mu^+ \nu_\mu}$ $\Rightarrow \nu_\mu$ beam (so called neutrino mode)
  - RHC: $\boxed{\pi^- \to \mu^- \overline{\nu}_\mu}$ $\Rightarrow \overline{\nu}_\mu$ beam (antineutrino mode)
- ν spectrum peaked at 600 MeV at 2.5° off-axis (towards SK)

Near detector complex at 280m

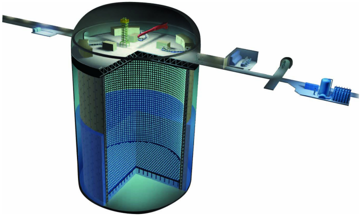


- On-axis INGRID:
  - iron and scintillator bars
  - monitor neutrino beam direction and intensity



- Off-axis ND280:
  - scintillator and water targets
  - trackers and calorimeters
  - observe neutrinos before oscillation
  - tune flux, cross-sections cross-section uncertainties

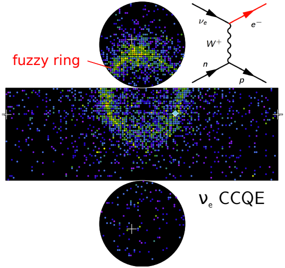
Super-Kamiokande (SK)



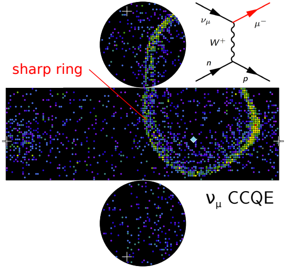
- 295 km from neutrino production point
- 1 km underground in Kamioka mine
- 50 kton of pure water
- 13,000 photomultiplier tubes

Neutrino detection in SK

fuzzy ring



sharp ring



Charged particle
⇒ Cherenkov ring
⇒ Ring reconstruction
⇒ Ring PID

Off-axis beam

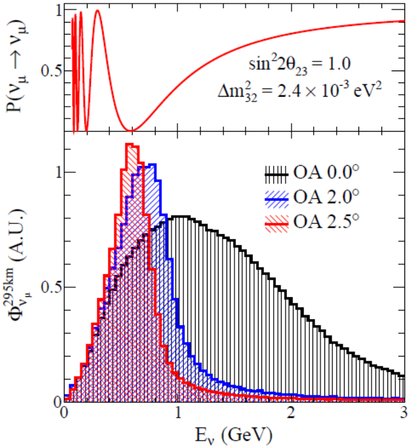


FIG. 1: Muon neutrino survival probability at 295 km and neutrino fluxes for different off-axis angles.

Near detector data and studies

Interactions in the near detector are separated in different categories:

- ν-mode (FGD1, FGD2): ν_μ CC0π, CC1π, CCother
- $\overline{\nu}$-mode (FGD1, FGD2): $\overline{\nu}_\mu$ CC1trk, CCNtrk, ν_μ wrong sign

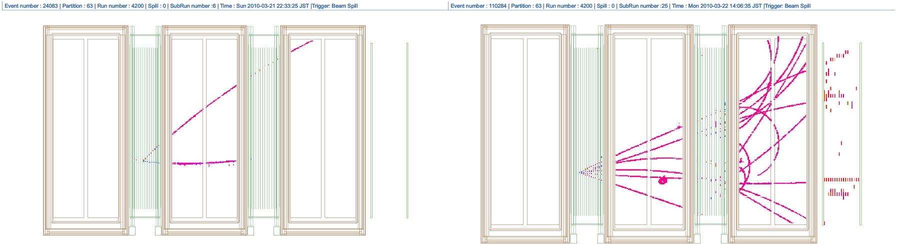
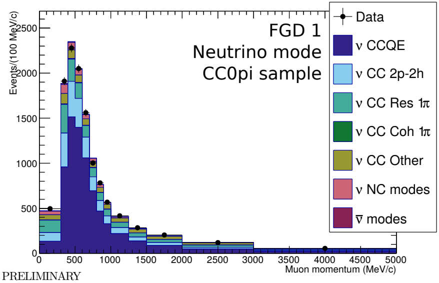
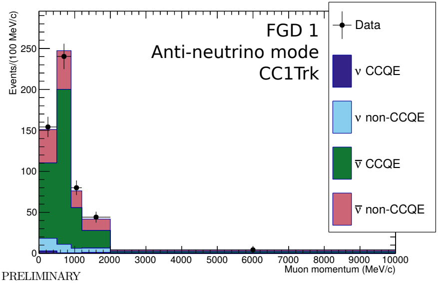


Figure: Left: Clear CC interaction ; Right: Deep inelastic event

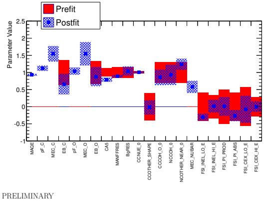
Near detector constraints

Use near detector data to tune initial neutrino flux and parameters of neutrino interactions model.

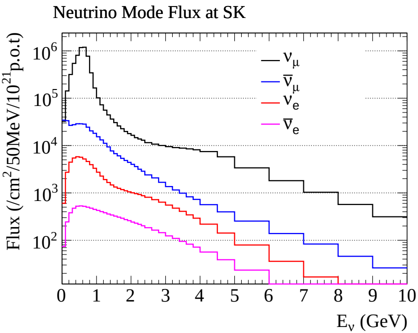


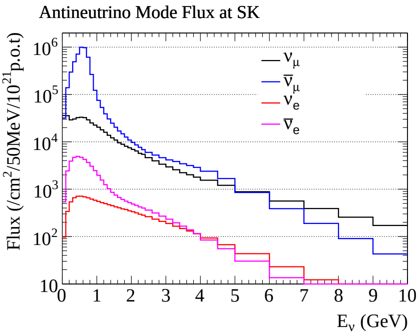


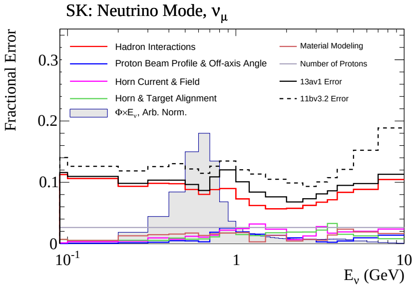
Total $\delta N_{SK}/N_{SK}$			
Beam mode	sample	ND280 constrained	W/o ND280
neutrino	μ-like	5.2%	12.2%
neutrino	e-like	6.9%	12.6%
antineutrino	μ-like	5.2%	12.5%
antineutrino	e-like	7.4%	14.1%

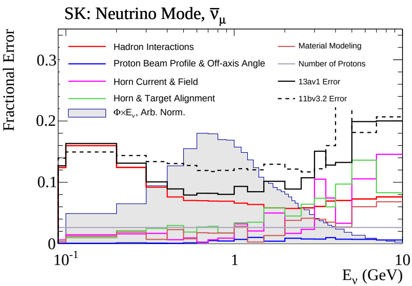


Flux at SK


Neutrino Mode Flux at SK
Flux (/cm^2/50MeV/10^{21}p.o.t)
10^2
10^3
10^4
10^5
10^6
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
0 1 2 3 4 5 6 7 8 9 10
E_ν (GeV)


Antineutrino Mode Flux at SK
Flux (/cm^2/50MeV/10^{21}p.o.t)
10
10^2
10^3
10^4
10^5
10^6
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
0 1 2 3 4 5 6 7 8 9 10
E_ν (GeV)


SK: Neutrino Mode, ν_μ
Fractional Error
0
0.1
0.2
0.3
Hadron Interactions
Proton Beam Profile & Off-axis Angle
Horn Current & Field
Horn & Target Alignment
$\Phi\times E_\nu$, Arb. Norm.
Material Modeling
Number of Protons
13av1 Error
11bv3.2 Error
10^{-1}
1
10
E_ν (GeV)


SK: Neutrino Mode, $\bar{\nu}_\mu$
Fractional Error
0
0.1
0.2
0.3
Hadron Interactions
Proton Beam Profile & Off-axis Angle
Horn Current & Field
Horn & Target Alignment
$\Phi\times E_\nu$, Arb. Norm.
Material Modeling
Number of Protons
13av1 Error
11bv3.2 Error
10^{-1}
1
10
E_ν (GeV)

Energy reconstruction

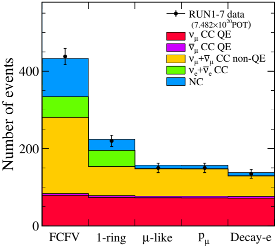
Super-Kamiokande:

- we assume the kinematics of a CCQE interaction

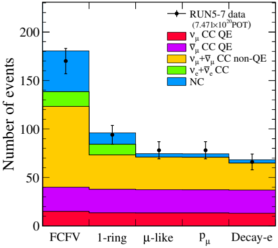
$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2\,(m_n - E_b)\,E_l}{2\,(m_n - E_b - E_l + p_l \cos\theta_l)}$$

  - $E_b = 27$ MeV is the binding energy of a nucleon inside ^{16}O
  - E_l, p_l, θ_l are the reconstructed lepton information

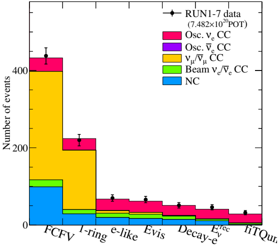
Event selection at Super-Kamiokande



(a) ν_μ in neutrino mode



(b) ν_μ in anti-neutrino mode



(c) ν_e in neutrino mode

Figure: Cut flow in CC selection

Systematic uncertainties

ν_μ (FHC)

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	4.13%
SKDet only	3.86%
FSI+SI only	1.48%
Flux	3.60%
Flux (pre-fit)	7.63%
2p-2h (corr)	3.46%
2p-2h-bar (corr)	0.20%
NC other (uncorr)	0.78%
NC 1gamma (uncorr)	0.00%
XSec nue/numu (uncorr)	0.01%
XSec Tot (corr)	4.00%
XSec Tot	4.08%
XSec Tot (pre-fit)	7.73%
Flux+XSec (ND280 constrained)	2.79%
Flux+XSec (All)	2.90%
Flux+XSec+SKDet+FSI+SI	5.03%
Flux+XSec+SKDet+FSI+SI (pre-fit)	12.0%

$\overline{\nu}_\mu$ (RHC)

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.90%
SKDet only	3.31 %
FSI+SI only	2.06 %
Flux	3.77%
Flux (pre-fit)	7.10%
2p-2h (corr)	2.96%
2p-2h bar (corr)	1.81%
NC other (uncorr)	0.75%
NC 1gamma (uncorr)	0.00%
XSec nue/numu (uncorr)	0.00%
XSec Tot (corr)	4.13%
XSec Tot	4.19%
XSec Tot (pre-fit)	9.32%
Flux+XSec (ND280 constrained)	3.26%
Flux+XSec (All)	3.35%
Flux+XSec+SKDet+FSI+SI	5.22%
Flux+XSec+SKDet+FSI+SI (pre-fit)	12.5%

Systematic uncertainties

ν_e (FHC)

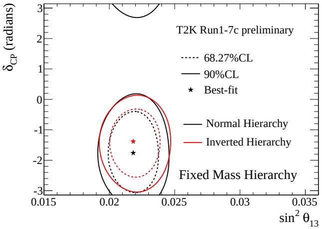
Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.46%
SKDet only	2.39%
FSI+SI only	2.50%
Flux	3.64%
Flux (pre-fit)	8.94%
2p-2h (corr)	3.87%
2p-2h bar (corr)	0.05%
NC other (uncorr)	0.16%
NC 1gamma (uncorr)	1.44%
XSec nue/numu (uncorr)	2.65%
XSec Tot (corr)	4.13%
XSec Tot	5.12%
XSec Tot (pre-fit)	7.17%
Flux+XSec (ND280 constrained)	2.88%
Flux+XSec (All)	4.17%
Flux+XSec+SKDet+FSI+SI	5.41%
Flux+XSec+SKDet+FSI+SI (pre-fit)	11.9%

$\overline{\nu}_e$ (RHC)

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.95%
SKDet only	3.09%
FSI+SI only	2.46%
Flux	3.77%
Flux (pre-fit)	8.03%
2p-2h (corr)	2.97%
2p-2h bar (corr)	2.36%
NC other (uncorr)	0.33%
NC 1gamma (uncorr)	2.95%
XSec nue/numu (uncorr)	1.50%
XSec Tot (corr)	4.32%
XSec Tot	5.45%
XSec Tot (pre-fit)	10.12%
Flux+XSec (ND280 constrained)	3.22%
Flux+XSec	4.63%
Flux+XSec+SKDet+FSI+SI	6.19%
Flux+XSec+SKDet+FSI+SI (pre-fit)	13.7%

δ_{CP}

Normal hierarchy						
Beam mode	Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$	Observed
neutrino	μ-like	135.8	135.5	135.7	136.0	135
neutrino	e-like	28.7	24.2	19.6	24.1	32
antineutrino	μ-like	64.2	64.1	64.2	64.4	66
antineutrino	e-like	6.0	6.9	7.7	6.8	4
Inverted hierarchy						
Beam mode	Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$	Observed
neutrino	μ-like	135.1	135.3	135.0	134.8	135
neutrino	e-like	25.4	21.3	17.1	21.3	32
antineutrino	μ-like	63.8	64.0	63.8	63.7	66
antineutrino	e-like	6.5	7.4	8.4	7.4	4



$\delta_{CP} \in [-3.16; -0.39]$ (Normal Hierarchy)
$\delta_{CP} \in [-2.09; -0.74]$ (Inverted Hierarchy)