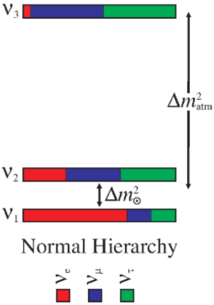
Highlights from T2K

David Hadley on behalf of the T2K collaboration
ICNFP2013

Neutrino Oscillations

$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
$$

$$
= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
$$

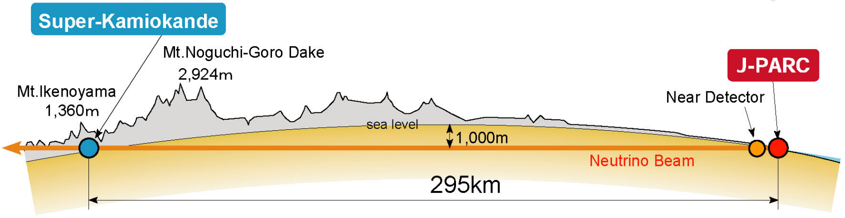


- Flavour states $\neq$ Mass states
- Measure Neutrino Mixing (PMNS) Matrix with neutrino oscillations

Two main oscillation analyses at T2K:

- $P(\mu \to \mu) \approx 1 - \sin^2(2\theta_{23}) sin^2(\frac{\Delta m^2 L}{4E})$
- $P(\mu \to e) \approx \sin^2(\theta_{13}) \sin^2(2\theta_{23}) sin^2(\frac{\Delta m^2 L}{4E})$

The T2K Experiment

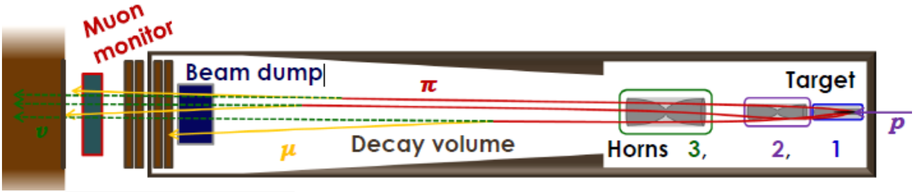


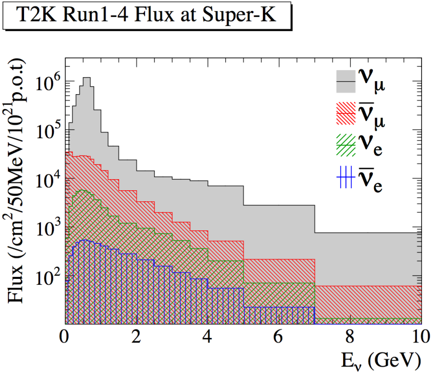
Goals

- discover ν_e appearance in a ν_μ beam
- make precise measurements of ν_μ disappearance
- study neutrino-nucleus interactions at $E_\nu \sim 1\mathrm{GeV}$

- A high intensity proton beam at J-PARC produces a narrow-band ν_μ beam with a peak energy of 0.6 GeVat the far detector,
- The Far detector is Super-Kamiokande, a 50kton water Cherenkov detector, located 2.5° off-axis and 295km from the production point.
- Detectors in the ND280 complex at 280m are used to directly measure the neutrino beam properties and neutrino-nucleus interaction cross sections.

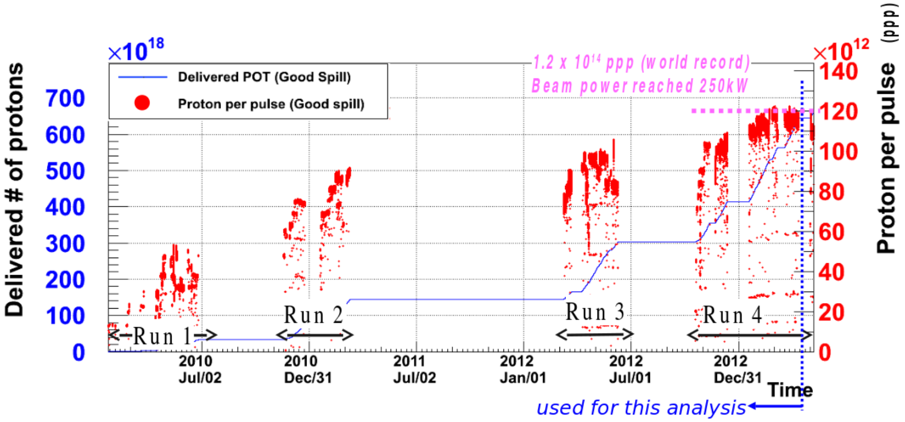
The T2K Beam





- 30 GeVproton beam hits graphite target
- Magnetic horns focus π^+
- 90% ν_μ beam from π^+ decay
- Beam peak at $\sim 0.6\mathrm{GeV}$
- Off-axis detectors
  - exposed to narrow-band beam near oscillation maximum
  - suppress high energy tail reduced backgrounds

The T2K Beam

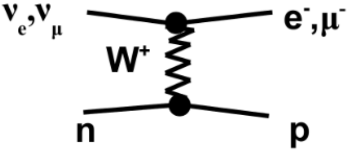


- T2K has collected 6.6×10^{20} POT to date (Run 1-4).
- $\sim 8\%$ of design POT so far.

Neutrino Interactions

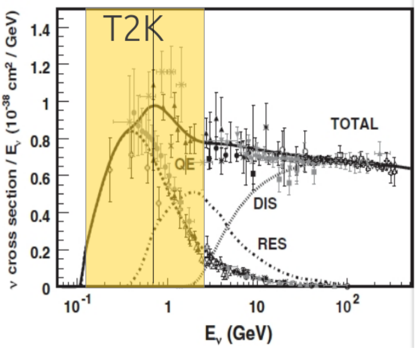
Charged Current
Quasi-elastic scattering

- $\nu_\mu + n \rightarrow \mu^- + p$
- $\nu_e + n \rightarrow e^- + p$
- E_ν reconstruction from μ momentum (ignoring nuclear effects)



$$E^{\nu}_{QE} = \frac{m_p^2 - m_\mu^2 + 2E_\mu m_n - m_n^2}{2\left(m_n - E_\mu + p_\mu \cos(\theta_\mu)\right)}$$

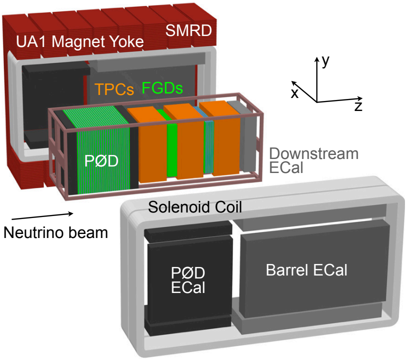
Formaggio & Zeller, Rev. Mod. Phys. 84 (2012)

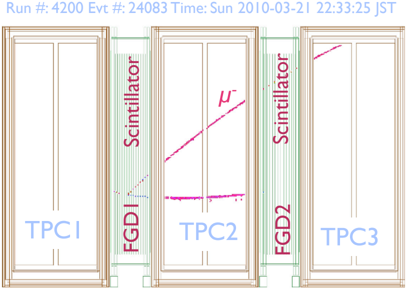


Resonant Single π Production

- $\nu_\mu + N \rightarrow \nu_\mu + N^*$
- $\nu_\mu + N \rightarrow \mu + N^*$
- $N^* \rightarrow N' + \pi$

Off-axis Near Detector (ND280)



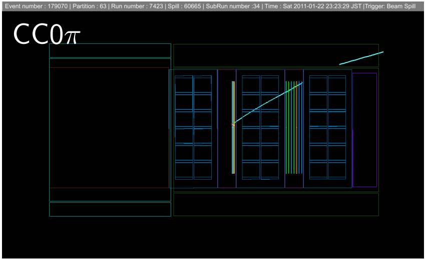


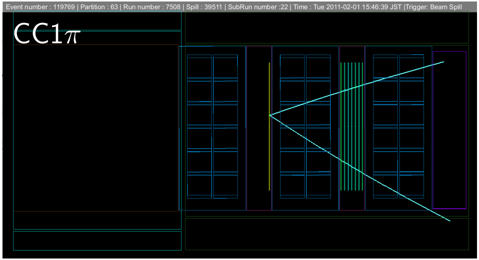
- Constrain beam flux and neutrino interaction model
- Measure cross sections

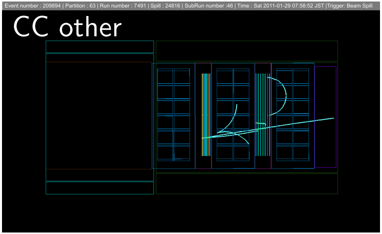
ND280 Tracking Detector

- The Fine Grained Detector (FGD1) consists of layers of $10 \times 10\mathrm{mm}$ plastic scintillator bars readout with Multi-Pixel Photon Counters (MPPCs).
- FGDs provide target mass and vertex reconstruction.
- The Time Projection Chambers (TPCs) provided PID based on $\mathrm{d}E/\mathrm{d}x$ in the argon based gas and momentum measurement from track curvature in the magnetic field.

ND280 Selection



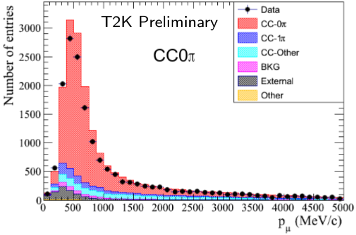


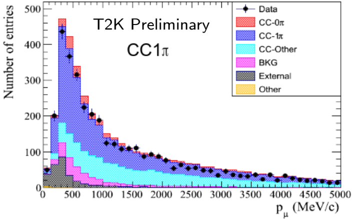


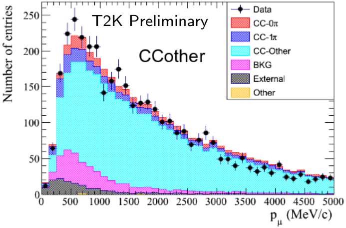
	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

- Measurements of neutrino interactions in the near detector.
- Select samples $1\mu + 0\pi$, $1\mu + 1\pi$, $1\mu + N\pi$.

ND280 Selection







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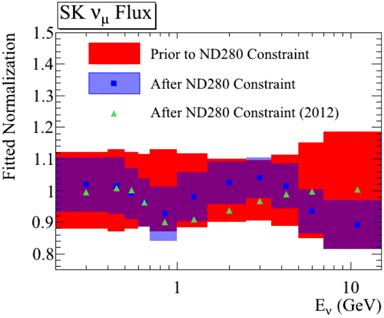
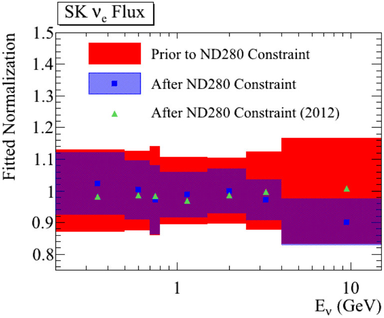
ND280 Constraint





Parameter	Prior to ND280 Constraint	After ND280 Constraint (Runs 1-4)
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063
CCQE Norm.*	1.00 ± 0.11	0.961 ± 0.076
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16
NC1π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25

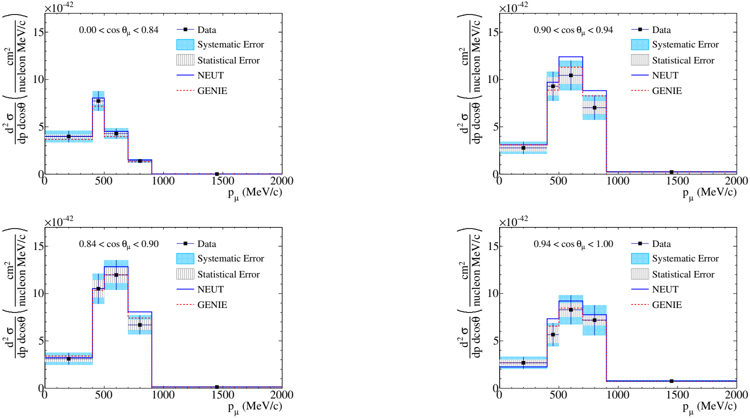
*For E_ν<1.5 GeV **For E_ν<2.5 GeV

- Constraint from near detector measurements gives a significant reduction on the flux and cross section uncertainties at SK.

	ν_e Prediction (Events)	Error from Constrained Parameters
No ND280 Constraint	22.6	26.5%
ND280 Constraint	20.4	3.0%

ND280 Flux Integrated CC Inclusive Cross Section Measurement

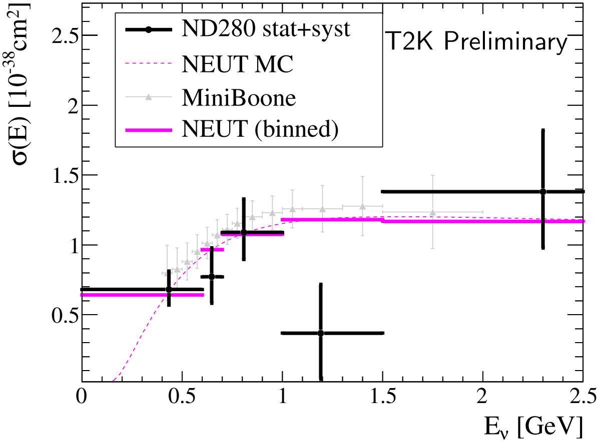
Phys. Rev. D 87, 092003 (2013)



- Select events with μ^-.
- Unfold the reconstructed $p_\mu - \cos(\theta_\mu)$ distributions to estimate the true muon kinematics.
- Measure double differential $p_\mu - \cos(\theta_\mu)$ distribution and total flux integrated cross section.
- Prediction from 2 neutrino MC generators (NEUT and GENIE).

ND280 Energy Dependent CCQE Cross Section Measurement

see talk by D. Hadley @ NuFact2013



- Select μ^- events, veto pions.
- Fit the MC model to $p_\mu - \cos(\theta_\mu)$ distribution to extract CCQE cross section in bins of E_ν
- A χ^2 test gives a p-value of 17% indicating agreement between the data and the cross section model.

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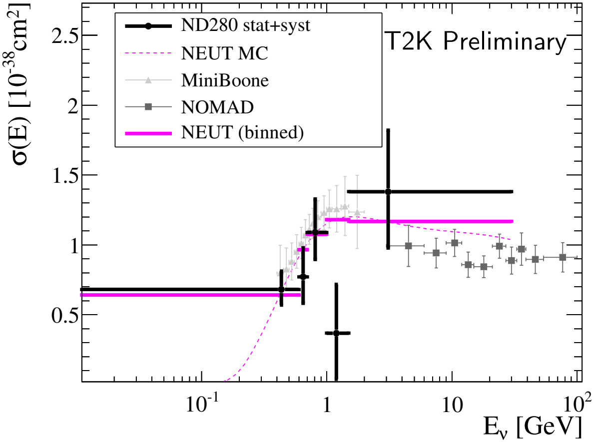

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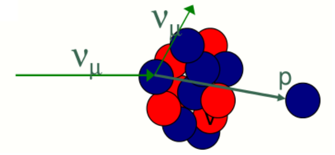
ND280 Neutral Current Elastic Cross Section Measurement

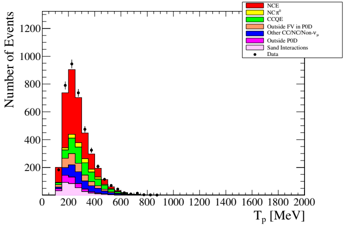
see talk by D. Ruterbories @ NuFact2013

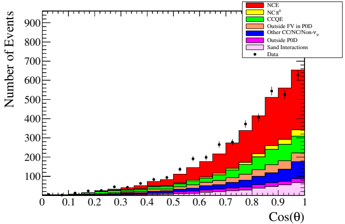


- Select protons reconstructed in the π^0 detector
- Veto Michel decay electrons
- Control contamination from external backgrounds with side-bands
- Measure a flux-integrated total cross section,

$$<\sigma>_{flux} = 2.24\times10^{-39} \pm 0.07(\text{stat.}) {}^{+0.53}_{-0.63} (\text{sys.}) \frac{\text{cm}^2}{\text{nucleon}}$$

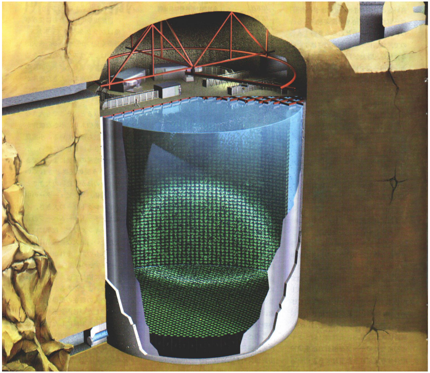
- cf. MC predictions
  - $\sigma_{\text{NEUT}} = 2.02 \times 10^{-39} \text{cm}^2/\text{nucleon}$
  - $\sigma_{\text{GENIE}} = 1.78 \times 10^{-39} \text{cm}^2/\text{nucleon}$



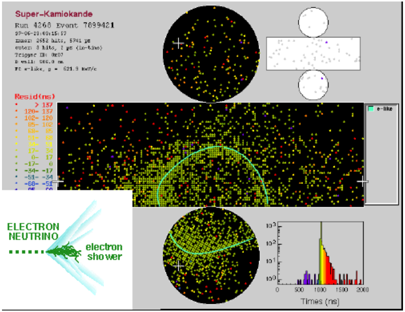


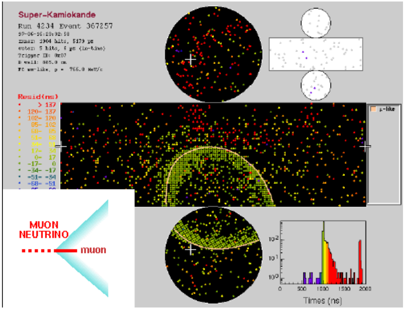
Far Detector

- 22.5kton Water Cherenkov Detector
- Cherenkov ring properties provide momentum and PID

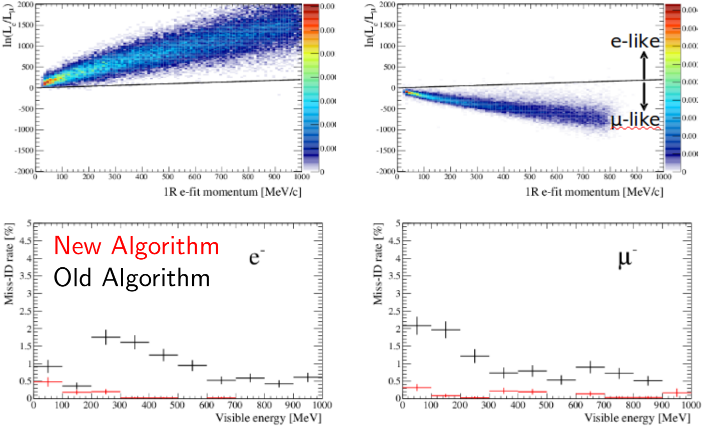


Example MC Event Displays





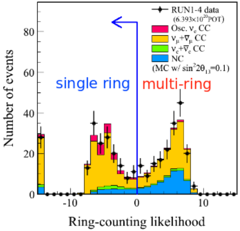
Far Detector PID

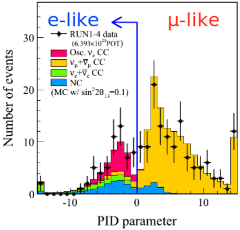


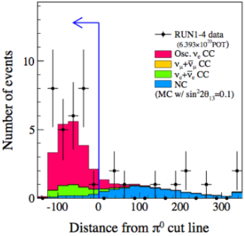
- New reconstruction algorithm gives improved background rejection and resolution.
  - Maximum likelihood fit for each particle hypothesis
  - Likelihood: $\prod_i^{\text{photo-tubes}} \lambda(\overrightarrow{p}|Q,t)$
  - Discriminating variable: (Best-fit point) Likelihood ratio for each hypothesis e.g. for e vs π^0: $\lambda_e(\hat{\overrightarrow{p}}, \hat{\overrightarrow{x}}|Q,t)/\lambda_{\pi^0}(\hat{\hat{\overrightarrow{p}}}, \hat{\overrightarrow{p}})$.

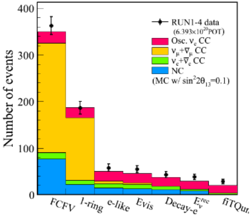
Event Selection for the ν_e appearance analysis

- Fully contained in fiducial volume
- $N_{\text{rings}} = 1$
- Electron-like PID
- $E_{\text{visible}} > 100\text{MeV}$
- Decay electron veto
- $E_{rec} < 1250\text{MeV}$
- π^0 veto

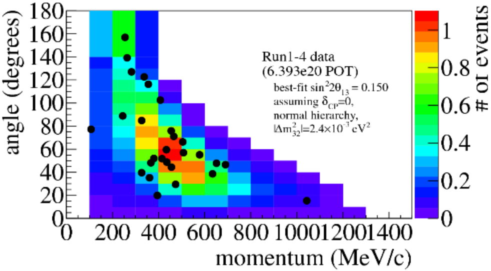


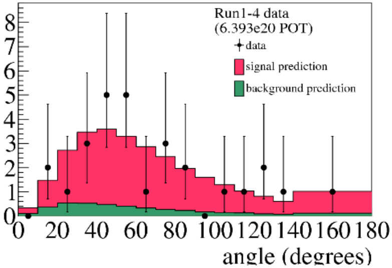


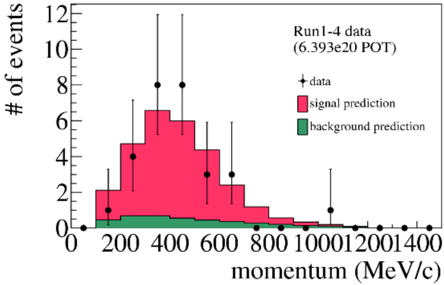


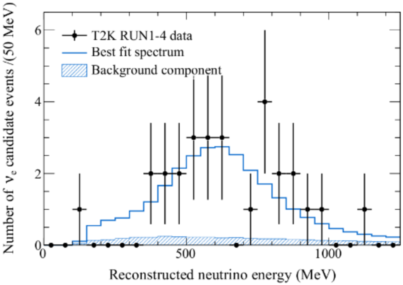


Fitted Distributions for the ν_e appearance analysis

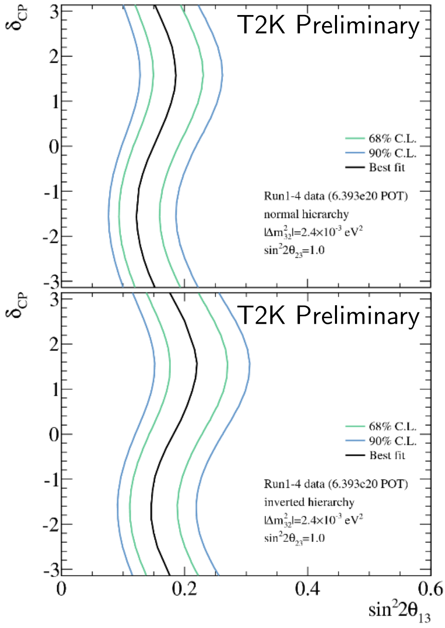








Results of the ν_e appearance anaylsis

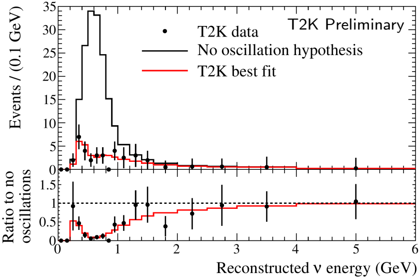


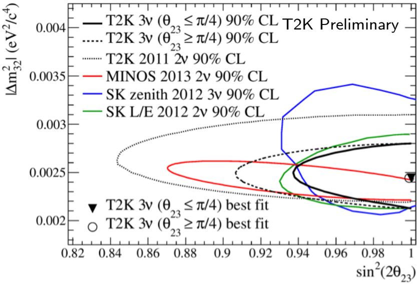
- Observed 28 events (expected 5.2 for background only hypothesis)
- 7.5σ exclusion of background-only hypothesis
- Concrete observation of ν_e appearance in a ν_μ beam
- Best-fit value / 68% CL / 90% CL for $sin^2 2\theta_{13}$ at various values of δ_{CP}.

	Best fit with one standard deviation
Normal hierarchy	$0.150^{+0.039}_{-0.034}$
Inverted hierarchy	$0.182^{+0.046}_{-0.040}$

Preliminary results for $\delta_{CP} = 0$, $\sin^2 2\theta_{23} = 1.0$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$.

Latest Results from the ν_μ appearance anaylsis





- 58 events observed (expected 204 ± 17 with no oscillation).
- NB contour significantly affected by octant (both results reported).

	$\sin^2 2\theta_{23}$	Δm^2_{32} [eV^2]	χ^2 / ndf
$\theta_{23} \leq \pi/4$	1.000	2.44×10^{-3}	56.04/71
$\theta_{23} \geq \pi/4$	0.999	2.44×10^{-3}	56.03/71

Summary

- J-PARC operating at 220kW in latest running period.
  - 6.63×10^{20} POT accumulated.
- Discovery of ν_e appearance in a ν_μ beam (7.5σ)
  - with only a fraction of the planned POT.
- Precision measurements of ν_μ disappearance very important in post-θ_{13} world.
- New Cross Section results released
  - CC Inclusive
  - CCQE
  - NCE
  - many more cross section analyses in progress.

Backup

$\nu_\mu \to \nu_\mu$ probability in a vacuum

$$P(\nu_\mu \to \nu_\mu) = 1 - (c_{13}^4 \ \sin^2 2\theta_{23} + s_{23}^2 \ \sin^2 2\theta_{13}) \sin^2 \Delta_{atm}$$
$$+ \left\{ c_{13}^2 \ (c_{12}^2 - s_{13}^2 \ s_{23}^2) \sin^2 2\theta_{23} + s_{12}^2 \ s_{23}^2 \ \sin^2 2\theta_{13} - c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{23} \ \sin 2\theta_{12} \ \cos\delta \right\}$$
$$\times \left\{ \frac{1}{2} \sin 2\Delta_{solar} \ \underline{\sin 2\Delta_{atm}} + 2 \underline{\sin^2 \Delta_{solar}} \ \sin^2 \Delta_{atm} \right\}$$
$$- \left\{ \sin^2 2\theta_{12} \ (c_{23}^2 - s_{13}^2 \ s_{23}^2)^2 + s_{13}^2 \ \sin^2 2\theta_{23} \ (1 - c_\delta^2 \ \sin^2 2\theta_{12}) \right.$$
$$+ 2 s_{13} \ \sin 2\theta_{12} \ \cos 2\theta_{12} \ \sin \theta_{23} \ \cos 2\theta_{23} \ c_\delta$$
$$- \frac{1}{2} c_{13} \ \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \ \cos\delta \ s_{23}^2 \ s_{12}^2$$
$$\left. + \sin^2 2\theta_{23} \ c_{13}^2 \ (c_{12}^2 - s_{13}^2 \ s_{12}^2) + s_{13}^2 \ s_{23}^2 \ \sin^2 2\theta_{13} \right\} \times \underline{\sin^2 \Delta_{solar}}$$

$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$
$$c_\delta = \cos\delta$$
$$\Delta_{atm} = \frac{\Delta m_{13}^2 \ L}{4 \ E_\nu}$$
$$\Delta_{solar} = \frac{\Delta m_{21}^2 \ L}{4 \ E_{/nu}}$$

T2K: L = 295 km, E_ν peaks at ~ 0.6 GeV
-> $\sin^2\Delta_{solar}$ ~ 0, $\sin 2\Delta_{atm}$ ~ 0

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\underbrace{\cos^4\theta_{13} \cdot \sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{\sin^2 2\theta_{13} \cdot \sin^2\theta_{23}}_{\text{Next-to-leading}}) \cdot \sin^2 \frac{\Delta m_{31}^2 \cdot L}{4E}$$

Leading

Next-to-leading
is different between 1st/2nd octants

Systematic Uncertainties in ν_e oscillation analysis

	$\sin^2 2\theta_{13} = 0$		$\sin^2 2\theta_{13} = 0.1$	
Error source	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit
Beam only	10.6	7.3	11.6	7.5
M_A^{QE}	15.6	2.4	21.5	3.2
M_A^{RES}	7.2	2.1	3.3	0.9
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1	4.8	9.3	6.3
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9	2.4	4.2	2.0
NC1π^0 norm.	2.7	1.9	0.6	0.4
CC other shape	0.3	0.3	0.1	0.1
Spectral Function	4.7	4.8	6.0	6.0
p_F	0.1	0.1	0.1	0.1
CC coh. norm.	0.3	0.3	0.3	0.2
NC coh. norm.	1.1	1.1	0.3	0.2
NC other norm.	2.3	2.2	0.5	0.5
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.4	2.4	2.9	2.9
W shape	1.0	1.0	0.2	0.2
pion-less Δ decay	3.3	3.1	3.7	3.5
SK detector eff.	5.7	5.6	2.4	2.4
FSI	3.0	3.0	2.3	2.3
PN	3.6	3.5	0.8	0.8
SK momentum scale	1.5	1.5	0.6	0.6
Total	24.5	11.1	28.1	8.8

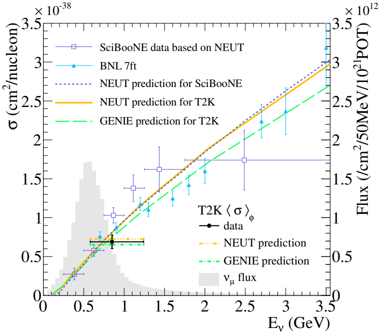
Fraction uncertainty on predicted number of ν_e events for each source of systematic error ($p - \theta$ analysis).

Beam Composition

Parent	Flux Percentage of Each Flavors ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0%	41.8%	31.9%	2.8%
$K^\pm$	4.0%	4.3%	26.9%	11.3%
K^0_L	0.1%	0.9%	7.6%	49.0%
Tertiary				
$\pi^\pm$	34.4%	50.0%	20.4%	6.6%
$K^\pm$	1.4%	2.6%	10.0%	8.8%
K^0_L	0.0%	0.4%	3.2%	21.3%

Parent	Flux Percentage of All Flavors ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
$\pi^\pm$	87.5%	5.5%	0.6%	0.0%
$K^\pm$	5.0%	0.5%	0.4%	0.0%
K^0_L	0.1%	0.2%	0.1%	0.1%

ND280 Flux Integrated CC Inclusive Cross Section Measurement



- Select events with μ^-.
- Unfold the reconstructed $p_\mu - \cos(\theta_\mu)$ distributions to estimate the true muon kinematics.
- Measure double differential $p_\mu - \cos(\theta_\mu)$ distribution and total flux integrated cross section.
- Prediction from 2 neutrino MC generators (NEUT and GENIE).