Results from T2K

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for the
T2K Collaboration

nuTURN 2012

Outline

Introduction

T2K experiment

T2K ν Analysis
- ν_μ disappearance analysis
- ν_e appearance analysis

T2K Current Status

Summary

Outline

The Parameters

$$\overset{\text{Flavour}}{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmo \& Accel}} \overbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}^{\text{Reactor \& Accel}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Reactor \& Solar}} \overset{\text{Mass}}{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}$$

where $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$

- Recent results show $\sin^2 2\theta_{13} \simeq 0.1$
- Is $\sin^2 2\theta_{23}$ maximal?
- No information on *CP* phase δ

Oscillations with a ν_μ beam

- ν_μ disappearance:

$$P_{\nu_\mu \to \nu_{x\neq\mu}} \simeq \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\Phi_{32}$$
$$\simeq sin^2 2\theta_{23}\sin^2\Phi_{32}$$

- $\nu_\mu \to \nu_e$

$$P_{\nu_\mu \to \nu_e} \simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\Phi_{32}$$

Where:

$$\Phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E} = \frac{1.27(\Delta m^2_{ij}/\mathrm{eV}^2)(L/\mathrm{km})}{E/\mathrm{GeV}}$$

Future possibilities

- Refine ν_e appearance
- Since $\nu_\mu \to \nu_e$ is sufficiently large:
  - look for *CPV* with $\bar{\nu}_\mu$ beam

$$A_{\mathrm{CP}} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar{\nu}_\mu\to\bar{\nu}_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar{\nu}_\mu\to\bar{\nu}_e}} = \frac{\Delta m^2_{21}}{4E}\,\frac{\sin 2\theta_{12}}{\sin\theta_{13}}\sin\delta$$

See Nakadaira's talk tomorrow

Outline

Tokai To Kamioka: "T2K"

Produce ν_μ beam at J-PARC and detect at Super-K

Primary Physics goals

- Precision measurement of ν_μ disappearance:

$$P_{\nu_\mu \to \nu_{x \neq \mu}} \simeq \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E_\nu)$$

- Discovery of $\nu_\mu \to \nu_e$ oscillation:

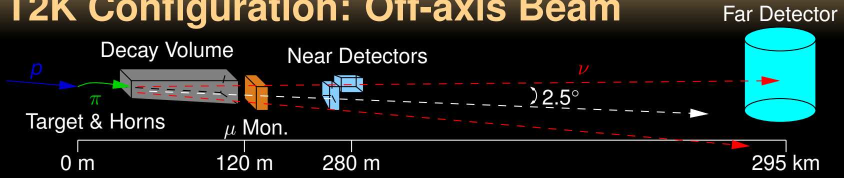
$$P_{\nu_\mu \to \nu_e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E_\nu)$$

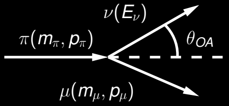
T2K Collaboration

- 12 countries
- 59 institutes
- $\simeq$ 500 collaborators

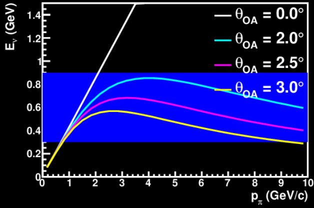
Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, USA.

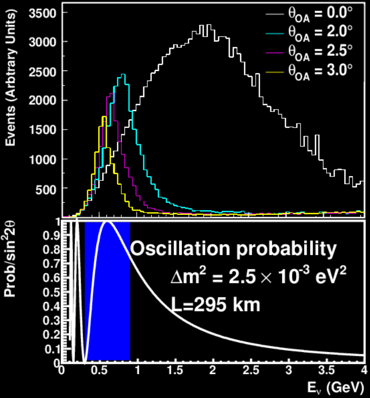
T2K Configuration: Off-axis Beam





$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{OA})}$$



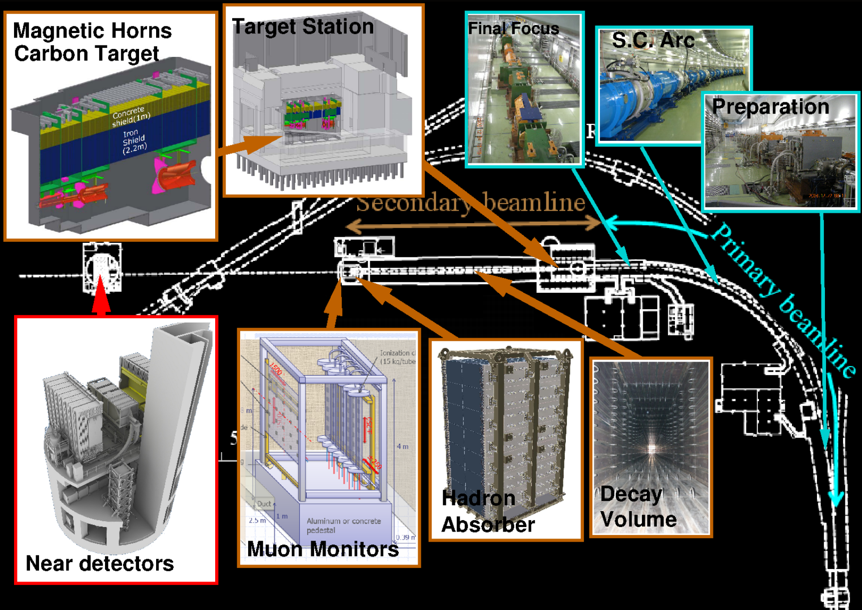


- Narrow E band
- Eliminates high E bkgs
- Tuned to osc. maximum

Tokai Site


Linac
$L = 330$ m
N
3 GeV Synchrotron (RCS)
Circumference=350 m
T2K Neutrino Beamline
30 GeV Synchrotron (MR)
Circumference=1600 m
Photo taken post March 2011

Tokai Site



Magnetic Horns
Carbon Target
Concrete shield(1m)
Iron Shield (2.2m)
Target Station
Final Focus
S.C. Arc
Preparation
Secondary beamline
Primary beamline
Near detectors
Muon Monitors
Hadron Absorber
Decay Volume
Aluminum or concrete pedestal

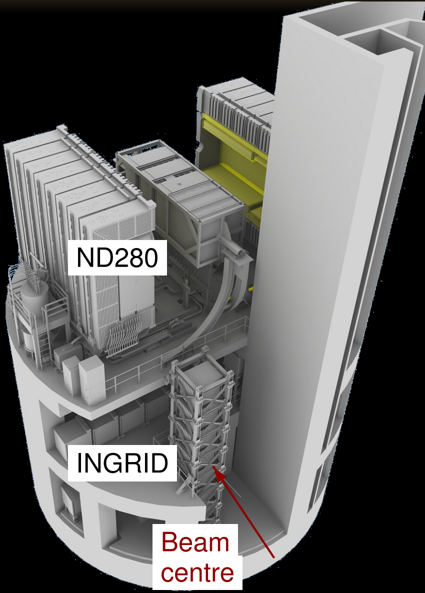
Near Detectors

Off Axis

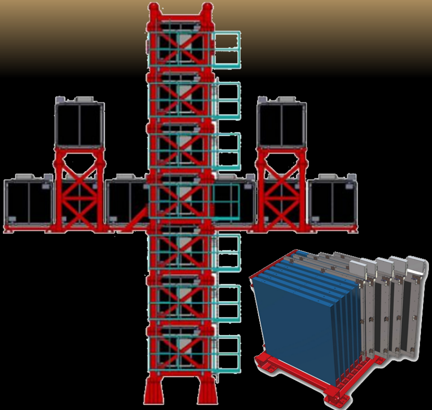
- "ND280"
- Flux in SK direction
- ν cross sections

On Axis

- "INGRID"
- ν_μ beam
  - profile
  - direction
  - intensity



On Axis Detector - INGRID



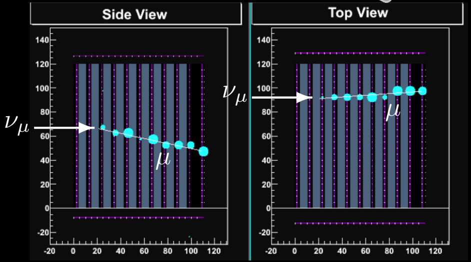
Design

- 14 modules in cross arrangement
- 10 m × 10 m
- Iron scintillator sandwich

Provides

- Beam parameters
- Rate, direction and profile measurements

Note:
$\Delta\theta \simeq 1 \text{ mrad} \Rightarrow \Delta E_{peak} \simeq 20 \text{ MeV}$



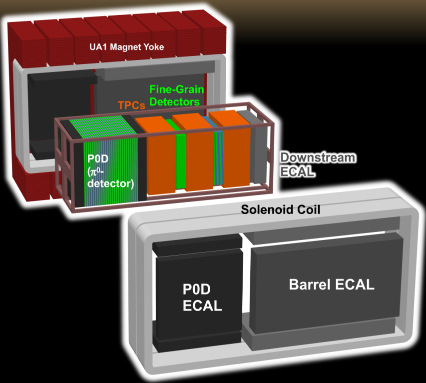
Off Axis Detector - ND280

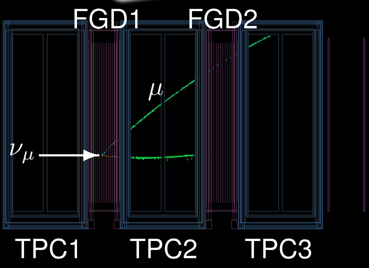
Design

- UA1 magnet, B=0.2 T
- Tracker
    - Time projection chambers (TPCs)
    - Fine Grained Detectors (FGDs): Tracking and target material (scintillator and water)
- π^0 detector (P0D)
- Electromagnetic calorimeter (ECAL)
- Side muon range detector (SMRD)

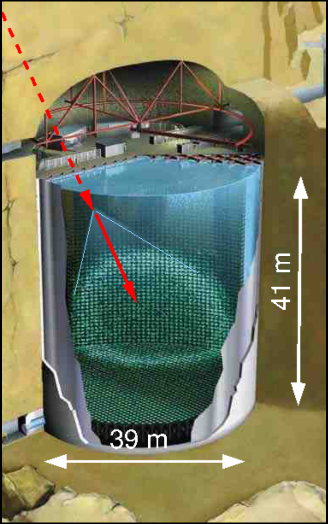
Purpose (for today's presentation)

- Tracker measuring CC ν_μ rate



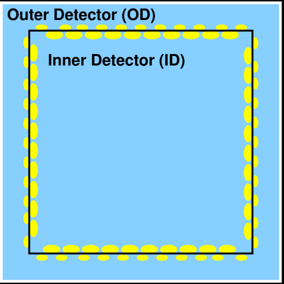


Far Detector - Super-Kamiokande



- Cerenkov light from charged leptons from ν interactions
- Use PMT pulse height & timing information
- Fit PMT hits to cone
  $\Rightarrow$ momentum & direction
- Good e/μ separation
  - "Sharp" muon like rings
  - "Fuzzy" electron like rings

- OD 1185 PMTs: Veto
- ID 11129 PMTs
- FV 22.5 kt
  2 m from ID wall



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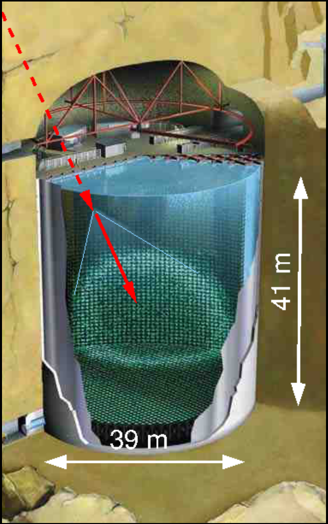

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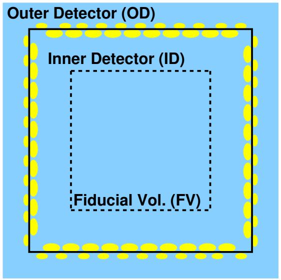

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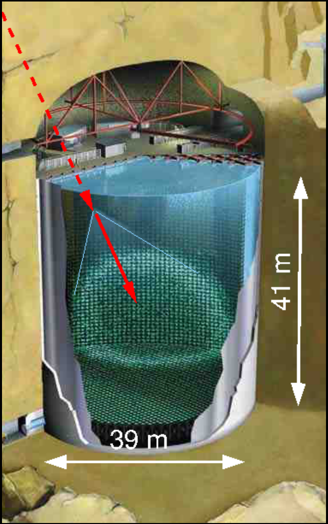

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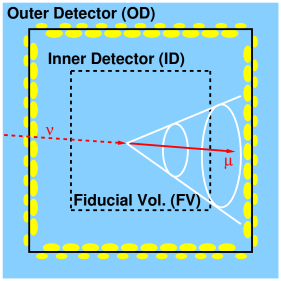
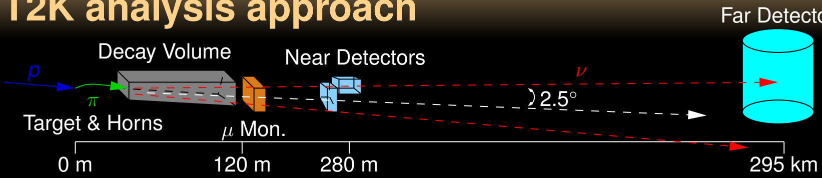


Outline

T2K analysis approach



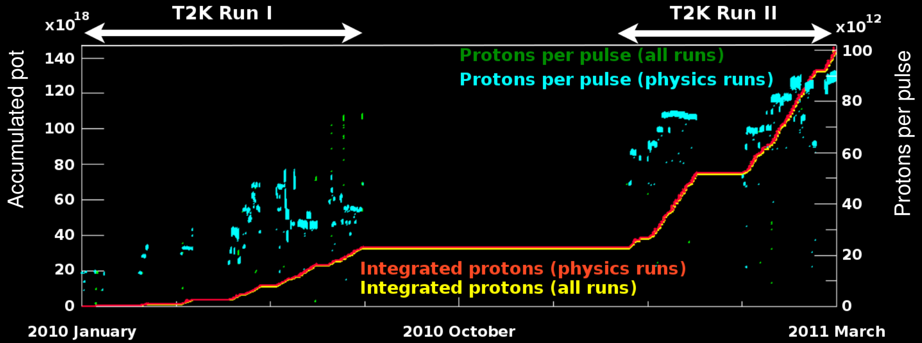
Determine the number of events expected the at Far Detector (SK):

$$N_{SK}^{exp}(E_{rec}) = \frac{N_{ND}^{Data}}{N_{ND}^{MC}} \sum_{E_{true}} P_{\nu_\mu \to \nu_x}(E_{true}) N_{SK}^{MC}(E_{rec}, E_{true})$$

- $N_{SK}^{MC}(E_{rec}, E_{true}) = \Phi\sigma\epsilon$ is MC prediction (w/o oscillations)
  - Φ: Neutrino flux
  - σ: Neutrino interaction cross sections
  - ϵ: Detector efficiency terms
- $\frac{N_{ND}^{Data}}{N_{ND}^{MC}}$ measured and simulated events at the near detector
- $P_{\nu_\mu \to \nu_x}(E_{true})$: oscillation probability

Compare/fit to number of observed events at T2K far detector (Super-K)

Data Set



T2K Run I

- 3.23×10^{19} pot
- Stable 50 kW operation

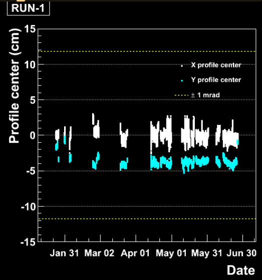
T2K Run II

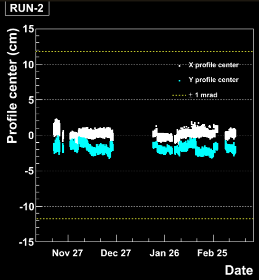
- 11.08×10^{19} pot
- Achieved stable 145 kW operation

- Total of 14.31×10^{19} pot used for analysis
- Corresponds to 2% planned data

Beam centre stability

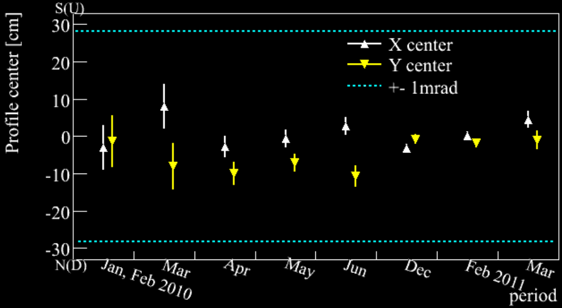
MUMON





Stable to $< \pm 1$ mrad (dashed lines)

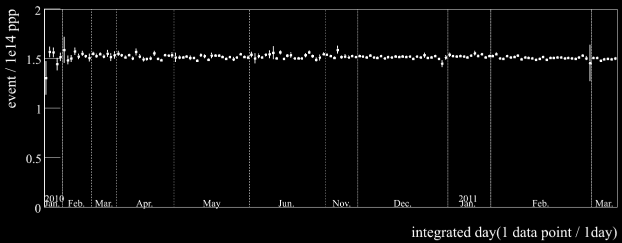
INGRID



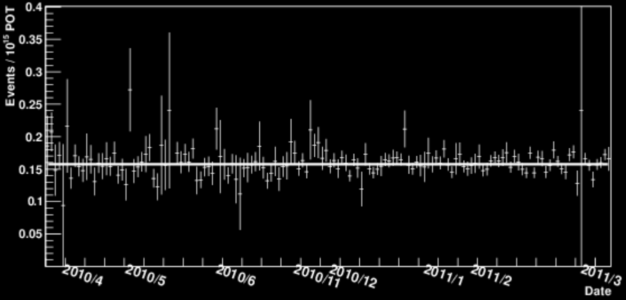
Event rate stability

ν event rate stable in both on and off axis detectors

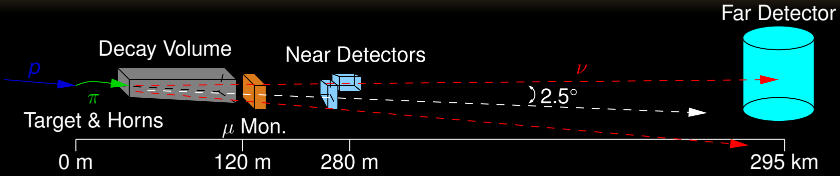
On Axis: INGRID

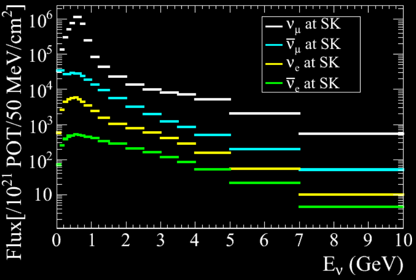


Off Axis: FGD



Neutrino Flux



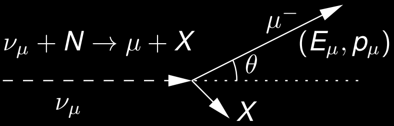


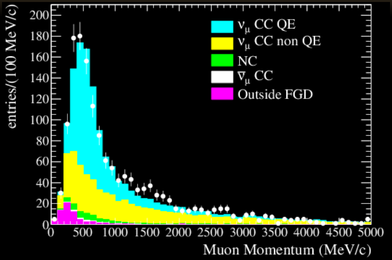
- Proton beam monitor measurements
- Hardon Production
  - NA61 experiment:
    - *p* on carbon target
    - π/k production
    - Phys. Rev. C 84, 034604 (2011)
  - Tuned to existing data
- Secondary hadronic interactions, particle decays, horns
  - GEANT3 simulation
  - Tuned to existing data

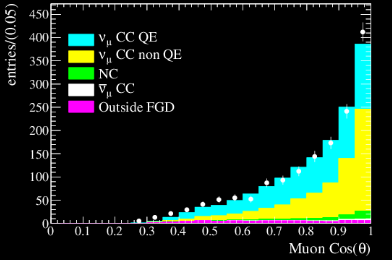
Neutrino Interactions

- Modelled with NEUT
  - Tuned by T2K using existing data from: SciBoone, MiniBoone, K2K
  - Cross checked w/ GENIE
- ν_μ CC constrained by ND280 measurements
  - 89% of Run I data
  - 1529 Events in FGD1
  - Good agreement w/ MC
  - Use measured ratio to further constrain interactions at FD

$\nu_\mu + N \to \mu + X$





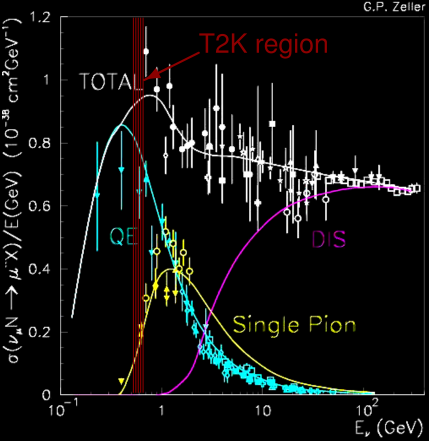


$$\frac{N_{ND}^{\nu_\mu CC,Data}}{N_{ND}^{\nu_\mu CC,MC}} = 1.036 \pm 0.028(stat)^{+0.044}_{-0.037}(det) \pm 0.038(phys)$$

ν interactions and E_ν reconstruction

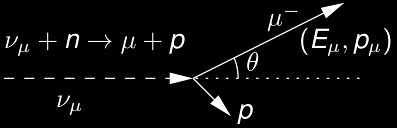
$$P_{\nu_\mu \to \nu_x} = P_{\nu_\mu \to \nu_x}(E_\nu)$$

ν_μ CC cross sections



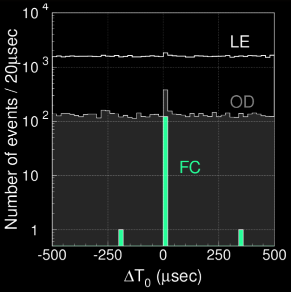
Charged Current Quasi-Elastic (CC-QE)

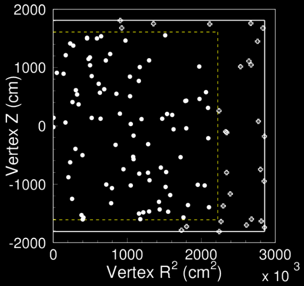
$$\nu_\mu + n \to \mu + p$$

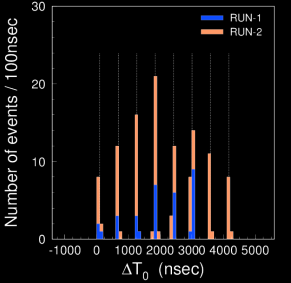


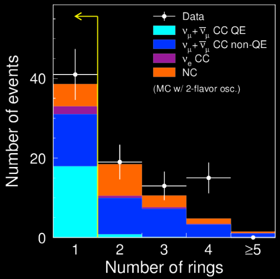
$$\Rightarrow E_\nu^{\mathrm{rec}} = \frac{m_n E_\mu - m_\mu^2/2}{m_n - E_\mu + p_\mu \cos\theta}$$

T2K ν event selection









Criteria	Evts
BT & FC	121
FV & $E > 30$ MeV	88
1 ring, e/μ like	41

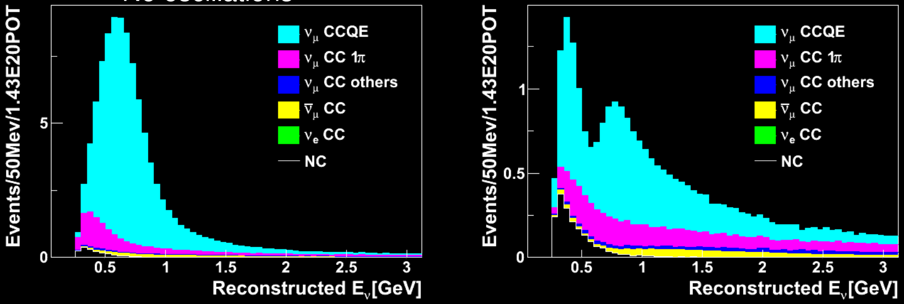
ν_μ analysis and E_ν reconstruction

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m^2_{32} L}{E_\nu} \right)$$

T2K far detector example distributions

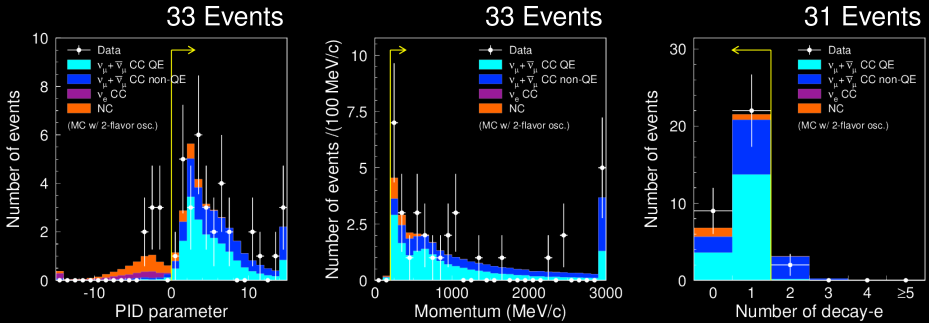
No oscillations

$\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{32} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$



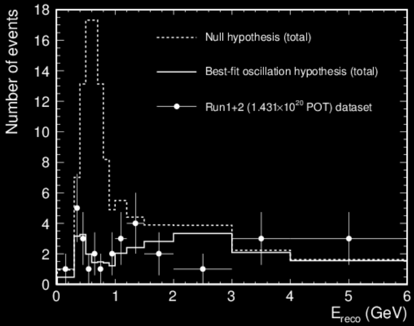
- Distortion of E_ν spectrum
- Reduction in number of events

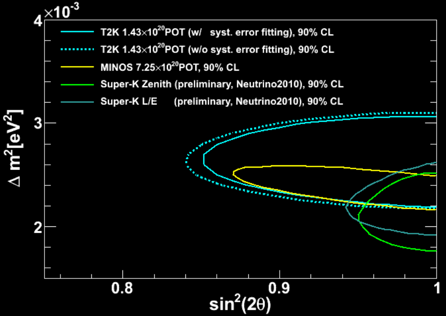
T2K ν_μ event selection



Criteria	Evts
FCFV, 1 Ring	41
PID	33
$p_\mu > 200$ MeV/c	33
$N_{decay-e} \leq 1$	31

ν_μ disappearance results Phys. Rev. D 85, 031103(R) (2012)

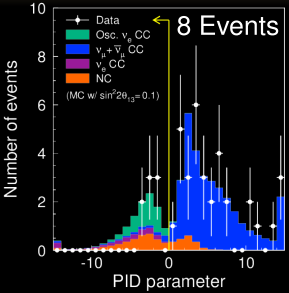


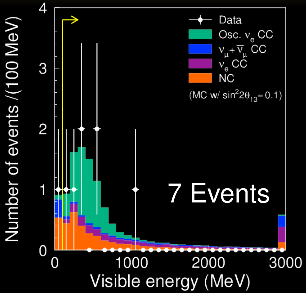


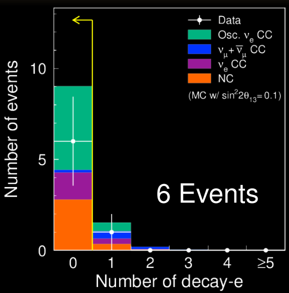
- Observe 31 events
- No osc. expectation: 104 ± 14
- Binned likelihood fit
- Best fit: $\sin^2 2\theta_{23} = 0.98$, $\Delta m^2_{32} = 2.65 \times 10^{-3}\ \mathrm{eV}^2$

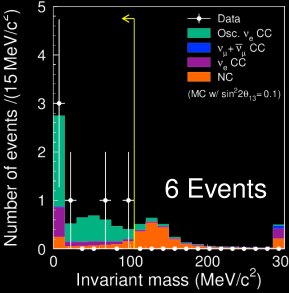
Source	Error N_{SK}^{expect}
Cross Sect/FSI	$+8.3\%\ -8.1\%$
FD eff.	$\pm 10.3\%$
Flux	$\pm 4.8\%$
ND eff., norm	$+6.2\%\ -5.9\%$
Total	$+15.4\%\ -15.1\%$

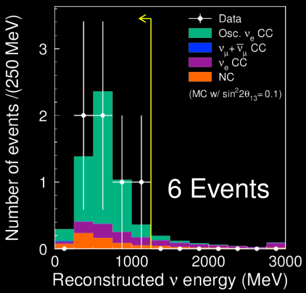
T2K ν_e event selection







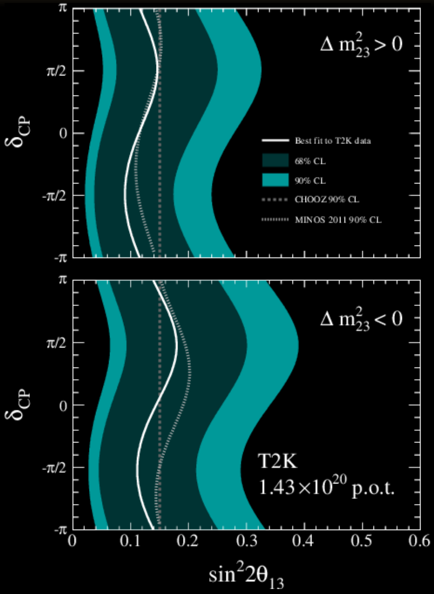




Criteria	Evts
FCFV, 1 Ring	41
PID	8
$E_{vis} > 100$ MeV	7
$N_{decay-e} < 1$	6
$M_{inv} < 105$ MeV/c^2	6
$E_\nu^{rec} < 1250$ MeV	6

ν_e appearance results

Phys. Rev. Lett. 107, 041801 (2011)

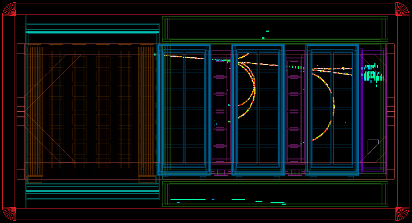


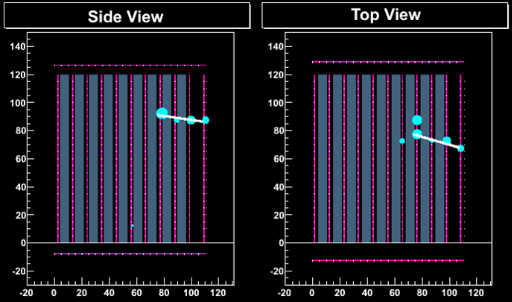
- Six events observed
- Expected background: 1.5 ± 0.3
- Prob. to observe 6 or more evts in null osc hyp is 0.007 (equiv 2.5σ)
- For $\sin^2\theta_{23}$ =1, $\Delta m^2_{23} = 2.4 \times 10^{-3}\mathrm{eV}^2$, $\delta_{CP} = 0$
  - Best fit: $\sin^2 2\theta_{13} = 0.11$
  - $0.03 < \sin^2 2\theta_{13} < 0.28$ @90% CL
- Consistent with earlier limits
- Recently confirmed by Daya Bay & RENO

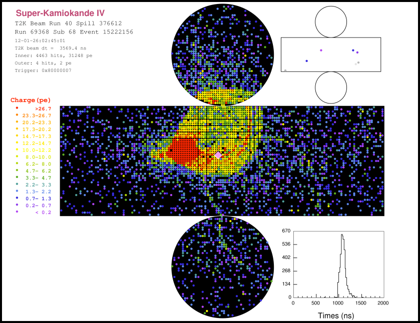
Outline

T2K Current Status

- Operation stopped by earthquake on 2011/03/11
- Beam w/o horns & 2011/12, 2012/01
- ν events seen in all detectors
- Now running steadily with all systems and up to 188 kW beam (*c.f.* 145 kW before earthquake)







Outline

Summary

- First ν_μ disappearance results from off-axis beam
  - Inconsistent with no-oscillation at 4.5σ
  - Consistent with Super-K, K2K, MINOS

Phys. Rev. D 85, 031103(R) (2012)

- First indication of $\nu_\mu \to \nu_e$ oscillations
  - Six events observed over expected background 1.5 ± 0.3
  - 0.007 probability of observing this if there are no oscillations (equivalent to 2.5σ indication)
  - Consistent with MINOS and Double Chooz

Phys. Rev. Lett. 107, 041801 (2011)

- T2K recovered from earthquake and has resumed operation with increased beam power.

Supplementary Material

Full $\nu_\mu \to \nu_e$ oscillation probability

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} T_1 + \alpha \sin 2\theta_{13} \overbrace{(T_2 - T_3)}^{\text{Interference}} + \alpha^2 T_4$$

Where:

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(A-1)\Delta]}{(A-1)^2} \quad \leftarrow\text{Atmospheric}$$

$$T_2 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

$$T_3 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

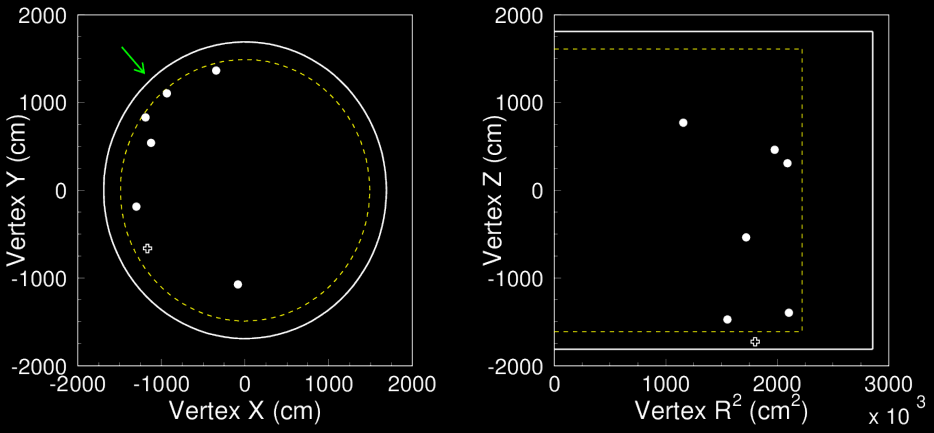
$$T_2 - T_3 = \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \frac{\sin(A\Delta)}{A} \frac{\sin[(A-1)\Delta]}{A-1}$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2} \quad \leftarrow\text{Solar}$$

And:

$$A \equiv \frac{2EV}{\Delta m^2_{31}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

ν_e vertex distributions



- Clustering at large R
- Kolmogorov-Smirnov test of R^2 distribution has p-value of 0.03
- No excess observed outside FV or in OD
- Eagerly waiting for more data

ν_e systematic error contributions

		$\sin^2 2\theta_{13}$=0		$\sin^2 2\theta_{13}$=0.1	
Error source	N_{ND}	N_{SK}	N_{SK}/N_{ND}	N_{SK}	N_{SK}/N_{ND}
SK Efficiency	$\pm$ 0.0	$\pm$ 14.7	$\pm$ 14.7	$\pm$ 9.4	$\pm$ 9.4
Cross section	$\pm$ 8.3	$\pm$ 13.5	$\pm$ 14.0	$\pm$ 9.8	$\pm$ 10.5
Beam Flux	$\pm$ 15.4	$\pm$ 16.1	$\pm$ 8.5	$\pm$ 14.9	$\pm$ 8.5
ND Efficiency	$^{+5.6}_{-5.2}$	$\pm$ 0.0	$^{+5.6}_{-5.2}$	$\pm$ 0.0	$^{+5.6}_{-5.2}$
Overall Norm.	$\pm$ 0.0	$\pm$ 0.0	$\pm$ 2.7	$\pm$ 0.0	$\pm$ 2.7
Total	$\pm$ 18.4	$\pm$ 25.6	$^{+22.8}_{-22.7}$	$\pm$ 20.2	$^{+17.6}_{-17.5}$

- Contributions to # of expected events from each systematic error group
- N_{SK}, N_{ND} are # of the expected events for far and near detectors
- Both signal and background events are included in N_{SK}
- N_{SK}/N_{ND} shows the SK expected events with ND normalization
- Per parameter breakdown on next slide

ν_e sys error contributions to # expected events

Error source			$\sin^2 2\theta_{13}$=0		$\sin^2 2\theta_{13}$=0.1	
		N_{ND}	N_{SK}	N_{SK}/N_{ND}	N_{SK}	N_{SK}/N_{ND}
SK Norm.	f^{SKnorm}	$\pm$ 0.0	$\pm$ 1.4	$\pm$ 1.4	$\pm$ 1.4	$\pm$ 1.4
SK Energy Scale	f^{Energy}	$\pm$ 0.0	$\pm$ 1.1	$\pm$ 1.1	$\pm$ 0.6	$\pm$ 0.6
SK Ring Counting	$f^{N_{ring}}$	$\pm$ 0.0	$\pm$ 8.1	$\pm$ 8.1	$\pm$ 5.0	$\pm$ 5.0
SK PID Muon	$f^{PID\mu}$	$\pm$ 0.0	$\pm$ 0.9	$\pm$ 0.9	$\pm$ 0.3	$\pm$ 0.3
SK PID Electron	f^{PIDe}	$\pm$ 0.0	$\pm$ 7.8	$\pm$ 7.8	$\pm$ 4.9	$\pm$ 4.9
SK POLfit Mass	f^{POLfit}	$\pm$ 0.0	$\pm$ 8.5	$\pm$ 8.5	$\pm$ 6.0	$\pm$ 6.0
SK Decay Electron	$f^{N_{dcy}}$	$\pm$ 0.0	$\pm$ 0.3	$\pm$ 0.3	$\pm$ 0.2	$\pm$ 0.2
SK π^0 Efficiency	$f^{\pi^0 eff}$	$\pm$ 0.0	$\pm$ 3.4	$\pm$ 3.4	$\pm$ 0.9	$\pm$ 0.9
CC QE shape	$f^{CCQEshape}$	$\pm$ 0.0	$\pm$ 3.1	$\pm$ 3.1	$\pm$ 4.3	$\pm$ 4.3
CC 1π	$f^{CC1\pi}$	$\pm$ 5.9	$\pm$ 3.7	$\pm$ 2.2	$\pm$ 4.2	$\pm$ 1.8
CC Coherentπ	f^{CCcoh}	$\pm$ 3.3	$\pm$ 0.2	$\pm$ 3.1	$\pm$ 0.3	$\pm$ 3.0
CC Other	$f^{CCother}$	$\pm$ 4.7	$\pm$ 0.3	$\pm$ 4.4	$\pm$ 0.1	$\pm$ 4.5
NC $1\pi^0$	$f^{NC1\pi^0}$	$\pm$ 0.1	$\pm$ 5.4	$\pm$ 5.3	$\pm$ 1.5	$\pm$ 1.4
NC Coherentπ	f^{NCcoh}	$<$ 0.1	$\pm$ 2.3	$\pm$ 2.3	$\pm$ 0.6	$\pm$ 0.6
NC Other	$f^{NCother}$	$\pm$ 1.1	$\pm$ 3.5	$\pm$ 2.3	$\pm$ 1.0	$\pm$ 0.2
$\sigma(\nu_e)$	$f^{\sigma(\nu_e)}$	$<$ 0.1	$\pm$ 3.4	$\pm$ 3.4	$\pm$ 5.3	$\pm$ 5.3
FSI	f^{FSI}	$\pm$ 0.0	$\pm$ 10.1	$\pm$ 10.1	$\pm$ 5.4	$\pm$ 5.4
Beam Norm.	$f^{\phi}_{SK/ND}$	$\pm$ 15.4	$\pm$ 16.1	$\pm$ 8.5	$\pm$ 14.9	$\pm$ 8.5
ND Efficiency	$f^{\epsilon_{ND}}$	$^{+5.6}_{-5.2}$	$\pm$ 0.0	$^{+5.6}_{-5.2}$	$\pm$ 0.0	$^{+5.6}_{-5.2}$
Overall Norm.	f^{norm}	$\pm$ 0.0	$\pm$ 0.0	$\pm$ 2.7	$\pm$ 0.0	$\pm$ 2.7
Total		$\pm$ 18.4	$\pm$ 25.6	$^{+22.8}_{-22.7}$	$\pm$ 20.2	$^{+17.6}_{-17.5}$

ν_μ systematic error contributions

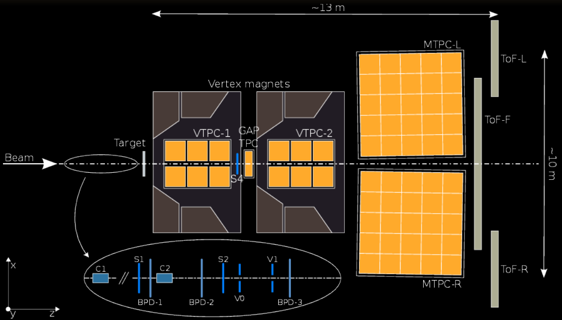
$N^{SK}_{exp.}$ error table

Error source	$\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$	Null Oscillation
SK Efficiency	+10.3% 10.3%	+5.1% -5.1%
Cross section and FSI	+8.3% -8.1%	+7.8% -7.3%
Beam Flux	+4.8% -4.8%	+6.9% -5.9%
ND Efficiency and Overall Norm.	+6.2% -5.9%	+6.2% -5.9%
Total	+15.4% -15.1%	+13.2% -12.7%

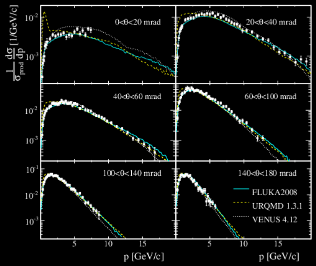
ν_μ systematic error contributions

Source of systematic errors	change of N^{SK}_{exp} ($\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$)	change of N^{SK}_{exp} ($\sin^2 2\theta = 1.0, \Delta m^2 = 2.32$)	change of N^{SK}_{exp} (Null Osc.)
f^{SK}_{CCQE0}	+1.0% -1.0%	+1.0% -1.0%	+1.4% -1.4%
f^{SK}_{CCQE1}			
f^{SK}_{CCQE2}	+3.2% -3.2%	+3.2% -3.2%	+3.1% -3.1%
f^{SK}_{CCQE3}			
f^{SK}_{CnCQE}	+6.5% -6.5%	+6.5% -6.5%	+3.3% -3.3%
f^{SK}_{NC}	+7.2% -7.2%	+7.0% -7.0%	+2.0% -2.0%
$f^{SK}_{CC\nu_e}$	+0.0% -0.0%	+0.0% -0.0%	+0.0% -0.0%
$f^{SK}_{E-scale}$	+0.0% -0.0%	+0.0% -0.0%	+0.0% -0.0%
f^{ND}	+6.2% -5.9%	+6.2% -5.9%	+6.2% -5.9%
f^{Xsec}_{CCQE}	+2.5% -2.5%	+2.4% -2.4%	+4.1% -4.1%
$f^{Xsec}_{CC1\pi}$	+0.4% -0.5%	+0.5% -0.6%	+2.2% -1.9%
$f^{Xsec}_{CCothers}$	+4.1% -3.6%	+4.1% -3.7%	+5.3% -4.7%
f^{Xsec}_{NC}	+0.9% -0.9%	+0.8% -0.8%	+0.8% -0.8%
$f^{Xsec}_{\nu_e/\nu_\mu}$	+0.0% -0.0%	+0.0% -0.0%	+0.0% -0.0%
f^{FSI}	+6.7% -6.7%	+6.6% -6.6%	+3.2% -3.2%
$f^{Flux}_{SK/ND}$	+4.8% -4.8%	+4.7% -4.7%	+6.9% -6.9%
Total	+15.4% -15.1%	+15.2% -14.9%	+13.2% -12.7%

NA61 experiment



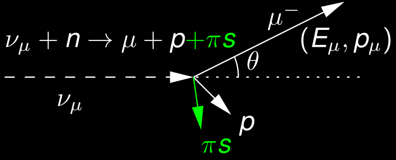
π^+ production spectra



- Large acceptance spectrometer
- TOF detectors
- 30 GeV proton beam
- Carbon targets
  - Thin 0.04λ
  - T2K replica
- $\pi^{\pm}$, $K^{\pm}$, K^0 production

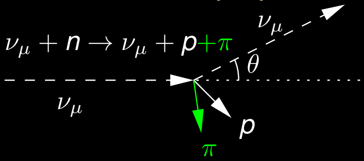
Backgrounds

CC-nQE



- Incorrect E_ν^{rec} determination

Neutral Current (NC)

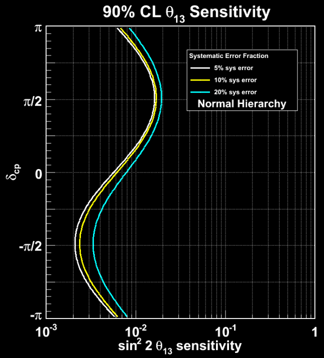


- π^0 can look like electron
- Hampers $\nu_\mu \rightarrow \nu_e$ search

- Intrinsic ν_e content in beam
- Muon/Electron separation

Full data set of 8×10^{21} pot (30 GeV)

ν_e appearance



- $\sin^2 2\theta_{12} = 0.8704$
- $\sin^2 2\theta_{23} = 1.0$
- $\delta m^2_{21} = 7.6 \times 10^{-5}\ \mathrm{eV}^2$
- $\delta m^2_{32} = 2.4 \times 10^{-3}\ \mathrm{eV}^2$

ν_μ disappearance

$$\delta(\sin^2 2\theta_{23}) < 0.01$$

$$\delta(\Delta m^2_{32}) < 10^{-4}\mathrm{eV}^2$$