New results from the T2K long baseline neutrino experiment

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For the T2K collaboration
The T2K Collaboration

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18/8/2011
1. Introduction to neutrino oscillations
2. Overview of the T2K experiment
3. Data collected by T2K
4. Oscillation analysis strategy
   1. Neutrino flux
   2. Neutrino interactions
   3. Near detector measurements
   4. Far detector selection and systematics
5. $\nu_\mu$ disappearance results
6. $\nu_e$ appearance results
7. Future of the T2K experiment
8. Future determination of $\theta_{13}$ (and CP violation?)
The flavor state of the neutrino, $\nu_\alpha$, is related to the mass states, $\nu_i$, by a non unity mixing matrix, $U_{\alpha i}$

$$|\nu_i> = \sum U_{\alpha i} |\nu_\alpha>$$

Since there are three observed flavors of neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$), $U$ contains three mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and a CP violating phase $\delta$.

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

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

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

“Atmospheric”: $\theta_{23} \sim 37^\circ - 53^\circ$

“CP sector”: $\theta_{13} < 11^\circ$

“Solar”: $\theta_{12} \sim 34^\circ$

Quark mixing: unitary matrix, small angles: $\theta^{CKM}_{12} \sim 13.0^\circ$, $\theta^{CKM}_{23} \sim 2.3^\circ$, $\theta^{CKM}_{13} \sim 0.2^\circ$

- Is $\theta_{23}$ exactly 45 degrees, or not?
- Is $\theta_{13}$ zero, or just small?
- Is there CP violation in the neutrino sector? Is it large?
- Is the mixing matrix unitary?
Neutrino oscillation: $\nu_\mu$ disappearance

Because of neutrino mixing, as the neutrinos propagate, the mass states interfere:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \text{Re}[U_{\beta i}U_{\alpha i}^*U_{\beta j}^*U_{\alpha j}]\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\sum_{i>j} \text{Im}[U_{\beta i}U_{\alpha i}^*U_{\beta j}^*U_{\alpha j}]\sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

Probability to observe $\nu_\beta$ after starting in flavor state $\nu_\alpha$ depends on:
- $L$ (km): Distance the neutrino has travelled
- $E$ (GeV): Energy of the neutrino
- $\Delta m^2$ (eV$^2$): Difference of the square of the mass eigenvalues

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

“Atmospheric”: $\Delta m_{23}^2 = 2.4 \times 10^{-3}$ eV$^2$

“Solar”: $\Delta m_{12}^2 = 7.59 \times 10^{-5}$ eV$^2$

Probability for $\nu_\mu$ oscillating into $\nu_x$:
Start with $\nu_\mu$ beam, will observe less at a later time, called “$\nu_\mu$ disappearance”

$$P(\nu_\mu \rightarrow \nu_{x\neq\mu}) = \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$
Existing measurements of $\nu_\mu$ disappearance

$\Delta m^2_{ij} = m_i^2 - m_j^2$

$L$, $E$ are determined from neutrino source

Extract $|\Delta m^2|$, $\sin^2 2\theta$ based on rate, energy spectrum after oscillation

Accelerator-produced neutrino beam (MINOS)
$L = 735 \text{ km}$, $E(\text{peak}) \sim 3 \text{ GeV}$

- $\Delta m^2_{23} = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2$
- $\sin^2 2\theta_{23} > 0.90$ (90% CL)

New result (2011) 1103.0340 [hep-ex]

- $\Delta m^2_{23} = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$ (68% CL)

Atmospheric neutrinos (Super-Kamiokande)
$L \sim 15 \text{ km} - 13,000 \text{ km}$, $E \sim 100 \text{ MeV} - 10 \text{ TeV}$

- $1.5 < \Delta m^2_{23} < 3.4 \times 10^{-3} \text{ eV}^2$
- $\sin^2 2\theta_{23} > 0.92$ (90% CL)

$P(\nu_\mu \rightarrow \nu_{x \neq \mu}) = \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{23} L}{4E} \right)$
Neutrino oscillation: $\nu_e$ appearance

Probability for $\nu_\mu$ oscillating into $\nu_e$ ($\nu_e$ appearance in $\nu_\mu$ beam)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right)$$

$$\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \left( \frac{\Delta m_{31}^2 L}{4E} \right)$$

$$+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \left( \frac{\Delta m_{31}^2 L}{4E} \right) \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right)$$

$\alpha = \Delta m_{12}^2 / \Delta m_{23}^2 \sim 0.04$

$\Delta m_{31}^2 \sim \Delta m_{23}^2$

Subleading terms depend on $\delta_{CP}$ differently for neutrinos (-) and antineutrinos (+)

Sakharov’s conditions require CP violation and baryon number violation
A.D. Sakharov, Pis’ma Zh. Eksp. Teor. Fiz. 5, 32 (1967) [JETP Lett. 5, 24 (1967)]

- CP violation in heavy, right handed neutrino decays creates lepton number asymmetry which can be converted to baryon number asymmetry (leptogenesis)

- CP violation with light neutrinos is suggestive of CP violation of the hypothetical heavy neutrino; see saw mechanism gives light neutrino mass and heavy partner
Existing measurements of $\nu_e$ appearance

Accelerator-produced neutrino beam (MINOS)
L=735 km, $E(\text{peak}) \sim 3$ GeV
- $2\sin^2\theta_{23}\sin^22\theta_{13} < 0.12$ (90% CL)
- $\nu_e$ and $\nu_\mu$ interact differently in matter which alters the oscillation probability
- “matter effects” depend upon sign($\Delta m^2$), called the mass hierarchy
  - $m_3 > m_1$ implies $\Delta m^2_{31} > 0$ (normal)
  - $m_3 < m_1$ implies $\Delta m^2_{31} < 0$ (inverted)
- MINOS is sensitive to this effect and so the limit depends on which hierarchy is assumed

Reactor $\bar{\nu}_e$ disappearance (CHOOZ)
L~1 km, $E\sim 3$ MeV
- $\sin^22\theta_{13} < 0.15$ at $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV$^2$
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The T2K experiment

T2K is designed to measure oscillations at the atmospheric $\Delta m^2$:
- Measure $\nu_\mu$ disappearance ($\Delta m^2_{23}$, $\theta_{23}$)
- Discover $\nu_e$ appearance? ($\theta_{13}$)

Produce a beam of $\nu_\mu$ on one side of Japan and detect it on the other
Creating an (offaxis) neutrino beam

Primary protons hit a target (carbon) producing secondary unstable mesons ($\pi, K$) which decay to a tertiary $\nu_\mu$ beam

At angles away from the parent pion’s direction, the neutrino energy is independent of pion momentum, resulting in a narrower neutrino energy spectrum.

Peak corresponds to oscillation maximum

Reduces backgrounds from higher energy neutrino interactions
Start with 30 GeV protons, produced at JPARC in Tokai-mura, Japan
The protons hit a 91 cm long graphite target, producing pions and kaons. The mesons are focused by three magnetic "horns" and then decay in a 100m long decay volume:

\[ \pi \rightarrow \mu + \nu_\mu \]

The muons are sampled using a pair of muon monitors as a real-time neutrino beam monitor.
Neutrino detectors

Off-axis@295km with Super-Kamiokande
Extract oscillation parameters from $\nu_\mu$, $\nu_e$ rates

On-axis with the INGRID detector
Determine neutrino beam direction

Off-axis with the ND280 detectors
Measure the unoscillated $\nu_\mu$ and $\nu_e$ rates
Constrain background processes
Neutrino interactions at T2K

Primary interaction is Charged Current Quasi-Elastic events
• Reconstruct neutrino energy from outgoing lepton
• Need e-μ separation for $\nu_e$, $\nu_\mu$ and momentum measurement

$CC\pi$ (single pion production) and $NC\pi$ are backgrounds
• $\nu_\mu$ disappearance: Same as CCQE if pion is not identified
• $\nu_e$ appearance: NC backgrounds are flux dependant and can mimic a $CC\nu_e$ interaction

• Final state interactions also alter how the underlying event is observed, e.g. absorption or charge exchange of $\pi^+$

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15
16 modules arranged in a cross
• X-Y iron-scintillator layers, 7.1 tons each
Count neutrino interactions in each module to determine neutrino rate vs. position
Extract beam direction better than 0.5 mrad
Monitor of neutrino beam vs. time
• \(~1.5 \nu / 10^{14}\) protons on target
• \(~10,000\) events / day
Suite of near detectors sit within UA1 (B=0.2T, 850 tons) magnet just above INGRID
- Current analysis use the Tracker to measure the unoscillated CC $\nu_\mu$ rate
- Future analyses will use ECals, P0D and SMRD

**Side Muon Range Detector**
- 87x17x0.7cm instrumented scintillator in magnet yoke
- Active veto, cosmic trigger

**Electromagnetic Calorimeters**
- X-Y Pb/scintillator planes
- P0D, Barrel, TPC3
- Tag photons, $e$ from Tracker and P0D

**Pi-zero Detector (P0D)**
- Pb/brass/scintillator planes with water bags (13.3 tons)
- Neutrino interaction target (CH+H$_2$O)
- Photons, electrons shower separable from MIPs
Example neutrino interactions in ND280

CC 1π
charged current
single pion production

\[ \nu_\mu \rightarrow W \rightarrow \Delta \rightarrow N' \]

CC neutrino interaction candidate

\[ \nu_\mu \rightarrow W \rightarrow \mu \rightarrow \text{track in TPC2} \]

CCQE
charged current
quasi-elastic

\[ \nu_\mu \rightarrow W \rightarrow \mu \rightarrow n \rightarrow p \]

Neutrino interaction upstream of ND280

Deep inelastic scattering candidate

P0D
DSECal

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295km away is the T2K far detector, Super-Kamiokande ("Super-K")

- 50kton water Cherenkov detector (22.5kton fiducial mass)
- 39.4 m diameter, 41.4 m tall cylindrical tank
- 11,129 inner photomultiplier tubes (PMTs) (40% photocathode coverage)
- 1885 veto PMTs located on the outside of the tank reject events entering the tank
- Cosmic ray rate in Kamioka mine is 1.77Hz at 2700m water equivalent
Neutrino events in Super-K

Cherenkov light emitted at a fixed angle produces ring(s) on the tank wall, recorded by PMTs

Muons from CC interactions produce well defined rings

Angle, momentum can be reconstructed from PMT charge, time information

Data event in Super-K: single muon

(c) Super-Kamiokande Collaboration
Neutrino events in Super-K

Electrons produce "fuzzy" rings, due to multiple scattering and showering
- CC $\nu_e$ events produce an electron
- Ability to tag electrons from $\mu$ decay from CC $\mu$ (deadtime-less DAQ)

Neutral pions produce two electron-like rings from decay photons
If one ring is not reconstructed, mimics CCQE $\nu_e$ signal

Data event: single electron
Scan over possible second ring directions and energies for a faint second ring
Select best match for observed light pattern
Cut on resulting invariant mass of two rings ($m\pi^0$) or $L_{2\gamma}/L_e$
Events with two true rings will have an invariant mass consistent with $\pi^0$
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Data collected

Run I: Jan 2010 – June 2010
6 bunches / spill / 3.54s
Stable running at $3.3 \times 10^{13}$ POT/spill
($\approx 54$ kW) with maximum at 100kW

Run II: Nov 2010–Mar 2011
8 bunches / spill / 3.04s
Stable running at 145 kW

Run I + Run II protons on target = $(0.32 + 1.11) \times 10^{20}$
= $1.43 \times 10^{20}$ POT (2% of T2K goal)
Neutrino beam stability

Neutrino rate at INGRID (1 point / day)
Stable to 1% over both run periods

Beam direction (x and y) at INGRID
Stable to <1 mrad

Beam direction (x and y) with the muon monitor
Stable to <1 mrad
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Analysis strategy

Neutrino flux prediction
Predict the flux from measurements of beam or external data (e.g. hadron production off the target)

Neutrino cross section prediction
Predict the cross section based on measurements of neutrino interactions at $E_{\nu} \sim 1 \text{ GeV}$
Neutrino flux prediction

Neutrino cross section prediction

Neutrino event rate at ND280 (CC $\nu_\mu$)

Compare prediction to inclusive ND280 CC $\nu_\mu$ selection
Extract a ratio of the rate R(CC $\nu_\mu$) between data and MC
Analysis strategy

Neutrino flux prediction

Neutrino cross section prediction

Neutrino event rate at ND280 (CC $\nu_\mu$)

Neutrino event rate at Super-K ($\nu_\mu, \nu_e$), with the normalization corrected by ND280

Correct the rate at Super-K by the normalization measured at ND280 and constrain the uncertainties
Analysis strategy

Neutrino flux prediction

Neutrino cross section prediction

Neutrino event rate at ND280 (CC $\nu_\mu$)

Neutrino event rate at Super-K ($\nu_\mu$, $\nu_e$), with the normalization corrected by ND280

Determine oscillation parameters
$\nu_\mu$ disappearance: $\Delta m^2_{23}$, $\theta_{23}$ (fit to energy spectrum)
$\nu_e$ appearance: $\theta_{13}$ (counting experiment)
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Neutrino flux prediction

Unoscillated flux at Super-K is $\nu_\mu$
- Also $\bar{\nu}_\mu$ (~6%)
- $\nu_e$ components (~1%)

Neutrinos at peak from $\pi^+$ decay, high energy flux from K decay

Geant3/FLUKA based flux prediction

Uncertainties are constrained with external measurements or in-situ monitors
Largest uncertainty is $\pi$, K production from the target (NA61 experiment)

<table>
<thead>
<tr>
<th>Source</th>
<th>ND</th>
<th>$\nu_e$ bkgd</th>
<th>$\nu_e$/ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam</td>
<td>2.2</td>
<td>0.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Pion production</td>
<td>5.7</td>
<td>6.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Kaon production</td>
<td>10.0</td>
<td>11.1</td>
<td>7.6</td>
</tr>
<tr>
<td>Other hadronic interactions</td>
<td>9.7</td>
<td>9.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Meson focusing, beam direction</td>
<td>2.8</td>
<td>2.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Total</td>
<td>15.4</td>
<td>16.1</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Total ($\nu_\mu$ signal) 4.8% after ND rate applied
@ $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV$^2$ $\sin^2 2\theta_{23} = 1.0$
π production from p+C

NA61/SHINE experiment at CERN
Designed to measure hadron production

30 GeV p beam on:
thin target (2cm) in 2007-2009 run
T2K replica target (91cm, 1.9λ) in 2010 run

Use TOF and dE/dx to select pions

Differential pion multiplicity reproduces simulation

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Neutrino interaction uncertainties

Cross section model, uncertainties set from external data at $E_\nu \sim 1$ GeV e.g. MiniBooNE, SciBooNE, K2K

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ signal</th>
<th>$\nu_e$ bkrd</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE nuclear model (@lowE)</td>
<td>2.5%</td>
<td>3.1%</td>
</tr>
<tr>
<td>CC1π</td>
<td>+0.4% -0.5%</td>
<td>2.2%</td>
</tr>
<tr>
<td>CC coherent π</td>
<td>+4.1% -3.6%</td>
<td>4.4%</td>
</tr>
<tr>
<td>NC all</td>
<td>0.9%</td>
<td>-</td>
</tr>
<tr>
<td>NC1π0</td>
<td>-</td>
<td>5.3%</td>
</tr>
<tr>
<td>NC coherent π</td>
<td>-</td>
<td>2.3%</td>
</tr>
<tr>
<td>NC other</td>
<td>-</td>
<td>2.3%</td>
</tr>
<tr>
<td>$\sigma(\nu_e)$</td>
<td>N/A</td>
<td>3.4%</td>
</tr>
<tr>
<td>Final State Interactions (FSI)</td>
<td>6.7%</td>
<td>10.1%</td>
</tr>
<tr>
<td>Total</td>
<td>+8.3% -8.1%</td>
<td>14.0%</td>
</tr>
</tbody>
</table>

- Modify $\pi$ re-interaction probabilities within cross section model according to external data to determine FSI uncertainty
- Alters the energy dependence of how backgrounds are reconstructed

$\nu_\mu$ signal @ $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV$^2$ $\sin^2 2\theta_{23} = 1.0$
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Basic CC $\nu_\mu$ selection in ND280

1. Require no tracks in TPC1 (veto P0D, sand $\nu$ interactions)
2. Select events which originate in FGD1 or FGD2 fiducial volume
3. Use the highest momentum, negative TPC2 or TPC3 track
4. Select $\mu$ from TPC $dE/dx$ information
ND280 CC $\nu_\mu$ sample

Reconstructed momentum and angle of the CC $\nu_\mu$ candidates after selection

- CC $\nu_\mu$ purity: 91%
- CCQE purity: 49%

No tuning to flux or cross section applied

Rate used to normalize expected number of events at far detector

$$R(\text{data/MC}) = 1.036 \pm 0.028 \text{ (stat)} \quad +0.044 \quad -0.037 \text{ (detector sys)} \quad \pm 0.038 \text{ (xsec model)}$$

Flux uncertainties on $\nu_e$ appearance analysis reduced by factor of 2 as a result

Dataset shown here: $2.88 \times 10^{19}$ POT
Select $\nu_e$ candidates at ND280 with TPC PID to check rate of intrinsic beam $\nu_e$

Additional backgrounds to $\nu_e$ selection, measured via control samples
- $\mu$ misidentified as $e$
- $e$ from photon conversion (photons emitted in $\nu_\mu$ interactions in FGD and other subdetectors)

Ratio of observed $\nu_e / \nu_\mu$ events is consistent with untuned prediction

$$\frac{N(\nu_e)}{N(\nu_\mu)} = R(e: \mu) = 1.0\% \pm 0.7\% \text{ (statistics)} \pm 0.3\% \text{ (systematics)}$$

$$\frac{R(e: \mu, \text{ data})}{R(e: \mu, \text{ MC})} = 0.6 \pm 0.4 \text{ (statistics)} \pm 0.2 \text{ (systematics)}$$

Improvements to the analysis:
- Improved rejection of backgrounds with ECals
- More data: $2.88 \times 10^{19}$ POT shown here
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Basic neutrino event selection at Super-K

**Basic neutrino selection (pre-cuts)**

- Event time within beam window
- No activity in the veto
- Visible E > 30 MeV
- Reconstructed vertex >2m from wall
- Single reconstructed ring

**Beam Time via GPS**

- Number of events / 40nsec vs. $\Delta T_0$ (nsec)

**Number of events vs. R^2 (cm^2)**

- Data vs. MC (w/ 2-flavor osc.)

**Number of events vs. Vertex Z (cm)**

- Data vs. MC (w/ 2-flavor osc.)

Events are consistent with expectation
$\nu_\mu$ and $\nu_e$ selection at Super-K

**$\nu_\mu$ selection**

1. $\mu$-like ring
2. $p_\mu > 200$ MeV/c
3. 0 or 1 decay electron

Signal CCQE $\nu_\mu$ Efficiency = 72%
Background CCnonQE Rejection = 79%

1. Select muon-like ring (CC $\nu_\mu$)
2. Sufficient momentum for $\mu$ PID
3. Reject CC1$\pi$ with decay electron cut
   - CCQE: $\mu \rightarrow e$
   - CC1$\pi$: above plus $\pi \rightarrow \mu \rightarrow e$

**$\nu_e$ selection**

1. Visible energy > 100 MeV
2. e-like ring
3. No decay electron
4. Invariant mass < 105 MeV/c$^2$
5. $E_\nu < 1250$ MeV

Signal $\nu_e$ Efficiency = 66%
Background Rejection:
- 77% for beam $\nu_e$
- 99% for NC

1. Energy above $\mu$, $\pi \rightarrow e$, $n \rightarrow \gamma$ threshold
2. Select electron-like ring (CC $\nu_e$)
3. Reject CC $\nu_\mu$ with decay electron cut
4. Remove NC$\pi^0$ background events
   - Calculate invariant mass assuming $2^{nd}$ ring
   - Reject invariant mass consistent with $\pi^0$
5. Beam CC $\nu_e$ have higher average energy than signal CC $\nu_e$
Super-K selection uncertainties

<table>
<thead>
<tr>
<th>Error source</th>
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<th>$\nu_e$ bkgd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring counting</td>
<td>3.9%</td>
<td>8.3%</td>
</tr>
<tr>
<td>Electron PID</td>
<td>3.8%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Invariant mass</td>
<td>5.1%</td>
<td>8.7%</td>
</tr>
<tr>
<td>$\pi^0$ rejection</td>
<td>-</td>
<td>3.6%</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Energy scale</td>
<td>0.4%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Decay electron eff</td>
<td>0.1%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Muon PID</td>
<td>-</td>
<td>1.0%</td>
</tr>
<tr>
<td>Total</td>
<td>7.6%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Evaluated with atmospheric $\nu$ control samples

Evaluated with a special control sample
- Select an atmospheric $\nu_e$ candidate
- Add a simulated photon to the event to create a \"hybrid $\pi^0$\"
- Difference in $\pi^0$ rejection efficiency between hybrid sample and pure simulated $\pi^0$ sample is set as uncertainty

Total uncertainty for $\nu_\mu$ analysis: 10.3% (predominantly ring counting)
Outline

1. Introduction to neutrino oscillations
2. Overview of the T2K experiment
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4. Oscillation analysis strategy
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   2. Neutrino interactions
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   4. Far detector selection and systematics
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6. $\nu_e$ appearance results
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ν_µ disappearance at T2K

For a fixed baseline (L=295km) oscillation probability is different for neutrinos of different energies

For a fixed baseline (L=295km) oscillation probability is different for neutrinos of different energies

Reconstruct neutrino energy from outgoing muon kinematics assuming QE interaction:

E_{ν}^{QE} = \frac{2M_{n}′E_{μ} - [M_{n}′^2 + m_{µ}^2 - M_{p}^2]}{2[M_{n}′ - E_{μ} + p_{µ}\cosθ_{µ}]}\]

Extract Δm^2, sin^22θ_{23} from observed change in overall rate and spectrum

Backgrounds are events where pion is unobserved (absorbed) or mistaken for muon

sin^2θ=1.0, Δm^2=2.4E-3eV^2

Note different scale!
ν\(_\mu\) disappearance results

31 events pass ν\(_\mu\) selection criterion; 103.7\(^{+16.6}_{-16.2}\) expected with no oscillations is excluded at 4.5σ.
No clustering in momentum, angle, radius according to background.
$\nu_\mu$ disappearance results

Two independent, 2 flavor, oscillation fits are consistent
- Method A: Maximum likelihood fit to normalization, spectrum shape, systematic parameters constrained in fit
- Method B: $\chi^2$ minimization fit over binned energy spectrum
  Both use Feldman-Cousins unified method to determine confidence intervals

Method A (solid)
Best fit: $\sin^2 2\theta_{23} = 0.99$, $|\Delta m^2_{23}| = 2.6 \times 10^{-3}$ eV$^2$
90%CL: $\sin^2 2\theta_{13} > 0.85$
2.1 $< |\Delta m^2| (\text{eV}^2) < 3.1 \times 10^{-3}$

Method B (dashed)
Best fit: $\sin^2 2\theta_{23} = 0.98$, $|\Delta m^2_{23}| = 2.6 \times 10^{-3}$ eV$^2$
90%CL: $\sin^2 2\theta_{13} > 0.84$
2.1 $< |\Delta m^2| (\text{eV}^2) < 3.1 \times 10^{-3}$
Consistent with previous measurements of $\nu_\mu$ disappearance (MINOS, Super-K)
1. Introduction to neutrino oscillations
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### νe appearance at T2K

**Background**

<table>
<thead>
<tr>
<th></th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam νe</td>
<td>0.76</td>
</tr>
<tr>
<td>νμ CC background</td>
<td>0.03</td>
</tr>
<tr>
<td>NC background</td>
<td>0.61</td>
</tr>
<tr>
<td>osc through θ_{12}</td>
<td>0.09</td>
</tr>
<tr>
<td>total:</td>
<td>1.49±0.34 (sys)</td>
</tr>
</tbody>
</table>

**Signal (νμ to νe osc)**

@sin^22θ_{13}=0.1,δcp=0  4.11
$\nu_e$ events after cuts

**$\nu_e$ selection**
- Visible energy $> 100$ MeV
- e-like ring
- No decay electron
- Invariant mass $< 105$ MeV/$c^2$
- $E_{\nu} < 1250$ MeV

6 candidate events observed for background of $1.49 \pm 0.34$
Basic distributions of $\nu_e$ candidates

Momentum, angle with respect to beam direction distributions are reasonable
Basic distributions of $\nu_e$ candidates

Clustering of candidates at high $R$ in beam direction
KS test of $R^2$ variable is 3% (does not include beam dir)
MC simulates neutrino interactions upstream of the detector (e.g. $\pi^0$ production)

- Only 1 $\nu_e$ event cut by FV selection (no excess of $\nu_e$ events outside FV)
- Dedicated sample of events entering tank (with activity in veto) agree
- No bias to radial distribution of atmospheric sample under T2K $\nu_e$ selection
Probability to see 6 events or more for for \( \sin^2 2\theta_{13} = 0 \) is 0.007 \((2.5\sigma \text{ equivalent})\)

Feldman-Cousins unified method
For \(|\Delta m^2_{23}| = 2.4 \times 10^{-3} \text{ eV}^2; \ \sin^2 2\theta_{23} = 1\)

Normal hierarchy \((\Delta m^2 > 0), \ \delta_{cp} = 0\)
best fit \(\sin^2 2\theta_{13} = 0.11\)
\(0.03 < \sin^2 2\theta_{13} < 0.28\) at 90\% C.L.

Inverted hierarchy \((\Delta m^2 < 0), \ \delta_{cp} = 0\)
best fit \(\sin^2 2\theta_{13} = 0.14\)
\(0.04 < \sin^2 2\theta_{13} < 0.34\) at 90\% C.L.

Excitement in the press

June 15th 2011

Neutrino particle 'flips to all flavours'

June 23rd 2011

Neutrinos
Delta force
A study of neutrinos may explain why things are made of matter, not antimatter
MINOS produced updated $\nu_e$ appearance results two weeks after T2K Overlay (not combined fit) of results indicates consistency.

L. Whitehead, Fermilab Wine and Cheese:
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http://www.kek.jp/intra-e/Introduction/column/110509map.html

Map of the damages at Tokai Campus (J-PARC)

1. Linac
2. 3GeV Synchrotron
3. 50GeV Synchrotron
4. Main Control Room
5. Material and Life Sciences Experimental Facility
6. 3 NBT
7. Neutrino Experimental Facility
8. Hadron Experimental Facility
9. Accelerator-Driven Transmutation Experimental Facility

3 GeV synchrotron power station
Road near 3 GeV RCS
LINAC
Neutrino Hall AC
Neutrino beam dump
It appeared there was a large misalignment in both horizontal and vertical directions.

~20 electromagnet mounts shifted more than a limit of simple adjustment.

All electromagnets will be realigned. Three teams will be done between August and October.
Plan is to resume experiment to make a determination of $\theta_{13}$, nonzero or not

- Accelerator is scheduled to resume in December
- Neutrino facility (near detector and beamline) are scheduled to be ready in November
- ND280 detectors were recommissioned and are operational
- 3rd horn was moved to remote handling cell and is OK

Enormous amount of work by collaborators, labs (KEK, JPARC) and funding agencies) to make this happen, to which we are very grateful

がんばれ、日本!
Keep it up, Japan!
Improvements to the oscillation analysis

Neutrino flux:
- NA61 results with K production
- NA61 results with replica target

Neutrino interactions:
- Add newer external data results
- e/π scattering data for FSI model

### Error source

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\nu_e$ bkrd</th>
<th>$\nu_\mu$ signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>±8.5</td>
<td>±4.8</td>
</tr>
<tr>
<td>$\nu$ flux</td>
<td>±14.0</td>
<td>+8.3 -8.1</td>
</tr>
<tr>
<td>$\nu$ interactions</td>
<td>±14.0</td>
<td>+8.3 -8.1</td>
</tr>
<tr>
<td>Near detector</td>
<td>+5.6 -5.2</td>
<td>+6.2 -5.9</td>
</tr>
<tr>
<td>Far detector</td>
<td>±14.7</td>
<td>±10.3</td>
</tr>
<tr>
<td>Total</td>
<td>+22.8 -22.7</td>
<td>+15.4 -15.1</td>
</tr>
</tbody>
</table>

ND280 (near) detector:
- Include CC $\nu_\mu$ spectrum information
- Improved CC $\nu_e$ measurement with ECal information; P0D HE $\nu_e$
- CCQE, $CC\pi^+$, $NC\pi^0$ measurements; O vs. C

Super-K (far) detector:
- Improved selection cuts, reconstruction for background separation
- Improved detector uncertainties and calibration techniques
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Other ways to measure $\theta_{13}$

Measure $\theta_{13}$ with $\bar{\nu}_e$ disappearance from intense MW reactor sources

$P(\nu_e \rightarrow \nu_{x\neq e}) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$

Use multiple detectors at different positions from reactor for a <1% measurement

Double Chooz is taking data with far detector since Dec 2010, near in 2012
Daya Bay detectors starts data taking this summer with near detector, all in 2012
Eventual sensitivity: $\sin^2 2\theta_{13} \approx 0.03 – 0.01$
Future measurements of $\delta_{CP}$

Long baseline experiments (T2K second phase, LBNE) can extract $\delta_{CP}$ by comparing $\nu_e$ appearance to $\bar{\nu}_e$ appearance:

\[
A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m_{12}^2 L}{4 E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta
\]

T2K creates a predominantly antineutrino beam by switching polarity of magnetic focusing horns to focus $\pi^-$ instead of $\pi^+$

Can combine results from a reactor with T2K ($\nu$ mode) to constrain values of $\delta_{CP}$ as long baseline experiments depend on $\delta_{CP}$ and $\theta_{13}$; reactors measure only $\theta_{13}$


Future long baseline experiments require very intense sources of neutrinos and or very large far detectors to make a determination of $\delta_{CP}$ at $>3\sigma$
The T2K experiment is designed to make precision measurements of:

- $\nu_\mu$ disappearance ($\Delta m^2_{23}, \theta_{23}$)
- $\nu_e$ appearance ($\theta_{13}$)

With dataset prior to the earthquake:

- Preliminary $\nu_\mu$ disappearance results are inconsistent with no-oscillation at 4.5$\sigma$ and consistent with previous experiments (MINOS, Super-K,K2K)
- 6 candidate $\nu_e$ events were observed, expected background is $1.49 \pm 0.34$

T2K will resume running to establish if $\theta_{13}$ is nonzero or not, conclusively

- Neutrino facility (beam, near detectors) ready to operate by November
- Accelerator is scheduled to resume in December 2011

T2K leads an exciting worldwide program in precision neutrino physics:

- Is $\theta_{23}$ maximal?
- Is $\theta_{13}$ nonzero?
- Is there CP violation in the neutrino sector?
Low rate of broken channels

Events / POT stable

Timing consistent with beam (FGD)
### $\nu_\mu$ selection (all cuts)

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>MC w/ 2-flavor oscillation</th>
<th>MC w/o osc.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>$\nu_\mu$ CCQE</td>
</tr>
<tr>
<td>Interaction in FV</td>
<td>-</td>
<td>141</td>
<td>24.0</td>
</tr>
<tr>
<td>FCFV</td>
<td>88</td>
<td>74.1</td>
<td>19.0</td>
</tr>
<tr>
<td>Single-ring</td>
<td>41</td>
<td>38.7</td>
<td>17.9</td>
</tr>
<tr>
<td>$\mu$-like</td>
<td>33</td>
<td>32.0</td>
<td>17.6</td>
</tr>
<tr>
<td>$P_\mu &gt; 200$ MeV/c</td>
<td>33</td>
<td>31.8</td>
<td>17.5</td>
</tr>
<tr>
<td>$N$(decay-e) $\leq$ 1</td>
<td>31</td>
<td>28.4</td>
<td>17.3</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>20 %</td>
<td>72 %</td>
</tr>
</tbody>
</table>

18/8/2011
K Mahn, TRIUMF seminar
νμ selection

Single-ring
μ-like
Pμ > 200 MeV/c
N(decay-e) ≤ 1

18/8/2011
# $\nu_e$ selection (all cuts)

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th><strong>BG expectation</strong></th>
<th>$\nu_{\mu} \rightarrow \nu_e$ expect.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>$\nu_{\mu}$ CC</td>
</tr>
<tr>
<td>Interaction in FV</td>
<td>-</td>
<td>141.3</td>
<td>67.2</td>
</tr>
<tr>
<td>FCFV</td>
<td>88</td>
<td>73.6</td>
<td>52.4</td>
</tr>
<tr>
<td>Single-ring</td>
<td>41</td>
<td>38.3</td>
<td>30.8</td>
</tr>
<tr>
<td>e-like</td>
<td>8</td>
<td>6.6</td>
<td>1.0</td>
</tr>
<tr>
<td>$E_{\text{vis}} &gt; 100$ MeV</td>
<td>7</td>
<td>5.7</td>
<td>0.7</td>
</tr>
<tr>
<td>No decay-e</td>
<td>6</td>
<td>4.4</td>
<td>0.1</td>
</tr>
<tr>
<td>$M_{\text{inv}} &lt; 105$ MeV/c²</td>
<td>6</td>
<td>1.9</td>
<td>0.04</td>
</tr>
<tr>
<td>$E_{\nu_{\text{rec}}} &lt; 1250$ MeV</td>
<td>6</td>
<td>1.3</td>
<td>0.03</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>1 %</td>
<td>&lt; 0.1 %</td>
</tr>
</tbody>
</table>
$\nu_e$ appearance results

6 candidate events are observed

PDF for expected number of Super-K $\nu_e$ events, including statistical and systematic errors

Blue: $\sin^2 2\theta_{13} = 0.1$
Red: $\sin^2 2\theta_{13} = 0$

$\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$
$\delta\text{cp}=0$
Future $\nu_e$ appearance sensitivity

90% CL $\theta_{13}$ Sensitivity

Pink line is final POT goal of T2K
Implications of large $\theta_{13}$ on future programme

Slide from Sam Zeller’s talk (informal discussion at FNAL about T2K results)
https://indico.fnal.gov/conferenceDisplay.py?confId=4546

- the asymmetry
  \[ \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \]
  is proportional to $\sim 1 / \sin\theta_{13}$

- the asymmetry gets smaller as $\theta_{13}$ increases
  \[ \sim 75\% \text{ for } \sin^2 2\theta_{13} = 0.01 \]
  \[ \sim 25\% \text{ for } \sin^2 2\theta_{13} = 0.10 \]
  $\delta_{CP} = \pi/2$
  factor $\sim 3$ reduction in CP asymmetry (independent of baseline)

- signal rate increases with $\theta_{13}$
  factor $\sim 10$ increase from 0.01 to 0.1
  so x3 improvement in stat sig of signal

(S. Parke)

(ignoring matter effects & backgrounds for now)

S. Zeller. FNAL. 06/17/11
Calculation of expectation at SK

\[ N_{SK}^{\exp} = R_{ND}^{\mu,\text{Data}} \times N_{SK}^{MC} / R_{ND}^{\mu,MC} \]

Ignoring sums over neutrino flavors, interaction modes

\[
\int \Phi_{\nu_\mu}^{SK}(E_\nu) \cdot P_{\text{osc}}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu) dE_\nu - \int \Phi_{\nu_\mu}^{ND}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu) dE_\nu
\]

- ND280 statistical uncertainty
- Flux uncertainty → expect cancellation in ratio
- Neutrino interaction cross section uncertainties
- SK reconstruction, selection uncertainties
- ND280 reconstruction, selection uncertainties

Slide from Mark Hartz’s FNAL seminar
Neutrino flux prediction

\( \nu_e \) comes from:
- \( \pi^+ \rightarrow \nu_\mu \) decay
- HE tail from \( K \rightarrow \nu_\mu \) decay (\( E_\nu > 2.5 \text{ GeV} \))

\( \nu_\mu \) comes from:
- \( \pi^+ \rightarrow \nu_\mu \) decay
- HE tail from \( K \rightarrow \nu_\mu \) decay (\( E_\nu > 1.5 \text{ GeV} \))
- \( \pi \rightarrow \mu \rightarrow \nu_\mu \) decay chain (\( E_\nu < 1.5 \text{ GeV} \))

---

Flux [\( 10^{21} \text{ POT/cm}^2/50 \text{MeV} \)]

ND280 Run I
- \( \nu_\mu \) at ND280
- \( \bar{\nu}_\mu \) at ND280
- \( \nu_e \) at ND280
- \( \bar{\nu}_e \) at ND280

SK Run I & Run II
- \( \nu_\mu \) at SK
- \( \bar{\nu}_\mu \) at SK
- \( \nu_e \) at SK
- \( \bar{\nu}_e \) at SK

18/8/2011
K Mann, TRIUMF seminar
Proton beam monitoring

Multiple beam monitors measure the proton beam on the way to the neutrino target.

Optical Transition Radiation is produced by the protons as they pass through a thin Ti foil in front of the neutrino target. The light is emitted perpendicular to the beam direction, and is recorded with a 40mm camera. OTR light is used to determine the beam profile and position on the target.
Error envelopes show the fractional error in each neutrino energy bin, but do not show correlations between bins. Error types described on slide 16.
Error envelopes show the fractional error in each neutrino energy bin, but do not show correlations between bins. Error types described on slide 16.
Neutrino interaction uncertainties

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ signal</th>
<th>$\nu_e$ bkrd</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE shape</td>
<td>2.5%</td>
<td>3.1%</td>
</tr>
<tr>
<td>CC1(\pi)</td>
<td>+0.4%</td>
<td>2.2%</td>
</tr>
<tr>
<td></td>
<td>-0.5%</td>
<td></td>
</tr>
<tr>
<td>CC coherent $\pi$</td>
<td>-</td>
<td>3.1%</td>
</tr>
<tr>
<td>CC other</td>
<td>+4.1</td>
<td>4.4%</td>
</tr>
<tr>
<td></td>
<td>-3.6%</td>
<td></td>
</tr>
<tr>
<td>NC all</td>
<td>0.9%</td>
<td>-</td>
</tr>
<tr>
<td>NC1(\pi^0)</td>
<td>-</td>
<td>5.3%</td>
</tr>
<tr>
<td>NC coherent $\pi$</td>
<td>-</td>
<td>2.3%</td>
</tr>
<tr>
<td>NC other</td>
<td>-</td>
<td>2.3%</td>
</tr>
<tr>
<td>$\sigma(\nu_e)$</td>
<td>N/A</td>
<td>3.4%</td>
</tr>
<tr>
<td>FSI</td>
<td>6.7%</td>
<td>10.1%</td>
</tr>
<tr>
<td>Total</td>
<td>+8.3</td>
<td>14.0%</td>
</tr>
<tr>
<td></td>
<td>-8.1%</td>
<td></td>
</tr>
</tbody>
</table>

$\nu_\mu$ signal assumes:

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

External data on $\pi^+$ interaction cross sections

- **FSI**: Modify $\pi$ re-interaction probabilities within cross section model according to external data to determine FSI uncertainty
- Alters the energy dependence of how backgrounds are reconstructed
Efficiency of CC $\nu_\mu$ events

Overall efficiency for CC $\nu_\mu$: 38.3 ±0.2% within FGD FV
Efficiency of CC $\nu_e$ events

Overall efficiency for CC $\nu_e$: 21.5 $\pm$ 0.6% (<2 GeV, within FGD FV)

Eff diff between $\nu_e$ and $\nu_\mu$ is due to:

• More stringent PID cuts (large mu misID reduction required)
• Large background at low energy from decay e and photons
Energy loss of the particle (dE/dx) can be used to separate particle type.

dE/dx resolution for MIPs is 8%.

Probability for a muon between 0.2 and 1.0 GeV to be identified using dE/dx as an electron is less than 0.2%.
Earthquake in Japan

On March 11th, 2011, Japan experienced a severe earthquake followed by a tsunami

- Magnitude 9 earthquake on Richter scale
- Magnitude 6+ at JPARC
- The tsunami did not reach JPARC
- Accelerator was not operating (maintenance day)

No reported injuries to members of the T2K collaboration or to JPARC employees
A reminder about neutrinos

In the Standard Model, there are three neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$
paired with an associated charged lepton partner: e, $\mu$, $\tau$

Neutrinos interact via the weak force ($W$, $Z$ bosons)

To detect neutrinos:
Need “nothing” coming in

Detect the outgoing lepton to determine neutrino flavor (CC only)

Nucleus can be excited or additional particles emitted (NC or CC)

18/8/2011
K Mahn, TRIUMF seminar