Neutrino Oscillation
Results from T2K

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on behalf of the T2K Collaboration

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Neutrino Oscillations

Neutrino flavor eigenstates related to mass eigenstates by PMNS mixing matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
c_{12} & s_{12} & 0 \\
-\bar{s}_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[s_{ij} = \sin \theta_{ij}, \quad c_{ij} = \cos \theta_{ij}\]

CPV phase \(\delta\)

Implies oscillation between flavors with probability:

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

What we know:

\(\theta_{23}, \Delta m_{23}^2\) – from atmospheric and accelerator neutrino experiments

\(\theta_{12}, \Delta m_{12}^2\) – from solar and reactor neutrino experiments

What we don’t know:

\(\text{Sgn}(\Delta m_{23}^2)\) – normal or inverted hierarchy \(\delta\) – need non-zero \(\theta_{13}\)

\(\theta_{13}\) – Can measure via \(\nu_\mu \rightarrow \nu_e\) oscillation:

\[
P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E_v}
\]
T2K Collaboration

~500 Members, 58 Institutes, 12 Countries
The T2K Experiment

- $\nu_\mu$ beam produced at JPARC in Tokai, Japan
  - 2.5 degree off axis to exploit $\pi$ decay kinematics $\rightarrow$ narrow band beam
- Super Kamiokande serves as the far detector
- Primary physics goals:
  - Discovery of $\nu_e$ appearance $\rightarrow$ non-zero $\theta_{13}$
  - Precision measurement of $\nu_\mu$ disappearance $\rightarrow$ $\theta_{23}$, $\Delta m^2_{23}$
T2K Neutrino Beamline

- Muon Monitor: Si array + IC array
- Horn: 3 Horns w/ 250kA
- Beam monitors: intensity, position profile
- Super-Conducting Magnets
- Near detector: (at 280m from target)
- Decay Volume: 110m length
- Target: Graphite, $\phi26 \times 900$ mm long
- Beam Dump: Helium cooling
- To Super-K
- Proton beam

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Run 1 + Run 2 Dataset

Run 1 (Jan – June 2010)
- 3.23x10^{19} p.o.t delivered

Run 2 (Nov 2010 – March 2011)
- 11.08x10^{19} p.o.t delivered
- Achieved 145 kW beam operation
- Ended 3/11/2011 due to earthquake

Total p.o.t 1.43x10^{20}, Less than 2% of T2K final goal
T2K Near Detectors

INGRID detector
- On axis near detector at 280 m
- 16 iron/scintillator modules
- Provide day-to-day monitoring of neutrino beam stability in rate, profile and direction

ND280 off-axis near detector
- 2.5° off-axis, 280 m from beam origin
- Detectors installed in recycled UA1 magnet
- Provide measurements of neutrino spectra prior to oscillation
- Provide cross-section measurements of important background channels
Near Detector Measurements

**ν_μ CC Inclusive**
- Select tracks beginning in FGD and identified as μ-like by the TPC
- Measured data/MC ratio provides normalization of expected number of events at SK

\[
R = 1.036 \pm 0.028 \text{(stat)} \pm 0.044 \text{(det. syst)} \pm 0.038 \text{(phys model)}
\]

**Beam ν_e Component**
- Select ν_e interactions in the FGD with tracks indentified as e-like using TPC dE/dx
- Largest source of background to ν_e oscillation analysis

\[
R(ν_e / ν_μ) = (1.0 \pm 0.7 \text{(stat)} \pm 0.3 \text{(syst)})
\]
Oscillation Analysis
Oscillation Analysis Overview

Flux Prediction
- Proton beam measurement
- Hadron production (NA61)

ND280 Measurements
- CC $\nu_\mu$ inclusive
- Beam $\nu_e$ component

Neutrino Interactions
- Interaction models
- External cross-section data

SK Measurement
- Selection of $\nu_\mu$ and $\nu_e$ signal candidates
- Compute signal expectation without oscillation
- Renormalize expectation using ND280 measurement
- Evaluate oscillation parameters using observed events
Flux Prediction

- T2K proton beam monitor measurements provide inputs to flux simulation
- Data from NA61 Experiment at CERN used to model pion production in target
- Kaon production modeled with FLUKA
- Out of target interactions, horn focusing, particle decays
  - GEANT3 simulation
  - Interaction cross sections tuned to existing data
Super Kamiokande Event Selection

Predefined event selection criteria for $\nu_\mu$ and $\nu_e$

1. Event time coincident with beam ($\pm 500\mu$s)

2. Event fully contained in ID, vertex reconstructed in fiducial volume (> 200 cm from wall in r and z)

3. Single ring event

4. PID parameter of ring consistent with electron or muon

Further event selection for specific analyses
$\nu_\mu$ disappearance analysis
SK $\nu_\mu$ Event Selection

- 33 single ring $\mu$-like events remain

- Additional cuts
  1. Less than 2 reconstructed decay electrons
  2. Reconstructed muon momentum larger than 200 MeV

- 31 events pass all selection cuts

<table>
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<tr>
<th>Interaction in FV</th>
<th>Data</th>
<th>MC w/ 2-flavor oscillation</th>
<th>MC w/o OSC.</th>
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<td>$P_{\mu} &gt; 200$ MeV/c</td>
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<td>N(decay-e) ≤ 1</td>
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<td>3 %</td>
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<tr>
<td></td>
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<td>43 %</td>
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</table>
Remaining $\nu_\mu$ Events

- We observe 31 events after all selection cuts
  - Expect 103.7 assuming no oscillation
  - Expect 28.3 w/ $\sin^2(2\theta_{23}) = 1$, $\Delta m^2_{23} = 2.4 \times 10^{-3}$
- Null-oscillation hypothesis excluded at 4.5$\sigma$
$\nu_\mu$ Analysis Results

- 2 flavor neutrino oscillation fit
  \[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2(1.27\Delta m^2_{23} L / E) \]
- 2 different fits performed
  - One allows varying systematic errors, the other fixes them
- Feldman-Cousins method used to construct confidence intervals

**Analysis Results:**

Best fit 1: $\sin^2(2\theta_{23}) = 0.99, |\Delta m^2_{23}| = 2.6 \times 10^{-3}$ eV$^2$

Best fit 2: $\sin^2(2\theta_{23}) = 0.98, |\Delta m^2_{23}| = 2.6 \times 10^{-3}$ eV$^2$

**Confidence intervals (90% C.L.)**

$\sin^2(2\theta_{23}) > 0.85, \quad 2.1 \times 10^{-3} < |\Delta m^2_{23}| < 3.1 \times 10^{-3}$ eV$^2$

$\sin^2(2\theta_{23}) > 0.84, \quad 2.1 \times 10^{-3} < |\Delta m^2_{23}| < 3.2 \times 10^{-3}$ eV$^2$

Good agreement between the analyses
\( \nu_e \) appearance analysis
SK $\nu_e$ Event Selection

8 single-ring e-like events remain

Further cuts are applied to reduce backgrounds

1. Visible energy $> 100$ MeV
2. No decay electrons
3. $M_{\text{inv}}$ with forced second ring $< 105$ MeV
4. Reconstructed neutrino energy $< 1250$ MeV

6 events remain after all selection cuts
## Remaining $\nu_e$ Events

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_{exp}$</th>
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<tr>
<td>Beam $\nu_e$</td>
<td>0.76</td>
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<tr>
<td>$\nu_\mu$ Neutral Current</td>
<td>0.61</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_e$ (solar)</td>
<td>0.09</td>
</tr>
<tr>
<td>$\nu_\mu$ Charged Current</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.49±0.34</strong></td>
</tr>
</tbody>
</table>

- We observe 6 events remaining after all selection cuts
  - Expect only 1.5 events from background ($\sin^2(2\theta_{13})=0$)
  - Expect 5.5 events assuming $\sin^2(2\theta_{13}) = 0.1$

- Vertex distribution of these events show clustering at large $R$
- KS test of $R^2$ distribution gives $p$-value of 0.03
- Do not observe accumulation of events outside the FV or in the OD
**ν_e Analysis Results**

- Confidence intervals produced using the Feldman-Cousins method
- Probability of observing 6 events if $\sin^2(2\theta_{13}) = 0 \rightarrow 0.7\% \ (2.5\sigma)$
- Normal hierarchy, $\delta = 0 \ 0.03 < \sin^2(2\theta_{13}) < 0.28$ at 90% C.L.
  - Best fit: $\sin^2(2\theta_{13}) = 0.11$
- Inverted hierarchy, $\delta = 0 \ 0.04 < \sin^2(2\theta_{13}) < 0.34$ at 90% C.L.
  - Best fit: $\sin^2(2\theta_{13}) = 0.14$

![Diagram showing confidence intervals for normal and inverted hierarchies]
Summary

• The $\nu_\mu$ disappearance and $\nu_e$ appearance analyses have been performed on a dataset corresponding to $1.43 \times 10^{20}$ p.o.t. (2% of T2K goal)

• $\nu_e$ appearance analysis:
  – 6 events observed (expect $1.5 \pm 0.03$)
  – Probability of observing 6 events with $\theta_{13}=0$ is $0.7\%$ ($2.5\sigma$)
  – 90% confidence interval of $0.03(0.04) < \sin^2(2\theta_{13}) < 0.28(0.34)$ for normal (inverted) hierarchy and $\delta = 0$

• $\nu_\mu$ disappearance analysis:
  – Null oscillation hypothesis excluded at $4.5\sigma$
  – $\sin^2(2\theta_{23}) > 0.85$ and $2.1 \times 10^{-3} < \Delta m^2_{23} < 3.1 \times 10^{-3}$ (90% CL)

• Recovery from earthquake:
  – Plan to restart accelerator by end of 2011
  – T2K will resume data taking soon after
Backup
Far Detector – Super Kamiokande

• 50 kton (22.5 fiducial) water Cherenkov detector
• Inner detector: ~11,000 20” PMTs
• Outer detector: ~8,000 8” PMTs
• Good e/μ identification using Cherenkov light pattern
  – Muons produce clean Cherenkov rings
  – Electrons produce “fuzzy” rings due to electromagnetic showers
NA61 Experiment

Large acceptance spectrometer and TOF detectors
30 GeV proton beam
Two types of targets used
0.04 \( \lambda \) “thin target”
T2K replica “long target”

Measure differential pion production multiplicity
5-10% systematic uncertainties for each point in \( p-\theta \) space
2.3% normalization uncertainty
Uncertainties propagated into oscillation analysis
NA61 data reproduced by FLUKA
Event Display of $\nu_e$ Candidate

Super-Kamiokande IV
T2K Beam Run 36 Spill 1039222
Run 67969 Sub 921 Event 218931934
10-12-22-14:15:18
T2K beam dt = 3782.6 ns
Inner: 4894 hits, 99.0 pe
Outer: 4 hits, 3 pe
Trigger: 0x80000007
D_wall: 244.2 cm
e-like, $p = 1049.0$ MeV/c

Charge (pe)
- $>26.7$
- 23.3–26.7
- 20.2–23.3
- 17.3–20.2
- 14.7–17.3
- 12.2–14.7
- 10.0–12.2
- 8.0–10.0
- 6.2–8.0
- 4.7–6.2
- 3.3–4.7
- 2.2–3.3
- 1.3–2.2
- 0.7–1.3
- 0.2–0.7
- $< 0.2$
Comparison of $\nu_\mu$ Analysis Results

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Comparison of $\Delta m^2$ and $\sin^2(2\theta)$ for different experiments.}
\end{figure}