New Results from the T2K Experiment: 
ν_e Appearance in a ν_μ Beam

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(on behalf of the T2K Collaboration)

Lomonosov Conference
22 August 2013
Neutrino Mixing

- Neutrinos have mass!

**Flavour eigenstates:** $\nu_e, \nu_\mu, \nu_\tau$

**Mass eigenstates:** $\nu_1, \nu_2, \nu_3$

1998 onwards: Probed with atmospheric neutrinos, long baseline accelerator neutrinos (SK, K2K, MINOS)

First measured last year! Short baseline reactor neutrinos (Daya Bay, RENO, DoubleChooz);
Long baseline accelerator neutrinos (T2K, MINOS, NOvA)

2001 onwards: Probed with solar neutrinos, long baseline reactor neutrinos (SK, SNO, KamLAND)
Experimental Probes

For Dirac neutrinos, standard parameterization of the PMNS matrix $U_{li}$ (for Dirac neutrinos) has:

- 3 mixing angles
- 2 mass square differences
- 1 CP phase

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix} \times \begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix} \times \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \times \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- $\sin^2(2\theta_{23}) > 0.95$ (90% C.L.)
- $\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3}$ eV$^2$
- $\sin^2(2\theta_{12}) = 0.857 \pm 0.024$
- $\Delta m^2_{12} = 7.59 \pm 0.20 \times 10^{-5}$ eV$^2$
- $\sin^2(2\theta_{13}) = 0.098 \pm 0.013$

What is the CP violating phase $\delta$? What is the mass hierarchy?
Oscillation @Accelerators

Long baseline accelerator:  
- Search for $\nu_e$ appearance  
- Sensitive to $\theta_{13}$, $\delta$, mass hierarchy

$\nu_e \nu_\mu \nu_\tau$

$P_{\mu \rightarrow \mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right)$

$P_{\mu \rightarrow e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right)$
Experimental goals:

- **Search for $\nu_e$ appearance** (focus of this talk)
- **Precision $\nu_\mu$ disappearance** (new results coming soon!)
- **Other ($\nu$ cross sections, sterile $\nu$ searches, etc.)**
T2K Collaboration

~ 500 members, 59 Institutes, 11 countries

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN

Poland
IEJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool

U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

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Previous T2K ν Osc. Results

2012 ν<sub>e</sub> Appearance

- 2011: Observe 6 evts (w/ BG 1.5 ± 0.3)
  - First indication of non-zero θ<sub>13</sub>
  - (2.5σ significance)

- 2012: Observe 11 evts (w/ BG 3.3 ± 0.4)
  - 3.1σ evidence for non-zero θ<sub>13</sub>

2013 ν<sub>μ</sub> Disappearance

- 2013: Competitive measurement of θ<sub>23</sub>
  - arXiv: 1308.0465

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Neutrino Beam

T2K is the first experiment to use an off-axis neutrino beam:

- Enhances signal at oscillation maximum
- Reduces backgrounds from other energies – e.g., $\pi^0$ BG greater at higher $E_\nu$
T2K Data Taking

- T2K analysed data for today's presentation: $6.39 \times 10^{20}$ P.O.T.
  - We have accumulated $6.63 \times 10^{20}$ P.O.T. to date
  - Previous $\nu_e$ appearance result (2012) used $3.01 \times 10^{20}$ P.O.T. → Statistics increased by factor $>2!$
- Thus far, ~8% of the total data has been collected (assuming design goal)
- Instantaneous luminosity of 220 kW ($1.2 \times 10^{14}$ protons per pulse) → World record!
- Many thanks to the J-PARC accelerator division for their efforts and much hard work

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Near Detector Suite

**INGRID (On-axis)**

- 16 modules of iron and scintillator
  - 14 in “cross” configuration
- Monitors stability of neutrino beam:
  - Direction: Off-axis angle determines narrow-band beam energy
  - Event rate: To confirm targeting efficiency

**ND280 (Off-axis)**

- Sits in 0.2 T magnetic field
- Tracker comprised of:
  - 2 Fine-Grain Detectors (FGDs)
    → 1.6 t plastic scintillator primary target
  - Detailed vertex information
  - 3 Time Projection Chambers (TPCs)
    → Track momentum from curvature
    → Particle identification from dE/dx
**GOAL:** Constrain neutrino flux & cross section parameters used for oscillation prediction (via MC) at T2K far detector

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<thead>
<tr>
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<tbody>
<tr>
<td>$M_A^{QE}$ (GeV/c²)</td>
<td>$1.27 \pm 0.19$</td>
<td>$1.22 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>$M_A^{RES}$ (GeV/c²)</td>
<td>$1.22 \pm 0.13$</td>
<td>$0.96 \pm 0.06$</td>
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<tr>
<td>CCQE Norm.</td>
<td>$0.95 \pm 0.09$</td>
<td>$0.96 \pm 0.08$</td>
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<tr>
<td>CC1π Norm.</td>
<td>$1.37 \pm 0.20$</td>
<td>$1.22 \pm 0.16$</td>
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- Significant reduction for event rate errors at the far detector
- Uncertainties on the cross section & flux parameters have been reduced

Error on Far Detector $\nu_e$ Prediction (After Near Detector Constraint)

- $\sin^2 2\theta_{13} = 0.1$: 4.7%, 3.5%, 3.0%
- $\sin^2 2\theta_{13} = 0.0$: 6.1%, 5.2%, 4.9%
Super-Kamiokande (far)

- 50,000 tonne water Chereknov detector
- 22.5 kton fiducial mass
- Inner Detector (ID) has 11,129 inward facing 50cm PMTs for ~40% photocathode coverage
- Outer Detector (OD) has 1885 20cm PMTs; OD used as passive shielding + active veto
- Stable operation for many years
- Good reconstruction in energy range of T2K beam
- Well-understood particle identification (see next slide)
SK Particle Identification

Muons:
- Minimal scattering
- Ring has sharp edges

Electrons:
- Electromagnetic shower
- EM scattering makes a "fuzzy" ring

Neutral Pions:
- $\gamma$s from $\pi^0$ decays shower and look like electrons

- Reliable PID particularly crucial to $\nu_e$ appearance analysis
- PID well-established at KEK beam test (1kton tank) in 1990s
**T2K $\nu_e$ Signal & BG**

- **Oscillation signal:**
  \[ \nu_\mu \rightarrow \nu_e \]
  - $e^-$
  - $p$ (undetected)

- **Beam $\nu_e$ background:**
  \[ \nu_e \rightarrow e^- \]
  - $1.56 \pm 0.20$ evts (2012)
  - $p$ (undetected)
  - Beam background has harder energy spectrum

- **Neutral current $\pi^0$ background:**
  \[ \nu_\mu \rightarrow \pi^0 \gamma \gamma \]
  - $1.26 \pm 0.35$ evts (2012)
  - N+others (undetected)
  - Can be removed by identifying second photon ring

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Improved $\pi^0$ Rejection

- New likelihood fitter used to distinguish electrons from $\pi^0$
- Assumes two electron-like rings produced at a common vertex
- Uses 12 parameters in fit:
  - Vertex ($X, Y, Z, T$)
  - Directions ($\theta_1, \varphi_1, \theta_2, \varphi_2$)
  - Momenta ($p_1, p_2$)
  - Conversion lengths ($c_1, c_2$)
- This 2D cut removes 70% of the $\pi^0$ background remaining after previous selection applied (for same signal efficiency)
- Total background is reduced by 27%
- 6.36 BG events $\rightarrow$ 4.64 BG events expected (in full Run 1 – 4 dataset)
**T2K $\nu_e$ Event Selection**

**$\nu_e$ Selection Criteria**

- # clustered veto hits < 16
- Distance to wall > 200 cm
- # of rings = 1
- PID of ring is e-like
- Visible energy > 100 MeV
- no Michel electrons
- New likelihood $\pi^0$ cut
- $0 < E_{\nu} < 1250$ MeV
\[ \nu_e \] Appearance Analysis

- **Expected background:**
  - \( 4.64 \pm 0.53 \) events

- **With the following assumptions:**
  - \( \sin^2 (2\Theta_{13}) = 0.1 \)
  - \( \sin^2 (2\Theta_{23}) = 1 \)
  - \( \delta_{\text{CP}} = 0 \)
  - normal mass hierarchy

  the expected signal is:
  - \( 20.4 \pm 1.8 \) events
  - \( 5.5 \sigma \) sensitivity to exclude \( \Theta_{13} = 0 \)

- **Oscillation parameters were extracted with two parallel analyses:**
  - Using the 1D \( E_\nu \) distribution (top)
  - Using the 2D \( p-\theta \) distribution (bottom)
ν\text{e} Appearance Results

- **28 ν\text{e} events observed** (recall 20.4 ± 1.8 expected for \(\sin^2(2\theta_{13}) = 0.1\))
- Comparison to null hypothesis gives **7.5\sigma** significance for \(\theta_{13} \neq 0\)

First direct observation (>5\sigma) of a ν appearance channel!

(N.B. These are 1D contours for various values of \(\delta_{\text{CP}}\) not 2D contours)
Other T2K Results: Cross Sections

- The near detectors can also be used to make cross section measurements.
- The T2K charged current inclusive cross section measurement was published earlier this year:
  - Uses same near detector event selection as 2012 osc. analysis.
- The CCQE sample from the 2012 osc. analysis has been used to measure $\sigma_{\text{CCQE}}(E_{\nu})$.
- Additional cross section results expected soon...

![T2K CC-Inclusive Cross Section Measurement](image)
Other T2K Results: $\nu_\mu$ Disappearance

- Preliminary results using Run 1 – 3 data ($3.01 \times 10^{20}$ P.O.T.) were first shown earlier this year
- Contours for both octants ($\theta_{23} < \pi/4$ and $\theta_{23} > \pi/4$) now provided (above)
  - Previously, only first octant ($\theta_{23} < \pi/4$) reported
- New $\nu_\mu$ disappearance results coming soon
  - Future results will be reported as $\sin^2(\theta_{23})$ NOT $\sin^2(2\theta_{23})$ to remove octant ambiguity
First observation of electron neutrino appearance!

- T2K has measured $\nu_e$ appearance in a $\nu_\mu$ beam
- $\theta_{13} = 0$ is excluded at the 7.5$\sigma$ level (assuming $\delta_{CP} = 0$ and $\theta_{23} = 45^\circ$)

Neutrino beam at J-PARC achieved stable operation with a 220 kW beam power

A total exposure of $6.39 \times 10^{20}$ P.O.T. has been collected & analysed to 2013-Apr-12, more than doubling the data sample used for the previous (2012) analysis

- A total of $6.63 \times 10^{20}$ P.O.T. has been accumulated

Near detector CC-inclusive cross section measurement has been published; other cross section measurements are on the way

Many other exciting results to come:

- A new $\nu_\mu$ disappearance measurement will be out soon
- Combined $\nu_\mu + \nu_e$ joint analysis is underway
- Comparison of accelerator results from T2K with reactor anti-neutrino results (measuring only $\theta_{13}$) may provide insight to $\delta_{CP}$ and mass hierarchy
Supplemental Slides
Open Questions

- **Q:** What do we still need to know?
- **A:** Two big questions in front of us now:

1) What is the CP violating phase $\delta$?
2) What is the mass hierarchy?

Ambiguity in sign of $m_3^2 - m_2^2$

Two possible mass hierarchies

$\rightarrow$ Electron neutrino appearance can help answer both questions!
Oscillation Probabilities

**Long baseline accelerator:** Sensitive to $\theta_{13}$, $\delta$, mass hierarchy

\[
P(\nu_\mu \rightarrow \nu_e) = \frac{4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}}{4} + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21}
\]

\[
-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} + 4S_{12}^2 C_{13}^2 (C_{12} C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21}
\]

where:

- $C_{ij} = \cos(\theta_{ij})$
- $S_{ij} = \sin(\theta_{ij})$
- $\Delta_{ij} = \Delta m_{ij} (L/E)$

CP violating (flips sign for anti-$\nu$)

**Short baseline reactor:** Sensitive only to $\theta_{13}$

\[
P_{\text{sur}} \approx 1 - \sin^2 2\theta_{13} \sin^2 (1.267 \Delta m_{31}^2 L/E)
\]
Beam Stability: Rate & Direction

Beam dir. stability < 1 mrad

Beam is quite stable in space (1 mrad tolerance) and time (within 1%)

INGRID neutrino event rate stable to <1% over full run period
Reconstructing $\nu$ Energy

- Only final state lepton is reconstructed
- Neutrino energy can be determined with certain assumptions:
  - Neutrino direction is known (beam direction)
  - Recoil nucleon mass is known (use neutron mass)
  - Target nucleon is at rest (not quite true; introduces smearing)

\[ E_{\nu}^{QE} = \frac{2 M_n E_e - (M_n^2 + m_e^2 - M_p^2)}{2 \left[ M_n - E_e + \sqrt{E_e^2 - m_e^2 \cos \theta_e} \right]} \]
Neutrino Interactions

- In the region of interest for T2K, large contribution from charge current quasi-elastic scattering:

  \[ \nu_e, \nu_\mu \rightarrow e^-, \mu^- \]

  [Diagram showing T2K signal at SK]

- Also significant CC contribution with pion in final state

- NC\(\pi^0\) is a major background mode from electron appearance:

  [Diagram showing T2K beam peak energy]

  Photons from \(\pi^0\) can fake electron signal
A Typical $\nu_e$ Candidate

Super-Kamlokanade IV
T2K Beam Run 0 Spill 1039222
Run 67969 Sub 921 Event 218931934
10-12-12:14:15:18
T2K beam dt = 1782.6 ns
Inner: 4804 hits, 9970 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

visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c²
recon. energy : 1120.9 MeV
Vertex Distributions

Vertex distributions for $\nu_e$ candidates at the far detector:

<table>
<thead>
<tr>
<th></th>
<th>RUN1+2+3</th>
<th>RUN4</th>
<th>RUN1+2+3+4</th>
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<tbody>
<tr>
<td>$D_{wall}$</td>
<td>34.4%</td>
<td>54.7%</td>
<td>20.9%</td>
</tr>
<tr>
<td>Fromwall beam</td>
<td></td>
<td>6.04%</td>
<td>85.6%</td>
</tr>
<tr>
<td>$R^2 + Z$</td>
<td>32.4%</td>
<td>98.1%</td>
<td>64.5%</td>
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</tbody>
</table>