Latest Results from T2K

*Observation of Electron Neutrino Appearance from a Muon Neutrino Beam*

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July 19, 2013
ICRR seminar

Official release of this result is to be at EPS conference in Stockholm.

Strict press embargo time: 21:30 (JST) on July 19th, 2013
No e-mails, no phone calls, no blogs, no tweets, ... until 21:30
Summary

- T2K has made the definitive observation of $\nu_e$ appearance from the $\nu_\mu$ beam
  - Using $6.39 \times 10^{20}$ Protons-On-Target beam data ($\times 2.1$ of 2012 analysis) obtained by the stable beam and detector operations
  - Analysis improvements also contributed: Improved Near $\nu$ Detector analysis, Improved $\pi^0$ background rejection at Super-K Far $\nu$ Detector, ...
  - 28 candidate events over $4.6 \pm 0.5$ (sys.) backgrounds
  - $\theta_{13} = 0$ is excluded at $7.5\sigma$

→ We have entered the era of $\nu_e$ appearance “measurement” for exploring the leptonic CPV and $\nu$ mass hierarchy!

- Now is the time to realize a new project in Japan
  - Hyper-K has great potential for discovering new physics
  - Need your strong support to the project
Neutrino Oscillation

- **Flavor eigenstate** \((\nu_e, \nu_\mu, \nu_\tau) \neq \text{Mass eigenstate} (\nu_1, \nu_2, \nu_3)\)

\[
\begin{pmatrix}
\nu_\alpha \\
\nu_\beta
\end{pmatrix} = \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

Two-flavor case

- Probability that a neutrino originally generated as \(\nu_\alpha\) will later be observed as \(\nu_\beta\) after traveling a distance of \(L\):

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 (2\theta) \sin^2 \left( \frac{1.27 \Delta m^2 (eV^2) L (km)}{E_\nu (GeV)} \right)
\]

\(\Delta m^2 = m_2^2 - m_1^2\)

\(\nu\) oscillation experiments:

- Measure the disappearance of \(\nu_\alpha\)
- Measure the appearance of \(\nu_\beta\)
Unknowns in Neutrino Oscillation Parameters

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

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

- \(\theta_{12} = 33.6^\circ \pm 1.0^\circ\) Solar \(\nu\), KamLAND
- \(\theta_{23} = 45^\circ \pm 6^\circ\) (90\%CL) Atm. \(\nu\), Acc. \(\nu\)
  \(\theta_{23}\): How close to 45°? Octant? (<45°, >45°?)
- \(\theta_{13} = 9.1^\circ \pm 0.6^\circ\)

Neutrino Mass Hierarchy

- Normal OR Inverted

\(\sim 7.6\text{e-}5\text{ eV}^2\)
\(\sim 2.4\text{e-}3\text{ eV}^2\)

Indication of \(\theta_{13}\neq0\) by T2K
PRL107, 041801 (2011)

Later precise measurements by reactor \(\nu\) experiments
\( \theta_{13} \) Measurements

- **Reactor neutrino experiments**: \( \bar{\nu}_e \) disappearance

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{1.27 \Delta m^2_{31} L(m)}{E_\nu(MeV)} \right)
\]

- **Accelerator neutrino experiments**: \( \nu_e \) appearance

\[
P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2 \theta_{23} \sin^2 \left( \frac{1.27 \Delta m^2_{31} L(km)}{E_\nu(GeV)} \right)
\]

Sub-leading terms:

\[
\begin{align*}
+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
+4S_{12}^2 C_{13}^2 (C_{12} C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21} \\
-8C_{13}^2 S_{13}^2 S_{23}^2 \frac{aL}{4E_\nu} (1 - 2S^2_{13}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \\
+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m^2_{31}} (1 - 2S^2_{13}) \cdot \sin^2 \Delta_{31}
\end{align*}
\]

\( \delta \rightarrow -\delta \)
\( a \rightarrow -a \)

for \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \)

Sensitivity to CPV phase \( \delta \) and \( \nu \) mass hierarchy

Opens the possibility to explore CPV in the lepton sector

NOTE: solar/atmospheric \( \nu \) data are also sensitive to \( \theta_{13} \)
T2K (Tokai-to-Kamioka) Experiment

Discovery of $\nu_e$ appearance ($\nu_\mu \rightarrow \nu_e$ oscillation)

- Direct detection of $\nu$ flavor mixing ($\theta_{13} \neq 0$) by an “appearance” channel
- Opens the possibility to probe the leptonic CP violation

Precision measurement of $\nu_\mu$ disappearance

- $\delta(\Delta m^2_{32}) \sim 1 \times 10^{-4} \text{eV}^2$, $\delta(\sin^2 2\theta_{23}) \sim 0.01$
T2K Data-Taking and ν_e Search History

In 2011
- First indication of ν_e appearance (2.5σ) using RUN1-2 data (2% of T2K full stat.)
- In 2012
- >3σ signal of ν_e appearance using RUN1-3 data (4% of T2K full stat.)

Earthquake (2011.3.11)

11 events over 3.3±0.4(sys.) bkgs

~5σ ν̅_e disappearance (Daya Bay/RENO)
Data Set in this Talk

Steady beam data accumulation during T2K RUN4
- Beam power reached 235kW
- Very stable Super-K operation: livetime ≈ 99%

Previous analysis (2012): RUN1+2+3, $3.010 \times 10^{20}$ POT (Protons-On-Target)

This analysis (2013): RUN1+2+3+4 (by April 12th), $6.393 \times 10^{20}$ POT

Analyzed up to April 12th, 2013
30GeV protons from J-PARC MR

**Near detectors**
- Target & Horns
- Muon monitor

**Decay volume**
- π⁺
- μ⁺

**Off-axis ν beam**
- Intense narrow-band @osc. max. (~0.6GeV)
  - Reduce high energy tail which creates BG

**Off-axis ν detector (ND280)**
- Measures ν flux/spectrum before oscillations @2.5° OA
- 0.2T magnet field

**SCMRD (magnet yolk)**
- ECAL
- Tracker
- FGD
- TPC

**Fine-Grained Detectors (FGDs)**
- Scintillator strips, 1.6t fiducial target, Detailed vertex info.

**Time Projection Chamber (TPCs)**
- Gas ionization, Momentum by curvature, PID by dE/dx

**NIM A659, 106 (2011)**
- 2.5° beam center
- 295km
- 0 120m 280m
Beam Stability

INGRID on-axis ν detector monitors beam intensity, direction, and profile.

- POT normalized ν event rate is very stable (<1%)
- Beam direction is controlled well within the design requirement of 1mrad (→ 2% shift in the peak energy of ν spectrum)
T2K Far $\nu$ Detector : Super-Kamiokande

- 50kton Water Cherenkov detector
  - 22.5kton fiducial mass
  - World largest "$\nu$ & proton-decay" detector

- Located in the Kamioka Observatory
  - 295km from J-PARC

- Excellent detection capability
  - Ring-shaped pattern on the detector wall

- Atmospheric $\nu$ data as control samples to study detector performance

- T2K trigger records all the PMT hits within $\pm 500\mu$s of the beam arrival time
  - Time synchronization by GPS
Electron/Muon PID at Super-K

- Particle identification using ring shape and opening angle
- Probability that a muon is mis-identified as an electron is <1%
- Very small $\nu_\mu$ CC background for $\nu_e$ appearance search
Signal and BG for T2K $\nu_e$ appearance search

signals

Single electron event by CC interaction of $\nu_e$ oscillated from $\nu_\mu$
- Mainly CCQE: $\nu_e + n \rightarrow e^- + p$
- Protons mostly have momenta below Cherenkov threshold

backgrounds

(1) intrinsic $\nu_e$ in the beam (from $\mu$, K decays)
(2) NC single $\pi^0$ events
  - overlap of 2 $\gamma$ rings
  - asymmetric decay
    (one of the $\gamma$ has very low energy)
Oscillation Analysis Strategy

**Neutrino Flux**
MC simulation of beamline based on hadron production meas. (NA61/SHINE) and beam monitor meas.

**Neutrino Interaction**
Model (NEUT) tuned/constrained with external data

**ND280 Measurements**
- $\nu_\mu$ CC enhanced samples (CC0$\pi$, CC1$\pi^+$, and CCother)
- Intrinsic $\nu_e$ and NC $\pi^0$ measurements as cross-check

**Constraint on flux & cross section**

**SK Prediction**

**Oscillation parameter fit**

**SK Data : $\nu_e$ candidates**
Predicted Neutrino Flux

**Fractional Error on $\nu_\mu$ flux @SK**

- Total
- Hadronic Interactions
- Proton Beam, Alignment and Off-axis Angle
- Horn Current & Field
- MC Stat.

**Fractional Error on $\nu_e$ flux @SK**

- Total
- Hadronic Interactions
- Proton Beam, Alignment and Off-axis Angle
- Horn Current & Field
- MC Stat.

$\nu_e$ fraction: <1% @ $E_\nu$ peak

Total flux error: 10~15%
Near Detector Constraint on SK Prediction

- SK flux parameters are constrained through their prior correlations with the ND280 $\nu_\mu$ flux parameters

\[ \nu_e \text{ and } \nu_\mu \text{ fluxes are correlated through parent hadrons} \]

- Subset of cross section parameters are correlated at near & far detectors: $M_A^{QE}$, $M_A^{RES}$, CCQE/CC$1\pi$/NC$1\pi^0$ normalizations
ND Fit Data Inputs

New $\nu_\mu$ CC sample classification: CC0$\pi$, CC1$\pi^+$, CCother

- In 2012 analysis, 2 categories: CCQE-like (1 track) & CCnonQE-like (2 tracks)
- Much better samples for constraining CCQE & CC1$\pi$ cross section parameters

Data are binned in two dimensions: $\mu$ momentum ($p$) and angle ($\cos \theta$)

- Finer binning than 2012 analysis

### Composition

<table>
<thead>
<tr>
<th></th>
<th>CCQE</th>
<th></th>
<th>CCQE</th>
<th></th>
<th>CCQE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>63.5 %</td>
<td></td>
<td>5.3 %</td>
<td></td>
<td>3.9 %</td>
<td></td>
</tr>
<tr>
<td>CCQE</td>
<td></td>
<td></td>
<td>Resonant</td>
<td>20.2 %</td>
<td>Resonant</td>
<td>39.5 %</td>
</tr>
<tr>
<td>Resonant</td>
<td>20.2 %</td>
<td></td>
<td>DIS</td>
<td>7.5 %</td>
<td>DIS</td>
<td>31.3 %</td>
</tr>
<tr>
<td>DIS</td>
<td>7.5 %</td>
<td></td>
<td>Coherent</td>
<td>1.4 %</td>
<td>Coherent</td>
<td>10.6 %</td>
</tr>
<tr>
<td>Coherent</td>
<td>1.4 %</td>
<td></td>
<td>Other</td>
<td>7.4 %</td>
<td>Other</td>
<td>13.3 %</td>
</tr>
<tr>
<td>Other</td>
<td>7.4 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Near Detector Distributions after the Fit

<table>
<thead>
<tr>
<th>(# of events)</th>
<th>CC0π</th>
<th>CC1π⁺</th>
<th>CCother</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>16912</td>
<td>3936</td>
<td>4062</td>
</tr>
<tr>
<td>Unconstrained MC</td>
<td>20016</td>
<td>5059</td>
<td>4602</td>
</tr>
<tr>
<td>Constrained MC</td>
<td>16803</td>
<td>3970</td>
<td>4006</td>
</tr>
</tbody>
</table>

Improved agreement after the fit
Constrained SK Flux and Cross Section Params

### Significant error reduction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior to ND Constraint</th>
<th>After ND Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{A}^{\text{QE}}$ (GeV)</td>
<td>$1.21 \pm 0.45$</td>
<td>$1.22 \pm 0.07$</td>
</tr>
<tr>
<td>$M_{A}^{\text{RES}}$ (GeV)</td>
<td>$1.41 \pm 0.22$</td>
<td>$0.96 \pm 0.06$</td>
</tr>
<tr>
<td>CCQE norm.</td>
<td>$1.00 \pm 0.11$</td>
<td>$0.96 \pm 0.08$</td>
</tr>
<tr>
<td>CC1$\pi$ norm.</td>
<td>$1.15 \pm 0.32$</td>
<td>$1.22 \pm 0.16$</td>
</tr>
</tbody>
</table>
T2K $\nu_e$ event selection at Super-K

1. Beam on-timing & Fully-contained (FC) in the inner detector
2. Vertex in the fiducial volume
3. Number of rings = 1
4. Electron-like PID
5. Visible energy > 100MeV
   - rejects low energy NC events and electrons from invisible $\mu, \pi$ decays
6. No delayed electron signal
   - rejects events with invisible $\mu, \pi$
7. Reconstructed $\nu$ energy < 1.25GeV
   - rejects intrinsic beam $\nu_e$ at high energy
8. Non-$\pi^0$-like

Improved by New Algorithm

Developed new $\pi^0$ rejection algorithm. The other cuts unchanged.
A New Event Reconstruction Tool: fiTQun

\[ L(x) = \prod_i P(i_{\text{unhit}}|x) \prod_i P(i_{\text{hit}}|x) f_q(q_i|x) f_t(t_i|x) \]

- A maximum likelihood fitter
- For a given track(s) hypothesis, a charge and time PDF is produced for every PMT
  - Charge PDF can be factorized into predicted charge and PMT response
- Track parameters \( x \) (vertex, direction, momentum, ...) are fit simultaneously to maximize the likelihood
  - Step-by-step reconstruction in the previous algorithm
  - For PID, compare final likelihoods for \( \pi^0 \) and electron assumptions
\( \pi^0 \) Background Rejection by fiTQun

This time, we use the fiTQun reconstruction only at the \( \pi^0 \) rejection cut (fiTQun will also improve vertex/angle/momentum resolutions, PID, etc.)

T2K MC events with \( \geq 1 \, \pi^0 \)

T2K MC \( \nu_e \) CC signal events

Horizontal: Reconstructed \( \pi^0 \) mass
Vertical: Likelihood ratio of \( \pi^0 \) and 1-ring electron hypotheses

Clear separation
**π⁰ Background Rejection by fiTQun**

Performance evaluation using “π⁰ particle guns” MC  
(with a flat momentum 0-500MeV/c)

Reconstructed π⁰ mass  

\[ \begin{align*}
\text{fiTQun} & \quad \text{POLfit} \\
\text{(original algorithm)} & \\ 
\end{align*} \]

**π⁰ rejection efficiency**

\[ \begin{align*}
\text{fiTQun} & \quad \text{POLfit} \\
\text{(original algorithm)} & \\ 
\end{align*} \]

True energy of the less energetic γ (MeV)

The 2nd γ ring is missed by POLfit. fiTQun doesn’t have such a pileup at zero, and the low mass tail is lower than POLfit.

fiTQun is more sensitive to lower energy photons than POLfit.  

**Improved performance**
## Predicted Number of Events at Each Cut

<table>
<thead>
<tr>
<th>Cut Description</th>
<th>$\nu_{\mu} CC$</th>
<th>$\nu_{e} CC$</th>
<th>NC</th>
<th>BG all</th>
<th>Sig. $\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>True FV</td>
<td>308</td>
<td>15.0</td>
<td>272</td>
<td>594</td>
<td>25.6</td>
</tr>
<tr>
<td>(2) FCFV</td>
<td>234</td>
<td>14.4</td>
<td>76.5</td>
<td>325</td>
<td>24.8</td>
</tr>
<tr>
<td>(3) 1 ring</td>
<td>135</td>
<td>9.2</td>
<td>21.6</td>
<td>166</td>
<td>21.5</td>
</tr>
<tr>
<td>(4) e-like</td>
<td>5.3</td>
<td>9.1</td>
<td>14.9</td>
<td>29.3</td>
<td>21.2</td>
</tr>
<tr>
<td>(5) $E_{\text{vis}}&gt;100\text{MeV}$</td>
<td>3.5</td>
<td>9.1</td>
<td>12.7</td>
<td>25.2</td>
<td>20.9</td>
</tr>
<tr>
<td>(6) No decay-e</td>
<td>0.7</td>
<td>7.4</td>
<td>10.6</td>
<td>18.7</td>
<td>18.6</td>
</tr>
<tr>
<td>(7) $E_{\nu\text{rec}}&lt;1.25\text{GeV}$</td>
<td>0.2</td>
<td>3.5</td>
<td>8.0</td>
<td>11.8</td>
<td>17.9</td>
</tr>
<tr>
<td>(8) fiTQuin $\pi^0$ cut</td>
<td>0.06</td>
<td>3.1</td>
<td>0.9</td>
<td>4.0</td>
<td>16.4</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&lt;0.1%</td>
<td>20%</td>
<td>0.3%</td>
<td>0.7%</td>
<td>64%</td>
</tr>
<tr>
<td>(8)' POLfit $\pi^0$ cut</td>
<td>0.12</td>
<td>3.2</td>
<td>2.3</td>
<td>5.6</td>
<td>16.8</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&lt;0.1%</td>
<td>21%</td>
<td>0.8%</td>
<td>0.9%</td>
<td>66%</td>
</tr>
</tbody>
</table>

NC BG reduced to ~40% compared to previous $\nu_e$ selection with keeping signal efficiency high

With $\sin^2 2\theta_{13} = 0.1$

$6.393 \times 10^{20}$ POT

unit = events

New Cut

Old Cut
Far Detector (Super-K) Stability

- **μ → e mis-PID**
  - RMS: 0.14%

- **e → μ mis-PID**
  - RMS: 0.19%

**Stable**

- **Decay-e tagging eff.**
  - ± 2%
Far Detector (Super-K) Systematics

Dominant error coming from the ring-counting, PID, $\pi^0$ rejection cuts

Error for $\nu_e$ CC components:
- Number of events in each $(p_e, \theta_e)$ in the atmospheric $\nu$ control sample is fit to evaluate the sys. errors on efficiencies

Error for $\pi^0$ BG components:
- $\pi^0$ topological control sample combining one data electron and one simulated $\gamma$ (hybrid $\pi^0$)

SK systematic error on predicted # of $\nu_e$ candidates is reduced (thanks to the new $\pi^0$ rejection)

$3.0\% \ (2012) \rightarrow 2.4\% \ \text{at} \ \sin^2 2\theta_{13} = 0.1$
**Predicted Number of $\nu_e$ Candidate Events**

### Predicted # of events w/ 6.393×10^{20} p.o.t.

<table>
<thead>
<tr>
<th>Category</th>
<th>$\sin^2 2\theta_{13} = 0$</th>
<th>$\sin^2 2\theta_{13} = 0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ signal</td>
<td>0.38</td>
<td>16.42</td>
</tr>
<tr>
<td>$\nu_e$ BG</td>
<td>3.17</td>
<td>2.93</td>
</tr>
<tr>
<td>$\nu_\mu$ BG</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu + \nu_e$ BG</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.64 ± 0.52</strong></td>
<td><strong>20.44 ± 1.80</strong></td>
</tr>
</tbody>
</table>

### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sin^2 2\theta_{13} = 0$</th>
<th>$\sin^2 2\theta_{13} = 0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux + $\nu$ int. (ND meas.)</td>
<td>4.9 %</td>
<td>3.0 %</td>
</tr>
<tr>
<td>$\nu$ int. (from other exp.)</td>
<td>6.7 %</td>
<td>7.5 %</td>
</tr>
<tr>
<td>Super-K + FSI + SI + PN</td>
<td>7.3 %</td>
<td>3.5 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.1 %</strong></td>
<td><strong>8.8 %</strong></td>
</tr>
<tr>
<td><strong>Total (2012)</strong></td>
<td><strong>13.0 %</strong></td>
<td><strong>9.9 %</strong></td>
</tr>
</tbody>
</table>

**Uncertainty reduced much by the ND measurement**
T2K Event Selection at Super-K

1. Event timing relative to the beam arrival timing

FC = Fully-Contained events

2. Fiducial volume cut

Spill structure (8 bunches) is clearly seen

Inner detector wall

FV boundary (2m from wall)
T2K $\nu_e$ Event Selection at Super-K

3. Number of rings = 1
   186 events

4. Electron-like PID
   58 events

5. Visible energy >100MeV
   Rejects low-E NC events, and electron from invisible $\mu$, $\pi$
   55 events

6. No $\mu$ decay electron
   Rejects events with invisible $\mu$, $\pi$
   43 events
T2K $\nu_e$ Event Selection at Super-K (cont’d)

7. Reconstructed $E_\nu < 1.25$ GeV
Reject intrinsic $\nu_e$ in the beam (high energy $\nu_e$ mainly from K)

8. fiTQun $\pi^0$ rejection cut
Reject events with $\pi^0$

28 events after all cuts

38 events

4.64 ± 0.52 events expected for $\sin^2 2\theta_{13} = 0$
20.44 ± 1.80 events expected for $\sin^2 2\theta_{13} = 0.1$
Observed $\nu_e$ Candidate Events (Several Examples)

All events have a clear showering ring
**ν_e Candidate Event Distributions**

**Vertex X-Y**
- Beam dir.
- ID wall
- FV boundary

**Direction (cosθ_{beam})**
- Number of events
- cos θ_{beam}

**Cumulative # of ν_e candidates vs. POT**
- KS probability to the constant event rate assumption = 97%

**Reasonable distributions**

**RUN1-4 data**
(6.393×10^9 POT)
- Osc. ν_e CC
- ν_e+ν_e CC
- ν_e+ν_µ CC
- NC
(MC w/ sin^2 2θ_{13} = 0.1)
Oscillation Parameter Fits

- Method 1: Maximum likelihood fit w/ Rate + ($p_e, \theta_e$) shape
- Method 2: Maximum likelihood fit w/ Rate + reconstructed $E_\nu$

\[
\mathcal{L}(N_{\text{obs.}}, x; o, f) = \mathcal{L}_{\text{norm}}(N_{\text{obs.}}; o, f) \times \mathcal{L}_{\text{shape}}(x; o, f) \times \mathcal{L}_{\text{syst.}}(f)
\]

**Method 1**

\[\nu_e \text{ signal} \]

\[\nu_e \text{ background} \]

**Method 2**

\[\nu_\mu \text{ background} \]

Shape difference allows to have a better discrimination of signal events from background

\[\sin^2 \theta_{13} = 0.1\]
\[\delta_{CP} = 0\]
\[\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2\]

(area normalized)
Sensitivity (Expected Significance to Exclude $\theta_{13}=0$)

Averaged log likelihood curve over many toy data with true $\sin^22\theta_{13}=0.1$

(Assuming $\delta_{\text{CP}}=0$, $\sin^22\theta_{23}=1.0$, and normal mass hierarchy)

RUN1-4 vs. RUN1-3 POT

-2*$\Delta$ ln$L^1$ vs. $\sin^22\theta_{13}$

RUN1-4 POT : 5.5$\sigma$
RUN1-3 POT : 3.9$\sigma$

w/ vs. w/o ND Constraint

-2*$\Delta$ ln$L^1$ vs. $\sin^22\theta_{13}$

w/ ND info. : 5.5$\sigma$
w/o ND info. : 4.7$\sigma$

NEW vs. OLD SK Selection

-2*$\Delta$ ln$L^1$ vs. $\sin^22\theta_{13}$

NEW (fiTQun) : 5.5$\sigma$
OLD (POLfit) : 5.0$\sigma$

Significance = $\sqrt{-2\Delta \ln L_{\theta_{13}=0}}$
RUN1-4 Data Fit Results : Method 1 (p-θ)

**Normal Hierarchy**

-2*ln L

**Inverted Hierarchy**

-2*ln L

Assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1.0$

$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$  

Best-fit values w/ 68% confidence intervals

$0.182^{+0.046}_{-0.040}$

$\theta_{13}=0$ is excluded at 7.5σ  

→ Definitive observation of electron neutrino appearance!
RUN1-4 Data Fit Results : Method 1 (p-θ)

Data and best-fit MC distributions

68%/90% C.L. regions for $\sin^2 2\theta_{13}$ for each value of $\delta_{CP}$

- **Normal Hierarchy**
  - Assuming $\sin^2 2\theta_{23}=1.0$

- **Inverted Hierarchy**
  - Assuming $\sin^2 2\theta_{23}=1.0$

**Momentum vs. Angle (p-θ)**

- Run1-4 data (6.393e20 POT)
- Best-fit $\sin^2 2\theta_{13} = 0.150$
- Assuming $\delta_{CP}=0$
- Normal hierarchy, $|\Delta m^2_{31}|=2.4\times10^{-3}\text{ eV}^2$
RUN1-4 Data Fit Results: Method 2 (rec. $E_\nu$)

Data and best-fit MC:
Reconstructed $E_\nu$ distribution

Assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1.0$

$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034} \quad \text{(NH)}$$

$$\sin^2 2\theta_{13} = 0.184^{+0.046}_{-0.041} \quad \text{(IH)}$$

Consistent with Method 1 results
**Effect of $\theta_{23}$ Uncertainty**

- $\nu_e$ appearance probability also depends on the value of $\theta_{23}$

\[
P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(\Delta m^2_{31} L/4E)
\]

- T2K $\nu_e$ appearance measurement in cooperation with other experiments may give some hint on $\theta_{23}$ octant
T2K Next Step:

Can T2K measure $\delta_{CP}$, Mass Hierarchy, $\theta_{23}$ Octant?

Detailed sensitivity studies are ongoing

- True NH
  - True $\sin^2 \theta_{23} = 0.5$
  - $\delta_{CP} = 0^\circ$
  - $\delta_{CP} = 90^\circ$

- NH
  - 90% CL

50% $\nu + 50\%$ anti-$\nu$

Full T2K stat.

w/ ultimate $\theta_{13}$ meas. w/o NOvA

Significance to exclude $\sin \delta = 0$:

Solid: stat. error only
Dashed: current sys.

T2K will make run plans (anti-$\nu$ run, ...) based on these studies.
Observation of $\nu_e$ appearance has just been made by T2K

→ We’ve entered the era of $\nu_e$ appearance “measurement”

T2K may constrain $\delta_{CP}$, mass hierarchy, and $\theta_{23}$ octant (in cooperation with reactor experiments, NOvA, and SK)

But, significance may not be large

To get a definitive conclusion on CPV and to measure $\delta_{CP}$, next generation long-baseline experiments are indispensable

Higher intensity beam + Larger neutrino detector

NOW IS THE TIME to realize a new project in Japan
Hyper-Kamiokande Project

Exploring full picture of neutrino oscillation
- w/ Higher intensity ν beam from J-PARC, Atmospheric ν

Astrophysical neutrinos
- Solar ν, Supernova, WIMP, solar flare, ...

Neutrino geophysics

Proton decay search

Total Mass : 0.99 Mton
Fiducial Mass : 0.56 Mton (x25 of Super-K)
\( \delta_{CP} \) Measurement (Accelerator \( \nu \))

x25 larger \( \nu \) target

= T2K x50

\( \sim 0.6 \text{GeV} \)

2.5° off-axis

x2 more beam \( \nu \)

7.5MW \text{year, } \nu: \text{anti-} \nu = 3:7, \text{ NH (known)}

\( \sin^2 2\theta_{13} = 1 \)

\( \delta_{CP} \)

\( \sin^2 2\theta_{13} \)

\( \delta \) precision (1\( \sigma \) error size)

< 20° at \( \delta = 90° \)

< 10° at \( \delta = 0° \)

For 74% of \( \delta \), \( \sin \delta = 0 \) is excluded with >3\( \sigma \)
Mass Hierarchy & $\theta_{23}$ Octant Sensitivity (Atm. $\nu$)

$<$10 years HK atmospheric $\nu$ data can determine the MH w/ $3\sigma$.
(Higher significance and earlier in larger $\theta_{23}$ case)

If $\sin^2 2\theta_{23} < 0.99$ (\(\sin^2 \theta_{23} < 0.45\) or $>0.55$), $\theta_{23}$ octant can be determined at $>3\sigma$ using 10 years of HK atmospheric $\nu$ data.
More Hyper-K Physics

Nucleon decay search
• x10 better sensitivity than SK
• >3σ discovery is possible for lifetime beyond SK limits

Supernova burst ν
• 250,000 ν (SN@10kpc)
• Variation of ν luminosity, temperature, flavor, ...
• MH determination?

Relic supernova ν
• 80 events/year (w/ Gd)

• 200 solar ν/day → ~3σ day/night asym.
• WIMP ν, Solar flare ν, ...
R&D Work and Studies ongoing

- Detector design optimization
  - Cavern stability, Tank shape, Number of compartments, PMT support structure, ...
- New photo-sensor development
  - Hybrid Photo Detector (HPD), Higher QE photo-cathode
- Water purification system
- Electronics/DAQ system
  - Electronics immersed in water?
- Software development
- Physics potential studies
  - Requirements for near detectors

Better performance w/ lower cost
International Hyper-K Working Group

Hyper-K is open to the international community

Three open meetings at IPMU (Kashiwa)

- **1st mtg in August 2012**
  - 100 participants at each mtg.
  - ~50% from abroad

- **2nd mtg in January 2013**

- **3rd mtg in June 2013**

- **Formed international WG**
  - Canada, Spain, Switzerland, Russia, U.K., U.S., and Japan

You are VERY WELCOME to join us!
Summary

- T2K has made the definitive observation of $\nu_e$ appearance from the $\nu_\mu$ beam
  - Using $6.39 \times 10^{20}$ Protons-On-Target beam data ($\times 2.1$ of 2012 analysis) obtained by the stable beam and detector operations
  - Analysis improvements also contributed: Improved Near $\nu$ Detector analysis, Improved $\pi^0$ background rejection at Super-K Far $\nu$ Detector, ...
  - 28 candidate events over $4.6 \pm 0.5$ (sys.) backgrounds
  - $\theta_{13} = 0$ is excluded at $7.5\sigma$

→ We have entered the era of $\nu_e$ appearance “measurement” for exploring the leptonic CPV and $\nu$ mass hierarchy!

- Now is the time to realize a new project in Japan
  - Hyper-K has great potential for discovering new physics
  - Need your strong support to the project
Supplement