Recent results from T2K

Yoshinari Hayato
for the T2K collaboration
Introduction

Neutrino oscillation ~ discovered in 1998 & extensively studied.

Flavor mixing & non-zero neutrino mass

~ Beyond the standard model ~

Parameters

- 3 oscillation angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$)
- 2 mass differences ($\Delta m_{12}^2$, $\Delta m_{32}^2$)
- 1 CP phase ($\delta$)

PMNS Matrix ($U_{\alpha i}$)

\[ |\nu_\alpha> = \Sigma U_{\alpha i} |\nu_i> \]

Weak Mass eigenstates

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

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\times
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\times
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\times
\begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\
0 & 0 & e^{i\frac{\alpha_{31}}{2}}
\end{pmatrix}
\]

Atmospheric & Reactor & Solar
& Accelerator & & &

& Reactor & &
Neutrino oscillation parameter measurements

\[
\sin^2 2\theta_{23} > 0.9
\]

\[
|\Delta m^2_{32}| \sim 2.5 \pm 0.2 \times 10^{-3} \text{ (eV/c}^2)^2
\]

(Atm. + Accl.)

\[
\sin^2 2\theta_{23} > 0.9
\]

\[
|\Delta m^2_{32}| \sim 2.5 \pm 0.2 \times 10^{-3} \text{ (eV/c}^2)^2
\]

(Solar + Reactor)

\[
\sin^2 \theta_{12} \sim 0.305 \pm 0.013
\]

\[
\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} \text{ (eV/c}^2)^2
\]

(Solar + Reactor)

\[
\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} \text{ (eV/c}^2)^2
\]

(Reactor + Accl.)

\[
\sin^2 2\theta_{13} = 0.098 \pm 0.013
\]

Daya-Bay collaboration
PRL 112 (2014) 061801

\[
\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}
\]

Daya Bay: 6 Detectors, 217 days

Daya-Bay collaboration PRL 112 (2014) 061801

\[
\sin^2 \theta_{13} = 0.090^{+0.008}_{-0.009}
\]
Neutrino mixing parameter measurements

Remaining issues

1) $\theta_{23}$ is really $45^\circ$ or $< 45^\circ$ or $> 45^\circ$ ?
   Current uncertainty of $\sin^2 \theta_{23}$ is still large

2) CP is violated or not ( $\delta = 0$ or not ) ?

3) Mass hierarchy ~ which is heavier ? ( $\Delta m^2_{32} > 0$ or $< 0$ ?)

**Normal hierarchy**

\[
\Delta m^2_{32} \sim 2.5 \pm 0.2 \times 10^{-3} \text{(eV/c}^2\text{)}^2
\]

**Inverted hierarchy**

\[
\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-3} \text{(eV/c}^2\text{)}^2
\]

\[
\Delta m^2_{32} \sim 2.5 \pm 0.2 \times 10^{-3} \text{(eV/c}^2\text{)}^2
\]
Tokai to Kamioka long baseline neutrino oscillation experiment (T2K)

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

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

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

Spain
IFAE, Barcelona
IFIC, Valencia
U. Sheffield
U. Warwick

Switzerland
ETH Zurich
U. Bern
U. Geneva

U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.

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

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U. Tokyo

Russia
INR

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

500 members,
59 Institutes,
11 countries
Tokai to Kamioka long baseline neutrino oscillation experiment (T2K)

- Search for the $\nu_e$ appearance
  \[ \rightarrow \text{measure } \theta_{13} \]
- Precision measurements of oscillation parameters with $\nu_\mu$ disappearance
  \[ \rightarrow \delta(\Delta m^2_{23}) \sim 1 \times 10^{-4} \text{ eV}^2, \delta(\sin^2 2\theta_{23}) \sim 0.01 \]
- Study $CP$ violation in the lepton sector (\& mass hierarchy)
Neutrino mixing parameter measurements in T2K

$\nu_{\mu}$ disappearance channel

precise measurement of $\theta_{23}$ & $\Delta m^2_{32} / \Delta m^2_{13}$

Expected sensitivity

$\delta(\Delta m^2_{23}) \sim 1 \times 10^{-4} \text{ eV}^2$, $\delta(\sin^2 2\theta_{23}) \sim 0.01$

To achieve this precision,

high statistics & small systematic errors are required.

$\nu_{\mu}$ Survival probability

$$P(\nu_{\mu} \to \nu_{\mu}) \approx 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta$$

$\Delta = \Delta m^2_{32}L/4E$ (Normal hierarchy)

$\Delta m^2_{13}L/4E$ (Inverted hierarchy)

$\sin^2 2\theta_{23} = 1.0$

$\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$

$\text{Oscillation maximum} \sim 600 \text{ MeV} @ 295\text{ km}$
Neutrino mixing parameter measurements in T2K

ν_e appearance channel

\sim \text{ precise measurement of } \theta_{13}

\begin{align*}
P(\nu_\mu \rightarrow \nu_e) &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} \quad (\text{leading term})
\end{align*}

\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}^2 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 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \\
&+ 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{align*}

\begin{align*}
a &= 2\sqrt{2} G_F n_e E_\nu \\
\text{For anti neutrinos,} \quad a \rightarrow -a, \quad \delta \rightarrow -\delta
\end{align*}

\begin{align*}
&\text{CP violating term}
\end{align*}
Neutrino mixing parameter measurements in T2K

$\nu_e$ appearance channel

\sim Study of CP violation in lepton sector

**Two methods**

*Use $\theta_{13}$ constraints from reactor $\bar{\nu}_e$ disappearance*

\begin{align*}
\sin^2 2\theta_{13} &= 0.1 \\
\delta &= 0 \\
\delta &= \pi/2 \\
\delta &= \pi \\
\delta &= -\pi/2
\end{align*}

\begin{align*}
\nu & \quad \text{sin}^2 2\theta_{13} = 0.1 \\
\text{anti-} \nu & \quad \text{sin}^2 2\theta_{13} = 0.1
\end{align*}

\begin{align*}
P(\nu_\mu \rightarrow \nu_e) & \quad \text{anti-} P(\nu_\mu \rightarrow \bar{\nu}_e)
\end{align*}

\begin{align*}
E_\nu (\text{GeV}) & \quad E_\nu (\text{GeV})
\end{align*}

**Compare difference between $\nu$ and $\bar{\nu}$ oscillations**

T2K is planning to run with anti-neutrino configuration (flip horn current).

Anti neutrino “test run” is planned in 2014.
T2K neutrino beam ~ Off axis beam ~

Maximize sensitivity in oscillation studies

- Use narrow band beam with peak energy at the oscillation maximum

**Off axis beam**

(ref.: BNL-E889 Proposal)

- Quasi-monochromatic beam ~ suppressed high energy ν
- Energy is tunable (Change off axis angle)

*Important to monitor beam direction!*

(1 mrad ~ peak $E_\nu$ shifts by ~16 MeV)

ν beam energy can be tuned by changing the off-axis angle.

![Diagram showing the T2K neutrino beam setup with energy distribution and oscillation significance](Image)

- **Target**
- **Horns**
- **Decay Pipe**
- **Far detector**
- **$\Theta$ (Off axis angle)**

**Graphs:**

- **$\nu$ energy distribution**
  - OA 0.0°
  - OA 2.0°
  - OA 2.5°
  - OA 3.0°

- **P(ν) distribution**

- **$\sin^2 \theta_{23} = 1.0$**
- **$m^2_{32} = 2.4 \times 10^{-3}$ eV²**
• Proton beam extracted every ~ 2.5 sec.
• Beam spill width ~ 5 μs
  8 bunches ( 6 bunches before Summer 2010 )
• Neutrino production target
  graphite target
  ( diameter = 26mm, L=90cm )
  He air cooled
• $\pi$ focusing ~ Triple horn system
  operated @ 250kA
  except for short period in Run 3 ( 205kA , 0.21 x $10^{20}$ pot )

**Increased beam power**
~ achieved by increasing the # of protons per pulse & repetition rate
Beam power has been continuously increased by
1) # of protons per spill was increased and
2) beam repetition rate has been shortened.

Run1(3.52s), Run2(3.2~3.04s), Run3(2.56s), Run4(2.48s)

Delivered # of protons: $6.63 \times 10^{20}$ protons on target

Analyzed # of protons: $6.57 \times 10^{20}$ protons on target

$\sim 8\%$ of T2K goal
Stability of the beam is very crucial
1 mrad change of the neutrino beam direction results in 2~3 % shift of the mean neutrino energy ( ~ 16 MeV )

- Muon monitor after the beam dump
  Spill by spill monitor of the neutrino direction and intensity of muon
- On axis near neutrino detector
  INGRID ( Fe + Scintillator )
  Day by day monitor of the neutrino interaction rate
  Neutrino beam direction monitor
T2K ~ Beam stability ~ monitored by muon monitor

Stability of beam direction is less than 1 mrad throughout whole run period.
T2K ~ Beam stability ~ monitored by INGRID

Monitor the number of interactions in the detector

Interaction rate / P.O.T.

Neutrino beam center position

- Observed neutrino interaction rate per P.O.T. has been stable within 0.7%
- Neutrino beam direction is stable within 1mrad

Neutrino beam has been confirmed to be stable.
T2K ~ Schematic diagram of the experiment

- Off axis detectors
- Neutrino flux measurements
- Neutrino interaction studies

UA1 magnet (0.2 T)
T2K far detector ~ Super-Kamiokande

- **Water Cherenkov detector** with fiducial volume 22.5kton
  - Inner detector (ID)
    - 11,129 20inch PMT
  - Outer detector (OD)
    - 1,885 8inch PMT
- **New DAQ system from 2008**
- **Realtime recording of all PMT hits within ±500μsec of each ν beam arrival time at SK by with GPS.**
T2K experiment ~ Analysis strategy

Extracting the “oscillation parameters” from observables
~ compare the data and the prediction with oscillations.

Prediction
Based on Monte-Carlo simulation with various constraints from the measurements

\[ \nu \text{ flux} \quad \downarrow \]

\[ \nu \text{ cross sections} \]

Beam simulation program
( FLUKA + GEANT3 w/ GCALOR )
+ \( \pi, K \) production data ( NA61 etc. )

\[ \downarrow \]

\[ \nu \text{ interaction simulation program} \]
( NEUT )
+ External constraints ( data )

Near detector measurements to constrain uncertainties of neutrino flux and neutrino interaction models

\[ \downarrow \]

prediction in SK
T2K neutrino beam ~ flux prediction

- Simulated with FLUKA 2008.3d + GEANT3 w/GCALOR
- Apply weights to the flux
  ~ Constraint from the external hadron production data sets
    CERN NA61/SHINE (Primarily used)
    > 90% coverage of $\nu$ parent pions,
    ~ 60% coverage of $\nu$ parent kaons
- Other data sets are used for outside of the NA61 coverage
  + systematic error evaluations
    T. Eichten et al. (Nucl. Phys. B44 1972)
    J.V. Allaby et al. (Tech. Rep. 70-12 CERN, 1970) etc..
T2K neutrino beam ~ flux prediction

Beam flux predicted based on
NA61/SHINE $\pi$ and K production measurements and
T2K proton beam measurements

T2K run 1-4 flux at ND280

T2K run 1-4 flux at SK

$\sim 95\%$ of $\nu_\mu$ at ND280 and SK are produced from $\pi^+$
T2K neutrino beam ~ Uncertainty of the flux prediction

**Source of uncertainties**

1. Proton beam measurement
2. Hadron production
3. Alignment error on target/horn
4. Horn current & field
5. Beam direction

- Uncertainties on the flux prediction below 15% near the flux peak.
- Uncertainties on the ratio of the near/far ratio less than 2% near the flux peak.

![Graph showing V_{\mu} uncertainty at Super-K](image)
Neutrino interactions

Charged current quasi-elastic scattering

$\nu + n \rightarrow l^- + p$

Neutral current elastic scattering

$\nu + N \rightarrow \nu + N$

Single $\pi, \eta, K$ resonance productions

$\nu + N \rightarrow l^- + N' + \pi$ ($\eta, K$)

Coherent pion productions

$\nu + X \rightarrow l^- + X' + \pi$

Deep inelastic scattering

$\nu + N \rightarrow l^- + N' + m\pi (\eta, K)$

$I : \text{lepton}, N, N' : \text{nucleon}, m : \text{integer}$

Cross-sections

$\sigma / E (10^{-38} \text{ cm}^2 / \text{GeV})$

$E_\nu (\text{GeV})$
Neutrino interactions in the detectors

Use charged lepton
from charged current quasi-elastic scattering (CCQE)

\[ \nu_l + n \rightarrow l^- + p \]

Dominant interaction
around the oscillation peak
\( \sim \) flux peak
can be reconstructed
from measured \( E_{lep} \) & \( \theta_{lep} \)

\[ E_{reco} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)} \]

\( (E_b: \text{Binding energy}) \)
Neutrino interactions in the detectors

Charged current quasi-elastic scattering (CCQE)

Fitting external data to determine the nominal and the error of the input parameters before fitting the T2K ND280 data

**CCQE cross-section**

\[ F_A(q^2) = \frac{F_A(0)}{\left(1 + \frac{q^2}{M_A^2}\right)^2} \]

Parameters (CCQE)

- \( M_A^{QE} = 1.21 \pm 0.45 \text{ GeV}/c^2 \)
- CCQE norm = 1 \pm 0.11
Neutrino interactions in the detectors

Possible background

$\nu_\mu$ disappearance

Around oscillation peak

$\nu + N \rightarrow \mu^- + N' + \pi^\pm$

proton and charged $\pi$ from NC interactions

$\nu + N \rightarrow \nu + p$

$\nu + N \rightarrow \nu + N' + \pi^\pm$

Fraction of each interaction

$\nu_\mu \rightarrow \mu^-$

$W^+$

$\pi^+$

$p$

$p$

True $E_\nu$ (GeV)

Cross-section (fb)

Fraction of events in bin

reconstructed $\nu$ energy (GeV)
Neutrino interactions in the detectors

Possible background

\( \nu_e \) appearance

NC 1 \( \pi^0 \) production

\( \nu + N \rightarrow \nu + N' + \pi^0 \)

If one of the \( \gamma \) from decay of \( \pi^0 \) can not be identified, identified as a candidate.

\# of \( \pi^0 \)

\~ Interaction cross-section

Decay kinematics

\~ Momentum distribution of \( \pi^0 \)

Source of errors in measuring oscillation parameters

\~ Need careful studies
Neutrino interactions in the detectors

Charged current quasi-elastic scattering (single pion productions)

Fitting external data (mainly from MiniBooNE) to determine the nominal and the error of the input parameters (before fitting the T2K ND280 data)

<table>
<thead>
<tr>
<th>Parameters (resonant π)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{\text{RES}}$</td>
<td>$1.41 \pm 0.22 \text{ GeV/c}^2$</td>
</tr>
<tr>
<td>CC1π norm</td>
<td>$1.15 \pm 0.32$</td>
</tr>
<tr>
<td>NC1π^0 norm</td>
<td>$0.96 \pm 0.33$</td>
</tr>
</tbody>
</table>
Neutrino interaction measurements in the near detectors

*Measure muon momentum & angular distributions in ND280*

*Use 3 samples ~ enrich different interaction modes*

CC 0π sample

- CCQE ~ 64%
- TPC1
- FGD1

CC 1π⁺ sample

- CC 1π ~ 40%
- TPC2
- FGD2

CC other sample

- CC DIS ~ 68%
- TPC3
- hadrons

Measure muon momentum & angular distributions in ND280

Use 3 samples ~ enrich different interaction modes
Neutrino interaction measurements in the near detectors

*Fit neutrino flux and neutrino interaction model parameters using* $p_{\mu} - \cos \theta_{\mu}$ *distributions of 3 samples from ND280*

Constrain uncertainties on

1) Neutrino flux at SK

2) Correlated neutrino interaction related parameters

- **CC 0π sample**
- **CC 1π+ sample**
- **CC other sample**

---

**Pre-fit**

**Post-fit**
Neutrino interaction measurements in the near detectors

Results from the ND280 neutrino interaction measurements

Both uncertainties on neutrino flux and neutrino interaction parameters are well constrained.
Neutrino interaction measurements in the near detectors

Measure electron momentum & angular distributions in ND280

Use 3 samples ~ enrich different interaction modes

Interactions in FGD and particle ID in TPC

Major background: photons from $\pi^0$ decays

Fit CC0$\pi$, CC1$\pi^+$ + CC Other and $\gamma$ sideband sample

Validation MC prediction of the intrinsic beam $\nu_e$ background using the data from ND280.

\[
\frac{\text{measured } \nu_e \text{ flux}}{\text{predicted } \nu_e \text{ flux}} = 1.06 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})
\]
T2K $\nu_\mu$ disappearance analysis
arXiv:1403.1532[hep-ex]
T2K $\nu_\mu$ disappearance analysis

$\nu_\mu$ Signal events in SK

Charged current quasi-elastic scattering

$\nu_\mu + n \rightarrow \mu^- + p$

Observed as single ring $\mu$-like event in SK.
( $\mu$-like events has sharp ring edge )

Background sources

Other charged current interactions
Only $\mu$ was detected.
Some of those background events could be eliminated by using decay electrons for example $\pi \rightarrow \mu \rightarrow e$.

protons and/or charged $\pi$ from neutral current interactions
T2K $\nu_\mu$ disappearance analysis

$\nu_\mu$ Signal events in SK

Event selection criteria

- Fully contained in fiducial volume
- 1 ring and identified as $\mu$-like
- Reconstructed momentum of $\mu > 200$ MeV/c
- 0 or 1 decay electrons

120 events are selected (6.57 x 10^{20} pot)

### Number of rings

<table>
<thead>
<tr>
<th>Number of rings</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

### Particle ID

<table>
<thead>
<tr>
<th>PID parameter</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu / \bar{\nu}_\mu$ CCQE</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu / \bar{\nu}_\mu$ CC non-QE</td>
<td></td>
</tr>
<tr>
<td>$\nu_e / \bar{\nu}_e$ CC</td>
<td></td>
</tr>
<tr>
<td>Neutral current</td>
<td></td>
</tr>
</tbody>
</table>

### # of decay electrons

<table>
<thead>
<tr>
<th>Number of decay-electrons</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
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<tr>
<td>3</td>
<td></td>
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<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
T2K $\nu_\mu$ disappearance analysis

Run 1 ~ 4 (6.57 x 10^{20} P.O.T.)

**Expected # of events**
without oscillation
= 446.0 ± 22.5 (syst.)

**Observed # of events**
= 120

**Expected # of events**
with oscillation
($\sin^2 \theta_{23}, \Delta m^2_{32}$) = (0.5, 2.4 x 10^{-3} eV^2/c^4)

<table>
<thead>
<tr>
<th>Event category</th>
<th># of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CCQE</td>
<td>77.93</td>
</tr>
<tr>
<td>$\nu_\mu$ CC non-QE</td>
<td>40.78</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>0.35</td>
</tr>
<tr>
<td>NC All</td>
<td>6.78</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>125.85</strong></td>
</tr>
</tbody>
</table>
T2K $\nu_{\mu}$ disappearance analysis

**Systematic uncertainties for # of events**

$$(\sin^2 \theta_{23}, \Delta m^2_{32}, \delta_{CP}) = (0.5, 2.4 \times 10^{-3} \text{ eV}^2/c^4, 0)$$

<table>
<thead>
<tr>
<th>Systematics</th>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux/XSEC (ND280 constraint)</td>
<td>2.7%</td>
</tr>
<tr>
<td>Other XSEC</td>
<td>4.9%</td>
</tr>
<tr>
<td>Super-K +FSI</td>
<td>5.6%</td>
</tr>
<tr>
<td>Total</td>
<td>8.1%</td>
</tr>
</tbody>
</table>

* Binding energy and SK energy scale are some of the dominant uncertainties affecting T2K $\Delta m^2_{32}$ precision, but they don’t appear in the left table of # of events since they don’t affect the overall normalization.

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**$N_{SK}$ per reconstructed energy (bin) with error**

[Graph showing $N_{SK}$ per reconstructed energy (bin) with error]
T2K $\nu_\mu$ disappearance analysis

**Uncertainties from the $\nu$ interactions with multi-nucleon in nucleus**

- Lively discussion motivated by CCQE cross section inconsistency between MiniBooNE and the other experiment
- Not incorporated directly into this analysis
  - But we have a large systematic uncertainty (100%) on decays of $\Delta$ resonances w/ prompt $\pi$ absorption ("$\pi$-less $\Delta$-decay"). It has similar impact on neutrino energy reconstruction as a 100% uncertainty in the multi-nucleon interaction model (Nieves model)
  - **Dedicated MC study shows the impact on oscillation analysis is small relative to our current statistical**
T2K $\nu_\mu$ disappearance analysis

Oscillation parameter fitting

Maximum likelihood fit based on

- # of observed events in SK ($N_{SK}$) and
- reconstructed energy of neutrino ($E_{\nu}^{\text{rec}}$)

$$L = L_{\text{norm.}} \times L_{\text{shape}} \times L_{\text{syst.}} \times L_{\text{osc.}}$$

Constraints from the other exp’s.

\[
\begin{align*}
\sin^2\theta_{12} &= 0.312 \pm 0.016 \\
\Delta m^2_{21} &= (7.50 \pm 0.20) \times 10^{-5} \text{ eV}^2/c^4 \\
\sin^2\theta_{13} &= 0.0251 \pm 0.0035 \\
(\text{from PDG 2012})
\end{align*}
\]

** $\delta_{CP}$ is unconstrained.
T2K $\nu_\mu$ disappearance analysis

Fit results ~ allowed oscillation parameter regions

*Large improvements from the previous publication.*

(3.01 x $10^{20}$ POT $\rightarrow$ 6.57 x $10^{20}$ POT)

Feldman-Cousins 2D confidence regions

Best fit parameters

<table>
<thead>
<tr>
<th></th>
<th>[NH]</th>
<th>[IH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.514</td>
<td>0.511</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>2.51</td>
<td>2.48</td>
</tr>
<tr>
<td>$N_{SK}^{\text{exp}}$</td>
<td>121.41</td>
<td>121.39</td>
</tr>
</tbody>
</table>
T2K $\nu_\mu$ disappearance analysis

Fit results $\sim$ allowed oscillation parameter regions

**Most precise measurement of $\theta_{23}$**

$\sim$ Favors (almost) maximal mixing

\[
\sin^2 \theta_{23} = 0.514 \\
\Delta m_{32}^2 = 2.51 \text{ eV}^2/c^4 \\
N_{SK}^{\text{exp}} = 121.41
\]

\[
\sin^2 \theta_{23} = 0.511 \\
\Delta m_{13}^2 = 2.48 \text{ eV}^2/c^4 \\
N_{SK}^{\text{exp}} = 121.39
\]
T2K $\nu_e$ appearance analysis
T2K $\nu_e$ appearance analysis

Charged current quasi-elastic scattering

$$\nu_e + n \rightarrow e^- + p$$

Observed as single ring e-like event in SK

Dominant background

1) $\nu_e$ in the beam
   intrinsic background

2) $\pi^0$ identified as 1 ring
   One $\gamma$ is not identified
   small opening angle of 2 rings
   low momentum faint ring

Search for the 1 ring e-like events
No decay electrons
not $\pi^0$ like (dedicated $\pi^0$ rejection)
Reconstructed $E_\nu$ is in the oscillation region
T2K $\nu_e$ appearance analysis ~ event selection in SK

- Fully contained event ~ no activity in the outer detector
- Reconstructed in the fiducial volume ( > 200cm from the wall )
- 1 ring and PID is electron-like
- Visible energy ( electron equiv. energy ) > 100 MeV
- No decay electrons
- Reconstructed $E_\nu < 1.25$ GeV
- special $\pi^0$ identifier ( New $\pi^0$ rejection )

**Particle ID**
- Fully contained event ~ no activity in the outer detector
- Reconstructed in the fiducial volume ( > 200cm from the wall )
- 1 ring and PID is electron-like
- Visible energy ( electron equiv. energy ) > 100 MeV
- No decay electrons
- Reconstructed $E_\nu < 1.25$ GeV
- special $\pi^0$ identifier ( New $\pi^0$ rejection )

**Reconstructed $E_\nu$**
- $\nu_\mu / \bar{\nu}_\mu$ CCQE
- $\nu_\mu / \bar{\nu}_\mu$ CC non-QE
- $\nu_e / \bar{\nu}_e$ CC
- Neutral current

**$\pi^0$ rejection**
- $\pi^0$ cut
- MC w/ sin$^2\theta_{13} = 0.1$
T2K $\nu_e$ appearance analysis

Expected # of events and observed # of events in Run 1 ~ 4 (6.57 x 10$^{20}$ P.O.T.)

**Expected # of events for $\theta_{13} = 0$**

\[ = 4.9 \pm 0.6 \text{ (syst.)} \]

<table>
<thead>
<tr>
<th>Total</th>
<th>4.92</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ signal</td>
<td>0.40</td>
</tr>
<tr>
<td>$\nu_e$ background</td>
<td>3.37</td>
</tr>
<tr>
<td>$\nu_\mu$ background</td>
<td>0.94</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ background</td>
<td>0.05</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ background</td>
<td>0.16</td>
</tr>
</tbody>
</table>

**Observed # of events** = 28

Reconstructed $E_\nu$

![Graph showing reconstructed neutrino energy distribution with data, best fit, and no oscillation regions. Data is represented by black dots with error bars, the best fit by a red line, and the no oscillation region by a blue shaded area.](graph.png)
T2K $\nu_e$ appearance analysis

Oscillation parameter fitting

Maximum likelihood fit based on

# of observed events in SK ( $N_{SK}$ ) and

observed momentum and direction of electron ($p_e, \theta_e$)

$$L = L_{\text{norm.}} \times L_{\text{shape}} \times L_{\text{syst.}} \times L_{\text{osc.}}$$

Constraints from

T2K Run 1-3 results

( PRL 111, 211803 (2013) )

and

the other experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{12}^2$</td>
<td>$7.6 \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$\Delta m_{32}^2$</td>
<td>$2.4 \times 10^{-3}$ eV$^2$</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{23}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{12}$</td>
<td>0.8495</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>0 degree</td>
</tr>
<tr>
<td>Earth matter density</td>
<td>2.6 g/cm$^3$</td>
</tr>
<tr>
<td>Mass hierarchy</td>
<td>normal</td>
</tr>
<tr>
<td>Base-line length</td>
<td>295 km</td>
</tr>
</tbody>
</table>

Electron momentum vs. angle distribution (MC)
T2K $\nu_e$ appearance analysis

**Expected # of events & Systematic uncertainties for # of events**

\((\sin^2\theta_{23}, \Delta m^2_{32}, \delta_{CP}) = (0.5, 2.4 \times 10^{-3} \text{ eV}^2/c^4, 0)\)

**Expected # of events w/ 6.57 \times 10^{20} \text{ POT}**

<table>
<thead>
<tr>
<th>Event category</th>
<th>$\sin^22\theta_{13}=0.0$</th>
<th>$\sin^22\theta_{13}=0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ signal</td>
<td>0.40</td>
<td>17.30</td>
</tr>
<tr>
<td>$\nu_e$ background</td>
<td>3.37</td>
<td>3.12</td>
</tr>
<tr>
<td>$\nu_\mu$ background (mainly NC$\pi^0$)</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>$\nu_\mu + \nu_e$ background</td>
<td>0.21</td>
<td>0.20</td>
</tr>
<tr>
<td>Total</td>
<td>4.92</td>
<td>21.56</td>
</tr>
</tbody>
</table>

**Systematic uncertainties for expected # of events**

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\sin^22\theta_{13}=0.0$</th>
<th>$\sin^22\theta_{13}=0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam flux + $\nu$ int.</td>
<td>4.8 %</td>
<td>2.9 %</td>
</tr>
<tr>
<td>constrained from ND280</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu$ int. (from other exp.)</td>
<td>7.1 %</td>
<td>7.6 %</td>
</tr>
<tr>
<td>Far detector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Final state interactions</td>
<td>7.3 %</td>
<td>3.5 %</td>
</tr>
<tr>
<td>+ photo nuclear effects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11.4 %</td>
<td>8.9 %</td>
</tr>
</tbody>
</table>
T2K $\nu_e$ appearance analysis

Fit results ~ comparison with data and MC with best fit parameter

- momentum vs angle
  - Run 1-4 data (6.570e20 POT)
  - best-fit $\sin^2 2\theta_{13} = 0.140$
  - assuming $\delta_{CP}=0$
  - normal hierarchy,
  - $|\Delta m_{32}^2|=2.4 \times 10^{-3}$ eV$^2$

- angle
  - Data
  - Signal prediction
  - Background prediction

Exclude $\theta_{13}=0$ at 7.3 $\sigma$ level

Best fit w/ 68% C.L. error:

$$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

90% allowed region:

$$0.090 < \sin^2 2\theta_{13} < 0.205$$

With following assumptions:

- $\delta_{CP}=0$, normal hierarchy,
- $|\Delta m_{32}^2|=2.4 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta_{23}=1$
T2K $\nu_e$ appearance analysis

Allowed oscillation parameter regions

Best fit parameters

\[ w/ 68\% \text{ C.L. errors } @ \delta_{\text{CP}}=0 \]

**Normal hierarchy**

\[ \sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032} \]

**Inverted hierarchy**

\[ \sin^2 2\theta_{13} = 0.170^{+0.044}_{-0.037} \]

Constraints on the other parameters in the fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$\Delta m^2_{12}$</td>
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</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>$2.4 \times 10^{-3} \text{ eV}^2$</td>
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<tr>
<td>$\sin^2 2\theta_{23}$</td>
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T2K $\nu_e$ appearance analysis

Allowed oscillation parameter regions

Comparison with $\theta_{13}$ from reactor

*From T2K*

**Normal hierarchy**

$$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

**Inverted hierarchy**

$$\sin^2 2\theta_{13} = 0.170^{+0.044}_{-0.037}$$

*From reactor experiments  ( PDG 2012 )*  

$$\sin^2 2\theta_{13} = 0.098 \pm 0.013$$

.arrow Discrepancy 

Signature of non-zero $\delta_{CP}$??
T2K $\nu_e$ appearance analysis

Combined fit with reactor constraints (from PDG 2012)

$$\sin^2 2\theta_{13} = 0.098 \pm 0.013$$

Regions above these lines (derived by Feldman-Cousins method) are excluded with 90% C.L.

- Normal hierarchy: $0.19\pi \sim 0.80\pi$
- Inverted hierarchy: $-1.00\pi \sim -0.97\pi$, $-0.04\pi \sim 1.00\pi$
Future Prospects

• $\nu_e$ appearance and $\nu_\mu$ disappearance combined fit
• Realistic (shape-dependent) systematic errors
  • Errors are assumed to be fully correlated between $\nu$/anti-$\nu$
Mid-term plan of MR

FX: We adopt the high repetition rate scheme to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Li. upgrade</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FX power [kW]</td>
<td>150!</td>
<td>200 !</td>
<td>240 ~ (300)!</td>
<td>~ 400!</td>
<td>750!</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SX power : User op. (study) [kW]</td>
<td>3 (10)</td>
<td>10 (20)</td>
<td>25 (30)</td>
<td>50 (100)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle time of main magnet PS! New magnet PS for high rep.</td>
<td>3.04 s</td>
<td>2.56 s</td>
<td>2.4 s</td>
<td>1.3 s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present RF system ! New high gradient rf system!</td>
<td>Install. #7,8</td>
<td>Install. #9</td>
<td>R&amp;D</td>
<td>Manufacture installation/test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring collimators</td>
<td>Additional shields</td>
<td>Add.collimators and shields (2kW)</td>
<td>Add.collimators (3.5kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection system ! FX system</td>
<td>New injection kicker</td>
<td>Kicker PS improvement, Septum 2 manufacture /test</td>
<td>LF septum, PS for HF septa manufacture /test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Expected POT is estimated based on the information.
\[ \sin^2 \theta_{23} / \Delta m^2_{32} \] 1\(\sigma\) Precision vs. POT

**POT fractions: 50% \(\nu\) + 50% anti-\(\nu\) case**

Solid Lines: no sys. err.

**Red Dashed:** with conservative systematic errors (~7% \(\nu\), ~14% anti-\(\nu\))

Precisions are expected to be improved drastically over the next few years.

Statistical limit of 1\(\sigma\) precision at full POT

- \(\sin^2 \theta_{23} (\theta_{23}) \) \(\sim 0.045 \) (\(\sim 2.6^\circ\))
- \(\Delta m^2_{32} \) \(\sim 4 \times 10^{-5} \text{ eV}^2\)

Assuming true: \(\sin^2 2\theta_{13} = 0.1\), \(\delta_{CP} = 0^\circ\), \(\sin^2 \theta_{23} = 0.5\), \(\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2\),

Normal hierarchy, \(\theta_{13}\) constrained by \(\delta(\sin^2 2\theta_{13}) = 0.005\)
Appearance 90% C.L. Sensitivity

$7.8 \times 10^{21}$ POT (POT fractions: 50% $\nu + 50%$ anti-$\nu$)

Solid Lines: no sys. err., Dashed: with 2012 sys. err. ($\sim 10%$ $\nu_e$, $\sim 13%$ $\nu_\mu$)

Case study (1): True $\delta_{CP} = 0^\circ$

Case study (2): True $\delta_{CP} = -90^\circ$

T2K only

T2K w/ Reactor $\delta(\sin^2 2\theta_{13}) = 0.005$

[NH] Normal hierarchy, [IH] Inverted hierarchy

Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\sin^2 \theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$, [NH]
Sensitivity for Resolving $\sin\delta_{\text{CP}} \neq 0$

$7.8 \times 10^{21}$ POT (POT fractions: $50\% \nu + 50\% \text{anti-}\nu$)

[NH] Normal hierarchy, [IH] Inverted hierarchy

Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$

$\theta_{13}$ constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$
T2K + NOvA Sensitivity for Resolving $\sin\delta_{CP} \neq 0$

Both T2K / NOvA: full POT (POT fraction: 50% $\nu$ + 50% anti-$\nu$).

Plots are for normal hierarchy.

Red: T2K alone, Blue: NOvA alone, Black: T2K + NOvA.

Sensitivity for resolving $\sin\delta = 0$.

Assuming 5% (10%) normalization uncertainty on signal (background).

Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$, $\theta_{13}$ constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$.
T2K + NO\text{vA} Sensitivity to Mass Hierarchy

Both T2K / NO\text{vA} : full POT ( POT fraction : 50% $\nu$ + 50% anti-$\nu$)

Plots are for normal hierarchy

Red: T2K alone, Blue: NO\text{vA} alone, Black: T2K + NO\text{vA}

solid(dash): w/o (w/) systematics

Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$, $\theta_{13}$ constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$
Summary

$\nu_\mu$ disappearance results
- We have measured $\theta_{23}$ with the world-leading precision
- New result favors maximal mixing

$\nu_e$ appearance results
- We have constrain the CP violating phase $\delta_{\text{CP}}$ by combining our $\nu_e$ appearance results with the reactor measurements
- Best fit is found at very interesting point, $\delta_{\text{CP}} \sim -\pi/2$. If it is true, severe competition with NO$\nu$A.
Important to increase statistics ASAP.

Future sensitivity study
- May be possible to constrain $\delta_{\text{CP}}$
- Combined analysis with NO$\nu$A enhances the sensitivities to $\delta_{\text{CP}}$ and the mass hierarchy
- Higher power at design value (750 kW) beam operation is anticipated.