Recent Results from T2K

Asher Kaboth
Outline

- Current State of Neutrino Physics
- The T2K Experiment
- Oscillation Results
- Cross Section Results
- Looking Forward
Neutrino Oscillations

Neutrinos have two sets of eigenstates: mass (propagation) and flavor (detection)

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} \\
    U_{\mu1} & U_{\mu2} & U_{\mu3} \\
    U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

\[
U_{ij} = \cos \theta_{ij}
\]

\[
s_{ij} = \sin \theta_{ij}
\]

Detection also depends on the mass splittings:

\[
\sin^2 \left( \frac{\Delta m^2 L}{2E} \right)
\]

\[
\Delta m^2 = m_i^2 - m_j^2
\]
Ways to Look for Oscillation

- **Solar**: $\nu_e$
- **Atmospheric**: $(\nu_\mu, \nu_e)$
- **Reactors**: $\bar{\nu}_e$
- **Beams**: $(\nu_\mu, \nu_e)$

Different sources with different flavors and energies allow broad searches for oscillation.
Status in 2010

Two mixing angles known; two mass splittings known

Imperial College
London
Unanswered Questions

\[
\begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} \\
    U_{\mu1} & U_{\mu2} & U_{\mu3} \\
    U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
= \begin{pmatrix}
    c_{12} & s_{12} & 0 \\
    -s_{12} & c_{12} & 0 \\
    0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
    c_{13} & 0 & s_{13}e^{i\delta} \\
    0 & 1 & 0 \\
    -s_{13}e^{-i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & c_{23} & s_{23} \\
    0 & -s_{23} & c_{23}
\end{pmatrix}
\]

Does the neutrino sector have a CP-violating phase?

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

Is \(\Delta m^2_{31}\) > 0 or < 0?

Is \(\theta_{23}\) > 45, < 45°, or = 45°?
Oscillations at T2K

T2K can look at two kinds of oscillation, with dependance on four oscillation parameters

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 (\Delta (1 - A))}{(1 - A)^2} + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 A \Delta}{A^2} + \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \frac{\sin((1 - A) \Delta)}{1 - A} \frac{\sin A \Delta}{A} \cos(\delta + \Delta) \]

Expanded under small \( \theta_{13}, \alpha \)

\[ A = \pm 2\sqrt{2} G_F n_e E \Delta m_{31}^2 \]

\[ \Delta = \frac{\Delta m_{31}^2 L}{E} \]

\[ \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \]

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

CP Violation!

Hierarchy?

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4 \cos^2(\theta_{13}) \sin^2(\theta_{23}) [1 - \cos^2(\theta_{13}) \sin^2(\theta_{23})] \sin^2 \left( \frac{\Delta m_{31}^2 L}{E_{\nu}} \right) \]

Maximal Mixing and Octant!
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The T2K collaboration

- The most intense accelerator neutrino

11 countries
59 institutions
~500 people

ND280

INGRID

Super-Kamiokande

J-PARC Facility (KEK/JAEA)

Design Intensity 750kW

3 GeV Synchrotron

Neutrino Beams (to Kamioka)

Main ring

Construction JFY2001~2008

Mount Ikenoyama

2,924m

Super-Kamiokande

Mount Noguchi-Goro Dake

1,302m

1,000m

Neutrino Beam

295km

Oxford University

Lancaster University

Imperial College London
Beam

T2K uses a conventional neutrino beam, getting its neutrinos from pion and kaon decay

However, it adds a fun new trick: using the kinematics of an off-axis beam to focus at the interesting energy and remove backgrounds
the corresponding flux predictions for the parameters are sampled according to their covariance and we use weighting methods when possible. The nuisance correlations that need to be treated. For error sources depend on whether the uncertainty source has a ton beam profile, or horn currents, are evaluated by their matics of the hadron interactions or the primary proton.

The sensitivities to nuisance parameters that arise from adjustments are made by weighting events based on kine-

The predicted flux at the SK and ND280 detectors, of the flux calculation are described in Ref. [43].

A. Weighting and systematic error evaluation

FIG. 5: The T2K flux prediction at SK (a) and ND280 (b).

The flux simulation begins with the primary proton beam line elements or changes to the horn currents, we evaluate hadron interaction and proton measurements [44, 45]. First, we model the interactions of the primary beam protons and subsequently produced parti-

cles through the magnetic horns and decay region, and get into a GEANT3 [48] simulation that tracks parti-

ton beam downstream of the collimator that sits in front of the T2K target. The interactions of particles in the target, beam line components, decay volume walls and the simulation, we hadron interaction data, alignment measurements, horn current and field measurements, and the beam direction

c includes in the graphite target with a FLUKA 2008 [46, 47]

To tune the flux model and study its uncertainties, ad-

ters 

Flux \(/(\text{cm}^2 \cdot \text{10}^{21} \cdot \text{POT} \cdot \text{100 MeV})\)

Neutrino Energy (GeV)

Integrated POT so far (Power history)

Run 1

Run 2

Earthquake

Run 3

Run 4

Integrated POT (Run29-49) :

Run 3

Run 4

Neutrino Energy (GeV)

Neutrino Energy (GeV)

SK

ND280

Neutrino Energy (GeV)
Stability of $\nu$ beam direction (INGRID)

Stability of $\nu$ beam direction is much better than 1 mrad during whole run period.

Fluctuation of $\nu$ interaction rate (/10$^{19}$ p.o.t) is less than 0.7% whole run period.

Horn 250kA data
Horn 205kA data

interaction rate normalized by # of protons (INGRID)

Interaction rate stable to 0.7%

Beam position stable to 0.4 mrad

Sixteen iron and scintillator modules in a cross shape; on-axis, monitoring beam position and rate

Beam direction [mrad]

T2K Run1 Jan.2010-Jun.2010
T2K Run2 Nov.2010-Mar.2011
T2K Run4 Oct.2012-May.2013

Horn 250kA data
Horn 205kA data

Horizontal direction
Vertical direction

# of events/1e14 protons

1
1.2
1.4
1.6
1.8
2
2.2
2.4
ND280

Muon range detector built into slots on the magnet

Fine Grained Detectors (FGDs)

Electromagnetic Calorimeter (ECal)

π^0 detector (P0D)

Time Projection Chambers (TPCs)

Beam

The T2K collaboration

Total: ~500 members in 57 institutions from 12 countries
- FGDs are primary targets for interactions on carbon and oxygen.
- Composed of layers of plastic scintillator read out with MPPCs.
- FGD2 (downstream) has water interspersed for oxygen target.
TPCs surround FGDs to provide precise determination of track properties

- Ar (95%), CF$_4$ (3%), iC$_4$H$_{10}$ (2%)

- Magnetic field allows for momentum determination

TPC tracks from FGD and P0D interactions
ND280

- P0D is dedicated detector for $\pi^0$ detection
- Interleaved scintillator and metals to allow photons from $\pi^0$ to shower
- Also contains water for oxygen target
ECals surround the inner detectors

Layers of lead and plastic scintillator

Assist in PID and energy determination as well as expanding phase space
The SK far detector [41], as illustrated in Fig. 3, is a 50 kt water Čerenkov detector located in the Kamioka Observatory. The cylindrically-shaped water tank is optically separated to make two concentric detectors: an inner detector (ID) viewed by 11,129 inward-looking 20-inch photomultipliers, and an outer detector (OD) with 18,855 outward-facing 8-inch photomultipliers. The fiducial volume is defined to be a cylinder whose surface is 2 m away from the ID wall, providing a fiducial mass of 22.5 kt. Čerenkov photons from charged particles produced in neutrino interactions form ring-shaped patterns on the detector walls, and are detected by the photomultipliers. The ring topology can be used to identify the type of particle and, for charged current interactions, the flavor of the neutrino that interacted. For example, electrons from electron neutrino interactions undergo large multiple scattering and induce electromagnetic showers, resulting in fuzzy ring patterns. In contrast, the heavier muons from muon neutrino interactions produce Čerenkov rings with sharp edges.

The T2K experiment uses a special software trigger to associate neutrino interactions in SK to neutrinos produced in the T2K beam. The T2K trigger records all the photomultiplier hits within \( \pm 500 \mu s \) of the beam arrival time at SK. Beam timing information is measured spill-by-spill at J-PARC and immediately passed to the online computing system at SK. The time synchronization between the two sites is done using the Global Positioning System (GPS) with \(< 150 \text{ ns}\) precision and is monitored with the Common-View method [42]. Spill events recorded by the T2K triggers are processed to apply the usual SK software triggers used to search for neutrino events, and any candidate events found are extracted for further T2K data analysis.

### Table I: T2K data-taking periods and the integrated protons on target (POT) for SK data collected in those periods.

<table>
<thead>
<tr>
<th>Run Period</th>
<th>Dates</th>
<th>Integrated POT by SK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>Jan. 2010-Jun. 2010</td>
<td>0.32 \times 10^{20}</td>
</tr>
<tr>
<td>Run 2</td>
<td>Nov. 2010-Mar. 2011</td>
<td>1.11 \times 10^{20}</td>
</tr>
</tbody>
</table>

The primary reason spills are rejected at SK is due to the requirement that there are no events in the 100 \( \mu s \) before the beam window, which is necessary to reject decay electrons from cosmic-ray muons.

In this paper, we present neutrino data collected during the three run periods listed in Table I. The total SK data set corresponds to 3.01 \( \times 10^{20} \) protons on target (POT) or 4% of the T2K design exposure. About 50% of the data, the Run 3 data, were collected after T2K and J-PARC recovered from the 2011 Tohoku earthquake. A subset of data corresponding to 0.21 \( \times 10^{20} \) POT from Run 3 was collected with the magnetic horns operating at 205 kA instead of the nominal value of 250 kA. The size of the total data set is approximately two times that of T2K's previously published electron neutrino appearance result [21].

We monitor the rate and direction of the neutrino beam over the full data-taking period with the INGRID detector. As illustrated in Fig. 4, the POT-normalized neutrino event rate is stable to within 1%, and the beam direction is controlled well within the design requirement of 1 mrad, which corresponds to a 2% shift in the peak energy of the neutrino spectrum.
Super-K Signals

- Muons produce clean, sharp rings—this is the signal for $\nu_\mu$ disappearance.
- Electrons scatter in the water and produce fuzzy rings—this is the signal for $\nu_e$ appearance.
- $\pi^0$ decay produces two photons which produce fuzzy rings—missing one fakes an electron.

Example event displays $\mu\mu e\pi^0 e$.
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  - Cross Section Results
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Spills used for neutrino events, and any candidate events found are monitored with the Common-View method \[42\]. Spill positioning system (GPS) with a baseline between the two sites is done using the Global Positioning System (GPS). The photomultiplier hits within a particular volume are used to study Cherenkov rings with sharp edges. In contrast, electrons from electron neutrino interactions undergo large multiple scattering and induce electromagnetic showers, resulting in fuzzy ring patterns. In conclusion, the ring topology can be used to identify specific events.

The SK far detector \[41\], as illustrated in Fig. 3, is a purpose detector that is situated along the same horizontal plane. The far detector utilizes a 0.2 T magnetic field generated by the rectangular Argon detector (R0D). The near detectors measure the properties of the beam profile of muons from hadron decay and monitors the ground from high energy neutrino interactions. This results in the oscillation region and minimizing feedback between the two sites.

The description of the component detectors can be found in the text. The oscillogram of muons on target (POT) for SK data collected in those data, the Run 3 data, were collected after T2K and J-PARC. The size subset of data corresponding to 0% of the T2K design exposure. About 50% of the data was used to study neutrino interactions. The ND280 detector is composed of two fine-grained scintillator bars and time projection chambers (TPCs). The tracking detector is sandwiched between three gaseous detectors (FGDs) \[39\] and a purpose detector that is situated along the same horizontal plane. The magnetic field is along the z-axis and the electron neutrino appearance probabilities (middle).

Use data to drive constraints as much as possible.
Flux Simulation

Use NA61/SHINE data for π, K production to tune simulation


Flux Simulation

FLUKA2008.3d
GEANT3+GCALOR

Target

Magnetic Horn

π⁺, K⁺, ...

Neutrino Producing decays

Decay volume

to ND280 or Super-K

a) NA61 π⁺ Weights

p_π (GeV/c)
θ_π (mrad)

Weights

Tuning weight

Int. Rate Tuning

Total Tuning

SK νμ flux

Pion Tuning

Kaon Tuning

b) NA61 π⁻ Weights

p_π (GeV/c)
θ_π (mrad)

Weights

Tuning weight

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Total Tuning

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b) NA61 π⁻ Weights

p_π (GeV/c)
θ_π (mrad)

Weights

Tuning weight

Int. Rate Tuning

Total Tuning

SK νμ flux
Flux Systematic

Consider 5 sources of systematic uncertainty

Generate covariance matrix for near-far effects

1. Proton beam measurement
2. Hadron production
3. Horn and beam alignment
4. Horn current and field
5. Beam direction

Fractional Error

ND280 $\nu_\mu$ flux

Flux Systematic

Imperial College
London
Cross Section Model

(NEUT/GENIE)

- Charged Current Quasi-Elastic (CCQE)
  - Llewellyn-Smith base model
  - Smith-Moniz fermi gas model for nucleus
- Single Pion Production (CC/NC1\(\pi\)) with Rein-Seghal resonance model
- Deep Inelastic Scattering (DIS) and Charged Current multi-\(\pi\)
  - GRV98 PDF
  - Bodek-Yang correction
- Final State Interactions (FSI)
  - Cascade model—track secondary particles until they exit the nucleus
  - Separate models used for low (<500 MeV) and high momentum

Most interactions are Charged Current Quasi Elastic

- Neutrino flavor determined from flavor of outgoing lepton i.e.
  - \(\nu_e\) for \(\nu_e\), \(\mu\) for \(\nu_\mu\)

Additional interactions important for analysis are \(CC\pi\) and \(NC\pi\) (single pion production)

- Rein-Seghal resonance model
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\[ \nu_\mu \rightarrow \mu \quad CCQE \]

\[ W \quad CCQE \]

\[ n \quad p \]

Additional interactions important for analysis are CCπ and NCπ (single pion production)

- Rein-Seghal resonance model

\[ \sigma/E \times 10^{-38} \text{cm}^2/\text{GeV} \]

\[ \nu (\text{GeV}) \]

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \quad 1.2 \]

Total (NC+CC)  
CC total  
CCQE  
DIS  
CC single π  
NC single π²
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# Cross Section Systematic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Interaction Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{A QE}}$</td>
<td>axial mass</td>
<td>CCQE</td>
</tr>
<tr>
<td>$M_{\text{A RES}}$</td>
<td>axial mass</td>
<td>$1\pi$</td>
</tr>
<tr>
<td>CCQE (3)</td>
<td>normalization</td>
<td>CCQE</td>
</tr>
<tr>
<td>CC1$\pi$ (2)</td>
<td>normalization</td>
<td>CC1$\pi$</td>
</tr>
<tr>
<td>NC$\pi^0$</td>
<td>normalization</td>
<td>NC1$\pi$</td>
</tr>
<tr>
<td>$p_f$</td>
<td>fermi momentum</td>
<td>CCQE/RFG</td>
</tr>
<tr>
<td>$E_b$</td>
<td>binding energy</td>
<td>CCQE/RFG</td>
</tr>
<tr>
<td>spectral function</td>
<td>model comparison</td>
<td>CCQE/SF</td>
</tr>
</tbody>
</table>

![Graph](image.png)

Also allow normalizations in three energy bins to allow for systematic error on shape variations.
Cross Section Systematic Parameters

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</thead>
<tbody>
<tr>
<td>$M_{\text{AQE}}$</td>
<td>axial mass</td>
<td>CCQE</td>
</tr>
<tr>
<td>$M_{\text{ARES}}$</td>
<td>axial mass</td>
<td>1$\pi$</td>
</tr>
<tr>
<td>CCQE (3)</td>
<td>normalization</td>
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</tr>
</tbody>
</table>

Use MiniBooNE 1$\pi$ data (CC and NC) and fit to NEUT predictions to generate input value

Add ad hoc parameters to improve the fit, but break internal theoretical purity

**CC$\pi^+$**

**NC$\pi^0$**

$M_{\text{ARES}} = 1.41$ GeV/$c^2$
Cross Section Systematic Parameters

<table>
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<td>$M_{\Lambda QE}$</td>
<td>axial mass</td>
<td>CCQE</td>
</tr>
<tr>
<td>$M_{\Lambda RES}$</td>
<td>axial mass</td>
<td>1π</td>
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<tr>
<td>CCQE (3)</td>
<td>normalization</td>
<td>CCQE</td>
</tr>
<tr>
<td>CC1π (2)</td>
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<td>CC1π</td>
</tr>
<tr>
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<td>model comparison</td>
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</tbody>
</table>
Near Detector Event Selection

- Select highest momentum negative, good quality track
- Check if the TPC PID indicates a muon
- Look at secondary tracks and identify three samples: CC0π, CC1π⁺, and CC other

<table>
<thead>
<tr>
<th>Sample</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC0π</td>
<td>72.6%</td>
</tr>
<tr>
<td>CC1π⁺</td>
<td>49.4%</td>
</tr>
<tr>
<td>CC other</td>
<td>73.8%</td>
</tr>
</tbody>
</table>
Detector Systematics

As far as possible, use data to constrain systematics; e.g. use cosmic samples to evaluate interdetector matching

Dominant systematics are pion secondary interactions and out of fiducial volume events

Figure 22: Sketch of the sub-detectors relevant for this analysis with the corresponding associated systematic components.
This technical note describes a fit to the ND280 Run 1 to Run 4 data using the Markov Chain Monte Carlo method. A description of the Markov Chain method can be found in [1].

This analysis uses one new feature compared to the method described the referenced note; instead of reweighting the predicted Monte Carlo (MC) spectra using binned pdf templates, the individual MC events are weighted event-by-event, according to the relevant variable(s) for the tweak being applied. Then, when all weights have been calculated, the MC events are binned to create the predicted spectra.

The Bayesian probability function used to fit the data depends on the data sample and flux, cross section, detector, and final state interactions (FSI) systematics, which will be described in subsequent sections. This function has the form:

$$-\ln(P) = \sum_{i}^{ND280\, bins} N_{i}^{p}(\vec{b}, \vec{x}, \vec{f}, \vec{d}) - N_{i}^{d} + N_{i}^{d} \ln[N_{i}^{d}/N_{i}^{p}(\vec{b}, \vec{x}, \vec{f}, \vec{d})]$$

$$+ \sum_{i}^{E_{\nu}\, bins} \sum_{j}^{E_{\nu}\, bins} \Delta b_{i}(V_{b}^{-1})_{i,j} \Delta b_{j}$$

$$+ \sum_{i}^{xsec\, pars} \sum_{j}^{xsec\, pars} \Delta x_{i}(V_{x}^{-1})_{i,j} \Delta x_{j}$$

$$+ \sum_{i}^{fsip\, pars} \sum_{j}^{fsip\, pars} \Delta f_{i}(V_{f}^{-1})_{i,j} \Delta f_{j}$$

$$+ \sum_{i}^{nd280\, det} \sum_{j}^{nd280\, det} \Delta d_{i}(V_{d}^{-1})_{i,j} \Delta d_{j}$$

Where $V_{ij}$ represents covariance matrices constraining systematic parameters labeled by $b$ for flux, $x$ for cross section, $f$ for FSI, and $d$ for detector. $N_{i}^{p} (\vec{b}, \vec{x}, \vec{f}, \vec{d})$ is the number of predicted events in a particular bin, given the values of the systematic parameters, and $N_{i}^{d}$ is the number of data events.
## ND280 Constraints

### Muon Momentum Distribution for the ND280 Dataset

![Muon momentum distribution](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior</th>
<th>Constraint (2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\Lambda\text{QE}}$ (GeV)</td>
<td>$1.21 \pm 0.45$</td>
<td>$1.240 \pm 0.072$</td>
</tr>
<tr>
<td>$M_{\Lambda\text{RES}}$ (GeV)</td>
<td>$1.41 \pm 0.22$</td>
<td>$0.965 \pm 0.068$</td>
</tr>
</tbody>
</table>

### Cross section Parameter Value

![Cross section parameter value](image)
Intrinsic Beam $\nu_e$

Use a selection of electron neutrino events and fit for the ratio of observed to expected $\nu_e$ events.

Find good agreement between this sample and the expectation from the $\nu_\mu$ analysis

$$f(\nu_e) = 1.055 \pm 0.058\text{(stat.)} \pm 0.079\text{(syst.)}$$
The T2K Experiment

30 April 2012
Sam Short

Near detector suite

Super-Kamiokande

Off-axis neutrino beam reduces the spread of muon neutrino energies.

Chosen off-axis angle is 2.5° which corresponds to a peak beam energy of 0.6 GeV.

The most intense accelerator νμ beam ever built is produced at J-PARC and directed (2.5° off-axis) toward SK.
ν_μ Disappearance

Run 1–3: 3.01x10^{20} POT

- Must be fully contained and in time with the T2K beam
- One muon-like ring
- One or fewer Michel electrons

Electrons from ν_μ are the signal we are looking for.

Čerenkov ring is sharp.

NC-𝜋₀ events are another important background.

Mimic electron if one ring is missed.

Example event displays µμeπ₀

All taken from MC simulation.

Run 1–3: 3.01x10^{20} POT
Fit Method

- Fit the 58 data events in reconstructed energy—expect 205 with no oscillation
- Dominant uncertainties come from detector uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty (no. of parameters)</th>
<th>$\frac{\delta n_{SK}^{exp}}{n_{SK}^{exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND280-uncorrelated cross section (11)</td>
<td>6.3%</td>
</tr>
<tr>
<td>Flux &amp; ND280-correlated cross section (23)</td>
<td>4.2%</td>
</tr>
<tr>
<td>Super-Kamiokande detector (8)</td>
<td>10.1%</td>
</tr>
<tr>
<td>Final- and secondary-state interactions (6)</td>
<td>3.5%</td>
</tr>
<tr>
<td>Total (48)</td>
<td>13.1%</td>
</tr>
</tbody>
</table>

Without ND280 Constraint: 21.8%
\[ \nu_\mu \rightarrow \nu_\mu \]

Maximal disappearance with $\sin^2 2\theta_{13} = 0.0$
Maximal disappearance with $\sin^2 2\theta_{13} = 0.098$

\[
\sin^2 (\theta_{23}) = 0.514 \pm 0.082
\]

\[
|\Delta m^2_{32}| = 2.44^{+0.17}_{-0.15} \times 10^{-3} \text{ eV}^2
\]
$\nu_\mu \rightarrow \nu_\mu$

- T2K data prefers maximal disappearance in a three neutrino model.
- Even with very statistically limited data, limits are very competitive with other experiments.
\(\nu_e\) Appearance

- Must be fully contained and in time with the T2K beam
- One electron-like ring
- No Michel electron
- Inconsistent with \(\pi^0\) mass
  - New \(\pi^0\) cut method for 2013: use a maximum-likelihood for reconstructing rings, including multi-particle states
  - Reduces background by 69%, losing only 2% of signal
- Reconstructed energy <1250 MeV
Fit Method

- Fit the data in momentum and angle or reconstructed energy
- Primary backgrounds from intrinsic beam $\nu_e$ with a smaller contribution from mis-reconstructed $\pi^0$
- Dominant systematic uncertainties come from interaction model not constrained by ND280

| Selection                  | Data | $\nu_\mu \to \nu_e$ | $\nu_\mu + \bar{\nu}_\mu$ | $\nu_e + \bar{\nu}_e$ | NC | Total
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interactions in FV</td>
<td>-</td>
<td>27.1</td>
<td>325.7</td>
<td>16.0</td>
<td>288.1</td>
<td>656.8</td>
</tr>
<tr>
<td>FCFV</td>
<td>377</td>
<td>26.2</td>
<td>247.8</td>
<td>15.4</td>
<td>83.0</td>
<td>372.4</td>
</tr>
<tr>
<td>+Single-ring</td>
<td>193</td>
<td>22.7</td>
<td>142.4</td>
<td>9.8</td>
<td>23.5</td>
<td>198.4</td>
</tr>
<tr>
<td>+e-like PID</td>
<td>60</td>
<td>22.4</td>
<td>5.6</td>
<td>9.7</td>
<td>16.3</td>
<td>54.2</td>
</tr>
<tr>
<td>+$p_e &gt; 100$MeV</td>
<td>57</td>
<td>22.0</td>
<td>3.7</td>
<td>9.7</td>
<td>14.0</td>
<td>49.4</td>
</tr>
<tr>
<td>+No decay-e</td>
<td>44</td>
<td>19.6</td>
<td>0.7</td>
<td>7.9</td>
<td>11.8</td>
<td>40.0</td>
</tr>
<tr>
<td>+$E_{\nu}^{\text{rec}} &lt; 1250$MeV</td>
<td>39</td>
<td>18.8</td>
<td>0.2</td>
<td>3.7</td>
<td>9.0</td>
<td>31.7</td>
</tr>
<tr>
<td>+Non-$\pi^0$-like</td>
<td>28</td>
<td>17.3</td>
<td>0.1</td>
<td>3.2</td>
<td>1.0</td>
<td>21.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Error source [%]</th>
<th>$\sin^2 2\theta_{13} = 0.1$</th>
<th>$\sin^2 2\theta_{13} = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam flux and near detector (w/o ND280 constraint)</td>
<td>2.9</td>
<td>4.8</td>
</tr>
<tr>
<td>$\nu$ interaction (external data)</td>
<td>(25.9)</td>
<td>(21.7)</td>
</tr>
<tr>
<td>Far detector and FSI+SI+PN</td>
<td>7.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Total</td>
<td><strong>8.8</strong></td>
<td><strong>11.1</strong></td>
</tr>
</tbody>
</table>

Down by ~1% from 2012
with normal hierarchy, $\sin^2 \theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$, and $\delta_{CP} = 0$

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

- The effect of the uncertainty of $\sin^2\theta_{23}$ and $\Delta m^2_{32}$ is non-negligible
- Data from $3.01 \times 10^{20}$ POT is used to constrain these parameters
- Correlation between SK detector systematics has negligible effect on the current analysis, as both analyses are statistically limited

![Image of correlation between $\sin^2\theta_{23}$ and $\Delta m^2_{32}$ with sensitivity study](image)
Constraints in $\delta_{\text{CP}}$

- Add an additional term to the likelihood fit to constrain $\sin^2 2\theta_{13}$ to $0.098 \pm 0.013$
- Marginalize over all parameters except $\delta_{\text{CP}}$
- Use the Feldman-Cousins method to determine the 90% confidence level exclusion

![Graph showing constraints in $\delta_{\text{CP}}$]
Outline

- Current State of Neutrino Physics
- The T2K Experiment
- Oscillation Results
- Cross Section Results
- Looking Forward
Cross Section Motivation

- Peak energy of T2K is a region of low knowledge
- Cross sections models have a large impact on oscillation analyses

![Graph showing cross section vs. energy](image)
**Current Cross Section Results**

![Graphs showing cross section data and comparisons with predictions.](image)

### νμ CC inclusive (1.43×10²⁰ POT)

\[
<\sigma>_{\text{flux}} = 2.24 \times 10^{-39} \pm 0.07\text{(stat.)} + 0.53 \text{(sys.)} \frac{\text{cm}^2}{\text{nucleon}}
\]

### νμ CCQE (2.9×10²⁰ POT)

### NC elastic (9.9×10¹⁹ POT; P0D water data)
Outline

- Current State of Neutrino Physics
- The T2K Experiment
- Oscillation Results
- Cross Section Results
- Looking Forward
Improvements

- Run 1–4 $\nu_\mu$ disappearance results to be released soon!
- New selections
  - $\pi^0$ sample at SK for backgrounds to appearance
  - More ND280 samples to better constrain cross section parameters
- Fit collectively over more samples simultaneously
Future Sensitivity

All plots with 50% $\nu$ and 50% $\bar{\nu}$ running

\[ \delta_{CP} = 0^\circ \]
\[ \delta_{CP} = 90^\circ \]

Current T2K POT

Full T2K POT

$\times 10^{21}$ POT

$\delta_{CP}$

NH
IH
Reactor

True $\delta_{CP} = -90^\circ$
True NH

$\sin^22\theta_{13}$

$\times 10^{-3}$

Current T2K POT

Full T2K POT

$\times 10^{21}$ POT

Reactor constraint: $0.1 \pm 0.005$

$\sin^22\theta_{13}$
Future of Cross Sections

Very little knowledge in the T2K peak region—lots of opportunity!

Imperial College London
Conclusions

- T2K has examined both $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ oscillations
- In the $\nu_\mu \rightarrow \nu_e$ mode, there is a hint of tension between T2K and reactor experiments
- The $\nu_\mu \rightarrow \nu_\mu$ mode shows oscillations consistent with maximal mixing
- Increased statistics, new samples, and new analysis methods will improve and refine these measurements and open the door to new parameters