Neutrino Oscillations in T2K: Recent Results and Future Sensitivities

Daniel Cheradack
(Colorado State University) for the T2K Collaboration

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors
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The University of Tokyo
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Outline

• Neutrino Oscillations
• The T2K Experimental Design
• Constraining the T2K Unoscillated Event Rate in Super-Kamiokande (SK)
• The recent $\nu_\mu \rightarrow \nu_\mu$ Measurement
• The recent $\nu_\mu \rightarrow \nu_e$ Measurement
• Future Sensitivities
Questions in Neutrino Physics

• This has been an exciting year in ν physics
• Non-zero $\theta_{13}$ opens a lot of doors both theoretically and experimentally
  – Indications of non-zero $\theta_{13}$ was shown by T2K (2.5$\sigma$) and MINOS (89% CL)
  – $\sin^2(2\theta_{13})$ measured by reactor $\nu_e$ - disappearance experiments
  – Discovery of $\nu_\mu \rightarrow \nu_e$ oscillations by T2K ($\sin^2(2\theta_{13}) \neq 0$ at 7.4$\sigma$)
• There are still many questions that need answers
  – What is the Mass Hierarchy (MH)
  – What is $\delta_{\text{cp}}$? is $\delta_{\text{cp}} \neq 0$?
  – Is $\theta_{23}$ maximal?, If not is it above or below 45° (what is the $\theta_{23}$ octant)?
  – Combined analyses (T2K + reactor) allow for measurements of $\sin^2(\theta_{23})$ and $\sin(\delta_{\text{cp}})$
• Recent T2K results can provide insight into these questions and provide high precision confirmation of previous results
• With full statistics T2K has the capability of measuring an indication of CP violation ($\delta_{\text{cp}} \neq 0$), and determining the $\theta_{23}$ octant
• Combined fits with NOvA may help determine the MH and increase sensitivity to CP violations and the $\theta_{23}$ octant
Neutrino Oscillation Formalism

\[
\begin{pmatrix}
\nu_e & \nu_\mu & \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
\nu_1 & \nu_2 & \nu_3
\end{pmatrix} U_{PMNS}
\]

\[
U_{PMNS} = \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i \delta_{cp}} \\
0 & 1 & 0 \\
-s_{13} e^{i \delta_{cp}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\]

For the T2K baseline (295km) and peak energy (0.6 GeV) the $\nu_e$-appearance oscillation probability, as a function of $\delta_{cp}$ is (NH):

\[
P(\nu_\mu \rightarrow \nu_e) \approx 0.051 - 0.014 \sin \delta_{cp} - 0.00002 \cos \delta_{cp}
\]

- T2K expects \(~5\%\) of the $\nu_\mu$ to oscillate to $\nu_e$ at the peak energy
- There is a \(27\%\) max asymmetry between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- The max asymmetry increases to \(39\%\) for $\theta_{23} = 39^\circ$
The T2K Collaboration

Large international collaboration with:
~500 members from
59 institutions in
11 different 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

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

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

Russia
INR

Germany
Aachen U.

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

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

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

Switzerland
ETH Zurich
U. Bern
U. Geneva
The T2K Experiment

- Study $\nu$ oscillations
- Generate high purity $\nu_\mu$ beam
- Constrain unoscillated flux and cross sections
  - Beam monitoring
  - INGRID (on-axis)
  - ND280 (off-axis)

- Measure oscillated event rates 295 km downstream at Super-Kamiokande (SK)
  - $\nu_\mu$ - disappearance
    $$P(\nu_\mu \to \nu_\mu) \propto \sin^2(2\theta_{23}), \Delta m_{32}^2$$
  - $\nu_e$ - appearance
    $$P(\nu_\mu \to \nu_e) \propto \sin^2(2\theta_{13}), \sin^2(\theta_{23}), \sin(\delta_{\text{cp}})$$
T2K $\nu$ Beamline

- Muon Monitor
  - Si array + IC array
- Horn
- Beam monitors
  - 3 Horns w/ 250kA
  - Intensity, position profile
- Super-Conducting Magnets
- Near detector
  - (at 280m from target)
- Decay Volume
  - 110m length
- Target
  - Graphite, $\Phi$26 x 900 mm long
  - Helium cooling
- Beam Dump
- Proton beam
Off-Axis Flux Optimization

- Off-axis beam provides:
  - Peak energy at $\sin^2(\Delta m^2 L/E)$ maximum
  - Narrow band spectrum
  - Reduced NC background
  - Dominant interaction at SK: CC quasi-elastic

- Optimal angle: 2.5°

- On-axis ND: INGRID
- Off-Axis ND: ND280
- Off-Axis FD: Super-Kamiokande (SK)
Flux Predictions and Uncertainties

• Interaction of 30 GeV protons with graphite target
  - Modeled with FLUKA2008
  - Tuned with NA61/SHINE data
• Propagation, focusing and decay of resulting π and K
  - GEANT3
  - GCALOR (neutrons)

• Flux prediction tuned with experimental data from:
  - Proton flux measurements
  - Horn current monitoring
  - Beamline alignment studies
  - Beam direction (INGRID & μ monitor data)
  - Hadron production uncertainties propagated from NA61/SHINE

• Experimental errors from above propagated to flux uncertainties (right)

INGRID and ND280

• T2K off-axis Near Detector (ND280)
  - Measure cross sections on water
  - Multiple sub detectors
  - Magnetic field (0.2 T)
    • Charge discrimination
    • Momentum determination
  - Low energy cross section measurements
  - Data used to constrain T2K event rate at SK

• INGRID (on-axis)
  - Monitor on-axis beam
  - Stability of direction and event rate

![Diagram of INGRID and ND280](image)
Cross Section Models

- NEUT MC generator used to simulate interactions.
- T2K energy region dominated by (quasi)elastic interactions.
- Resonant $\pi$ production contributes significantly above ~750 MeV.
- Current questions:
  - Meson Exchange Currents vs $M_A^{\text{eff}}$.
  - Relativistic Fermi Gas model vs Spectral Functions.
  - Resonant $\pi$ kinematics.
- Constraints on the cross sections provided by:
  - ND280 (flux + xsec fit).
  - External data (MiniBooNE).
Cross Section Data

• Data from ND280 is used to constrain the **flux \times cross section** prediction for T2K in SK
• ND280 data are divided by **topology**
  - 0 \(\pi\) tracks (QE - like, right)
  - 1 \(\pi\) track (resonance - like)
  - Multi \(\pi\) tracks (DIS - like)
• Each sample is binned in \(p_\mu - \theta_\mu\)

**The MC is fit to the data**
• Fit results are propagated to the T2K prediction at SK
• Cross section parameters are split into two groups:
  - Best-fit central values used to generated T2K prediction at SK
  - Nuisance parameters which are marginalized
• Flux parameters are fit simultaneously (within uncertainties shown on Slide 8)
Constrain the T2K Prediction at SK: Flux $\times$ Cross Section Fit

- Fit to the ND280 data greatly improves constraints on flux $\times$ cross section
- Results of fit to ND280 data:
  - Flux normalizations (top right, $\nu_\mu$)
  - Cross section params. propagated to T2K prediction for SK (bottom right)
- Other fit params (cross section and detector response) marginalized
- **Dominant residual error**: Lack of constraints on marginalized cross section parameters
- New ND280 data samples are being explored / incorporated to improve constraints for future analyses

### Table: Parameter Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior to ND280 Constraint</th>
<th>After ND280 Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{GE}$ (GeV)</td>
<td>1.21 ± 0.45</td>
<td>1.223 ± 0.072</td>
</tr>
<tr>
<td>$M_A^{RES}$ (GeV)</td>
<td>1.41 ± 0.22</td>
<td>0.963 ± 0.063</td>
</tr>
<tr>
<td>CCQE Norm.*</td>
<td>1.00 ± 0.11</td>
<td>0.961 ± 0.076</td>
</tr>
<tr>
<td>CC1$\pi$ Norm.**</td>
<td>1.15 ± 0.32</td>
<td>1.22 ± 0.16</td>
</tr>
<tr>
<td>NC1$\pi^0$ Norm.</td>
<td>0.96 ± 0.33</td>
<td>1.10 ± 0.25</td>
</tr>
</tbody>
</table>

*For $E_\nu < 1.5$ GeV  **For $E_\nu < 2.5$ GeV
T2K Events in the SK Detector

- 50 kt Water Cherenkov Detector
- 22.5 kt Fiducial Volume
- $\mu$ - ring
  - Relatively straight trajectory
  - Clear ring edges
- $e^-$ - ring
  - $e^-$ scatter more than $\mu^-$
  - 'Fuzzy' ring edges
- $\pi^0$ induced backgrounds
  - $\pi^0 \rightarrow \gamma + \gamma$, produce two $e^-$ - like rings
  - Must resolve both rings to reject

Monte Carlo Simulations
**νμ - Disappearance Event Selection**

**SK Selection Cuts**

- \( E_{\text{vis}} > 100 \text{ MeV} \)
- Veto hits < 16
- Fully contained
  (Fid. Vol. = 200 cm)
- Single ring
- Muon-like
- \( p_\mu > 200 \text{ MeV} \)
- 0 or 1 Michel e\(^-\)
νμ - Disappearance Fitting

- Scan over values of:
  - $\Delta m^2_{32}$
  - $\sin^2(2\theta_{23})$
- Scan 1st and 2nd octant separately
- Calculate likelihood of data originating from prediction

\[
\chi^2 = 2 \sum_{E_r} \left( N_{SK}^{\text{data}} \ln \frac{N_{SK}^{\text{data}}}{N_{SK}^{\exp}} + \left( N_{SK}^{\exp} - N_{SK}^{\text{data}} \right) \right) + (f - f_0)^T C^{-1} (f - f_0)
\]

Statistical Constraints in $E_\nu$ Bins

Systematic Prior Constraints
\[ \nu\rightarrow \mu \] Disappearance Results

- Best-fit oscillation parameter values:
  \[ \sin^2(\theta_{23}) = 0.514 \pm 0.082 \]
  \[ |\Delta m^2_{32}| = 2.44^{+0.17}_{-0.15} \times 10^{-3} \text{ eV}^2/\text{c}^2 \]
- Data prefers 2nd \( \theta_{23} \) octant
- 1\( \sigma \) confidence intervals are consistent with:
  - Maximal mixing (\( \sin^2(\theta_{23}) \))
  - The MINOS result (\( \Delta m^2_{32} \))

\[ \chi^2 = 2 \sum_{E_r} \left( N_{SK}^{data} \ln \frac{N_{SK}^{data}}{N_{SK}^{exp}} + \left( N_{SK}^{exp} - N_{SK}^{data} \right) \right) + (f - f_0)^T C^{-1} (f - f_0) \]

Statistical Constraints in \( E_{\nu} \) Bins

Systematic Prior Constraints
$\nu_\mu$ - Disappearance Comparison

<table>
<thead>
<tr>
<th>$\sin^22\theta_{23}$</th>
<th>$\Delta m_{32}^2$</th>
<th>$\chi^2 / \text{ndf}$</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\exp}$</th>
<th>$p$-value</th>
<th>Null Oscillation Expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{23} \leq \pi/4$</td>
<td>1.000</td>
<td>$2.44 \times 10^{-3}$</td>
<td>56.04 / 71</td>
<td>58</td>
<td>57.97†</td>
<td>$204.7 \pm 16.7$</td>
</tr>
<tr>
<td>$\theta_{23} \geq \pi/4$</td>
<td>0.999</td>
<td>$2.44 \times 10^{-3}$</td>
<td>56.03 / 71</td>
<td>58</td>
<td>57.92†</td>
<td>$204.7 \pm 16.7$</td>
</tr>
</tbody>
</table>
$\nu_e$ - Appearance Event Selection

SK Selection Cuts

- Veto hits < 16
- Fully contained
  (Fid. Vol. = 200 cm)
- $E_{\text{vis}} > 100$ MeV
- Single ring
- Electron-like
- $100 < E_\nu < 1250$ MeV
- 0 Michel $e^-$
- Cut to remove $\pi^0$ background
Event Selections Improvements

- **Old \( \pi^0 \) cut**: Use reco. \( \pi^0 \) mass
- **New \( \pi^0 \) cut**: Add fitter
  - Forces fits to \( \pi^0 \) and e\(^-\) hypotheses
  - Fits 12 parameters
    - Vertex (4)
    - Direction (2x2)
    - Momenta (2)
    - Conversion distances (2)

2D cut removes 70% more \( \pi^0 \) background than previous method

- More sensitive to low energy photons
- Better discrimination in \( \pi^0 \) mass tail
Event Selections Improvements

- **Old $\pi^0$ cut:** Use reco. $\pi^0$ mass
- **New $\pi^0$ cut:** Add fitter
  - Forces fits to $\pi^0$ and $e^-$ hypotheses
  - Fits 12 parameters
    - Vertex (4)
    - Direction (2x2)
    - Momenta (2)
    - Conversion distances (2)
  - Calculate likelihood for each hypothesis
  - Also reconstruct $\pi^0$ mass
- **2D cut** removes 70% more $\pi^0$ background than previous method
- More sensitive to low energy photons
- Better discrimination in $\pi^0$ mass tail
$\nu_e$ - Appearance Event Rate Prediction and Uncertainties

### 2013 Event Rate Predictions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Total $\nu_e$</th>
<th>$\nu_e$ sig.</th>
<th>$\nu_e$ bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal SK MC</td>
<td>21.64</td>
<td>17.36</td>
<td>3.02</td>
</tr>
<tr>
<td>Before ND280 fit</td>
<td>22.57</td>
<td>17.94</td>
<td>3.24</td>
</tr>
<tr>
<td>After ND280 fit</td>
<td>20.44</td>
<td>16.42</td>
<td>2.93</td>
</tr>
<tr>
<td>ND280+ Old $\pi^0$ cut</td>
<td>22.50</td>
<td>16.78</td>
<td>3.08</td>
</tr>
<tr>
<td>ND280+ New $\pi^0$ cut</td>
<td>21.90</td>
<td>17.35</td>
<td>3.30</td>
</tr>
</tbody>
</table>

### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\sin^2 2\theta_{13} = 0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/o ND280 fit</td>
</tr>
<tr>
<td>Beam only</td>
<td>11.6</td>
</tr>
<tr>
<td>$M^Q_{QE}$</td>
<td>21.5</td>
</tr>
<tr>
<td>$M^A_{RES}$</td>
<td>3.3</td>
</tr>
<tr>
<td>CCQE norm. ($E_\nu &lt; 1.5$ GeV)</td>
<td>9.3</td>
</tr>
<tr>
<td>CC1$\pi$ norm. ($E_\nu &lt; 2.5$ GeV)</td>
<td>4.2</td>
</tr>
<tr>
<td>NC1$\pi^0$ norm.</td>
<td>0.6</td>
</tr>
<tr>
<td>CC other shape</td>
<td>0.1</td>
</tr>
<tr>
<td>Spectral Function</td>
<td>6.0</td>
</tr>
<tr>
<td>$pF$</td>
<td>0.1</td>
</tr>
<tr>
<td>CC coh. norm.</td>
<td>0.3</td>
</tr>
<tr>
<td>NC coh. norm.</td>
<td>0.3</td>
</tr>
<tr>
<td>NC other norm.</td>
<td>0.5</td>
</tr>
<tr>
<td>$\sigma_{\nu_e}/\sigma_{\nu_\mu}$</td>
<td>2.9</td>
</tr>
<tr>
<td>W shape</td>
<td>0.2</td>
</tr>
<tr>
<td>pion-less $\Delta$ decay</td>
<td>3.7</td>
</tr>
<tr>
<td>SK detector eff.</td>
<td>2.4</td>
</tr>
<tr>
<td>FSI</td>
<td>2.3</td>
</tr>
<tr>
<td>PN</td>
<td>0.8</td>
</tr>
<tr>
<td>SK momentum scale</td>
<td>0.6</td>
</tr>
<tr>
<td>Total</td>
<td>28.1</td>
</tr>
</tbody>
</table>

Run 1-4 $\rightarrow$ $6.393 \times 10^{20}$ POT
\( \nu_e \) - Appearance Event Rate Prediction and Uncertainties

2013 Event Rate Predictions

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<th>( \nu_e ) bkg.</th>
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<table>
<thead>
<tr>
<th>Parameters</th>
<th>( \nu_\mu ) bkg.</th>
<th>( \bar{\nu}_\mu ) bkg.</th>
<th>( \bar{\nu}_e ) bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal SK MC</td>
<td>1.05</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>Before ND280 fit</td>
<td>1.17</td>
<td>0.07</td>
<td>0.16</td>
</tr>
<tr>
<td>After ND280 fit</td>
<td>0.89</td>
<td>0.05</td>
<td>0.14</td>
</tr>
<tr>
<td>ND280+ Old ( \pi^0 ) cut</td>
<td>2.33</td>
<td>0.13</td>
<td>0.16</td>
</tr>
<tr>
<td>ND280+ New ( \pi^0 ) cut</td>
<td>1.03</td>
<td>0.06</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Run 1-4 \( \rightarrow 6.393 \times 10^{20} \) POT

Systematic Uncertainties

\( \sin^2 2\theta_{13} = 0.1 \)

Predicted Number of T2K \( \nu_e \) - appearance Events in SK (Signal + Background)
\( \nu_e \) - Appearance Fitting and Results

- Fit to maximize the likelihood that:
  - \( N_{\text{obs}} = \mathcal{P}_{\text{poisson}}(N_{\text{pred}}) \)
  - An e\(^-\) has a particular p\(_e\) - \( \theta_e \)
  - Systematic fluctuations are consistent with priors
- Scan over \( \sin^2(2\theta_{13}) \) space
- Other osc. params. are fixed
  - \( \Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2 \)
  - \( \sin^2(2\theta_{23}) = 1.0 \)
  - \( \delta_{\text{cp}} = 0^\circ \)
- Best fit, assuming above params.
  - \( \text{NH}: \sin^2(2\theta_{13}) = 0.150^{+0.039}_{-0.034} \)
  - \( \text{IH}: \sin^2(2\theta_{13}) = 0.182^{+0.046}_{-0.040} \)
- 1\(\sigma\) C.L. errors
- Excludes \( \sin^2(2\theta_{13}) = 0 \) at 7.4\(\sigma\)
\( \nu_e \) - Appearance Results

- Repeat fit for other oscillation parameter values
  - \(-\pi < \delta_{\text{cp}} < \pi\)
  - MH \((\pm |\Delta m^2_{32}|)\)
  - \(\sin^2(\theta_{23})\) (backup slide)
- Results consistent across runs
Future Sensitivities

- **Daya Bay:**
  - Measures $\bar{v}_e$ - disappearance
  - $P(\bar{v}_e \rightarrow \bar{v}_e) \propto \sin^2(2\theta_{13})$
  - Very high precision
- **T2K:**
  - Measures $v_e$ - appearance
  - $P(v_\mu \rightarrow v_e) \propto \sin^2(2\theta_{13}), \sin^2(\theta_{23}), \sin(\delta_{cp})$
  - Differences due to $\theta_{23}$ and $\delta_{cp}$
- If the Daya Bay result is assumed in T2K fits then T2K is sensitive to:
  - CP violation
  - The $\theta_{23}$ octant
  - MH (with NOvA)

- **Study T2K sensitivity w.r.t.:**
  - Exposure: up to $7.8 \times 10^{21}$ POT
  - Run plan: $\nu$ vs $\bar{\nu}$ beam
  - Combined analysis: T2K + NOvA
  - Systematic uncertainty projections
T2K Spectra at SK for $7.8 \times 10^{21}$ POT

- Calculated FD spectra for full T2K statistics
  - Project SK MC to higher exposure
  - Estimate $\bar{\nu}$ beam MC from flux ratios
- Simultaneous fit of $\nu_\mu$, $\nu_e$, $\bar{\nu}_\mu$, and $\bar{\nu}_e$ samples
- Oscillation parameter uncertainties
  - Fix solar terms
  - Allow atmospheric terms to float within current uncertainties
  - Project $\theta_{13}$ uncertainties to Daya Bay systematic uncertainty:
    \[ \sin^2(2\theta_{13}) = 0.1 \pm 0.005 \]
    - MH and $\delta_{cp}$ are unconstrained
- Assume various true values for: $\theta_{13}$, $\theta_{23}$, $\delta_{cp}$, and MH
T2K 50% $\nu$ / 50% $\bar{\nu}$ + Daya Bay

- No Systematics (solid)  
  Ability to determine CP violation as a function of true $\delta_{CP}$

- With systematics (dashed)  
  ~10% for $\nu_e$ and ~13% for $\nu_\mu$
  - $\nu$ samples assumes 2012 level systematics
  - $\bar{\nu}$ samples assume +10% additional uncertainty
T2K + NOvA + Daya Bay

- Produce T2K spectra in GLoBES
- Reproduce NOvA event spectra in GLoBES (right)
- Reproduce NOvA results (below) using generated spectra

**Systematic Uncertainties:**
- Treat T2K and NOvA equally
- Allow normalizations to float
  - Signal: 5%
  - Background: 10%
- T2K-only consistent across both studies

Note: $\sigma = \sqrt{\Delta \chi^2}$
Combined Sensitivities and Optimal Run Plan

- **CPV sensitivity**
  - Greatly enhanced by combined fit
  - Flat for run ratios $\nu > 30%/70\% \bar{\nu}$

- **Mass Hierarchy**
  - Almost no sensitivity alone
  - Large enhancement to NO
    - A degenerate region
      - Prefers more $\nu$ running in combined fit

- **Evaluated other metrics**
  - Metrics mostly flat for: $70%/30\% < \nu\bar{\nu} < 30%/70\%$

- **50%/50% $\nu\bar{\nu}$ running**

- **Variable $\nu\bar{\nu}$ running**
Combined Sensitivities and Optimal Run Plan

- **CPV sensitivity**
  - Greatly enhanced by combined fit
  - Flat for run ratios $\nu > 30\%/70\% \bar{\nu}/\nu$

- **Mass Hierarchy**
  - Almost no sensitivity alone
  - Large enhancement to NO
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- Evaluated other metrics
- Metrics mostly flat for: $70\%/30\% < \nu/\nu < 30\%/70\%$

**Plots**

- CPV Determination
- Mass Hierarchy Determination
T2K + NovA + Daya Bay:
Allowed Regions in $\delta_{cp}$ - vs - $\sin^2(\theta_{23})$

- $\delta_{cp} = 0^\circ$
  - $\sin^2(\theta_{23}) = 0.5$
  - $\sin^2(\theta_{23}) = 0.39$
  - $\sin^2(\theta_{23}) = 0.39$

- $\delta_{cp} = -90^\circ$
  - $\sin^2(\theta_{23}) = 0.5$
  - $\sin^2(\theta_{23}) = 0.39$
  - $\sin^2(\theta_{23}) = 0.39$

True Value, $\Delta m^2 > 0$
- T2K, Unknown MH: Red
- NOvA, Unknown MH: Blue
- T2K + NOvA with systematics: Black

NH 100% $\nu$
NH 50% $\nu$
NH 50% $\bar{\nu}$
T2K + NovA + Daya Bay: 90% C.L. Regions in $\delta_{cp}$ -vs- $\sin^2(\theta_{23})$

- **NH**
- **CP Violation**
- **Mass Hierarchy**
- **$\theta_{23}$ Octant**
Evaluating Future Systematics

• New Method to propagate systematics
  – Easily combine any set of systematics
  – Add new parameters and remove old ones
  – Scale prior widths with each systematic
  – Adjust $\bar{\nu}/\nu$ and $\nu_e/\nu_\mu$ correlations

• Allows for updated systematics studies as we move forward

• Allows people working new models on ND analysis to project the impact of their work to the oscillation analyses
Sensitivity to CP Violation

- POT: $7.8 \times 10^{21}$ all $\nu$ running, $\nu_e$ - appearance only
- Each individual NIWG systematic + All NIWG Systematics
- Normalization systematic of 5% (left) and 10% (right)
Sensitivity to CP Violation

- POT: $7.8 \times 10^{21}$ all 50%/50% $\nu/\bar{\nu}$ running, $\nu_e$ - appearance + $\nu_\mu$ - disappearance
- Each individual NIWG systematic + All NIWG Systematics
- Normalization systematic of 5% (left) and 10% (right)
Moving Forward

- Ultimate goal: a tool for groups (NIWG, BANFF, etc) to propagate new Systematics to sensitivities
  - Executable to generate response functions using T2KReweight
    - Loop over SK events and calculate new systematic weights
    - Generates inputs to GLoBES style sensitivity calculations
  - Executable to that produces a set of sensitivity plots for a give set of inputs
    - Event rate and smearing functions (standard set)
    - Response functions
    - Exposure
    - Parameter correlations

- Must be careful about treatment of $\nu/\bar{\nu}$ and $\nu_e/\nu_\mu$ correlations
  - Fits results are very sensitive to levels of correlation
  - The amount that can be learned about one xsec type from the others is limited by
    - Realistic measurement statistics
    - Differences in the physics properties measured

http://www.t2k.org/asg/sensitivity/meeting2/2013-10-02/T2K_Repsonse_Functions_Sept13_Collab_Meeting.pdf/view
Conclusions

- The T2K experiments doubled its statistics in the past year and results are improving.
- Analysis techniques continue to improve:
  - Better constraints from ND280
  - Improved $\pi^0$ rejection at Super-Kamiokande
- Measured $\nu_\mu \rightarrow \nu_e$ oscillations rejecting $\theta_{13} = 0$ at 7.4$\sigma$.
- Continue to improve constraints in $\Delta m^2_{32}$ and $\theta_{23}$.
- Future will bring improved measurements and sensitivity to CP violation, $\theta_{23}$ octant and the mass hierarchy:
  - Beam upgrades will accelerate POT accumulation.
  - Antineutrino running pilot run proposed for 2014.
  - Combined fits with NOvA and Daya Bay will open doors to new physics.
Backup Slides
Neutrino Oscillation Formalism

\[
\begin{pmatrix}
\nu_e & \nu_\mu & \nu_\tau
\end{pmatrix} = U_{PMNS}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
U_{PMNS} = \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-\frac{s_{12}}{\sqrt{2}} & \frac{c_{12}}{\sqrt{2}} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i \delta_{cp}} \\
0 & 1 & 0 \\
-s_{13} e^{-i \delta_{cp}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & -\frac{s_{23}}{\sqrt{2}} \\
0 & \frac{s_{23}}{\sqrt{2}} & c_{23}
\end{pmatrix}
\]

\[
P(\nu_\mu \to \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Phi_{31} \left( 1 + \frac{2a}{\Delta m_{31}^2} (1 - 2s_{13}^2) \right)
\]

\[
+ 8 c_{13}^2 s_{12} s_{13} s_{23} \left( c_{12} c_{23} \cos(\delta_{cp}) - s_{12} s_{13} s_{23} \right) \cos \Phi_{32} \sin \Phi_{31} \sin \Phi_{21}
\]

\[
- 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin(\delta_{cp}) \sin \Phi_{32} \sin \Phi_{31} \sin \Phi_{21}
\]

\[
+ 4 s_{12}^2 c_{13}^2 \left( c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{13} s_{23} \cos(\delta_{cp}) \right) \sin^2 \Phi_{21}
\]

\[
- 8 c_{13}^2 s_{13}^2 s_{23}^2 \left( 1 - 2s_{13}^2 \right) \frac{aL}{4E} \cos \Phi_{32} \sin \Phi_{31}
\]
Pre-fit ND280 / SK Flux Correlations
Pre-fit ND280 / SK Flux Correlations

E_\nu (0-10 GeV) for each detector, flavor
Flux Constraints – All $\nu$ Samples

- **SK $\nu_\mu$ Flux**
  - Prior to ND280 Constraint
  - After ND280 Constraint

- **SK $\bar{\nu}_\mu$ Flux**
  - Prior to ND280 Constraint
  - After ND280 Constraint

- **SK $\nu_e$ Flux**
  - Prior to ND280 Constraint
  - After ND280 Constraint

- **SK $\bar{\nu}_e$ Flux**
  - Prior to ND280 Constraint
  - After ND280 Constraint
CC 1\(\pi\) and CC multi \(\pi\) samples
ND280 Pre-fit and Post-fit Matrices
Fixed Oscillation Parameters in Oscillations Fits to SK Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.6 \times 10^{-5} \text{eV}^2$</td>
</tr>
<tr>
<td>$\Delta m_{32}^2$</td>
<td>$2.4 \times 10^{-3} \text{eV}^2$</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{12}$</td>
<td>0.8704</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{23}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.1 (or 0)</td>
</tr>
<tr>
<td>$\delta_{\text{CP}}$</td>
<td>0</td>
</tr>
<tr>
<td>Mass hierarchy</td>
<td>Normal</td>
</tr>
<tr>
<td>$\nu$ travel length</td>
<td>295 km</td>
</tr>
<tr>
<td>Earth density</td>
<td>2.6g/cm$^3$</td>
</tr>
</tbody>
</table>

*Fit Parameter in Disappearance Fits*

*Fit Parameter in Appearance Fits*
$\nu_\mu$ - Disappearance Event Rate

<table>
<thead>
<tr>
<th>RUN1+2+3 $(\sin^2 2\theta_{23}, \Delta m^2_{32})=(1.0, 2.4\times10^{-3} \text{ eV}^2)$</th>
<th>Data</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MC</td>
<td>$\nu_\mu + \bar{\nu}_\mu$</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>CCQE</td>
</tr>
<tr>
<td>TrueFV</td>
<td>-</td>
<td>299.35</td>
</tr>
<tr>
<td>FCFV</td>
<td>174</td>
<td>168.86</td>
</tr>
<tr>
<td>Single-ring</td>
<td>88</td>
<td>85.65</td>
</tr>
<tr>
<td>Muon-like PID</td>
<td>66</td>
<td>69.67</td>
</tr>
<tr>
<td>$p_\mu &gt; 200 \text{MeV/c}$</td>
<td>65</td>
<td>69.25</td>
</tr>
<tr>
<td>$N_{\text{decay-e}} \leq 1$</td>
<td>58</td>
<td>59.86</td>
</tr>
<tr>
<td>Efficiency from Interaction [%]</td>
<td>-</td>
<td>20.0</td>
</tr>
<tr>
<td>Efficiency from FCFV [%]</td>
<td>-</td>
<td>35.4</td>
</tr>
</tbody>
</table>

Source of uncertainty:

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$1R_\mu \delta N_{SK}/N_{SK}$</th>
<th>$1R \delta N_{SK}/N_{SK}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperK detector</td>
<td>10.05%</td>
<td>3.20%</td>
</tr>
<tr>
<td>BANFF (prefit)</td>
<td>21.66%</td>
<td>24.57%</td>
</tr>
<tr>
<td>BANFF (postfit)</td>
<td>4.13%</td>
<td>4.71%</td>
</tr>
<tr>
<td>Uncorrelated XSec</td>
<td>6.34%</td>
<td>4.18%</td>
</tr>
<tr>
<td>FSI+SI</td>
<td>3.49%</td>
<td>2.30%</td>
</tr>
<tr>
<td>Total (BANFF prefit)</td>
<td>25.33%</td>
<td>25.14%</td>
</tr>
<tr>
<td>Total (BANFF postfit)</td>
<td>13.32%</td>
<td>7.52%</td>
</tr>
</tbody>
</table>

$E_{\nu}^{\text{rec}} = \frac{(M_n - V_{\text{nuc}}) \cdot E_i - m_1^2/2 + M_n \cdot V_{\text{nuc}} - V_{\text{nuc}}^2/2 + (M_p^2 - M_n^2)/2}{M_n - V_{\text{nuc}} - E_i + P_1 \cos \theta_{\text{beam}}}$. 
$\nu_\mu$ - Disappearance Comparison

<table>
<thead>
<tr>
<th>$\sin^22\theta_{23}$</th>
<th>$\Delta m_{32}^2$</th>
<th>$\chi^2$ / ndf</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{exp}}$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{23} \leq \pi/4$</td>
<td>1.000</td>
<td>2.44e-3</td>
<td>56.04 / 71</td>
<td>58</td>
<td>57.97†</td>
</tr>
<tr>
<td>$\theta_{23} \geq \pi/4$</td>
<td>0.999</td>
<td>2.44e-3</td>
<td>56.03 / 71</td>
<td>58</td>
<td>57.92†</td>
</tr>
</tbody>
</table>

† Null Oscillation Expectation 204.7±16.7
\( \nu_e \) - Appearance

\[ \sin^2(\theta_{23}) \text{ -vs- } \sin^2(2\theta_{13}) \]

**Normal Hierarchy**

- Dotted lines indicate 2012 1\( \sigma \) range on \( \sin^2(\theta_{23}) \)
- Large effect on the best-fit central value
- Error bands increase for lower values of \( \sin^2(\theta_{23}) \)

**Inverted Hierarchy**

- T2K Run1-4 \( \nu_e \) appearance (6.393c20 POT)
- Normal hierarchy
- \(|\Delta m^2_{\odot}|=2.4\times10^{-3}\text{ eV}^2\)
- \(\delta_{CP}=0\)
- 68% C.L.
- 90% C.L.
- Best fit
- PDG2012 1\( \sigma \) range

- T2K Run1-4 \( \nu_e \) appearance (6.393c20 POT)
- Inverted hierarchy
- \(|\Delta m^2_{\odot}|=2.4\times10^{-3}\text{ eV}^2\)
- \(\delta_{CP}=0\)
- 68% C.L.
- 90% C.L.
- Best fit
- PDG2012 1\( \sigma \) range
$\nu_e$ - Appearance Runs 1-3 vs Run 4
# νe - Appearance Event Rate Prediction and Uncertainties

## 2013 Event Rate Predictions

<table>
<thead>
<tr>
<th></th>
<th>sin^22θ_{13} = 0.1</th>
<th>sin^22θ_{13} = 0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nominal</td>
<td>Pre ND280 fit</td>
</tr>
<tr>
<td>νe CC signal</td>
<td>17.4</td>
<td>17.9</td>
</tr>
<tr>
<td>νμ background</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>νμ background</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>νe background</td>
<td>3.0</td>
<td>3.3</td>
</tr>
<tr>
<td>νe background</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>21.6</td>
<td>22.6</td>
</tr>
</tbody>
</table>

## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Error source</th>
<th>sin^22θ_{13} = 0.1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre ND280 fit</td>
<td>Post ND280 fit</td>
</tr>
<tr>
<td>Flux</td>
<td>11.6</td>
<td>7.6</td>
</tr>
<tr>
<td>M_A^{QE} (GeV)</td>
<td>21.2</td>
<td>3.2</td>
</tr>
<tr>
<td>M_A^{RES} (GeV)</td>
<td>3.4</td>
<td>1.0</td>
</tr>
<tr>
<td>CCQE norm (E_ν &lt; 1.5 GeV)</td>
<td>9.1</td>
<td>6.3</td>
</tr>
<tr>
<td>CC1π norm (E_ν &lt; 2.5 GeV)</td>
<td>4.0</td>
<td>2.1</td>
</tr>
<tr>
<td>NCIπ⁺₀ norm</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>CC other shape (GeV)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Spectral function</td>
<td>6.1</td>
<td>6.1</td>
</tr>
<tr>
<td>p_F (MeV)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>CC coherent norm</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>NC coherent norm</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>NCIπ⁺₀+NC other norm</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>σ_νeCC/σ_νμCC</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>W shape (MeV)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Pionless delta decay</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>SK detector efficiency</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>FSI+SI</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Photo-nuclear</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>SK energy scale</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>27.9</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Run 1-4 → 6.393x10^{20} POT
\( \nu_e \) - Appearance Event Rate Prediction and Uncertainties

### 2013 Event Rate Predictions

<table>
<thead>
<tr>
<th>( \sin^2 2\theta_{13} = 0.1 )</th>
<th>Nominal</th>
<th>Pre ND280 fit</th>
<th>Post ND280 fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e ) CC signal</td>
<td>17.4</td>
<td>17.9</td>
<td>16.0</td>
</tr>
<tr>
<td>( \nu_\mu ) background</td>
<td>1.1</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>( \bar{\nu}_\mu ) background</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>( \nu_e ) background</td>
<td>3.0</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td>( \bar{\nu}_e ) background</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>21.6</td>
<td>22.6</td>
<td>20.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \sin^2 2\theta_{13} = 0.0 )</th>
<th>Nominal</th>
<th>Pre ND280 fit</th>
<th>Post ND280 fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e ) CC signal</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>( \nu_\mu ) background</td>
<td>1.1</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>( \bar{\nu}_\mu ) background</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>( \nu_e ) background</td>
<td>3.3</td>
<td>3.5</td>
<td>3.2</td>
</tr>
<tr>
<td>( \bar{\nu}_e ) background</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>4.9</td>
<td>5.3</td>
<td>4.6</td>
</tr>
</tbody>
</table>

### Systematic Uncertainties

- 6.39 \times 10^{20} \text{ p.o.t.}
- \( \sin^2 2\theta_{13} = 0.1 \)
- \( \sin^2 2\theta_{23} = 1.0 \)
- \( \Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2 \)
- (Normal hierarchy)
- \( \delta_{CP} = 0 \)

**Reconstructed neutrino energy (MeV)**

\[
E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos \theta_e)}
\]

**Run 1-4 \( \rightarrow 6.393 \times 10^{20} \text{ POT} \)**
• Other Backup for nue?:
  - contribution of rate and shape terms?
  - P-value calculation
  - Erec analysis
Combined Fit 90% CL Allowed Regions
Event Rate Expectations for T2K and NOvA