Precision Measurement of Muon Neutrino Disappearance with T2K

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for the
The T2K Collaboration

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Neutrino Physics at T2K

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

New: Study effects of multinucleon interactions

Disappearance: \( \nu_\mu \to \nu_\mu \)

\[
P(\nu_\mu \to \nu_\mu) \simeq 1 - 4 \cos^2(\theta_{13}) \sin^2(\theta_{23}) \left[ 1 - \cos^2(\theta_{13}) \sin^2(\theta_{23}) \right] \sin^2\left( \frac{\Delta m^2_{32} L}{4E} \right)
\]

Appearance: \( \nu_\mu \to \nu_e \)

\( \theta_{13}, \delta_{cp} \)

Next Talk

Neutrino Interactions

See Posters from E. Scantamburlo and L. Haegel
Talk from A. Hillairet on Saturday
The T2K Experiment
2.5° off-axis angle

– Peak at oscillation minimum
– Fewer backgrounds from high energy
– Monitored by the INGRID on-axis detector
Accumulated POT

- Total Accumulated POT for Physics
- \(\nu\)-Mode Beam Power
- \(\bar{\nu}\)-Mode Beam Power

Run 1-4: 6.57 \(\times 10^{20}\) POT (8% of our goal)

Run 5: Includes 0.5 \(\times 10^{20}\) POT \(\bar{\nu}\)-mode beam
Analysis Step 1: Flux and cross section models, constrained by external data

- Flux simulation in Fluka and Geant
- Constrain with NA61 hadron production data
- 10-15% flux uncertainty at SK
- NEUT simulation with nuclear effects
- Constrain effective parameters to external data (mostly MiniBooNE)
- ~15% uncertainty in CCQE rate
Analysis Step 2: Fit ND280 data to constrain flux and cross section parameters

Multi-function detector
- Trackers, TPCs, EM calorimeters, \( \mu \) detector and \( \pi^0 \) detector
- Magnetized with UA1 magnet
- 280 m from target, 2.5° off-axis

Posters from E. Scantamburlo and L. Haegel
Analysis Step 2: Fit ND280 data to constrain flux and cross section parameters

- Fit for $p$ and $\theta$ in CC$\nu_\mu$ samples
- Use exclusive subsamples to isolate cross section components

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>CC 0(\pi)</td>
<td>64% QE</td>
</tr>
<tr>
<td>CC 1(\pi^+)</td>
<td>40% Resonance</td>
</tr>
<tr>
<td>CC other</td>
<td>68% DIS</td>
</tr>
</tbody>
</table>

A. Hillairet’s talk on Saturday
Analysis Step 2: Fit ND280 data to constrain flux and cross section parameters

Flux and cross section errors at SK reduced from > 20% to 2.7%

Total Error on SK expectation: 8.1%*

*Now reduced to 7.6% in joint analyses
Analysis Step 3: Select $\nu_\mu$ CCQE events at Super-K

- Use ring shape to separate $\mu$ and $e$
- Select for CCQE final states
  - 1 ring
  - $\leq 1$ decay electron
- Use $p_\mu$ and $\theta_{\text{beam}}$ to reconstruct $E_\nu$

\[
E_\nu = \frac{m_p^2 - m_n'^2 - m_\mu^2 + 2m_n'E_\mu}{2(m_n' - E_\mu + p_\mu \cos \theta_{\text{beam}})}
\]

\[
m_n' = m_n - E_b
\]
Analysis Step 3: Select $\nu_\mu$ CCQE events at SuperK

- Data
  - 81.0% $\nu_\mu$ CCQE
  - 17.5% $\nu_\mu$ CC non-QE
  - 1.5% NC

120 Events
98.5% CC $\nu_\mu$
Analysis Step 4: Fit for oscillations

Extract $\theta_{23}, \Delta m^2_{32}$

- Data (120 events)
  - No oscillations (446 events)
  - Best oscillation fit

Normal Hierarchy

$\sin^2 \theta_{23} = 0.514^{+0.055}_{-0.056}$

$\Delta m^2_{32} = 2.51 \pm 0.10$

Inverted Hierarchy

$\sin^2 \theta_{23} = 0.511 \pm 0.055$

$\Delta m^2_{13} = 2.48 \pm 0.10$

Maximal Disappearance

$\sin^2 \theta_{23} = \frac{1/2}{\cos^2 \theta_{13}} = 0.513$
Analysis Step 4: Fit for oscillations
Extract $\theta_{23}, \Delta m^2_{32}$

Most precise measurement of $\sin^2(\theta_{23})$!

Best fit at maximal disappearance
– Result narrower than sensitivity by 0.04 in $\sin^2(\theta_{23})$
Multinucleon Interactions

- Neutrinos may interact with multiple nucleons
  - Looks CCQE, but has different kinematics
  - Potential explanation for discrepancies in $M_A$ measurements

- Studied potential for bias in our result from neglecting multinucleon interactions
Multinucleon Interactions

- For the current analysis, the effect is small relative to our total error
  - Mean biases were small (<1%)
  - However, there is the potential for biases in $\sin^2\theta_{23}$ similar in size to our current systematic error

- Future analyses will include multinucleon interactions in the default cross-section model with systematic uncertainties
Conclusions

• Analyzed $6.57 \times 10^{20}$ POT of neutrino data
  – Accumulated our first $0.5 \times 10^{20}$ POT of antineutrino data

• Made the most precise measurement of $\sin^2 \theta_{23}$ and favor maximal disappearance

• Only 8% of our goal POT accumulated so far
Backup Slides
Analysis Step 2: Fit ND280 data to constrain flux and cross section parameters

Flux and cross section would be > 20% without ND280 constraint

<table>
<thead>
<tr>
<th>Error on # of $\nu_\mu$ Events</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ND280-constrained $\Phi$ &amp; $\sigma$</td>
<td>2.7%</td>
</tr>
<tr>
<td>Unconstrained cross section</td>
<td>4.9%</td>
</tr>
<tr>
<td>SK efficiency &amp; hadronic interactions in water</td>
<td>5.6%</td>
</tr>
<tr>
<td>Other oscillation parameters</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8.1%</strong></td>
</tr>
</tbody>
</table>
Analysis Structure

Cross section model
  -> External σ data
    -> Initial σ estimate, and errors

Hadron prod. from NA61
  -> Initial Φ estimate, and errors

Flux Simulation
  -> Fit to ND280 data
    -> Post-fit Φ, σ estimate, errors

Fit to ND280 data
  -> Fit to SK data
    -> \( \sin^2 \theta_{13}, \delta_{cp}, \sin^2 \theta_{23}, |\Delta m^2_{32}| \)
Sensitivity vs. Data Fit

68% (dashed) and 90% (solid) CL Contours

- T2K [NH]
- T2K Sens. for best-fit pars. [NH]
Multinucleon Interactions

• Long-standing tension over $M_A$ in CCQE interactions
  – “Natural” value of 1.0 GeV from $e$-scattering
  – $>1.2$ GeV in $\nu$ scattering

• New models involving $2p-2h/np-nh$ interactions have been proposed to reconcile the tension

• Several papers have investigated the possible effect on T2K or a T2K-like experiment

**Multinucleon Study in T2K**

- **Multi-nucleon interactions:**
  - increase the CCQE-like cross-section and
  - introduce energy reconstruction biases (no longer 2 body QE kinematics)

- **MC study to investigate this possible bias directly**
  - $\nu_\mu$ disappearance – more sensitive to the spectral shape
  - We introduce a $2p-2h$ model into both ND280 and SK fake data
  - Replace $\pi$-less $\Delta$ decay already in NEUT

**Graph: CCQE vs. Nieves multi-N and pionless $\Delta$-decay**

- **Arbitrary Units**
  - CCQE
  - Nieves multi-N ($\times 5$)
  - Pionless $\Delta$-decay ($\times 5$)

**References:**
- J. Nieves et al., PRC83, 045501 (2011) for lepton kinematics
- J. Sobczyk, PRC86, 015504 (2012) for nucleon ejection (ND280-only)
Biases in Oscillation Fits

<table>
<thead>
<tr>
<th>Metric</th>
<th>Bias</th>
<th>RMS</th>
<th>Data Fit Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{32}$ ($10^{-3}$ eV$^2$)</td>
<td>-0.005 (-0.2%)</td>
<td>0.014 (0.6%)</td>
<td>±0.10</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.0012 (0.3%)</td>
<td>0.016 (3.6%)</td>
<td>±0.055</td>
</tr>
</tbody>
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