Using the T2K near detector in neutrino oscillation measurements

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The PMNS matrix and some Quantum Mechanics tells us:

- \[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E_\nu} \]

- \[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} \left[ 1 - \cos^2 \theta_{13} \sin^2 \theta_{23} \right] \sin^2 \frac{\Delta m_{32}^2 L}{4E_\nu} \]
Oscillation probabilities are dependent on the neutrino energy (both include the term $\sin^2 \frac{\Delta m^2 L}{4E_\nu}$).

CCQE is the dominant interaction process for T2K’s neutrino energy spectrum.

The neutrino energy is reconstructed from the outgoing lepton’s momentum and angle.
CC1\(\pi\) would appear to be CCQE if the pion is absorbed before leaving the nucleus, or is otherwise not detected.

For NC1\(\pi^0\) the \(\pi^0\) decay photons would produce charged leptons which could be mistakenly identified as originating from a CCQE interaction.

In both cases, the energy spectrum would be distorted.
How can ND280 contribute?

- The observed neutrino energy spectrum at SK is a function of the oscillation parameters, the interaction cross sections, and the neutrino flux provided by the beam.
- The measurements at ND280 constrain the beam flux at SK.
- Our cross section model has parameters that are common to ND280 and SK.
- ND280 has detector systematics of its own to consider.
Primary proton interactions with the target are modelled with FLUKA2008, with constraints from external data (such as NA61/SHINE).

GEANT3 with GCALOR simulates propagation of secondary/tertiary pions/kaons and their decays.

This provides the flux at ND280 and SK, and the correlations between ND280 and SK flux bins of energy.

Fit to ND280 data includes normalization parameters for the ND280 flux bins. The correlations are then used to constrain SK flux bins.
NEUT is used to simulate neutrino interactions.

The model also includes nuclear model parameters (detector specific and not shown.) These are not propagated to the SK oscillation analysis.

Sufficient information from the simulation is saved to allow an event weight to be calculated if a parameter is varied.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior to ND280 Constraint</th>
<th>After ND280 Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$ (GeV)</td>
<td>1.21 ± 0.45</td>
<td>1.240 ± 0.072</td>
</tr>
<tr>
<td>$M_A^{RES}$ (GeV)</td>
<td>1.41 ± 0.22</td>
<td>0.965 ± 0.068</td>
</tr>
<tr>
<td>CCQE Norm. $E_\nu &lt; 1.5$ GeV</td>
<td>1.00 ± 0.11</td>
<td>0.966 ± 0.076</td>
</tr>
<tr>
<td>CCQE Norm. $1.5 &lt; E_\nu &lt; 3.5$ GeV</td>
<td>1.00 ± 0.30</td>
<td>0.93 ± 0.10</td>
</tr>
<tr>
<td>CCQE Norm. $E_\nu &gt; 3.5$ GeV</td>
<td>1.00 ± 0.30</td>
<td>0.85 ± 0.11</td>
</tr>
<tr>
<td>CC1\pi Norm. $E_\nu &lt; 2.5$ GeV</td>
<td>1.15 ± 0.32</td>
<td>1.26 ± 0.16</td>
</tr>
<tr>
<td>CC1\pi Norm. $E_\nu &gt; 2.5$ GeV</td>
<td>1.00 ± 0.40</td>
<td>1.12 ± 0.17</td>
</tr>
<tr>
<td>NC1\pi^0 Norm.</td>
<td>0.96 ± 0.33</td>
<td>1.14 ± 0.25</td>
</tr>
</tbody>
</table>

$M_A^{QE}$ is the mass parameter in the axial dipole form factor for quasielastic interactions. (Affects shape of CCQE cross section.)

$M_A^{RES}$ is the mass parameter in the axial dipole form factor for resonant pion production interactions (Affects the shape of CC1\pi and NC\pi^0 cross sections.)
Nearly all are calculated using control samples (i.e. not the neutrino spill data itself.) These include:

- Sand muons.
- Cosmic muons.
- Stopping TPC1-FGD1 protons and muons.

Methods of propagation in the fit:

- Event weight (Black): Weight based on MC comparison to control samples or external information.
- Event migration (Blue): Reconstructed quantities are changed and the selection re-performed using the new quantities.
Occur outside nucleus pion produced in.

Geant4 model differs from external data.

Data uncertainties large, limited momentum range (extrapolate outside it).

Two sets of weights:
1. Correct MC to Data.
2. Variation according to Data uncertainty.

Given pion interaction process cross sections, calculate probability of the relevant pion trajectories in the event. Changing cross section changes probability. Event weight is ratio of probabilities.

Absorption of $\pi^+$ on Carbon-12.

Geant4 cross section is in blue.

Data is in black. The extrapolated points begin after the points get much denser, below and above the data region.
For the 2013 analysis ND280 provided 3 $\nu_\mu$ samples defined by the particles leaving the nucleus.

- **CC-0π**: A muon and no pions. Dominated by CCQE.
- **CC-1π⁺**: A muon and a positive pion. Dominated by CC1π.
- **CC-Other**: A muon and any other combination of pions.

These plots show the nominal Monte Carlo distribution and that re-weighted with the fit results, in comparison to the data for the CC-0π sample.
Impact on the oscillation analysis

Electron neutrino appearance

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\sin^2 \theta_{13} = 0.1$</th>
<th>$\sin^2 \theta_{13} = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam flux and near detector</td>
<td>2.9</td>
<td>4.8</td>
</tr>
<tr>
<td>(w/o ND280 constraint)</td>
<td>(25.9)</td>
<td>(21.7)</td>
</tr>
<tr>
<td>$\nu$ interaction (external data)</td>
<td>7.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Far detector and FSI+SI+PN</td>
<td>3.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Total</td>
<td>8.8</td>
<td>11.1</td>
</tr>
</tbody>
</table>

- For muon neutrino disappearance, this corresponds to a 21.6% uncertainty due to beam flux and near detector constrainable cross section parameters without the ND280 constraint, and 2.7% with the constraint.

- Overall, a large reduction in uncertainty for both electron neutrino appearance and muon neutrino disappearance analyses!

Muon neutrino disappearance

Overall, a large reduction in uncertainty for both electron neutrino appearance and muon neutrino disappearance analyses!
Measuring neutrino oscillation parameters at T2K requires a good understanding of the neutrino flux at the far detector and the relevant interaction cross sections.

The T2K near detector (ND280) makes measurements that constrain flux and cross section model parameters at the far detector.

The ND280 constraint reduces uncertainties in the oscillation parameter measurements to a great extent, allowing more precise measurements than would otherwise be possible.