Measurement of the $\nu_\mu$ Charged Current Quasielastic Scattering Cross Section on Water with the T2K Off-Axis Near Detector

Jeremy P. Lopez
Tianlu Yuan, Alysia Marino
University of Colorado Boulder
6 August 2015
The T2K Experiment

- Create beam of $\nu_\mu$ at J-PARC accelerator in Tokai, Ibaraki
- Measure oscillations at Super-Kamiokande (SK)
- SK is off-axis, have on-axis and off-axis near detectors
T2K Collected Beam

- $\nu$ Mode: $7.00 \times 10^{20}$ Protons on Target (POT)
- $\bar{\nu}$ Mode: $4.04 \times 10^{20}$ POT
- This measurement: Using Run 1-4 $\nu$ Data
The ND280 Off-Axis Near Detector

- $\pi^0$ Detector
- Tracker:
  - 3 TPCs
  - 2 Fine Grained Detectors (FGDs)
- Electromagnetic calorimeters (ECals)
- Muon detectors (in magnet yoke)

Off-axis measurement gives narrower energy spectrum!

\[
\sin^2\theta_{23} = 1.0
\]
\[
\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2
\]

The ND280 $\pi^0$ Detector (POD)

- ECals: Scintillator & Lead
- Water target: Scintillator, Brass, & Water
- Water can be drained for measurement with just non-water materials

The CCQE Cross Section

- Dominant event type seen in T2K $\nu_\mu$ disappearance analysis
- SK has a water target, ND280 a mix of scintillator, water, brass, lead, etc.
- Few published cross section measurements on water target
The CC0π Cross Section

• Final state interactions (FSI), multinucleon correlations and other effects mean that a variety of final states are measured.

• Rather than measure the CCQE cross section, we use a topological definition of the signal:
  • Charge current (muon candidate found)
  • No pions
  • Any number of nucleons

• We refer to this as the CC0π topology.
Measuring the Water Cross Section

- We want a flux-averaged double differential cross section of $\nu_\mu$ CC0$\pi$ interactions on water

$$\langle \frac{d^2\sigma}{dp_\mu d\cos\theta_\mu} \rangle = \frac{1}{\Delta_i \phi^w \varepsilon^w_i} \frac{N^w_i - B^w_i}{U} \quad - \quad \frac{1}{\Delta_i \phi^a \varepsilon^a_i} \frac{N^a_i - B^a_i}{U}$$

- **N**: measured signal, **B**: expected background, **\varepsilon**: efficiency, **\phi**: Integrated neutrino flux, **\Delta**: Bin size factor
- **U**: Unfolding process
Iterative Bayesian Unfolding

- Detector response in air and water data sets not the same

- Build “smearing matrix” describing migration from truth bins to measured bins
- Use Bayes’ theorem & smearing matrix to reconstruct truth distributions from measured data
- Similar to matrix inversion but with more stable results

Event Selection

- Good beam, detector, & track quality
- Muon candidate is highest momentum negative track
- Vertex in the P0D water target fiducial volume
- Muon candidate appears in the P0D and tracker
- Only 1 reconstructed track in the P0D
Efficiency and Purity

For all CC0\(\pi\) (not just water):

- Overall efficiency \(\sim 20\%\)
  - Low efficiency at high angles, below \(\sim 500\) MeV due to detector geometry
- Purity \(\sim 80\%\)
  - CC1\(\pi\) topology the main background
Expected Signal

- Using NEUT MC to unfold “data” from Genie MC
- Systematic uncertainties still need to be finalized before looking at real data
Systematics

Several types:
1) Flux
2) Interaction (Cross section, final state interaction)
3) Detector

For 1) and 2):
- Flux known to about 10%, typically most important uncertainty in T2K cross section analyses
- Flux, cross section & FSI uncertainties propagated by varying the models and reweighting simulated pseudo-data accordingly
Cross Section and Flux Systematics

• Using Neut MC to unfold small amount of toy “data” from Genie MC
Detector Systematics

- Cover things like:
  - Momentum reconstruction
  - Direction reconstruction
  - Track efficiency
  - Charge reconstruction
Detector Systematic Example: Momentum Reconstruction

- Tracks built from Kalman filter algorithm
- Tracker (TPC/FGD) momentum systematics well understood
- P0D momentum systematics determined from cosmics stopping in the P0D fiducial volume
- Vary reconstructed momentum scale & resolution in MC events
- Initial studies: Uncertainties in pre-unfolded distributions of a few % except in low stats/high angle bins (many poorly reconstructed events)

Fractional uncertainty in pre-unfolded distribution due to momentum systematics

Genie MC, Water Out Geometry

p [GeV]
Conclusions

• Have a well-developed plan for measuring the CC0π cross section on water
• Data for this measurement already collected
• Have implemented subtraction method for cross section extraction from ND280 data
• Treatment of systematics still in progress, expect results soon
• Starting to think about how to best combine this work with other T2K CC0π analyses
Detector Systematics

<table>
<thead>
<tr>
<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0D Momentum Loss Scale</td>
</tr>
<tr>
<td>Tracker Momentum Scale</td>
</tr>
<tr>
<td>P0D Momentum Loss Resolution</td>
</tr>
<tr>
<td>Tracker Momentum Resolution</td>
</tr>
<tr>
<td>Tracker Efficiency</td>
</tr>
<tr>
<td>P0D/Tracker Matching Efficiency</td>
</tr>
<tr>
<td>Out of Fiducial Volume Background</td>
</tr>
<tr>
<td>P0D Fiducial Mass Uncertainty</td>
</tr>
<tr>
<td>Direction Resolution</td>
</tr>
<tr>
<td>Track Pileup</td>
</tr>
<tr>
<td>Charge Mis-ID</td>
</tr>
</tbody>
</table>

- Most detector systematics are small effects
- Expect that flux/cross section/FSI uncertainties will be more important in end result
Systematic Example 2: Out of Fiducial Volume Events

- Tricky: Mix of detector & model uncertainties
- Small fraction of events in selection occur outside the fiducial volume
- Most are near edges of fiducial volume
- Should mostly cancel after subtraction
- Still working ways to constrain this background

<table>
<thead>
<tr>
<th>Config</th>
<th>Out of FV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>2.89%</td>
</tr>
<tr>
<td>Air</td>
<td>4.02%</td>
</tr>
</tbody>
</table>

Expected fraction of selection from Genie MC

- Genie MC, Water out geom.
- Out of FV only

POD Backgrounds

T2K Work in Progress