THE T2K CROSS-SECTION RESULTS AND PROSPECTS FROM THE OSCILLATION PERSPECTIVE

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T2K experiment

- Muon neutrino/anti neutrino beam is generated at J-PARC accelerator and detected at Super-Kamiokande detector.
- Measure neutrino oscillation parameters
- Neutrino interaction study using near detector
Why Neutrino interaction model is important for neutrino oscillation?

- CCQE interaction is the dominant contribution for T2K.
- Neutrino energy can be reconstructed as:
  \[ E_{\nu}^{\text{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_i^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_i \cos \theta_i)} \]
- The spectrum can be distorted by:
  - pion production mode, which is absorbed inside the nucleus/detector.
  - Nucleon-Nucleon correlation inside the nucleus.
  - Fermi momentum, boundary energy...

Precise understanding of neutrino interaction model is essential for Oscillation Analysis!
T2K Oscillation analysis strategy

1. **Flux Model**
   - **Near Detector Data**
   - **Near Detector Fit**
   - Predict number of events at ND
   - Predict event rate at SK

2. **Beam Monitor Data**
   - Constraint

3. **Cross-section Model**
   - **Near Detector Model**
   - **SK Detector Model**

4. **Oscillation Parameters**

**Inputs:****
- **Hadron production data from NA61/SHINE**
- **Cross-section data from other experiment**

**Reweighting:**
- From flux model to beam monitor data
- From cross-section model to near detector model

**To:**
- Oscillation parameters
T2K Oscillation analysis strategy

Hadron production data from NA61/SHINE

Reweighting

beam monitor data

constraint

Near Detector data

flux model

Predict number of event at ND

Near Detector Fit

Predict event rate at SK

Oscillation Fit

SK data

Cross-section data from other experiment

Reweighting

cross-section model

Near detector model

This talk

Oscillation Parameters
Cross-section model for 2017 Oscillation analysis

• We used 22 neutrino cross-section parameters in 2016.
• We have 31 neutrino cross-section parameters in 2017.
  • 13 parameters for CCQE-like samples
  • 3 parameters for CC single pion samples
  • 9 parameters for CC Other and other mode.
  • 6 parameters for Final State Interaction (FSI)
Cross-section parametrization (CCQE-like)

- MAQE: Axial mass
  - dipole form factor is used.
- Binding energy: found reweighting not working correctly.
  - not used in the fit
  - Will check the effects on oscillation analysis
- Fermi momentum of C and O.
- 5 parameters for multi-nucleon effects (2p2h) new!
- 5 parameters for Random Phase Approximation (RPA) model new!

\[ F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^{QE^2})^2} \]
Multi-nucleon effects (2p2h) Parameters

- Interaction in which more than one nucleon participate.
- Pion-less Delta Decay (PDD-like) and N-N Correlation (non-PDD-like)
- Introduced shape parameters in addition to normalization
  - +1 corresponds to fully PDD-like
  - -1 corresponds to fully non-PDD-like

Pair Correlation

Delta absorption
New Random Phase Approximation (RPA) model

- Long-range nuclear effects
- Introduced RPA in the fit as effective parameters
- Introduced new parameters based on Bernstein polynomials.

\[
f(x) = \begin{cases} 
A(1 - x')^3 + 3B(1 - x')^2x' + 3p_1(1 - x')x'^2 + Cx'^3, & x < U \\
1 + p_2 \exp(-D(x - U)), & x > U 
\end{cases}
\]

\[x' = \frac{Q^2}{U}\]

Uncertainties on the parameters cover the theoretical uncertainty on the RPA correction factor.
Cross-section parametrization (CC1_{π})

- Based on Rein-Sehgal model
  - MARES: Axial mass.
  - CA5: Axial form factor value at $Q^2=0$
  - background: Isospin 1/2 non-resonant background
- Re-tuning using bubble chamber data. new!
Near detector fit

- Fit to data to constrain cross-section model and flux parameters
- Separated by number of charged pions for neutrino mode (CC0π, CC1π, CCOther)
- Different separation for anti-neutrino mode (CC1Track, CCNtrack)
- Separate data sets in FGD1 and FGD2 (water targets)
Near detector fit results

- Flux parameters stay around nominal.
- Good agreement compared to 2016 results
Near detector fit results

These results should not be taken as the cross section results, but effective parameters which effectively describe the data and propagate the uncertainty to the oscillation analysis.
Near detector fit results

• The fit reproduces the data well with a p-value of 0.47 (0.08 in 2016)
  • Thanks to more degrees of freedom by adding new RPA parameters
• Flux + cross-section uncertainties at SK ~3.22% for (e-like and μ-like)

The latest oscillation fit results are shown in the Patrick’s (Sep. 27th) and Jiae's (Sep. 26th) talk
The latest cross-section measurements are shown in the Ciro’s (Sep. 25th) talk.
Effects of different models on oscillation analysis

- Check the robustness of the fit against neutrino interaction modeling
  - The choice of interaction model
  - Alternative model which is not included in the MC
- Interaction model which cannot be covered by current model may introduce spectrum distortion at far detector and effects to oscillation parameters

Fitting “fake datasets” at Near/Far detector to evaluate biases on the oscillation parameters, due to the choice of interaction model

“fake datasets” = simulated data set by alternate model
Fake data fitting

Hadron production data from NA61/SHINE

Beam monitor data

Cross-section data from other experiment

Reweighting

Flux model

Constraint

Predict number of event at ND

Near Detector replica data

Near detector model

Near Detector Fit

Predict event rate at SK

Oscillation Fit

Oscillation Parameters

SK data

Reweighting

SK replica data

Reweighting

Replace with the fake data
Interaction models studied using 2016 framework

- Martini 2p2h model
- Spectral Function
- effective RPA model
- Nieves vs NEUT model difference

Bias definition

$$\text{Bias } 1 = \frac{\text{fit}_{\text{fake data}} - \text{fit}_{\text{Asimov}}}{\sigma_{\text{Asimov}} 1}$$

Absolute bias on the $\sin^2 \theta_{23}$ parameters

$\sim 0.2\sigma$ for the model above
Prospects for 2017 framework

- Proposed cross-section model
  - Alternative model for form factor
  - Improved CC single pion model
  - Improved Pion Multiplicity tuning
  - Binding energy effects

- Data-driven fake data
  - Data-MC difference at Near Detector
    - Assigned to
      - 1p1h
      - 2p2h Delta-like
      - 2p2h non-Delta-like
    - Checked that the effects on $\delta_{CP}$ is negligible,
      Study is on-going for $\sin^2\theta_{23}$ vs $\Delta m^2_{23}$
  - Minerva data-driven fake data

Error size of each form factor model

T2K preliminary
Summary

• T2K has been developing new interaction modeling for oscillation analysis in 2017.
  • The near detector fit reproduce the data well with a p-value of 0.47.
• We have performed “fake” data study to investigate the robustness against various cross-section models for oscillation analysis.
• We are pursuing to do various “fake” data studies with 2017 framework.
Reference


Backup
anti-neutrino mode events

FGD1 AntiCC 1Track

FGD1 AntiCC N-Track

PRELIMINARY

FGD1 CC 1Track

FGD1 CC N track

PRELIMINARY
The bias of various binding energy.

preliminary
Bernstein RPA model
In this study, $\Delta m^2_{32}$ is biased to lower values.

$\sin^2\theta_{23}$ is biased towards maximal disappearance.

- Leads to narrower contour than fit to nominal prediction.

Shift towards maximal also seen in 1-D contour for oscillation parameter set B (bottom).