PROCEEDINGS OF SCIENCE

The T2K cross-section results and prospects from the oscillation perspective

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T2K is a long baseline neutrino experiment in Japan[1]. Its main physics motivation is the precise measurement of neutrino oscillation parameters ($\theta_{23}, \Delta m^2_{23}, \theta_{13}, \delta_{CP}$) by ν_μ disappearance and ν_e appearance. Neutrino oscillation analysis requires precise understanding of neutrino-nucleus interactions to predict event rates at the far detector. ND280 is a near detector complex used to measure the neutrino beam before oscillation, which allows us to constrain uncertainties in the neutrino interaction and accelerator flux models. In these proceedings, the neutrino-nucleus interaction model used in T2K's 2017 oscillation analysis and the result of a fit to the ND280 data are presented. A study of the robustness of the fit to the choice of neutrino interaction model will also be discussed.

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1. T2K experiment

The T2K experiment is a long baseline neutrino oscillation experiment in Japan. A pure muon neutrino beam is produced at J-PARC (Japan Proton Accelerator Reseach Complex). Neutrinos are detected at a near detector complex (ND280) located 280 meters from the target, and at the far detector – Super-Kamiokande – located 295 km away from J-PARC. These detectors are placed 2.5 degrees off-axis with respect to the neutrino beam, which provides a narrow energy-spread neutrino beam peaked at 0.6 GeV, which is the oscillation maximum for the T2K baseline. The T2K near detector complex contains several subdetectors: two Fine Grained Detectors (FGD), three Time Projection Chambers (TPC), and a Pi-zero detector (P0D). The Super-Kamiokande (SK) far detector is a large water Cherenkov detector. It can distinguish electrons and muons with good resolution: less than 2% misidentification. The main goal of the T2K experiment is to search for CP violation in the lepton sector via electron neutrino appearance, and precise measurement of neutrino oscillation parameters $(\Delta m^2_{32}, \theta_{23})$ via muon neutrino disappearance.

2. Cross-section modeling for oscillation analysis

Neutrino oscillation parameter estimation is done by fitting the expected neutrino energy spectrum to the observed data. Expected events at SK in each bin i can be written as the product of the ϕ, cross-section parameters σ, detector efficiency at SK ε, and PMNS oscillation probabilities.

$$N_{SK}(i) = \phi_{SK}(i)\sigma(i)\varepsilon_{SK}(i)P(\nu_\alpha \to \nu_\beta) \tag{2.1}$$

In T2K, the main interaction mode is charged current quasi-elastic (CCQE) scattering. The neutrino energy can be reconstructed from lepton momentum and angle with respect to the beam, assuming the target nucleon is at rest:

$$E^{\nu}_{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l) - p_l \cos\theta_l} \tag{2.2}$$

In the far detector, events with a single Cherenkov ring are selected as the signal sample. However, the reconstructed energy can be different from the true energy due to various effects like the Fermi motion of nuclei in the nucleus. What's more, other interaction modes can contaminate the signal sample, such as resonant pion production events where the pion is absorbed in the nucleus. To predict the neutrino energy spectrum, precise understanding of neutrino interactions and their uncertainties is essential for oscillation analysis. This paper describes the interaction model used in the 2017 oscillation analysis and the constraints provided by near detector data. The investigation of the bias on the oscillation parameters caused by different interaction models will also be reported.

3. T2K cross-section model in 2017 oscillation analysis

The neutrino interaction model used in this analysis is based on NEUT [2], whose CCQE model was based on the Llewellyn-Smith neutrino-nucleon scattering formaism [3]. CCQE interactions are controlled by 8 parameters: an axial vector mass parameter that alters both the normalization and shape of the cross-section in Q^2, plus the Fermi momentum of carbon and oxygen. We introduced random phase approximation (RPA) effects motivated by a model by Nieves *et al.* [4] in the fit as effective parameters. The RPA effects are described as a weighting factor to the CCQE interactions. We parametrized the RPA correction factor based on a Bernstein polynomial.

$$f(Q^2) = \begin{cases} A(1-x')^3 + B(1-x)^2 x' + p_1(1-x')x'^2 + Cx'^3 & x < U \\ 1 + p_2 \exp(-D(x-U)) & x > U \end{cases} \tag{3.1}$$

where $x = Q^2/U$. p_1 and p_2 are set to keep the continuity condition at U.

$$p_1 = C + \frac{UD(C-1)}{3} \tag{3.2}$$

$$p_2 = C - 1 \tag{3.3}$$

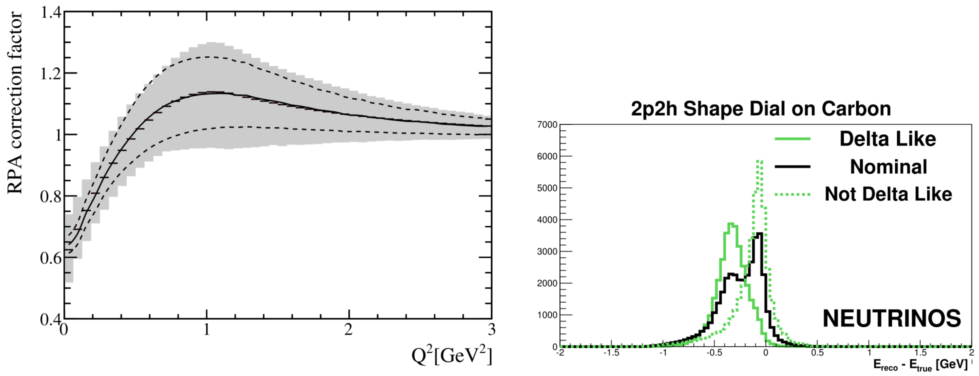

Figure 1: Left: RPA correction factor (black solid line) and its error (shaded area) overlaid the RPA factor and theoretical uncertainties (black dashed lines) calculated by Nieves [4]. Right: Reconstructed energy - true energy difference of 2p2h shape dials. Green lines corresponds to the fully pionless delta decay-like, while green dashed line corresponds to fully non-pionless delta decay-like.

A, B, C, D, and U are the free parameters used in the fit. The nominal parameters are set by fitting Nieves [4] RPA as a function of Q^2. The uncertainties are set to cover Nieves RPA 1σ theoretical uncertainties (Fig. 1).

The 2-particle-2-hole (2p2h) process is the interaction of the neutrino with two nucleons. Since the 2p2h contribution does not produce QE kinematics, the reconstructed neutrino energy (Eq. 2.2) is biased (Fig. 1). A NEUT 2p2h model based on Nieves et al. contains five parameters. We introduced shape parameters of carbon and oxygen in addition to three normalization parameters. These shape parameters can distinguish the 2p2h interaction via delta resonance from the other nucleon-nucleon correlations (Fig 2). The normalization of 2p2h, 2p2h in anti-neutrino mode, and normalization of carbon to oxygen are also used.

In NEUT, the Rein-Sehgal [7] model is used for CC and NC single pion production interactions. We parametrize Rein-Sehgal model by three free parameters: axial mass, the value of the axial form factor at zero transferred 4-momentum, and the normalization of the isospin 1/2 non-resonant component. We tuned the initial values of these parameters using external data [9] including bubble chamber data [8]. Four NC normalization parameters are also used in the fit.

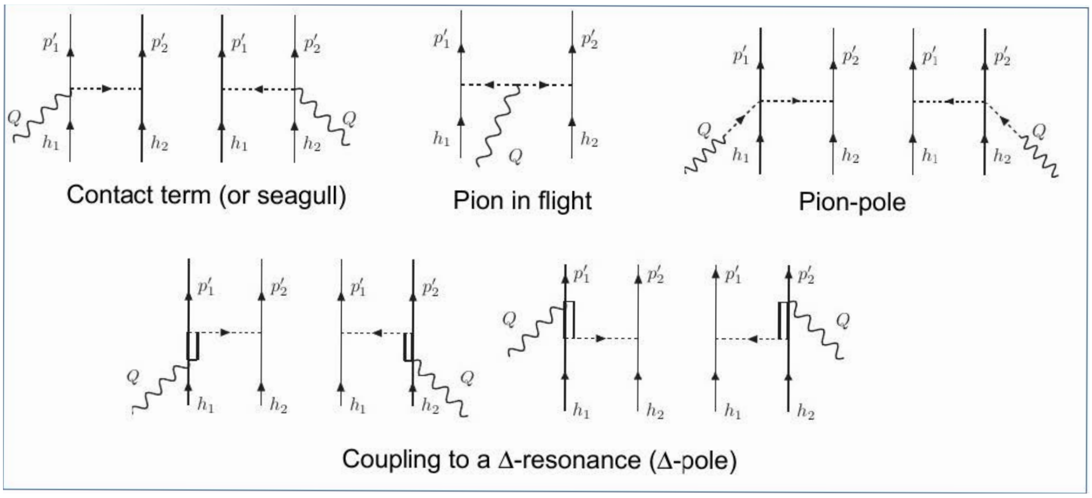

Figure 2: 2p2h diagrams (adapted from [5][6]). Single lines represent nucleons, double lines represent the Δ, dased lines represent pions and curly lines represent the W boson.

Other high energy processes (DIS, etc) share a single normalization parameter. The relative ν_e/ν_μ cross-section normalization and CC coherent interaction are modeled with two parameters. Final state interactions (FSI) such as pion production and pion absorption are parameterized by six parameters. They are implemented with a cascade model in NEUT and introduced in the ND280 fit. More information about the cross-section parametrisation can be found in [10],

4. Near detector fits

Near detector fits are performed to constrain interaction and flux parameters. The events are categorized by the number of charged pions (CC0π, CC1π, CCOther) and detectors (FGD1, FGD2) for neutrino mode. A different categorization is applied to anti-neutrino mode ($\bar{\nu_\mu}$ CC 1-Track, $\bar{\nu_\mu}$ CC N-Track, ν_μ CC 1-Track, ν_μ CC N-Track). Fig 3 shows the lepton momentum distributions of FGD1 $CC0\pi$ and $CC1\pi$ samples before fitting is applied. Fig 4 shows the same plots after fitting. The data - MC difference becomes smaller and postfit results reproduced the data well with a p-value of 45%.

Fig. 5 shows the flux parameter shift relative to its nominal value. There are small shifts in most parameters compared to the 2016 results [10]. On the other hand, there are large shifts in the 2p2h shape parameters and RPA parameters in Fig 6. These shifts indicate 2p2h are fully pionless delta decay-like and CCQE interaction below $Q^2 < 1$ GeV is enhanced.

5. Robustness against cross-section modeling and bias on oscillation parameters

If interaction models not included in the MC's cross-section model do exist in nature, then the T2K MC would under- or over-predict the observed event rates at the two detectors. The near detector fit can correct the MC prediction, but it can also create biases due to the differing energy dependence of the neutrino fluxes at the near and far detectors. We performed a "simulated data"

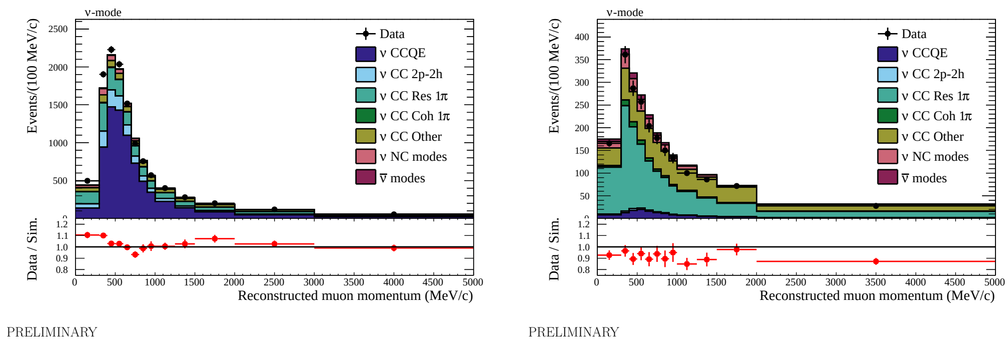

Figure 3: Reconstructed muon momentum distributions of the neutrino-mode ν_μ CC-0π samples in FGD1 (left) and CC-1π samples in FGD1 (right). All distributions are shown prior to the ND280 fit.

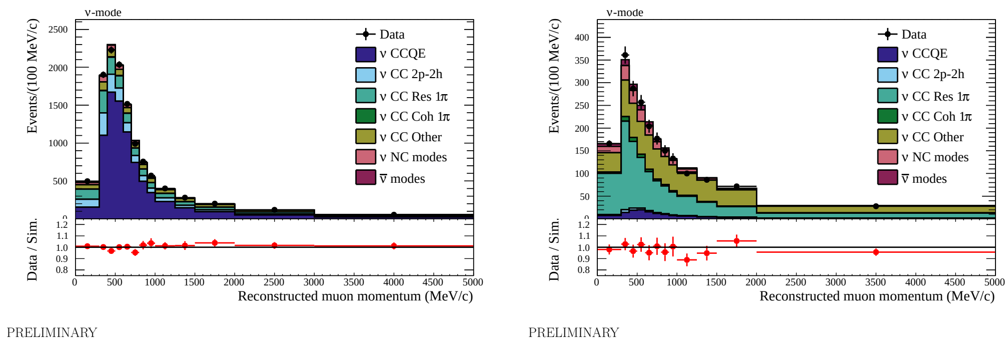

Figure 4: Reconstructed muon momentum distributions of the neutrino-mode after the ND280 fit: ν_μ CC-0π samples in FGD1 (left) and CC-1π samples in FGD1 (right).

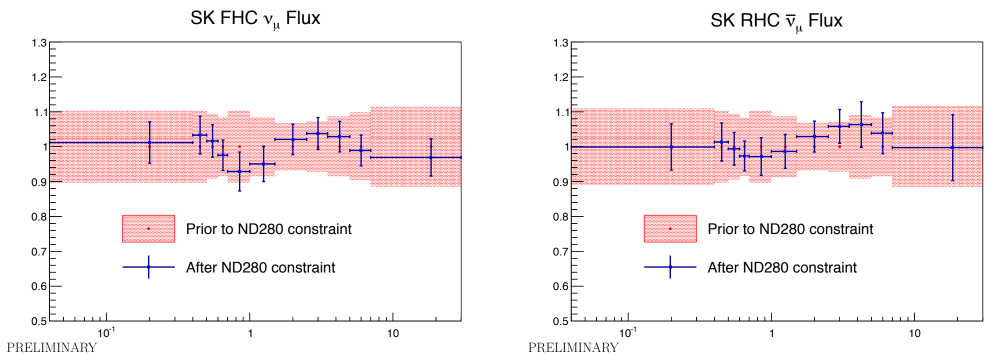

Figure 5: The SK flux parameters shown as a fraction of the nominal value. The bands indicate the 1 σ uncertainty on the parameters before (red) and after (blue) the near detector fit.

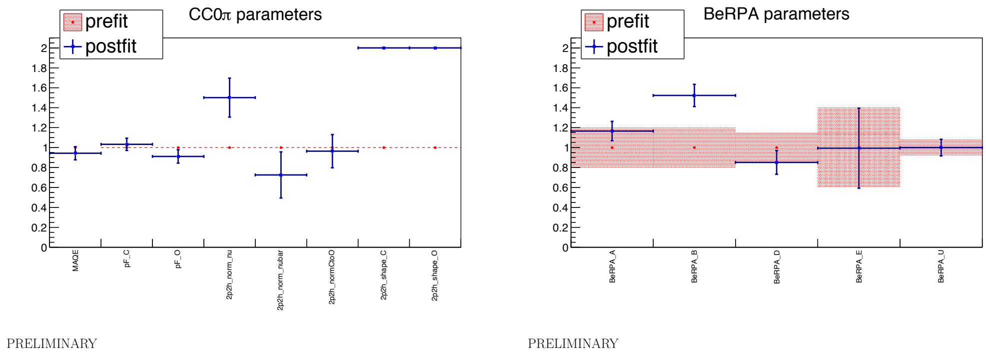

Figure 6: Cross-section parameters before (red) and after (blue) the near detector fit. The parameters which have no red area are fit unconstrained.

study to investigate the bias on oscillation parameters due to the choice of neutrino interaction model, as well as to investigate variations that are not yet implemented in the model. The strategy is the same as that used in the normal oscillation analysis, except for fitting simulated data instead of real data in near detector and far detector. These simulated data are generated applying the weights of the model of interest to nominal MC. The same weights are applied to both ND and SK. The bias is defined by the deviation of the best fit point:

$$bias = \frac{best\,fit_{Asimov} - best\,fit_{simulateddata}}{\sigma_{Asimov}} \tag{5.1}$$

We performed simulated data fits of several models using the 2016 T2K oscillation analysis framework [10]. A range of model variations were investigated; see [10] for details. Fig. 7 shows the SK muon neutrino energy spectrum with a model by Martini *et al* [11] whose 2p2h modeling is different from that in the T2K MC. The fit results for Δm^2_{32} were found; we confirmed the bias is below 0.2 σ for each oscillation parameter and each model.

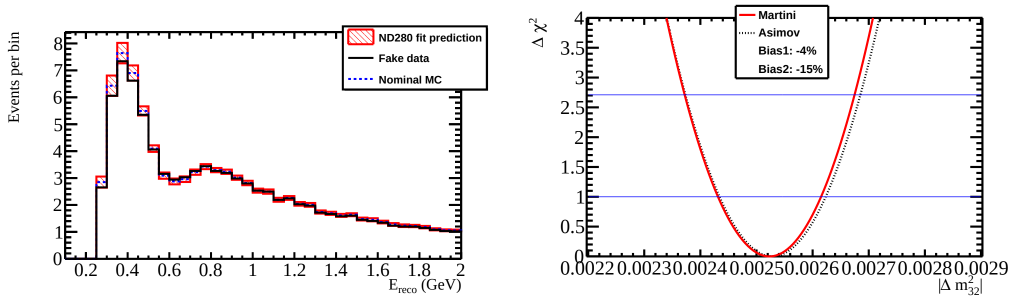

Figure 7: Left: Reconstructed muon energy spectrum of simulated data (black line) and the prediction based on the near detector fit to the Martini simulated data (red shaded area) at SK. Right: A comparison between the Martini and Asimov simulated data fits for true oscillation parameters: $\sin^2\theta_{23} = 0.528$, $\sin^2(\theta_{13}) = 0.025$, $\sin^2(\theta_{12}) = 0.306$, $\delta_{cp} = -1.601$, $\Delta m^2_{32} = 2.509\times10^{-3}eV^2$, $\Delta m^2_{21} = 7.5\times10^{-5}eV^2$

In addition to these interaction models, we are planning to perform a simulated data study including an alternative form factor model (z-expansion[13], 3-component model [12]) using the 2017 oscillation framework. We also plan to use data-driven generated simulated data to investigate the observed data - MC difference at the ND280 this year.

6. Summary and prospects

The cross-section models used in T2K's 2017 oscillation analysis are shown. Using these parameters, the near detector fit results have good agreement with the data, with a p-value of 45%. A robustness check against the choice of neutrino interaction model is also shown using the 2016 T2K oscillation analysis framework. The details of this oscillation analysis can be found in [14][15]. Several simulated data studies will be done with the 2017 oscillation analysis framework to demonstrate that the result is robust against uncertainties in the cross-section model.

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