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Recent Cross-section Results from the T2K Experiment

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One of the largest systematic uncertainties affecting neutrino oscillation measurement comes from present limited knowledge of (anti-)neutrino-nucleus interactions. Neutrino scattering understanding is crucial for the interpretation of neutrino oscillation since it affects background estimation and neutrino energy reconstruction. Thus, precise (anti-)neutrino-nucleus cross section measurements are vital for the present and future long-baseline neutrino oscillation experiments. The T2K long-baseline neutrino oscillation experiment, in addition to its contributions to neutrino oscillation measurement, has a wide program of neutrino interaction cross section measurements using its near detector complex. With multiple targets (hydrocarbon, water, argon, iron), and with on- and off-axis detectors which sample different neutrino spectra from the same beamline, T2K is able to investigate atomic number and energy dependent behavior in a single experiment. In this proceeding an overview of the T2K neutrino cross sections, focusing on the latest results is presented.

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1. The T2K experiment and cross section measurement

The T2K (Tokai to Kamioka) experiment is a long-baseline accelerator neutrino experiment in Japan designed for accurate oscillation measurement. The neutrino beam comes from the J-PARC facility in the east coast of Japan. Located close to the beam source, there is a near detector complex, which contains an on-axis near detector INGRID to measure neutrino flux and beam direction, and an off-axis (2.5^{o}) detector ND280 to measure neutrino cross section. From 2019, there is another off-axis (1.5^{o}) detector WAGASCI in operation which measures cross section with slightly higher neutrino energy and wider angular acceptance than ND280. The far detector Super-Kamiokande (SK) measures the oscillated muon neutrino and electron neutrino spectra with water Cherenkov technology, which enables precise measurement of the neutrino mixing angle θ_{23} and mass difference $|\Delta m^2_{32}|$, at the same time probing θ_{13} and the CP-violating phase δ_{CP}.

Inside ND280, where most of the cross section measurements take place, there are two Fine Grained Detectors (FGDs), which act as both neutrino target and scintillation trackers. While FGD1 is a pure hydrocarbon (C_8H_8) target, FGD2 contains alternating layers of water (H_2O) to allow water measurement. Sandwiching the FGDs are three Time Projection Chambers (TPCs), which provide excellent tracking of charged particles. With the uniform magnetic from magnet, TPCs can measure energy loss and momentum, thus enabling accurate particle identification of charged particles.

The T2K off-axis neutrino beam is peaked at 0.6 GeV. At this energy, most neutrino interactions come from the charged-current (CC) quais-elastic (QE) channel. On the high energy tail, the CC resonant (RES) interaction with pion production is the second most important channel. Meanwhile from recent studies, it is known that between the QE and RES peak, there exists a non-negligible contribution of 2particle-2hole (2p2h) interaction where a neutrino interacts with multiple nucleons at the same time. In SK only muon kinematics is used to reconstruct the neutrino energy, with a non-negligible smearing and bias caused by nuclear effects. The correction of such nuclear effects can be tuned by measuring pions and protons at the near detector.

Neutrino interaction measurement is difficult. Apart from the intrinsically small cross section, there are complications coming from the fact that the interaction target is always (except on hydrogen) not a free nucleon but a heavy nucleus. That means the initial state nucleon is bound with certain initial momentum and binding energy; and the outgoing hadrons may undergo final state interactions (FSI) where pions and nucleons can be absorbed or produced. Experimentally, neutrino cross sections are usually measured in terms of the final state topology. For example, the CC0π topology refers to the final state that contains a charged lepton and no meson; while the CC1π^+ topology contains a charged lepton, one π^+ and no other meson. Each topology contains a mix of CC-QE, RES and 2p2h events, strongly dependent on how the FSI are modelled.

To decouple different model ingredients and nuclear effects in neutrino interaction modelling, T2K measures neutrino cross sections in multiple targets, neutrino beam mode, topology and physical observables. The recent cross section results at ND280 are summarized below.

2. Joint carbon and oxygen ν_μ CC0π cross section measurement

In [1] T2K reports the first simultaneous measurement of the double differential ν_μ CC0π cross section on carbon and oxygen as a function of the outgoing muon kinematics. This is possible by selecting neutrino interactions at FGD1 (C_8H_8) and FGD2 (C_8H_8 and H_2O) at the same time. For interactions in each FGD multiple signal samples can be selected with muons and possibly protons going into different sub-detectors with different acceptance. Most of the events come from the signal sample with only one reconstructed muon going into the TPC and no protons. There are also control samples specifically designed to constrain and validate the modelling of the primary backgrounds in the signal samples. The selected events are binned in reconstructed muon kinematics and a binned likelihood fit is applied to subtract the background and unfold the detector response from data. Apart from the carbon and oxygen cross sections, the ratio between them also provides useful information to validate various models' ability to extrapolate between carbon and oxygen nuclear targets. The extracted cross sections are compared to prediction from different Monte Carlo neutrino-nucleus interaction event generators. The level of agreement is quantified by the χ^2 statistics, which takes into account the correlation between bins.

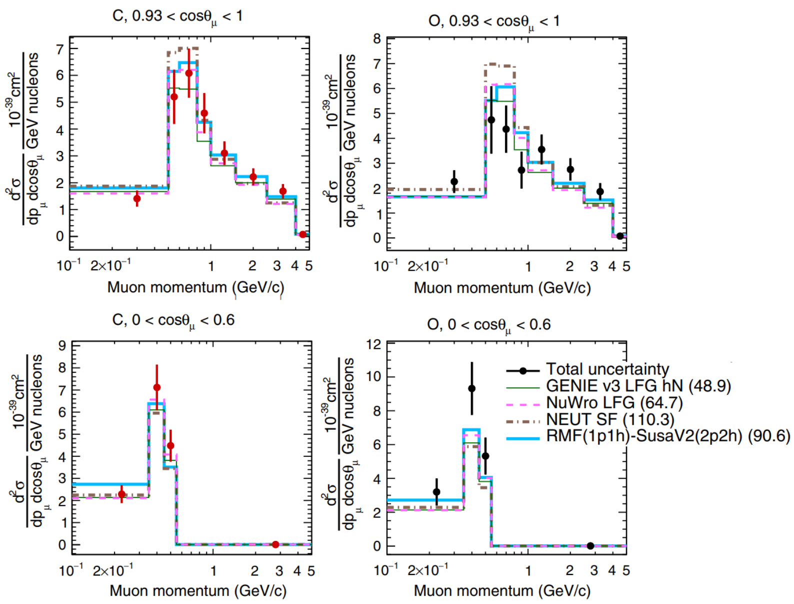

Figure 1: Double differential cross sections per nucleon measured in [1]. The most forward bin and a high angle bin are shown. The legend shows the χ^2 agreement compared to models, over a total of 58 bins.

In this analysis, the largest discrepancies of models with data is visible in the very forward-going muons. For example, Fig. 1 shows the measured cross sections in the most forward bin ($0.93 < \cos\theta < 1$). Both the carbon and oxygen data favour the simple local Fermi gas (LFG) nuclear ground state models in neutrino generators. The agreement is largely due to the substantial random phase approximations (RPA) corrections that suppresses cross section in the low energy transfer region. The more sophisticated nuclear models such as spectral function (SF) and relativistic mean field (RMF) show an excess in this region and yield larger χ^2. In the higher angle bins, LFG model underestimates the data, especially for oxygen. In this region, cross sections are mostly contributed by CC-QE which is more affected by the nucleon form factors, and it cannot explain the carbon-oxygen difference. It is speculated that such disagreement may be due to the insufficient modelling of non-QE interactions such as 2p2h and pion absorption FSI, which is derived based on the simple Fermi gas model.

3. Joint ν_μ and $\bar{\nu}_\mu$ CC0π cross section measurement

In [2] T2K reports the first combined measurement of the double-differential ν_μ and $\bar{\nu}_\mu$ CC0π cross sections on C_8H_8. Apart from the ν_μ and $\bar{\nu}_\mu$ cross sections, the sum, difference and asymmetry are also calculated to enhance the sensitivity to nuclear effects. Neutrino interactions happening in FGD1 are selected and analyzed. Since the ν_μ background in the $\bar{\nu}_\mu$ data is relatively large, a joint measurement helps minimizing the correlated flux (and detector) systematic uncertainties and results in a more precise $\bar{\nu}_\mu$ measurement.

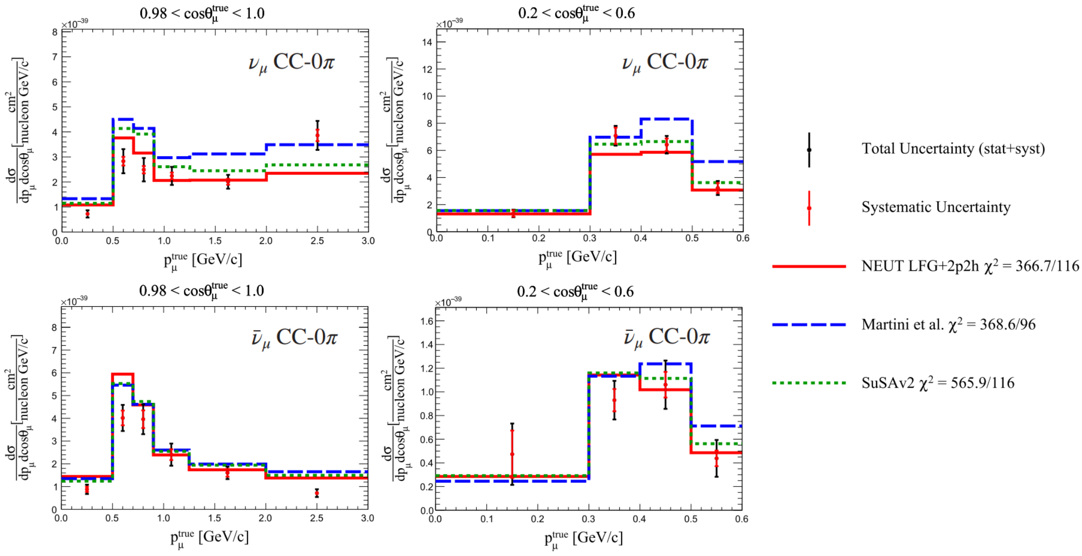

Figure 2: Double differential cross sections per nucleon measured in [2]. The most forward bin and a high angle bin are shown. The legend shows the χ^2 agreement compared to models, divided by the total number of bins used in the calculation.

This analysis employs a similar method of binned likelihood fit as in [1]. Fig. 2 shows the measured cross sections, again in the most forward bin and a high angle bin. Relative to the LFG models, models again shows an excess at forward angles, and a deficit at higher angles. On the other hand, this measurement shows particular sensitivity to 2p2h, where distinctive model predictions for the axial-vector component can be translated to ν_μ-$\bar{\nu}_\mu$ cross section difference. However, for the models being tested, they generally have a large χ^2 per cross section bin, meaning that no model can describe both the ν_μ and $\bar{\nu}_\mu$ data well.

4. CC1π^+Xp cross section measurement on transverse kinematic imbalance

Compared to CC0π modelling, CC1π interaction is an even more uncharted territory. On the theoretical side, there is less model development, and sophisticated models like SF do not always have predictions in the pion channel. Experimentally, pion cross section data are more scarce and less precise. In [3] T2K measures the differential cross section of ν_μ CC1π^+ interaction in terms of muon and pion kinematics. However in these phase spaces, models mostly show normalization differences, which is not effective in discriminating them. Alternative measurements involving the final state hadronic correlations are needed to better characterize the nuclear effects in pion channel.

T2K recently performed a cross section measurement in the ν_μ CC1π^+ channel with at least one proton in the final state (hereby referred as CC1π^+Xp), as a function of three transverse kinematic imbalance (TKI) variables [4, 5]. These observables are designed to characterize the nuclear effects most relevant to oscillation experiments: the initial nuclear state, the Fermi motion of initial state nucleon, and the FSI of outgoing hadrons.

The first observable δp_{TT} is the double-transverse momentum imbalance. A double-transverse axis is defined with the ν and μ^- direction, and the π^+ and p momenta are projected onto this axis [4]:

$$\delta p_{TT} = \frac{\vec{p}_\nu \times \vec{p}_T^{\,\mu}}{|\vec{p}_\nu \times \vec{p}_T^{\,\mu}|} \cdot (\vec{p}_T^{\,\pi} + \vec{p}_T^{\,\mathrm{p}}), \tag{1}$$

where $\vec{p}_i$ is the momentum of particle i, and $\vec{p}_T^{\,i}$ is its transverse component relative to the neutrino direction. In the absence of nuclear effects, $\delta p_{TT} = 0$ due to momentum conservation; while inside a nuclear medium, an imbalance is caused by the initial state of the bound nucleon, and the FSI experienced by the outgoing pion and proton.

The second observable p_N is the initial nucleon momentum, which probes the Fermi motion inside nucleus. Assuming the target nucleus is at rest and there is no FSI, p_N can be solved as [5, 6]

$$p_N = \sqrt{\delta p_T^2 + p_L^2}, \tag{2}$$

where $\delta \vec{p}_T = \vec{p}_T^{\,\mu} + \vec{p}_T^{\,\pi} + \vec{p}_T^{\,p}$, $p_L = \frac{1}{2}\beta - \frac{1}{2}\frac{\delta p_T^2 + M_{\mathrm{A}'}^2}{\beta}$, and $\beta = M_{\mathrm{A}} + p_L^{\mu} + p_L^{\pi} + p_L^{\mathrm{p}} - E_\mu - E_\pi - E_{\mathrm{p}}$. p_L^i and E_i are the particle longitudinal momentum and energy. The target nucleus mass M_A and the residual nucleus mass M_A' are related by $M_{\mathrm{A}'} = M_{\mathrm{A}} - M_{\mathrm{p}} + \langle\epsilon\rangle_{\mathrm{p}}$, where M_{p} is the proton mass, and $\langle\epsilon\rangle_{\mathrm{p}}$ is the proton mean excitation energy.

The third observable $\delta\alpha_T$ is the transverse boosting angle [5, 7]:

$$\delta\alpha_T = \cos^{-1}\frac{-\vec{p}_T^{\,\mu} \cdot \delta\vec{p}_T}{p_T^{\mu}\,\delta p_T}. \tag{3}$$

This observable quantifies whether the hadronic system is accelerated or decelerated by the nuclear effects. Before FSI, the isotropic Fermi motion of the initial-state nucleon produces a flat $\delta\alpha_T$ distribution; after FSI, hadrons are usually slowed down which makes $\delta\alpha_T > 90^{\mathrm{o}}$.

The measurement is done in the FGD1 (C_8H_8), with phase space constraint on the signal particle ($\cos\theta_{\mu/\pi/\mathrm{p}} > 0.342$, $250 < p_\mu/\mathrm{MeV} < 7000$, $150 < p_\pi/\mathrm{MeV} < 1200$, $450 < p_{\mathrm{p}}/\mathrm{MeV} < 1200$). There is one signal sample where the μ^-, π^+ and p tracks all come from the same vertex in FGD1 and go into TPC. The signal purity is above 60%, and there are four CC-other control samples to constrain multi-pion background. An unregularized likelihood fit is used to extract the number of signal events, and efficiency-corrected to obtain the differential cross sections.

Fig. 3 shows the measured TKI cross sections, compared to several generator predictions. NEUT uses the relativistic Fermi gas (RFG) as the nuclear ground state for pion production, which does not match the data well in both shape and normalization. For NuWro, two nuclear models are picked: Bodek-Ritchie parametrization of RFG (BRRFG), and effective SF. These models affect the nuclear properties like nucleon momentum and binding energy, and give better agreement than the simple Fermi gas models. GiBUU uses an LFG-based nuclear ground state, where its transport

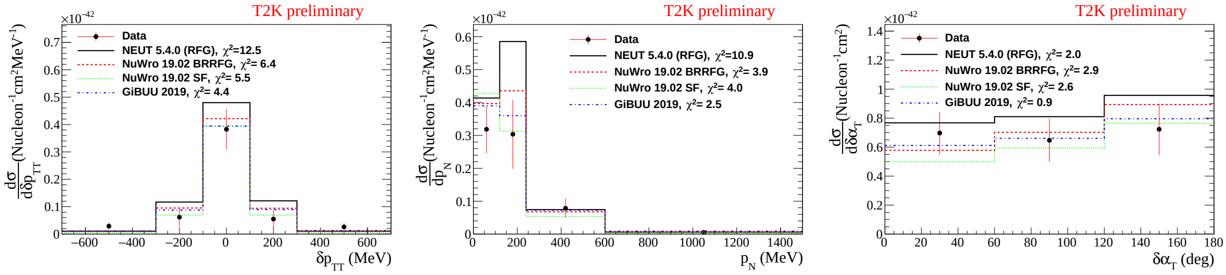

Figure 3: Measured TKI differential cross sections per nucleon, compared to model predictions.

theory treats all neutrino interaction modes, nucleon correlation and FSI in a consistent framework. As opposed to the CC0π measurement, this time data prefers the more sophisticated nuclear models, with best agreement in GiBUU. In particular the p_N data shows that the nucleon Fermi motion is poorly modelled in simple Fermi gas models. While the current model sensitivity in $\delta\alpha_T$ is limited, it provides a unique probe of FSI and distangles the different nuclear effect contributions. This measurement is complementary to the MINERνA CCπ^0 one [8], systematically probing resonance production on nucleons. It is possible for future analyses to isolate hydrogen interactions from carbon ones by selecting events with small δp_{TT} and p_N [4, 9], which further enhances nuclear model sensitivity and provides new “free nucleon data" since the bubble chamber experiments.

5. Summary

T2K has a broad cross section program which aims to understand neutrino interactions in all aspects. Using the technique of joint measurements and hadronic variables like TKI, valuable data are provided to validate and improve the modelling of various interaction channels and nuclear medium effects. With the continuous effort and the upcoming ND280 upgrade, T2K will be the keystone in precision neutrino oscillation measurement.

References

[1] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **101**, 112004 (2020).

[2] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **101**, 112001 (2020).

[3] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **101**, 012007 (2020).

[4] X.-G. Lu *et al.*, Phys. Rev. D **92**, 051302 (2015).

[5] X. Lu and J. T. Sobczyk, Phys. Rev. C **99**, 055504 (2019).

[6] A. P. Furmanski and J. T. Sobczyk, Phys. Rev. C **95**, 065501 (2017).

[7] X.-G. Lu *et al.*, Phys. Rev. C **94**, 015503 (2016).

[8] D. Coplowe *et al.* (MINERνA Collaboration), Phys. Rev. D **102**, 072007 (2020).

[9] P. Hamacher-Baumann, X. Lu, and J. Martín-Albo, Phys. Rev. D **102**, 033005 (2020).