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T2K recent results of cross-section measurements

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Modern neutrino oscillation experiments use complex nuclei as targets, thus it is crucial to understand the neutrino-nucleus scattering since it affects the background estimation and energy reconstruction. Furthermore, neutrino oscillation physics has entered in the precision era, requiring accelerator neutrino experiments to reduce systematic errors to the level of a few percent, particularly in view of the measurement of the CP phase and of the mass hierarchy. Driven by this motivation, in the last decade there has been considerable theoretical and experimental activity in the investigation of neutrino-nucleus cross sections in the few GeV and sub-GeV energy regions, where the flux of the long- and short-baseline experiments are peaked.
The T2K experiment is extremely active in this field providing useful information for a deeper understanding of the neutrino-nucleus scattering. In this work, after a quick overview of the detector, the most recent cross-section results are discussed.

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1. The T2K experiment

The T2K (Tokai to Kamioka) experiment is a long-baseline neutrino oscillation experiment based in Japan [1]. The neutrino beam is produced by the J-PARC accelerator complex located in Tokai, on the east cost of Japan, and it travels toward the far detector Super-Kamiokande, located in the Kamioka mine, 295 km from the neutrino production point. A near detector complex is located 280 m from the beam target and it is used to measure the unoscillated flux and the neutrino cross-sections. The near detector complex consists of two detectors: one on the beam axis, called INGRID and the other off-axis, called ND280. The first serves also as monitor of the neutrino beam profile and direction. It is made of 16 identical modules of iron and scintillator layers, 14 are arranged in a cross centered on the beam axis and two additional modules are placed at an off-axis position off the main cross to monitor the asymmetry of the beam. Another module, called the proton module, is made only of scintillator planes and is located on the beam axis, in front of the main cross. ND280 is located off-axis and consists of several sub-detectors as shown in Fig. 1. Placed inside the refurbished UA1/NOMAD magnet, which provides a magnetic field of 0.2 T, there are: a π^0 detector (PØD) made of scintillator layers alternated with water modules; two fine-grained detectors (FGDs) acting as target for neutrino interactions: the upstream FGD contains only scintillator bars arranged in x and y directions with respect to the beam direction, while in the downstream FGD there are additional water layers alternated with scintillator layers; FGDs are installed between three Time Projection Chambers (TPCs) designed for 3D track reconstruction, particle identification and determination of momentum and charge; a sampling calorimeter (ECal) surrounds all the inner detectors. It consists of layers of plastic scintillator alternated with lead and allows the reconstruction of tracks and showers in order to distinguish between muons, electrons and pions. The T2K flux is peaked around 0.6 GeV allowing to study the (anti)neutrino-nucleus scattering in an energy region where the main interaction channels are charged-current (CC) quasi elastic (CCQE), CC resonant pion production (CC-RES) and CC deep inelastic scattering (CC-DIS). Since neutrinos interact with a bounded nucleon, nuclear effects alter the expected final state particle types and kinematics. Indeed, correlations between the bounded nucleons can lead to multinucleon knock-out (also called 2p2h). In these processes a neutrino interacts with a correlated pair of nucleons that is knocked-out from the nucleus. Another possible process is the scattering or

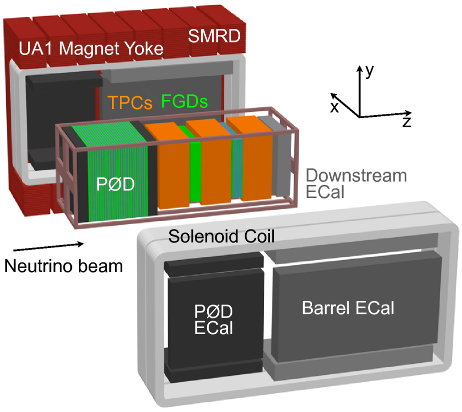

Figure 1: View of the ND280 off-axis detector. Figure taken from [1].

the absorption of the final state hadrons in the nuclear environment, called final state interactions (FSI), which can also produce additional final state particles. The reconstruction of the true neutrino interaction type is limited not only by the unavoidable nuclear effects but also by detector acceptance and efficiencies. Therefore to minimize the model dependence of the measurements, it is better to define experimental observables using final states with inclusive topologies like CC interactions without pion in the final state (**CC-0π**) and CC interactions with one pion in the final state (**CC-1π**).

2. T2K recent cross section results

T2K recently performed an updated measurement of the ν_μ CC inclusive flux integrated cross-section on hydrocarbon (the target is the upstream FGD). The statistics in the previous measurement, published in Ref. [2], was limited and only the forward-going muons were analysed. In the updated measurement the statistic have been increased using more data ($\sim 5.7 \times 10^{21}$ protons on target (POT)), while the acceptance has been improved by selecting also the high-angle and backward-going muons (with respect to the beam direction) using the timing information between the ND280 sub-detectors. For the selection of particles that enter the TPCs, the TPC particle identification (PID) is performed, while to identify particles that do not enter the TPCs, ECal PID is used if there is an associated ECal segment. Finally, the cross section is extracted as a function of the muon kinematic by performing an extended binned likelihood fit. The background, which is mainly due to pions misidentified as muons, is constrained by two control regions. The ν_μ CC inclusive cross-section is shown in Fig. 2 both the case in which the nominal Monte Carlo used as prior in the fit is NEUT [3] (blue bands) or GENIE [7] (black crosses). The result is then compared against NEUT, with Relativistic Fermi Gas (RFG) as the nuclear model and NuWro [4], with Local Fermi Gas (LFG). As can be noticed, both RFG and LFG overestimate the cross section in low momentum bins, as can be seen in the bottom left plot in Fig. 2.

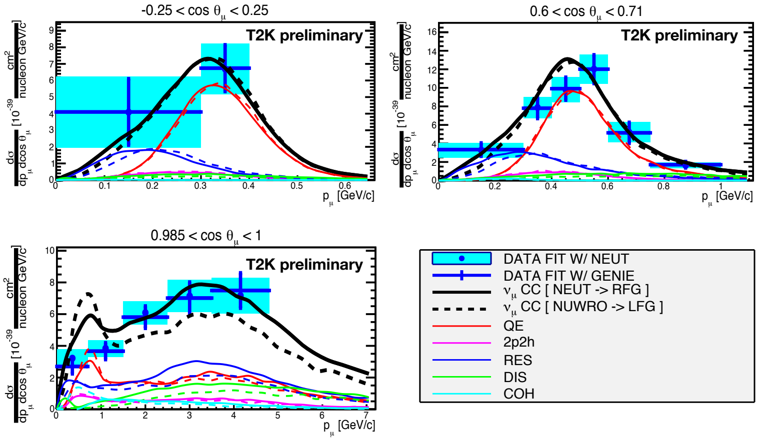

Figure 2: ν_μ CC inclusive cross-section for three different muon angle bins compared against NEUT and NuWro. Blue bands and dots are the results obtained using NEUT or GENIE as prior respectively.

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Recently T2K published two double-differential ν_μ CC-0π cross sections as a function of the outgoing muon kinematics, one on hydrocarbon (CH) [5] and another on water [6]. The next step has been to measure this cross section also as function of the proton kinematics. This measurement can give in principle more information on nuclear effects that using the muon kinematics alone. Three complementary measurements have been performed in this direction. They share the same selection and use the same statistics corresponding to $\sim 5.7 \times 10^{21} POT$.
One is the CC-0π flux-integrated multi-differential cross section on CH extracted as a function of the muon/proton scattering angle and the proton momentum. The selection is similar to the one used in Ref. [5]. The CC-0π events have been further divided into events with zero (CC-0π-0p), one proton (CC-0π-1p) and more than one proton (CC-0π-Np) in the final state. The background, mainly due to CC-RES and CC-DIS events, has been constrained using two samples where these interactions dominate. As an extraction method, an extended maximum-likelihood fit is exploited, similar to the one performed in Ref. [5].

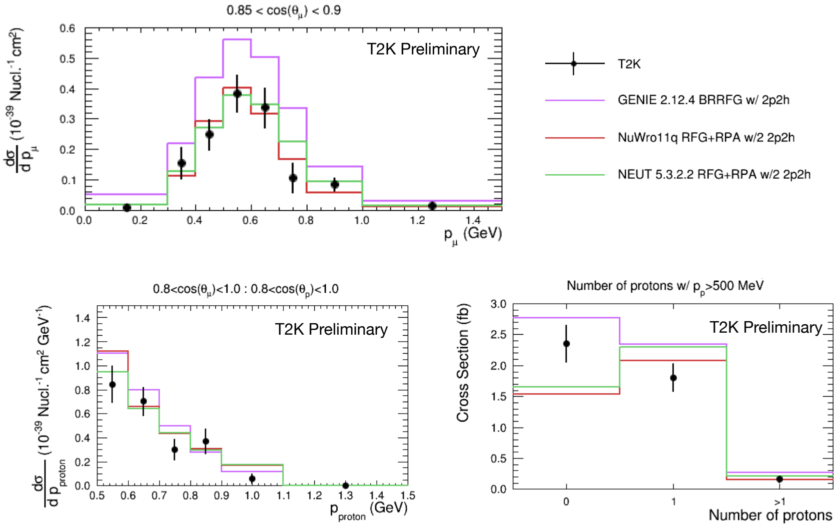

Figure 3: Top left: ν_μ CC-0π-0p cross-section for the forward muon scattering angle bin. Bottom left: ν_μ CC-0π-1p cross-section for one proton and muon angle bin. Bottom right: ν_μ CC-0π cross section as function of the number of protons. The results are compared against GENIE.

The CC-0π-0p cross section has been extracted as function of the muon momentum and angle and the result for the very forward bin is shown in the top left plot in Fig. 3. Then, if there is one proton with momentum greater than 500 MeV/c, the cross section has been extracted as function of the muon and proton angle and momentum. The cut on the proton momentum is necessary since for lower value the efficiency is almost zero. The result for one bin in muon and proton angle is shown in bottom left plot in Fig. 3. The cross section has been reported also as function of the number of protons (bottom right plot) again requiring the cut in momentum. The results are compared against GENIE, NuWro and NEUT showing to favour RFG plus random phase approximation (RPA, a non-perturbative method to describe microscopic quantum mechanical interactions in many body systems).

Another measurement that use the proton kinematics is the CC-0π cross-section extracted using the so-called single transverse variables (STV), indicated as δp_T, $\delta \phi_T$ and $\delta \alpha_T$ [8]. They can give information about the presence of nuclear effects in neutrino interactions with bounded nucleons as discussed in Ref. [8]. The same selection strategy as the multi-differential CC-0π cross-section described above is used. An extended maximum-likelihood fit with a Tikhonov regularisation term [9] is used to extract the cross section in bins of STV. In order to mitigate model-dependence, the phase space has been restricted using the following constraints on the muon/proton momentum and cosine of the scattering angle: $p_\mu > 250\,MeV/c$, $p_p > 450\,MeV/c$, $cos\theta_\mu > -0.6$ and $cos\theta_p > 0.4$. The extracted cross sections compared against different model, performed using the tool NUISANCE [10], are shown in Fig. 4.

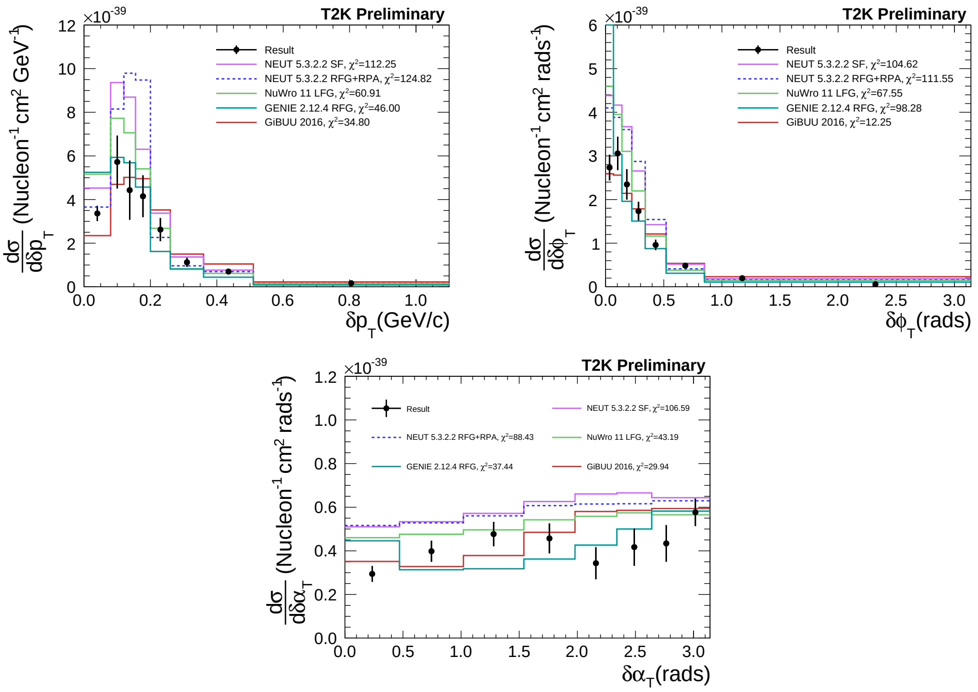

Figure 4: ν_μ CC-0π cross-section as function of the STV: δp_T (top left) $\delta \phi_T$ (top right) and $\delta \alpha_T$ (bottom). The results are compared against different generators.

Data strongly disfavor RFG in favor of LFG. GiBUU [11] results to be closer to data in δp_T and $\delta \phi_T$. The peak in the first bin of the GENIE prediction visible in $\delta \phi_T$ is related to the FSI model implemented in this generator.

A third ongoing analysis is the ν_μ CC-0π cross section on CH with inferred proton kinematics. Under the hypothesis of stationary target and elastic scattering it is possible to infer proton kinematics from the measured muon kinematics and compare with the measured one. Non-zero imbalance between inference and the measured proton indicates the presence of nuclear effects or non-QE interactions. The extraction method, contrary to the other analyses, is the Bayesian unfolding. The results are under collaboration review.

3. Conclusions and future outlook

Over the past ten years, a complicated experimental and theoretical picture has emerged regarding neutrino-nucleus interactions. Many models have been developed and measurements performed, but a comprehensive picture has not yet emerged. T2K can give an important contribution at the GeV energy scale confirmed by many works published in the last years.
Other analyses are ongoing using water as target and antineutrino as probe: the ν_μ CC inclusive and CC-0π carbon over oxygen cross-sections ratio using the most downstream FGD, the integrated $\bar{\nu}_\mu$ CC-0π cross-section on CH at the proton module and the double-differential $\bar{\nu}_\mu$ CC-0π cross-section on water using the P0D. As next step of the CC-0π cross-section on CH at ND280, the first simultaneous extraction of the double-differential ν_μ and $\bar{\nu}_\mu$ CC-0π cross section is ongoing. This analysis strategy will allow the extrapolation of the sum, the difference and the asymmetry, namely the ratio between the difference and the sum, of the two cross sections [12]. The sum isolates the axial-vector interference term of the cross-section, the difference enhances the sensitivity to the multinucleon component and the asymmetry is a direct estimation on any possible bias due to mismodelling of neutrino interactions on the measurement of δ_{CP}.

References

[1] K. Abe *et al.*, *The T2K Experiment,* Nucl. Instrum. Meth. A **659**, 106 (2011).

[2] K. Abe *et al.*, *Measurement of the inclusive ν_μ charged current cross section on carbon in the near detector of the T2K experiment,* Phys. Rev. D **87**, no. 9, 092003 (2013).

[3] Y. Hayato, *A neutrino interaction simulation program library NEUT,* Acta Phys. Polon. B **40**, 2477 (2009).

[4] C. Juszczak, J. A. Nowak and J. T. Sobczyk, *Simulations from a new neutrino event generator,* Nucl. Phys. Proc. Suppl. **159**, 211 (2006).

[5] K. Abe *et al.*, *Measurement of double-differential muon neutrino charged-current interactions on C_8H_8 without pions in the final state using the T2K off-axis beam,* Phys. Rev. D **93**, no. 11, 112012 (2016).

[6] K. Abe *et al.*, *First measurement of the ν_μ charged-current cross section without pions in the final state on a water target,* arXiv:1708.06771.

[7] C. Andreopoulos, C. Barry, S. Dytman, H. Gallagher, T. Golan, R. Hatcher, G. Perdue and J. Yarba, *The GENIE Neutrino Monte Carlo Generator: Physics and User Manual,* arXiv:1510.05494.

[8] X.-G. Lu *et al.*, *Measurement of nuclear effects in neutrino interactions with minimal dependence on neutrino energy,* Phys. Rev. C **94**, no. 1, 015503 (2016).

[9] A. N. Tikhonov, Soviet Math. Dokl.4(1963), 1035.

[10] P. Stowell *et al.*, *NUISANCE: a neutrino cross-section generator tuning and comparison framework,* JINST **12**, no. 01, P01016 (2017).

[11] O. Buss *et al.*, *Transport-theoretical Description of Nuclear Reactions,* Phys. Rept. **512**, 1 (2012).

[12] C. Riccio on behalf of the T2K Collaboration, *Muon antineutrino charged-current cross sections without pions in the final state at T2K,* arXiv:1705.00067.