PROCEEDINGS OF SCIENCE

Measurements of Neutrino Interaction Cross Sections at T2K

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T2K is a long baseline neutrino experiment producing a beam of muon neutrinos and antineutrinos at the Japan Particle Accelerator Research Centre and measuring their oscillation by comparing the measured neutrino rate and spectrum at a near detector complex and at the water-Cherenkov detector Super Kamiokande, located 295 km away. The intense neutrino beam and the set of near and far detectors offer a unique opportunity to measure neutrino cross sections for interactions on different nuclei (C and O primarily), for different neutrino energies and flavours. In particular, the combination of near detectors at different off-axis angles, enable an improved control on the energy-dependence of the neutrino cross section. T2K is also pioneering new analysis techniques which target the exclusive measurement of the neutrino-interaction final state, including the kinematics of its hadronic part. An overview of most recent T2K cross section analyses will be presented, including a new measurement of coherent pion production in neutrino and antineutrino scattering on Carbon nuclei.

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1. Experimental setup and cross section analyses at T2K

T2K is a long baseline neutrino experiment in Japan and its main goal is the study of neutrino oscillations. The predicted event rates in the oscillation analysis samples depend - among other factors - on the predicted cross section for various neutrino interaction modes. Thus, in order to have precise oscillation analysis it is necessary to have a good knowledge about the cross sections. In addition to the application in the oscillation analysis, cross section measurements can be used to explore nuclear effects or rare processes.

T2K experiment has a rich program of cross section measurements in the near detectors site. By using different detectors it is possible to measure neutrino interactions on multiple targets and at different angles with respect to the neutrino beam axis - which effectively means measuring interactions at different energy spectra. It is also possible to have joint measurements and extract cross section for different targets or angles simultaneously.

There are three near detector sets used for the cross section analyses: on-axis INGRID detector, $1.5°$ off-axis detectors of WAGASCI and Baby MIND experiments and $2.5°$ off-axis detector ND280 (most cross section measurements in T2K's history were based on data collected with the latter). Data is obtained for neutrino and anti-neutrino beam modes.

The Interactive Neutrino GRID (INGRID) detector consists of 14 Fe/scintillator modules arranged in two sets that form a 'cross' shape: 7 modules along vertical axis and 7 modules along horizontal axis. The additional scintillator module, called the Proton Module, is located in front of the central INGRID module. The primary task of INGRID is to monitor neutrino beam direction and intensity.

Near detector ND280 measures charged current neutrino interactions in the tracker, which consists of two scintillator fine grain detectors (FGDs) and three gaseous time projections chambers. ND280 is equipped with a magnet, which allows for the particle's charge identification and momentum measurement. Fine grain detectors provide interaction target. The upstream FGD1 is built of scintillator layers, while the downstream FGD2 is built of scintillator layers interleaved with water. Time projection chambers provide excellent tracking of charged particles and allow for particle identification via energy loss measurement combined with the momentum measurement.

1.1 Neutrino interactions and event topologies

At T2K energy scale mostly sub-GeV interactions are studied and the biggest contribution comes from the quasielastic and resonant interactions. One of the important systematic uncertainty sources in the oscillation analysis is related to cross section systematics, in particular final state interactions. Particles produced in the neutrino interaction may reinteract within the nucleus. Events are classified according to their final state topology, which is defined by the particles exiting the nucleus. In particular a commonly used labels are: CC0π topology (which refers to the events with single muon and no pion in the final state) and CC1π topology (events with single muon and single charged pion in the final state).

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2. Simultaneous measurement of the ν_μ CC0π cross section on O and C at ND280

In 2020 T2K reported [1] the simultaneous measurement of neutrino CC0π cross section on oxygen and carbon at ND280. This was the first joint cross section measurement for oxygen and carbon at T2K. The information about neutrino interactions on oxygen is of key importance for the oscillation analysis, as the far detector is a water target detector. Events in the signal samples were required to contain single muon-like track of negatively charged particle and any number of reconstructed proton tracks originating from the same vertex as muon (or no proton tracks at all). Based on the location of reconstructed interaction vertex the signal samples were selected as the oxygen-enhanced or the carbon-enhanced.

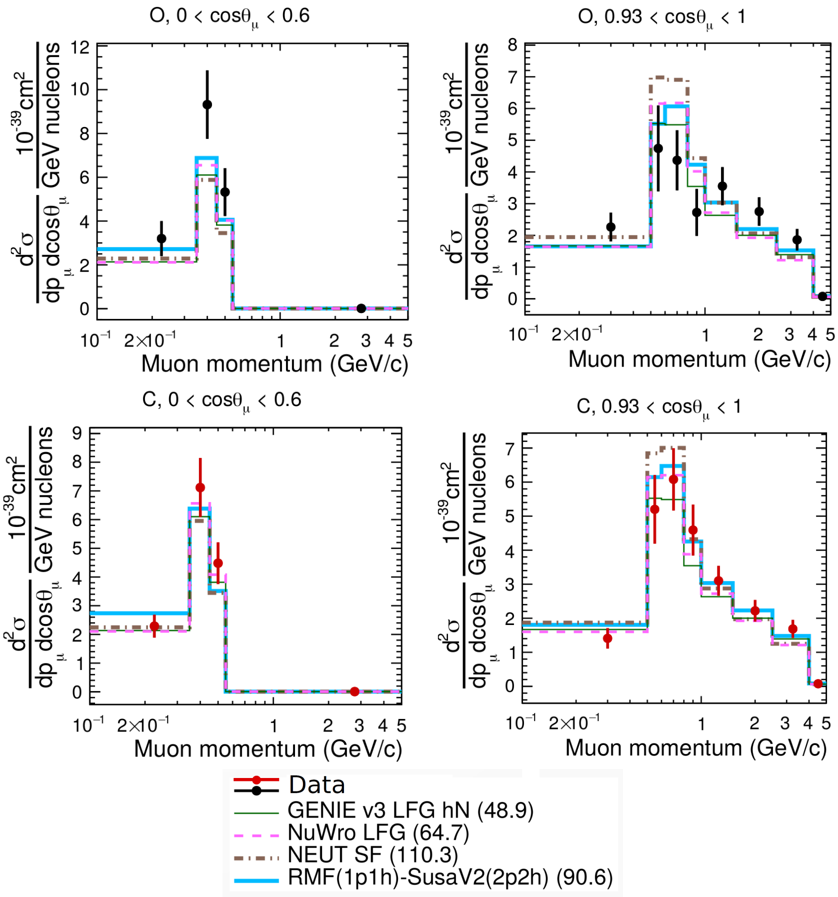

Figure 1: Double differential cross sections per nucleon (non-exhaustive). Top plots: cross section on oxygen, bottom plots: cross section on carbon. Data results (black/red points with error bars) are compared with several MC generators. The values in brackets represent the χ^2 agreement with models. Plots taken from [1]. Legend modified for a better readability.

The cross sections were reported as the double differential in muon kinematic variables: momentum and cosine of the polar angle. The ratio of cross sections was calculated as well. Predictions of various models were compared with the measurement (see Fig. 1) and it was found that results were best described by nuclear ground state models with local Fermi gas and random phase approximation suppression.

3. Joint On/Off axis ν_μ CC0π measurement on scintillator with FGD1 and the Proton Module

Another important measurement of neutrino CC0π process was the first joint on-axis/off-axis measurement at T2K [2], which recently passed the collaboration review. Due to different on/off axis energy spectra, this analysis allows to better understand the energy dependence of the cross section and provide additional constraints on neutrino flux modelling. In this measurement only interactions on scintillator material (hydrocarbon) were taken into account. Off-axis sample was based on neutrino interactions in FGD1 of ND280, with a single reconstructed muon track, any number of proton tracks and no pion signatures. For the on-axis interactions data were collected with the INGRID detector. Reconstructed muon tracks had to start in the scintillator material of the Proton Module with a possible segment in the downstream INGRID module.

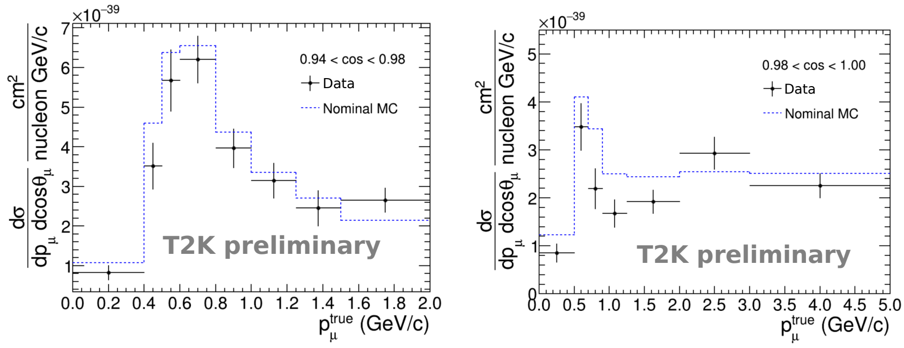

Figure 2: Double differential cross section per nucleon reported for the off-axis near detector. Data results are compared with NEUT 5.3.2 predictions.

The cross section on hydrocarbon was reported as double differential in muon momentum and cosine of the polar angle for on-axis neutrino flux and off-axis neutrino flux. The results (non-exhaustive) for the off-axis flux are presented in Fig. 2. The publication with these results is in preparation - it will provide comparison with various Monte Carlo models.

4. Transverse kinematic imbalance (TKI) in ν_μ CC1π^+ production channel containing at least one proton

One of the goals of the T2K's cross section program is to explore nuclear medium effects. The limited knowledge of these effects is one of the dominant sources of systematic uncertainty in the oscillation analysis. In 2021 T2K published [3] the measurement of transverse kinematic imbalance (TKI) in the CC1π^+ events, i.e., events with one muon and one charged pion in the final state. Additionally at least one proton in the final state was required too. Data samples were based on the events with neutrino interactions in FGD1 subdetector of ND280. Observables of interest (TKI variables) were based on measured momenta of the reconstructed muon, pion and proton tracks. Three TKI variables were used: the total initial nucleon momentum p_N, the double transverse momentum imbalance δp_{TT} (defined as the sum of pion and proton momenta projections on the double transverse axis $\hat{z}_{TT}$), and the transverse boosting angle $\delta\alpha_T$. TKI variables are visualised in Fig. 3 (top).

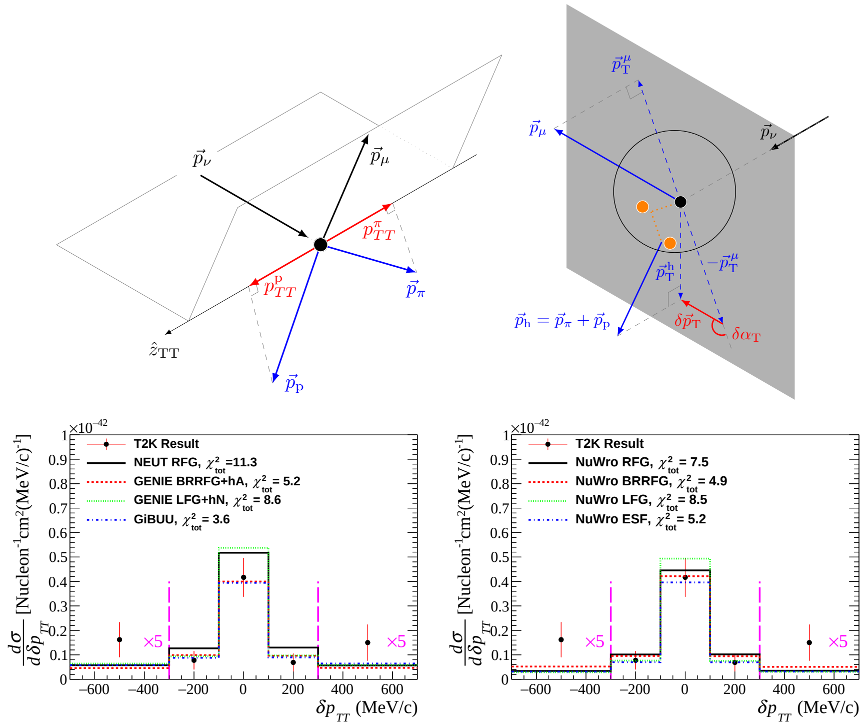

Figure 3: Top: Visualisation of the TKI variables. In the left illustration the double transverse axis $\hat{z}_{TT}$ is oriented perpendicularly to the incoming neutrino direction and the emitted muon direction. The double transverse momentum imbalance is taken as $\delta p_{TT} = p^{p}_{TT} + p^{\pi}_{TT}$. In the right illustration the gray plane is perpendicular to the incoming neutrino direction. Orange circles symbolize possible final state interactions of the outgoing hadrons. Figures adapted from [4, 5].
Bottom: Differential cross section as a function of the double transverse momentum imbalance δp_{TT}. Data results were compared with several Monte Carlo generators. Plots taken from [3].

Bottom plots in Fig. 3 present the extracted differential cross section on hydrocarbon as a function of δp_{TT}. The cross section was reported also as a function of other TKI observables. The important conclusion from this study was that data disfavoured Monte Carlo generators with simple Fermi gas models and there was a slight preference for GiBUU generator.

5. ν_μ and $\bar{\nu}_\mu$ CC coherent pion production on carbon

T2K cross section program includes studies of rare processes, such as the recent measurement of neutrino and anti-neutrino CC coherent pion production on carbon [6]. In case of coherent interactions neutrino doesn't interact on a single nucleon but on nucleus as a whole. This channel is not well modelled theoretically. The measurement was based on data collected in FGD1 of ND280. Signal samples consisted of events with two tracks (muon-like and pion-like), low energy deposit around the interaction vertex and low momentum transferred squared. Due to statistical limitations results were reported as single energy bin cross sections (see Fig. 4). In order to obtain cross section for carbon, first the cross section was extracted for interactions in the entire FGD1 and then it was rescaled based on FGD1 chemical composition. The results of this analysis are preliminarily approved by the collaboration and the publication is in preparation.

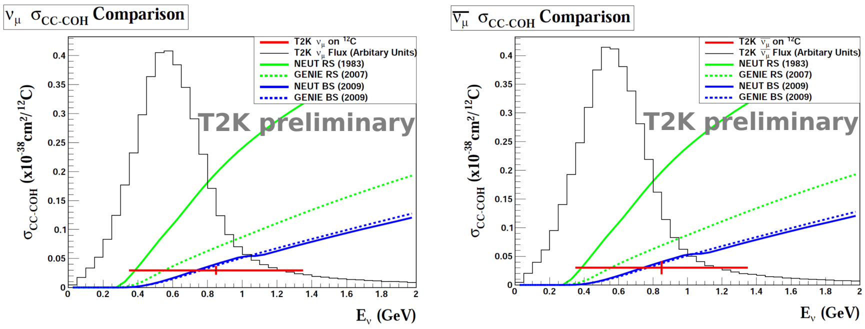

Figure 4: CC coherent cross section on carbon for ν_μ (left) and $\bar{\nu}_\mu$ (right). Data resuts were compared with several Monte Carlo generators.

6. Summary and outlook

The cross section measurements validate neutrino interaction models and allow to constrain systematic uncertainties in the oscillation analysis. Experimental setup of near detectors at T2K provides possibility for measurements on multiple targets and at different neutrino beam angles. One can expect many new T2K cross section results in future. Currently there are several ongoing analyses which study single pion production at ND280, as well as an analysis focused on single kaon production. The ν_μCC0π measurement is ongoing for the WAGASCI detector and there are plans for a joint analysis for ND280 and WAGASCI. The upgrade of the near detector ND280 [7] is expected to give us new possibilities for the cross section measurements with broader angular acceptance and better reconstruction of the hadronic part of the interactions.

References

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