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Combined neutrino and antineutrino charged current cross section measurement on carbon with zero final state pions in the T2K near detector complex

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T2K is a long baseline neutrino oscillation experiment, located in Japan. A muon (anti)neutrino beam peaked at 0.6 GeV is produced in the J-PARC facility and measured by near detectors and the Super-Kamiokande far detector. The main goal is to measure the neutrino oscillation parameters. T2K can run in both neutrino and antineutrino mode, enhancing the sensitivity to charge-parity violation (CPV) in the lepton sector. Measuring oscillation parameters requires precise knowledge of the (anti)neutrino interaction cross sections.

We present an improved cross section analysis which utilizes combined data samples of multiple detectors and in multiple beam configurations, the first of its kind. It will be used to measure the muon neutrino and antineutrino cross sections on carbon with no final state pions. This technique fully exploits the correlations between the samples' systematic uncertainties, allowing for their efficient cancellation. Since the two utilized T2K near detectors sample different neutrino energy spectra, this measurement will allow to better understand the energy dependence of neutrino interactions, thereby offering a direct probe of the processes that are responsible for the largest uncertainties in T2K oscillation analyses.

In addition, by measuring both neutrino and antineutrino cross sections, it is possible not only to better tune theoretical models of nuclear effects such as multinucleon interactions, but also to properly understand the asymmetry between neutrino and antineutrino interactions, the latter being of fundamental importance for CPV experiments that measure the asymmetry between neutrino and antineutrino oscillation rates.

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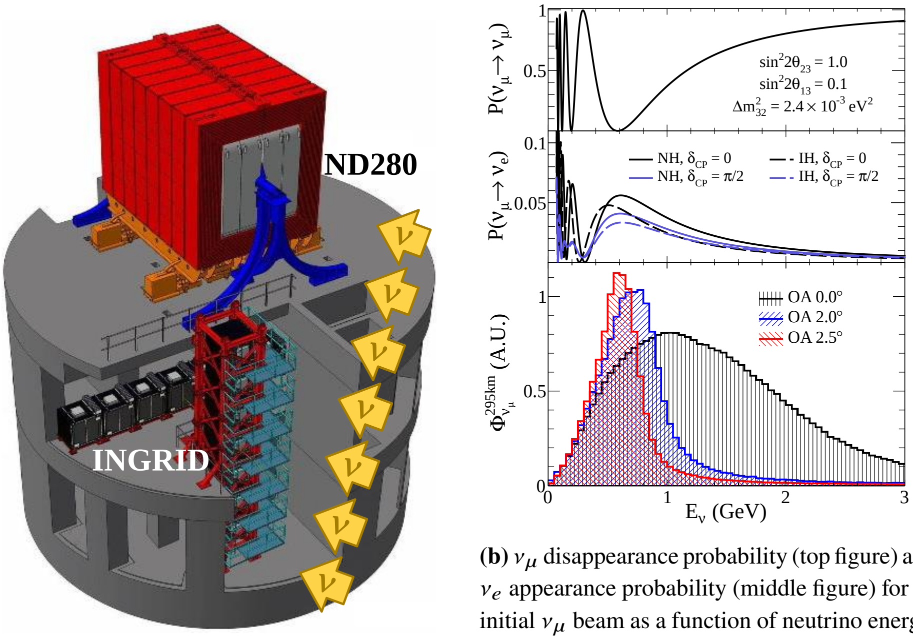
1. The T2K Experiment

T2K (Tokai-to-Kamioka) is a long-baseline neutrino oscillation experiment based in Japan, designed to measure the neutrino oscillation parameters. It is based around a high intensity muon neutrino or antineutrino beam which is produced at the J-PARC accelerator complex in Tokai. The initial beam is measured in the near detector complex, located 280 m from the beam source. At a distance of 295 km from the source, the oscillated beam is measured by the Super-Kamiokande (SK) far detector, a 50 kt water Cherenkov detector. T2K was the first neutrino oscillation experiment to employ the off-axis technique, angling the neutrino beam 2.5° away from SK in order to achieve a narrower neutrino energy beam spectrum with a flux peak at 0.6 GeV, shown in Figure 1b. At this energy, the oscillation probability at the far detector is maximized. As SK can distinguish between muons and electrons, the neutrino oscillation parameters are measured through the ν_μ and $\overline{\nu}_\mu$ disappearance channel and the ν_e and $\overline{\nu}_e$ appearance channel. T2K has been taking data since 2010 and has produced world-leading neutrino oscillation parameter measurements. It was the first experiment to observe the appearance of electron neutrinos in a muon neutrino beam [1] and was able to exclude CP conservation in the lepton sector at the 3σ confidence interval [2].

2. The ND280 and INGRID Near Detectors

The T2K near detector complex is shown in Figure 1a and consists of several detectors which measure the unoscillated neutrino spectrum 280 m from the beam source. They are vital for the oscillation analysis, constraining the neutrino cross sections and flux. Due to the intense neutrino beam, they are very well suited for neutrino-nucleus cross section measurements. The two detectors utilized in this analysis are the ND280 off-axis detector and the INGRID on-axis detector [3]. The former is placed in line with the SK far detector, at a 2.5° off-axis angle. It is fully magnetized, thus enabling the measurement of the particles' charge sign. The ND280 off-axis detector consists of several sub-detectors, the main ones being the two Fine Grained Detectors (FGDs) which are sandwiched between the three Time Projection Chambers (TPCs), and the Pi-Zero Detector (P0D) located upstream from the FGDs and TPCs. The first FGD consists of hydrocarbon scintillator bars, placed in alternating orientations and is used as the fiducial volume for the off-axis samples in this analysis. The second FGD features additional passive water layers sandwiched in between the active scintillator layers. The gas-argon TPCs are high-resolution gaseous tracking detectors. They act as a tracker for the particles' trajectories and are capable of measuring their momentum and charge. The FGDs, TPCs and the P0D are surrounded by electromagnetic calorimeters which provide an almost all-encompassing coverage of the inner detectors with regard to outgoing tracks. The on-axis INGRID detector [4] consists of a horizontal and vertical array of seven identical modules each which are arranged in a cross pattern. The cross is centered on the neutrino beam center. Each of the modules measures 1 m × 1 m × 1 m and consists of active scintillator planes sandwiched between passive iron plates which provide more stopping power. An additional module, the proton module (PM), has been placed between the vertical and horizontal center INGRID modules. Unlike the INGRID modules, the PM contains only scintillator planes and is thus fully active thus enabling a higher 3D tracking resolution. This analysis uses the PM as the fiducial volume of the on-axis samples together with the subsequent center INGRID module used as a downstream tracker.



(a) The T2K near detector complex, composed of the ND280 off-axis detector (top) and the INGRID on-axis detector (bottom).

(b) ν_μ disappearance probability (top figure) and ν_e appearance probability (middle figure) for an initial ν_μ beam as a function of neutrino energy. The latter shows the probability for normal and inverted mass hierarchy and maximum and no CP violation. The bottom figure shows the neutrino energy spectra at different angles.

Figure 1

3. Signal Definition and Cross Section Extraction

In general, the initial interaction between the neutrino and the nucleus is obfuscated by poorly-understood nuclear effects and final state interactions in the nuclear medium. Therefore, in order to ensure a minimal bias from the input simulation which is fitted to the data, the signal is defined in terms of the final event topology instead of the initial interaction. Moreover, the cross sections are binned in terms of the observable muon kinematics (instead of quantities like the neutrino energy which would need to be reconstructed): its momentum and the angle between the incoming neutrino and the outgoing muon. The signal is defined as events with one muon and zero pions in the final state topology which has the largest share of CCQE events, the most important channel for the energy range of T2K. In addition to these signal samples, additional control samples are defined for both detectors in order to constrain the background modeling.

The ν_μ and $\overline{\nu}_\mu$ cross sections are simultaneously extracted with a binned likelihood fit which uses the samples from the on-axis and off-axis detectors. The fit attempts to achieve the best possible agreement between the data and simulated Monte Carlo events, as measured by:

$$\chi^2_{\text{stat}} = \sum_{j}^{\text{reco bins}} 2\left[N_j^{\text{MC}} - N_j^{\text{Data}} + N_j^{\text{Data}} \log\left(N_j^{\text{Data}}/N_j^{\text{MC}}\right)\right] \tag{1}$$

where N_j^{MC} and N_j^{Data} are the number of events in a reconstructed bin j for Monte Carlo (MC) and data respectively. During the fit procedure, the MC events can be altered by several sets of parameters. One set, the so-called *template parameters*, will act directly on all true signal events in the truth bins and can thus be used to alter the simulated cross section freely, as they are completely unconstrained. Other fit parameters allow for corrections in the simulated model of the incoming neutrino flux, the detector response and the interaction models used. These are nuisance parameters and prior knowledge can be used to help constrain them and not have the fit explore configurations that would be very unphysical. This is achieved by adding the following penalty term to χ^2_{stat}:

$$\chi^2_{\text{syst}} = \left(\vec{p} - \vec{p}_{\text{prior}}\right) \left(V^{\text{syst}}_{\text{cov}}\right)^{-1} \left(\vec{p} - \vec{p}_{\text{prior}}\right) \tag{2}$$

where $\vec{p}$ is the vector of systematic nuisance parameters, $\vec{p}_{\text{prior}}$ are their prior values, and $V^{\text{syst}}_{\text{cov}}$ is the covariance matrix in which all the uncertainties and correlations between the different parameters are encoded. Without this penalty term the fit would be severely underconstrained.

The fit result then allows to unfold from reconstructed space into truth space by weighting the MC events with the final best-fit parameters to obtain the number of true signal events N_i^{signal} in truth bin i. The double-differential cross section is then computed using this number:

$$\frac{\mathrm{d}^2\sigma^\alpha}{\mathrm{d}p_\mu \mathrm{d}\cos\theta_\mu} = \frac{N_i^{\text{signal, }\alpha}}{\epsilon_i^{\text{MC}} \Phi N_{\text{nucleons}}} \times \frac{1}{\Delta p_\mu \Delta \cos\theta_\mu} \tag{3}$$

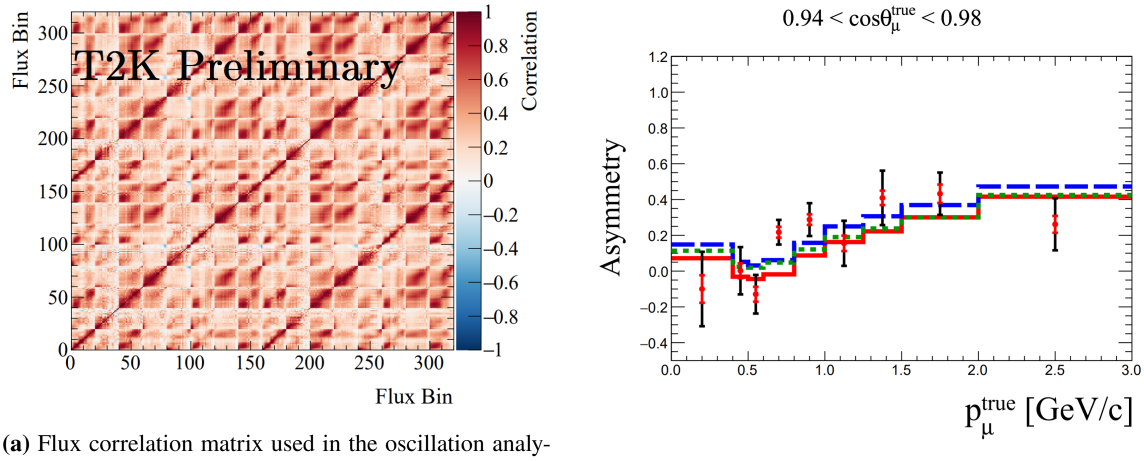
where α indicates the neutrino type (ν_μ or $\overline{\nu}_\mu$), ϵ_i^{MC} is the detection efficiency for that bin, Φ is the integrated flux, N_{nucleons} is the number of target nucleons and $\Delta p_\mu \Delta \cos\theta_\mu$ is the bin width.

3.1 A Joint On-axis and Off-axis Measurement

Simultaneously utilizing samples from both the on-axis and off-axis near detectors has several advantages. As the measured neutrino interaction rate is a product of the flux and the cross sections, there is a degeneracy between the two. However, the difference in the two fluxes between the ND280 off-axis and the INGRID on-axis detectors shown in Figure 1b can break this degeneracy. In addition, the fluxes at the different detectors of T2K are highly correlated as they detect neutrinos originating from the same source, as can be seen in Figure 2a which shows the correlations between the ND280 off-axis and the SK flux. Similar correlations between the on-axis and off-axis detectors can be exploited to reduce the flux uncertainty in the cross section measurement by providing a more stringent constraint via the flux parameter penalty term given in Equation 2 which will confine the flux parameters to only vary in specific ways. Furthermore, as the fluxes are peaked at different energies, with the INGRID flux having a much longer high-energy tail, the cross section can be studied as a function of energy. In the scope of this analysis, T2K's flux simulation framework has been adapted to be able to determine the flux covariances between arbitrary detector planes and for all neutrino flavors. This analysis is thus an important step towards planned future multi-axis measurements with next-generation neutrino detectors such as DUNE and Hyper-K [5].

3.2 A Joint ν_μ and $\overline{\nu}_\mu$ Measurement

As described in [6], the ν_μ and $\overline{\nu}_\mu$ cross sections differ by the sign of the axial-vector interference term. This term contains reactions in which the neutrino interacts with multiple correlated nucleons, so-called 2p2h interactions. Therefore, the sum and difference of the ν_μ and $\overline{\nu}_\mu$ cross sections can be used to directly evaluate this term and the quantity independent of this contribution. Moreover, as δ_{CP} measurements try to measure the asymmetry in the oscillation rates between neutrinos and antineutrinos, it is essential to correctly account for the unrelated interaction asymmetry $((\sigma^{\nu} - \sigma^{\overline{\nu}})/(\sigma^{\nu} + \sigma^{\overline{\nu}}))$ between the two in order to avoid biases. This was done in [8] using only the ND280 off-axis detector. The measured CC-0π asymmetry is shown in Figure 2b for one slice of $\cos\theta_{\mu}$ and various momentum bins and has been compared to several interaction models. Although none of the models considered in this work are able to describe the full phase space of the neutrino and antineutrino CC-0π cross sections (see Table III in [8]), it is difficult to determine the source of the problem. A better understanding will therefore be of critical importance for future neutrino oscillation experiments.



(a) Flux correlation matrix used in the oscillation analysis for neutrino energy bins between the ND280 off-axis detector (bins 0-79 in ν-mode, 80-159 in $\overline{\nu}$-mode) and SK (bins 160-239 in ν-mode, 240-319 in $\overline{\nu}$-mode) for ν_{μ}, $\overline{\nu}_{\mu}$, ν_{e} and $\overline{\nu}_{e}$ fluxes (each having 20 bins) [7].

(b) Measured CC-0π cross section asymmetry with systematic (red bars) and total (black bars) uncertainty. The result is compared to the NEUT LFG+2p2h (red), Martini *et al.* (blue) and SuSAV2 (green) interaction models [8].

Figure 2

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