Recent Results from the T2K ND280 Detector

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The T2K near detector complex, ND280, is located at the J-PARC accelerator facility in Tokai, Japan, 280 m downstream from the target. These proceedings will summarise recent physics results from ND280.

1 Introduction

T2K is a long-baseline neutrino oscillation experiment based in Japan designed to look for $\nu_\mu \rightarrow \nu_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance. In 2013 T2K reported [1] the discovery of ν_e appearance from a pure ν_μ beam. The beam is produced from the in-flight decay of pions and exploits the pion decay kinematics by positioning its detectors 2.5° off the beam axis. This improves the monochromaticity of the resulting ν_μ energy spectrum, reduces its high energy tail and selects a peak energy close to the ν_μ oscillation maximum for the 295 km T2K baseline. In order to quantify oscillations one must first predict the expected neutrino interaction rate and flavour composition, in the absence of oscillations, at some fixed baseline from the beam origin. In T2K this is facilitated by a near detector complex at 280 m from the graphite target used to produce the ν_μ beam. The off-axis near detector, ND280 and on-axis near detector, INGRID are used to constrain the neutrino flux and cross section parameters of the JPARC neutrino beam. Additionally, due to the large number of target materials present in the ND280 complex, it can provide information on neutrino-nucleon cross sections at energies around 1 GeV.

2 Off-axis near detector: ND280

The near detector at 280 m, ND280, illustrated in Figure 1, sits 2.5° from the beam axis and comprises a dedicated upstream, scintillator-based, π^0 detector (P0D) followed by a tracker region composed of three gaseous time projection chambers (TPCs) interleaved with two 0.8 ton fine grained scintillator detectors (FGDs). The P0D, TPCs and FGDs are surrounded by hermetic electromagnetic lead/scintillator sampling calorimeters (ECALs). A large electromagnet surrounds these sub-detectors, providing a 0.2 T field. The gaps in the flux-return are instrumented with scintillating paddles for muon tagging and constitute the side muon-range detector (SMRD). The P0D can be operated with or without a passive water target in order to permit on-water or on-carbon rate and cross section measurements. Additional target materials can be found in the two scintillator/brass sampling calorimeter sub-modules either side of the central P0D fiducial volume. The FGDs are scintillator based calorimeters with FGD1 having a pure hydrocarbon target mass and FGD2 containing a passive water target, again permitting on-carbon and on-water rate and cross section measurements. The large fiducial mass of lead in the ECALs can further be exploited for cross section studies, investigations into interactions on gaseous argon atoms in the TPC are currently underway.

3 T2K near detector constraint

Before ND280 can constrain the neutrino flux and cross section parameters, models of each must first be constructed. The T2K flux prediction [2] is derived from *in-situ* measurements of the proton beam and on-axis measurements of the neutrino beam, coupled with Monte Carlo (MC) simulations of the neutrino flux. The GEANT3/FLUKA based flux simulation is itself tuned using external data from hadron production experiments including NA61/SHINE. The official T2K MC event generator (NEUT) takes the flux prediction as an input and is subsequently used to predict neutrino interaction rates and flavour composition at the near and far detectors. NEUT cross section models are tuned to external lepton and pion scattering data. Uncertainties on NEUT cross section models are calculated [1] by varying model parameters such as axial-mass, fermi-momentum and binding energy (and their respective shapes and normalisations) in fits to external data from experiments such as MiniBooNE.

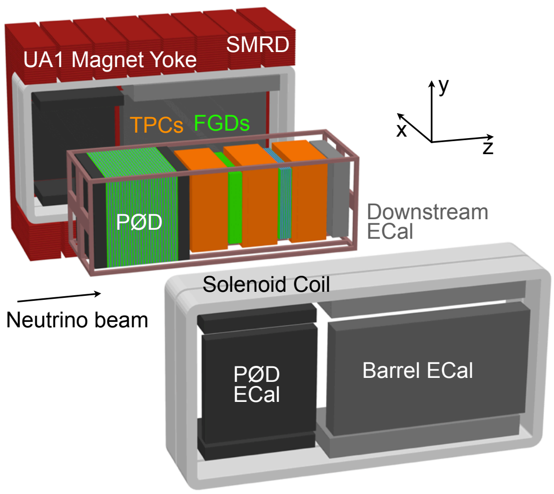

Figure 1: ND280: the T2K off-axis near detector at 280 m.

The ND280 constraint makes use of an inclusive charged current (CC) event sample which is classified according to three final state topologies: CC0π, CC1π^+ and CCOther. The CC0π subsample is predominantly composed of CC quasi-elastic (CCQE) events (i.e. the $\nu_l + n \rightarrow l^- + p$ signal channel at the far detector), the CC1π^+ sample is 40% resonant pion production ($\nu_l + p \rightarrow l^- + \pi^+ + p$) and CCOther, which is dominated by the deep inelastic scattering ($\nu_l + N \rightarrow l^- + N' + \pi^\pm + \pi^0 + ...$) component, covers all remaining toplogies. In each case the events require a reconstructed muon track in the fiducial volume of FGD1, which is identified by tagging the scattered lepton according to its energy loss in the TPCs. The efficiency (purity) of selecting CC0π, CC1π^+ and CCOther events are 50.1% (72.6%), 29.5% (49.4%) and 35.2% (73.8%) respectively. The inclusive CC selection, measured by ND280, is subsequently used to reweight the flux prediction at the far detector. The effect of applying the ND280 constraint on T2K systematic uncertainties is shown in Table 1. Contributions to the flux and cross section uncertainty that are correlated between near and far detectors are constrained by ND280. Systematics arising from differences in near and far detector target nuclei and hadronic interactions are not. In total there are 25 beam parameters, 21 cross section parameters and 210 ND280 systematic parameters in the fit. The far detector systematic is independent of the ND280 constraint. The ND280 constraint reweights 22 far detector flux parameters and 5 shared cross section parameters. After applying the ND280 constraint, the uncorrelated flux and cross section uncertainties remain the dominant contribution to the total T2K systematic.

Source	$\delta N_{\nu_\mu}/N_{\nu_\mu}$	$\delta N_{\nu_e}/N_{\nu_e}$
ND280 constrained flux + cross section	21.8%(2.7%)	26.0%(3.1%)
Uncorrelated flux + cross section	5.0%	4.7%
Hadronic interactions	3.0%	2.4%
Far detector systematic	4.0%	2.7%
Total	23.5%(7.7%)	26.8%(6.8%)

Table 1: Fractional error ($\delta N/N$) of the predicted number of ν_μ and ν_e events at the T2K far detector without (with) the near detector constraint.

4 Measuring the intrinsic ν_e component of the beam

There is an irreducible ν_e contamination of the JPARC ν_μ beam arising from muon and kaon decays. It is important to measure and constrain this effect using ND280 as it affects the predicted ν_e rate at the far detector. The CC inclusive ν_e selection, using particle identification in the TPCs and ECALs, is split into two different event classifications: CCQE-like and CCnonQE-like, with a constraint imposed using *in-situ* $e^\pm$ control samples. The T2K MC prediction is of a 1.2% ν_e component in the ν_μ beam [3]. The number of measured ν_e events $N_{\nu_e}^{\text{meas}}$ compared to the number predicted by MC $N_{\nu_e}^{\text{MC}}$ gives a ratio $N_{\nu_e}^{\text{meas}}/N_{\nu_e}^{\text{MC}} = 1.01 \pm 0.10$. Electron neutrinos coming from muon and kaon decay are also measured separately, resulting in ratios of $N_{\nu_e}^{\text{meas}}/N_{\nu_e}^{\text{MC}} = 0.68 \pm 0.30$ and $N_{\nu_e}^{\text{meas}}/N_{\nu_e}^{\text{MC}} = 1.10 \pm 0.14$, respectively.

5 Cross section measurements

T2K has performed the first measurement of CC inclusive ν_μ interactions on carbon at neutrino energies of ∼1 GeV [4]. The measurement is reported as a flux-averaged double-differential cross section, binned in muon momentum and angle. The data used were taken in 2010 and 2011, with a total of 10.8×10^{19} protons-on-target (POT). The analysis is performed on 4485 inclusive CC candidate events selected in FGD2. The flux-averaged total cross section is measured to be $\langle\sigma_{\text{CC}}\rangle_\Phi = (6.91 \pm 0.13(\text{stat}) \pm 0.84(\text{syst})) \times 10^{-39}\text{cm}^2/\text{nucleon}$ for a mean ν_μ energy of 0.85 GeV.

Additionally, ND280 has made the first differential cross-section measurements of CC inclusive ν_e interactions on carbon at neutrino energies of ∼1 GeV [5]. The measurement is reported as a function of electron momentum, electron scattering angle and four-momentum transfer of the interaction. The flux-averaged total cross section measured to be $\langle\sigma_{\text{CC}}\rangle_\Phi = (1.11 \pm 0.09(\text{stat}) \pm 0.18(\text{syst})) \times 10^{38}\text{cm}^2/\text{nucleon}$ for a mean ν_e energy of 1.3 GeV. A data sample with a total of 5.90×10^{20} POT was analysed. The differential and total cross section measurements agree with the predictions of the NEUT and GENIE MC event generators. The NEUT prediction is 1.23×10^{38} cm^2/nucleon and the GENIE prediction is 1.08×10^{38} cm^2/nucleon. The total ν_e charged-current cross section result is in agreement with data from the Gargamelle experiment. The total flux-averaged cross sections for ν_μ and ν_e on carbon, along with their respective NEUT and GENIE MC expectations are plotted in Figure 2.

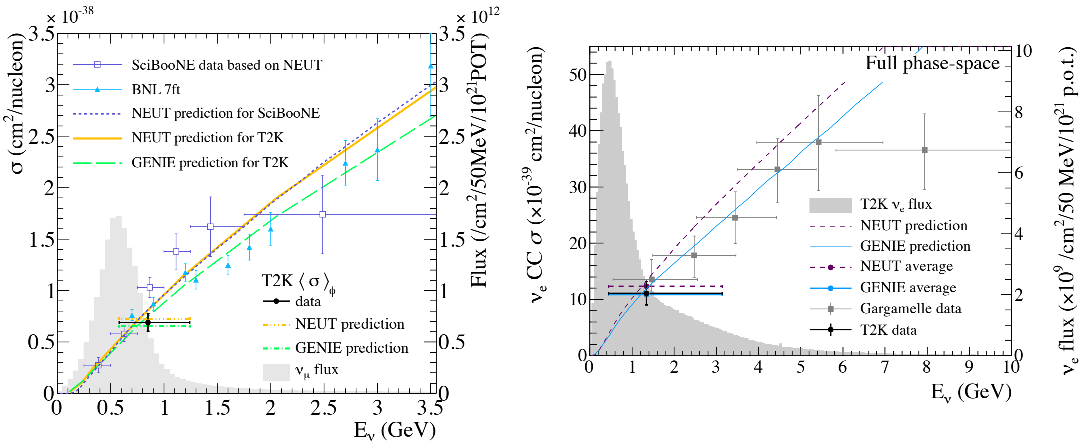

Figure 2: Total flux-averaged cross section for ν_μ *(left)* and ν_e *(right)* on carbon with MC expectations from NEUT and GENIE.

The on-axis interactive neutrino grid (INGRID), also located at the ND280 complex has measured the CC inclusive ν_μ cross section on iron and hydrocarbon [6] for a mean neutrino energy of 1.51 GeV. The flux-averaged total cross sections are $\langle\sigma_{\rm CC}\rangle_\Phi = (1.444{\pm}0.002({\rm stat})^{+0.189}_{-0.157}({\rm syst}))\times 10^{38}{\rm cm}^2/{\rm nucleon}$ and $\langle\sigma_{\rm CC}\rangle_\Phi = (1.379{\pm}0.009({\rm stat})^{+0.178}_{-0.147}({\rm syst}))\times10^{38}{\rm cm}^2/{\rm nucleon}$ respectively, with a ratio of $1.047 \pm 0.007({\rm stat}) \pm 0.035({\rm syst})$.

6 Conclusions and outlook

The T2K near detector complex is essential to constrain the flux and cross section parameters that are correlated between the near and far detectors. Additionally, it provides an accurate measurement of the intrinsic, irreducable ν_e contamination. As more data are acquired, a rich sample of neutrino-nucleon cross section measurements are becoming accessible. Such measurements not only enhance the precision of T2K oscillation results, but also provide important constraints for other experiments in the field.

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