The T2K Experiment

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Abstract. T2K is a long-baseline neutrino oscillation experiment built to make precision measurements of θ_{13}, θ_{23} and $\Delta m^2{}_{32}$. It achieves this by utilising an off-axis, predominantly ν_μ, neutrino beam from J-PARC to Super-Kamiokande, and a near detector complex which constrains the beam's direction, flux, composition and energy. To date T2K has published ν_μ-disappearance and ν_e-appearance results, the latter excluding $\theta_13 = 0$ at over 3σ and therefore constituting first evidence for ν_e-appearance in a ν_μ beam. In addition to oscillation physics, the on-axis (INGRID) and off-axis (ND280) near detectors provide the capability for a broad neutrino-nucleus interaction physics programme at neutrino energies below 1GeV.

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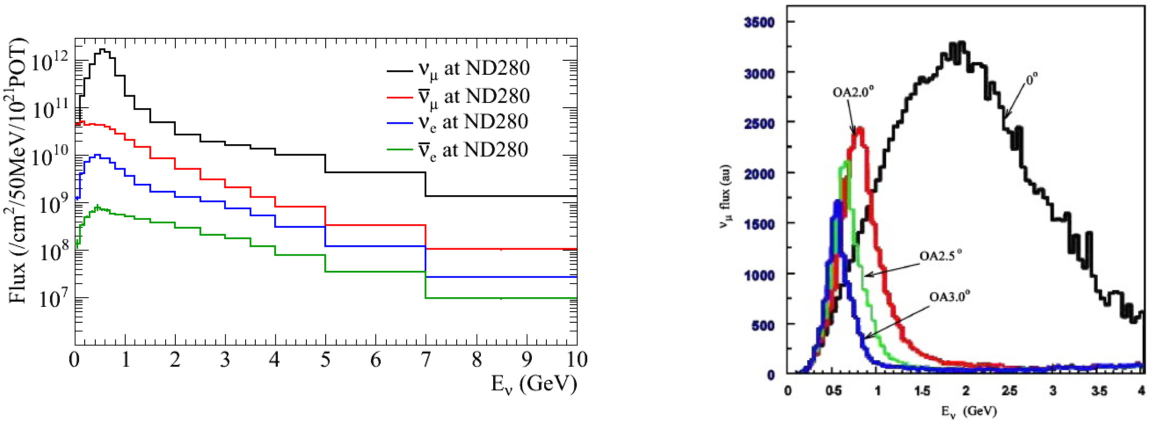
T2K OVERVIEW

The T2K experiment [1], based in Japan, is a long-baseline neutrino oscillation experiment built to make precision measurements of θ_{13}, θ_{23} and $\Delta m^2{}_{32}$.

The first stage of the experiment is a neutrino beam generated at the J-PARC proton accelerator facility. 30 GeV protons are collided with a graphite target and three magnetic horns focus the resulting positive pions and kaons down a 110m decay tunnel. These decay in flight to produce a beam of predominantly ν_μ, though some $\overline{\nu}_\mu$ ($\approx 6\%$), ν_e ($\approx 1\%$) and $\overline{\nu}_e$ ($< 1\%$) are also produced (Figure 1a)[2].



(a) The contribution of each neutrino flavour to the flux through ND280.

(b) The effect on the neutrino energy spectrum of moving off the beam axis.

FIGURE 1. The J-PARC Neutrino Beam

The beam then travels 295km through Japan to the famous Super-Kamiokande detector [3]. Located under 1000m of Mt. Ikenoyama, Super-Kamiokande is a 50kT cylindrical water-Cherenkov detctor the inner part of which is instrumented with ≈ 13000 photo-multiplier tubes (PMTs). These PMTs image the Cherenkov rings produced by charged particles eminating from neutrino interactions in the water, and have sufficient timing and directional resolution to identify neutrinos which have originated in the T2K beam (Figures 2a and 2b).

Additionally, Super-Kamiokande's particle identification separates the primary Cherenkov ring according to whether it showered or not which, for charged-current interactions, allows it to discriminate between ν_μ and ν_e events (Figure 2c). However, because showering electrons appear almost identical to showering photons, neutral-current π^0 production is an important background.

The T2K experiment is also noteworthy as the world's first off-axis neutrino beam: the J-PARC beam is directed such that Super-Kamiokande lies 2.5° off the beam's axis. There are two reasons for doing this, which are illustrated in Figure 1b. First, the neutrino flux is increased at the optimal energy for ν_e appearance at Super-Kamiokande ($\approx 0.6 GeV$). Second, a substantial fraction of the higher energy neutrinos are removed - neutrinos which do not contribute to the oscillation signal but can generate significant neutral-current backgrounds.

In addition to the beam and far-detector, T2K includes a near detector complex 280m downstream of the beam target. It contains two detectors: the on-axis "INGRID" was built primarily for measuring the beam normalisation and direction, while the off-axis "ND280" measures the beam's composition and energy spectrum in the direction of Super-Kamiokande as well as performing neutrino-nucleus interaction physics analyses.

INGRID

The INGRID detector consists of 16 identical 1.24m square modules. The modules are positioned in a cross, centred on the beam axis, formed of horizontal and vertical arms containing 7 modules each. Two additional modules are then placed in the left and right top-corners (Figure 3a). This placement allows INGRID to effectively measure the beam's profile and hence direction with sub-milliradian precision (Figure 4).

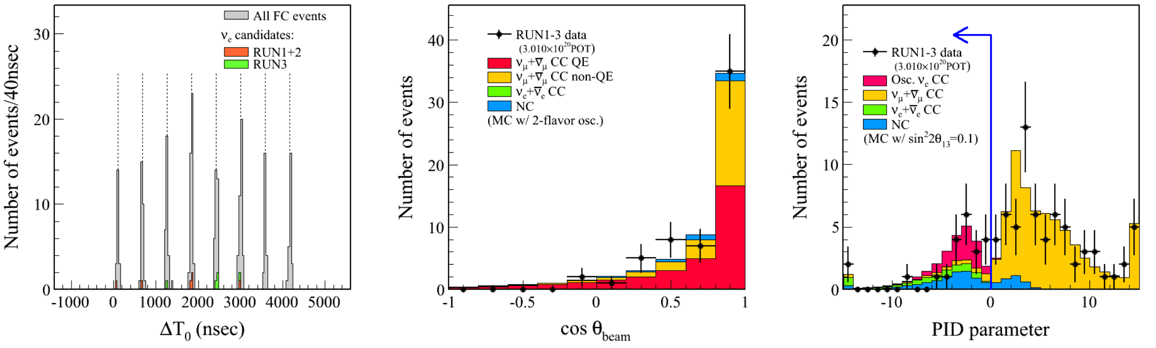
Each module is formed of $9 \times 65mm$-thick iron plates sandwiched between 11 x-y planes of plastic scintillator bars ($50mm \times 10mm$). Such coarse-grained readout and thick dead-regions means that INGRID's reconstruction is essentially limited to measuring the vertex position and primary-lepton angle for charged-current ν_μ interactions. There is however, an additional scintillator-only module placed between the two central modules which can resolve a recoil proton from ν_μ CCQE interactions.

In addition to its beam profiling INGRID is also capable of some interaction physics, for example a ν_μ Inclusive charged-current measurement. Such a measurement would be able to exploit the fact that modules at different off-axis angles each see a different energy spectrum from the same beam.

ND280

The off-axis near-detector, "ND280" (Figure 3b) was built to measure the beam composition and energy spectrum in the direction of Super-Kamiokande. It can also perform a full programme of neutrino interaction physics, both to reduce systematics in the oscillation measurement and as a valid physics goal in its own right.

One of the key interaction measurements for input to the oscillation analysis will be neutral-current π^0 production which, as discussed earlier, is an important background for ν_e-appearance at Super-Kamiokande. The upstream-most component of ND280, the Pi-Zero Detector (P0D) was built with this purpose in mind. The central part of the P0D

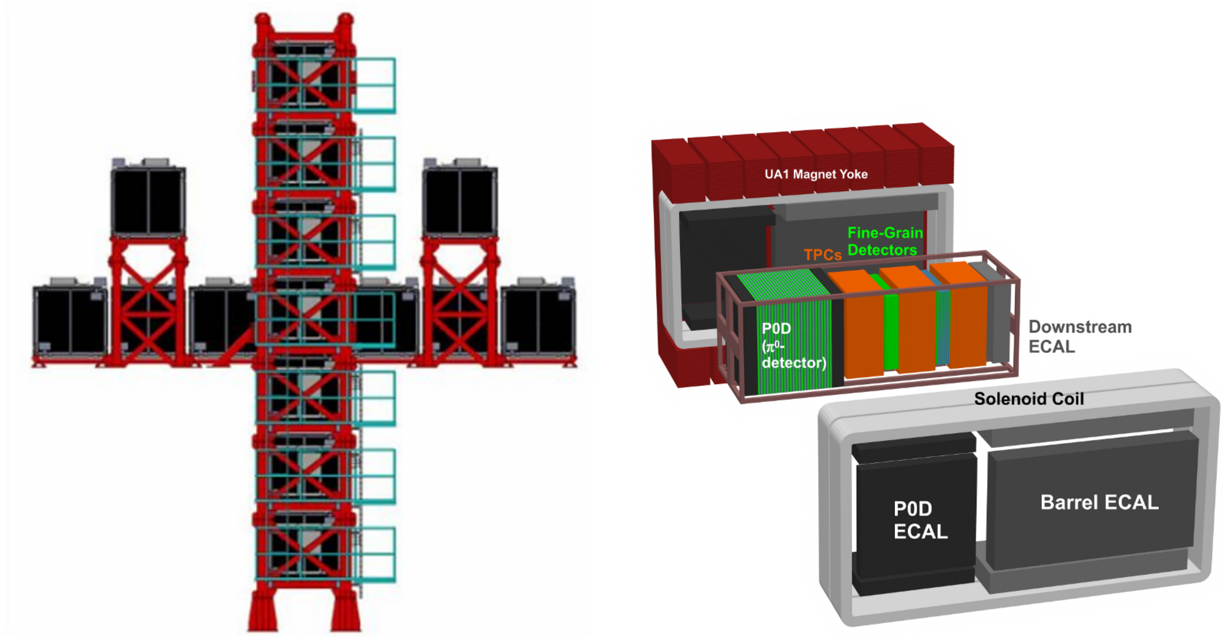


(a) The time from trigger of events from the ν_e selection. The 8-bunch structure of the T2K beam can be seen clearly.

(b) The reconstructed angle w.r.t the T2K beam of events from the ν_μ selection.

(c) The cut placed on Super-Kamiokande's Particle Id parameter as part of the ν_e selection.

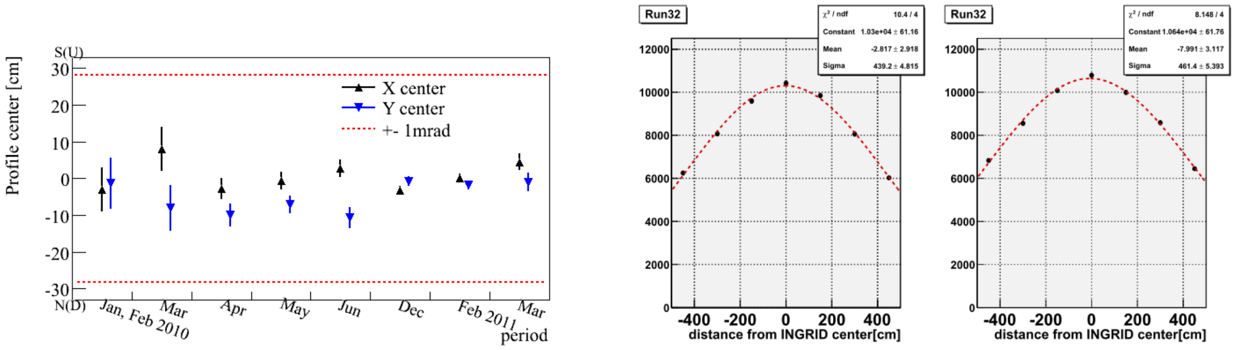
FIGURE 2. Data-MC comparissons for event selections at Super-Kamiokande.



(a) Layout of the INGRID modules looking downstream. The cross shape is centred on the beam's axis.

(b) Exploded view of the ND280 off-axis near detector. The beam enters from the left side of the diagram.

FIGURE 3. Near Detectors



(a) The stability of the beam direction as determined in INGRID, giving sub-milliradian precision.

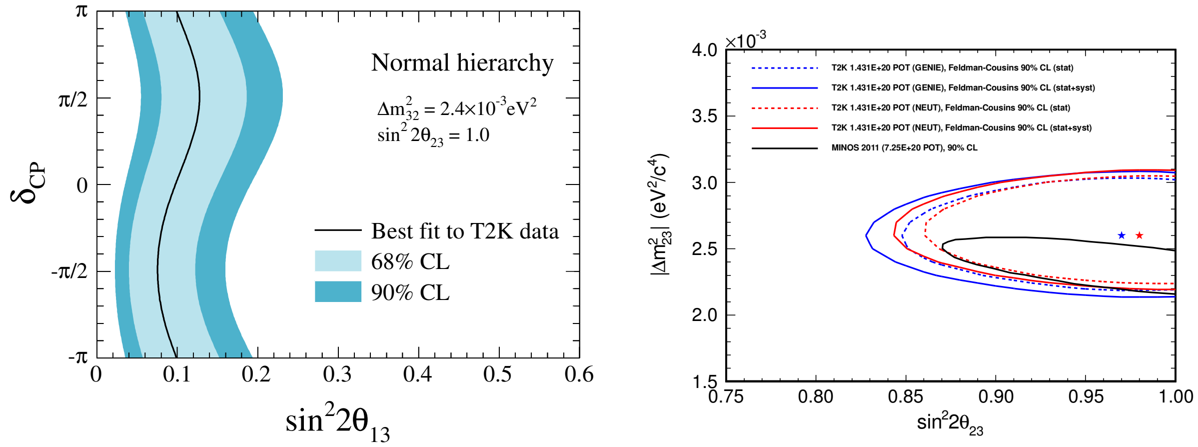
(b) The beam profile fitted to data from the horizontal and vertical INGRID modules.

FIGURE 4. Determining the beam direction using INGRID

alternates water targets (for maximum applicability to Super-Kamiokande) with xy-modules of triangular plastic scintillator bars and brass foils to encourage photon conversion. Up and downstream of the central target region are calorimeter regions where the plastic scintillator modules are instead interleaved with lead sheets to further improve photon containment. The water targets can be drained and re-filled at will to provide an additional control of the water contribution to the interaction rate in the P0D.

The second interaction targets are the two Fine Grained Detectors (FGDs) which are built with square plastic scintillator bars. The upstream FGD1 is built solely from 15 xy-modules of scintillator bars and is the primary target region for most of ND280's physics analyses. Meanwhile in FGD2, 8 of those modules are replaced with non-drainable water targets such that the two FGDs have almost identical target masses. The 10 mm-square scintillator bars provide sufficient resolution to track secondary final-state particles while also having enough mass to ensure a good event rate.

Downstream of each of the P0D and two FGDs is a gas Time Projection Chamber (TPC) for high-resolution tracking



(a) The best-fit value, 68% and 90% CL regions for $sin^2 2\theta_{13}$ shown as a function of the assumed value of δ_{CP} , for a normal mass hierarchy.

(b) Best-fit point and 90% CL contours for $sin^2 2\theta_{23}$ vs Δm^2_{23} compared to MINOS (black). Contours are shown for both the Genie (blue) and Neut (red) generators, with (solid) and without (dashed) systematic errors.

FIGURE 5. Oscillation results

of particles leaving the target detectors. It's sub-millimetre position resolution makes the TPC essential to analysis requiring charge and momentum determination from curvature, and particle identification from energy loss.

Together, the P0D, FGDs and TPCs are surrounded on all but the upstream-face by electromagnetic-calorimeters (ECals). The FGDs and TPCs are surrounded by the "Tracker ECals" which each alternate over 30 1.75 mm-thick lead sheets with layers of 40 mm × 10 mm plastic scintillator bars with 1.75 mm-thick lead sheets. These provide containment of escaping particles, additional particle identification and conversion of photons. The ECals surrounding the P0D are much smaller, containing only 6 scintillator layers with 4 mm-thick lead sheets, since they need only veto incoming backgrounds and detect photons escaping at high angle from the P0D.

All of these subsystems are then encased within the 0.2 T magnet, formerly used by the NOMAD and UA1 experiments. Gaps between the iron plates of the magnet yoke are instrumented with the Side Muon Ranging Detector (SMRD) - slabs of plastic scintillator which provide the detector's cosmic trigger, but can also contribute to the reconstruction of escaping muons.

This combination of subdetector systems provides an ideal environment for a broad range of neutrino interaction studies. The spatial resolution and particle identification capabilities of the FGDs and TPCs allow studies of multiple final-state topologies. In addition the ability to conduct studies on the multiple target materials present in the two near detectors (steel, lead, brass, carbon and water) will be a significant asset in helping to resolve the nuclear effects involved in neutrino-nucleus interactions.

PHYSICS RESULTS AND POTENTIAL

T2K's ν_e-appearance result, presented at ICHEP 2012 [4], corresponded to a beam exposure of 3.01×10^{20} protons-on-target. The analysis selected 11 candidate ν_e events it total, where if $\theta_{13} = 0$ only 3.2 events would have been expected. This lead the analysis to exclude $\theta_{13} = 0$ at 3.2σ, constituting the world's first evidence of ν_e appearance in a ν_μ beam (see Figure 5a).

In the most recent ν_μ-disappearance result [5] 31 candidate ν_μ events were selected, where 103 would be expected in the case of no oscillations. The fitted result for $sin^2 2\theta_{23}$ vs Δm^2_{23} is compatible though not yet competitive with MINOS as a result of only being completed on the smaller exposure of 1.4×10^{20} protons-on-target (an updated result should be expected soon). Figure 5b shows the resulting 90% CL contours for both of the neutrino generators used in T2K (GENIE and NEUT) indicating that neutrino interactions will become increasingly important in the near future.

In addition to oscillation results the ND280 near detector is beginning to produce analyses from its neutrino interactions programme. Elsewhere in these proceedings are reported the first flux-averaged ν_μ inclusive CC cross section [6], and ongoing analyses for ν_μ CCQE, ν_μ CC-1π^+ and NC-π^0 production.

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