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New results from the T2K experiment

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The T2K (Tokai to Kamioka) experiment is a long baseline neutrino oscillation experiment designed to probe the θ_{13} neutrino mixing parameter by looking for the appearance of ν_e in an almost pure ν_μ beam. The concurrent measurement of ν_μ disappearance allows refined measurements of the atmospheric Δm^2 and of the θ_{23} mixing parameters. A neutrino beam is produced at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan, and aimed at 2.5° off the direction of the Super-Kamiokande (SK) detector, 295 km away. The resulting narrow energy band neutrino beam at the Super-K location, peaked at about 600 MeV, is optimized to maximize the probability of oscillation at the atmospheric Δm^2 scale, minimizing at the same time the background for ν_e searches. The neutrino beam is monitored by an on-axis non-magnetic detector, INGRID, and an off-axis magnetic near detector, ND280, both located at J-PARC at about 280 m from the target. In addition, the primary proton beam and the muons from the secondary pion decays in the neutrino beam-line are monitored on a spill by spill basis to provide further constraints on the determination of the neutrino beam. T2K has successfully operated since January 2010, and it has been presently paused due to the recent earthquake in Japan. Results on the search for ν_e appearance and measurements of ν_μ disappearance have been presented in this talk.

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1. Introduction

The T2K experiment is a long baseline neutrino oscillation experiment. A ν_μ beam with a peak energy of 600 MeV/c is produced using a high intensity proton accelerator complex at JPARC (Japan). Neutrinos are observed at a Near Detector complex (ND280) before the oscillation and at SuperKamiokande (SK), a 50 kton water Cherenkov detector located in the Kamioka mine, at a distance of 295 km from JPARC.
The purposes of the experiment are to measure neutrino oscillation probabilities that in the three generation framework are written as:

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(1.27\Delta m^2_{23} L/E) \tag{1.1}$$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{23} L/E). \tag{1.2}$$

The main physics motivations of the experiment are:

- Discovery of $\nu_\mu \to \nu_e$ oscillations measuring the only missing angle θ_{13} in the PMNS (Pontecorvo-Maki-Nakagawa-Sakata[1]) matrix through Eq. 1.1.
- Precision measurement of oscillation parameters in ν_μ disappearance (Eq. 1.2).

To achieve these goals, T2K will accumulate 8×10^{21} $p.o.t.$ (Protons On Target) which corresponds to 5 years of running with the design beam power of 0.75 MW.
A key element of the T2K design is that the neutrino beam is directed so that the beam axis misses SuperKamiokande by 2.5°. The reason for the off-axis beam is related to the kinematics of the pion decay: pions in a wide momentum range contribute to a narrower energy spread for neutrinos. This results in a considerable improvement in the quality of the beam for the measurement of oscillation parameters as it is centered on the expected oscillation maximum.

The first results, for both, ν_e apperance and ν_μ disappearance, based on 1.43×10^{20} $p.o.t.$ (2% of the T2K physics goal) collected during the first two physics run (from January to June 2010 and from November 2010 to March 2011) are presented here.

2. Experimental setup

The T2K experimental setup is shown in Fig. 1 and fully described in [2]. To produce the T2K neutrino beam, protons are extracted from the JPARC Main Ring in eight bunches (six during first run) every 3 s. The protons are then transported to a graphite target where the collisions between the protons and the target produce hadrons. The hadrons, focused and charge selected by three magnetic horns, enter the decay volume where they decay mainly into muons and muon neutrinos. The remaining undecayed pions and other hadrons, as well as the muons, are stopped by a beam dump, installed 100 m downstream of the target, followed by a muon monitor (MUMON) that ensures the stability of the beam by measuring the high energy muons crossing the beam dump.

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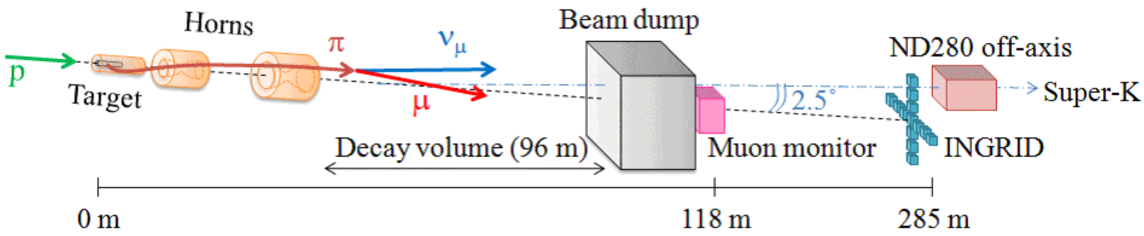

Figure 1: Schematic view of the T2K neutrino beamline and of the near detectors

Neutrinos are then detected in a near detector complex located about 280 m downstream of the target. It comprises an on-axis detector (INGRID) and an off-axis detector (ND280). INGRID is composed of 14 modules (seven horizontal and seven vertical spanning different angles) of alternating iron and plastic scintillator planes. Its purpose is to count the number of neutrino charged current interactions in each module to reconstruct the profile and the direction of the beam.
The Off-axis ND280 consists of several detectors installed in the ex-UA1 magnet, operated at 0.2 T: a π^0 detector (P0D) to measure interactions with π^0 production, an electromagnetic calorimeter (ECAL) to measure the electromagnetic activity and a Side Muon Range Detector (SMRD) embedded in the magnet yokes. Finally a Tracker system, composed of two Fine Grained Detectors (FGD) and 3 Time Projection Chambers (TPC) [3] measure ν_μ and ν_e interaction rates by reconstructing the lepton momentum from the curvature and separating electrons from muons using dE/dx.
As far detector, T2K uses the SuperKamiokande detector[4], a 22.5-kt fiducial mass ring-imaging water Cherenkov detector located at a depth of 2700 meters water equivalent in the Kamioka mine. The detector is optically separated into two concentric cylindrical regions instrumented with Hamamatsu PMTs. SK has good capability to distinguish muons from electrons by analyzing the sharpness of a Cherenkov ring. A muon makes a sharp edge ring and an electron makes a fuzzy one due to electromagnetic showers. The electron/muon misidentification probability, estimated using atmospheric neutrinos, is about 1% for the T2K neutrino energy.

3. T2K Analysis

In SK, ν_e appearance and ν_μ disappearance result in an excess of single ring e-like events and in a deficit of single ring μ-like events, respectively. The event selection in SK was established before the beginning of the data taking and aims to select an enriched sample of charged current quasi elastic (CCQE) ν_e or ν_μ interactions. The prediction of the number of expected events in SK is based on the simulation of the neutrino flux and of the interaction rates and on the observation of neutrino interactions at the Near Detector.

Prediction of neutrino flux and interaction rates The neutrino flux prediction is based on the simulation of the proton interactions with the target and on the propagation of the secondary particles through the target, the horns and the decay volume. The simulation is based on models tuned to experimental data. In particular the most significant constraint comes from the NA61 experiment

[5] that measure pion production in most of the relevant T2K phase space. Neutrinos coming from kaon decay as well as pions produced in phase spaces not covered by NA61 are simulated using FLUKA[6] and constrained with other external data. The predicted flux at SK is shown in Fig.2. The uncertainty on the flux prediction is dominated by the mesons production cross-sections and it is reduced thanks to the normalization with ND280 data.
The stability of the proton and of the neutrino beams is ensured by the measurements of the proton beam monitors, MUMON, and INGRID; all are well within the T2K tolerances.
The interactions of the neutrinos in the detectors are simulated with the NEUT Monte Carlo generator[7]. The uncertainties of the interaction models are determined by comparisons with models, variation of the models parameters and comparison with external data. The dominant sources of the uncertainty are the final state interactions of the pions.

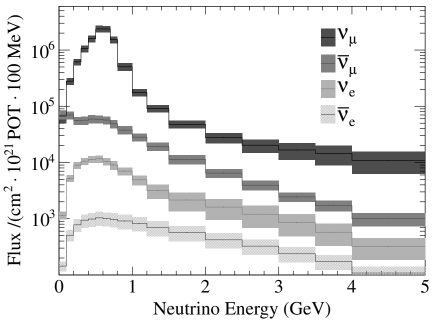

Figure 2: Expected neutrino flux at SK.

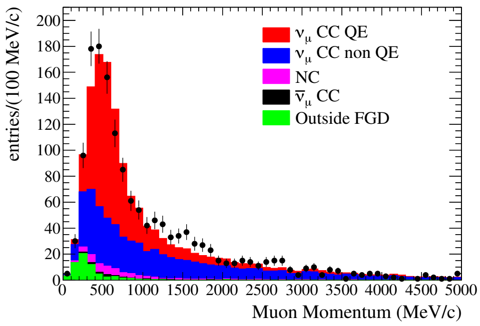

Figure 3: Reconstructed muon momentum for events selected in the ND280 tracker.

Normalization with ND280 measurements The ND280 input to this first T2K oscillation analysis is based on the selection of inclusive CC ν_μ interactions in the Tracker. The analysis is based on Run1 only data (2.9×10^{19} $p.o.t.$) and it is done by selecting tracks starting in the FGD fiducial volume and entering the downstream TPC where the momentum and the charge of the tracks are reconstructed. The lepton is then identified as the most energetic negative track in the event and the particle identification is done using the dE/dx in the TPC. In this way either muons or electrons can be selected.
For the CC ν_μ analysis, the momentum distribution of the selected muons is shown in Fig.3 and shows good agreement between data and MC. The measured data/MC ratio is

$$R_{ND}^{\mu,Data}/R_{ND}^{\mu,MC} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det.syst.}) \pm 0.038(\text{phys.syst.}) \tag{3.1}$$

Eq 3.1 is used to normalize the prediction of the events at SK ($N_{exp}^{SK} = N_{MC}^{SK} \times R_{ND}^{\mu,Data}/R_{ND}^{\mu,MC}$).
Another ND280 analysis has been done to confirm the ν_e beam component in the beam by selecting electrons instead of muons in the TPC. This component is the main background to the ν_e appearance search in T2K. The measured ν_e/ν_μ ratio at ND280, in agreement with MC expectation, is

$$N(\nu_e)/N(\nu_\mu) = (1.0 \pm 0.7(stat) \pm 0.3(syst))\%. \tag{3.2}$$

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SuperKamiokande event selection The SK selection criteria were fixed before the data were collected, aiming to select a CCQE enhanced sample of interactions of oscillated electron neutrinos. We select a sample of fully-contained fiducial volume (FCFV) events by requiring: no activity in the outer detector or 100 μs before the beam trigger time; $>$ 30 MeV energy deposited in the inner detector; reconstructed vertex in the fiducial region; one reconstructed ring. The requirement of a single ring is fulfilled by 41 events, 8 of which are e-like and 33 μ-like.

4. ν_e appearance analysis

In the ν_e appearance analysis[8], to further reject the background, we also require: visible energy > 100 MeV; no delayed activity, to reject the electrons from muon decays; after the forced reconstruction of 2 rings, the invariant mass must be < 105 MeV; reconstructed neutrino energy (with the assumption of quasi-elastic kinematics) < 1250 MeV.
Among the 8 single ring e-like events, 2 are rejected by these further cuts. The number of expected events if θ_{13} is zero is 1.5 ± 0.3 mainly coming from intrinsic ν_e beam component (0.8) and from neutrino interactions producing π^0 with the second ring not identified (0.6). The reconstructed neutrino energy for these events is shown in Fig. 4.
The 6 remaining events tend to have the reconstructed vertex near the edge of the fiducial volume, giving a Kolmogorov-Smirnov probability for such square radius distribution of 3%. Further analyses of the out of fiducial volume events and of the SK reconstruction efficiency using atmospheric data do not show any reason to reject these events as background. The probability of observing 6 events with an expectation of 1.5 is 0.7% which corresponds to a 2.5σ significance for θ_{13} different from 0. The confidence intervals, built with the Feldman-Cousins unified method, are shown in Fig. 5 for different values of δ_{CP}: for $\delta_{CP} = 0$ and normal (inverted) hierarchy we obtain $0.03(0.04) < sin^2(2\theta_{13}) < 0.28(0.34)$ at 90% C.L.

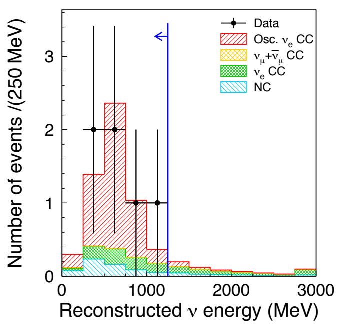

Figure 4: Reconstructed energy of ν_e candidates.

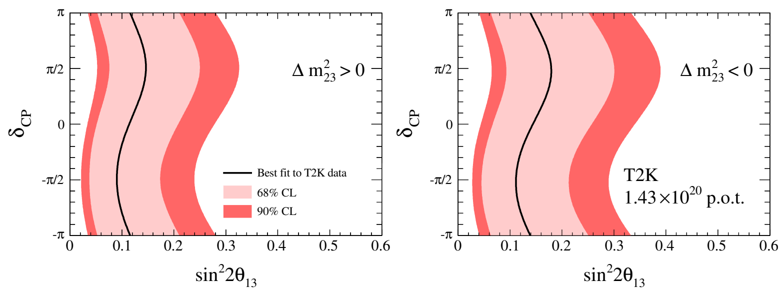

Figure 5: The confidence intervals for $\sin^2(2\theta_{13})$ for normal (left) and inverted (right) mass hierarchy.

5. ν_μ disappearance analysis

For the ν_μ disappearance analysis we require single ring μ-like events with less than 2 decay electrons and a reconstructed muon momentum larger than 200 MeV/c. Thirty one events passed

these criteria while we expect $103.6^{+13.7}_{-13.1}$ events without oscillation. We exclude the no oscillation hypothesis to 4.5σ. The reconstructed energy of the 31 events is shown in Fig. 6 with the superimposed curves showing the expected spectrum for no oscillation and the best fit oscillation values.
To extract the oscillation parameters we perform two analyses, one using a maximum likelihood method incorporating the correlated systematics errors (Analysis A) and one using a binned likelihood-ratio method without fitting the systematics (Analysis B). In Fig. 7 we show the 90% C.L. for our two analyses: the results are fully comparable and in good agreement with SK and MINOS results. At 90% C.L. we measure $sin^2(2\theta_{23}) > 0.84$ and $2.1 \times 10^{-3} < \Delta m^2_{23}(eV^2) < 3.1 \times 10^{-3}$.

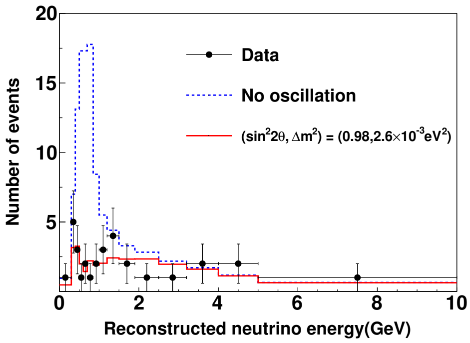

Figure 6: Reconstructed energy of ν_μ candidates.

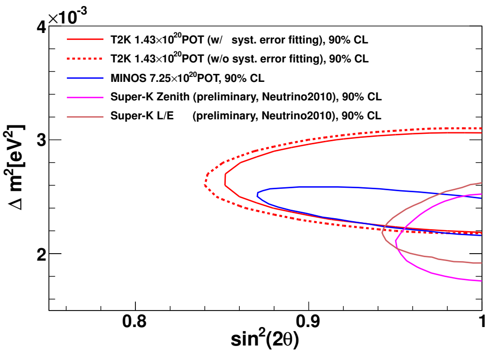

Figure 7: The confidence intervals for $\sin^2(2\theta_{23})$ and Δm^2_{23}

6. Conclusions

We presented T2K oscillation analyses based on 1.43×10^{20} $p.o.t.$ (2% of the T2K physics goal). With this data set we observe 6 ν_e candidates corresponding to a 2.5σ indication of θ_{13} different from zero. We also perform the first ν_μ disappearance analysis in an off-axis neutrino beam showing the potentiality of this technique once more statistics are collected.
The experiment is currently recovering from the March 2011 earthquake in Japan. We plan to restart physics data taking in January 2012. The aim is to accumulate 10^{21} $p.o.t.$ by summer 2013.

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