

T2K results and future plans

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Abstract. We present the $\nu_\mu \rightarrow \nu_e$ appearance and the ν_μ disappearance results, using a total of 1.43×10^{20} protons on target collected with the T2K experiment. T2K is long baseline neutrino experiment in Japan with detectors located at J-PARC, Tokai, and at Kamioka in the Gifu Prefecture, situated 295 km away from J-PARC. The muon neutrino beam is produced and measured at the near detectors at J-PARC whilst the neutrino rates after oscillation are measured with the Super-Kamiokande detector, at Kamioka. A total of six events pass all the selection criteria for $\nu_\mu \rightarrow \nu_e$ oscillations at the far detector Super-Kamiokande, leading to $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ for $\delta_{CP} = 0$ and normal (inverted) hierarchy at 90% C.L. The ν_μ disappearance analysis excludes no oscillations at 4.3σ . At 90% C.L., the best fit values are $\sin^2 2\theta_{23} > 0.84$ and $2.1 \times 10^{-3} < \Delta m_{23}^2 (\text{eV}^2) < 3.1 \times 10^{-3}$. Finally, we present an overview of the T2K plans from 2011 onwards.

1. Introduction

The main goal of the T2K (Tokai-to-Kamioka) long baseline neutrino experiment [1] is to measure the appearance of electron neutrinos from a beam of muon neutrinos, thereby measuring θ_{13} , the last unknown mixing angle in the lepton sector. The results on the muon into electron neutrino appearance [2] and the muon neutrino disappearance presented in these proceedings are based on the data collected in the the first two periods of data taking from January 2010 to March 2011. This is followed by an overview of the future goals for data collections at T2K.

2. The T2K experiment

The T2K experiment's main components are the beam source, the near detector complex and the far detector. Details of the T2K experimental setup are described in Ref. [1]. Here we provide a brief review of the main components. The T2K muon neutrino beam is produced at J-PARC² and detected with Super-Kamiokande, the far detector, located in Kamioka in the Gifu Prefecture 295 km away from J-PARC. T2K adopts the off-axis method [3] to generate a narrow-band neutrino beam using the new proton synchrotron at J-PARC. The neutrino beam is thus directed at an angle of 2.5° with respect to the baseline connecting the proton target and Super-Kamiokande, corresponding to a peak energy of about 0.6 GeV, which maximizes the effect of the neutrino oscillation at 295 km and minimizes the background to electron-neutrino appearance detection. The angle can be reduced down to 2.0° , allowing variation of the peak neutrino energy, if necessary.

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² Japan Proton Accelerator Research Complex jointly constructed and operated by KEK and JAEA.

The near detector site at about 280 m from the production target houses on-axis and off-axis detectors with respect to the direction of the neutrino beam. The on-axis detector INGRID (Interactive Neutrino GRID) [4] is composed of an array of iron/scintillator sandwiches and its main goal is to measure the neutrino beam direction and profile. INGRID can measure the beam centre with a precision better than 28 cm corresponding to 1 mrad or a shift of around 2% in the peak of the neutrino energy spectrum. The off-axis detector (ND280), see Ref. [5] of this conference proceedings, is a multipurpose magnetised detector which measures the muon neutrino flux and energy spectrum and intrinsic electron neutrino contamination in the direction of Super-Kamiokande. It also measures the rates for exclusive neutrino reactions, relevant to the disappearance and appearance searches at Super-Kamiokande. These measurements are essential in order to characterize signals and backgrounds that are observed in the Super-Kamiokande far-detector. The off-axis detector measures both charged and neutral particles. It consists of a water-scintillator detector optimized to identify the π^0 's (the PØD); a tracker system consisting of time projection chambers (TPCs) [6] and fine grained detectors (FGDs) optimized to study charged current interactions; and finally an electromagnetic calorimeter (ECal) that surrounds the PØD and the tracker. The whole off-axis detector is placed in a 0.2 T magnetic field provided by the recycled UA1 magnet, which also serves as part of a side muon range detector (SMRD).

The far detector, Super-Kamiokande, is located in the Mozumi mine, near the village of Higashi-Mozumi, Gifu, Japan. A detailed description of the detector can be found elsewhere [7]. Here we provide a summary. The detector cavity lies under the peak of Mt. Ikenoyama, with 1000 m of rock equivalent to 2700 meters-water-equivalent (m.w.e.) which reduces the cosmic ray background by around five orders of magnitude compared to at the Earth's surface.

Super-Kamiokande is a water Cherenkov detector with a fiducial volume (FV) of 22.5 kton within its cylindrical inner detector (ID). Surrounding the ID is the 2 m-wide outer detector (OD). The inner detector (ID) is a cylindrical space 33.8 m in diameter and 36.2 m in height which currently houses along its inner walls 11,129 inward-facing 50 cm diameter PMTs. The OD contains along its inner walls 1,885 outward-facing 20 cm diameter PMTs. The ID and OD boundaries are defined by a cylindrical structure about 50 cm wide. The front-end readout electronics allows for a zero-deadtime software trigger. Spill timing information, synchronized by the Global Positioning System (GPS) with < 150 ns precision, is transferred online to Super-Kamiokande and triggers the recording of photomultiplier hits within ± 500 μ s of the expected arrival time of the neutrinos. Super-Kamiokande has been running since 1996 and has had four distinct running periods. The latest period, SK-IV, is running stably and features upgraded PMT readout electronics.

Construction of the neutrino beamline started in April 2004. The complete chain of accelerator and neutrino beamline was successfully commissioned during 2009, and T2K began accumulating neutrino beam data for physics analysis in January 2010.

Construction of the majority of the ND280 detectors was completed in 2009 with the full installation of INGRID, the central ND280 off-axis sub-detectors (PØD, FGD, TPC and downstream ECal) and the SMRD. The ND280 detectors began stable operation in February 2010. The rest of the ND280 detector (the ECals) was completed in the fall of 2010.

The results presented in these proceedings are based on the first two physics runs: run 1 (Jan-Jun 2010) and run 2 (Nov 2010-Mar 2011) whereas the proton beam power was continually increased and reached 145 kW with 9×10^{13} protons per pulse by March 2011. A total of 1.43×10^{20} protons on target (p.o.t.) were collected for analysis, corresponding to about 2% of the final approved goal for T2K.

3. Indication of electron neutrino appearance

The $\nu_\mu \rightarrow \nu_e$ analysis at Super-Kamiokande requests only a single electron-like (e -like) ring, thus selecting a sample enhanced in ν_e charged-current quasi-elastic interactions (CCQE). The

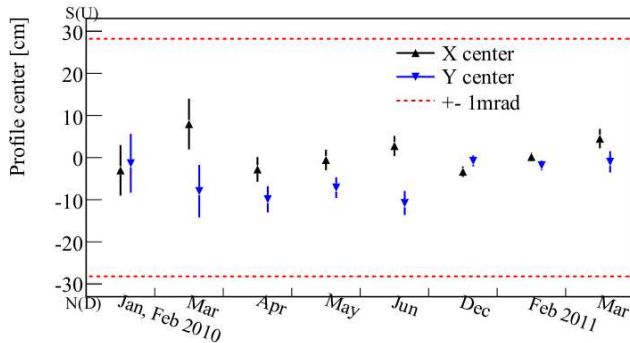


Figure 1. Beam centering stability in horizontal (x, South–North) and vertical (y, Down–Up) directions as a function of time, as measured by INGRID. Errors shown are only statistical. The dashed lines correspond to a change of beam direction by ± 1 mrad.

selection criteria for this analysis were fixed from Monte Carlo (MC) studies before analysing the data and were optimized for the initial running conditions.

The main backgrounds to the $\nu_\mu \rightarrow \nu_e$ oscillated events are due to the intrinsic ν_e contamination in the beam and to the neutral current (NC) interactions with a misidentified π^0 .

The observed number of events is compared to expectations based on neutrino flux and cross-section predictions for signal and all sources of backgrounds, which are corrected using an inclusive ν_μ charged-current (CC) measurement in the off-axis near detector.

We compute the neutrino beam fluxes starting from models and tune them to experimental data. A detailed description can be found in Ref. [8] of this conference proceedings. The estimated uncertainties of the intrinsic ν_μ and ν_e fluxes below 1 GeV are around 14%. Above 1 GeV, the intrinsic ν_e flux error is dominated by the uncertainty on the kaon production rate with resulting errors of 20–50%.

The neutrino beam profile and its absolute rate ($1.5 \text{ events}/10^{14} \text{ p.o.t.}$) as measured by INGRID were stable and consistent with expectations. The beam profile center (Fig. 1) indicates that beam steering was better than ± 1 mrad. The correlated systematic error is $\pm 0.33(0.37)$ mrad for the horizontal(vertical) direction. The error on the Super-Kamiokande position relative to the beamline elements was obtained from a dedicated GPS survey and is negligible.

The NEUT MC event generator [9], which has been tuned with recent neutrino interaction data in an energy region compatible with T2K, is used to simulate neutrino interactions in the near and far detectors. The GENIE [10] generator provides a separate cross-check of the assumed cross-sections and uncertainties, and yields consistent results.

A list of reactions and their uncertainties relative to the CCQE total cross-section is shown in Table 1. An energy-dependent error on CCQE is assigned to account for the uncertainty in the low energy cross-section, especially for the different target materials between the near and far detectors.

An inclusive ν_μ CC measurement in the off-axis near detector is used to constrain the expected event rate at the far detector. The results are described in Ref. [11] of this conference proceedings. The measured data/MC ratio is

$$R_{ND}^{\mu,Data} / R_{ND}^{\mu,MC} = 1.036 \pm 0.028(\text{stat.})_{-0.037}^{+0.044}(\text{det.syst.}) \pm 0.038(\text{phys.syst.}), \quad (1)$$

where $R_{ND}^{\mu,Data}$ and $R_{ND}^{\mu,MC}$ are the p.o.t. normalized rates of ν_μ CC interactions in data and MC. The detector systematic errors mainly come from tracking and particle identification efficiencies, and physics uncertainties are related to the interaction modeling. Uncertainties that effectively cancel between near and far detectors were omitted.

At the far detector, we extract a fully-contained fiducial volume (FCFV) sample by requiring no event activity in either the OD or in the 100 μs before the event trigger time, at least 30

Table 1. Summary of systematic uncertainties for the relative rate of different charged-current (CC) and neutral-current (NC) reactions to the rate for CCQE.

Process	Systematic error
CCQE	energy-dependent (7% at 500 MeV)
CC 1π	30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV)
CC coherent π^\pm	100%
CC other	30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV)
NC $1\pi^0$	30% ($E_\nu < 1$ GeV) – 20% ($E_\nu > 1$ GeV)
NC coherent π	30%
NC other π	30%
FSI	energy-dependent (10% at 500 MeV)

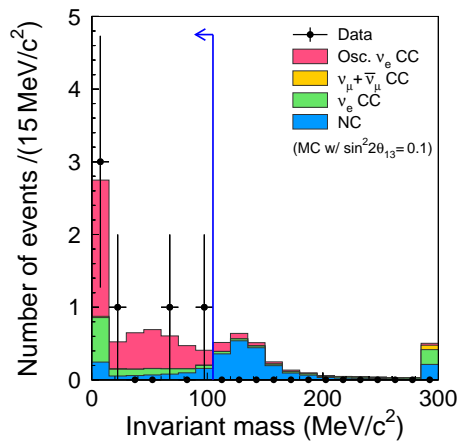


Figure 2. Invariant mass distribution reconstructing each event as two rings. The data are shown using points with statistical error bars and the MC predictions are the histograms. The last bin shows overflow entries and the vertical line the applied cut at 105 MeV.

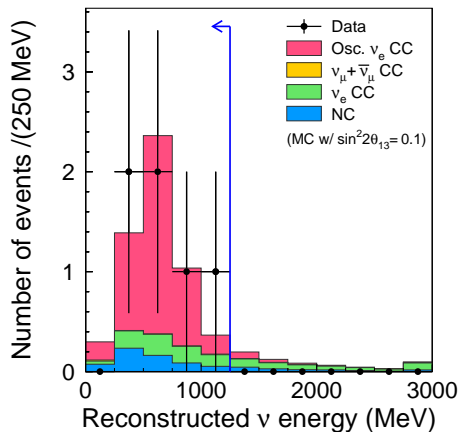


Figure 3. Same as Fig. 2 for the reconstructed neutrino energy spectrum of the events which pass all ν_e appearance signal selection criteria with the exception of the energy cut. The vertical line shows the applied cut at 1250 MeV.

MeV electron-equivalent energy deposited in the ID (defined as visible energy E_{vis}), and the reconstructed vertex in the fiducial region. The data have 88 such FCFV events that are within the timing range from -2 to $10 \mu\text{s}$ around the beam trigger time. The accidental contamination from non-beam related events is determined from the sidebands to be 0.003 events. A Kolmogorov-Smirnov (KS) test of the observed number of FCFV events as a function of accumulated p.o.t. is compatible with the normalized event rate being constant (p -value = 0.32). Forty-one events are reconstructed with a single ring, and eight of those are e -like. Six of these events have $E_{vis} > 100$ MeV and no delayed-electron signal. To suppress misidentified π^0 mesons, the reconstruction of two rings is forced by comparison of the observed and expected light patterns calculated under the assumption of two showers, and a cut on the two-ring invariant mass $M_{inv} < 105$ MeV/ c^2 is imposed. No events are rejected (Fig. 2). Finally, the neutrino energy E_ν^{rec} is computed using the reconstructed momentum and direction of the ring, by assuming quasi-elastic kinematics and neglecting Fermi motion. No events are rejected

Table 2. Event reduction for the ν_e appearance search at the Super-Kamiokande. The numbers of data and ν_μ CC, intrinsic ν_e CC, NC, and ν_e CC signal MC expected events are presented after each selection criterion. All MC CC samples include three-flavor oscillations for $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$.

	Data	ν_μ CC	ν_e CC	NC	$\nu_\mu \rightarrow \nu_e$ CC
(0) interaction in FV	n/a	67.2	3.1	71.0	6.2
(1) fully-contained FV	88	52.4	2.9	18.3	6.0
(2) single ring	41	30.8	1.8	5.7	5.2
(3) e -like	8	1.0	1.8	3.7	5.2
(4) $E_{vis} > 100$ MeV	7	0.7	1.8	3.2	5.1
(5) no delayed electron	6	0.1	1.5	2.8	4.6
(6) non- π^0 -like	6	0.04	1.1	0.8	4.2
(7) $E_\nu^{rec} < 1250$ MeV	6	0.03	0.7	0.6	4.1

by requiring $E_\nu^{rec} < 1250$ MeV, whose purpose was to suppress events from the intrinsic ν_e component arising primarily from kaon decays (Fig. 3). The data and MC reductions after each selection criterion are shown in Table 2. The ν_e appearance signal efficiency is estimated from MC to be 66% while rejection for $\nu_\mu + \bar{\nu}_\mu$ CC, intrinsic ν_e CC, and NC are $> 99\%$, 77% , and 99% , respectively. Of the surviving background NC interactions constitute 46%, of which 74% are due to π^0 mesons and 6% originate from single gamma production.

Examination of the six data events shows properties consistent with ν_e CC interactions. The distribution of the cosine of the opening angle between the ring and the incoming beam direction is consistent with CCQE events. The event vertices in cylindrical coordinates (R, ϕ, z) show that these events are clustered at large R , near the edge of the FV in the upstream beam direction. A KS test on the R^2 distribution of our final events yields a p -value of 0.03. If this was related to contamination from penetrating particles produced in upstream neutrino interactions, then the ID region outside the FV should show evidence for such events, however this is not observed. In addition, an analysis of the neutrino interactions occurring in the OD volume is consistent with expectations.

To compute the expected number of events at the far detector N_{SK}^{exp} , we use the near detector ν_μ CC interaction rate measurement as normalization, and the ratio of expected events in the near and far detectors, where common systematic errors cancel. Using Eq. 1, this can be expressed as:

$$N_{SK}^{exp} = \left(R_{ND}^{\mu, Data} / R_{ND}^{\mu, MC} \right) \cdot N_{SK}^{MC}, \quad (2)$$

where N_{SK}^{MC} is the MC number of events expected in the far detector. Due to the correlation of systematic errors in the near and far detector samples, Eq. 2 reduces the uncertainty on the expected number of events. Event rates are computed incorporating three-flavor oscillation probabilities and matter effects [12] with $\Delta m_{12}^2 = 7.6 \times 10^{-5}$ eV², $\Delta m_{23}^2 = +2.4 \times 10^{-3}$ eV², $\sin^2 2\theta_{12} = 0.8704$, $\sin^2 2\theta_{23} = 1.0$, an average Earth density $\rho = 3.2$ g/cm³ and $\delta_{CP} = 0$ unless otherwise noted. The expectations are 0.03(0.03) $\nu_\mu + \bar{\nu}_\mu$ CC, 0.8(0.7) intrinsic ν_e CC, and 0.1(4.1) $\nu_\mu \rightarrow \nu_e$ oscillation events for $\sin^2 2\theta_{13} = 0(0.1)$, and 0.6 NC events. As shown in Table 3, the total systematic uncertainty on N_{SK}^{exp} depends on θ_{13} . Combining the above uncertainties the total far detector systematic error contribution to $\delta N_{SK}^{exp} / N_{SK}^{exp}$ is 14.7%(9.4%) for $\sin^2 2\theta_{13} = 0(0.1)$.

Our oscillation result is based entirely on comparing the number of ν_e candidate events with predictions, varying $\sin^2 2\theta_{13}$ for each δ_{CP} value. Including systematic uncertainties the expectation is $1.5 \pm 0.3(5.5 \pm 1.0)$ events for $\sin^2 2\theta_{13} = 0(0.1)$. The probability to observe six or more candidate events is 7×10^{-3} for $\sin^2 2\theta_{13} = 0$. Thus, we conclude that our

Table 3. Contributions from various sources and the total relative uncertainty for $\sin^2 2\theta_{13} = 0$ and 0.1, and $\delta_{CP} = 0$.

Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) near detector	$+5.6\%$ -5.2%	$+5.6\%$ -5.2%
(3) near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
(4) cross section	$\pm 14.0\%$	$\pm 10.5\%$
(5) far detector	$\pm 14.7\%$	$\pm 9.4\%$
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$	$+22.8\%$ -22.7%	$+17.6\%$ -17.5%

data indicate ν_e appearance from a ν_μ neutrino beam. At each oscillation parameter point, a probability distribution for the expected number of events is constructed, incorporating systematic errors [13], which is used to make the confidence interval (Fig. 4), following the unified ordering prescription of Feldman and Cousins [14].

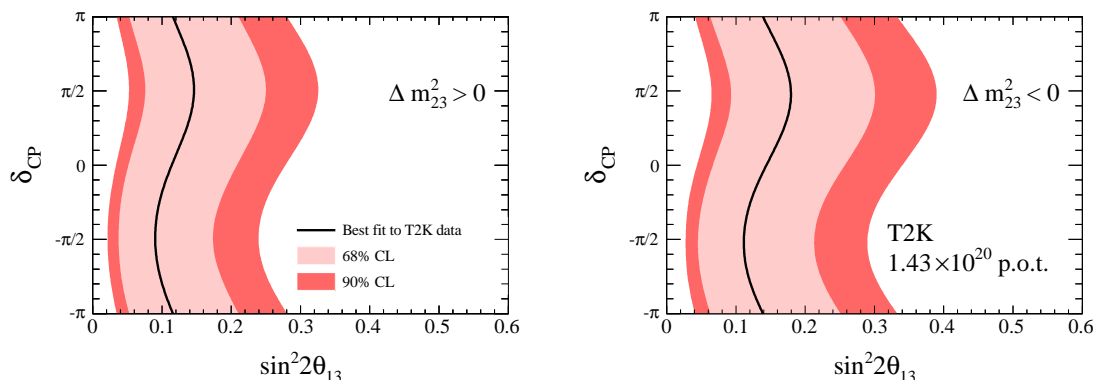


Figure 4. The 68% and 90% C.L. regions for $\sin^2 2\theta_{13}$ for each value of δ_{CP} consistent with the observed number of events in the three-flavor oscillation case for normal (left) and inverted (right) mass hierarchy. The other oscillation parameters are fixed (see text). The best fit values are shown with solid lines.

This result converted into a confidence interval yields $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ at 90% C.L. for $\sin^2 2\theta_{23} = 1.0$, $|\Delta^2 m_{23}^2| = 2.4 \times 10^{-3} \text{ eV}^2$, $\delta_{CP} = 0$ and for normal (inverted) neutrino mass hierarchy. Under the same assumptions, the best fit points are 0.11(0.14), respectively. For non-maximal $\sin^2 2\theta_{23}$, the confidence intervals remain unchanged to first order by replacing $\sin^2 2\theta_{13}$ by $2 \sin^2 \theta_{23} \sin^2 2\theta_{13}$. More data are required to firmly establish ν_e appearance and to better determine the angle θ_{13} . These results have been published in Ref. [2] and are consistent with the results published subsequently by the MINOS collaboration [15] that measures $2 \sin^2 \theta_{23} \sin^2 2\theta_{13} < 0.12(0.20)$ at 90% C.L. for $\delta_{CP} = 0$ and the normal (inverted) mass hierarchy. More details are given in Ref. [16] in this conference proceedings.

4. Muon neutrino disappearance

We present preliminary results on the ν_μ disappearance analysis in the following. The ν_μ analysis follows the same steps of the $\nu_\mu \rightarrow \nu_e$ appearance analysis up to the single ring selection criteria, that corresponds to the event reduction criteria in Table 2 number (2). From the selected events, that are predominantly CCQE, thirty-three ν_μ -like events are identified. By adding a further cut on the minimum muon momentum and on the observed delayed electrons, the CCQE purity

Table 4. Event reduction for the ν_μ disappearance search at Super-Kamiokande. The selection criteria (0) to (2) are shown in Table 2. The numbers of data and ν_μ CCQE, ν_μ CC non-CCQE, intrinsic ν_e CC and NC MC expected events are presented after each selection criterion. All MC CC samples include three-flavor oscillations for $\sin^2 2\theta_{23} = 1$ and $\Delta m_{23}^2 = 0.0024 \text{ eV}^2$.

	Data	ν_μ CCQE	ν_μ CC non-CCQE	ν_e CC	NC
(3) μ -like	33	17.6	12.4	<0.1	1.9
(4) $P_\mu > 200 \text{ MeV}$	33	17.5	12.4	<0.1	1.9
(5) 0 or 1 delayed electron	31	17.3	9.2	<0.1	1.8

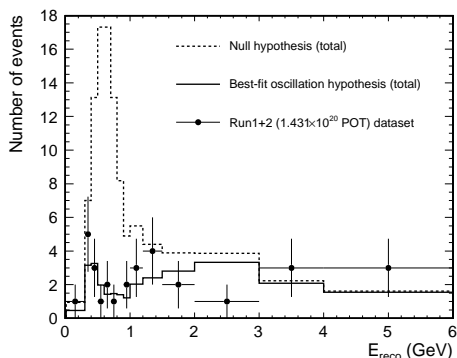


Figure 5. Reconstructed neutrino energy spectrum of the thirty-one single μ -like ring events (points with statistical error bars), with no oscillations and best-fit MC prediction (histograms).

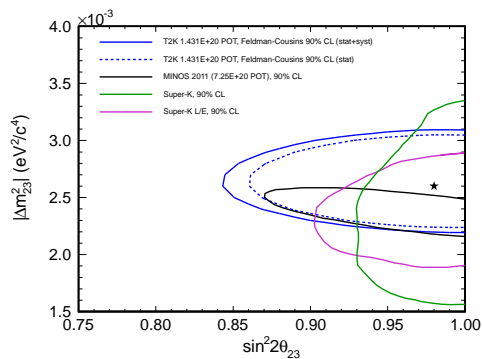


Figure 6. The 90% ν_μ -disappearance confidence regions (with and without systematics) compared with Super-Kamiokande and MINOS results. The star indicates the best fit point.

is increased with a negligible decrease in efficiency. A total of thirty-one single μ -ring events are observed with an expected number of events of about 104 without oscillations.

The same strategy as for the $\nu_\mu \rightarrow \nu_e$ analysis with regard to the beam simulation, the neutrino interactions and the treatment of the ND280 results is adopted (see Section 3). The data and MC reductions after each selection criterion are shown in Table 4.

The reconstructed energy spectrum of the thirty-one single μ -like ring events in the combined run 1 and 2 dataset, with prediction for no oscillations, and best-fit prediction is presented in Figure 5. The statistical significance of the observed deficit without oscillations is 4.3σ . The energy spectrum in Figure 5 is shown in a variable binning scheme for the purpose of illustration only; the actual analysis used equal-sized 50 MeV bins. The best fit parameters are $\sin^2 2\theta_{23} = 0.98$, $|\Delta m_{23}^2| = 2.6 \times 10^{-3} \text{ eV}^2$, and the corresponding 90% Feldman-Cousins confidence regions (with and without systematic errors) for the 2-flavour ν_μ -disappearance fit are shown in Figure 6. We also perform an independent oscillation analysis that gives very similar results: $\sin^2 2\theta_{23} = 0.99$, $|\Delta m_{23}^2| = 2.6 \times 10^{-3} \text{ eV}^2$ with a statistical significance of the observed deficit without oscillations of 4.4σ . Our results are consistent with the ones from Super-Kamiokande[17] and MINOS [18].

5. Future prospects

The T2K data taking stopped abruptly on March 11 2011 due to the Great East Japan Earthquake. No serious damages were found in the accelerator complex, the neutrino beamline or the near detectors. The Super-Kamiokande detector was not affected by the earthquake. We

are on schedule to resume operations at J-PARC in December 2011 with the T2K experiment expected to start data taking as soon as possible early 2012. The current goal is to collect 1×10^{21} p.o.t. by summer 2013. Such a data sample will allow the confirmation of a non-zero value of θ_{13} with 5 sigma statistical significance at the present best fit value.

6. Conclusions

The T2K experiment, which comprises a new neutrino beamline and new near detector complex at J-PARC and the upgraded Super-Kamiokande detector, has been constructed successfully and collected data from January 2010 to March 2011 for a total of 1.43×10^{20} p.o.t. We published our first results on the ν_e appearance analysis [2] where we report the observation of six single ring e -like events. The probability to observe six or more events is 7×10^{-3} for $\sin^2 2\theta_{13} = 0$. This result yields $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ at 90% C.L. for $\sin^2 2\theta_{23} = 1.0$, $|\Delta m_{23}^2| = 2.4 \times 10^{-3} \text{ eV}^2$, $\delta_{CP} = 0$ and for normal (inverted) neutrino mass hierarchy. Under the same assumptions, the best fit points are $0.11(0.14)$, respectively. These results are consistent with the results published subsequently by MINOS.

We presented preliminary results on the ν_μ disappearance analysis using the same data set. A total of thirty-one single ring μ -like events are observed at the far detector, yielding to the best fit parameters of $\sin^2 2\theta_{23} = 0.98$, $|\Delta m_{23}^2| = 2.6 \times 10^{-3} \text{ eV}^2$, consistent with the results from Super-Kamiokande and MINOS.

T2K has collected 2% of its projected data and is on schedule to restart data taking early 2012. J-PARC will start operation in December 2011.

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