Latest results from T2K

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Abstract

T2K (Tokai-to-Kamioka) is a long baseline accelerator neutrino experiment. The main goal of T2K is to measure the mixing angle θ_{13} by searching for an electron neutrino appearance in the initially almost pure muon neutrino beam. The new ν_e-appearance results obtained by the 15th of May, 2012, are presented. In the data sample, corresponding to 2.56×10^{20} protons on target, 10 ν_e candidate events pass the selection criteria, while the expected number of ν_e-like events in case of θ_{13}=0 is 2.73 ± 0.37 (syst). The probability to observe ten or more candidate events due to the background is 8×10^{-4}, equivalent to 3.2σ significance. At 90% C.L., the data are consistent with $0.036(0.045) < \sin^2 2\theta_{13} < 0.211(0.253)$ for $\delta_{\rm CP} = 0$ and normal (inverted) hierarchy.

1 Introduction

T2K is a second generation long baseline (LBL) accelerator neutrino experiment: in contrast to the first generation experiments, like K2K, MINOS and OPERA, T2K has neutrino detectors located slightly offset with respect to the initial proton beam (off-axis angle is 2.5°).

Experiment T2K (Tokai-to-Kamioka) is an International Collaboration of about 500 members from 59 institutes of 12 countries [1]. The source of muon neutrinos and near detectors are located at the Japan Proton Accelerator Research Complex (J-PARC, Tokai Village, Ibaraki Prefecture, Japan), while as a far detector the well-known Super-Kamiokande (SK) detector located at 295 km is used (Kamioka, Gifu Prefecture, Japan).

A primary goal of the T2K is a measurement of the mixing angle θ_{13} by detecting the electron neutrinos at the far detector in the initially almost pure muon neutrino beam ("ν_e-appearance").

A secondary goal is a precision measurement of so-called atmospheric oscillation parameters $(\theta_{23}, \Delta m^2_{32})$ by detecting a deficit of muon neutrinos at the far detector ("ν_μ-disappearance").

2 Physics motivation: neutrino oscillations

At present it is known that neutrinos are produced and detected in weak interactions as leptons of three flavours: electron ν_e, muon ν_μ and tau ν_τ (for a detailed review of neutrino parameters see [2]). Neutrino flavour eigenstates $|\nu_\alpha\rangle$ ($\alpha = e, \mu, \tau$) are not equal to the neutrino mass eigenstates $|\nu_i\rangle$ with mass eigenvalues m_i ($i = 1, 2, 3$). A conversion from the mass basis to the flavour basis is governed by the 3×3 unitary matrix U_{PMNS} (Pontecorvo-Maki-Nakagawa-Sakata)[3, 4], which can be parametrized in such a way, that it only depends on 3 mixing angles and one CP-violating phase: $\theta_{12}, \theta_{23}, \theta_{13}$ and $\delta_{\rm CP}$.

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

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where $s_{ij} \equiv \sin\theta_{ij}; c_{ij} \equiv \cos\theta_{ij}$.

Two of these four parameters are measured in solar/reactor and atmospheric/accelerator experiments, respectively: $\theta_{12} \approx 34^\circ$ and $\theta_{23} \approx 45^\circ$. The corresponding mass squared differences, defined as $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, have the following values: $\Delta m^2_{12} \approx 7.6 \times 10^{-5}$ eV^2/c^4 and $|\Delta m^2_{32}| \approx 2.4 \times 10^{-3}$ eV^2/c^4. The sign of the Δm^2_{32} is remained undetermined ("mass hierarchy problem").

Before T2K the best upper limit for θ_{13} was obtained in 1999 by the reactor experiment CHOOZ and slightly corrected in 2010 by the LBL experiment MINOS: $\theta_{13} < 11^\circ$ ($\sin^2 2\theta_{13} < 0.15$) [5, 6].

In 2011-2012, the T2K, MINOS, Daya Bay and RENO collaborations reported indications of non-zero θ_{13} in accelerator and reactor experiments [7, 8, 9, 10]. If θ_{13} has non-zero value, then one can study a potential CP-violation in the lepton sector.

The "appearance" probability $P(\nu_\mu \to \nu_e)$ to observe an electron neutrino at the distance L from the source of the muon neutrinos with an inital energy E_ν can be written in the following way:

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(\Delta m^2_{31}L/(4E_\nu)) \\ & - 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}\sin\delta_{CP} \\ & + 4s^2_{12}c^2_{13}(c^2_{12}c^2_{23} + s^2_{23}s^2_{12}s^2_{13} - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta_{CP})\sin^2\Delta_{21} \\ & + 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{21}\sin\Delta_{31} \\ & - 8c^2_{13}s^2_{13}s^2_{23}(1 - 2s^2_{13})(aL/4E_\nu)\cos\Delta_{32}\sin\Delta_{31} \\ & + 4c^2_{13}s^2_{13}s^2_{23}(1 - 2s^2_{13})(2a/\Delta m^2_{31})\sin^2\Delta_{31}, \end{aligned} \tag{1}$$

where $\Delta_{ij} \equiv \Delta m^2_{ij}/(4E_\nu); a \equiv 2\sqrt{2}G_F n_e E_\nu$; G_F - Fermi constant; n_e - electron concentration of the matter.

To obtain an approximate value of the mixing angle θ_{13} the first (leading) term of the equation (1) would be enough, however the other terms are important to study the CP-violation (second term), mass hierarchy (third and fourth terms) and matter effects (last two terms).

The "disappearance" probability $P(\nu_\mu \to \nu_\mu)$ in two-flavour oscillation scenario has the following form:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(\frac{\Delta m^2_{32}L}{4E_\nu}). \tag{2}$$

Using the equations (1-2) and other inputs one can compute the expected number of events N^{exp}_{SK} and the neutrino energy spectra at the far detector and compare them with observed number of events N^{obs}_{SK} and the measured energy spectrum. Fitting these two numbers in it is possible to get the parameters in question (θ, Δm^2).

3 T2K experimental method

Muon neutrinos in the accelerator experiments are produced as tertiary particles of proton interactions in a special target. In the T2K [11] protons are accelerated at J-PARC in three stages: 1) at LINAC - up to 400 MeV (currently 181 MeV); 2) at Rapid Cycling Synchrotron (RCS) - up to 3 GeV; 3) at Main Ring (MR) - up to 30 GeV, after which the protons are extracted into the neutrino beamline in 8 bunches per spill (6 before November 2010).

Neutrino beamline consists of two main parts: primary section, which transports the protons from the MR to a target, and secondary section, where the secondary particles (pions, kaons etc.) are produced and decayed. The positive pions produced in a graphite target are collected and focused into the decay volume by three horns. Muon neutrinos are mainly produced in the π^+-decays: $\pi^+ \to \mu^+\nu_\mu$. Undecayed hadrons and low energy muons ($p_\mu < 5$ GeV/c) are absorbed by the beam dump, which is followed by the muon monitors (MUMON) providing

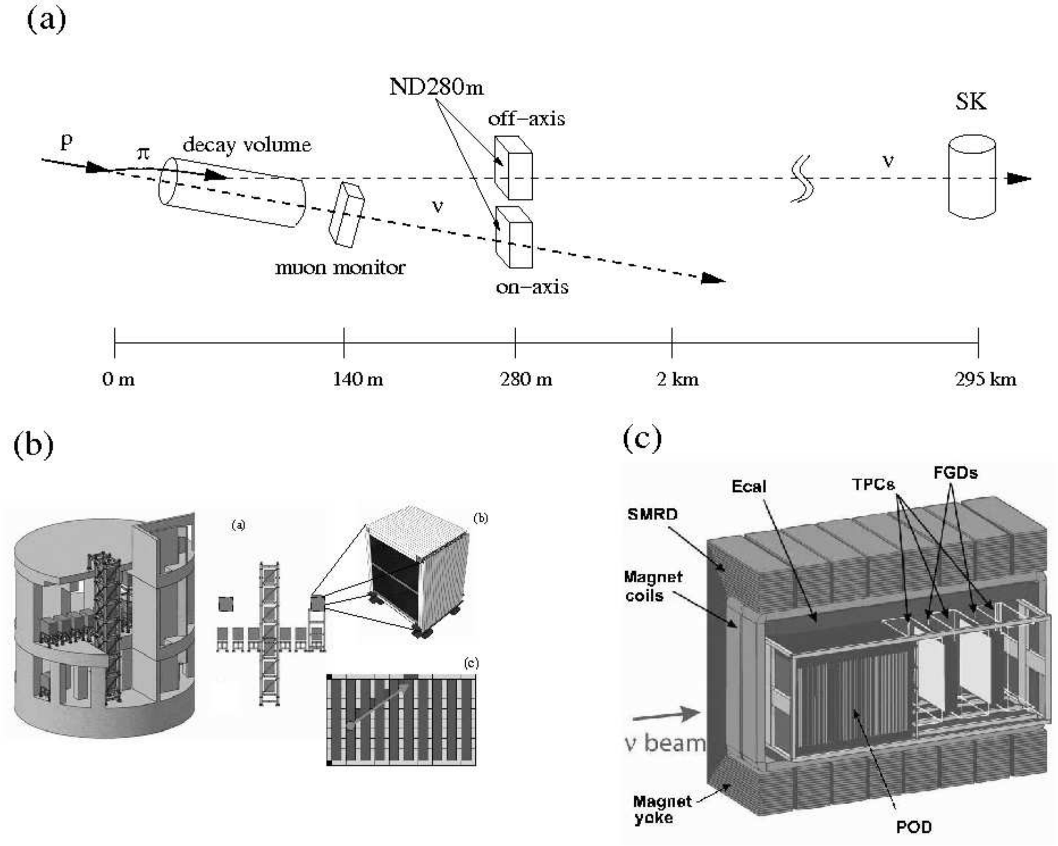

Figure 1: T2K experimental setup: a) a schematic view of the beam line and detectors; b) and c) near detectors: INGRID (b) and the off-axis ND280 (c)

the information on the intensity and profile of the high energy muons. In order to check the intensity, direction, profile and losses of the proton beam the primary section is equipped with many beam monitors.

The near detector complex ND280 is located in a specially excavated pit at about 280 meters from the target. It consists of two independent detectors (Fig. 1): the INGRID at 0° with respect to the proton beam axis (on-axis), and the ND280 at 2.5° (off-axis). The on-axis near detector INGRID (Interactive Neutrino GRID) is used to monitor the neutrino beam profile, direction and interaction rates on the day-by-day basis. The off-axis near detector ND280 consists of a $\pi0$-detector (P0D), a tracker with two fine-grained detectors (FGD) sandwiched by three time projection chambers (TPC). The tracker and P0D are surrounded by the components of the electromagnetic calorimeter (ECAL), and all of them are installed inside an UA1/NOMAD magnet which provides a magnetic field of 0.2 T in the direction perpendicular to the off-axis beam (X-direction). The yoke of the magnet is instrumented as a side muon range detector. The main function of the off-axis ND280 complex is to measure the neutrino flux, energy spectrum, interaction rates and cross-sections *before* the oscillation.

The far detector SK is a 50-kton water Cherenkov detector (22.5 kt in the fiducial volume, FV) located at 295 km also at 2.5°. SK detector consists of two main parts: the inner detector (ID) with about 11,100 photomultipliers (20" Hamamatsu PMT) and the outer detector (OD) with about 1900 PMTs (8"). The main feature of SK detector is an excellent particle identification of muons and electrons with about 99% efficiency.

The main advantages of the off-axis conception are as follows: 1) at 0° the neutrino energy is propotional to the parent pion momentum $E_\nu \sim p_\pi$, while at 2.5° the neutrinos have almost monochromatic spectrum with a high beam intensity; 2) the neutrino energy peak corresponds

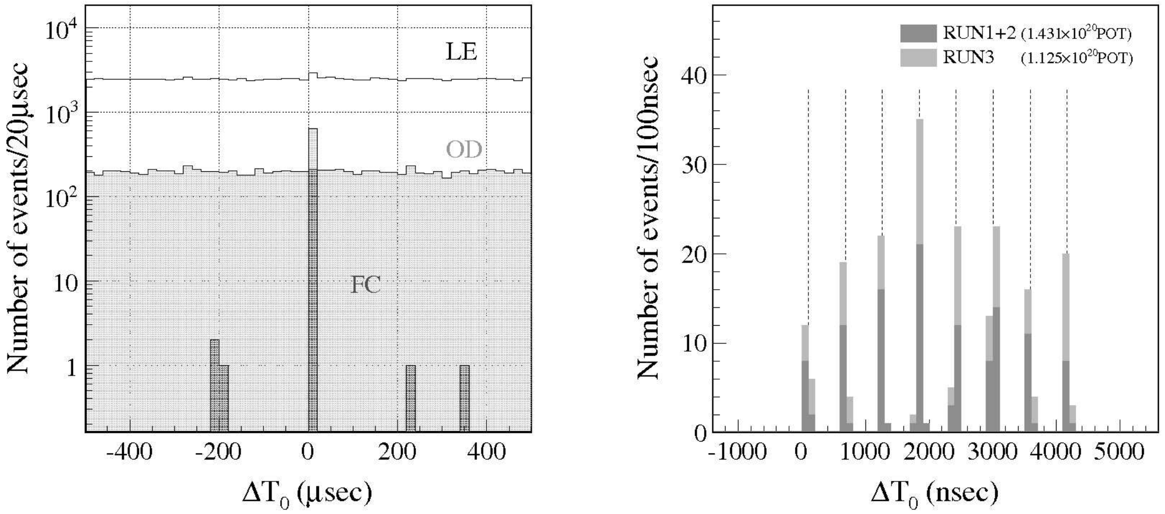

Figure 2: Timing of events at T2K Far Detector (SK). Left: all events; right: FC events (LE - Low energy trigger; OD - outer detector; FC - fully conatined events).

to the first oscillation maximum; 3) the beam ν_e-contamination at SK is low ($\sim 1\%$); 4) the background from the neutral current (NC) ν_μ-interactions at the high energy tail is considerably suppressed.

4 T2K experimental data and selection criteria

T2K beam data taking was started in January 2010 and paused because of the Great East Japan Earthquake in March 2011, then resumed in March 2012. The current analysis of ν_e-appearance events was carried out for 2.56×10^{20} protons on target (p.o.t.) collected in three runs Run I (Jan – Jun 2010), Run II (Nov 2010 – Mar 2011) and Run III (Mar 2012 - Jun 2012)[1]. The beam power reached 200 kW in 2012 with 1×10^{14} protons per pulse.

A direction of the off-axis beam during the runs had being checked by means of the MUMON and INGRID which demonstrated, that the beam direction was stable well within ±1 mrad (1 mrad shift corresponds to about 2% shift of the E_ν peak energy at 295 km). INGRID also showed a very stable neutrino interaction rate of about 1.5 events per 10^{14} p.o.t.

The signature of the neutrino interaction in the SK detector is a single electron- or muon-like Cherenkov ring caused by a lepton from a charged-current quasi-elastic (CCQE) process in the water: $\nu_l + n \to l^- + p$, where $l = e, \mu$. The main backgrounds in case of the ν_e-appearance are the intrinsic ν_e from the beam and NC-interactions with $\pi^0 \to \gamma\gamma$ in the final states: $\nu_X + n \to n + \pi^0$ when one photon is missed and another one mimics the electron. In case of the ν_μ-disappearance the main background comes from the charged-current processes with one charged pion in the final state (CC1π): $\nu_\mu + n \to \mu^- + n + \pi^+$ or $\nu_\mu + p \to \mu^- + p + \pi^+$.

In order to reject these background events the selection criteria were fixed from Monte Carlo (MC) studies before the data were collected. The observed number of events N_{SK}^{obs} obtained after applying these selection criteria is compared to the expected number of events N_{SK}^{exp}, computed taking into account a neutrino flux, cross-section predictions and using the analysis of events in the off-axis near detector. For the neutrino flux prediction at SK many inputs were used: a) the beam monitor data; b) the hadron production calculations based on the results of the NA61/SHINE CERN experiment [12] and MC simulations; c) the cross-sections data based on neutrino interaction models (NEUT and GENIE) and external measurements by MiniBooNE, SciBooNE, NOMAD; d) the detector systematic uncertainties. These input parameters were constrained by a fit to the CCQE and non-CCQE measurements at the near detector ND280.

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[1] The results presented here are based on the data (2.56×10^{20} p.o.t.) collected by the 15th of May, 2012.

Table 1: T2K Main Systematics Uncertainties

Source of Systematic Error	$\sin^2(2\theta_{13})$=0.0	$\sin^2(2\theta_{13})$=0.1
Flux and cross section with ND280 fit	8.7%	5.7%
Neutrino cross section (external experiments)	5.9%	7.5%
SK and Final State Interactions	7.7%	3.9%
Total Error (2012)	**13.4%**	**10.3%**
Previous (2011) result	≈ 23%	≈ 18%

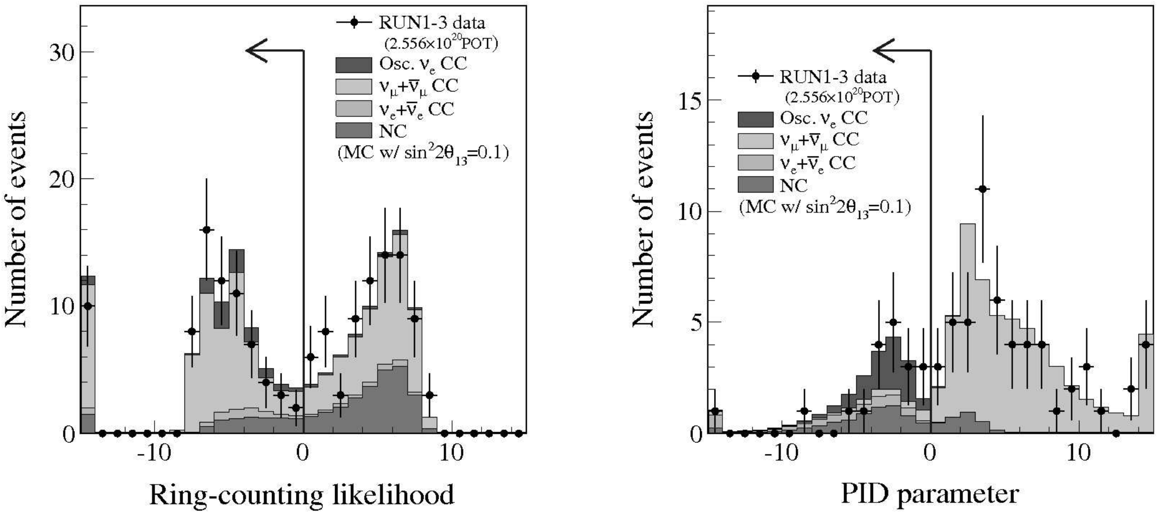

Figure 3: Ring counting at T2K Far Detector (SK). Left: 74 events with a single ring are selected; right: 19 e-like (selected) and 55 μ-like single-ring events.

It should be noted that the systematics uncertainties in the 2012 analysis are reduced (see Table 1) with respect to that of the 2011 analysis due to a number of factors: 1) including the kaon production data from the NA61/SHINE CERN experiment [13]; 2) ND280 provides constraints on the flux an cross section models (with correlations and anti-correlations); 3) constraints of the cross section models by the external experiments (MiniBooNE, SciBooNE, NOMAD).

To satisfy the general selection criteria related to the ν_e-appearance and ν_μ-disappearance analyses the event at SK should have the following parameters: its timing is within the range from -2 to 10 μs around the beam trigger time; it's a fully-contained (FC) event which means that the vertex and the ring are within the ID, and there is no activity in the OD (Fig. 2). 209 events survived these criteria. This number was reduced to 151 after demanding the energy deposited in the ID to be at least 30 MeV (visible energy E_{vis}) and the vertex to be in the fiducial volume (FCFV) constrained by an inward 2 meter distance from each ID wall. 74 events have a single Cherenkov ring: 19 e-like and 55 μ-like (Fig. 3).

5 ν_e-appearance results

13 out of 19 e-like events have $E_{vis} > 100$ MeV and no delayed-electron signal. To suppress misidentified π^0 mesons, the reconstruction of two rings is forced, and a cut on the two-ring invariant mass $M_{inv} < 105$ MeV/c^2 is imposed. To suppress the background from the intrinsic ν_e component, the reconstructed neutrino energy required to be $E_\nu^{rec} < 1250$ MeV. Three events were rejected after the last two cuts (Fig. 4), so, the number of the candidate ν_e-events is N_{SK}^{obs} = 10.

The expected number of events computed for zero θ_{13} is $N_{SK}^{exp} = 2.73 \pm 0.37$, where the total systematic uncertainty ±13.4% is taken into account. So, the probability to observe 10 or

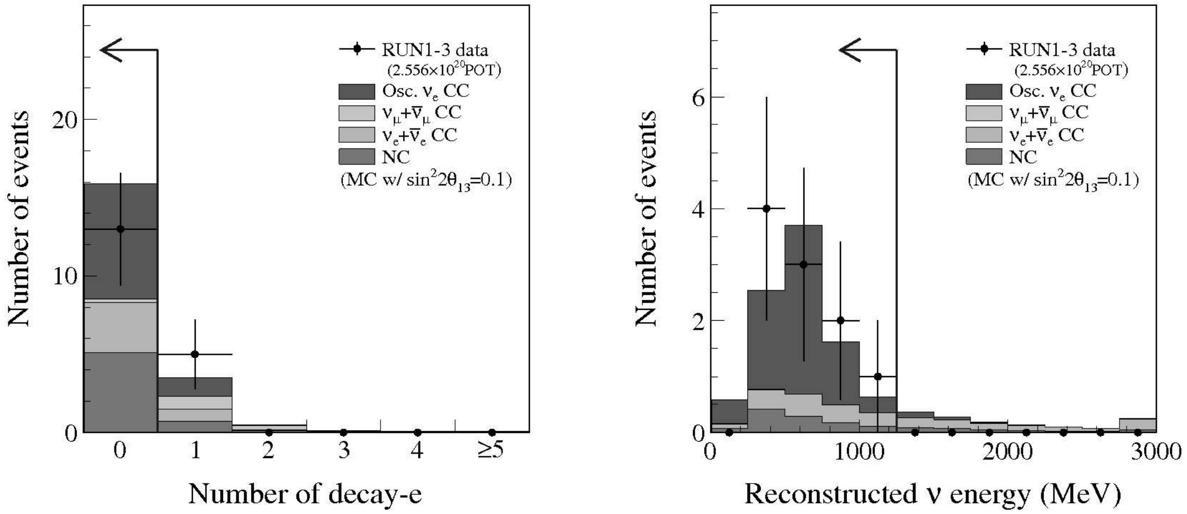

Figure 4: Selecting events at T2K Far Detector (SK). Left: 13 events have no delayed electrons; right: 10 candidate events survive after energy cut.

more events due to the background is 0.08% (3.2σ significance).

To extract the oscillation parameter θ_{13} we use three analysis methods: 1) maximum likelihood fit of the rate and two dimensional distribution of the momentum and angle of the detected electrons (p_e, θ_e); 2) maximum likelihood fit of the rate and reconstructed neutrino energy E_ν^{recon}; 3) "rate only" analysis which is just a single bin counting experiment analysis based on the Feldman and Cousins method [14].

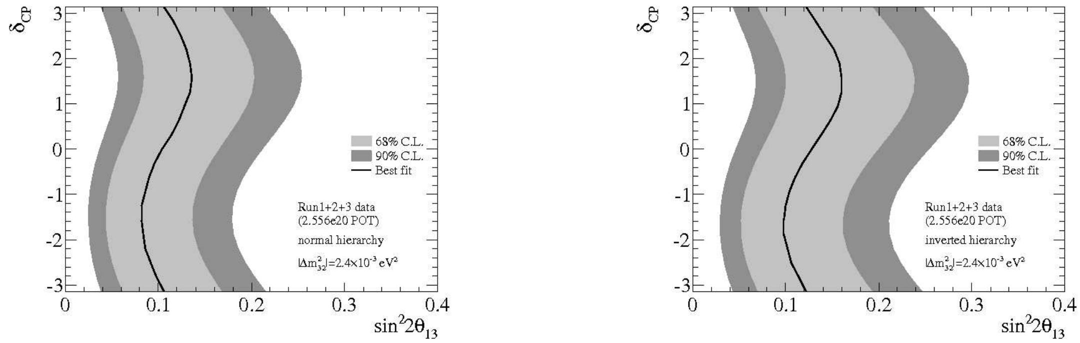

Figure 5: T2K intervals $(\delta_{CP}, \sin^2 2\theta_{13})$ obtained by the method of fitting the rate and two dimensional (p_e, θ_e) distribution. Left: normal mass hierarchy ($\Delta m^2_{32} > 0$); right: inverted mass hierarchy ($\Delta m^2_{32} < 0$).

All three methods demonstrate consistent results. The 90% confidence intervals of θ_{13} calculated by the first method for $\delta_{\rm CP} = 0$ can be seen in the Fig. 5: $0.036 < \sin^2 2\theta_{13} < 0.211$ for a normal mass hierarchy ($\Delta m^2_{32} > 0$) and $0.045 < \sin^2 2\theta_{13} < 0.253$ for an inverted mass hierarchy ($\Delta m^2_{32} < 0$). The best fit value for $\delta_{\rm CP} = 0$ is $\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$ for a normal mass hierarchy and $\sin^2 2\theta_{13} = 0.128^{+0.070}_{-0.055}$ for an inverted mass hierarchy.

6 Conclusions

The oscillation results obtained by the 15th of May, 2012, in the off-axis accelerator neutrino experiment T2K are presented. In the data sample, corresponding to 2.56×10^{20} p.o.t., 10 ν_e candidate events pass the selection criteria, while the expected number of background events for θ_{13}=0 is 2.73 ± 0.37 (syst.). The probability to observe ten or more candidate events due to background is 0.08%, equivalent to 3.2σ significance. At 90% C.L., the data are consistent with $0.036(0.045) < \sin^2 2\theta_{13} < 0.211(0.253)$ for $\delta_{\rm CP} = 0$ and normal (inverted) hierarchy. The best fit value for $\delta_{\rm CP} = 0$ is $\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$ for a normal mass hierarchy and $\sin^2 2\theta_{13} = 0.128^{+0.070}_{-0.055}$ for an inverted mass hierarchy. More data (including the appearance and disappearance channels) obtained by the end of the Run III (June, 2012) will be analyzed and published soon.

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