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Recent results from the T2K experiment

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Summary. — T2K is a long-baseline experiment which has been designed to measure neutrino oscillations. A high intensity beam of muon neutrinos is produced at the J-PARC accelerator complex and sent towards the near detector station (280 meters away from the neutrino source) and the far detector Super-Kamiokande (295 km). The change in the measured intensity and composition of the beam is used to provide information on the oscillation parameters. The T2K experiment has discovered electron neutrino appearance with a significance of 7.3σ, measured the associated θ_{13} mixing angle and provided the first hint for the δ_{CP} phase. T2K has also delivered the world's best measurement of the θ_{23} angle by looking at the disappearance of muon neutrinos. Several useful neutrino cross section measurements have also been performed by the T2K experiment. A summary of the recent oscillation measurements as well as selected cross section results are presented.

PACS 14.60.Pq – Neutrino mass and mixing.

1. – Introduction

Neutrinos play an important role in the standard model of particle physics and cosmology. They interact both via charged current (CC) and neutral current (NC) exchange but the flavor of the neutrino is determined by the charged lepton that is produced in charged current reaction: electron for ν_e, muon for ν_μ and taon for ν_τ interactions. Neutrinos also oscillate which means that they change their flavor from one to another as they travel. This fact was first revealed by the Super-Kamiokande (Super-K) experiment in 1998 [1]. From the theoretical point of view neutrino oscillations are a quantum-mechanical effect where the observed in nature neutrino flavor states from the Standard Model: ν_e, ν_μ, ν_τ propagate in space as linear combinations of the mass eigenstates: ν_1, ν_2, ν_3. The relation between neutrino flavor states and the mass eigenstates is described by the

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Pontercorvo-Maki-Nakagawa-Sakata (PMNS) matrix, which can be parametrized using three mixing angles $\theta_{13},\ \theta_{23},\ \theta_{12}$ and one complex phase δ_{CP} ($c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$).

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

The description of the oscillation probabilities requires two more parameters which are two independent differences of mass squared of the neutrinos: $\Delta m^2_{21},\ \Delta m^2_{32(13)}$. Thanks to Super-K's discovery, neutrino oscillation physics became one of the most dynamically developing areas of research in particle physics. Results from Super-K have been confirmed and supplemented later by many experiments which provided information about all mixing angles and mass splittings with a good precision [2]: $\sin^2 2\theta_{12} = 0.846 \pm 0.021,\ \sin^2 2\theta_{23} > 0.981,\ \sin^2 2\theta_{13} = 0.093 \pm 0.008, \Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\,\mathrm{eV}^2,\ |\Delta m^2_{32(13)}| = (2.44(2.52) \pm 0.06(0.07)) \times 10^{-3}\,\mathrm{eV}^2$.

Although most of the mixing parameters have been measured, there are still open questions in the neutrino oscillation physics. Two of the most important questions are: is there a CP violation in the neutrino sector (a non-zero value of δ_{CP} phase) and what is the neutrino mass hierarchy related to the sign of $\Delta m^2_{32(13)}$: normal (NH) $m_3 > m_2 > m_1$ or inverted (IH) $m_2 > m_1 > m_3$?

2. – The T2K experiment

The T2K collaboration consists of approximately 500 people from 59 institutions in 11 countries. The goals of the T2K experiment are to look for two channels of neutrino oscillations: ν_e appearance in the ν_μ beam and the disappearance of muon neutrinos from the beam. The oscillation probability formulas for these channels are shown below, respectively:

$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq{} & \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E} \\ & - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\sin\delta_{CP} \\ & + (\text{CP term, solar term, matter term}), \end{aligned} \tag{2a}$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2\theta_{23}\sin^2 2\theta_{13})\sin^2\frac{\Delta m^2 L}{4E}, \tag{2b}$$

where Δm^2 is either Δm^2_{32} for normal mass hierarchy or Δm^2_{13} for inverted mass hierarchy.

As you can see, ν_e appearance probability is sensitive to θ_{13} and δ_{CP} while ν_μ disappearance formula is sensitive to θ_{23} and $\Delta m^2_{32(13)}$. These parameters are in the main scope of the T2K experiment measurements.

T2K is a long-baseline neutrino experiment with an almost pure ν_μ beam produced by the J-PARC proton accelerator. Neutrinos are sent towards the near detector station at 280 m and Super-Kamiokande detector, located 295 km away from J-PARC. A schematic view of the T2K setup is shown in fig. 1. T2K uses the off-axis beam idea to produce a narrow-band neutrino beam with one of the near detectors (ND280) and the far detector

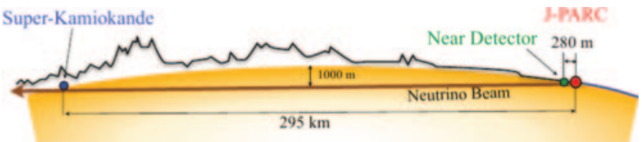

Fig. 1. – Schematic view of the T2K experiment including the path of muon neutrinos from J-PARC to the far detector.

located 2.5° away from the main axis. This setup allows T2K to produce a neutrino beam with a narrow energy spectrum peaked at 0.6 GeV which is tuned to maximize the neutrino oscillation probability at 295 km. This configuration also minimizes the background to the ν_e appearance measurement.

2·1. *T2K neutrino beamline.* – The T2K neutrino beamline consists of two consecutive parts: a primary and secondary beamline. The primary beamline guides the 30 GeV proton beam from the J-PARC's Main Ring (MR) accelerator to the target station. In the secondary beamline, the protons extracted from MR interact with the graphite target and produce secondary pions which are focused by a set of magnetic horns. The polarity of the horns can be changed to focus either positively or negatively charged pions and produce either neutrinos or anti-neutrinos. Pions enter a 96 m long decay volume where they decay and produce muons which are stopped on the beam dump and neutrinos which travel further away to the near and far detectors.

2·2. *Near detectors station.* – The near detectors station is located 280 m away from the neutrino target and consists of two main parts: off-axis and on-axis detector. The off-axis detector (ND280) is built of several sub-detectors encapsulated in the UA1/NOMAD magnet which is the source of a 0.2 T magnetic field. The main ND280 components are: Pizero detector (P0D), Tracker - containing three Time Projection Chambers (TPCs) filled with an argon-based gas mixture and two Fine-Grained Detectors (FGDs), Electromagnetic Calorimeter (ECAL) and Side Muon Range Detector (SMRD). The goal of the ND280 detector is to measure the neutrino flux before the oscillation occurs. The off-axis detector also provides information about the instrinsic ν_e contamination in the beam and measures various neutrino cross sections. A schematic view of the ND280 detector is shown in fig. 2.

The on-axis detector, called INGRID, is composed of 16 iron/scintillator modules and an additional scintillator only module (proton module). The goal of the INGRID detector is to monitor the beam rate, direction and stability by counting muons from ν_μ charged current interactions. INGRID is also capable of measuring various neutrino cross sections.

2·3. *Super-Kamiokande far detector.* – The Super-Kamiokande detector is a far detector for the T2K experiment. This is the world's largest land-based water Cherenkov detector which has been operating since 1996 and its technology and operations are well understood [3]. The detector is located 1 km deep underground in the Mozumi mine and is a cylindrical tank filled with 50 kton of pure water. 13 000 photomultipliers on the walls of the tank detect the Cherenkov light (rings) emitted by the charged particles produced in neutrino interactions. A schematic view of the Super-K detector is depicted in fig. 3. The Super-Kamiokande detector has a well established electron-muon discrimination technique which is very important to distinguish between ν_e and ν_μ interactions. The

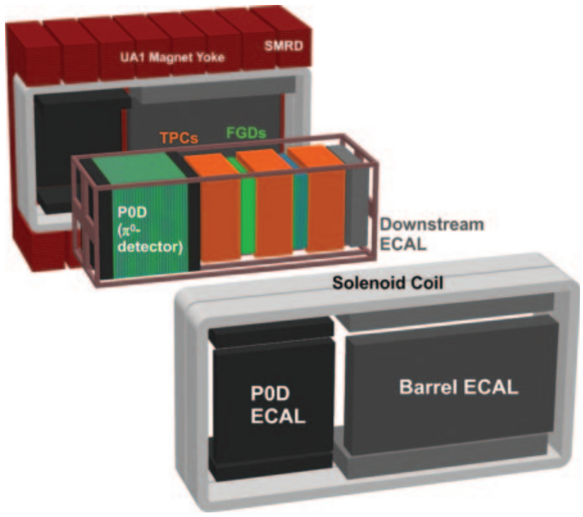

Fig. 2. – ND280 off-axis detector and its different components. Neutrino beam enters from the left.

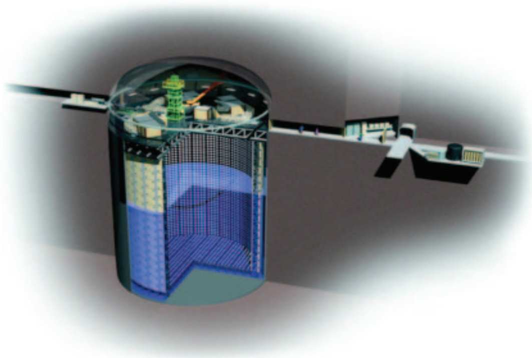

Fig. 3. – Super-Kamiokande far detector.

Cherenkov rings in the detector can be classified as electron-like or muon-like, depending on their appearance. The muon ring has sharp edges while the the electron ring is more fuzzy because of a larger amount of multiple scattering. The mis-identification for a muon as an electron and vice versa is less than 1%.

3. – Neutrino oscillation measurements in T2K

The T2K experiment has been collecting physics data since the beginning of 2010 and exceeded 1×10^{21} protons on target (POT) on March 26, 2015. In the analyses presented in this paper 6.57×10^{20} POT has been used.

The strategy for the neutrino oscillation measurements in T2K is based on the data collected by the near and far detector. The data from the near detector (ND280) is fitted using several inputs: neutrino flux prediction, neutrino cross section models and

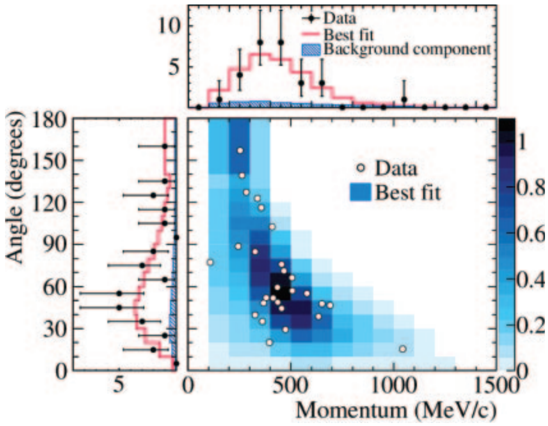

Fig. 4. – The distribution of ν_e candidate events in p_e-θ_e plane along with the MC prediction for the best fit value of $\sin^2 2\theta_{13} = 0.140$ (normal hierarchy) [4].

their uncertainties and uncertainties for the event selection in the near detector. The output of the ND280 fit along with the far detector systematic uncertainties are used as inputs for the far detector fit. A fit to the Super-K data is performed using the PMNS neutrino oscillation model and provides the estimates for the oscillation parameters. The important role of the near detector in T2K is illustrated by the total systematic uncertainty for the predicted rate of ν_μ CC (ν_e CC) candidate events, which is reduced from 23.5% (26.8%) to 7.7% (6.8%) with ND280 constraint.

3˙1. *ν_e appearance discovery.* – There are 28 electron neutrino candidates selected in the Super-Kamiokande detector after all analysis cuts and 4.92 ± 0.55 events were expected from the Monte Carlo simulation in the no-oscillation hypothesis ($\theta_{13} = 0$). A maximum likelihood fit in the outgoing electron momentum (p_e) and angle (θ_e) plane was performed to extract the value of θ_{13} angle. Far detector data along with the best fit in the p_e-θ_e plane are shown in fig. 4. The fitted value for the normal mass hierarchy is: $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ and inverted hierarchy: $\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$. The significance for non-zero value of θ_{13} is 7.3σ, which is equivalent to the discovery of ν_e appearance. More details of this analysis can be found in [4].

3˙2. *ν_μ disappearance.* – The muon neutrino disappearance study is described in detail in [5]. There are 120 ν_μ candidates selected and the simulation predicts 446 ± 22.5 events in the no-oscillation scenario. The values for $\sin^2\theta_{23}$ and $\Delta m^2_{32(13)}$ were obtained using an un-binned maximum likelihood fit. Contours for 68% and 90% C.L. from the fit are shown in fig. 5. The best fit values are $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$, $\Delta m^2_{32} = (2.51 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$ for the normal hierarchy and $\sin^2\theta_{23} = 0.511 \pm 0.055$, $\Delta m^2_{13} = (2.48 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$ for the inverted hierarchy.

3˙3. *Joint ν_μ/ν_e measurement.* – The analyses presented previously incorporate either ν_μ or ν_e sample in the oscillation fit and keep other non-related oscillation parameters fixed. Equations (2) show that there is an interdependence between the ν_e appearance and ν_μ disappearance formulas via mixing angles. In order to take this interdependence into account a simultaneous fit to both ν_μ and ν_e samples in Super-Kamiokande has

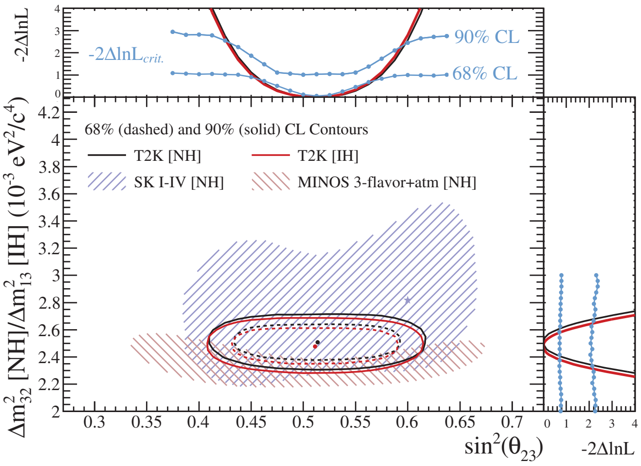

Fig. 5. – The 68% and 90% C.L confidence regions for $\sin^2\theta_{23}$ and Δm^2_{32} (NH) or Δm^2_{13} (IH). Super-Kamiokande and MINOS 90% C.L. regions are shown for the comparisons for NH. T2K's 1D profile likelihoods are shown for each parameter separately on the top and right [5].

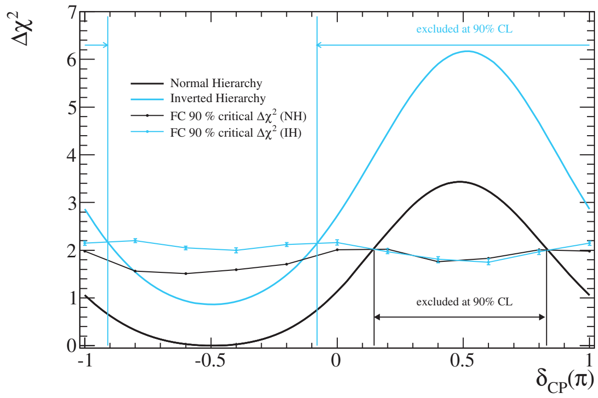

Fig. 6. – Profiled $\Delta\chi^2$ as a function of δ_{CP} for the joint ν_μ/ν_e analysis with reactor constraint. Critical values for $\Delta\chi^2$ along with the excluded regions are also shown [6].

been performed. The oscillation parameters $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, Δm^2, δ_{CP} are obtained simultaneously from the binned maximum likelihood fit in the bins of reconstructed neutrino energy. The following values of the oscillation parameters were obtained for normal (inverted) hierarchy: $\sin^2\theta_{23} = 0.524^{+0.057}_{-0.059}$ $(0.523^{+0.055}_{-0.065})$, $\sin^2\theta_{13} = 0.042^{+0.013}_{-0.021}$ $(0.049^{+0.015}_{-0.021})$, $\Delta m^2_{32} = 2.51^{+0.11}_{-0.12} \times 10^{-3}\,\text{eV}^2$ $(\Delta m^2_{13} = 2.49 \pm 0.12 \times 10^{-3}\,\text{eV}^2)$. An additional analysis with the constraint on θ_{13} from the reactor experiments included in the T2K fit has been performed. The result of this study is shown in fig. 6. The analysis with the reactor constraint allowed us to obtain regions of δ_{CP} excluded at 90% C.L.: $[0.15, 0.83]\pi$ for the normal hierarchy and $[-0.08, 1.09]\pi$ for the inverted hierarchy. It can be also seen that values of δ_{CP} close to $-\pi/2$ are preferred. The details of the joint analysis can be found in [6].

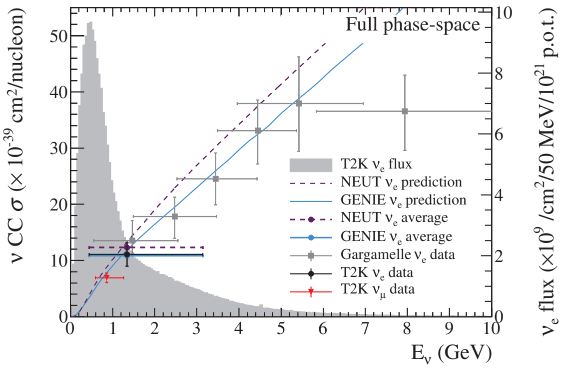

Fig. 7. – Total ν_e charged current inclusive cross section measured by the T2K experiment. The T2K off-axis ν_e flux distribution is shown in grey. NEUT and GENIE predictions along with their flux-averaged predictions and Gargamelle data are also plotted.

4. – Selected cross section results from T2K

To be able to measure subtle differences in the reconstructed neutrino energy spectra, *e.g.* induced by the different values of δ_{CP}, it is crucial to understand systematic errors and decrease them. The major systematic uncertainties which affect oscillation measurements are the neutrino flux uncertainties and neutrino cross section uncertainties. From the point of view of the neutrino interactions and future neutrino oscillation experiments there is also a need for cross section measurements on various nuclei. The near detector of the T2K experiment is a very well suited tool to measure neutrino cross sections. Some of the cross sections can be also measured at Super-Kamiokande. Two selected T2K cross section results are presented in the following sections.

4˙1. ν_e *charged current inclusive cross section.* – The tracking sector of the ND280 detector has been used to select ν_e interactions on carbon. The most significant background for this analysis is the conversion of photons into e^+e^- pairs, and is constrained by a side-band sample. A Bayesian unfolding technique is employed to make the first ν_e differential cross section measurement at energies 1 GeV as a function of electron momentum, electron scattering angle and four-momentum transfer of the interaction [7]. The total flux-averaged ν_e charged current cross section on carbon is: $\langle\sigma\rangle_\Phi = 1.11 \pm 0.09(\text{stat}) \pm 0.18(\text{syst}) \times 10^{-38}\,\text{cm}^2/\text{nucleon}$. The differential and total cross sections agree with the predictions from the NEUT and GENIE Monte Carlo generators. The total cross section from T2K also agrees with the data from the Gargamelle experiment. The T2K result along with Monte Carlo predictions and Gargamelle data is shown in fig. 7.

4˙2. ν_μ *charged current inclusive cross section.* – A measurement of the ν_μ charged current inclusive cross section has been done using the INGRID detector [8]. INGRID consists of the standard modules, where iron (Fe) makes up 96.2% of the target mass, and the proton module where hydrocarbon (CH) makes up 98.6% of the target mass. This allowed us to measure neutrino cross sections on iron and hydrocarbon and their cross section ratio. The flux-averaged ν_μ CC inclusive cross section on iron is measured to be: $(1.444 \pm 0.002(\text{stat})\,^{+0.189}_{-0.157}(\text{syst})) \times 10^{-38}\,\text{cm}^2/\text{nucleon}$ and on

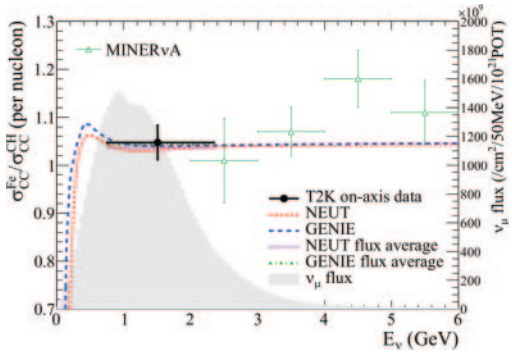

Fig. 8. – The inclusive ν_μ charged current cross section ratio on Fe/CH with predictions from NEUT and GENIE. The T2K on-axis ν_μ flux distribution is shown in grey. The MINERνA result is also plotted.

CH: $(1.379\pm0.009(\text{stat})\,^{+0.178}_{-0.147}(\text{syst}))\times10^{-38}$ cm^2/nucleon. The CC-inclusive cross section ratio on different target nuclei is expected to be different from the unity due to the difference in the ratio of neutrons and protons in the nuclei. In addition the ratio is also affected by nuclear effects, especially at low energies. The result of the T2K measurement along with the Monte Carlo predictions for NEUT and GENIE Monte Carlo is shown in fig. 8. The cross section ratio is: $1.047\pm0.007(\text{stat})\pm0.035(\text{syst})$. This result agrees well with the predictions from the neutrino interaction model implemented in NEUT and GENIE.

5. – Conclusions

The analyses presented in this paper use 8.4% of the total approved POT for the T2K experiment. With this amount of data T2K has already become the world-leading long-baseline neutrino experiment. T2K has discovered ν_e appearance in the accelerator muon neutrino beam with a significance of 7.3 σ and has also measured the associated θ_{13} angle. The combination of T2K's result with reactor measurements provided the first hint for δ_{CP} and excluded some regions of δ_{CP} at 90% C.L. Muon neutrino disappearance analysis in T2K resulted in the world's best measurement of the θ_{23} mixing angle. The T2K experiment has also a broad neutrino cross section program, out of which two selected results have been presented. It is necessary to stress that T2K is taking data in the anti-neutrino mode and we can expect new and exciting anti-neutrino results soon.

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