Latest (Anti) Neutrino Oscillation Results from T2K

Joanna Zalipska for the T2K Collaboration

National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland

joanna.zalipska@ncbj.gov.pl

Abstract. The T2K long-baseline neutrino oscillation experiment has been running since 2010 in both neutrino and anti-neutrino modes. Results presented here refer to joint analysis of ν_μ disappearance and ν_e appearance for neutrino data giving the world-leading measurements of δ_{CP} , θ_{23} and Δm^2_{32}. Also the first results of analysis of anti-neutrino beam are discussed here which allows to test the CPT symmetry and perform an electron anti-neutrino appearance search.

1. Introduction

Neutrinos are the only elementary particles which can spontaneously transform flavour. This phenomenon is called neutrino oscillation. Since we have tree neutrino types of different flavour such as ν_e, ν_μ, and ν_τ we can observe mixing of all three types of neutrinos. The neutrino oscillations were proved to exist by two experiments. The Super-Kamiokande experiment first announced discovery of neutrino oscillations in 1998 measuring atmospheric neutrinos [1]. Few years later their results were followed by prove of neutrino oscillations in solar neutrino sector by the SNO experiment [2]. Both of those discoveries were awarded the Nobel Prize in Physics in 2015. Since then we are following those studies by measurements of neutrino oscillations under controlled beam conditions using artificially produced neutrino beams. The first experiment of that type was K2K, later followed by the MINOS and OPERA experiments. Currently the T2K (experiment which results are discussed here) [3] and NOvA are running long baseline neutrino oscillation experiments. They are dedicated to answer still unknown questions in neutrino physics. On the one side they provide precise measurement of oscillation parameters such as $\theta_{23,}$ θ_{13} and Δm^2_{32} [4,5], and at the same time both experiments try to answer questions weather the CP symmetry is violated or conserved in neutrino sector and what is the neutrino mass hierarchy.

Process of neutrino oscillations is possible thanks to the fact that neutrino flavour states are not identical to neutrino mass eigenstates, but they are mixed as described by the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

That matrix can be paramemtrized by the three mixing angles θ_{12}, θ_{13}, and θ_{23} and one CP violating phase δ_{CP} as shown here:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta_{CP}} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The probability of neutrino to transform the flavour can be expressed as:

$$P(\alpha \to \beta) = |\sum_{ij} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} exp(-i\frac{L\Delta m^2_{ij}}{2E})|$$

In general the neutrino oscillations can occur only when two conditions are fulfilled: first the mixing angle is not equal zero, second the $\Delta m^2=m_i^2-m_j^2$ is not zero. Therefore, observation of neutrino oscillations proves that neutrinos are not massless and besides measurements of neutrino mixing parameters they allow to experimentally probe neutrino masses by measuring the mass squared differences as Δm^2. The T2K experiment studies neutrino oscillation using accelerator produced ν_μ beam by measuring probability of ν_μ to disappear, so called ν_μ->ν_μ oscillations. On the other hand it was also able to measure the appearance of ν_e in produced ν_μ beam, ν_μ->ν_e oscillation, as the first experiment in the world. What currently drives people attention are measurements of neutrino oscillations for anti-neutrino beam, which can lead us to discovery of already mentioned CP violation effect in neutrino sector. The T2K experiment also is taking data for anti-neutrino beam. Consequently it was able to study the disappearance on anti-neutrinos ν_μ->ν_μ oscillation and tried to measure the appearance of anti-ν_e in anti-ν_μ beam, the ν_μ->ν_e oscillations. The first of those transformations mentioned in the last sentence can provide test of the CPT symmetry. It is possible thanks to the fact that probability of muon neutrinos to survive, P(ν_μ->ν_μ), depends on cosδ_{CP} only; therefore all terms are CP conserving. Situation is different when we try to probe the appearance of electron neutrinos, ν_μ->ν_e. Probability which describes that transformation has CP violating terms which depend on sinδ_{CP}. On one side, if CP is violated we expect different probability of neutrinos to oscillate than for situation when δ_{CP} equals 0 or π. On the other hand, the probability of anti-neutrinos to oscillate as ν_μ->ν_e will be different that for neutrino oscillations of ν_μ->ν_e if δ_{CP} is not zero. The maximum effect of the CP violation corresponds to the value of δ_{CP} equals $\pi/2$. That paper will summarize results of neutrino and anti-neutrino oscillations measurements performed by the T2K experiment.

2. Overview of the T2K experiment

The T2K experiment is an accelerator neutrino experiment located in Japan which uses a 30 GeV proton beam produced by the JPARC accelerator in Tokai to create almost pure ν_μ beam. Protons are send on the graphite target where they produce positive and negative pions and kaons as a result on the interaction. Those charged particles are focused by the horn magnets which select either positive or negative pions. When π^+ are selected then they originated ν_μ beam. Contrary, when horns are operated in so called reverse horn current mode the π^- are focused and sent to the decay pipe. Then they decay producing the ν_μ beam. The T2K experiment start its operation in 2010 and analyzed 6.2x10^{20}POT (protons on target) of neutrino beam data. Since 2014 we were collecting data for the anti-neutrino mode. The results presented here are based on the analysis of the 4.0x10^{20}POT collected statistics for anti-neutrino run.

The experiment is composed on the near and far detector stations. One of the near detectors – INGRID is placed on the beam axis and it is used to monitor the beam intensity and stability during its operation. The other near detector station, so called ND280 is placed 280m from the neutrino production point and is located 2.5deg off-axis. Moving detectors off-axis ensures the narrow energy spectrum of neutrinos, which is peaked at 600MeV near the energy where we expect maximum probability of neutrino oscillations. The phenomena of oscillations are measured by the Super-Kamiokande (SK) far detector which is located 295km from the beginning of neutrino beam. SK is a water Cherenkov detector which records muons and electrons coming out of charged current interactions of ν_μ and ν_e [6]. It is 40m by 40m water tank placed 1km underground. The SK detector is equipped with more than 11000 20” photomultiplier tubes measuring the Cherenkov light. It has the ability to distinguish ν_μ and ν_e induced events by studying pattern of the Cherenkov ring seen be the photosensors. The miss-identification probability is less than 1%. Consequently we can study ν_μ->ν_μ and ν_μ->ν_e oscillations separately.

3. Overview of oscillation analysis

In order to perform oscillation analysis the initial inputs of neutrino flux prediction and cross-section of ν interactions are necessary. Measurement of π and K production in the interaction of proton beam with a graphite target using data collected by the NA61/SHINE experiment are used to tune particle production uncertainty. This allows to predict neutrino flux with precision as good as 10% [7]. Also external data of MiniBoone and Minerva are used to model neutrino interaction cross-sections. As a next step the near detector data of the T2K experiment are used to perform the fit which allows to constrain flux and cross-section parameters (as described in Section 4). Using that information the prediction of event rates in the far detector Super-Kamiokande are made. Selection of the neutrino data in SK are described in Ref.[8]. Predicted number of events and their spectra are compared with the detected ν_μ and ν_e induced events in the far detector and the oscillation parameters are derived.

4. Near Detector measurement

The near detector ND280 has an important role to provide the reference measurement of unoscillated neutrino flux and measure cross-sections of neutrino interactions. The ND280 is a tracker detector which is placed inside the former UA1/NOMAD magnet creating 0.2T magnetic field. There are two detector types which acts as a target for neutrino interactions: P0D – the detector which is dedicated to measure π^0 production in neutrino induced events and the Fine-Grained Detector (FGD) – the scintillator detector which is used to provide reference measurements for oscillation analysis. The FGD is interlayed with the Time Projection Chamber detectors (TPC). They ensure tracking of the particles coming out of ν interaction, their identification and momentum reconstruction. The Electromagnetic Calorimeter and Side Muon Range Detector are used to measure particles escaping the tracker volume.

Thanks to the fact that detector is placed in the magnetic field we are able to distinguish interactions of ν from ν by identifying the sign of the outgoing lepton. The analysis of the near detector data relies on the information about presence of the π^+ in the interaction. The selected sample of ν_μ charged current events are split into sub-categories depending on the fact if π^+ was present in the interaction or there were more charged or neutral pions present. It allows to be sensitive to various type of neutrino interaction processes such as: charged current quasi elastic interactions (with no pions coming out of the interaction), the processes where pions are produced through the resonanses and deep inelastic interactions. Consequently the near detector data measurement provides ν_μ and ν_e flux measurement and allows to reduce predicted flux uncertainty in the far detector side [8]. It also allows to constrain parameters describing models of neutrino interaction cross-sections. To summarize the flux and cross-section related systematic uncertainty on predicted number of ν_μ events in SK is reduced from 9.2% to 3.4% when the near detector measurement is taken into account.

5. Oscillation analysis results

5.1 Neutrino data results

The ν data were collected from 2010 till 2013 and corresponds to $6.2\text{x}10^{20}$POT of analyzed statistics [8]. For that period 120 ν_μ induced events were observed in the Super-Kamiokande far detector when 446.0+-22.5 are expected in case of no oscillation (for $\sin^2 2\theta_{32}=0.0$). Therefore, the clear disappearance signal of produced ν_μ beam is observed. In case of the maximal mixing for $\sin^2 2\theta_{23}=1.0$

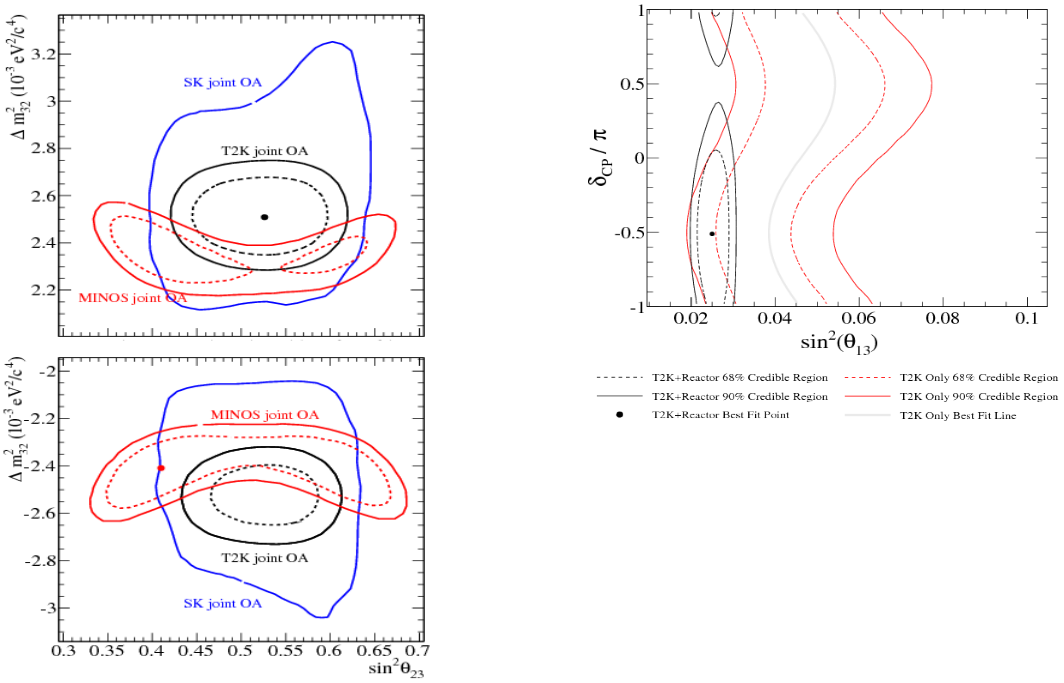

Fig.1 Left – allowed region of oscillation parameters $\sin^2\theta_{23}$, Δm^2_{32} for normal (upper plot) and inverted (bottom plot) mass hierarchy; Right – allowed region of $\sin^2\theta_{13}$, δ_{CP} assuming normal mass hierarchy.

the expected number of ν_μ events is 125.85 (here also the $\Delta m^2_{32}=2.4\text{x}10^{-3}\text{eV}^2/\text{c}^4$ was assumed). When the ν_e selection is applied in the Super-Kamiokande data then 28 data events are found. In case of no ν_μ->ν_e oscillation, for $\sin^2 2\theta_{13}=0.0$, the predicted background is 4.92+-0.55 (estimated based on the assumption of other oscillation parameters as $\sin^2 2\theta_{23}=1.0$, $\Delta m^2_{32}=2.4\text{x}10^{-3}\text{eV}^2/\text{c}^4$ and $\delta_{CP}=0.0$), but for $\sin^2 2\theta_{13}=0.1$ we expect to find 21.59 ν_e events. Consequently the evidence of ν_μ->ν_e transition is observed.

We perform combined 3-flavour fit to the energy spectra of ν_μ-induced and ν_e-induced events at the same time. It allows to be sensitive for correlation between oscillation parameters. During the fit four parameters such as Δm^2_{23}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$ and δ_{CP} are simultaneously determined. As a result we obtain the world best precise measurement of $\sin^2\theta_{23}$=0.524+0.057-0.059 (normal hierarchy) and 0.523+0.055-0.065 (inverted hierarchy). The allowed region of mixing parameters are shown on the left plot in Fig.1 with agreement to MINOS and Super-Kamiokande atmospheric neutrino results. The results for the other mixing angle gives $\sin^2\theta_{13}$=0.042+0.013-0.021 (normal hierarchy) and 0.049+0.015-0.021 (inverted hierarchy). The allowed region of parameters in δ_{CP} and $\sin^2\theta_{13}$ phacespace in shown in the right plot of Fig.1. When we combine the T2K results with the most precise measurement of θ_{13} mixing parameter obtained by reactor experiment [11] then the allowed region of parameters shrinks. As a result we can exclude $\delta_{CP}=[0.15,0.83]\pi$ for normal hierarchy and $\delta_{CP}=[-0.08,1.09]\pi$ for inverted hierarchy at 90% confidence level. We can also conclude that the favored value of δ_{CP} is $-\pi/2$.

5.2 Anti-neutrino data results

The anti-neutrino data were collected from 2014 and results presented in this paper corresponds to $4.0\text{x}10^{20}$POT. For anti-neutrino run the ν_μ disappearance and ν_e appearance analyses were performed separately [9, 10].

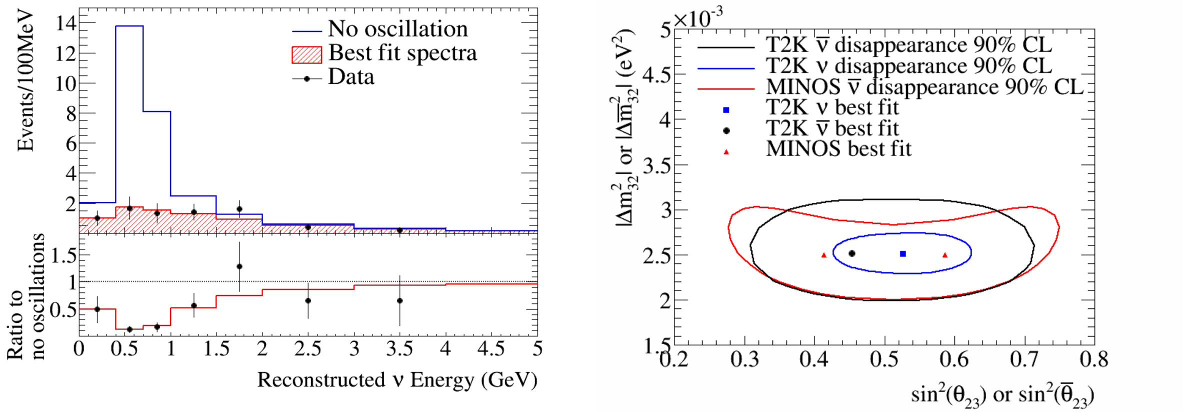

Fig.2 Left – Distribution of reconstructed neutrino energy for ν_μ data and MC; Right – Allowed region of parameters for ν_μ and ν_μ oscillations.

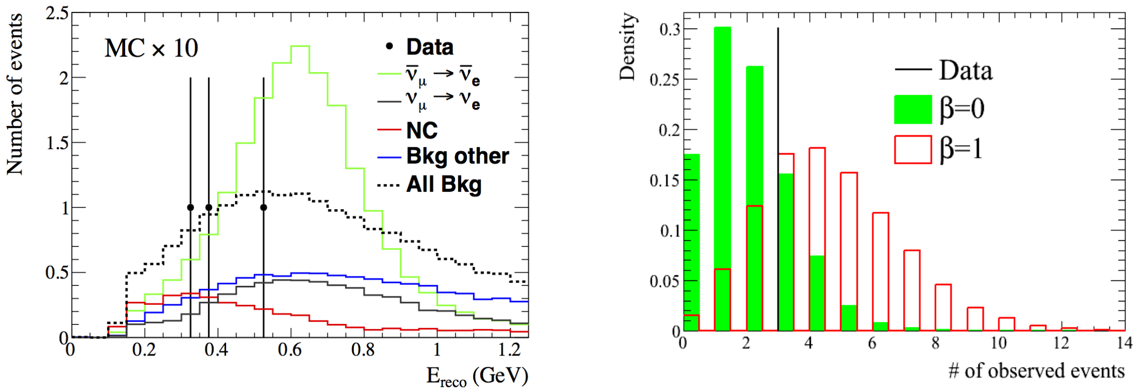

Fig.3 Left – Distribution of reconstructed neutrino energy for ν_e data and MC; Right – Distribution of expected number of events for set of toy MC experiments.

There are 34 muon events found in the anti-neutrino run at the far detector. In case of no oscillation the expected number of events is 103.6 (for $\sin^2 2\theta_{32}=0.0$). The clear signature of observed ν_μ disappearance is shown on energy spectrum distribution of muon events in the left plot of Fig.2. During fitting procedure to ν_μ data all oscillation parameters were fixed except $\sin^2\theta_{23}$ and Δm^2_{32}. Results, presented on the right plot of Fig.2 shows that obtained mixing parameters for anti-neutrinos are consistent with those measured by T2K for neutrino beam (proving that CPT is conserved). On the other hand results are consistent with other measurements of anti-neutrinos performed by MINOS and Super-Kamiokande. The measured values for the oscillation parameters were found to be $\sin^2\theta_{23}=0.45+0.38-0.64$ and $|\Delta m^2_{32}|=2.51+0.29-0.26 \text{ x } 10^{-3}$ eV^2/c^4.

For the T2K ν_e induced events we detected 3 events when 1.3 events are expected in case of no oscillation and 3.7 events are expected if anti-neutrinos oscillate same as neutrinos assuming normal mass hierarchy and $\delta_{CP}=-\pi/2$ (see left plot of Fig.3 for energy distribution of those events). To be more accurate the expected number of events depends on the value of assumed δ_{CP} phace and mass hierarchy. For normal mas hierarchy we expect 3.7, 4.3 and 4.9 events for δ_{CP} equales $-\pi/2$, 0 and $\pi/2$ respectively; when for inverted mass hierarchy those numbers change to 4.2, 4.9 and 5.5 expected events. Since the statistics of accumulated data is so low we introduce the β parameter which rescales the probability of ν_e appearance:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \to \bar{\nu}_e)$$

β=0 corresponds to situation when no ν_e oscillation occurs while β=1 represents the case where ν_e appearance occurs with the same oscillation parameters as ν_e appearance. The toy experiments were performed which throws parameters θ_{23}, θ_{13}, Δm^2_{32} and δ_{CP} to obtain the expected number of events for each toy MC for two values of parameter β (0 or 1). Obtained distribution of expected number of events for those two scenarios shown in right plot of Fig.3 shows that with 3 detected events those two scenarios can not be distinguished. Therefore, more statistics is needed to judge whether ν_μ->ν_e oscillation occurs.

6. Summary remarks

The T2K is a world-leading experiment of neutrino physics, which so far provided the most precise measurement of θ_{23} mixing angle and discovered the appearance of ν_e in ν_μ beam. We also start to be sensitive to unknown δ_{CP} violating phase. T2K starts to analyze the anti-neutrino data and proves that ν_μ disappearance is consistent with neutrino results. Results based on statistics discussed here are insufficient to allow us to draw conclusion regarding ν_e appearance. For the most up-to date situation reader may refer to results announced during Neutrino 2016 and ICHEP 2016 conferences.

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