論文の内容の要旨

Measurement of neutrino interactions on water and search for electron anti-neutrino appearance in the T2K experiment

(T2K実験における水標的でのニュートリノ反応の測定と反電子ニュートリノ出現現象の探索)

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Particle physics is one of the branches of physics to investigate a fundamental theory to explain the origin and behavior of elementary particles which compose our universe with no substructure. The most successful theory is the standard model (SM) which was born in 1970s and has explained almost all experimental results. However, there are many mysteries which are not described by the SM: origin of mass of neutrinos, origin of matter-antimatter asymmetry in the universe, existence of dark matter, dark energy and so on. To answer these questions, there have been many theoretical and experimental approaches.

Physics of neutrino is one of them. Neutrino is a neutral lepton and one of the fundamental particles in the SM. In 1998, a property of neutrinos to change their flavor while flying (neutrino oscillation) was observed through a measurement of atmospheric neutrinos by Super-Kamiokande collaboration. The observation requires to modify the SM because an existence of the neutrino oscillation indicates the non zero masses of the neutrinos with a mixing of their flavor and mass eigenstates. In addition, the observation of neutrino oscillation indicates possible CP violation in the lepton sector through the flavor mixing. It is possible to explain the matter-antimatter asymmetry with large CP violation in the lepton sector and leptogenesis scenario, however, the CP violation in the lepton sector is not observed so far. In addition, we have a question about modeling of the flavor mixing in the lepton sector. In the current understand, the flavor mixing of the neutrino is explained that the three flavor and three mass eigenstates are mixed through a 3×3 unitary matrix (PMNS matrix). To validate if this standard three flavor mixing model is correct or not, consistency checks between theoretical predictions with the model and experimental measurements are needed through many experiments with several points of views. However, due to difficulty of the neutrino detection, the enough number of the consistency checks have not been performed in the lepton sector compared with that in the quark sector, which has been checked with many measurements of the unitary matrix elements. At present, the flavor mixing structure in the lepton sector can be measured only through the

measurement of the neutrino oscillation. A precise understanding of the neutrino oscillation is important to observe the CP violation in the lepton sector for the first time in the world and to validate the three flavor mixing model.

T2K is a long baseline neutrino oscillation experiment, started from 2009. A muon neutrino beam produced by J-PARC accelerator is measured by the Super-Kamiokande detector to measure probabilities of neutrino oscillations. Main purposes of the T2K are the first observation of CP violation in lepton sector and an investigation of flavor mixing structure. In this thesis, three analyses are performed to achieve precise neutrino oscillation measurements in the T2K experiment.

The first analysis is measurements of inclusive charged current muon neutrino cross sections with water, plastic, iron and their ratios. The purpose of the measurements is to understand difference of the neutrino-nucleus interactions between the plastic and water target that is one of systematic uncertainties in the T2K. The analysis is performed with a new water target detector, water module, one of the T2K near detectors located at on-axis. Main results of the measurements are $\sigma_{\mathrm{CC}}^{\mathrm{H_2O}} = (0.840^{+0.010}_{-0.010}(\mathrm{stat.})^{+0.10}_{-0.081}(\mathrm{syst.})) \times 10^{-38}\mathrm{cm}^2/\mathrm{nucleon}$ and $\frac{\sigma_{\mathrm{CC}}^{\mathrm{H_2O}}}{\sigma_{\mathrm{CC}}^{\mathrm{CH}}} = 1.028^{+0.016}_{-0.016}(\mathrm{stat.})^{+0.053}_{-0.053}(\mathrm{syst.})$ for muons whose angle is less than 45 degree and momentum is more than 0.4 GeV with the mean neutrino energy of 1.5 GeV, as shown in Fig. 1. These are the best measurement of the neutrino interaction with water target and the first measurement of the cross section ratio of water and plastic. Because there has been almost no data of the water target, the uncertainty of the difference of the neutrino interaction with water and plastic have been assigned based on only prediction with the modeling of the neutrino interaction without data for the T2K oscillation analysis. This measurement ensures correctness of the uncertainty with experimental data for the first time in the world and improves reliability of the oscillation analysis of the T2K.

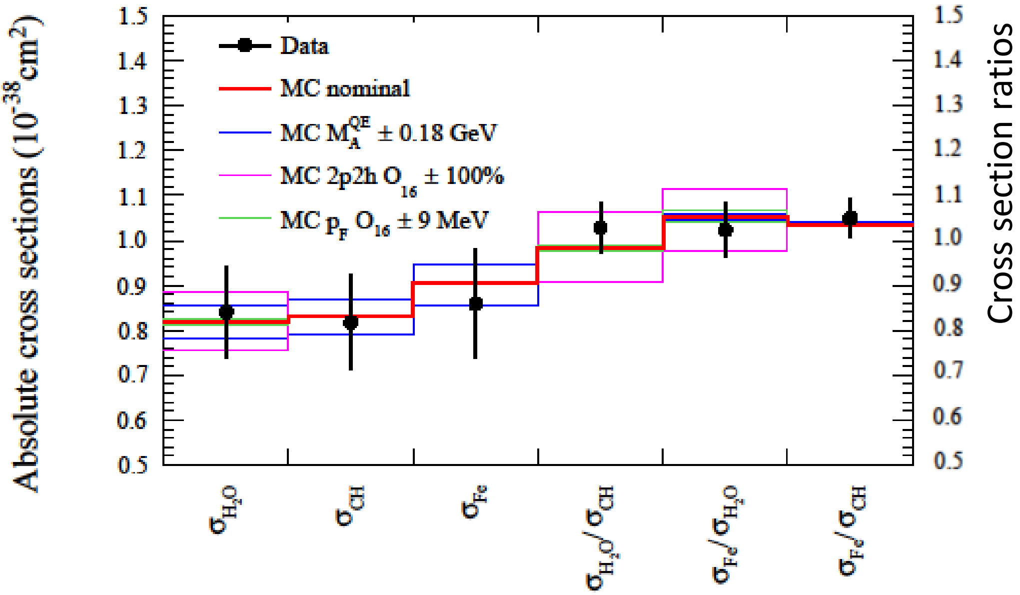


Figure 1: Results of cross section measurement (black point) with total uncertainties (black line) and theoretical predictions by NEUT (solid lines).

The second analysis is a validation of the measurement of the T2K near detector, ND280. The ND280 measures neutrino flux and interactions and constrains their uncertainties for the T2K oscillation measurements. However, it is impossible to check if the constraint is correct or not at the far detector directly because not only the flux and interactions but also the neutrino oscillations affect the neutrino events at the Super-Kamiokande. In this analysis, observed neutrino event rates at other near detectors located at on-axis, water module and Proton Module, are compared with Monte Carlo prediction with the constraint from the ND280. This is the first trial to cross check the constraint from the near detector based on real data in any long baseline neutrino experiments. A left plot in Fig. 2 shows the ratio of the measured forward scattered muons at the on-axis detectors and their Monte Carlo predictions with the constraint from the ND280. They are statistically consistent with the prediction with a p-value of 0.303. This ensures the correctness of the constraint from the ND280. On the other hand, the measured event rates of large angle muons and protons, which are not included in the ND280 measurement, are not consistent with the prediction as shown in a right plot in Fig. 2 with a p-value of 4×10^{-4}. It indicates the over prediction of the number of emitted protons and gives a significant hint to improve a modeling of the neutrino interactions.

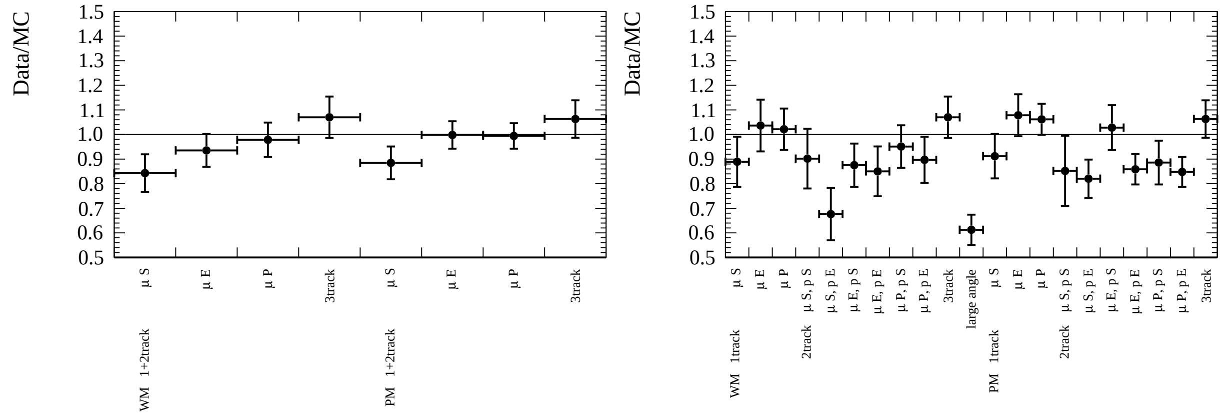
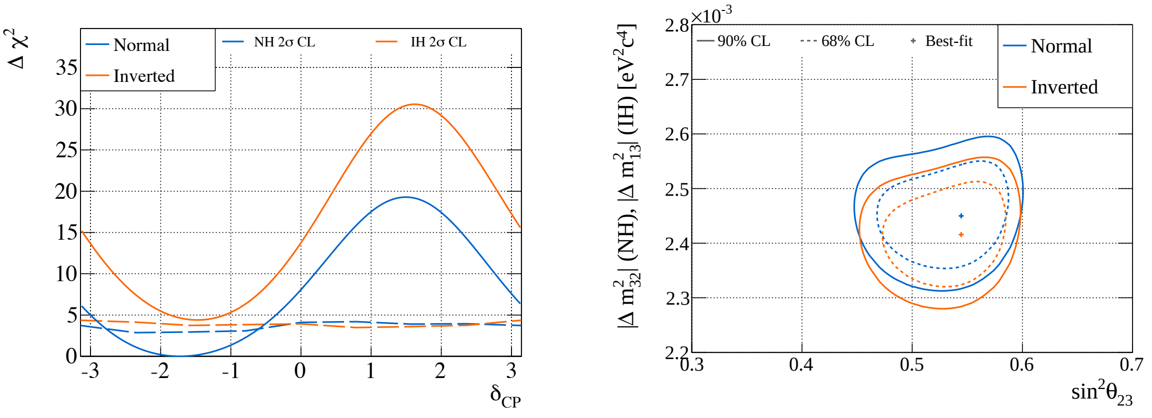


Figure 2: Ratio of the total number of selected events between data and Monte Carlo predictions with the constraint from the ND280 for each event sample with different number of tracks and muon kinematics. The left figure shows only the information of forward scattered muons. The right figure includes the information of large angle scattered muons and protons. S, E and P in label of the figure mean that the reconstructed track is stopped, escaped and penetrated from the detector respectively.

The third analysis is a measurement of the neutrino oscillations with doubled statistics compared with the last T2K analysis performed in 2016. The accumulated number of protons used for the analysis is 1.49×10^{21} with neutrino beam and 1.12×10^{21} with anti neutrino beam. Four types of the neutrino oscillations, $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\overline{\nu}_\mu \to \overline{\nu}_\mu$ and $\overline{\nu}_\mu \to \overline{\nu}_e$, are measured by the Super-Kamiokande. The four oscillations are jointly fitted to extract the parameters of the unitary matrix in the standard three flavor mixing model (PMNS matrix): δ_{CP}, θ_{23}, Δm^2_{32} and θ_{13} as well as mass hierarchy, which is order of neutrino mass eigenstates. The measured values with 1σ uncertainties are $\delta_{CP} = -1.72^{+0.58}_{-0.61}([-2.739, -0.6078]$ with 2σ intervals), $\sin^2\theta_{23} = 0.544^{+0.046}_{-0.029}$, $\Delta m^2_{32} = 2.450^{+0.065}_{-0.068}\times10^{-3}eV^2$ and $\sin^2 2\theta_{13} = 0.0871^{+0.0043}_{-0.0045}$ with the normal hierarchy assumption and constraint from solar and reactor neutrino experiments. The δ_{CP}, θ_{23} and Δm^2_{32} are measured with the best accuracy in the world as shown in Fig. 3. $\delta_{CP} = 0$,



δ_{CP} $\Delta m^2_{32} - \sin^2\theta_{23}$

Figure 3: Contours of the δ_{CP} with critical $\Delta\chi^2$ values of 2σ (left) and contours of the Δm^2_{32} vs $\sin^2\theta_{23}$ (right) with constraint from solar and reactor neutrino experiments.

corresponding to CP conservation, is excluded with a significance of 2σ for the first time in the world. Normal hierarchy is more preferred than inverted hierarchy with a Bayes factor of 10.49 with the reactor constraint. These results are consistent with other neutrino oscillation experiments. In addition, a search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation is performed. $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation is not observed so far although it is predicted by the standard oscillation framework. Two hypothesis are tested in this analysis as shown in Fig. 4. One hypothesis assumes a probability of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ is zero and the other assumes the probability is the same as the prediction from the PMNS matrix parameters. P-value of the former (latter) hypothesis is calculated to be 0.219 (0.213) based on information of only the total number of observed event. With additional information of lepton kinematics, the p-value of the former (latter) hypothesis is calculated to be 0.233 (0.087). Both of the hypotheses are not excluded. This analysis is performed with the best sensitivity in the world

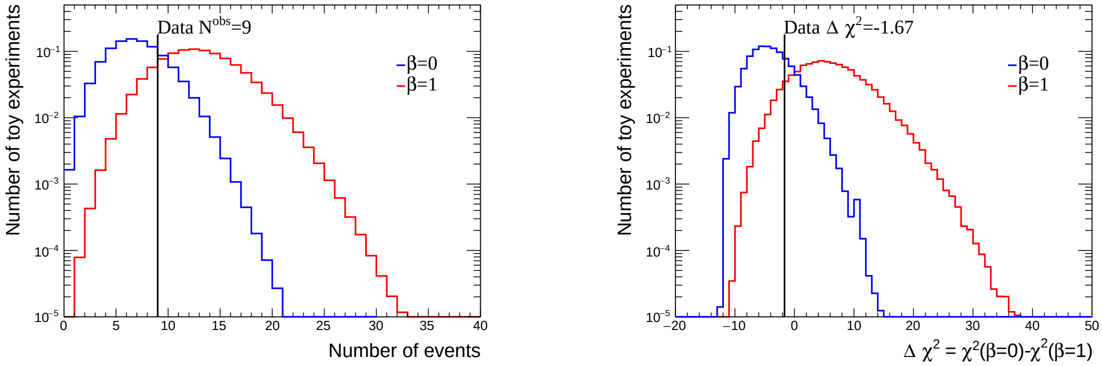


Figure 4: Results for rate only analysis (left) and rate+shape analysis (right). $\beta = 0$ means a hypothesis assuming a probability of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ is zero and $\beta = 1$ means the other hypothesis.