T2KK Sensitivity with more Systematic Error Terms

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Abstract

The effect of the systematic uncertainties in CP violation and mass hierarchy measurement of T2KK experiment is studied. The systematic errors in neutrino beam flux, neutrino cross section and detection efficiency, including the relative uncertainties between neutrino and anti-neutrino and inter-detector efficiencies, are considered.

1. Introduction

T2KK is a proposed experiment to locate two Megaton size detectors at both kamioka and korea, and measure the neutrino oscillation using same neutrino beam produced in J-Parc facility [8]. The CP violation and mass hierarchy are possible to be probed simultaneously via $\nu_\mu \to \nu_e$ oscillation and improve their sensitivities thanks to larger matter effect. However these sensitivities will be affected depending on the systematic errors because $\nu_\mu \to \nu_e$ signal event rate is expected to be small compared to many backgrounds coming from the unoscillated ν_μ and the intrinsic beam ν_e interactions.

The possible systematic errors can be divided into three categories : neutrino beam flux, cross section and detection efficiency. In addition to the absolute flux normalization, the relative flux difference could be uncertain. Though the off-axis angles of neutrino beam are same, these two detector are not exactly on the same baseline. The asymmetry of neutrino beam spread perpendicular to the beam direction will lead to these uncertainties. Since CP violation and mass hierarchy are measured by the difference of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities, the relative uncertainties, such as $\nu/\bar{\nu}$ ratio of flux, cross section, detection efficiency are important. The detector-related systematic errors should be considered. Even if kamioka and korea detectors are identical, the acceptance and energy scale cannot be completely same due to the condition of each detector, such as detector gain, water scattering, etc. Among these error sources understanding which systematic term has large effect for the T2KK sensitivities may be important not only for T2KK but also other long baseline experiment.

2. Analysis

Only three systematic error terms are considered in [8] (signal normalization 5 %, background normalization 5 %, background energy spectrum index 5 %). These are common for two detectors and ν and $\bar{\nu}$ measurements. In this paper we introduced nine systematic error terms as shown in Table 1. Two independent terms (1a & 1b) are introduced for the difference of the absolute normalization of the backgrounds between two detectors. One term (1c) for the relative uncertainties of background between ν and $\bar{\nu}$ runs. We assumed the uncertainty of the background spectrum shape is correlated between two detectors and ν-$\bar{\nu}$ runs (1d). One absolute normalization term (2a) and one error on $\nu/\bar{\nu}$ ratio (2b) are considered in the signal rate calculation. One systematic error term (2c) is for the efficiency difference of two detectors. The systematic errors related to the observed

Table 1 Implemented systematic error terms

Systematic Error Source	Error
1. Background	
1a. absolute normalization (kamoka)	5 %
1b. absolute normalization (korea)	5 %
1c. difference between ν and $\bar{\nu}$	5 %
1d. spectrum shape	5 %
2. Signal	
2a. $\sigma(\nu_e)$	5 %
2b. $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	5 %
2c. detector efficiency difference	1 %
3. Energy scale	
3a. difference between kamioka and korea	1 %
3b. difference between near and far detectors	1 %

neutrino energy scale are also assigned. Two systematic error terms for the energy scale are introduced. One is for that between kamioka and korea detectors (3a) and one is for the relative difference between two detectors and the beam monitor located at J-Parc site (3b). Please note that the error values quoted in Table 1 are optimistically estimated with expectation for the future progress in understanding the systematic errors.

We used same analysis framework as used in [8] but slightly improved in some details. In this framework the signal rate is calculated based on the analytical method. The signal spectrum is obtained by multiplying ν_μ ($\bar{\nu}_\mu$) neutrino flux, cross section, efficiency, and $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) oscillation probability as function of the neutrino energy. The signal rate is calculated for charged current quasi-elastic (CCQE) and non-quasi-elastic (CCnQE), separately. The 40 GeV 4 MW proton beam is assumed for the calculation of T2K neutrino beam flux for kamioka, which has been distributed inside T2K collaboration. The flux spectrum for korea was calculated for T2KK analysis using same beam simulation code. The spectrum shape and the normalization of anti-neutrino beam is assigned to be same as those of neutrino. The water Cherenkov detector of 0.27 Mton fiducial mass are assumed for kamioka and korea, respectively, with the same off-axis angle of 2.5 degrees. For comparison we derived the sensitivity for T2K 2nd phase (T2K-II) with 0.54 Mton fiducial mass. The beam time is 4 (2) years for neutrino run and 4 (6) years for anti-neutrino run for T2KK (T2K-II). The smearing method for deriving the reconstructed neutrino energy measured in the detector slightly changed in order to improve the detector response in water Cherenkov detector. The matrix method is adopted, which coefficient are taken from Super-K Monte Carlo simulation data. Four matrices are prepared for CCQE ν_e, CCnQE ν_e, CCQE $\bar{\nu}_e$ and CCnQE $\bar{\nu}_e$ interactions, respectively. The binning of the matrix is 10 MeV interval from 0−4 GeV. Then the signal spectrum is divided into five energy binning of 400−500, 500−600, 600−700, 800−900, 900−1200 MeV. The same background spectrum are used as used in [8] for both ν and $\bar{\nu}$ runs.

χ^2 method is employed to evaluate the sensitivities and defined as follows:

$$\chi^2 = \sum_{k=1}^{4}\left(\sum_{i=1}^{5}\frac{\left(N(e)_i^{obs} - N(e)_i^{exp}\right)^2}{\sigma_i^2}\right) + \sum_{j=1}^{9}\left(\frac{\epsilon_j}{\sigma_j}\right)^2$$

where $N(e)_i^{obs}$ is the observed events in each detector and neutrino run, $N(e)_i^{exp}$

is the expected events in each oscillation parameters, ϵ_j and σ_j is the systematic term and error.

3. Result

Fig. 1 and 2 shows the sensitivities with new and previous systematic error terms (normal hierarchy assumed). In general T2K-II sensitivities become decreased in some regions compared to the previous systematic error estimation. The sensitive region shifted to higher $\sin^2 2\theta_{13}$ for mass hierarchy, and for CP violation the sensitive region becomes narrow in $\sin^2 2\theta_{13}$ >0.02 region. Meanwhile T2KK sensitivities does not changed largely in all $\sin^2 2\theta_{13}$ region. Similar tendency is seen in inverted hierarchy case also. We investigated which systematic error source contributes largely to the deterioration of the sensitivity in T2K-II and found that background $\nu/\bar{\nu}$ ratio (1c), background spectrum (1d), and $\sigma(\nu)/\sigma(\bar{\nu})$ (2b) are responsible for that. Especially $\sigma(\nu)/\sigma(\bar{\nu})$ error seems to reduces CP violation sensitivity in the large $\sin^2 2\theta_{13}$ region. As for the stable sensitivity of T2KK it seems that the uncertainties in systematic errors are constraint thanks to the simultaneous measurements at both kamioka and korea. It could be one of the advantages in T2KK experiment.

Fig. 3 and 4 shows the change of the sensitivities by increasing the background (1a,1b,1c,1d) and the cross section (2a,2b) systematic errors from 5 % to 10 %, 15 %, respectively Actually T2K-II sensitivities are found to be affected significantly while those of T2KK are relatively stable. By increasing the background systematic error, the sensitive region slightly shifted to higher $\sin^2 2\theta_{13}$ in T2K-

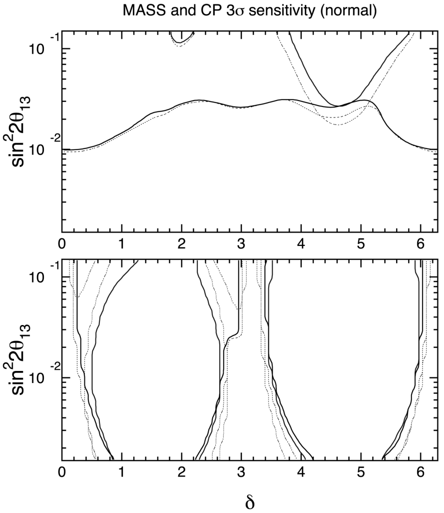

Fig. 1 Mass hierarchy (upper) and CP violation (lower) sensitivities with new (solid) and previous (dotted) systematic error terms for T2K-II (blue) and T2KK (black). The significant level is 3 σ. Normal hierarchy case is assumed.

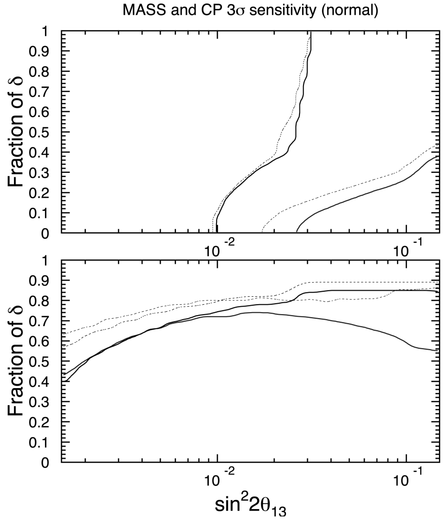

Fig. 2 Same orientations as in Fig. 1 but horizontal and vertical axis are represented by the $\sin^2 2\theta_{13}$ vs fraction of δ.

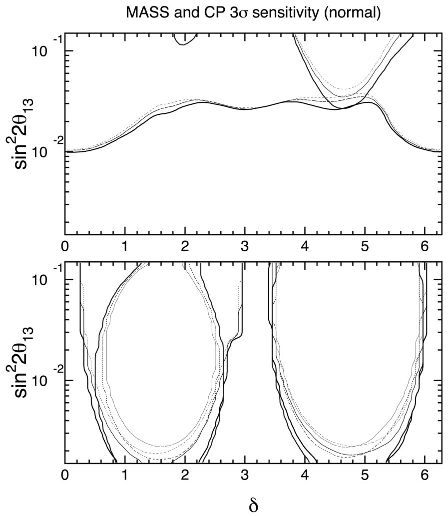

Fig. 3 Mass hierarchy (upper) and CP violation (lower) sensitivities for different background systematic errors : solid (5 %), dashed (10 %), dotted (15 %). Blue curves shows T2K-II and black shows T2KK.

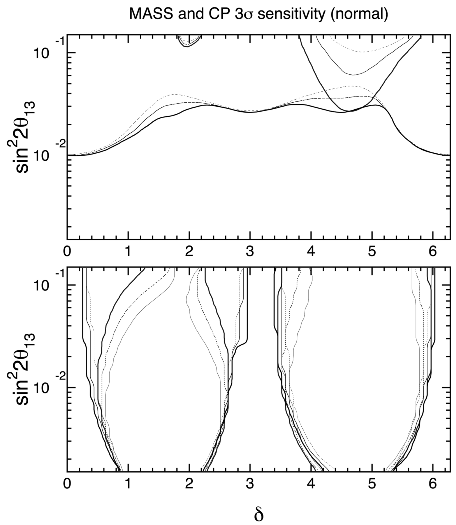

Fig. 4 Mass hierarchy (upper) and CP violation (lower) sensitivities for different cross section systematic errors : solid (5 %), dashed (10 %), dotted (15 %). Blue curves shows T2K-II and black shows T2KK.

II mass hierarchy measurement. In CP violation measurement both T2K-II and T2KK will lose sensitivities in small $\sin^2 2\theta_{13}$ region less than 0.01. By increasing the cross section systematic error, the mass hierarchy sensitivity will change significantly in T2K-II. The sensitive region less than 0.1 will lose gradually for larger systematic error. In CP violation measurement 30∼50 % sensitive region will decrease in T2K-II, especially in larger $\sin^2 2\theta_{13}$ region, while less than 10 % effect in T2KK.

4. Summary

Preliminary study of the systematic error effect in T2KK is presented. Mass hierarchy sensitivity is relatively stable for T2KK probably thank to the constraint of the simultaneous measurement at different long baseline while T2K-II sensitivity will be affected by the background and cross section errors mainly related to $\nu/\bar{\nu}$ uncertainties. Both T2KK and T2K-II will lose CP violation sensitivities by changing systematic error values but T2K-II is more sensitive especially in $\sin^2 2\theta_{13} > 0.01$ region.

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References

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