# Toward Realistic Evaluation of The T2KK Physics Potential

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## Abstract

The Tokai-to-Kamioka-and-Korea (T2KK) experiment has a high sensitivity to determine the neutrino mass hierarchy for a combination of relatively large ($\sim 3.0^\circ$) off-axis angle beam at Super-Kamiokande (SK) and small ($\sim 0.5^\circ$) off-axis angle beam for 100kton water Čerenkov detector at $L \sim 1,000$ km in Korea. We elaborate our previous analyses by using the realistic energy resolution for the reconstructed neutrino energy and applying the detector efficiency for both $\nu_\mu$ and $\nu_e$ event. We also take account of the $\pi^0$ background and probability of the particle miss identification between $\mu$ and $e$. It is found that the mass hierarchy pattern can be determined at $3\sigma$ level for $\sin^2 2\theta_{\text{RCT}} \equiv \sin^2 2\theta_{13} \gtrsim 0.08$ (0.09) when the hierarchy is normal (inverted), after $5 \times 10^{21}$ POT exposure. We also find that the leptonic CP phase can be constrained as ±45° at $1\sigma$ level for both hierarchy assumed without anti-neutrino running, when $\sin^2 2\theta_{\text{RCT}} = 0.10$ and $\delta_{\text{MNS}} = 0^\circ$. However, $\delta_{\text{MNS}}$ cannot be determined at $3\sigma$ level.

## 1. Introduction

Under the three generation framework, neutrino oscillation is governed by 2 mass-squared differences and 4 independent parameters in the Maki-Nakagawa-Sakata (MNS) matrix [1], that is 3 mixing angles and 1 CP phase ($\delta_{\text{MNS}}$). The absolute value of the larger mass-squared difference, $|\delta m^2_{13}| \equiv |m^2_3 - m^2_1|$, and one of the MNS matrix elements $U_{\mu 3} \equiv \sin\theta_{\text{ATM}}$, are determined by the atmospheric neutrino observation [2, 3]. The first generation long baseline neutrino oscillation experiments, K2K [4] and MINOS [5] confirmed the results of them. But, the sign of the $\delta m^2_{13}$ has not been determined. The Tokai-to-Kamioka (T2K) neutrino oscillation experiment [4], which is one of the next generation accelerator based long baseline experiment, plans to measure the value of $|\delta m^2_{13}|$ and $U_{\mu 3}$ more precisely by using the off-axis beam (OAB). The value of the smaller mass-squared difference, $\delta m^2_{12}$ and the value of other MNS elements, $4|U_{e1}U_{e2}|^2 \equiv \sin^2 2\theta_{\text{SOL}}$ are measured by the solar neutrino observations [7]. The results of the KamLAND experiment [8] is consistent with these results. The sign of the $\delta m^2_{12}$ can be determined from the matter effect inside the sun. The value of the $|U_{e3}| \equiv \sin\theta_{\text{RCT}}$ is only known the upper bound from the reactor experiment [9]. In coming reactor experiments [10], plan to measure the unknown element $|U_{e3}|$ from $\bar{\nu}_e$ survival probability. The leptonic CP phase, $\delta_{\text{MNS}} = -\arg U_{e3}$ [11], has not been measured yet.

The mass hierarchy pattern will be remained as the unknown parameter after new experiments. We named $\delta m^2_{13} > 0$ ($\delta m^2_{13} < 0$) as the normal (inverted) hierarchy. In our previous studies [12], we explore in detail the physics impacts of the idea [13] for placing an additional far detector in Korea along the T2K neutrino beam line. We examined the effects of placing a 100kton water Čerenkov detector in Korea, about 1000km away from J-PARC [14], for accumulating $5 \times 10^{21}$

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POT (protons on target). We find that this Tokai-to-Kamioka-and-Korea (T2KK) neutrino oscillation experiment has the good capability to determine the neutrino mass hierarchy pattern by comparing the $\nu_e$ event numbers at SK and that at a far detector in Korea. The CP phase can also be determined from the amplitude and oscillation phase of the $\nu_\mu \to \nu_e$ probability. By studying these physics merits of the T2KK experiment semi-quantitatively, we find that the most optimal combination is a 3.0° OAB at SK and a 0.5° OAB at $L = 1000$km in Korea for the mass hierarchy determination. The CP phase can also be determined without an anti-neutrino phase for this optimal combination, when the value of $U_{e3}$ is not too small [12]. A magnificence setup of the T2KK idea has been studied in related research [15], The idea of placing two detectors along one neutrino beam has also been studied for the Fermi Lab. neutrino beam [16].

Because of simplicity, we omitted the following points in our previous studies [12]. The first one is the detail of the matter profile between Japan and Korea and its uncertainty. This point has been shown in Ref.[17]. The second, we did not take into account the background from the $\pi^0$ which is produced by the neutral current (NC) interaction. It was not also considered that the events from the nuclear resonance for the $\mu$- and $e$-event and the effect of the energy reconstruction. The third point is the detector efficiency. From the SK study [2], the efficiency of the $\mu$-like event is almost 100%, but, for $e$-like event is roughly 90%. Because the capability of the mass hierarchy determination and the CP phase measurement depend on the number of the $\nu_e$ event, we have to include these efficiencies in the analysis. We also have to consider the probability of the particle miss identification between $\nu_\mu$ and $\nu_e$ event. The probability of this miss-PID is less than 1%. But this probability cannot be negligible, because of many $\nu_\mu$ event. In this work, we reanalyze the capability of the T2KK experiment including these points and estimate the impact to the T2KK capability.

## 2. Event Numbers

### 2.1. *Charged current event*

In this work, we use the reconstructed energy, $E_{\rm rec}$, from the 1-ring event for the event binning. For this purpose, we make the event distribution functions for converting the neutrino energy, $E_\nu$ to $E_{\rm rec}$ with the detector resolution by using Monte Carlo event generator, `nuance` [18].

Because $E_{\rm rec}$ is estimated from the energy and scattered direction of the 1-ring event, we adapt the following selecting criteria for choosing the 1-ring event from the all events generated by `nuance` :

$$\text{Only one charged lepton } (\mu/e) \text{ with } |p_l| > 200\text{MeV}. \tag{1a}$$

$$\text{No high energy } \pi^\pm \ (|p| < 200\text{MeV})\,. \tag{1b}$$

$$\text{No high energy } \gamma \ (|p| < 30\text{MeV})\,. \tag{1c}$$

$$\text{No } \pi^0,\ K^0,\ \text{and } K^\pm\,. \tag{1d}$$

The lower limit of the total momentum in the first criteria eq. (1a) is from the threshold of the water Čerenkov detector for $\nu_\mu$ event [3]. The other criteria is need to eliminate the multi-ring events [3].

After applying the detector resolution, we find that the shape of the event distribution for the CCQE interaction can be fitted with three Gaussians. The same as CCQE event, the fit function for the nuclear resonance event is also obtained. Since the number of the intermediate state for the heavy resonance meson depends on the $E_\nu$, the fit function for the nuclear resonance event is described the superimpose of three Gaussians between $E_\nu = 0.55$GeV and 1.2GeV and that with four Gaussians for $E_\nu > 1.2$GeV. The solid line in Fig. 1 is the fit

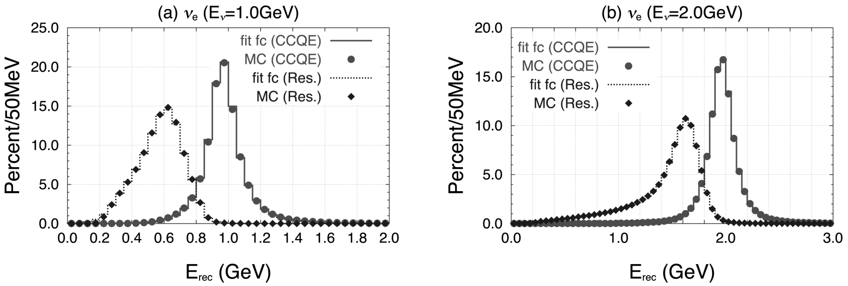

**Fig. 1** The solid line shows the fitting function for the CCQE event which is used in our analysis and the dotted line is for the nuclear resonance event, with $E_\nu = 1.0\text{GeV}$ in (a) and $E_\nu = 2.0\text{GeV}$ in (b). Each distribution functions is normalized independently. The solid circle (diamond) stands for the data of the CCQE (nuclear resonance) event from the Monte Carlo calculation by `nuance` [18].

function for the CCQE event. The shape of the fitting function for the nuclear resonance event is shown as the dotted lines in Fig. 1. Each distribution functions is normalized independently. The solid circle (diamond) stands for the data of the CCQE (nuclear resonance) event from the Monte Carlo calculation by `nuance` [18]. From this figure, the fitting functions, which we use in this work, well reproduce the event distribution from the Monte Carlo generator.

### *2.2. Neutral current event*

Both of the mass hierarchy and the CP phase is determined by the $\nu_e$ appearance event. Because some of the $\pi^0$ which is produced by the NC interaction seems as the $\nu_e$ event, we have to estimate the event numbers of the $\pi^0$ and the probability for the particle miss identification between $\pi^0$ and $\nu_e$ event.

At first, we generate the events which include all interaction mode for each OAB flux with 100kton fiducial volume water Čerenkov detector at 1000km away from J-PARC after $5 \times 10^{21}$ POT exposure. All the generated event are selected by the following event cut criteria :

$$\text{No charged leptons.} \tag{2a}$$

$$\text{Only one } \pi^0 \,. \tag{2b}$$

$$\text{No high energetic } \pi^{\pm} \ (|p| < 200\text{MeV})\,. \tag{2c}$$

$$\text{No high energetic } \gamma \ (|p| < 30\text{MeV})\,. \tag{2d}$$

$$\text{No } K^0 \text{ and } K^{\pm}. \tag{2e}$$

These selecting criteria choose the CC-like event from the NC event set. After adopting these event selections, the $\pi^0$ event distribution for each OAB against the $\pi^0$ total momentum is shown in Fig. 2 (a).

Figure 2(a) indicates that there are many one-$\pi^0$ events for the smaller OAB. Some of them become the background of the $\nu_e$ event. If the energy of one $\gamma$ is larger than the other, that $\gamma$ makes a strong ring which seems as the $\nu_e$ signal. The $\pi^0$ background also cannot discriminate the $\nu_e$ event, when the opening angle between two $\gamma$s is small. These facts suggest that the probability for miss PID between $\pi^0$ and $\nu_e$ event can be denoted by the energy ratio of two $\gamma$s and the opening angle between them at the laboratory frame naively. The energy ratio of

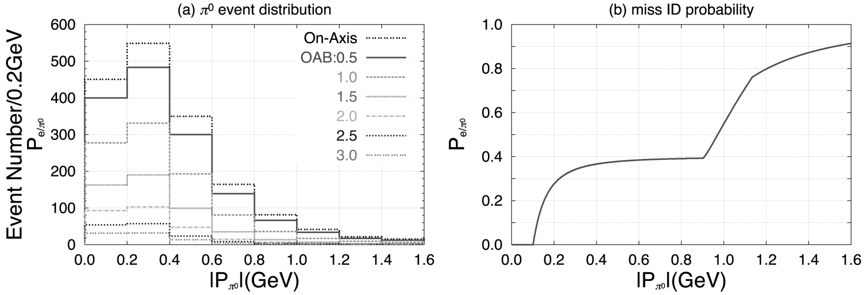

**Fig. 2** (a): The $\pi^0$ event distribution of each OAB for 100kton water Čerenkov detector at $L = 1000$km with $5 \times 10^{21}$POT exposure, after adapting the event cut criteria. (b): Probability of the particle miss identification from the $\pi^0$ event to the $e$-like event, eq. (5). The horizontal axis of the both figures is the $\pi^0$ total momentum.

two $\gamma$s is given

$$R \equiv \frac{E_2}{E_1 + E_2} = \frac{1}{2}(1 - x) \,, \qquad x \equiv \beta \cos\hat{\theta} \ (\hat{\theta} < 90^\circ) \,, \tag{3}$$

where we define as $E_2 < E_1$, $\hat{\theta}$ is the angle between one of the $\gamma$ and the $\pi^0$ accelerate direction from the $\pi^0$ rest frame to the laboratory frame and $\beta$ is the velocity of the $\pi^0$. By using $x$ and $\beta$, the opening angle between two $\gamma$s is written as

$$C \equiv \cos\theta_{\gamma\gamma} = \frac{2\beta^2 - 1 - x^2}{1 - x^2} \,. \tag{4}$$

By using $R$ and $C$, the probability for the miss PID can be naively assumed as

$$P_{e/\pi^0}(|p_{\pi^0}|) \equiv \frac{1}{\beta}\int_0^{\beta} [\Theta(Rc - R) + f(R, C)\Theta(R - Rc)\Theta(C - Cc)]\, dx \,, \tag{5}$$

where $\Theta(x)$ is the step function and

$$f(R, C) \ \ \equiv \ \ 1.0 - \left(\frac{R - Rc}{0.5 - Rc}\right)^{1/2} \left(\frac{1.0 - C}{1.0 - Cc}\right)^{3/2} \,. \tag{6}$$

Here, $Rc$ and $Cc$ is critical energy ratio and opening angle for miss PID. We assume that $Rc = 0.2$ and $Cc = \cos 17^\circ$. The reconstruct energy $E_{\rm rec}$ of each $\pi^0$ background is derived from $\pi^0$ total momentum and the scattered direction which are from the Monte Carlo calculation.

### *2.3. Total event numbers*

The numbers of $\nu_e$ and $\nu_\mu$ event thought CC interaction in the $i$-th energy bin, $E^i_{\rm rec} \equiv 0.2 \times i\,({\rm GeV}) \leq E < 0.2\,(i+1)({\rm GeV})$, are calculated as

$$N^{i,X}_{\beta}(\nu_\alpha) = MN_A \int_{E^i_{\rm rec}}^{E^{i+1}_{\rm rec}} dE \int_0^{\infty} dE_\nu \Phi_{\nu_\alpha}(E_\nu)\ P_{\nu_\alpha \to \nu_\beta}(E_\nu)\ \hat{\sigma}^X_\beta(E_\nu)\ F^X_\beta(E; E_\nu) \,, \tag{7}$$

where $M$ is the detector mass, $N_A = 6.017 \times 10^{23}$ is the Avogadro constant, $\Phi_{\nu_\alpha}$ is the $\nu_\alpha$ flux ($\nu_{\alpha,\beta} = \nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$) from J-PARC, $P_{\nu_\alpha \to \nu_\beta}$ is the neutrino oscillation probability including the matter effect. Because the $\pi^0$ or $\gamma$ which makes a ring is rarely produced by the nuclear effect of the oxygen for the CCQE interaction, the cross section for the 1-ring CCQE event is reduced at high energy. Including this effect, we use "effective" cross section, $\hat{\sigma}_\beta^X(E_\nu)$, not only for nuclear resonance event, but also CCQE event. For the nuclear resonance event, "effective" cross section is obtained from the total CC cross section. These relations are estimated from the Mote Carlo calculation. $F_\beta^X(E; E_\nu)$ is the converting functions from $E_\nu$ to $E_{\rm rec}$, which are derived from the fitting functions. Both of the "effective" cross section and the converting function for the anti-neutrinos are different from those of neutrinos. But we use the same converting function and the same relation between the "effective" cross section for the anti-neutrino and that of the CCQE and CC interaction, because the flux of the anti-neutrinos is negligibly small and the cross section of them is also smaller than that of the neutrinos.

The total event number from the CC interaction in each bin is

$$N_\alpha^{i,\rm CC} = \varepsilon_\alpha \sum_{X=\rm CCQE,Res} \left[ N_\alpha^{i,X}(\nu_\mu) + N_\alpha^{i,X}(\nu_e) + N_{\bar{\alpha}}^{i,X}(\bar{\nu}_\mu) + N_{\bar{\alpha}}^{i,X}(\bar{\nu}_e) \right] , \qquad (8)$$

for $\alpha = e$ and $\mu$. Here $\varepsilon_e$ and $\varepsilon_\mu$ is the detector efficiency for each flavor.

A few of $\mu$-event seems like a $e$-event for a water Čerenkov detector. The probability of this miss PID is less than 1% but this cannot be negligible, because of many $\mu$-event. After adding the event number from $\pi^0$ decay of each $i$-th bin ($N_{\pi^0}^i$) to the $e$-like event, the total event number are written as

$$N_e^i = N_e^{i,\rm CC} + P_{\mu/e} N_\mu^{i,\rm CC} + N_{\pi^0}^i \, , \qquad N_\mu^i = (1 - P_{\mu/e}) N_\mu^{i,\rm CC} \, , \qquad (9)$$

where $P_{\mu/e}$ is the probability of miss PID between $\mu$ and $e$.

## 3. Analysis Method

In order to quantify the T2KK physical potential and the effect of the systematic errors, we introduce a $\chi^2$ function as

$$\Delta\chi^2 \equiv \chi^2_{\rm SK} + \chi^2_{\rm Kr} + \chi^2_{\rm sys} + \chi^2_{\rm para} \, . \qquad (10)$$

The first two terms, $\chi^2_{\rm SK}$ and $\chi^2_{\rm Kr}$, measure the parameter dependence of the fit to the SK and the Korean detector data, respectively,

$$\chi^2_{\rm SK,Kr} = \sum_i \left\{ \left( \frac{(N_e^i)^{\rm fit} - (N_e^i)^{\rm input}}{\sqrt{(N_e^i)^{\rm input}}} \right)^2 + \left( \frac{(N_\mu^i)^{\rm fit} - (N_\mu^i)^{\rm input}}{\sqrt{(N_\mu^i)^{\rm input}}} \right)^2 \right\} , \qquad (11)$$

where $N_{\mu,e}^i$ is given in eq. (9), and its square root gives the statistical error. For calculating these event, we consider a 100kton fiducial volume water Čerenkov detector at Korea with $5 \times 10^{21}$ POT exposer. The summation is over all bins from 0.4GeV to 5.0GeV for $N_\mu$, 0.4GeV to 1.2GeV for $N_e$ at SK, and 0.4GeV to 2.8GeV for $N_e$ at Korea, because the neutrino flux is small in the higher energy region, and also the rapid oscillate and the cross section is small in the lower energy region.

$(N^i_\alpha)^{\rm fit}$ is calculated by allowing the model parameters to vary freely and by including the systematic errors. We take into account six types of the systematic errors in this analysis. The first systematic error is for the uncertainty in the matter density, for which we assume 6% overall uncertainty along the baseline, independently for T2K ($f_\rho^{\rm SK}$) and the Tokai-to-Korea experiment ($f_\rho^{\rm Kr}$). The second ones are for the overall normalization of each neutrino flux, for which we assume 3% errors $f_{\nu_\beta}$. This normalization factor are taken independently for SK and Korea direction. The third ones are for the cross sections ($f_\alpha^X$), where $\alpha$ denotes $\ell \equiv e = \mu$ and $\bar\ell \equiv \bar e = \bar\mu$ and $X$ is CCQE (CC) for the CCQE (nuclear resonance) event, respectively. Because both of the CCQE and CC cross section for $\nu_e$ and $\nu_\mu$ are expected to be very similar theoretically, we assign a common overall error of 3% for $\nu_e$ and $\nu_\mu$, and also an independent 3% error for $\bar\nu_{e,\mu}$ CCQE cross sections ($f_\alpha^{\rm CCQE}$). For nuclear resonance event, we assume 20% error for the CC cross sections of $\nu_{e,\mu}$ and $\bar\nu_{e,\mu}$ independently ($f_\alpha^{\rm CC}$). Also, we introduce the 50% systematic error for the cross section of the $\pi^0$ background ($f_{\pi^0}$). The event number of the $\pi^0$ background is not only proportional to the uncertainty of the $\pi^0$ cross section but also the uncertainty of the initial neutrino flux. Because of simplicity, we assume that the normalization of primary neutrino flux, $f_{\nu_\mu}$, only affects the $N^i_{\pi^0}$. The fourth one is the uncertainty of the fiducial volume, for which we assign 3% error independently for SK ($f_{\rm V}^{\rm SK}$) and the Korean detector ($f_{\rm V}^{\rm Kr}$). The fifth one is the uncertainty of the detection efficiency for each $e$- and $\mu$-like event. In this analysis, we use $\delta\varepsilon_e = 5\%$ and $\delta\varepsilon_\mu = 1\%$, which are taken common for SK and Korean detector. The last one is for the probability of the miss PID between $\mu$ and $e$. The uncertainty for this probability is assumed 1%. We also take this value as common for SK and Korean detector. According to these systematic errors, $\chi^2_{\rm sys}$ is written as

$$\begin{aligned}
\chi^2_{\rm sys} \;=\;& \sum_{\beta=e,\bar e,\mu,\bar\mu}\left(\frac{f_{\nu_\beta}-1.0}{0.03}\right)^2 + \sum_{D={\rm SK,\ Kr}}\left\{\left(\frac{f_\rho^D-1.0}{0.06}\right)^2+\left(\frac{f_{\rm V}^D-1.0}{0.03}\right)^2\right\}\\
&+\sum_{\alpha=\ell,\bar\ell}\left\{\left(\frac{f_\alpha^{\rm CCQE}-1.0}{0.03}\right)^2+\left(\frac{f_\alpha^{\rm CC}-1.0}{0.20}\right)^2\right\}+\left(\frac{f_{\pi^0}-1.0}{0.50}\right)^2\\
&+\left\{\left(\frac{\varepsilon_e-0.9}{0.05}\right)^2+\left(\frac{\varepsilon_\mu-1.0}{0.01}\right)^2\right\}+\left(\frac{P_{\mu/e}-0.01}{0.01}\right)^2 . \qquad (12)
\end{aligned}$$

Finally, $\chi^2_{\rm para}$ accounts for external constraints on the model parameters

$$\begin{aligned}
\chi^2_{\rm para} \;=\;& \left(\frac{\left(m_2^2-m_1^2\right)^{\rm fit}-8.2\times10^{-5}{\rm eV}^2}{0.6\times10^{-5}}\right)^2+\left(\frac{\sin^2 2\theta_{\rm SOL}^{\rm fit}-0.83}{0.07}\right)^2\\
&+\left(\frac{\sin^2 2\theta_{\rm RCT}^{\rm fit}-\sin^2 2\theta_{\rm RCT}^{\rm input}}{0.01}\right)^2 . \qquad (13)
\end{aligned}$$

The first two terms correspond to the present experimental constraints from solar neutrino oscillation [7] and KamLAND [8]. In the last term, we assume that the planned future reactor experiments [10] should measure $\sin^2 2\theta_{\rm RCT}$ with the expected uncertainty of 0.01. In total, our $\chi^2$ function depends on 26 parameters, the 6 model parameters and the 20 normalization factors.

## 4. Results

### 4.1. *Mass hierarchy*

For searching the best combination of the off-axis angle at SK and that for a Korean detector with 100kton fiducial volume water Čerenkov detector, we first calculate the expected number of the $\mu$-like and $e$-like events at both detectors by assuming either normal or inverted hierarchy. After calculating the events, we examine that the obtained event numbers can be fitted for the opposite hierarchy by adjusting the all 26 parameters.

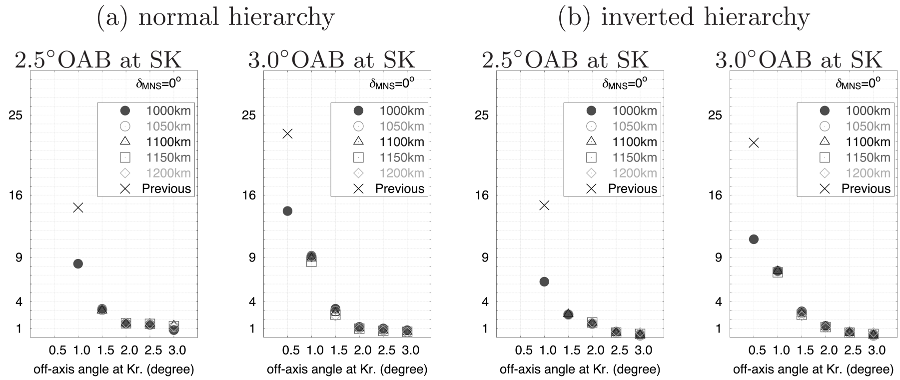
(a) normal hierarchy (b) inverted hierarchy

**Fig. 3** Minimum $\Delta\chi^2$ of the T2KK experiment after $5\times10^{21}$ POT exposure for 100kton water Čerenkov detector in Korea and SK, as the function of the off-axis angle and the baseline length of the far detector from J-PARC, when the normal hierarchy is assumed in generating the events for (a), and the inverted hierarchy is assumed for (b) in the fit with 2.5° and 3.0° OAB at SK. The black cross in each figures denotes the optimal $\Delta\chi^2$ for the previous setup.

We show in Fig. 3 that the minimum $\Delta\chi^2$ expected at the T2KK experiment after $5\times10^{21}$ POT exposure, as the function of the off-axis angle and the baseline length for a Korean detector. Figure 3(a) shows the results, when the normal hierarchy is assumed in generating the events and the inverted hierarchy is assumed in the fit. The opposite case, generating the event with the inverted hierarchy and fitted with the normal hierarchy is shown in Fig. 3(b). Each of the solid-circle, open-circle, open-triangle, open-square, and open-diamond, denotes the baseline length $L$ = 1000km, 1050km, 1100km, 1150km, and 1200km, respectively. The parameters are chosen

$$\begin{array}{lll}
\sin^2\theta_{\rm ATM}=0.5\,, & \sin^2 2\theta_{\rm SOL}=0.83\,, & \sin^2 2\theta_{\rm RCT}=0.10\,,\\
\left|\delta m^2_{13}\right|=2.5\times10^{-3}{\rm eV}^2\,, & \delta m^2_{12}=8.2\times10^{-5}{\rm eV}^2\,, & \delta_{\rm MNS}=0^\circ\,,\\
\varepsilon_e=90\%\,, & \varepsilon_\mu=100\%\,, & P_{\mu/e}=1\%\,,\\
\rho_{\rm SK}=2.6{\rm g/cm}^3\,, & \rho_{\rm Kr}=3.0{\rm g/cm}^3\,, &
\end{array} \qquad (14)$$

for generating the input event numbers. The black cross in each figures is the optimal results with the previous setup.

It is clearly seen from Fig. 3 that the best combination of off-axis angle are 3.0° at SK and 0.5° for a Korean detector at $L$ = 1000km. When the off-axis angle is fixed 2.5° at SK, the optimum OAB for a Korean detector is 1.0° at $L$ = 1000km. That is, the combination of the narrow band beam at SK and the wide band beam for a Korean detector is still the best combination to determine the mass hierarchy.

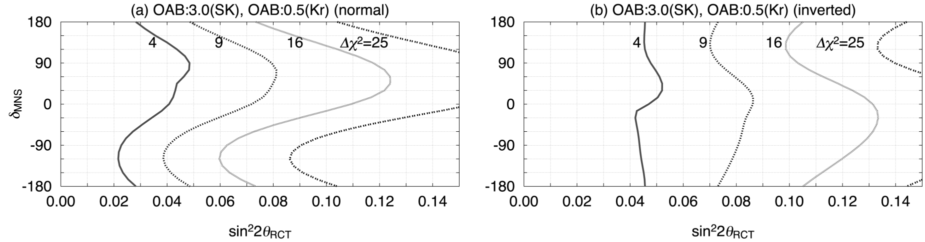

**Fig. 4** Capability of the T2KK experiment to determine the neutrino mass hierarchy, (a): when the normal hierarchy is assumed in generating the event number as input, and (b): the inverted hierarchy is assumed. The event numbers are obtained for a combination of 3.0° OAB at SK and 0.5° OAB at $L = 1000$km with a 100kton water Čerenkov detector after $5 \times 10^{21}$ POT exposure.

The capability of the T2KK experiment to determine the mass hierarchy pattern in Fig. 4. When the normal hierarchy is assumed in generating the event numbers and in fitting with the inverted hierarchy for (a). The opposite condition is shown in (b). The event numbers are generated for the best combination, 3.0° OAB at SK and 0.5° OAB at $L = 1000$km. In each figures, the input event numbers are obtained for the model parameters at various $\sin^2 2\theta_{\rm RCT}$ and $\delta_{\rm MNS}$, which is horizontal and vertical axis of each figures respectively, the other model parameters are same as in eq. (14). The fit has been performed by surveying the whole parameter space with the opposite hierarchy. The minimum of the $\Delta\chi^2$ are shown as contours for $\Delta\chi^2_{\rm min} = 4, 9, 16, 25$. The wrong hierarchy can be excluded with the corresponding $\Delta\chi^2_{\rm min}$ if the true value of $\sin^2 2\theta_{\rm RCT}$ and $\delta_{\rm MNS}$ lie in the right-hand side of each contour. Figure 4 suggests that we can distinguish the normal hierarchy from the inverted one with $\Delta\chi^2_{\rm min} \geq 9$ when $\sin^2 2\theta_{\rm RCT} \geq 0.08$. When the inverted hierarchy is realized in the nature, $\sin^2 2\theta_{\rm RCT} \geq 0.09$ is needed to determine the mass hierarchy with $\Delta\chi^2_{\rm min} \geq 9$.

### *4.2. CP phase*

Figure. 5 shows the capability of the T2KK experiment for measuring $\delta_{\rm MNS}$ and $\sin^2 2\theta_{\rm RCT}$ when the normal hierarchy assumed for (a) and the inverted hierarchy for (b). Allowed regions in the plane of $\sin^2 2\theta_{\rm RCT}$ and $\delta_{\rm MNS}$ are shown for the combination of 3.0° OAB at SK and 0.5° OAB at $L = 1000$km with 100kton detector after $5 \times 10^{21}$ POT exposure. The input value of $\sin^2 2\theta_{\rm RCT}$ is 0.10 and 0.04 for $\delta_{\rm MNS} = 0°$ and the other input parameters are same as those in eq. (14). The input points are indicated as the solid blobs. $\Delta\chi^2 =1$, 4, and 9 contours are shown by the solid, dotted, and dashed lines, respectively. The thick lines stand for the same hierarchy and the thin lines show that the wrong mass hierarchy is chosen in the fit, where the local minimum of the $\Delta\chi^2$ is pointed as a solid square.

From Fig. 5, we find that $\delta_{\rm MNS}$ can be constrained to ±45° at $1\sigma$ level for $\sin^2 2\theta_{\rm RCT} = 0.10$ and ±60° for $\sin^2 2\theta_{\rm RCT} = 0.04$. However, we cannot determine the CP phase at $3\sigma$ level for $\delta_{\rm MNS} = 0°$, even when $\sin^2 2\theta_{\rm RCT} = 0.10$. Moreover, there is the shadow island which is arose from the opposite hierarchy assumption in both cases for $\sin^2 2\theta_{\rm RCT} = 0.04$. In the previous analysis [12], we can constrain the $\delta_{\rm MNS}$ with ±30° at $1\sigma$ level and ±60° at $3\sigma$ level for $\delta_{\rm MNS} = 0°$ with both $\sin^2 2\theta_{\rm RCT} = 0.10$ and 0.04. Comparing the difference between this result and the previous one, the capability of the CP phase measurement for this setup becomes worse than the previous one.

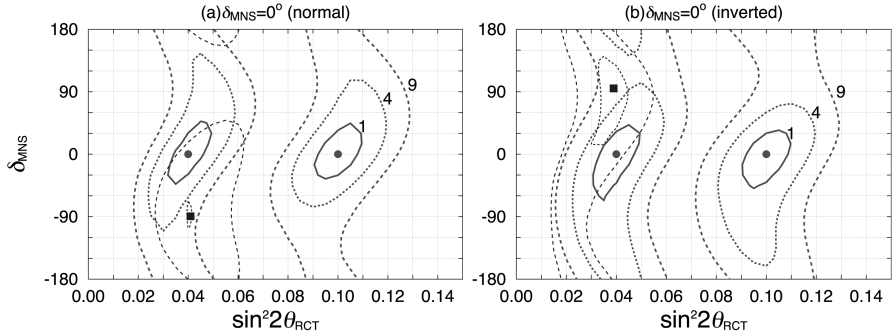

**Fig. 5** Capability of the T2KK experiment for measuring $\sin^2 2\theta_{\mathrm{RCT}}$ and $\delta_{\mathrm{MNS}}$ when the normal hierarchy is assumed for (a) and the inverted hierarchy for (b). The input points are indicated as the solid blobs. $\Delta\chi^2$ =1, 4, and 9 contours are shown by the solid, dotted, and dashed lines, respectively. The thick lines stand for the same hierarchy and the thin lines show that the wrong mass hierarchy is chosen in the fit, where the $\Delta\chi^2$ local minimum is pointed as a solid square.

## 5. Conclusion

In this paper, we elaborate our previous analysis [12] by using the realistic energy resolution and the event efficiency of the water Čerenkov detector by using the reconstructed neutrino energy for both $\nu_\mu$ and $\nu_e$ charged current event, which include the CCQE and nuclear resonance event. We also take account of the $\pi^0$ background and particle miss identification between $e$- and $\mu$-event.

The best combination for determining the mass hierarchy pattern is 3.0° OAB at SK and 0.5° OAB for a Korean detector which is assumed 100kton fiducial volume water Čerenkov detector at $L$ = 1000km away from J-PARC. The mass hierarchy can be distinguished at $\Delta\chi^2_{\mathrm{min}} > 9$ level for $\sin^2 2\theta_{\mathrm{RCT}} \gtrsim 0.08$ (0.09) when the normal (inverted) hierarchy assumed, after $5 \times 10^{21}$ POT exposure. The $\pi^0$ background suppress the potential of the T2KK experiment for mass hierarchy determination strongly. On the other hand, the contribution of the nuclear resonance event helps to discriminate the mass hierarchy. We also examine the prospect of the CP phase measurement for the T2KK experiment. The leptonic CP phase can be constrained as ±45° at $1\sigma$ level for $\sin^2 2\theta_{\mathrm{RCT}} = 0.1$ and $\delta_{\mathrm{MNS}} = 0°$ without anti-neutrino running for both hierarchy assumption. However, $\delta_{\mathrm{MNS}}$ cannot be constrained at $3\sigma$ level.

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## References

[1] Z. Maki, M. Nakagawa, and S. Sakata, Prog. Theor. Phys. **28**, 870 (1962).
[2] see *e.g.,* , J. Hosaka, *et al.*, (Super-Kamiokande collaboration), Phys. Rev. **D74**, 032002 (2006) [arXiv:hep-ex/0604011].
[3] Y. Ashie, *et al.*, (Super-Kamiokande Collaboration), Phys. Rev. **D71**, 112005 (2005) [arXiv:hep-ex/0501064].

[4] M.H. Ahn, *et al.*, (K2K Collaboration), Phys. Rev. **D74**, 072003 (2006) [arXiv:hep-ex/0606032].

[5] M. Kordosky, D. Petyt, and *et al.*, (MINOS Collaboration), arXiv:0711.0769.

[6] Y. Itow, *et al.*, hep-ex/0106019.

[7] see *e.g.,* , J. Hosaka, *et al.*, (Super-Kamiokande Collaboration), Phys. Rev. **D73**, 112001 (2006) [hep-ex/0508053]; B. Aharmin, *et al.*, (SNO Collaboration), nucl-ex/0610020.

[8] S. Abe, *et al.*, (The KamLAND collaboration), arXiv:0801.4589.

[9] M. Apollonio, *et al.*, Eur. Phys. J. **C27**, 331 (2003) [hep-ex/0301017].

[10] F. Ardellier, *et al.*, (Double CHOOZ collaboration), arXiv:hep-ex/0606025; Daya Bay Collaboration, arXiv:hep-ex/0701029; J. Cao, (RENO collaboration), Nucl. Phys. Proc. Suppl.**155**, 229 (2006) [hep-ex/0509041].

[11] W.-M. Yao, *et al.*, in Review of Particle Physics, Journal of Physics **G33**, 1, (2006).

[12] K. Hagiwara, N. Okamura, and K. i. Senda, Phys. Lett. **B637**, 266 (2006) [arXiv:hep-ph/0504061]; K. Hagiwara, N. Okamura, and K. i. Senda, Phys. Rev. **D76**, 093002 (2007) [arXiv:hep-ph/0607255]; K. Hagiwara and N. Okamura, JHEP01(2008)022 [arXiv:hep-ph/0611058].

[13] Talk given by K. Hagiwara at Fujihara Seminar on Neutrino Mass and Seesaw Mechanism (SEESAW 1979-2004), Tsukuba, Ibaraki, Japan, 23-25 Feb. 2004, Published in Nucl. Phys. Proc. Suppl. **137** 84 (2004) [arXiv:hep-ph/0410229].

[14] J-PARC home page, `http://j-parc.jp/`.

[15] M. Ishitsuka, T. Kajita, H. Minakata, and H. Nunokawa, Phys. Rev. **D72**, 033003 (2005) [arXiv:hep-ph/0504026]; T. Kajita, H. Minakata, S. Nakayama, and H. Nunokawa, Phys. Rev. **D75**, 013006 (2007) [arXiv:hep-ph/0609286].

[16] O. Mena Requejo, S. Palomares-Ruiz, and S. Pascoli, Phys. Rev. **D72**, 053002 (2005) [hep-ph/0504015]; O. Mena, S. Palomares-Ruiz, and S. Pascoli, Phys. Rev. **D73**, 073007 (2006) [hep-ph/0510182].

[17] Talk given by K-i. Senda at T2KK07, Hongou, Tokyo, Japan, 30 Sep. and 1 Oct., 2007.

[18] D. Casper, Nucl.Phys.Proc.Suppl. **112** 161, (2002), [arXiv:hep-ph/0208030].