Revisiting T2KK and T2KO physics potential and $\nu_\mu - \bar{\nu}_\mu$ beam ratio*

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Abstract

We revisit the sensitivity study of a Tokai-to-Kamioka-and-Korea (T2KK) and Tokai-to-Kamioka-and-Oki (T2KO) proposals where a 100 kton detector is placed in Korea (L = 1000 km) and Oki island (L = 653 km) in Japan, respectively, in addition to the Super-Kamiokande (SK) for determination of the neutrino mass hierarchy and leptonic CP phase (δ_{CP}). We systematically study the ν_μ and $\bar{\nu}_\mu$ focusing beam ratio and find that the T2KK and T2KO experiments can improve their sensitivity to both the mass hierarchy determination and leptonic CP phase measurement simultaneously, using ν_μ and $\bar{\nu}_\mu$ focusing beams with 3 : 2 - 2.5 : 2.5 beam ratio.

INTRODUCTION

Determination of the neutrino mass hierarchy and CP violating phase in the Maki-Nakagawa-Sakata (MNS) mixing matrix has been next targets in the neutrino physics. Ideas of extending the Tokai-to-Kamioka (T2K) experiment with additional water Čerenkov detectors placed in Korea (Tokai-to-Kamioka-and-Korea: T2KK) [1–12] or in Oki island (Tokai-to-Kamioka-and-Oki: T2KO) [11, 13] as well as at Super-Kamiokande (SK) site has been proposed to address those questions. It has been shown that the T2KK experiment with a 100 kton fiducial-volume detector in Korea in addition to the SK detector is an appealing proposal. In this presentation, we revisit the sensitivity study of the T2KK [8, 10] and T2KO [11] experiments for the neutrino mass hierarchy and CP phase, studying the dependence of the sensitivities on the ν_μ and $\bar{\nu}_\mu$ focusing beam ratio systematically with dedicated estimation of backgrounds. Especially, the treatment of the NC π^0 backgrounds is improved in this analysis.

SENSITIVITY ANSLYSES AND RESULTS

We use the ν_μ and $\bar{\nu}_\mu$ focusing beam fluxes from the J-PARK with the proton energy of 40 GeV [14]. The baseline length from the J-PARK to the SK, Oki and Korea detectors are taken to be 295 km, 653 km and 1000 km, respectively. The averaged matter densities, $\bar{\rho}$, along the baseline between J-PARK and SK, Oki and Kr detectors have been evaluated in Refs. [10, 11] and taken to be 2.60, 2.75 and 2.90 g/cm^3, respectively. NC single-π^0 events can be a substantial background source for ν_e and $\bar{\nu}_e$ appearance modes and affect the sensitivity to the mass hierarchy and CP phase significantly [8]. We consider the uncertainties of the background due to the π^0 rejection [15] and axial masses of the single pion production processes, assigning the 11% normalization uncertainty for the total NC single-π^0 backgrounds and 13% and 15% normalization uncertainties for the NC resonant and coherent single-π^0 backgrounds, respectively.

In Fig. 1, the sensitivity of the T2KK experiments to the mass hierarchy determination is shown. The true value of $\sin^2\theta_{23}$ is assumed to be 0.5. It is shown that including $\bar{\nu}_\mu$ focusing beam can improve the sensitivity, especially in high sensitivity regions. Although there are reduction of sensitivities in some $\delta_{\rm CP}$ regions by including $\overline{\nu}_\mu$ focusing beams, the reduction is minimized with the $\nu_\mu : \overline{\nu}_\mu = 4:1$ beam ratio for both OAB cases. On the other

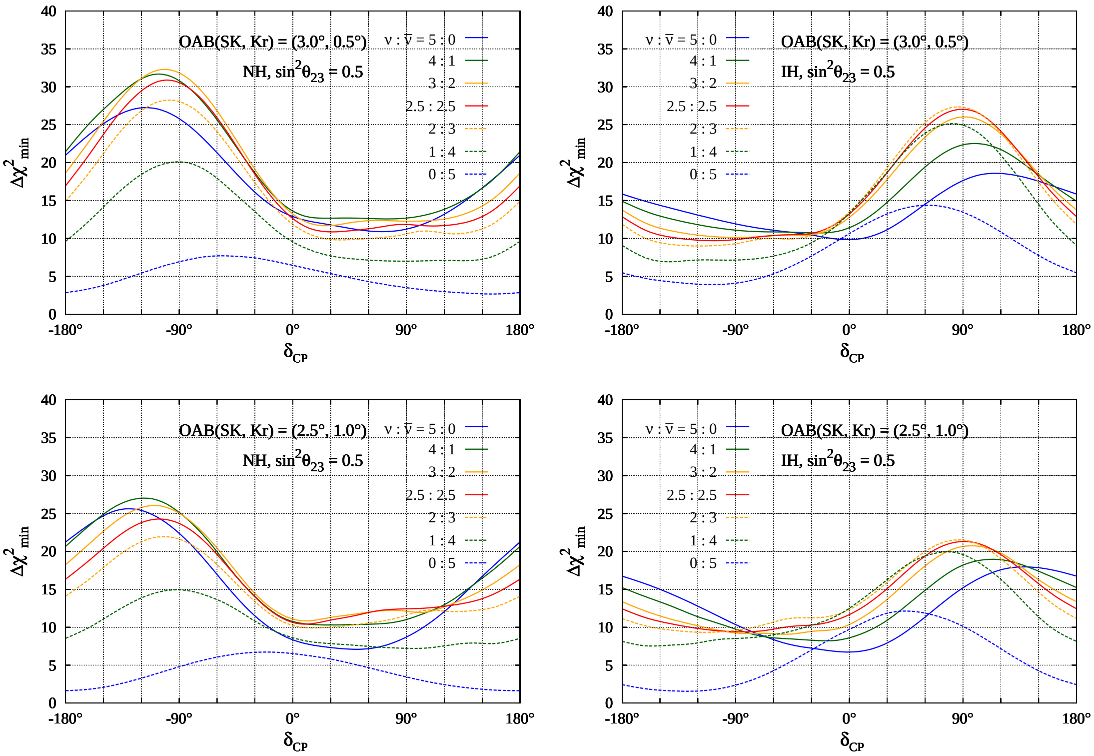


FIG. 1: The $\Delta\chi^2$ minimum for the T2KK experiment to reject the wrong mass hierarchy as a function of the leptonic CP phase, $\delta_{\rm CP}$. The left and right plots are for the normal and inverted hierarchy cases, while the upper and lower plots are for the 3.0° (0.5°) and 2.5° (1.0°) off-axis beam at SK (Kr) detector, respectively.

hand, comparing the lowest $(\Delta\chi^2)_{\rm min}$ in the whole range of the CP phase, the ν_μ and $\bar{\nu}_\mu$ focusing beam ratio of 4 : 1 is the best for the 3.0° OAB at SK, and 3 : 2 - 2 : 3 are best for the 2.5° OAB at SK. In terms of the highest sensitivity, 4 : 1, 3 : 2 and 2.5 : 2.5 beam ratios give comparable sensitivity for the normal hierarchy, but 3 : 2 and 2 : 3 are significantly better than 4 : 1 for the inverted hierarchy case. Thus, around 3 : 2 - 2.5 : 2.5 would be a preferred choice for both OAB cases.

In Fig. 2, we show the sensitivities of the T2KO experiment. The improvement by including $\overline{\nu}_\mu$ focusing beam is significant in the high sensitivity region, while the sensitivities in the low sensitivity region does not change so much, preferring the running ratio of 3 : 2 - 2 : 3. Comparing to the T2KK, the sensitivity is lower by 30% − 70% in $(\Delta\chi^2)_{\rm min}$. The lower sensitivity in the T2KO is basically due to the smaller matter effects.

Next, let us discuss the sensitivity to the CP phase measurements. In Fig. 3, we show the 1σ uncertainties of CP phase measurements as functions of the CP phase for the four experiments: (a) T2KK with 3.0° OAB at SK, (b) T2KK with 2.5° OAB at SK, (c) T2KO and (d) $\rm T2K_{122}$, where a 100 kton detector is placed at the Kamioka site along with SK detectors with the total detector volume of 122.5 kton. The uncertainty of the CP phase measurement is smallest around $\delta_{\rm CP} \sim 0°$ and $\sim 180°$,while the sensitivity is worst around $\delta_{\rm CP} \sim \pm 60°$ and $\sim \pm 120°$ as clearly seen in the $\rm T2K_{122}$. This low sensitivity reflects the

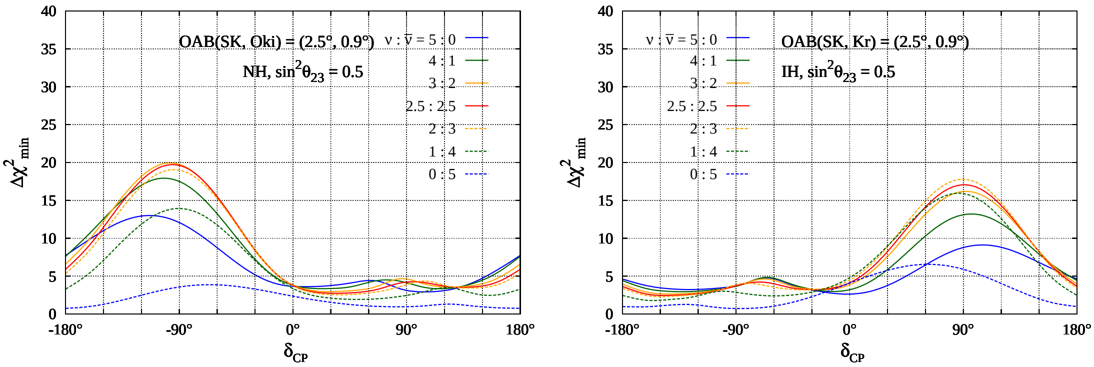
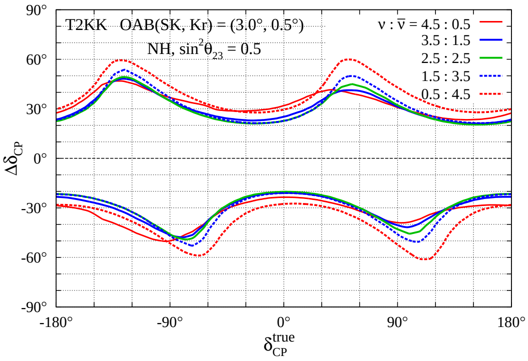
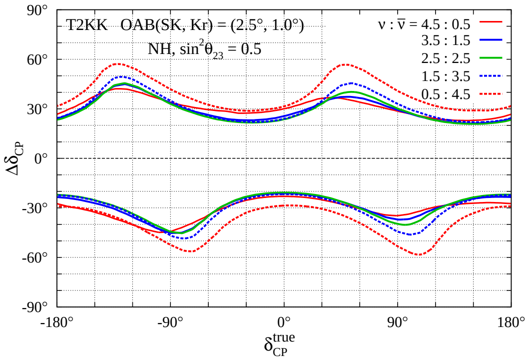


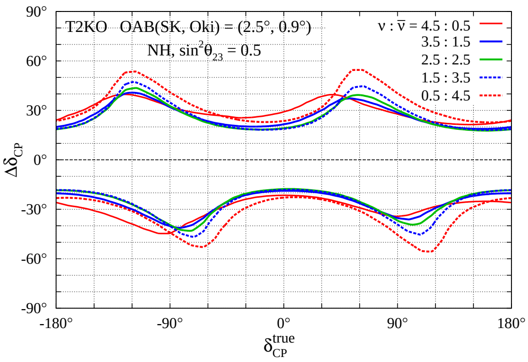
FIG. 2: Same as Fig. 1, but for the T2KO experiment with the 2.5° (0.9°) OAB at SK (Oki).



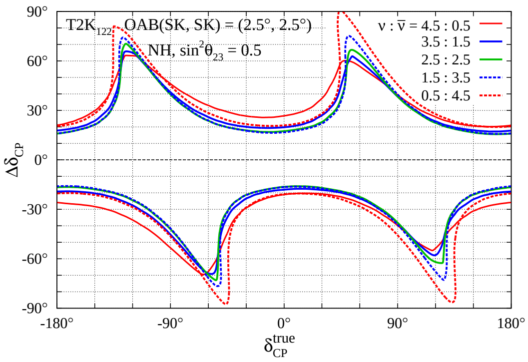
(a) T2KK with 3.0° OAB at SK



(b) T2KK with 2.5° OAB at SK



(c) T2KO



(d) $T2K_{122}$

FIG. 3: The 1σ uncertainty of CP phase measurements as functions of the CP phase when $\sin^2\theta_{23} = 0.5$, and mass hierarchy is known to be the normal hierarchy.

degeneracy between δ_{CP} and $\pi - \delta_{CP}$ in the $\sin\delta_{CP}$ term in the $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ oscillation probability, and we need information of $\cos\delta_{CP}$ to resolve it. The accuracy of the CP phase measurement around these low sensitivity regions with the T2KK and T2KO is significantly better than that with the $T2K_{122}$. The T2KK and T2KO observe up to the second peak of the $\nu_\mu \to \nu_e$ oscillation and are more sensitive to the $\cos\delta_{CP}$ term, allowing more accurate measurements of the CP phase around those low sensitive regions.

As for the ν_μ and $\bar{\nu}_\mu$ focusing beam ratio, the ratio between 3.5 : 1.5 and 1.5 : 3.5 give the smaller uncertainty in most of the CP phases, except for the low sensitivity region, where the ratio of 4.5 : 0.5 gives the best accuracy. Using the 2.5 : 2.5 beam ratio, the three experiments measure the CP phase with the uncertainty of $\sim 20° - 50°$ (T2KK with 3.0° OAB), $\sim 20° - 45°$ (T2KK with 2.5° OAB and T2KO) and $\sim 15° - 70°$ (T2K$_{122}$), depending on the CP phase. For the inverted hierarchy case, the uncertainties show similar dependences on the ν_μ and $\bar{\nu}_\mu$ focusing beam ratio as the normal hierarchy case.

CONCLUSION

As discussed in this presentation, the T2KK and T2KO experiments can improve their sensitivity to both the mass hierarchy determination and leptonic CP phase measurement using ν_μ and $\bar{\nu}_\mu$ focusing beams with 3 : 2 - 2.5 : 2.5 beam ratio. The T2KK experiment allows us to determine the mass hierarchy and measure the leptonic CP phase simultaneously. The T2KO experiment also has sensitivity to the CP phase measurement, while its physics potential for the mass hierarchy determination is not as good as the T2KK experiment.

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[1] K. Hagiwara, Nucl.Phys.Proc.Suppl. **137** (2004) 84.

[2] M. Ishitsuka, T. Kajita, H. Minakata and H. Nunokawa, Phys.Rev. **D72** (2005) 033003.

[3] K. Hagiwara, N. Okamura and K.-i. Senda, Phys.Lett. **B637** (2006) 266.

[4] K. Hagiwara, N. Okamura and K.-i. Senda, Phys.Rev. **D76** (2007) 093002.

[5] T. Kajita, H. Minakata, S. Nakayama and H. Nunokawa, Phys.Rev. **D75** (2007) 013006.

[6] K. Hagiwara and N. Okamura, JHEP **0801** (2008) 022.

[7] P. Huber, M. Mezzetto and T. Schwetz, JHEP **0803** (2008) 021.

[8] K. Hagiwara and N. Okamura, JHEP **0907** (2009) 031.

[9] F. Dufour, T. Kajita, E. Kearns and K. Okumura, Phys.Rev. **D81** (2010) 093001.

[10] K. Hagiwara, N. Okamura and K. Senda, JHEP **1109** (2011) 082.

[11] K. Hagiwara, T. Kiwanami, N. Okamura and K.-i. Senda, `arXiv:1209.2763` (2012).

[12] F. Dufour, `arXiv:1211.3884` (2012).

[13] A. Badertscher, T. Hasegawa, T. Kobayashi, A. Marchionni, A. Meregaglia *et al.*, `arXiv:0804.2111` (2008).

[14] A.K. Ichikawa, private communication.

[15] T. Barszczak, Ph.D. thesis, University of California, Irvine (2005).