PHYSICAL REVIEW D **95,** 055005 (2017)

Sensitivity of the T2HKK experiment to nonstandard interactions

Shinya Fukasawa,* Monojit Ghosh,† and Osamu Yasuda‡

Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

(Received 2 December 2016; published 6 March 2017)

If the flavor-dependent nonstandard interactions (NSIs) in neutrino propagation exist, then the matter effect is modified, and the modification is parametrized by the dimensionless parameter $\epsilon_{\alpha\beta}$ ($\alpha, \beta = e, \mu, \tau$). In this paper, we discuss the sensitivity of the T2HKK experiment, the possibility of which is now seriously discussed as a future extension of the T2K experiment, to such NSIs. On the assumption that $\epsilon_{\alpha\mu} = 0$ ($\alpha = e, \mu, \tau$) and $\epsilon_{\tau\tau} = |\epsilon_{e\tau}|/(1 + \epsilon_{ee})$, which are satisfied by other experiments to a good approximation, we find that, among the possible off-axis flux configurations of 1.3°, 1.5°, 2.0°, and 2.5°, the case of the off-axis angle 1.3° gives the highest sensitivity to ϵ_{ee} and $|\epsilon_{e\tau}|$. Our results show that the 1.3° off-axis configuration can exclude NSIs for $|\epsilon_{ee}| \gtrsim 1$ or $|\epsilon_{e\tau}| \gtrsim 0.2$ at 3σ. We also find that in the presence of NSIs T2HKK (for the off-axis angle 1.3°) has better sensitivity to the two CP phases [δ_{CP} and $\arg(\epsilon_{e\tau})$] than DUNE. This is because of the synergy between the two detectors, i.e., one in Kamioka and one in Korea. T2HKK has better sensitivity to the CP phases than the atmospheric neutrino experiment at Hyper-Kamiokande in inverted hierarchy, but in normal hierarchy, the atmospheric neutrino experiment has the best sensitivity to the CP phases.

DOI: 10.1103/PhysRevD.95.055005

I. INTRODUCTION

It has been established by the successful experiments in the past that neutrinos have masses and mixings [1]. The three mixing angles θ_{12}, θ_{13}, and θ_{23} and two mass-squared differences Δm^2_{31} and Δm^2_{21} in the standard three-flavor neutrino oscillation framework are measured as $(\Delta m^2_{21}, \sin^2 2\theta_{12}) \simeq (7.5 \times 10^{-5}\ \mathrm{eV}^2,\ 0.86)$, $(|\Delta m^2_{31}|, \sin^2 2\theta_{23}) \simeq (2.4 \times 10^{-3}\ \mathrm{eV}^2, 1.0)$, and $\sin^2 2\theta_{13} \simeq 0.09$. The remaining unknowns are the value of the Dirac CP phase δ_{CP}, the sign of Δm^2_{31} (the mass hierarchy, i.e., normal or inverted), and the octant of θ_{23} (the sign of $\pi/4 - \theta_{23}$, i.e., lower or higher). It is expected that these unknowns will be determined by the future neutrino oscillation experiments, particularly the accelerator-based long-baseline neutrino experiments [2,3]. These experiments in the future cannot only measure the oscillation parameters in the standard three-flavor mixing scenario but also probe the new physics by looking at the deviation from the standard three-flavor neutrino mixing framework.

Flavor-dependent neutral current neutrino nonstandard interactions (NSIs) [4–6] have been studied as one of the new physics candidates which can be searched at the future neutrino experiments [7,8]. In the presence of these NSIs, the neutrino propagation feels the extra contribution to the matter effect, and hence long-baseline experiments with a longer baseline length L (typically $L \gtrsim 1000$ km) and the atmospheric neutrino experiments are expected to have sensitivity to the neutral current NSIs. Recent studies of neutral current NSIs in long-baseline and atmospheric neutrino experiments can be found in Refs. [9–34].

The possibility of a second detector in Korea for the T2K [35] experiment was discussed in the past [36–51]. Recently, there has been a renewed interest in the idea of placing the second detector in Korea as a part of the T2HK plan [2], and the plan with the second detector in Korea is now called the T2HKK project [52]. The original plan of the T2HK project is to build a large tank of water with Čerenkov detectors in the Kamioka site. Under the T2HKK project, there will be two tanks of equal volume instead of building a single tank, and then one of the tanks will be built in Korea. Depending on the location of the second detector in Korea, one has different options for the flux in terms of the Off-axis Angle (OA). According to the Hyperkamiokande (HK) Collaboration, there are various flux options between 1° and 3° off-axis configurations are under consideration at present [53]. In the T2HKK project, there are some discussions on which location is the most advantageous from the physics point of view. In this paper, for the first time, we study the sensitivity of T2HKK to NSIs and discuss the result of optimization for the NSIs parameters ϵ_{ee} and $|\epsilon_{e\tau}|$ with respect to the different flux options. We also compare its sensitivity with that of DUNE [3] and the atmospheric neutrino experiment at HK [54]. While a similar analysis was done in the past [47], the new points in the present paper are the optimization with respect to the location, which can be expressed in terms of the off-axis angle, and the comparison of the sensitivity with DUNE and the atmospheric neutrino at HK.

This paper is organized as follows. In Sec. II, we describe the constraints on NSIs in propagation. In Sec. III, we study

*fukasawa-shinya@ed.tmu.ac.jp
†monojit@tmu.ac.jp
‡yasuda@phys.se.tmu.ac.jp

the sensitivity of the T2HKK experiment to NSIs and compare our results with DUNE and HK. We will also compare our results with the T2HK configuration. In Sec. IV, we draw our conclusions.

II. PRELIMINARIES

A. Nonstandard interactions

Let us start with the effective flavor-dependent neutral current neutrino nonstandard interactions in propagation given by

$$\mathcal{L}_{\rm eff}^{\rm NSIs} = -2\sqrt{2}\epsilon_{\alpha\beta}^{ff'P} G_F(\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\beta L})(\bar{f}_P\gamma^\mu f'_P), \tag{1}$$

where f_P and f'_P stand for fermions with chirality P and $\epsilon_{\alpha\beta}^{ff'P}$ is a dimensionless constant which is normalized by the Fermi coupling constant G_F. The presence of NSIs in Eq. (1) modifies the Mikheyev-Smirnov-Wolfenstein (MSW) potential in the flavor basis from

$$\sqrt{2}G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{2}$$

to

$$\mathcal{A} \equiv \sqrt{2}G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}, \tag{3}$$

where $\epsilon_{\alpha\beta}$ is defined by

$$\epsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \frac{N_f}{N_e}\epsilon_{\alpha\beta}^f. \tag{4}$$

N_f ($f = e, u, d$) stands for number densities of fermions f. Here, we defined the NSIs parameters as $\epsilon_{\alpha\beta}^{fP} \equiv \epsilon_{\alpha\beta}^{ffP}$ and $\epsilon_{\alpha\beta}^{f} \equiv \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}$. In the three-flavor neutrino oscillation framework with NSIs, the neutrino evolution is given by the Schrodinger equation

$$i\frac{d}{dx}\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix} = [U{\rm diag}(0, \Delta E_{21}, \Delta E_{31})U^{-1} + \mathcal{A}]\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix}, \tag{5}$$

where U is the leptonic mixing matrix defined by

$$U \equiv \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}, \tag{6}$$

and $\Delta E_{jk} \equiv \Delta m_{jk}^2/2E \equiv (m_j^2 - m_k^2)/2E$, $c_{jk} \equiv \cos\theta_{jk}$, $s_{jk} \equiv \sin\theta_{jk}$.

As far as the neutrino oscillation on the Earth is concerned, we have the following limits on $\epsilon_{\alpha\beta}$ from the compilation of various neutrino data at 90% C.L. [55,56][1]:

$$\begin{pmatrix} |\epsilon_{ee}| < 4\times 10^0 & |\epsilon_{e\mu}| < 3\times 10^{-1} & |\epsilon_{e\tau}| < 3\times 10^0 \\ & |\epsilon_{\mu\mu}| < 7\times 10^{-2} & |\epsilon_{\mu\tau}| < 3\times 10^{-1} \\ & & |\epsilon_{\tau\tau}| < 2\times 10^1 \end{pmatrix}. \tag{7}$$

It was pointed out in Refs. [58,59] that the high-energy atmospheric neutrino data, in which the matter effects are dominant, are consistent with NSIs only when the following equality is approximately satisfied:

$$\epsilon_{\tau\tau} = \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}. \tag{8}$$

In this paper, we assume the relation (8) exactly. It may seem that the condition (8) forces $|\epsilon_{e\tau}|$ to be smaller than it should be, near the region $|1+\epsilon_{ee}| \ll 1$. However, Eq. (8) turns out to be a reasonable condition even in the region $|1+\epsilon_{ee}| \ll 1$ because of the following arguments. The constraint from the high-energy atmospheric neutrino data is that the smaller eigenvalue in the matter potential (3) with $\epsilon_{\alpha\mu} = 0$ should be smaller than $0.2\times\sqrt{2}G_F N_e$ (see Eq. (13) in Ref. [31]). For $|1+\epsilon_{ee}| \ll 1$, this implies $\sqrt{4|\epsilon_{e\tau}|^2 + \epsilon_{\tau\tau}^2} - \epsilon_{\tau\tau} < 0.4$. This condition in principle allows us to take a large value of $|\epsilon_{e\tau}|$. However, we have checked explicitly that such a large value of $|\epsilon_{e\tau}|$ gives a very bad fit to the HK atmospheric neutrino data assuming the standard scenario, and therefore $|\epsilon_{e\tau}| \ll 1$ should be satisfied near the region $|1+\epsilon_{ee}| \ll 1$.[2] This result is consistent with the discussion in Ref. [47] based on an

[1]See Ref. [57] for the constraints on NSIs at production and detection.

[2]At present, we have only the very weak bound on $|\epsilon_{e\tau}|$. If we find $|1+\epsilon_{ee}| \ll 1$ experimentally in the future, however, then by combining $|1+\epsilon_{ee}| \ll 1$ and the high-energy atmospheric neutrino data, we will obtain the very strong bound on $|\epsilon_{e\tau}|$.

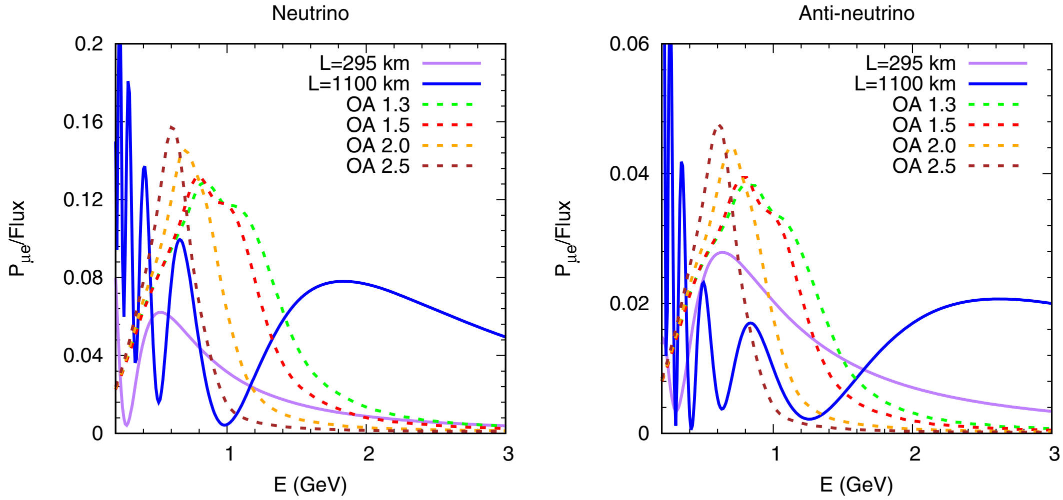

FIG. 1. The flux (dashed curves) at different off-axis angles and the appearance oscillation probabilities (solid curves) in Kamioka ($L = 295$ km) and in Korea ($L = 1100$ km) in the standard oscillation scenario in normal hierarchy. The left (right) panel is for neutrinos (antineutrinos). The baseline length $L = 1088$ km at an angle 1.3° is slightly different from $L = 1100$ km, but the difference between the oscillation probabilities at $L = 1088$ km and at $L = 1100$ km is invisibly small.

analytic formula on the disappearance probability. Namely, the high-energy atmospheric neutrino data are perfectly consistent with its behavior $1 - P(\nu_\mu \to \nu_\mu) \propto 1/E^2$ inferred from the standard oscillation scenario, while in the presence of NSIs with $\epsilon_{\mu\alpha} = 0$, it has the behavior $1 - P(\nu_\mu \to \nu_\mu) \sim c_1/E + O(1/E^2)$, where c_1 satisfies $c_1 \propto \epsilon_{\tau\tau} - |\epsilon_{e\tau}|^2/(1+\epsilon_{ee})$ in the case of $|\epsilon_{\tau\tau} - |\epsilon_{e\tau}|^2/(1+\epsilon_{ee})| \ll 1$ (see Eq. (9) in Ref. [47]). Therefore, the condition (8) is a good approximation also in the region $|1+\epsilon_{ee}| \ll 1$, and the ansatz (8) is justified.

If Eq. (8) is satisfied, then $\epsilon_{\tau\tau}$ can be eliminated. Furthermore, we have

$$\left|\frac{\epsilon_{e\tau}}{1+\epsilon_{ee}}\right| \lesssim 0.8 \quad \text{at } 3\sigma \text{ C.L.} \tag{9}$$

from the atmospheric neutrino data of Super-kamiokande [17].

From the above two constraints (7) and (8), the following ansatz is a good approximation to analyze the sensitivity to NSIs:

$$\mathcal{A} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}. \tag{10}$$

The allowed region in the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane at 90% C.L. is given by the following:

$$-4 \lesssim \epsilon_{ee} \lesssim 4, \qquad |\epsilon_{e\tau}| \lesssim 3, \qquad \left|\frac{\epsilon_{e\tau}}{1+\epsilon_{ee}}\right| \lesssim 0.6. \tag{11}$$

B. T2HKK experiment

The T2HKK experiment is a proposal for the future extension of the T2K experiment. In this proposal, a water Čerenkov detector is placed not only in Kamioka (at a baseline length $L = 295$ km) but also in Korea (at $L \simeq 1100$ km), whereas the power of the beam at J-PARC in Tokai Village is upgraded to 1.3 MW. As in the T2K experiment, it is assumed that T2HKK uses an off-axis beam at a 2.5° angle between the directions of the decaying charged pions and neutrinos, and the neutrino energy spectrum has a peak approximately at 0.6 GeV. This off-axis beam at an angle 2.5° reaches Korea, and the corresponding off-axis angle on the surface in Korea ranges from 1.3° to 2.5° with the baseline 1088 km (for 1.3°) to 1100 km (for 1.5°, 2.0°, and 2.5°), depending on the location of the detector in Korea.[3] The flux and the appearance oscillation probabilities for neutrinos and antineutrinos at various off-axis angles in normal hierarchy are shown in Fig. 1. The label in the y axis corresponds to the value of $P_{\mu e}$, whereas the unit of the fluxes is arbitrary. As we can see from Fig. 1, the first oscillation maximum occurs at $E \simeq 1.8$ (2.6) GeV, whereas the second one appears at $E \simeq 0.7$ (0.8) GeV for neutrinos (antineutrinos). From Fig. 1, we observe the following:

(i) Among the different off-axis fluxes, the flux corresponding to the lowest off-axis angle (i.e., OA 1.3) peaks at 0.8 GeV, and the flux at the highest off-axis angle (i.e., OA 2.5) peaks at 0.6 GeV.

[3]The other flux options which are also under consideration are 1.8°, 1.9°, and 2.2° [53], which are not considered in this work.

(ii) The relative heights of the peak of the fluxes is maximum for OA 2.5 and minimum for OA 1.3.

(iii) The off-axis fluxes corresponding 2.5° and 2.0° can mainly probe the physics at the second oscillation maxima for $L = 1100$ km, while the off-axis fluxes corresponding to 1.3° and 1.5° can also cover a part of the first oscillation maxima for the Korean baseline.

III. SENSITIVITY OF T2HKK TO ϵ_{ee} AND $|\epsilon_{e\tau}|$

In this section, we discuss the sensitivity of the T2HKK experiment to the nonstandard interaction in propagation with the ansatz (10). For comparison, we also study the sensitivity of the DUNE [3] and the atmospheric neutrino experiments at HK [54]. Since $\epsilon_{\tau\tau}$ is expressed in terms of ϵ_{ee} and $|\epsilon_{e\tau}|$, the only new degrees of freedom are ϵ_{ee}, $|\epsilon_{e\tau}|$ and $\arg(\epsilon_{e\tau})$. First of all, in Sec. III A, assuming that Nature is described by the standard three-flavor scheme, we discuss the bounds on ϵ_{ee} and $|\epsilon_{e\tau}|$. In our analysis, we assume that the true numbers of events are those of the standard three-flavor scenario, and the test numbers of events are those with NSIs. We discuss the region of the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane in which T2HKK can exclude the hypothesis with NSIs. Second, in Sec. III B, assuming that NSIs exists, we consider whether the two complex phases δ_{CP} and $\arg(\epsilon_{e\tau})$ can be determined separately.

The neutrino flux of the T2HKK experiment in Korea is taken from Ref. [60]. To calculate the event rates for the T2HKK setup, we proceed in the following way. First, we have matched the number of events corresponding to the T2HK setup as given in Ref. [2], taking the 2.5° off-axis flux. The detector volume in this case is 560 kt. Then, we scale these numbers of events for the Korean baseline corresponding to different off-axis configurations. For T2HKK project, we have taken 280 kt detector both in Kamioka and in Korea. Note that, as we have taken the backgrounds corresponding to the T2HK setup and scale them down for the Korean baseline, the neutral current π^0 backgrounds at the high energies are ignored, and thus our results of T2HKK may be optimistic. For the T2HKK setup, we have taken a total integrated beam power of 15.6×10^{21} protons on target (pot) with 10^{21} pot/yr. Thus, this corresponds to a 15.6-year running of the beam. For T2HKK, we have taken an overall systematic error of 3.3% for both the appearance and disappearance channels in the neutrino mode and 6.2% (4.5%) for the appearance (disappearance) channel in the antineutrino mode. The systematic error is the same for both the signal and the background.[4] For DUNE, we have taken a flux of beam power 1.2 MW with 10^{21} pot/yr and 34 kt liquid argon detector. In our analysis, we have considered a ten-year running of DUNE unless otherwise mentioned. The number of events is taken from Ref. [3]. The systematic error for DUNE is 2% (10%) for the appearance channel and 5% (15%) for the disappearance channel, corresponding to the signal (the background). The systematic errors in the neutrino and antineutrino modes are the same for DUNE. The simulations of T2HKK and DUNE have been performed with the softwares GLoBES [61,62] and MonteCUBES [63].

[4]Note that in our work we followed the configuration of T2HK as given in Ref. [2]. According to the T2HKK report [53] (which appeared on the same day as our paper appeared in arXiv), the total detector volume is around 380 kt, which will be split into 190 kt for each of Kamioka and Korea. The total exposure in this report is 2.7×10^{22} pot with ten years of running.

TABLE I. The numbers of appearance events for neutrinos and antineutrinos expected at the second detector in Korea. $\theta_{23} = \pi/4$, $\delta = -\pi/2$ with normal hierarchy is assumed.

Off-axis degree	1.3°	1.5°	2.0°	2.5°
Neutrinos	515	438	368	309
Antineutrinos	39	34	25	17

Assuming the operation with $\nu : \bar{\nu} = 1:1$, as well as the oscillation parameters $\theta_{23} = \pi/4$, $\delta_{CP} = -\pi/2$ with normal hierarchy, the expected numbers of appearance events in Korea are shown in Table I, while those in Kamioka are 3219 neutrinos and 420 antineutrinos. The expected numbers of appearance events at DUNE are 1897 neutrinos and 229 antineutrinos. Thus, we understand that, among all the off-axis configurations, the number of events is maximum for 1.3°. This is because the 1.3° off-axis configuration covers the major portion of the first oscillation maxima where the appearance channel probability has a significant contribution (cf. Fig. 1). From the above discussion, it is also clear that the number of events in the Kamioka detector is almost 1.8 times that of the number of events for DUNE. Simulation of the atmospheric neutrino at HK is done with the codes which were used in Refs. [17,64–66] and is described in detail in Ref. [17]. We assume here the data size from the HK atmospheric neutrino experiment for 15 years with 560 kt fiducial volume.

A. Bounds on ϵ_{ee} and $|\epsilon_{e\tau}|$

First, let us discuss the case of the region $(\epsilon_{ee}, |\epsilon_{e\tau}|)$, in which we can test the difference between NSIs with ansatz (10) and the standard three-flavor scheme. Here, we take the best-fit values for most of the standard oscillation parameters as the reference values[5]:

$$\sin^2(2\bar{\theta}_{12}) = 0.87 \qquad \sin^2(2\bar{\theta}_{23}) = 1.0$$
$$\sin^2(2\bar{\theta}_{13}) = 0.085 \qquad \Delta\bar{m}^2_{21} = 7.9 \times 10^{-5}\ \text{eV}^2$$
$$\Delta\bar{m}^2_{32} = 2.4 \times 10^{-3}\ \text{eV}^2 \qquad \bar{\delta}_{CP} = -90^\circ. \tag{12}$$

[5]The oscillation parameters with bars (without bars) stand for the true (test) value throughout this paper.

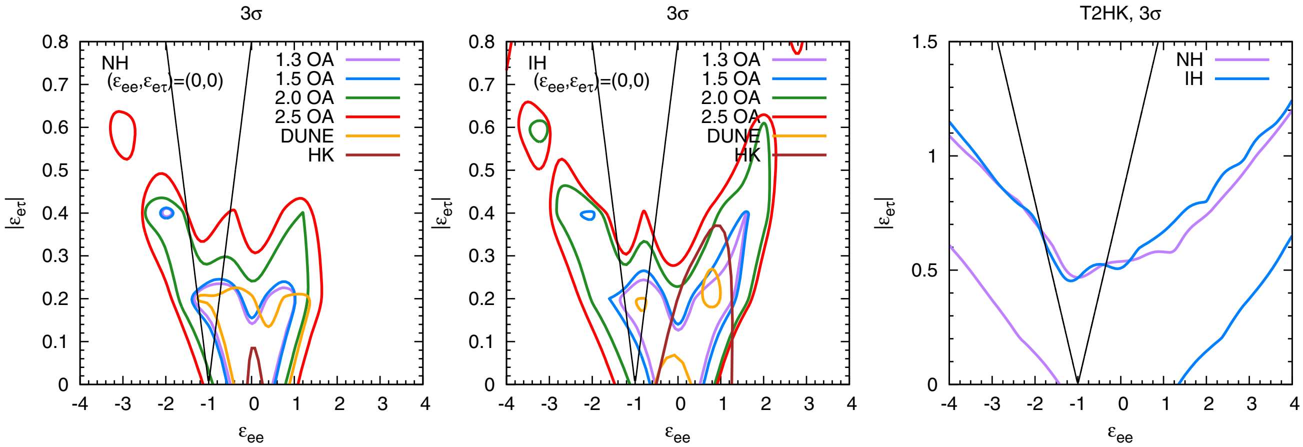

FIG. 2. The excluded region in the (ϵ_{ee}, $|\epsilon_{e\tau}|$) plane. The hypothesis with NSIs is excluded at 3σ outside each curve. The thin solid diagonal straight line stands for the bound $|\tan\beta| \equiv |\epsilon_{e\tau}/(1+\epsilon_{ee})| \lesssim 0.8$ [17] at 3σ from the current atmospheric data by Superkamiokande. Upper left pane: Normal mass hierarchy. Upper right panel: Inverted mass hierarchy. Lower panel: The bounds from T2HK with the detector of volume 560 kt in Kamioka only.

For the parameters θ_{12}, θ_{13}, Δm^2_{21}, and Δm^2_{32}, our choice of true parameters is consistent with the best-fit values as obtained by the global analysis of the world neutrino data [67–69]. The status of θ_{23} at this moment is quite intriguing. The latest T2K data favor maximal mixing [70], whereas the NOνA data disfavor maximal mixing at 2.5σ [71]. Thus, one needs more data from both the experiments to resolve this issue. For our work, we have taken θ_{23} to be maximal in the true spectrum and marginalized from 40° to 50° in the test spectrum. Regarding δ_{CP}, both the experiments obtain a best-fit value of −90°, which we also take as true value in our analysis. We have marginalized δ_{CP} in the test spectrum from −180° to 180°. For the NSIs parameters, we have taken $\bar{\epsilon}_{ee} = |\bar{\epsilon}_{e\tau}| = \arg(\bar{\epsilon}_{e\tau}) = 0$. In the test spectrum, we have marginalized over $\arg(\epsilon_{e\tau})$ from −180° to 180°. The results are shown in Fig. 2, where the curves are drawn at 3σ ($\Delta\chi^2 = 11.83$ for 2 degrees of freedom). NSIs with the ansatz (10) can be distinguished from the standard three-flavor scheme outside the curves. For comparison, we have also shown the excluded regions by the long-baseline experiment DUNE, the atmospheric neutrino experiment HK, and T2HK with the detector of volume 560 kt in Kamioka only. From Fig. 2, we observe that the case at off-axis angle 1.3° has the highest sensitivity to (ϵ_{ee}, $|\epsilon_{e\tau}|$). This is because i) the number of events is the largest at off-axis angle 1.3°, as we can see from Table I, and ii) due to the relatively broadband nature of the flux, the 1.3° off-axis configuration covers the wider energy range in the probability spectrum among the other off-axis configurations. The sensitivity at the 1.5° off axis is similar to that of 1.3°, while the sensitivities at 2.0° and 2.5° are worse than sensitivities at 1.3° and 1.5°. If we compare the sensitivity of the T2HKK with T2HK, then we find that T2HKK is far more powerful than T2HK in terms of constraining the value of the NSIs parameters. These results are true for both normal and inverted hierarchies. The sensitivity of DUNE to NSIs is comparable to T2HKK at 1.3° for normal hierarchy and better in inverted hierarchy. The sensitivity of the HK atmospheric neutrino experiment is the highest for both the hierarchies. In Table II, we have given the 90% C.L., as well as 3σ bounds on ϵ_{ee} and $|\epsilon_{e\tau}|$ for the different experimental setups which are considered in our analysis. From the table, we see that the sensitivity of the 1.3° configuration in constraining (ϵ_{ee}, $|\epsilon_{e\tau}|$) is 1 order of magnitude higher than the configuration of 2.5°.

In Fig. 3, χ^2 to exclude a particular choice ϵ_{ee}, ($|\epsilon_{e\tau}|$) = (0.8, 0.2) is plotted as a function of the running time. Here, for comparison, we have extended the DUNE runtime to 15 years. From the figures, we see that the sensitivity in normal hierarchy (NH) is better than in inverted hierarchy. This is because in inverted hierarchy (IH) the MSW effect enhances the antineutrino probabilities and the cross section of the antineutrinos is almost one-third of the neutrinos. Thus, the number of events in the IH is less

TABLE II. The bounds on ϵ_{ee} and $|\epsilon_{e\tau}|$ at 90% C.L., (3σ) by each experiment in the case of normal hierarchy.

Experiment	ϵ_{ee} 90% C.L (3σ)	$\|\epsilon_{e\tau}\|$ 90% C.L (3σ)
T2HK	−4 to +4 (−4 to +4)	<0.9 (<1.1)
T2HKK (OA 1.3°)	−0.2 to 0.2 (−1.4 to 1.1)	<0.02 (<0.24)
T2HKK (OA 1.5°)	−0.2 to 0.2 (−1.4 to 1.1)	<0.02 (<0.24)
T2HKK (OA 2.0°)	−1.2 to 0.6 (−3.5 to 1.4)	<0.03 (<0.44)
T2HKK (OA 2.5°)	−1.4 to 1.0 (−3.5 to 1.8)	<0.2 (<0.5)
DUNE	−0.1 to 0.4 (−1.2 to 1.4)	<0.04 (<0.23)
atm (HK)	−0.05 to 0.1 (−0.1 to 0.2)	<0.035 (<0.1)

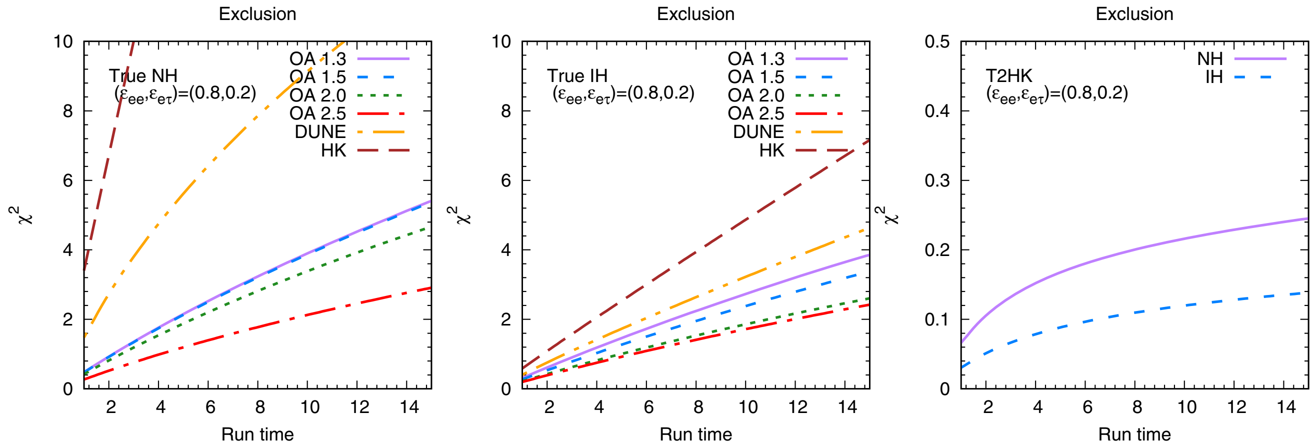

FIG. 3. χ^2 to exclude $(\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)$ as a function of the running time. Upper right panel: Inverted mass hierarchy. Lower panel: The bounds from T2HK with the detector in Kamioka only.

as compared to the normal hierarchy. Similar to that of Fig. 2, the sensitivity of 1.5° is comparable with 1.3°, and the sensitivities at 2.0° and 2.5° are poor. The significance to exclude NSIs is the best for the HK atmospheric neutrino experiment, and it is followed by DUNE. Notice that the sensitivity of T2HK with the detector in Kamioka only has poor sensitivity, and therefore the second detector in Korea greatly improves its sensitivity at all the off-axis angles. From the figure, we notice that T2HKK at off-axis angle 1.3° can exclude the case with $(\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)$ at 2σ within its proposed runtime for both the hierarchies, whereas DUNE and HK can exclude the same by more than 3σ in for NH. For IH, the sensitivity of DUNE is similar to that of the 1.3° configuration of T2HKK, and the sensitivity of HK is around 2.5σ in 15 years of running. The sensitivity of the T2HK experiment is less than 1σ for both the hierarchies.

B. *CP*-violating phases

Next let us consider the implication for the T2HKK experiment in the case with an affirmative result of NSIs. As a reference value for NSIs, we take $(\bar{\epsilon}_{ee}, |\bar{\epsilon}_{e\tau}|) = (0.8, 0.2)$, which lies outside each exclusion curve in the $(\epsilon_{ee}, |\epsilon_{e\tau}|)$ plane at 90% C.L.[6]

The ansatz (10) contains the two phases δ_{CP} and $\arg(\epsilon_{e\tau})$. In the presence of NSIs, it is important how precisely we can determine these two phases. So, we study the correlation between δ_{CP} and $\arg(\epsilon_{e\tau})$ around a certain set of the two phases. Here, we assume that the true oscillation parameters are

$$\bar{\epsilon}_{ee} = 0.8, \qquad |\bar{\epsilon}_{e\tau}| = 0.2,$$
$$\bar{\phi}_{31} \equiv \arg(\bar{\epsilon}_{e\tau}) = 0, \qquad \bar{\delta}_{CP} = -\frac{\pi}{2}.$$

[6]Notice that Fig. 2 is depicted for 3σ and the allowed region at 90% C.L. is smaller than that at 3σ.

The allowed regions at 90% C.L., around the true value $[\bar{\delta}_{CP}, \arg(\bar{\epsilon}_{e\tau})]$ are shown in Fig. 4 for $(\bar{\epsilon}_{ee}, |\bar{\epsilon}_{e\tau}|) = (0.8, 0.2)$. In these plots, we have marginalized over ϵ_{ee} from -4 to $+4$ and $|\epsilon_{e\tau}|$ from 0 to 2. To clarify the roles of the two detectors, in the case of the off-axis angle 1.3°, separate contours are given in Fig. 5 for the result from the detector in Kamioka (purple curve) and that from the detector in Korea (blue curve) and for that from the combination of the two (green curve). As we can see from Fig. 4, T2HKK at the off-axis angles 1.3° and 1.5° has good sensitivity also in the sensitivity to the *CP* phases. In the case of off-axis angle 1.3°, the sensitivity of T2HKK is better than that of DUNE. This can be explained as follows. The detector in Kamioka, which has a shorter baseline length, has poor sensitivity to the matter effect and therefore to ϵ_{ee} and $|\epsilon_{e\tau}|$. This is why the allowed region of the Kamioka detector is large in Fig. 5 (purple contour), since the uncertainty in ϵ_{ee} and $|\epsilon_{e\tau}|$ increases the uncertainty in the *CP* phases. However, from the result of the detector in Korea, we have stronger constraint on ϵ_{ee} and $|\epsilon_{e\tau}|$. If we use this information, then the detector in Kamioka gives better sensitivity to δ_{CP} because of its high statistics. To confirm this, in Fig. 5, we also draw the contours for the Kamioka detector assuming ϵ_{ee} and $|\epsilon_{e\tau}|$ are known (the red dotted contours where we do not marginalize over ϵ_{ee} and $|\epsilon_{e\tau}|$), and we see that the allowed region shrinks profoundly. So, the sensitivity of the combined T2HKK detector complex to the *CP* phases is better than that of DUNE. This synergy of the detectors in Kamioka and in Korea in the determination of the *CP* phases is the striking advantage of the T2HKK experiment. On the other hand, the HK atmospheric neutrino experiment has disjoint allowed regions particularly in the inverted mass hierarchy. If one assumes that HK could separate neutrinos and antineutrinos, then we have confirmed that these disjoint regions disappear. Thus, as far as sensitivity to the *CP* phases is concerned, its performance is not as good as the

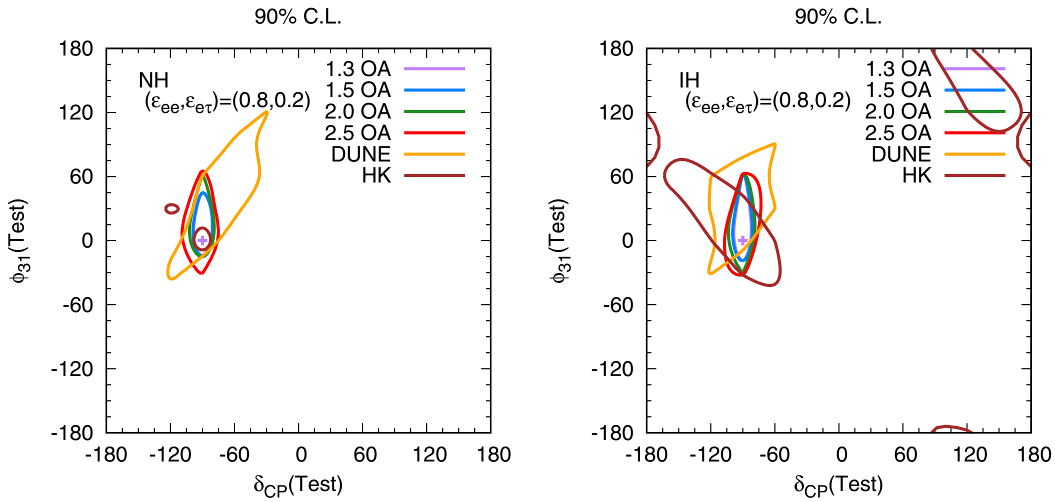

FIG. 4. The correlation between δ_{CP} and $\phi_{31} \equiv \arg(\epsilon_{e\tau})$ for normal hierarchy (left panel) and inverted hierarchy (right panel). The true value is $(\bar{\delta}_{CP}, \bar{\phi}_{31}) = (-\pi/2, 0)$.

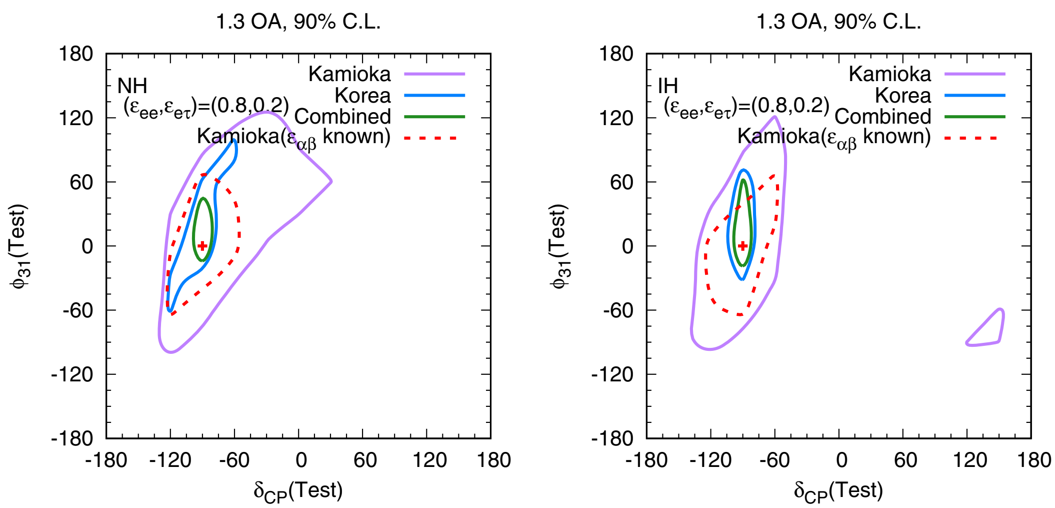

FIG. 5. The correlation between δ_{CP} and $\phi_{31} \equiv \arg(\epsilon_{e\tau})$ for normal hierarchy (left panel) and inverted hierarchy (right panel) at the off-axis angle 1.3°. The true values are $\bar{\phi}_{31} = 0$ and $\bar{\delta}_{CP} = -\pi/2$. The dotted curves, which are given for the detector in Kamioka without marginalizing over ϵ_{ee} and $|\epsilon_{e\tau}|$, are also shown to show the contribution of these two parameters.

T2HKK experiment in inverted hierarchy. But for normal hierarchy, the sensitivity of HK in constraining the *CP* phases is best among all the other setups because of the huge Earth matter effects.

IV. CONCLUSION

We have studied the sensitivity of the T2HKK experiment to the nonstandard interaction in propagation with the ansatz (10). With the ansatz (10), we obtained the region in the (ϵ_{ee}, $|\epsilon_{e\tau}|$) plane in which T2HKK can distinguish NSIs from the standard three-flavor scenario. As far as the sensitivity to NSIs is concerned, T2HKK at the off-axis angle 1.3° is the best option, and with this option, T2HKK can discriminate NSIs at 3σ from the standard case for approximately $|\epsilon_{ee}| \gtrsim 1$ and $|\epsilon_{e\tau}| \gtrsim 0.2$. The sensitivity of DUNE is comparable to that of T2HKK with a 1.3° off-axis flux configuration in normal hierarchy, but it is better in the inverted hierarchy. We find that the sensitivity of the HK atmospheric experiment is the highest among the other setups considered in this work.

On the other hand, if the value of $|\epsilon_{e\tau}|$ is relatively large $|\epsilon_{e\tau}| \gtrsim 0.2$, then we can determine the two phases δ_{CP}, $\arg(\epsilon_{e\tau})$ separately by T2HKK or DUNE. As far as the sensitivity to the *CP* phases is concerned, T2HKK is better than DUNE. The powerful feature of determination of the two *CP* phases is the remarkable advantage of the T2HKK experiment. The atmospheric neutrino experiment at HK is inferior to the two long-baseline experiments in inverted hierarchy but superior in normal hierarchy.

Since the matter effect A and the baseline length L appear in the form of $AL/2 \sim L/4000$ km in the oscillation probability, long-baseline neutrino experiments with longer baseline lengths ($L \gtrsim 1000$ km) are sensitive to the matter effect. Hence, they are also sensitive to NSIs. The nice feature of the T2HKK experiment is that, while the detector in Kamioka with a shorter baseline length is advantageous to measure δ_{CP} because of its high statistics, the one in Korea with a longer baseline length has better sensitivity to the matter effect as well as ϵ_{ee} and $|\epsilon_{e\tau}|$. We have seen that the sensitivity to ϵ_{ee} and $|\epsilon_{e\tau}|$ is the best at the off-axis angle 1.3°. Thus, we conclude that T2HKK at the off-axis angle 1.3° is expected to be the best option to make the synergy of the two detectors effectively determine the NSIs parameters ϵ_{ee} and $|\epsilon_{e\tau}|$ as well as the CP phases δ_{CP} and $\arg(\epsilon_{e\tau})$.

ACKNOWLEDGMENTS

The authors thank the Hyper-Kamiokande Collaboration for providing the neutrino flux of T2HKK in Korea. M. G. would like to thank Mark Hartz for many useful discussions and Chandan Gupta for help in ROOT. This research was partly supported by a Grant-in-Aid for Scientific Research of the Ministry of Education, Science and Culture, under Grants No. 25105009, No. 15K05058, No. 25105001, and No. 15K21734.

[1] C. Patrignani *et al.* (Particle Data Group Collaboration), Chin. Phys. C **40**, 100001 (2016).
[2] K. Abe *et al.* (Hyper-Kamiokande Working Group Collaboration), arXiv:1412.4673.
[3] R. Acciarri *et al.* (DUNE Collaboration), arXiv:1512.06148.
[4] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).
[5] M. M. Guzzo, A. Masiero, and S. T. Petcov, Phys. Lett. B **260**, 154 (1991).
[6] E. Roulet, Phys. Rev. D **44**, R935 (1991).
[7] T. Ohlsson, Rept. Prog. Phys. **76**, 044201 (2013).
[8] O. G. Miranda and H. Nunokawa, New J. Phys. **17**, 095002 (2015).
[9] A. Friedland and I. M. Shoemaker, arXiv:1207.6642.
[10] R. Adhikari, S. Chakraborty, A. Dasgupta, and S. Roy, Phys. Rev. D **86**, 073010 (2012).
[11] A. Esmaili and A. Yu. Smirnov, J. High Energy Phys. 06 (2013) 026.
[12] S. Choubey and T. Ohlsson, Phys. Lett. B **739**, 357 (2014).
[13] A. Chatterjee, P. Mehta, D. Choudhury, and R. Gandhi, Phys. Rev. D **93**, 093017 (2016).
[14] M. Masud, A. Chatterjee, and P. Mehta, J. Phys. G **43**, 095005 (2016).
[15] A. de Gouvêa and K. J. Kelly, Nucl. Phys. **B908**, 318 (2016).
[16] Z. Rahman, A. Dasgupta, and R. Adhikari, J. Phys. G **42**, 065001 (2015).
[17] S. Fukasawa and O. Yasuda, Adv. High Energy Phys. **2015**, 1 (2015).
[18] S. Choubey, A. Ghosh, T. Ohlsson, and D. Tiwari, J. High Energy Phys. 12 (2015) 126.
[19] P. Coloma, J. High Energy Phys. 03 (2016) 016.
[20] J. Liao, D. Marfatia, and K. Whisnant, Phys. Rev. D **93**, 093016 (2016).
[21] C. Soumya and R. Mohanta, Phys. Rev. D **94**, 053008 (2016).
[22] M. Blennow, S. Choubey, T. Ohlsson, D. Pramanik, and S. K. Raut, J. High Energy Phys. 08 (2016) 090.
[23] D. V. Forero and P. Huber, Phys. Rev. Lett. **117**, 031801 (2016).
[24] K. Huitu, T. J. Kärkkäinen, J. Maalampi, and S. Vihonen, Phys. Rev. D **93**, 053016 (2016).
[25] P. Bakhti and Y. Farzan, J. High Energy Phys. 07 (2016) 109.
[26] M. Masud and P. Mehta, Phys. Rev. D **94**, 013014 (2016).
[27] P. Coloma and T. Schwetz, Phys. Rev. D **94**, 055005 (2016).
[28] M. Masud and P. Mehta, Phys. Rev. D **94**, 053007 (2016).
[29] S. K. Agarwalla, S. S. Chatterjee, and A. Palazzo, Phys. Lett. B **762**, 64 (2016).
[30] S.-F. Ge and A. Yu. Smirnov, J. High Energy Phys. 10 (2016) 138.
[31] S. Fukasawa and O. Yasuda, Nucl. Phys. **B914**, 99 (2017).
[32] J. Liao, D. Marfatia, and K. Whisnant, Phys. Lett. **B767**, 350 (2017).
[33] S. Fukasawa, M. Ghosh, and O. Yasuda, arXiv:1609.04204.
[34] M. Blennow, P. Coloma, E. Fernandez-Martinez, J. Hernandez-Garcia, and J. Lopez-Pavon, arXiv:1609.08637.
[35] K. Abe *et al.* (T2K Collaboration), Prog. Theor. Exp. Phys. **2015**, 043C01 (2015).
[36] S. B. Kim, KOSEF-JSPS Joint Seminar on New Developments in Neutrino Physics, Korea Institute for Advanced Study, Seoul, 2000 (unpublished).
[37] K. Hagiwara, Nucl. Phys. B, Proc. Suppl. **137**, 84 (2004).
[38] M. Ishitsuka, T. Kajita, H. Minakata, and H. Nunokawa, Phys. Rev. D **72**, 033003 (2005).
[39] K. Hagiwara, N. Okamura, and K.-i. Senda, Phys. Lett. B **637**, 266 (2006); **641**, 491(E) (2006).
[40] K. Hagiwara, N. Okamura, and K.-i. Senda, Phys. Rev. D **76**, 093002 (2007).
[41] T. Kajita, H. Minakata, S. Nakayama, and H. Nunokawa, Phys. Rev. D **75**, 013006 (2007).
[42] V. Barger, P. Huber, D. Marfatia, and W. Winter, Phys. Rev. D **76**, 053005 (2007).
[43] K. Kimura, A. Takamura, and T. Yoshikawa, J. High Energy Phys. 03 (2008) 016.
[44] N. C. Ribeiro, H. Nunokawa, T. Kajita, S. Nakayama, P. Ko, and H. Minakata, Phys. Rev. D **77**, 073007 (2008).
[45] P. Huber, M. Mezzetto, and T. Schwetz, J. High Energy Phys. 03 (2008) 021.

[46] K. Hagiwara and N. Okamura, J. High Energy Phys. 07 (2009) 031.
[47] H. Oki and O. Yasuda, Phys. Rev. D **82**, 073009 (2010).
[48] K. Hagiwara, N. Okamura, and K.-i. Senda, J. High Energy Phys. 09 (2011) 082.
[49] K. Hagiwara, T. Kiwanami, N. Okamura, and K.-i. Senda, J. High Energy Phys. 06 (2013) 036.
[50] F. Dufour, arXiv:1211.3884.
[51] K. Hagiwara, P. Ko, N. Okamura, and Y. Takaesu, arXiv:1605.02368.
[52] T. Nakaya, 18th International Workshop on Neutrino Factories and Future Neutrino Facilities (NuFact16), Quy Nhon, Vietnam, 2016 (unpublished).
[53] K. Abe *et al.* (Hyper-Kamiokande Proto-Collaboration), arXiv:1611.06118.
[54] K. Abe *et al.*, arXiv:1109.3262.
[55] S. Davidson, C. Pena-Garay, N. Rius, and A. Santamaria, J. High Energy Phys. 03 (2003) 011.
[56] C. Biggio, M. Blennow, and E. Fernandez-Martinez, J. High Energy Phys. 08 (2009) 090.
[57] Y. Grossman, Phys. Lett. B **359**, 141 (1995).
[58] A. Friedland, C. Lunardini, and M. Maltoni, Phys. Rev. D **70**, 111301 (2004).
[59] A. Friedland and C. Lunardini, Phys. Rev. D **72**, 053009 (2005).
[60] Hyper-Kamiokande Collaboration, fluxfiles, 2016, https://wiki.hyperk.org/working-groups/wg8-beam-accelerator/fluxfiles.
[61] P. Huber, M. Lindner, and W. Winter, Comput. Phys. Commun. **167**, 195 (2005).
[62] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, Comput. Phys. Commun. **177**, 432 (2007).
[63] M. Blennow and E. Fernandez-Martinez, Comput. Phys. Commun. **181**, 227 (2010).
[64] R. Foot, R. R. Volkas, and O. Yasuda, Phys. Rev. D **58**, 013006 (1998).
[65] O. Yasuda, Phys. Rev. D **58**, 091301 (1998).
[66] O. Yasuda, arXiv:hep-ph/0006319.
[67] D. V. Forero, M. Tortola, and J. W. F. Valle, Phys. Rev. D **90**, 093006 (2014).
[68] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, and T. Schwetz, J. High Energy Phys. 01 (2017) 087.
[69] F. Capozzi, G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, and A. Palazzo, Phys. Rev. D **89**, 093018 (2014).
[70] L. Magaletti, NOW2016, Otranto, Italy, 2016 (unpublished).
[71] P. Vahle, Neutrino 2016, London, 2016 (unpublished).