Probing Nonstandard Neutrino Physics at T2KK

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Abstract

Having a far detector in Korea for the J-PARC neutrino beam in addition to one at Kamioka has been shown to be a powerful way to lift neutrino parameter (Δm^2 and mixing angles) degeneracies. In this talk, I report the sensitivity of the same experimental setup to nonstandard neutrino physics, such as quantum decoherence, violation of Lorentz symmetry (with/without CPT invariance), and nonstandard neutrino interactions with matter. In many cases, two detector setup is better than one detector setup at SK. This observation makes another support for the two detector setup.

1. Introduction

The neutrino mass induced neutrino oscillation has been identified as a dominant mechanism for neutrino disappearances through a number of the neutrino experiments: the atmospheric [1], solar [2], reactor [3], and accelerator [4] experiments. After passing through the discovery era, the neutrino physics will enter the epoch of precision study, as the CKM phenomenology and CP violation in the quark sector. The MNS matrix elements will be measured with higher accuracy, including the CP phase(s), and the neutrino properties such as their interactions with matter etc. will be studied in a greater accuracy.

In recent years [5, 6], the physics potential of the Kamioka-Korea two detector setting which receive an intense neutrino beam from J-PARC was considered in detail, and it has been demonstrated that the two detector setting is powerful enough to resolve all the eight-fold parameter degeneracy [7, 8, 9], if θ_{13} is in reach of the next generation accelerator [4, 11] and the reactor experiments [12, 13]. The degeneracy includes the parameters θ_{13}, δ and octant of θ_{23}, and it is doubled by the ambiguity which arises due to the unknown sign of Δm^2_{31}. The detector in Korea plays a decisive role to lift the last one. For related works on Kamioka-Korea two detector complex, see, for example, [14, 15, 15, 16]. This observation was the main motivation for this series of workshops, and a lot of speakers gave talks about physics potential at the Kamioka-Korea two detector setup in the past three workshops.

During the course of precision studies, it will become natural to investigate nonstandard physics related with neutrinos. In this talk, I will show that the

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Kamioka-Korea identical two detector setting is also a unique apparatus for studying nonstandard physics (NSP), by demonstrating that the deviation from the expectation by the standard mass-induced oscillation can be sensitively probed by comparing yields at the intermediate (Kamioka) and the far (Korea) detectors. In this talk, I discuss the potential of the Kamioka-Korea setting, concentrating on $\nu_\mu - \nu_\tau$ subsystem in the standard three-flavor mixing scheme, and focus on ν_μ disappearance measurement. We consider three different types of nonstandard neutrino physics:

- Quantum decoherence (QD) [18, 19, 20]
- Tiny violation of Lorentz symmetry with/without CPT [21, 22, 23]
- Nonstandard neutrino interactions of neutrinos with matter due to some new physics [24, 25]

The first two cases go beyond the conventional quantum field theory framework, whereas the last case is strictly within the conventional QFT.

In analyzing the nonstandard physics, we aim at demonstrating the powerfulness of the Kamioka-Korea identical two detector setting, compared to other settings. For this purpose, we systematically compare the results obtained with the following three settings (the number indicate the fiducial mass):

- Kamioka-Korea setting: Two identical detectors one at Kamioka and the other in Korea each 0.27 Mton
- Kamioka-only setting: A single 0.54 Mton detector at Kamioka
- Korea-only setting: A single 0.54 Mton detector at somewhere in Korea.

Among the cases we have examined Kamioka-Korea setting always gives the best sensitivities, apart from two exceptions of violation of Lorentz invariance in a CPT violating manner, and the nonstandard neutrino interactions with matter. Whereas, the next best case is sometimes Kamioka-only or Korea-only settings depending upon the problem.

This talk is organized as follows. In Sec. 2., we illustrate how we can probe nonstandard physics with Kamioka-Korea two detector setting, with a quantum decoherence as an example of nonstandard neutrino physics. In Sec. 3., we discuss quantum decoherence. In Sec. 4., we discuss possible violation of Lorentz invariance. In Sec. 5., we discuss non-standard neutrino matter interactions, and the results of study is summarized in Sec. 6.. This talk is based on the work [26], where one can find more plots and detailed discussions covered in this talk.

2. Basic Ideas

Let me first describe the basic strategy of our analysis adopted in the following sections. For the purpose of illustration, we consider quantum decoherence (QD), for which the ν_μ survival probability is given by

$$P(\nu_\mu \to \nu_\mu) = P(\overline{\nu}_\mu \to \overline{\nu}_\mu) = 1 - \frac{1}{2}\ \sin^2 2\theta\ \left[1 - e^{-\gamma(E)L} \cos\left(\frac{\Delta m^2 L}{2E}\right)\right], \quad (1)$$

with $\gamma(E) = \gamma/E$ as an illustration. The $\overline{\nu}_\mu$ survival probability is the same as above, assuming CPT invariance in the presence of QD. Then one can calculate the number of ν_μ and $\overline{\nu}_\mu$ events observed at two detectors placed at Kamioka and Korea, using the above survival probability and the neutrino beam profiles. For simplicity, let us consider the number of observed neutrino events both at

Kamioka and Korea, for each energy bin (with 50 MeV width) from $E_\nu = 0.2$ GeV upto $E_\nu = 1.4$ GeV. In Fig. 1, we show the ν_μ event spectra at detectors located at Kamioka and Korea for the pure oscillation $\gamma = 0$ (the left column) and the oscillation plus QD with two different QD parameters, $\gamma = 1 \times 10^{-4}$ GeV/km (the middle column) and $\gamma = 2 \times 10^{-4}$ GeV/km (the right column). * One observes the spectral distortion for non-vanishing γ. In particular, the spectral distortions are different between detectors at Kamioka and Korea due to the differect L/E values at the two positions.

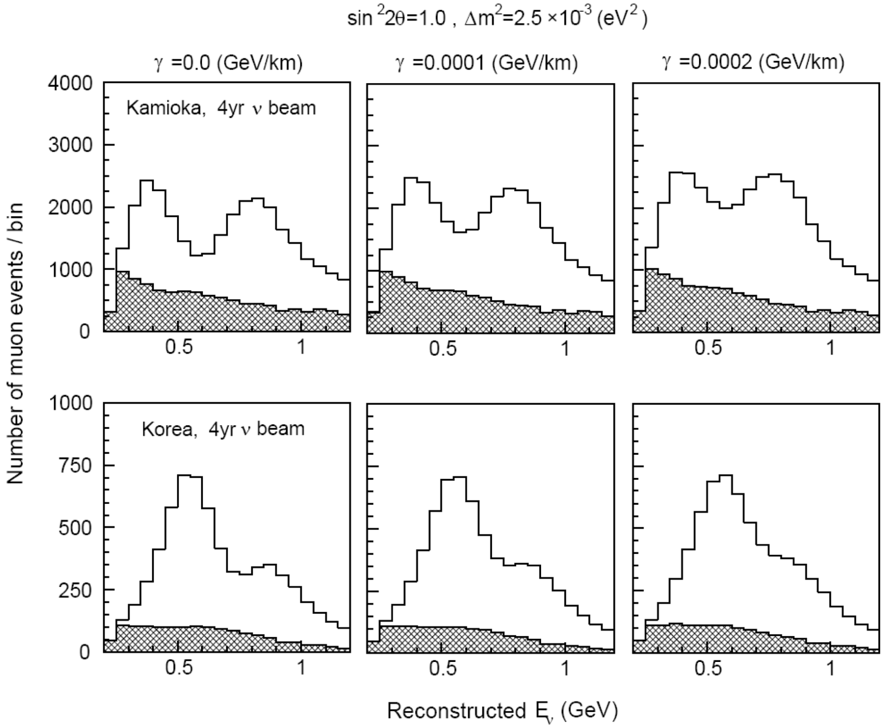

Fig. 1 Event spectra of neutrinos at Kamioka (the top panel) and Korea (the bottom panel) for $\gamma = 0$ (the left column), 1×10^{-4} GeV/km (the middle column), and $\gamma = 2 \times 10^{-4}$ GeV/km (the right column). The hatched areas denote the non-quasi-elastic events.

Assuming the actual data at Kamioka and Korea are given (or well described) by the pure oscillation with $\sin^2 2\theta = 1$ and $\Delta m^2 = 2.5 \times 10^{-2}$ eV^2, we could claim that $\gamma = 1 \times 10^{-4}$ GeV/km (shown in the middle column), for example, would be inconsistent with the data. One can make this kind of claim in a more proper and quantitative manner using the χ^2 analysis, which is described in details in Ref. [26].

*In order to convert this γ in unit of GeV/km to γ defined in Eq. (2), one has to multiply 0.197×10^{-18}.

3. Quantum Decoherence (QD)

3.1. Motivation

When a quantum system interacts with environment, quantum decoherence (QD) could appear. A classic example is a two-slit experiment with electron beams. If we do not measure which hole an electron passes through, one observes an interference pattern. On the other hand, if we try to determine which hole an electron passes through using some device, the interference pattern will be distorted. As the disturbance becomes stronger, the interference will be distorted more, thus it eventually disappears.

It has been speculated for some time that there may be a loss of quantum coherence due to environmental effect or quantum gravity and space-time foam, etc.. Although quantum decoherence (QD) due to rapid fluctuation of environment is conceivable, QD due to quantum gravity is still under debate among theoreticians. In this talk, I present our phenomenological study of QD, namely how this effect can be probed by the Kamioka-Korea setting. rather than discuss the ground on the origin of QD within quantum gravity. For previous analyses of decoherence in neutrino experiments, see e.g., [19, 27, 28].

As discussed in Sec. 1. we consider the $\nu_\mu - \nu_\tau$ two-flavor system. Since the matter effect is a sub-leading effect in this channel we employ vacuum oscillation approximation in this section. The two-level system in vacuum in the presence of quantum decoherence can be solved to give the ν_μ survival probability Eq. (1) [19, 20]. Notice that the conventional two-flavor oscillation formula is reproduced in the limit $\gamma(E) \to 0$. Since the total probability is still conserved in the presence of QD, the relation $P(\nu_\mu \to \nu_\tau) = 1 - P(\nu_\mu \to \nu_\mu)$ holds.

Nothing is known for the energy dependence of $\gamma(E)$ from the first principle including quantum gravity. Therefore, we examine, following [19], several typical cases of energy dependence of $\gamma(E)$, which are purely phenomenological ansatzs:

$$\gamma(E) = \gamma \left(\frac{E}{\text{GeV}} \right)^n \quad (\text{with } n = 0, 2, -1) \tag{2}$$

In this convention, the overall constant γ has a dimension of energy or $(\text{length})^{-1}$, for any values of the exponent n. We will use γ in GeV unit in this section. In the following three subsections, we analyze three different energy dependences, $n = 0, -1, 2$ one by one.

3.2. Numerical results and discussions

First, let me consider the case with $n = -1$: $\gamma(E) \propto \frac{1}{E}$. It turns out that the correlations between Δm^2 and $\sin^2 2\theta$ at three experimental setups. Note that there are strong correlations between $\sin^2 2\theta$ and γ for the Kamioka-only and Korea-only setups, and the slope of the correlation for the Kamioka-only setup is different from that for the Korea-only setup (see Fig. 2 in Ref. [26]). Therefore the Kamioka-Korea setup can give a stronger bound than each experimental setup. This advantage can be seen in Fig. 2, where we present the sensitivity regions of γ as a function of $\sin^2 2\theta$ (left panel) and Δm^2 (right panel).

We can repeat the same analysis for other cases $n = 0$ and $n = 2$. In Table 1, we summarize the bounds on γ at 2σ CL achievable by three different experimental settings, along with the upper bounds on γ at 90% CL obtained by analyzing the atmospheric neutrino data in [19], for the purpose of comparison.

In the case of $\frac{1}{E}$ dependence of $\gamma(E)$, the sensitivity to γ in the Kamioka-Korea setting is better than the Korea-only and the Kamioka-only settings by a factor greater than 3 and 6, respectively. Also all the three settings can improve the

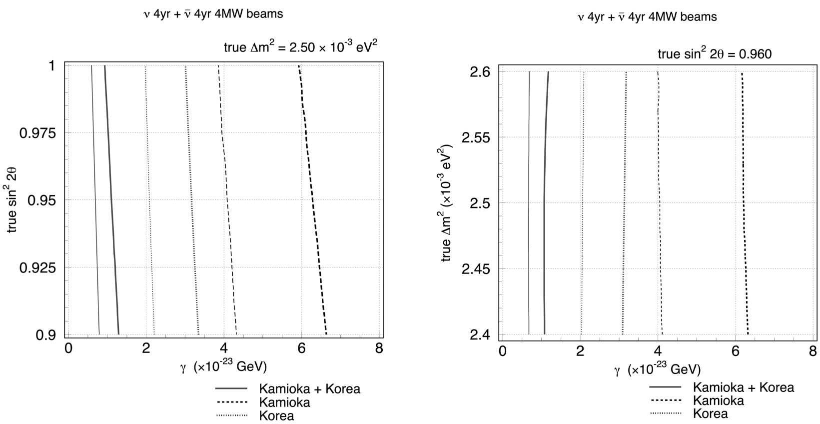

Fig. 2 The sensitivity to γ as a function of $\sin^2 2\theta \equiv \sin^2\theta_{23}$ (left panel) and $\Delta m^2 \equiv \Delta m^2_{32}$ (right panel). The case of 1/E dependence of $\gamma(E)$. The red solid lines are for Kamioka-Korea setting with each 0.27 Mton detector, while the dashed black (dotted blue) lines are for Kamioka (Korea) only setting with 0.54 Mton detector. The thick and the thin lines are for 99 % and 90 % CL, respectively. 4 years of neutrino plus 4 years of anti-neutrino running are assumed. The other input values of the parameters are $\Delta m^2_{31} = +2.5 \times 10^{-3}$ eV^2 (with positive sign indicating the normal mass hierarchy) and $\sin^2\theta_{23}$=0.5. The solar mixing parameters are fixed as $\Delta m^2_{21} = 8 \times 10^{-5}$ eV^2 and $\sin^2\theta_{12}$=0.31.

current bound almost by two orders of magnitude. This case demonstrates clearly that the two-detector setup is more powerful than the Kamioka-only setup.

For $n = 0$ (the case of an energy independent constant $\gamma(E)$), we find that the sensitivity to γ in the Kamioka-Korea setting is better than the Korea-only and the Kamioka-only settings by a factor greater than 3 and 8, respectively. Also Kamioka-Korea two detector setting can improve the current bound by a factor of ~ 3.

Finally, for $n = 2$ with $\gamma(E) \propto E^2$, the sensitivity to γ in the Kamioka-Korea setting is better than the Korea-only and the Kamioka-only settings by a factor greater than 3 and 5, respectively. On the other hand, the current bound imposed by the atmospheric neutrino data surpasses those of our three settings by almost $\sim$4 orders of magnitude. Because the spectrum of atmospheric neutrinos spans a wide range of energy which extends to 100-1000 GeV, it gives much tighter constraints on the decoherence parameter for quadratic energy dependence of $\gamma(E)$. In a sense, the current Super-Kamiokande experiment is already a powerful neutrino spectroscope with a very wide energy range, and could be sensitive to nonstandard neutrino physics that may affect higher energy neutrinos such as QD with $\gamma(E) \sim E^2$.

4. Violation of Lorentz Symmetry

4.1. Motivation

Lorentz symmetry is one of the cornerstones of the quantum field theory, which is a mathematical tool for high energy physics nowadays. Therefore it is important to test this symmetry experimentally as accurately as possible. There may be a small violation of Lorentz symmetry, which would modify the usual energy-momentum dispersion relations. In such a case, neutrinos can have both velocity mixings and the mass mixings, which are CPT conserving [21]. Also there could be CPT-violating interactions in general [21, 22, 23]. Then, the energy of neutrinos with

Table 1 Presented are the upper bounds on decoherence parameters γ defined in (2) for three possible values of n. The current bounds are based on [19] and are at 90% CL. The sensitivities obtained by this study are also at 90 % CL , and correspond to the true values of the parameters $\Delta m^2 = 2.5 \times 10^{-3}\text{eV}^2$ and $\sin^2 2\theta_{23} = 0.96$.

n	Curent bound	Kamioka-only	Korea-only	Kamioka-Korea
$n = 0$	$< 3.5 \times 10^{-23}$	$< 8.7 \times 10^{-23}$	$< 3.2 \times 10^{-23}$	$< 1.1 \times 10^{-23}$
$n = -1$	$< 2.0 \times 10^{-21}$	$< 4.0 \times 10^{-23}$	$< 2.0 \times 10^{-23}$	$< 0.7 \times 10^{-23}$
$n = 2$	$< 0.9 \times 10^{-27}$	$< 9.2 \times 10^{-23}$	$< 6.0 \times 10^{-23}$	$< 1.7 \times 10^{-23}$

definite momentum in ultra-relativistic regime can be written as

$$\frac{mm^\dagger}{2p} = cp + \frac{m^2}{2p} + b, \tag{3}$$

where m^2, c, and b are 3×3 hermitian matrices, and the three terms represent, in order, the effects of velocity mixing, mass mixing, and CPT violation [22]. The energies of neutrinos are eigenvalues of (3), and the eigenvectors give the "mass eigenstates". Notice that while c is dimensionless quantity, b has dimension of energy. For brevity, we will use GeV unit for b.

Within the framework just defined above, we can work in the $\nu_\mu - \nu_\tau$ two flavor subsystem, and derive the ν_μ survival probability, which depends on six parameters. We further assume that three matrices m^2, c and b are diagonalized by the same unitarity transformations with the same mixing angles: namely, $\theta_m = \theta_c = \theta_b \equiv \theta$. Then the ν_μ survival probability is given by :

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \ \sin^2 \left[L \left(\frac{\Delta m^2}{4E} + \frac{\delta b}{2} + \frac{\delta c E}{2} \right) \right], \tag{4}$$

and we recovers the case treated in [29]. Here, $\delta b \equiv b_2 - b_1$ and $\delta c \equiv c_2 - c_1$, where $c_{i=1,2}$ and $b_{i=1,2}$, are the eigenvalues of the matrix c and b. Note that we still have 4 parameters, θ, Δm^2, δb and δc. The survival probability for the anti-neutrino is obtained by the following substitution:

$$\delta c \to \delta c, \quad \delta b \to -\delta b \tag{5}$$

The difference in the sign changes signify the CPT conserving vs. CPT violating nature of c and b terms. As pointed out in [30], the analysis for violation of Lorentz invariance with δc term is equivalent to testing the equivalence principle [31]. The oscillation probability in (4) looks like the one for conventional neutrino oscillations due to Δm^2, with small corrections due to the Lorentz symmetry violating δb and δc terms. In this sense, it may be the most interesting case to examine as a typical example with the Lorentz symmetry violation. Note that the sign of δb and δc can have different effects on the survival probabilities, so that the bounds on δb and δc could depend on their signs, although we will find that the difference is rather small.

4.2. Numerical results and discussions

For ease of analysis and simplicity of presentation, we further restrict our analysis to the case of either $\delta b = 0$ and $\delta c \neq 0$ (CPT conserving), or $\delta b \neq 0$ and $\delta c = 0$ (CPT violating).

Let me first examine violation of Lorentz invariance with CPT conservation, namely $\delta b = 0$ and $\delta c \neq 0$. Unlike the case of quantum decoherence, the sensitivities to δc achieved by the Kamioka-Korea setting is slightly better than those of the Korea-only and the Kamioka-only settings but not so much. The sensitivity is weakly correlated to θ, and the best sensitivity is achieved at the maximal θ. There is almost no correlation to Δm^2.

Next we consider the CPT and Lorentz violating case ($\delta c = 0$ and $\delta b \neq 0$). In this case, unlike the system with decoherence, the sensitivity is greatest in the Kamioka-only setting, though the one by the Kamioka-Korea setting is only slightly less by about $15-20\%$. Whereas, the sensitivity by the Korea-only setting is much worse, more than a factor of 2 compared to the Kamioka-only setting. The reason for this lies in the ν_μ and $\overline{\nu}_\mu$ survival probabilities. In this scenario, the effect of the nonvanishing δb appears as the difference in the oscillation frequency between neutrinos and anti-neutrinos, if the energy dependence is neglected. In this case, the measurement at different baseline is not very important. Then the Kamioka-only setup turns out to be slightly better than the Kamioka-Korea setup. This case is also unique by having the worst sensitivity at the largest value of Δm^2. Also, the correlation of sensitivity to $\sin^2 2\theta$ is strongest among the cases examined in this paper, with maximal sensitivity at maximal θ. (See the right and the left panels of Fig. 5 of Ref. [26] for details.)

I summarize the results in Table 2, along with the present bounds on δc and δb, respectively. We quote the current bounds on δc's from Ref.s [32, 33] which was obtained by the atmospheric neutrino data,

$$|\delta c_{\mu\tau}| \lesssim 3 \times 10^{-26}. \tag{6}$$

We note that the current bound on $\delta c_{\mu\tau}$ obtained by atmospheric neutrino data is quite strong. The reason why the atmospheric neutrino data give much stronger limit is that the relevant energy is much higher (typically $\sim$ 100 GeV) than the one we are considering ($\sim$ 1 GeV) and the baseline is larger, as large as the Earth diameter.

For the bound on δb, Barger et al. [34] argue that

$$|\delta b_{\mu\tau}| < 3 \times 10^{-20}\ \text{GeV} \tag{7}$$

from the analysis of the atmospheric neutrino data.

Let me compare the sensitivity on δb within our two detector setup with the sensitivity at a neutrino factory. Barger et al. [34] considered a neutrino factory with 10^{19} stored muons with 20 GeV energy, and 10 kton detector, and concluded that it can probe $\delta b < 3 \times 10^{-23}$ GeV. The Kamioka-Korea two detector setup and Kamioka-only setup have five and six times better sensitivities compared with the neutrino factory with the assumed configuration. Of course the sensitivity of a neutrino factories could be improved with a larger number of stored muons and a larger detector. A more meaningful comparison would be possible, only when one has configurations for both experiments which are optimized for the purposes of each experiment. Still we can conclude that the Kamioka-Korea two-detector setup could be powerful to probe the Lorentz symmetry violation.

5. Nonstandard Neutrino Interactions with Matter

5.1. Motivations

In the presence of new physics around electroweak scale, neutrinos might have nonstandard neutral current interactions with matter [24, 25, 35, 36], $\nu_\alpha + f \to \nu_\beta + f$ ($\alpha, \beta = e, \mu, \tau$), with f being the up quarks, the down quarks and electrons.

Table 2 Presented are the upper bounds on the velocity mixing parameter δc and the CPT violating parameter δb (in GeV). The current bounds are based on [32, 33, 34] and are at 90% CL. The sensitivites obtained in this study are also at 90 % CL , and correspond to the true values of the parameters $\Delta m^2 = 2.5 \times 10^{-3}\text{eV}^2$ and $\sin^2 2\theta_{23} = 0.96$.

LV parameters	Curent bound	Kamioka-only	Korea-only	Kamioka-Korea
$\lvert\delta c\rvert$	$< 3 \times 10^{-26}$	$\lesssim 5 \times 10^{-23}$	$\lesssim 4 \times 10^{-23}$	$\lesssim 3 \times 10^{-23}$
$\lvert\delta b\rvert$ (GeV)	$< 3.0 \times 10^{-20}$	$\lesssim 1 \times 10^{-23}$	$\lesssim 0.5 \times 10^{-23}$	$\lesssim 0.6 \times 10^{-23}$

In such a case, the low energy effective Hamiltonian describing interaction between neutrinos and matter is modified as follows:

$$H_{\text{eff}} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix} \tag{8}$$

where ϵ's parameterize the nonstandard interactions (NSI) of neutrinos with matter. Here, G_F is the Fermi constant, N_e denotes the averaged electron number density along the neutrino trajectory in the earth.

In this work we truncate the system so that we confine into the $\mu - \tau$ sector of the neutrino evolution, which is justified when ϵ's are sufficiently small. Then, the time evolution of the neutrinos in flavor basis can be written as

$$i\frac{d}{dt}\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[U \begin{pmatrix} 0 & 0 \\ 0 & \frac{\Delta m^2_{32}}{2E} \end{pmatrix} U^\dagger + a \begin{pmatrix} 0 & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} \end{pmatrix} \right] \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}, \tag{9}$$

where U is the flavor mixing matrix and $a \equiv \sqrt{2}G_F N_e$. In the 2-2 element of the NSI term in the Hamiltonian is of the form $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$ because the oscillation probability depend upon ε's only through this combination. In the following, we set $\varepsilon_{\mu\mu} = 0$ for simplicity, and study the sensitivity on $\varepsilon_{\tau\tau}$. At the end, the result should be interpreted as $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$. The evolution equation for the anti-neutrinos are given by changing the signs of a and replacing U by U^*.

Since we work within the truncated 2 by 2 subsystem, we quote here only the existing bounds of NSI parameters which are obtained under the same approximation. By analyzing the Super-Kamiokande atmospheric neutrino data the authors of [37] obtained

$$|\varepsilon_{\mu\tau}| \lesssim\ 0.15, \quad |\varepsilon_{\tau\tau}| \lesssim\ 0.5, \tag{10}$$

at 99 % CL for 2 degrees of freedom.[†]

5.2. Numerical results and discussions

In Fig. 3, presented are the allowed regions in $\varepsilon_{\mu\tau} - \varepsilon_{\tau\tau}$ space for 4 years neutrino and 4 years anti-neutrino running of the Kamioka-only (upper panels), the Korea-only (middle panels), and the Kamioka-Korea (bottom panels) settings. The input values $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$ are taken to be vanishing.

As in the CPT-Lorentz violating case and unlike the system with decoherence, the Korea-only setting gives much worse sensitivity compared to the other two

[†] A less severe bound on $|\varepsilon_{\tau\tau}|$ is derived in [38] by analyzing the same data but with $\varepsilon_{e\tau}$ and without $\varepsilon_{\mu\tau}$

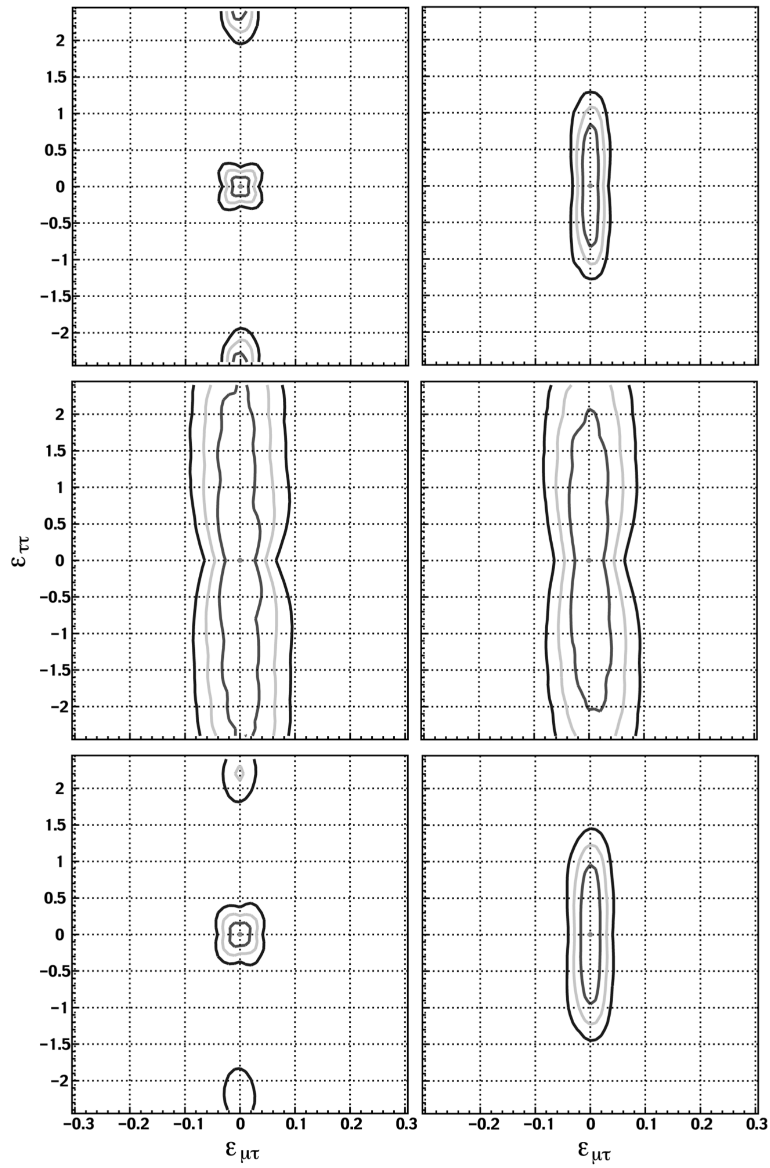

Fig. 3 The allowed regions in $\varepsilon_{\mu\tau} - \varepsilon_{\tau\tau}$ space for 4 years neutrino and 4 years anti-neutrino running. The upper, the middle, and the bottom three panels are for the Kamioka-Korea setting, the Kamioka-only setting, and the Korea-only setting, respectively. The left and the right panels are for cases with $\sin^2\theta \equiv \sin^2\theta_{23} = 0.45$ and 0.5, respectively. The red, the yellow, and the blue lines indicate the allowed regions at 1σ, 2σ, and 3σ CL, respectively. The other input values of the parameters are idential to those in Fig. 2

settings. Again the Kamioka-only setting has a slightly better sensitivity than the Kamioka-Korea setting. However we notice that the Kamioka-only setting has multiple $\varepsilon_{\tau\tau}$ solutions for $\sin^2\theta_{23} = 0.45$. The fake solutions are nearly eliminated in the Kamioka-Korea setting.

The sensitivities of three experimental setups at 2 σ CL can be read off from Fig. 3. The approximate 2 σ CL sensitivities of the Kamioka-Korea setup for $\sin^2\theta = 0.45$ ($\sin^2\theta = 0.5$) are:

$$|\epsilon_{\mu\tau}| \lesssim 0.03\ (0.03), \quad |\epsilon_{\tau\tau}| \lesssim 0.3\ (1.2). \tag{11}$$

Here we neglected a barely allowed region near $\epsilon_{\tau\tau} = 2.3$. The Kamioka-only or Kamioka-Korea setup can improve the current bounds on ε's by factors of 8 (8) and 60 (16), which are significant improvement.

There are a large number of references which studied the effects of NSI and the sensitivity reach to NSI by the ongoing and the various future projects. We quote here only the most recent ones which focused on sensitivities by superbeam and reactor experiments [39] and neutrino factory [40], from which earlier references can be traced back.

By combining future superbeam experiment, T2K [4] and reactor one, Double-Chooz [13], the authors of [39] obtained the sensitivity of $|\epsilon_{\mu\tau}|$ to be ~ 0.25 when it is assumed to be real (no CP phase) while essentially no sensitivity to $\epsilon_{\tau\tau}$ is expected. The same authors also consider the case of NOνA experiment [11] combined with some future upgraded reactor experiment with larger detector as considered, e.g., in [41, 42] and obtained $\epsilon_{\mu\tau}$ sensitivity of about 0.05 which is comparable to what we obtained.

While essentially no sensitivity of $\epsilon_{\tau\tau}$ is expected by superbeam, future neutrino factory with the so called golden channel $\nu_e \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\mu$, could reach the sensitivity to $\epsilon_{\tau\tau}$ at the level of $\sim$ 0.1-0.2 [40]. Despite that the sensitivity to $\epsilon_{\mu\tau}$ by neutrino factory was not derived in [40], from Fig. 1 of this reference, one can naively expect that the sensitivity to $\epsilon_{\mu\tau}$ is similar to that of ϵ_{ee} which is ~ 0.1 or so. We conclude that the sensitivity we obtained for $\epsilon_{\mu\tau}$ is not bad.

6. Conclusion

The Kamioka-Korea two detector system for the J-PARC neutrino beam was shown to be a powerful experimental setup for lifting the neutrino parameter degenracies and probing CP violation in neutrino oscillations. In this talk, I presented the sensitivities of the same setup to nonstandard neutrino physics such as quantum decoherence, tiny violation of Lorentz symmetry, and nonstandard neutrino interactions with matter. Generally speaking, two detector setup is more powerful than one detector setup at Kamioka, not only for lifting the neutrino parameter degeneracies, but also probing/constraining nonstandard neutrino physics. The sensitivities of three experimental setups at 90% CL are summarized in Table 1 and Table 2 for quantum decoherence and Lorentz symmetry violation with/without CPT symmetry, respectively. We can say modestly that future long baseline experiments with two detector setup can improve the sensitivities on nonstandard neutrino physics in many cases, in addition to lifting the neutrino parameter degeneracies. It would be highly desirable to make such neutrino physics facilities realitic in the near future.

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