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Constraints on the flavor-dependent non-standard interaction in propagation from atmospheric neutrinos

Osamu Yasuda

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

Abstract. The sensitivity of the atmospheric neutrino experiments to the non-standard flavor-dependent interaction in neutrino propagation is studied under the assumption that the only nonvanishing components of the non-standard matter effect are the electron and tau neutrino components ϵ_{ee}, $\epsilon_{e\tau}$, $\epsilon_{\tau\tau}$ and that the tau-tau component satisfies the constraint $\epsilon_{\tau\tau} = |\epsilon_{e\tau}|^2/(1+\epsilon_{ee})$ which is suggested from the high energy behavior for atmospheric neutrino data.

1. Introduction

Neutrino oscillations in the standard three-flavor scheme are described by three mixing angles, θ_{12}, θ_{13}, θ_{23}, one CP phase δ, and two independent mass-squared differences, Δm^2_{21} and Δm^2_{31}. Thanks to the recent progress of the experiments with solar, atmospheric, reactor and accelerator neutrinos, the three mixing angles and the two mass-squared differences have been determined. The only oscillation parameters which are still undetermined are the value of the CP phase δ and the sign of Δm^2_{31} (the mass hierarchy). In the future neutrino long-baseline experiments with intense neutrino beams the sign of Δm^2_{31} and δ are expected to be determined [2, 3]. As in the case of B factories, such high precision measurements will enable us to search for deviation from the standard three-flavor oscillations (see, e.g., Ref. [4]). Among such possibilities, in this talk, we will discuss the effective non-standard neutral current flavor-dependent neutrino interaction with matter, given by

$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\,\epsilon_{\alpha\beta}^{fP} G_F (\overline{\nu}_\alpha \gamma_\mu P_L \nu_\beta)\,(\overline{f}\gamma^\mu P f'), \tag{1}$$

where f and f' stand for fermions (the only relevant ones are electrons, u and d quarks), G_F is the Fermi coupling constant, and P stands for a projection operator that is either $P_L \equiv (1-\gamma_5)/2$ or $P_R \equiv (1+\gamma_5)/2$. If the interaction (1) exists, then the standard matter effect is modified. We will discuss atmospheric neutrinos which go through the Earth, so we make an approximation that the number densities of electrons (N_e), protons, and neutrons are equal Defining $\epsilon_{\alpha\beta} \equiv \sum_P \left(\epsilon_{\alpha\beta}^{eP} + 3\epsilon_{\alpha\beta}^{uP} + 3\epsilon_{\alpha\beta}^{dP}\right)$, the hermitian 3×3 matrix of the matter potential becomes

$$\mathcal{A} \equiv A \left(\begin{array}{ccc} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{array} \right), \tag{2}$$

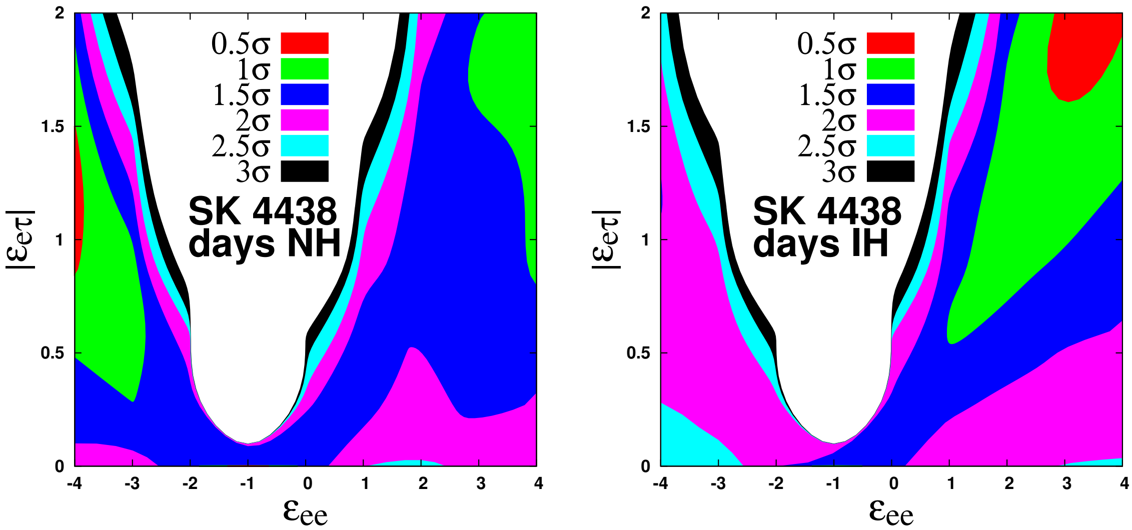

Figure 1. The allowed regions in the $(\epsilon_{ee},\ |\epsilon_{e\tau}|)$ plane from the SK atmospheric neutrino data for a normal (inverted) mass hierarchy.

where $A \equiv \sqrt{2}G_F N_e$ stands for the matter effect due to the charged current interaction in the standard case. With this matter potential, the Dirac equation for neutrinos in matter becomes

$$i\frac{d}{dx}\left(\begin{array}{c}\nu_e(x)\\ \nu_\mu(x)\\ \nu_\tau(x)\end{array}\right)=\left[U\mathrm{diag}\left(0,\Delta E_{21},\Delta E_{31}\right)U^{-1}+\mathcal{A}\right]\left(\begin{array}{c}\nu_e(x)\\ \nu_\mu(x)\\ \nu_\tau(x)\end{array}\right), \tag{3}$$

where U is the leptonic mixing matrix, and $\Delta E_{jk} \equiv \Delta m^2_{jk}/2E \equiv (m^2_j - m^2_k)/2E$.

Constraints on $\epsilon_{\alpha\beta}$ have been discussed by many authors (see, e.g., Refs. [4], [5] and references therein), and it is known that the bounds on ϵ_{ee}, $\epsilon_{e\tau}$ and $\epsilon_{\tau\tau}$ are much weaker than those on $\epsilon_{\alpha\mu}$ $(\alpha = e, \mu, \tau)$. Taking into account the various constraints, in the present talk we take the ansatz

$$\mathcal{A} = A\left(\begin{array}{ccc}1+\epsilon_{ee} & 0 & \epsilon_{e\tau}\\ 0 & 0 & 0\\ \epsilon^*_{e\tau} & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee})\end{array}\right), \tag{4}$$

and analyze the sensitivity to the parameters $\epsilon_{\alpha\beta}$ $(\alpha, \beta = e, \tau)$ of the atmospheric neutrino experiment at Superkamiokande (SK) and the future Hyperkamiokande (HK) facility [6]. This talk is based on the work [5] and the readers are referred to Ref. [5] for details.

2. The constraint of the Superkamiokande atmospheric neutrino experiment on ϵ_{ee} and $|\epsilon_{e\tau}|$

First let us discuss the constraint of the SK atmospheric neutrino experiment on the non-standard interaction in propagation with the ansatz (4). The independent degrees of freedom in addition to those in the standard oscillation scenario are ϵ_{ee}, $|\epsilon_{e\tau}|$ and $\arg(\epsilon_{e\tau})$. We have performed a χ^2 analysis for the SK atmospheric neutrino data for 4438 days [7].

The result for the Superkamiokande data for 4438 days is given in Fig. 1, where the allowed region is plotted in the $(\epsilon_{ee},\ |\epsilon_{e\tau}|)$ plane. It is understood that, at each point in this plane,

χ^2 is marginalized with respect to the parameters θ_{23}, $|\Delta m^2_{31}|$, δ and $\arg(\epsilon_{e\tau})$. All other oscillation parameters are fixed for simplicity and the reference values used here are the following: $\sin^2 2\theta_{12} = 0.86$, $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{21} = 7.6 \times 10^{-5}\mathrm{eV}^2$. The best-fit point for the normal (inverted) hierarchy is (ϵ_{ee}, $|\epsilon_{e\tau}|$) = (-1.0, 0.0) ((3.0, 1.7)) and the value of χ^2 at this point is 79.0 (78.6) for 50 degrees of freedom, and goodness of fit is 2.8 (2.7) σCL, respectively. The best-fit point is different from the standard case (ϵ_{ee}, $|\epsilon_{e\tau}|$) = (0, 0), and this may be because we use only the information on the energy rate and the sensitivity to NSI is lost due to the destructive phenomena between the lower and higher energy bins (See the discussions in subsect. 3.1). The difference of the value of χ^2 for the standard case and that for the best-fit point for the normal (inverted) hierarchy is $\Delta\chi^2 = 2.7$ (3.4) for 2 degrees of freedom (1.1 σCL (1.3 σCL)), respectively, and the standard case is certainly acceptable for the both mass hierarchies in our analysis. From the Fig. 1 we can read off the allowed region for $|\tan\beta| \equiv |\epsilon_{e\tau}|/|1+\epsilon_{ee}|$, and we conclude that the allowed region for $|\tan\beta|$ is approximately

$$|\tan\beta| \equiv \frac{|\epsilon_{e\tau}|}{|1+\epsilon_{ee}|} \lesssim 0.8 \qquad \text{at } 2.5\sigma\text{CL}.$$

3. Sensitivity of the Hyperkamiokande atmospheric neutrino experiment to ϵ_{ee} and $|\epsilon_{e\tau}|$

Let us now discuss the potential sensitivity of HK to ϵ_{ee} and $|\epsilon_{e\tau}|$. Since HK is a future experiment, the simulated numbers of events are used as "the experimental data", and we vary ϵ_{ee} and $\epsilon_{e\tau}$ as well as the standard oscillation parameters trying to fit to "the experimental data". Here we perform an analysis on the assumption that we know the mass hierarchy, because some hint on the mass hierarchy is expected to be available at some confidence level by the time HK will accumulate the atmospheric neutrino data for twenty years.

3.1. The case with the standard oscillation scenario

First of all, let us discuss the case where "the experimental data" is the one obtained with the standard oscillation scenario. The values of the oscillation parameters which are used to obtain "the experimental data" are the following: $\Delta\bar{m}^2_{31} = 2.5 \times 10^{-3}\mathrm{eV}^2$, $\sin^2\bar{\theta}_{23} = 0.5$, $\bar{\delta} = 0$, $\sin^2 2\bar{\theta}_{12} = 0.86$, $\sin^2 2\bar{\theta}_{13} = 0.1$, $\Delta\bar{m}^2_{21} = 7.6 \times 10^{-5}\mathrm{eV}^2$, where the bar notation stands for the reference values for "the experimental data". As in the case of the analysis of the SK data, we vary the oscillation parameters θ_{23}, $|\Delta m^2_{32}|$, δ and $\arg(\epsilon_{e\tau})$ while fixing the other oscillation parameters $\sin^2 2\theta_{12} = 0.86$, $\sin^2 2\theta_{13} = 0.1$ and $\Delta m^2_{21} = 7.6 \times 10^{-5}\mathrm{eV}^2$.

We have performed both energy rate and energy spectrum (with two energy bins) analyses, and the results from the energy rate (spectrum) analysis are given by the upper (lower) panel in Fig. 2. From the energy rate analysis we have $|\epsilon_{e\tau}/(1+\epsilon_{ee})| \lesssim 0.3$ at 2.5σCL. On the other hand, from the energy spectrum analysis we get $-0.1 \lesssim \epsilon_{ee} \lesssim 0.2$ and $|\epsilon_{e\tau}| < 0.08$ at 2.5σ (98.8%) CL for the normal hierarchy and to $-0.4 \lesssim \epsilon_{ee} \lesssim 1.2$ and $|\epsilon_{e\tau}| < 0.34$ at 2.5σ (98.8%) CL for the inverted hierarchy. From Fig. 2 we note that the allowed regions from the energy rate analysis are much larger than those from the energy spectrum analysis for both mass hierarchies, and that the allowed regions for the inverted hierarchy are larger than those for the normal hierarchy for both rate and spectrum analyses. This is because we lose the significance (particularly for the high energy bin in the spectrum analysis and for the inverted hierarchy case both in rate and spectrum analyses). We believe that this is also the reason why the allowed regions in the SK case are so large.

3.2. The case in the presence of NSI

Next let us discuss the case where "the experimental data" is the one obtained with $(\epsilon_{ee}, \epsilon_{e\tau}) \neq (0, 0)$. The analysis is the same as the one in subsect. 3.1, except that the "the experimental

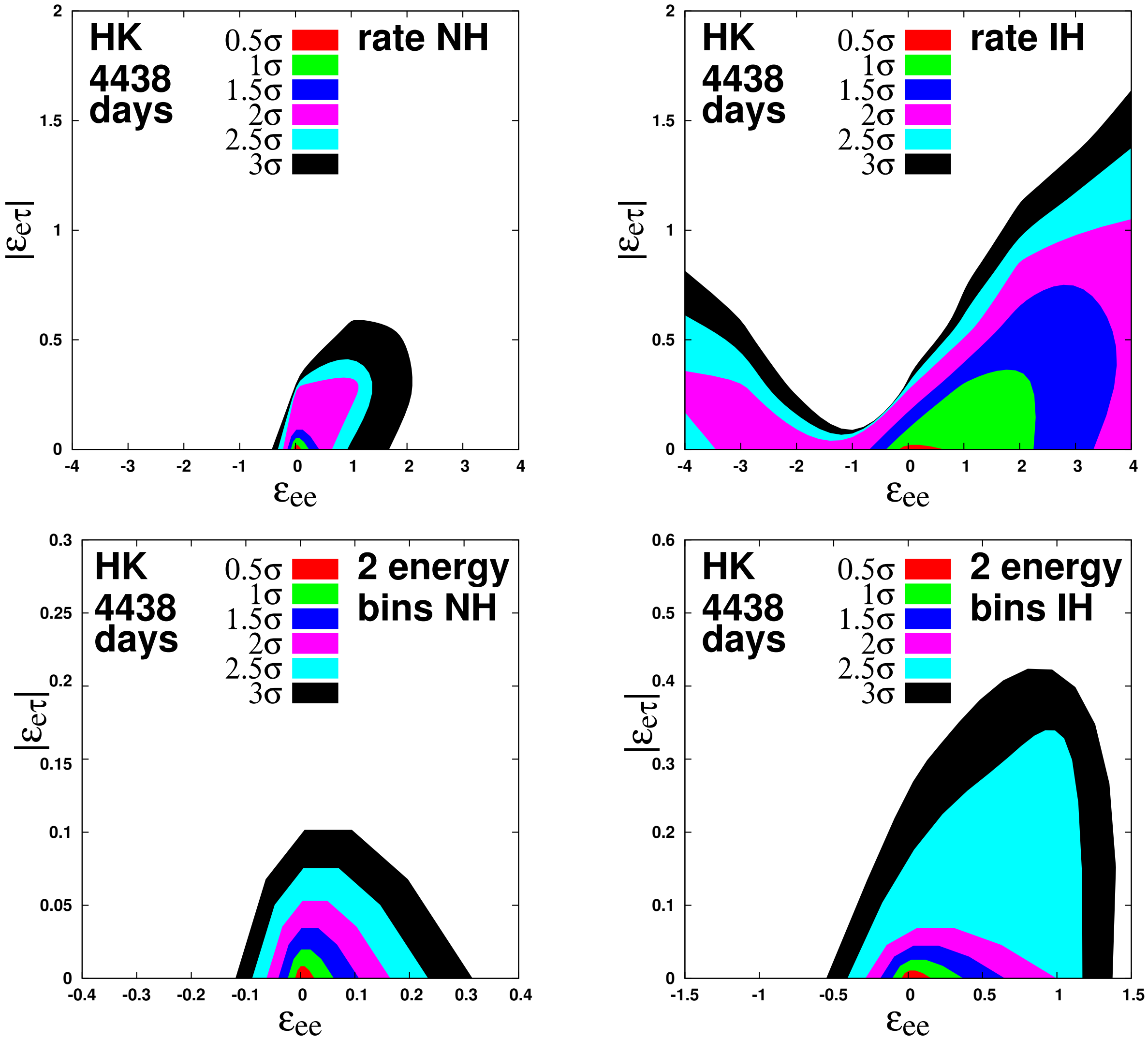

Figure 2. The allowed regions in the (ϵ_{ee}, $|\epsilon_{e\tau}|$) plane from the HK atmospheric neutrino data for a normal (inverted) mass hierarchy from the energy-rate (two energy-bin) analysis.

data" is produced assuming the presence of NSI, and here we perform only an energy spectrum analysis. The results are shown in Fig. 3, where the allowed regions at 2.5σCL ($\Delta\chi^2 = 8.8$ for 2 degrees of freedom) around the true points are depicted. The straight lines $|\epsilon_{e\tau}| = 0.8 \times |1+\epsilon_{ee}|$ in Fig. 3 stand for the approximate bound from the SK atmospheric neutrinos in Fig. 1, and we have examined only the points below these straight lines. As seen from Fig. 3, the errors in ϵ_{ee} and $|\epsilon_{e\tau}|$ are small for $|\epsilon_{ee}|\lesssim 2$ in the case of the normal hierarchy and for $-3\lesssim\epsilon_{ee}\lesssim 1$ in the case of the inverted hierarchy. The errors are large otherwise, and the reason that the errors are large is because a sensitivity is lost due to a destructive phenomenon between neutrinos and antineutrinos as was discussed in subsect. 3.1.

4. Conclusions

In this talk we have discussed the constraint of the SK atmospheric neutrino data on the non-standard flavor-dependent interaction in neutrino propagation with the ansatz (4). From the

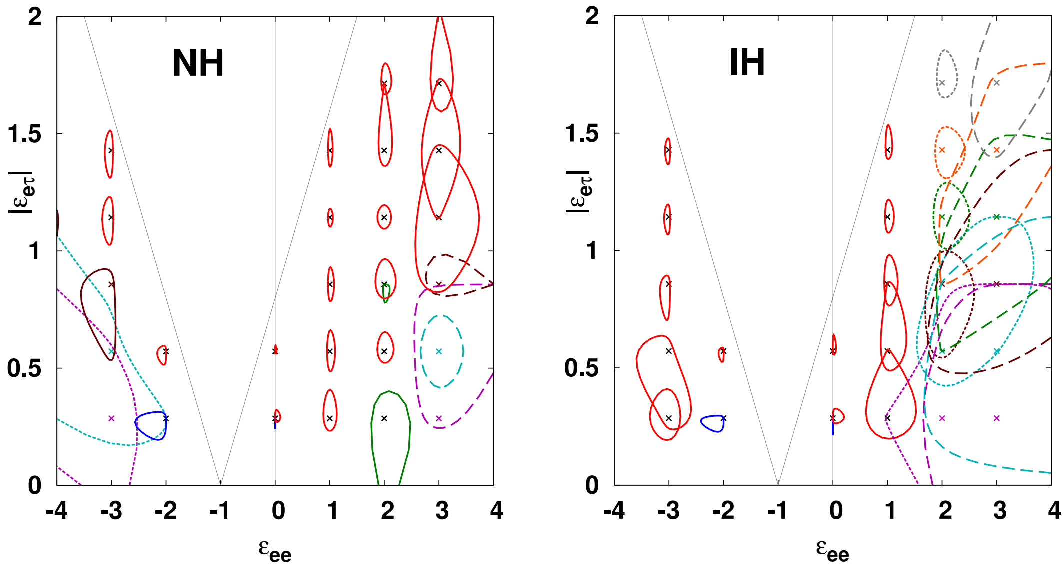

Figure 3. The allowed region at 2.5σCL around the point $(\epsilon_{ee}, |\epsilon_{e\tau}|) \neq (0, 0)$, where $\bar{\delta} = \arg(\bar{\epsilon}_{e\tau}) = 0$ is assumed.

SK atmospheric neutrino data for 4438 days, we have obtained the bound $|\epsilon_{e\tau}|/|1+\epsilon_{ee}| \lesssim 0.8$ at 2.5σCL, while we have little constraint on ϵ_{ee}.

We have also discussed the sensitivity of the future HK atmospheric neutrino experiment to NSI by analyses with the energy rate and with the energy spectrum. If nature is described by the standard oscillation scenario, then the HK atmospheric neutrino data will give us the bound $|\epsilon_{e\tau}|/|1 + \epsilon_{ee}| \lesssim 0.3$ at 2.5σCL from the energy rate analysis, and from the energy spectrum analysis it will restrict ϵ_{ee} to $-0.1 \lesssim \epsilon_{ee} \lesssim 0.2$ and $|\epsilon_{e\tau}| < 0.08$ at 2.5σ (98.8%) CL for the normal hierarchy and to $-0.4 \lesssim \epsilon_{ee} \lesssim 1.2$ and $|\epsilon_{e\tau}| < 0.34$ at 2.5σ (98.8%) CL for the inverted hierarchy. On the other hand, if nature is described by NSI with the ansatz (4), then HK will measure the NSI parameters ϵ_{ee} and $|\epsilon_{e\tau}|$ relatively well for $|\epsilon_{ee}| \lesssim 2$ in the case of the normal hierarchy and for $-3 \lesssim \epsilon_{ee} \lesssim 1$ in the case of the inverted hierarchy. It is important to use information on the energy spectrum to obtain strong constraint, because a sensitivity to NSI would be lost due to a destructive phenomena between the low and high energy events.

Acknowledgments

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