

Physics case for ν_τ detection

Toshihiko Ota

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
Föhringer Ring 6, 80805 München, Germany

E-mail: toshi@mppmu.mpg.de

Abstract. In this talk, we discuss physics cases in which the detection of tau neutrino plays an important role. Some examples of the utility of ν_τ detection in new physics search are given.

1. Introduction

In the past decade, ν_τ -detection experiments achieved great success. The DONUT experiment observed neutrinos interacting with tau lepton through charged current [1], which was the first direct evidence of the existence of *tau neutrino*. The OPERA experiment reported the observation of a ν_τ event originating from $\nu_\mu \rightarrow \nu_\tau$ oscillation [2]. Experimental technique of ν_τ detection has made progress, which is nicely summarized in [3]. In this talk, we discuss the utility of ν_τ detection in future oscillation experiments. Of course, if an experiment is aimed at examining and confirming the consistency of the standard oscillation framework in the tau sector, ν_τ detection is essential on purpose. On the other hand, the general consensus holds that information of ν_τ -detection channel makes only a sub-dominant impact on determination of the standard oscillation parameters, because of the limited detector size. Here, we leave the detailed discussions on the standard oscillation to IDS-NF interim design report [4], and in the following, focus on the role of ν_τ detection in new physics search. At first sight, ν_τ detection seems to be helpful to reveal a new physics effect associated with tau flavour. However, since the maximal mixing between ν_μ and ν_τ transmits the effect from the tau sector to the muon sector, the ν_μ -detection channel also acquires a sensitivity to the new physics effect in the tau sector. Therefore, it is often the case that ν_τ detection is not an essential component to discover the tau-associated new physics signals. In this talk, we try to give some examples of physics cases in which information of ν_τ detection has a significant impact.

2. New physics search

We categorise new physics effects into two groups in terms of their origin:

- (i) **High energy origin** — If the Standard Model (SM) is an effective theory of fundamental theories which are realized at the higher energy scales, the full Lagrangian at the electroweak scale is described with the SM Lagrangian and the series of the non-renormalizable terms which are the remnant of physics at the high energy scales. Here, we discuss the effect of Non-Standard neutrino Interactions (NSI). The most of the new physics effects categorised into this group (e.g., non-unitarity of the lepton mixing matrix induced by dimension six operators) can also be parameterized as NSIs. We discuss the current bounds and future prospect on the NSI search, especially focus on the usefulness of ν_τ detection.

	Beam (channel)	2L2Q	4L	NU
Conventional beam	$\pi (\mu \rightarrow \tau)$	$7.9 \cdot 10^{-5}$	n/a	$4.4 \cdot 10^{-6}$
Beta beam	$\beta (e \rightarrow \tau)$	$< 10^{-6}$	n/a	$1.0 \cdot 10^{-5}$
Neutrino factory	$\mu (\mu \rightarrow \tau)$	$< 10^{-6}$	$1.0 \cdot 10^{-3}$ ($3.2 \cdot 10^{-5}$)	$4.4 \cdot 10^{-6}$
	$\mu (e \rightarrow \tau)$	$< 10^{-6}$	$1.0 \cdot 10^{-3}$ ($3.2 \cdot 10^{-5}$)	$1.0 \cdot 10^{-5}$

Figure 1. Model independent bounds to the tau-associated source and detection NSIs. Note that the numbers correspond to the bound to $|\epsilon_{\alpha\tau}^s|^2$. Thanks to the chiral enhancement, the effect of $|\epsilon_{\mu\tau}^s|^2$ in conventional beam experiments is still allowed to be significantly large ($\sim 10^{-4}$). Table is taken from [5].

- (ii) **Low energy origin** — New particles and interactions are introduced at the electroweak scale, which affect the nature of neutrino. Light sterile (SM singlet) states and a new long range force mediated by light gauge boson are categorized into this group. In this talk, we discuss the sensitivities to the parameters associated with sterile neutrinos.

2.1. High energy origin: NSI

If the NSIs — four-fermion interactions including a neutrino or two — are left in the low energy effective theory, the standard formula of neutrino oscillation must be modified. The initial and the final states are no more the pure flavour states but the flavour mixture states,

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma \neq \alpha} |\nu_\gamma\rangle, \quad \langle \nu_\beta^d| = \langle \nu_\beta| + \sum_{\gamma \neq \beta} \langle \nu_\gamma|, \quad (1)$$

and neutrinos receive the additional matter effect potential,

$$(V_{\text{NSI}})_{\alpha\beta} = \sqrt{2}G_F N_e \epsilon_{\alpha\beta}^m, \quad (2)$$

in their propagation. These epsilon parameters are defined as the proportion of the non-standard effects to the standard ones. Currently, the effective interactions with neutrinos are not strongly constrained, because of the difficulty in their direct detection. The model independent bounds are investigated in [5, 6, 7]. The bounds to the propagation NSI are summarized as [6]¹

$$|\epsilon_{\alpha\beta}^m| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}. \quad (3)$$

Figure 1 shows the constraints to the tau-associated NSIs at neutrino beam source and detection, which originate from the effective interactions with mass dimension six. Although these direct bounds shown in Eq. (3) still allow NSIs to take large values, it is hard to derive such large NSIs from high energy models. Since NSIs are related with the corresponding charged lepton processes in typical models, they are in general constrained from the observation of the charged sector. For example, in the minimal supersymmetric standard model (MSSM), NSIs are induced by the one-loop diagrams with the slepton mixings, which are similar to the corresponding charged lepton

¹ The NSI in the μ - τ sector is also constrained from the observation of atmospheric neutrinos [8, 9].

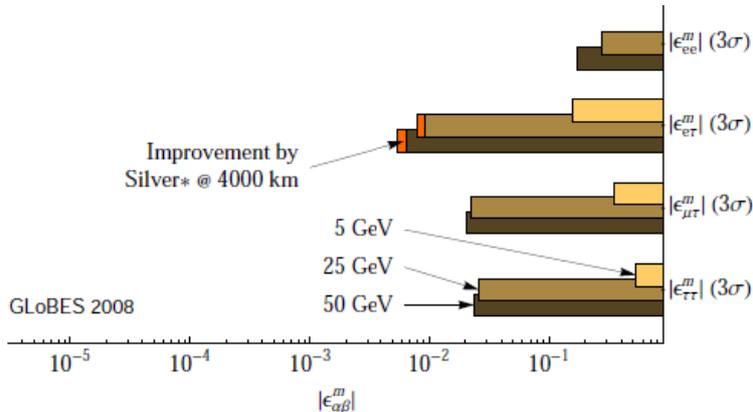


Figure 2. Sensitivities to NSIs in propagation at the IDS-NF baseline setup of neutrino factory. The silver channel $\nu_e \rightarrow \nu_\tau$ slightly improves the sensitivity to $\epsilon_{e\tau}^m$ but does not to the others. The figure is taken from [13]

flavour violating (LFV) processes. Therefore, NSI and charged LFV are strongly correlated with each other [10, 11]. The typical size of NSI in the MSSM is evaluated as [10]

$$|\epsilon_{\mu\tau}^m| \sim |\epsilon_{\mu\tau}^s| \text{ at neutrino factory} \simeq 10^{-3} \sqrt{\frac{\text{Br}(\tau \rightarrow \mu\gamma)}{10^{-7}}}, \quad (4)$$

which is far below the upper bound of the model independent bound and also below the expected future sensitivity at neutrino factory (see Fig. 2 and [12, 13, 14]). Figure 2 also indicates that an additional ν_τ detector does not help to improve the sensitivity. In order to obtain large NSIs in a theoretically motivated model, it is necessary to invoke the mechanism to avoid the correlation with the charged lepton sector. Operators with Higgs doublets can provide only NSIs without the corresponding charged lepton processes by using the vacuum expectation value of Higgs doublet [15, 16]. However, the implementation of such higher dimensional operators to high energy models raises the non-trivial issue [17]. The use of the chiral enhancement mechanism might be another possibility to break the $SU(2)_L$ relation. The operators,

$$\mathcal{O}_{ED} = (\overline{L}_\tau \mu_R)(\overline{d}_R Q), \quad \mathcal{O}_{EU} = (\overline{L}_\tau \mu_R)(\overline{Q} u_R), \quad (5)$$

contain both the NSI and the charged LFV. However, the NSI effect in pion decay gets enhanced and the LFV tau decays do not. After taking into account the constraints from the rare tau decays, the current bounds to $|\epsilon_{\mu\tau}^s|^2$ induced from these operators can become almost 10^{-4} , which is fairly in the range of the expected sensitivity of MINSIS proposal [18] — ν_τ near detector at NuMI. Finally, it should be repeated that the realization of the model independent upper bounds requires a lot to the models.

2.2. Low energy origin: sterile neutrino

The introduction of sterile neutrinos is motivated from both theoretically and experimentally aspects. A plausible motivation might be that all the three observations — appearance signal at LSND and MiniBooNE, recent re-calculation of reactor neutrino flux, and the measurement of neutrinos from gallium decays — suggest the same mass squared difference $\sim 1 \text{ eV}^2$ [20, 21]. Here, following [19], we see the future sensitivity to the parameters associated with the sterile state and its improvement by the ν_τ -detection channel.

At present, the mixing angle between tau and sterile neutrinos is not strongly constrained, and neutrino factory is expected to improve the current bound significantly. Naively, an additional

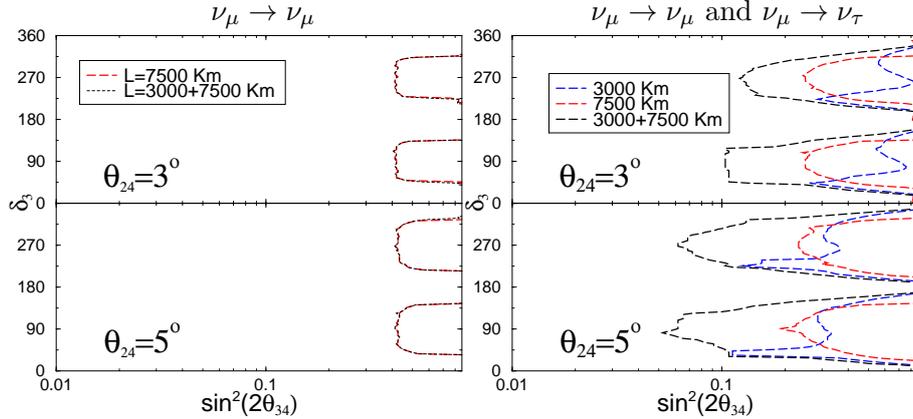


Figure 3. Discovery potential of the additional CP-violating phase δ_3 associated with a sterile neutrino. The synergy of two channels significantly improves the discovery reach. Plots are taken from [19].

ν_τ detector seems to assist in making the sensitivity better. However, the effect of ν_τ -detection information is quite limited [19, 22], because disappearance channel at magic baseline ($L = 7,500$ km) is sensitive to the mixing angle and its large statistics dominate the sensitivity. On the other hand, Figure 3 shows that the discovery reach to the additional CP-violating phase associated with sterile state is improved by the synergy of the ν_μ and the ν_τ detection channels.

3. Summary

In this talk, we have tried to find possible physics cases in which ν_τ detection plays an important role. Here, we have seen two examples — i) Search for chiral enhanced source NSI at near detector of conventional beam experiments, and ii) Discovery of new CP-violating effects associated with sterile neutrinos at neutrino factories.

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