

Can ICARUS and OPERA ν_τ appearance experiments detect new flavor physics ?

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Abstract

In this letter we explore whether we have a chance to observe a flavor-changing effect in τ appearance experiments ICARUS and OPERA.

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The atmospheric neutrino anomaly [1] and the solar neutrino deficit [2] are well described by the neutrino oscillation. Therefore many experiments are being planned to observe the oscillation directly and some of them are now carried out [3]. For example, the atmospheric neutrino anomaly is very naturally explained by the $\nu_\mu \rightarrow \nu_\tau$ oscillation and for the direct measurement of this oscillation (transition) there are two experiments proposed at CERN, ICARUS [4] and OPERA [5], that aim at observation of tau neutrino appearance events and they will start to take data in 2005 [6, 7].

Moreover it is expected that almost all the oscillation parameters will be determined by oscillation experiments in near future (see for example [8]). Though in studies of those experiments their main concerns are how well they can determine the oscillation parameters, it is also pointed out that a long baseline experiment can probe new types of flavor changing interactions with the oscillation manner [9, 10, 11, 12]. Among such new effects to probe the μ - τ flavor-changing effects is most important since in many models to explain a large mixing for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation, large μ - τ flavor changing interactions are accompanied. In the previous [12], we investigated the feasibility to observe such exotic interactions in oscillation experiments and showed that the $\nu_\mu \rightarrow \nu_\tau$ channel works most effectively to explore the μ - τ flavor violating interactions [16]. Fortunately, ICARUS and OPERA use this channel and hence in this work we examine the performance of ICARUS and OPERA for the new interaction search in the three-generation framework.

First we briefly review the key idea for exotic interaction search in an oscillation experiment. In the following, we consider only the μ - τ flavor violating effects. In a long baseline experiment, what we really observe are the signals caused by the secondary charged particles such as muons. That is, we do not observe neutrinos themselves. In other words neutrinos are unobserved intermediate states. Therefore, if there are some kinds of new interactions that can induce the completely same final states as the standard model does, then the interference between these two amplitudes takes place. It means that the effect of new interactions appears with the strength of not the square of the exotic coupling but itself.

The contribution of the new interactions can be divided into three stages, neutrino beam production, its propagation, and its detection. First we refer to the production process. The neutrino beam of the CNGS [6] facility is produced by pion decay. In this case we can parametrize the effect of the exotic interactions in pion decay as the shift in the muon

neutrino state from pure flavor eigenstate, $|\nu_\alpha\rangle$, to mixed state, $|\nu_\alpha^s\rangle$ [9], because the helicity states of the muon and the neutrino are fixed in this decay:

$$|\nu_\mu^s\rangle = U_{\mu\alpha}^s |\nu_\alpha\rangle, \quad U_{\mu\alpha}^s = (0, 1, \epsilon_{\mu\tau}^s) \quad (1)$$

where $\epsilon_{\mu\tau}^s$ denotes the ratio of the coupling of the exotic decay of pions, $\pi^+ \rightarrow \mu^+ \nu_\tau$, to the standard one. Next, during the beam propagation from CERN to GranSasso, the neutrinos feel the matter effect due to not only an ordinary interaction but also the new ones, which can be interpreted as the shift of the potential [10]:

$$H_{\text{matter}\alpha\beta} = \frac{a}{2E_\nu} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & \epsilon_{\mu\tau}^m \\ 0 & \epsilon_{\mu\tau}^{m*} & 0 \end{pmatrix}, \quad (2)$$

where $a \equiv 2\sqrt{2}G_F n_e E_\nu$ is the standard matter effect whose origin is the weak interaction, n_e is the electron number density, and E_ν is the neutrino energy. Finally at the detection process neutrinos are also affected by the new flavor-changing interactions. To parametrize these effect, in principle, will be very complicated since we have to deal with the hadronic process. However, in this letter, we assume for simplicity that we regard the neutrino state at the detection process as the flavor mixed state, $|\nu_\alpha^d\rangle$ [9], just like source state,

$$|\nu_\tau^d\rangle = U_{\tau\alpha}^d |\nu_\alpha\rangle, \quad U_{\tau\alpha}^d = (0, \epsilon_{\mu\tau}^d, 1). \quad (3)$$

If more precise treatment in the detection process are required, we have to take into account the parton distribution and give ϵ^d s the energy dependences [12]. Note that all ϵ 's are complex numbers, *i. e.*, $\epsilon_{\mu\tau}^{s,m,d} = |\epsilon_{\mu\tau}^{s,m,d}| e^{i\phi^{s,m,d}}$ [9].

Then we estimate the shift of the event number induced by the new physics in ICARUS and OPERA, and consider the condition that the difference from the standard model becomes significant. Because of low statistics and high neutrino energy, these two experiments are not assumed to see their energy spectra and we follow the assumption.

We set the condition for the criterion to insist the observation of new physics that the deviation of the number of event caused by the new interactions, $|N_\tau^{\text{NP}}|$, is grater the error for the number of event expected by standard interaction, N_τ^{SM} . Here N_τ^{SM} and N_τ^{NP} are

$$N_\tau^{\text{SM}} = C \int dE_\nu f_{\nu_\mu}(E_\nu) P_{\nu_\mu \rightarrow \nu_\tau}^{\text{SM}}(E_\nu) \sigma_{\nu_\tau}(E_\nu) \text{eff}(E_\nu), \quad (4)$$

$$N_\tau^{\text{NP}} = C \int dE_\nu f_{\nu_\mu}(E_\nu) \{P_{\nu_\mu \rightarrow \nu_\tau}(E_\nu) - P_{\nu_\mu \rightarrow \nu_\tau}^{\text{SM}}(E_\nu)\} \sigma_{\nu_\tau}(E_\nu) \text{eff}(E_\nu). \quad (5)$$

Here f_{ν_μ} is the muon neutrino flux and σ_{ν_τ} is the charged current cross section for tau neutrino, and they are given in Ref.[6]. C is defined as $N_{\text{pot}} M_{\text{det}}[\text{kton}] N_A \times 10^9$, where N_A is the Avogadro's number, N_{pot} is the total number of proton on target in the beam production, and M_{det} is the detector mass. Incidentally ICARUS has a mass of 5ktons and that of OPERA is 1.8ktons. The standard oscillation probability without exotic interactions, $P_{\nu_\mu \rightarrow \nu_\tau}^{\text{SM}}$ and that with the new physics effects, $P_{\nu_\mu \rightarrow \nu_\tau}$ can be approximated as

$$P_{\nu_\mu \rightarrow \nu_\tau}^{\text{SM}} = \sin^2 2\theta_{23} \cos^4 \theta_{13} \left(\frac{\delta m_{31}^2}{4E} L \right)^2, \quad (6)$$

$$\begin{aligned} P_{\nu_\mu \rightarrow \nu_\tau} &= P_{\nu_\mu \rightarrow \nu_\tau}^{\text{SM}} \\ &+ 2 \sin 2\theta_{23} \cos 2\theta_{23} \cos^2 \theta_{13} (Re[\epsilon_{\mu\tau}^s] - Re[\epsilon_{\mu\tau}^d]) \left(\frac{\delta m_{31}^2}{4E} L \right)^2 \\ &- 2 \sin 2\theta_{23} \cos^2 \theta_{13} (Im[\epsilon_{\mu\tau}^s] + Im[\epsilon_{\mu\tau}^d]) \left(\frac{\delta m_{31}^2}{4E} L \right) \\ &+ 4 \sin^3 2\theta_{23} \cos^2 \theta_{13} Re[\epsilon_{\mu\tau}^m] \left(\frac{a}{4E} L \right) \left(\frac{\delta m_{31}^2}{4E} L \right), \end{aligned} \quad (7)$$

where θ_{ij} 's are the lepton mixing angles defined with the following mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (8)$$

δm_{31}^2 is the larger mass difference, and L is the baseline length, 732km. To derive eq.(7), we treat δm_{21}^2 and ϵ as the perturbations and adapt high energy approximation $\delta m_{31}^2 L \ll E_\nu$, which is now appropriate assumption, and then extract terms of $\mathcal{O}(\epsilon, \delta m_{31}^2)$. The detail of this derivation is given in Ref.[12, 13]. We use the detection efficiency, $\text{eff}(E_\nu)$, estimated in Ref.[4, 5]. The condition that we set in the beginning of this paragraph, the number of events induced by new physics is larger than the error in the standard oscillation assumption, can be described as follows:

$$\sqrt{\sigma_{\text{sta}}^2 + \sum_{\alpha=1}^n \left(\frac{\partial N_\tau^{\text{SM}}}{\partial \lambda_\alpha} \right)^2 \sigma_{\text{par}_\alpha}^2 + \sigma_{\text{sys}}^2} < |N_\tau^{\text{NP}}|. \quad (9)$$

There are three kinds of errors with different origins: (i) The statistical one, σ_{sta} , which is estimated by $\sqrt{N_{\tau}^{\text{SM}}}$. (ii) The errors coming from the uncertainties of the oscillation parameters. These are represented as the second term in the square root of eq.(9) according to the error propagation prescription, where λ_{α} is one of n parameters included in N_{τ}^{SM} and $\sigma_{\text{par}\alpha}$ is its uncertainty. Exactly speaking, this treatment works well only when N_{τ}^{SM} depends *linearly* on all the parameters. In general, dependence of λ_{α} s is not so simple. However since here the oscillation probability can be approximated as $\sin^2 2\theta_{23} \cos^4 \theta_{13} (\delta m_{32}^2 L/4E_{\nu})^2$ in almost all energy region referred now, by regarding $\sin^2 2\theta_{23} \cos^4 \theta_{13} (\delta m_{32}^2)^2$ as *one* parameter included in N_{τ}^{SM} , this method can be justified approximately. It is expected that the precision of $\sin^2 2\theta_{23}$, $\Delta(\sin^2 \theta_{23})$, becomes 1% and that of δm_{31}^2 , $\Delta(\delta m_{31}^2)$, reduced to be 3% in the next-generation-experiments [8]. Moreover the uncertainty of $\cos^2 \theta_{13}$ does not affect the error estimation because of the smallness of θ_{13} . From these consideration the σ_{par} is calculated as

$$\begin{aligned} \sigma_{\text{par}}^2 &\simeq \Delta(\sin^2 2\theta_{23} \cos^4 \theta_{13})(\delta m_{32}^2)^2 \\ &\quad + 2(\sin^2 \theta_{23} \cos^4 \theta_{13})(\delta m_{32}^2)\Delta(\delta m_{32}^2). \end{aligned} \quad (10)$$

(iii) The systematic error, σ_{sys} , which is given in Ref.[4, 5, 7]. The ICARUS collaboration reports the relation between the detection efficiency and the background event rate, and give some studies with different event selection rules in Ref.[4]. Among them, we pick out two cases, and refer as ICARUS-A and B. The efficiencies and errors for these cases are given in Table I.

	M_{det}	eff	σ_{sys}^2	N_{τ}^{SM}	total error
ICARUS-A	5kt	0.081	11	40.4	7.4
ICARUS-B		0.047	1.5	23.5	5.2
OPERA	1.8kt	0.091	0.75	16.3	4.3

TABLE I: The experimental parameters and the total error for ICARUS and OPERA. Here, we assume $N_{\text{pot}} = 5 \times 4.5 \times 10^{19}$ pots. Total errors are given by the left hand side of eq.(9).

Now, we show our results. Here, we expect that the CERN proton beam will achieve 4.5×10^{19} pot per year and assume 5 year running. The total error in each experiment is

indicated in Table I. For numerical calculation we use the following theoretical parameters:

$$\begin{aligned}\sin \theta_{12} &= 1/2, & \sin \theta_{23} &= 1/\sqrt{2}, & \sin \theta_{13} &= 0.1, \\ \delta m_{31}^2 &= 3 \times 10^{-3}[\text{eV}^2], & \delta m_{21}^2 &= 5 \times 10^{-5}[\text{eV}^2], \\ \delta &= \pi/2.\end{aligned}\tag{11}$$

Since eq.(7) is good approximation in this context, we can expect the numerical results do not depend on δm_{21} , $\sin \theta_{12}$, δ , and $\sin \theta_{13}$.

We firstly categorize the flavor-changing interactions into two classes by Lorentz and $SU(2)_L$ properties. The first one corresponds to the case that there exists an effective flavor-changing interaction of singlet/triplet type, say

$$(\bar{l}_\tau \tau^2 C \bar{q})(q C^\dagger \tau^2 l_\mu) + \text{h.c.} \text{ and/or } (\bar{l}_\tau \tau^a C \bar{q})(q C^\dagger \tau^a l_\mu) + \text{h.c.} \supset (\bar{\nu}_\tau \gamma^\sigma \mu)(\bar{d} \gamma_\sigma u) + \text{h.c.}, \tag{12}$$

where l, q are the lepton and quark doublets respectively and τ^a is the Pauli matrix and here C denotes charge conjugation. This type of an interaction is induced by the exchange of $SU(2)_L$ singlet and/or triplet scalar [12, 14]. New physics effects are expected to be the same order of magnitude at the source, the matter and the detector for this case. In this case, there is a constraint for ϵ 's from $SU(2)_L$ counter part process of eq.(12) like $\tau^- \rightarrow \mu^- \pi^0$ [14]. Isospin breaking effect somewhat relaxes the limit. However after all, we have to set the $\epsilon_{\mu\tau}^s \lesssim \mathcal{O}(10^{-2})$. Therefore we set $|\epsilon_{\mu\tau}^{s,m,d}| = 0.01$ for the new physics parameters. The left plot of Fig.1 shows dependence of the region that satisfy the condition eq.(9). The inside of this contour represents that we can observe the new effect at 1σ confidence level. The right one is a section of the left one at $\epsilon_{\mu\tau}^m = 0.01i$, though there the contours denote the difference of the event number due to the new effect from the expected number with standard oscillation assumption. These behaviors can be very well understood by eq.(7). It strongly depends on the phases of the exotic interaction couplings. In some regions the total effect can exceed the range of the error.

Next, we assume that $|\epsilon_{\mu\tau}^s| = 0.01$ and $|\epsilon_{\mu\tau}^{m,d}| = 0$. This parameter set corresponds the situation that the new interaction is doublet type, namely,

$$(\bar{l}_\tau C \bar{d}_R)(q C^\dagger \mu_R) + \text{h.c.} \supset (\bar{\nu}_\tau \mu_R)(\bar{d}_R u_L) + \text{h.c.}.\tag{13}$$

This is induced by the $SU(2)_L$ doublet intermediation. From the relation [15],

$$\bar{u} \gamma_5 d = \frac{-i}{m_u + m_d} \partial_\sigma (\bar{u} \gamma^\sigma \gamma_5 d), \tag{14}$$

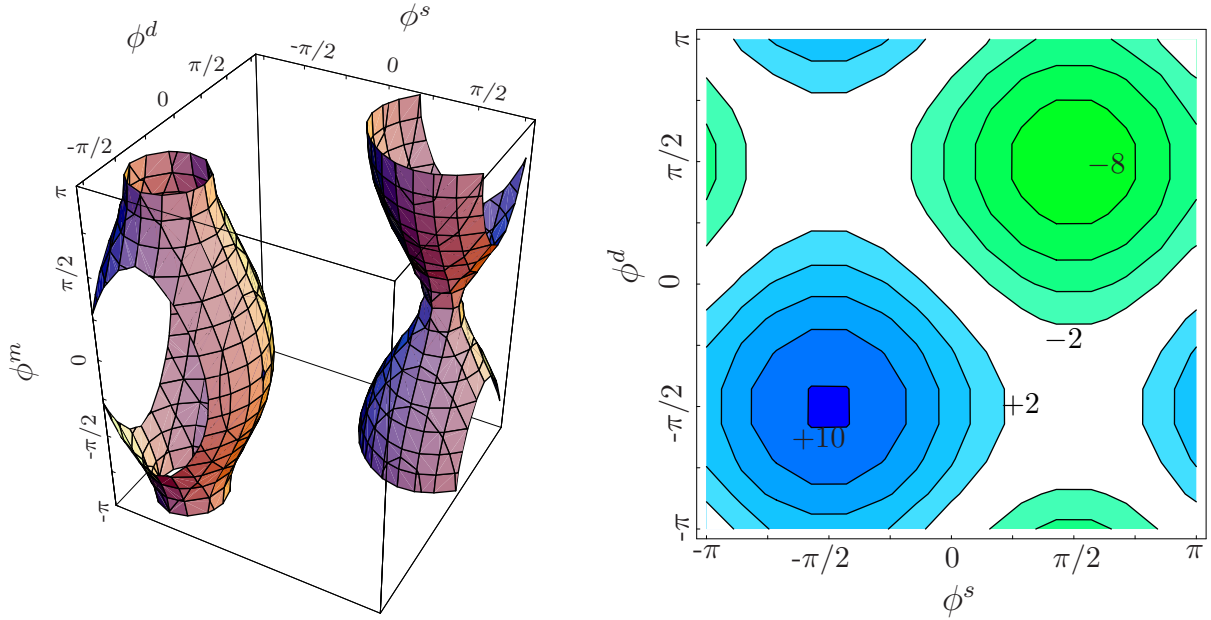


FIG. 1: The left plot represents the phase dependence of the contour which denotes 1σ deviation of the event number from that with the standard expectation when the magnitudes of all the exotic couplings, $|\epsilon_{\mu\tau}^{s,m,d}|$ are assumed to be 0.01 in the case of ICARUS-A. The right one is the expected event number due to new interactions, N_{τ}^{NP} in the presence of the new physics couplings $|\epsilon_{\mu\tau}^{s,d}| = 0.01$ and $\epsilon_{\mu\tau}^m = 0.01i$ in ICARUS-A. This plot is almost the same as that of $\epsilon_{\mu\tau}^m = 0$. In the region around the $(-\pi/2, -\pi/2)$ and $(\pi/2, \pi/2)$, the deviation from the standard case becomes significant beyond the error indicated in Table I.

the doublet mediation amplitude gets the enhancement factor, $m_{\pi}^2/(m_u + m_d)$, in the pion decay process. On the contrary there is no such an enhancement on the propagation and detection processes. Therefore $\epsilon_{\mu\tau}^s$ is much bigger than $\epsilon_{\mu\tau}^{m,d}$ and hence only $\epsilon_{\mu\tau}^s$ can contribute to the oscillation phenomenon. This enhancement allows us to search the smaller exotic coupling, which included in the elementary process, by $\mathcal{O}(10^{-2})$ than that in the singlet and triplet cases, eq.(12). In this case there is a constraint on the effective coupling from the $SU(2)_L$ counter process, $\tau^- \rightarrow \mu^- + \pi^0$, namely $\epsilon_{\mu\tau}^s \lesssim \mathcal{O}(10^{-2})$. The results of this calculation are presented in Fig.2. This is also well understood by eq.(7). In the region around $\phi^s = \pm\pi/2$ the gaps from the standard oscillation expectation become large. However, they do not reach 1σ level of significant even if the events of ICARUS and OPERA are combined.

Finally, we discuss the sensitivity for different oscillation parameters from eq.(11). As we noted again and again, eq.(7) is a very good approximation in this context. It shows that

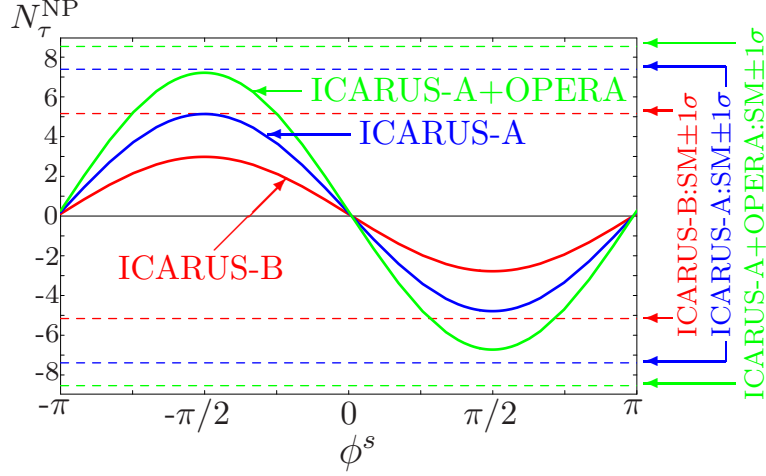


FIG. 2: Expected event number made by the new physics coupling $|\epsilon_{\mu\tau}^s| = 0.01$ and $|\epsilon_{\mu\tau}^{m,d}| = 0$ in ICARUS-A. The horizontal axis represents the complex phase of the $\epsilon_{\mu\tau}^s$ and the vertical axis indicates the event number deviation from standard model expectation, N_{τ}^{NP} .

the sensitivity does not depend on the sub-leading oscillation parameters, δm_{21}^2 , $\sin \theta_{12}$, δ , and also independent of $\sin \theta_{13}$ since all terms depend only on $\cos \theta_{13}$. According to the fact that the statistical error is dominant among the three kinds of errors, the condition eq.(9) reduces to $P_{\nu_{\mu} \rightarrow \nu_{\tau}} - P_{\nu_{\mu} \rightarrow \nu_{\tau}}^{\text{SM}} > \sqrt{P_{\nu_{\mu} \rightarrow \nu_{\tau}}^{\text{SM}}}$. From eqs.(6) and (7), it is found that this inequality depends essentially on two parameters, δm_{31}^2 and $\sin \theta_{23}$. For example even if $\delta m_{31}^2 \simeq 5 \times 10^{-3}$ eV², though the event number itself increases, we have almost same sensitivity as that with $\delta m_{31}^2 = 3 \times 10^{-3}$ eV². Note that here $\delta m_{31}^2 L/4E \ll 1$ [17].

To conclude, we summarize the results of the paper. We roughly evaluated the feasibility to search the new physics with ICARUS and OPERA, and got the following conclusions.

- There is a possibility for the observation of the new interaction effects whose magnitude is $|\epsilon_{\mu\tau}^{s,m,d}| \gtrsim \mathcal{O}(10^{-2})$. This value is around the current bound.
- The effects strongly depend on the phases of the couplings.
- To explore much smaller ϵ , more statistics is necessary. For this purpose, it is important to raise the efficiency even if the some background events contaminate the total tau events.

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interaction, however it is obvious for the appearance channel to get an advantage against the disappearance channel because of the statistical error.

- [17] Of course, if the expected number is very small then the error due to the parameter uncertainty and the systematic error become important. Therefore in such a case the plot for the sensitivity has slightly different shape. For example, if $\delta m_{31}^2 \simeq 1 \times 10^{-3} \text{eV}^2$, the decrease of the event number will spoil the sensitivity.