Tau neutrino

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I. MOTIVATION

In the paper from Andre de Gouvea *et al.* (1904.07265)[1], they compute the number of tau neutrinos in the far detector (fig.2 in the paper). Here the Figure(1). The figure has two curves, one for the true energy of the incident neutrino (dashed) and the other for the reconstructed energy(solid). The decay chain is something like:

$$\nu_\tau N \to \tau + X \tag{1}$$

where $\tau \to \nu_\tau +$ hadron. We do not measure the tau, only the hadronic debris. Therefore, we cannot reconstruct the energy of the incident neutrino very well (part of the energy is lost in the final neutrino). This explains why the solid curves are to the the left of the dashed ones. For the plots, we have

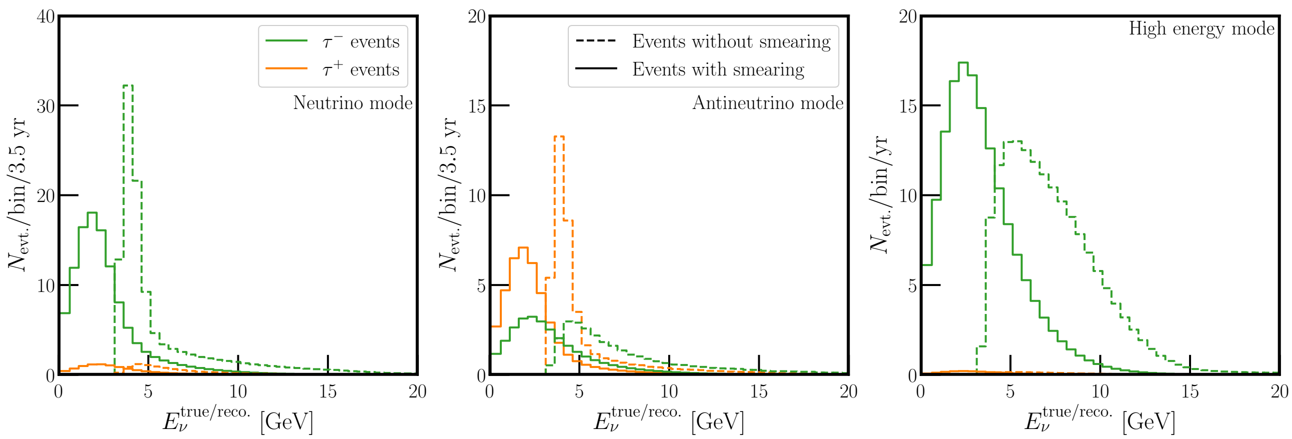

FIG. 1. Expected number of ν_τ-identified signal events per 0.5 GeV bin as a function of the true (dashed) or reconstructed (solid) neutrino energy. The left panel displays the expected number of events when in neutrino mode, the center panel displays the antineutrino mode, and the right panel displays high-energy mode events. In each panel, we show the contribution due to neutrinos in green and antineutrinos in orange. Each distribution has been normalized to the expected run-time in each mode, 3.5 years for neutrino and antineutrino modes and 1 year for high-energy mode.

$$N_{\text{events}}^{\text{SM}} = \phi_\mu P(\nu_\mu \to \nu_\tau)\sigma_\tau \tag{2}$$

since in the SM, there is no tau neutrino at source. So, the tau neutrino only appears at the far detector through conversion. In our model, we have

$$P_{\mu\beta}^{\text{NSI}} = \left| S_{\beta\mu}^{\text{SM}} - p_\mu \epsilon_{\mu i}^* S_{\beta i}^{\text{SM}} \right|^2 , \tag{3}$$

where we have a sum over i.

II. THE MODEL

The EFT Lagrangian that modifies the neutrino interactions is defined by [2]

$$\begin{aligned}\mathscr{L}_{\text{WEFT}} \supset -\frac{2\,V_{jk}^{CKM}}{v^2}\Big\{ & [1+\epsilon_L^{jk}]_{\alpha\beta}\left(\bar{u}^j\gamma^\mu P_L d^k\right)\left(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta\right) + [\epsilon_R^{jk}]_{\alpha\beta}\left(\bar{u}^j\gamma^\mu P_R d^k\right)\left(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta\right) \\ & + \frac{1}{2}\left[\epsilon_S^{jk}\right]_{\alpha\beta}\left(\bar{u}^j d^k\right)\left(\bar{\ell}_\alpha P_L \nu_\beta\right) - \frac{1}{2}\left[\epsilon_P^{jk}\right]_{\alpha\beta}\left(\bar{u}^j \gamma^5 d^k\right)\left(\bar{\ell}_\alpha P_L \nu_\beta\right) \\ & + \frac{1}{4}\left[\epsilon_T^{jk}\right]_{\alpha\beta}\left(\bar{u}^j \sigma^{\mu\nu} P_L d^k\right)\left(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta\right) + \text{h.c.}\Big\} .\end{aligned} \tag{4}$$

Here, V^{CKM} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix, $v = 1/(\sqrt{2}G_F) \approx 246\,\text{GeV}$ is the vacuum expectation value of the SM Higgs field and ϵ_X are the Wilson coeficients, with $X = L, R, S, P, T$ for left-handed, right-handed, scalar, pseudo-scalar and tensor, respectively. The Roman (Greek) symbols denote the quark (lepton) generations. This Lagrangian is based on the Weak Effective Field Theory (WEFT), that acts bellow electroweak scale [3].

For simplicity, we only study $(\epsilon_P)_{\alpha\beta}$ which we will denote as $\epsilon_{\alpha\beta}$.

III. METHODOLOGY

We have extracted from the plots of fig. I the number of true events as well as the reconstructed ones for all channels. The latter is only needed for cross-check. Using the number of true events as input, we have obtained the reconstructed events by ourselves. This was achieving by a smearing function given by

$$f(E_{\rm rec}, E_{\rm true}) = \exp\left[-\frac{1}{2}\left(\frac{E_{\rm rec} - bE_{\rm true)}}{rE_{\rm true}}\right)^2\right] \tag{5}$$

where $b = 0.45$, and $r = 0.25$.

Explicitly,

$$\frac{dN_{\rm events}}{dE_\nu^{\rm reco}} = \int {\rm d}E_\nu^{\rm true} \frac{dN_{\rm events}}{dE_\nu^{\rm true}} f(E_{\rm rec}, E_{\rm true}) \tag{6}$$

We have checked that the points reconstructed by ourselves in this way agree with the reconstructed points of the plots of fig I. Normalization factors were added, to guarantee that the total number of reconstructed events is the same as the true events.

In the plots, the following parameters were fixed

$$\sin^2\theta_{12} = 0.310; \quad \sin^2\theta_{13} = 0.02240; \quad \sin^2\theta_{23} = 0.582;$$
$$\delta_{\rm CP} = -2.50{\rm rad} \quad \Delta m_{21}^2 = 7.39 \times 10^{-5}{\rm eV}^2 \quad \Delta m_{31}^2 = 2.525 \times 10^{-3}{\rm eV}^2 \tag{7}$$

The baseline is 1300km for DUNE as well as the matter density is $\rho = 2.848 g/cm^3$.

It is possible to obtain the number of events for other values by re-scaling as below

$$\frac{dN_{\rm events}(\hat{x})}{dE_\nu^{\rm true}} = \phi_\mu P_{\mu\tau}^{\hat{x}}\sigma_\tau = \frac{P_{\mu\tau}^{\hat{x}}}{P_{\mu\tau}^{x}}\frac{dN_{\rm events}(x)}{dE_\nu^{\rm true}} \tag{8}$$

where x is a vector with the parameters defined in Eq. (7), while $\hat{x}$ is a vector with a different choice for any of the parameters. In the presence of NSI, it is still possible to obtain a perturbative formula for the conversion probability. Or one can resort to numerical methods. In any case, it is straightforward to obtain the event rates for any chosen value of the standard parameters or/and NSI.

The above analysis was applied to study the sensitivity on $\epsilon_{\mu\tau}$. Fixing the values of the standard parameters as in Eq. (7) we obtained (preliminary result)

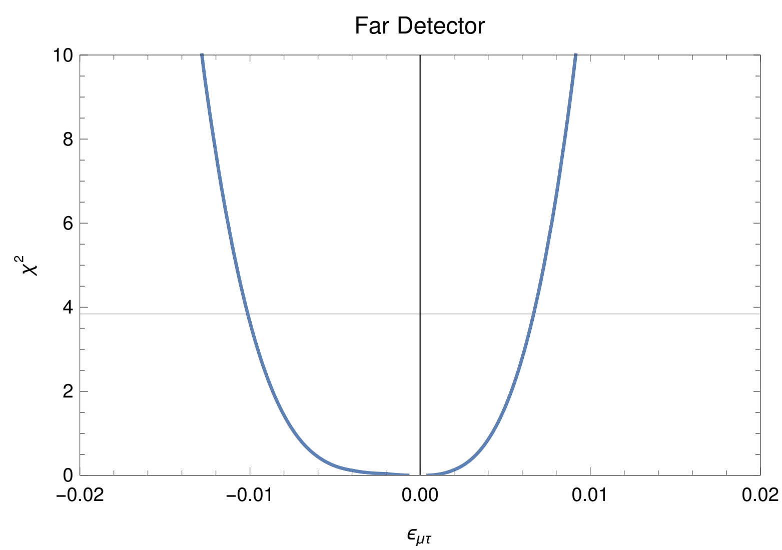

FIG. 2. Sensitivity on $\epsilon_{\mu\tau}$ at the far detector, considering running of 3.5 years at neutrino mode, 3.5 years at anti-neutrino mode, and 1 year at high-energy mode. The line is for 95%C.L.

The current bound (from pion decay) is around 2×10^{-3} at 90%C.L. [3]. The sensitivity from DUNE is at least one order of magnitude higher.

We can also study the sensitivity at the near detector. We will consider that $L = 1$km, and that the near detector will contain 70 ton $\mathrm{N_{far}}$ = 40 kton. This is particularly interesting, since the standard event rate

IV. TO DO

- We can re-scale the plots simply by doing

$$N_{\text{events}}^{\text{NSI}} = \phi_\mu P_{\mu\tau}^{\text{NSI}} \sigma_\tau = \frac{P_{\mu\tau}^{\text{NSI}}}{P_{\mu\tau}^{\text{SM}}} N_{\text{events}}^{\text{SM}} \tag{9}$$

  So the first step is to compute the ratio $\frac{P_{\mu\tau}^{\text{NSI}}}{P_{\mu\tau}^{\text{SM}}}$ using the oscillation parameters in the paper as a function of the energy. They used

$$\sin^2\theta_{12} = 0.310; \quad \sin^2\theta_{13} = 0.02240; \quad \sin^2\theta_{23} = 0.582;$$
$$\delta_{\text{CP}} = -2.50\text{rad} \quad \Delta m_{21}^2 = 7.39\times 10^{-5}\text{eV}^2 \quad \Delta m_{31}^2 = 2.525\times 10^{-3}\text{eV}^2 \tag{10}$$

  The baseline is 1300km for DUNE. We only need the value for the matter in the case of DUNE. I am using $\rho = 2.848 g/cm^3$.

- From reference [] we have **We divide the simulated data in energy bins of constant width $\Delta E_\nu = 0.5$ GeV, between 0 and 20 GeV, for our analyses**.

- Need to relate the plot with the reconstructed and true energy. Gaussian transformation?

  The differential rate

$$\frac{dN_{\text{events}}^{\text{NSI}}}{dE_\nu^{\text{true}}} = \phi_\mu P_{\mu\tau}^{\text{NSI}} \sigma_\tau = \frac{P_{\mu\tau}^{\text{NSI}}}{P_{\mu\tau}^{\text{SM}}} \frac{dN_{\text{events}}^{\text{SM}}}{dE_\nu^{\text{true}}} \tag{11}$$

  in terms of true energy and the differential rate

$$\frac{dN_{\text{events}}^{\text{NSI}}}{dE_\nu^{\text{true}}} = \phi_\mu P_{\mu\tau}^{\text{NSI}} \sigma_\tau = \frac{P_{\mu\tau}^{\text{NSI}}}{P_{\mu\tau}^{\text{SM}}} \frac{dN_{\text{events}}^{\text{SM}}}{dE_\nu^{\text{true}}} \tag{12}$$

  are connected by

$$\frac{dN_{\text{events}}^{\text{NSI}}}{dE_\nu^{\text{reco}}} = \int \frac{dN_{\text{events}}^{\text{NSI}}}{dE_\nu^{\text{true}}} \frac{\mathrm{d}\mathscr{R}}{\mathrm{d}E_\nu^{\text{reco}}}(E_\nu^{\text{reco}}, E_\nu^{\text{true}})\, \mathrm{d}E_\nu^{\text{true}} \tag{13}$$

  where

$$\frac{\mathrm{d}\mathscr{R}}{\mathrm{d}E_\nu^{\text{reco}}}(E_\nu^{\text{reco}}, E_\nu^{\text{true}}) = \frac{1}{\sqrt{2\pi}\,\sigma_E} \exp\left[-\frac{1}{2}\left(\frac{E_\nu^{\text{reco}} - bE_\nu^{\text{true}}}{\sigma_E}\right)^2\right] \tag{14}$$

  with $\sigma_E = rE_\nu^{\text{true}}, b = 0.45, r = 0.25$

  For an explanation of reconstructed and true energy[1]

[1] From GLOBES manual [4], section 10.1 we have the explanation of reconstructed and true energy.

Appendix A: EXTRA

in [1] they have (appendix A)

$$\sigma_E = 7\% \left(\frac{E_\nu}{1\text{GeV}}\right) + 3.5\% \sqrt{\frac{E_\nu}{1\text{GeV}}} \tag{A1}$$

For example in [5] they quote the following function

$$\frac{\mathrm{dR}}{\mathrm{d}N_h} = \frac{1}{\sqrt{2\pi}\,\sigma_h(T_e)} \exp\left[-\frac{1}{2}\left(\frac{N_h - \bar{N}_h(T_e)}{\sigma_h(T_e)}\right)^2\right] \tag{A2}$$

As an example they use

$$\sigma_h(\bar{N}_h) = 1.21974 + 1.60121\sqrt{\bar{N}_h} - 0.14859\bar{N}_h. \tag{A3}$$

the transformation between reconstructed energy and true energy is given by

$$S^f_{N_h} = \int \frac{\mathrm{d}S^f_s}{\mathrm{d}T_e}(T_e)\,\frac{\mathrm{d}\mathscr{R}}{\mathrm{d}N_h}(T_e, N_h)\,\mathrm{d}T_e \tag{A4}$$

For us $\frac{\mathrm{d}S^f_s}{\mathrm{d}T_e}(T_e)$ is the spectrum as function of true energy, $S^f_{N_h}$ is spectrum in terms of reconstructed energy and $\frac{\mathrm{dR}}{\mathrm{d}N_h}$ is the resolution function.

in another words, we begin with spectrum of true energy and due the resolution we really observe the spectrum of the reconstructed energy. in reference [1] the Figure 2 of this paper have these two distributions. We reproduce here this figure in 1

- Assuming that the near detector is better than the far detector, we can use the same plot to study the tau neutrino flux in this case. We can just use the same plot, but now we set $L = 0$. This gives the number of events due to tau neutrino in our model (the expected number in the SM is zero.)

[1] A. De Gouvêa, K. J. Kelly, G. V. Stenico, and P. Pasquini, Phys. Rev. D **100**, 016004 (2019), arXiv:1904.07265 [hep-ph].
[2] A. Falkowski, M. González-Alonso, and Z. Tabrizi, JHEP **11**, 048 (2020), arXiv:1910.02971 [hep-ph].
[3] A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, and Z. Tabrizi, JHEP **10**, 086 (2021), arXiv:2105.12136 [hep-ph].
[4] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, Computer Physics Communications **177**, 432–438 (2007).
[5] M. C. Gonzalez-Garcia, M. Maltoni, J. a. P. Pinheiro, and A. M. Serenelli, (2023), arXiv:2311.16226 [hep-ph].