Matter effect in $P_{\mu\tau}$ at long baselines

Srubabati Goswami[1,2⋆], Supriya Pan[2] and Animesh Chatterjee[3]

1 Northwestern University, Department of Physics and Astronomy, Evanston, IL 60208, USA
2 Physical Research Laboratory, Ahmedabad, Gujarat, 380009, India
3 European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland

⋆ sruba.goswami@gmail.com

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Abstract

In the simple two-generation case, the probability $P_{\mu\tau}$ is not affected by interactions of neutrinos in matter. But for three-generation case, at baselines of the order of 9000 km, matter effects become important for this channel. This is a genuine three-flavour effect. We study how the presence of non-standard interactions (NSI) alters the $P_{\mu\tau}$ at these baselines. We observe large deviations from the standard matter effect. In particular, we find energies and baselines for which the phases governing the NSIs do not play any role. This may facilitate a better determination of NSI parameters if tau neutrinos can be detected.

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1 Introduction

Observation from several terrestrial experiments using neutrinos from the sun, cosmic rays, accelerator, and reactor have conclusively established the phenomenon of neutrino oscillation in which one neutrino flavor can get converted to other flavors. This requires neutrinos to have small but non-zero masses and mixing between the different flavor states. The aforementioned experiments have determined most of the oscillation parameters quite precisely, and the data indicated that ν_μ and ν_τ are almost maximally mixed. Yet the detectors have observed either the muon neutrinos or the electron neutrinos since the detectors are not sensitive to ν_τ on an event-by-event basis. Super Kamiokande collaboration did a statistical analysis and reported that no τ appearance is excluded at 4.6σ confidence level [2]. IceCube collaboration also excluded the absence of ν_τ at 3.2σ from a search of statistical excess of cascade like neutrinos [1]. In the simple two-generation picture, the matter effect does not play any role in the $\nu_\mu - \nu_\tau$ oscillation probability since the matter potential due to the neutral current interactions is the same for ν_μ and ν_τ and thus contributes to an overall phase. However, for three generations and very long baselines, this conclusion changes, and there can be a significant matter effect in the probability $P_{\mu\tau}$ [3]. This is a genuine three-generation effect. In the next section, we consider the matter effect due to the non-standard interactions of the neutrinos in the $\nu_\mu - \nu_\tau$ sector, which can provide signatures of new physics.

2 Matter effects in $P_{\mu\tau}$

The total Hamiltonian for neutrinos propagating in matter is given as,

$$H_F^{tot} = \frac{1}{2E}[U\,\mathrm{diag}(0,\Delta_{21},\Delta_{31})U^\dagger + \mathrm{diag}(A,0,0)]\,, \tag{1}$$

where matter potential $A = 2\sqrt{2}G_F N_e E$, G_F is the Fermi constant, N_e is the electron density in matter, $\Delta_{ij} = m_i^2 - m_j^2$ is the mass-squared difference between ν_i and ν_j states, and U is the PMNS mixing matrix.

In the One Mass Scale Dominance (OMSD) approximation, i.e., $\Delta_{21} = 0$, the probability $\nu_\mu \to \nu_\tau$ is,

$$\begin{aligned} \mathrm{P}_{\mu\tau}^{\mathrm{mat}} &= \cos^2\theta_{13}^{\mathrm{m}} \sin^2 2\theta_{23} \sin^2\left[1.27(\Delta_{31}^{\mathrm{m}} + \mathrm{A} + \Delta_{31})\mathrm{L}/2\mathrm{E}\right] \\ &\quad + \sin^2\theta_{13}^{\mathrm{m}} \sin^2 2\theta_{23} \sin^2\left[1.27(\Delta_{31}^{\mathrm{m}} - \mathrm{A} - \Delta_{31})\mathrm{L}/2\mathrm{E}\right] - \cos^2\theta_{23} \mathrm{P}_{\mu e}^{\mathrm{mat}}\,. \end{aligned} \tag{2}$$

The maximal matter effect happens when $\mathrm{E_{res}} \simeq \mathrm{E_{peak}^{vac}}$, which gives [3]

$$\rho \mathrm{L}_{\mu\tau}^{\max} \simeq (2\mathrm{p}+1)\,\pi\, 5.18 \times 10^3\, (\cos 2\theta_{13})\ \mathrm{Km\ gm/cc}\,. \tag{3}$$

From Eq. (3), for p=1 and $\sin^2 2\theta_{13} = 0.1$, L $\sim$ 9700 Km and $\mathrm{P}_{\mu\tau}^{\mathrm{matter}} - \mathrm{P}_{\mu\tau}^{\mathrm{vac}} \approx -0.7$ In the left panel of figure 1, the probability $P_{\mu\tau}$ as a function of energy is shown for 9700 km both in matter and vacuum. From the plot, it is clear that there is considerable matter effect in this channel around $\sim$ 6 GeV, which is close to the resonance energy and over the broad energy range of 10-20 GeV.

3 Non-standard interactions

Considering NSI in only the $\mu - \tau$ sector, the total Hamiltonian is,

$$H_{NSI}^{tot} = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger + \frac{A}{2E} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & \epsilon_{\mu\tau} \\ 0 & \epsilon_{\mu\tau} & 0 \end{pmatrix}\,. \tag{4}$$

The probability of $\nu_\mu \to \nu_\tau$ conversion is calculated as,

$$\begin{aligned} \mathrm{P}_{\mu\tau}^{\mathrm{NSI}} = \sin^2 2\theta_{23}^M \Big\{ & \cos^2\theta_{13}^M \sin^2[1.27(\Delta_{31}^m + A + \Delta_{31} + A\epsilon_{\mu\tau}\cos\phi_{\mu\tau}(1+\cos^2\theta_{13}^m)\sin 2\theta_{23})L/2E] \\ & + \sin^2\theta_{13}^M \sin^2[1.27L(\Delta_{31}^m - A - \Delta_{31} - A\epsilon_{\mu\tau}\cos\phi_{\mu\tau}(1+\sin^2\theta_{13}^m)\sin 2\theta_{23})L/2E] \\ & - \sin^2 2\theta_{13}^M \sin^2\theta_{23}^M \cos^2\theta_{23}^M \sin^2[1.27(\Delta_{31}^m + A\epsilon_{\mu\tau}\cos\phi_{\mu\tau}\cos 2\theta_{13}^m \sin 2\theta_{23})L/2E] \Big\}\,, \end{aligned} \tag{5}$$

$$\sin\theta_{13}^M = \sin\theta_{13m}\left[1 - \frac{A\epsilon_{\mu\tau}\cos^2\theta_{13m}\sin 2\theta_{23}}{\sqrt{A^2 - 2A\Delta_{31}\cos 2\theta_{13} + \Delta_{31}^2}}\right]\,, \tag{6}$$

$$\sin\theta_{23}^M = \sin\theta_{23} + \epsilon_{\mu\tau}\cos\theta_{23}\cos 2\theta_{23}\frac{(A + \Delta_{31}\sin^2\theta_{13})}{\Delta_{31}\cos^2\theta_{13}}\,. \tag{7}$$

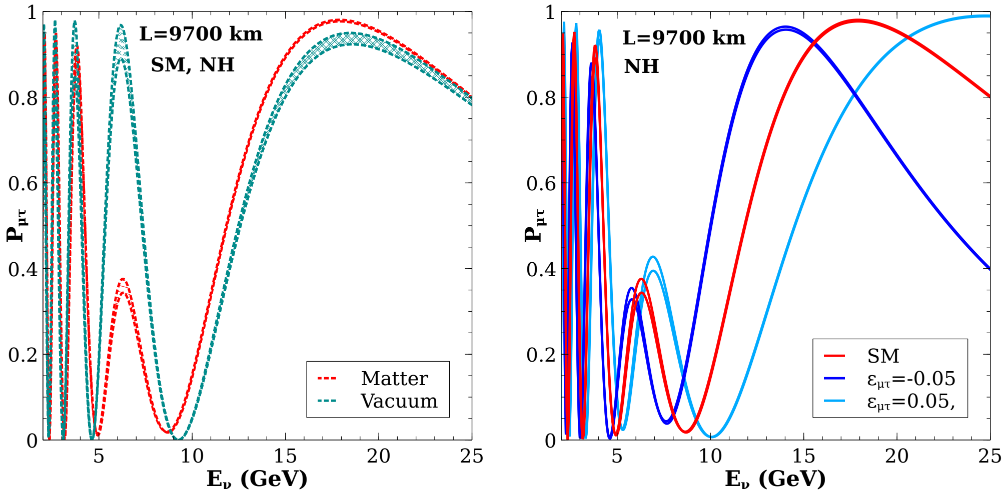

Figure 1: $P_{\mu\tau}$ versus neutrino energy E (in GeV) for normal hierarchy (NH) of neutrino mass states for at $L = 9700$ Km, $\Delta_{31} = 0.0025$ eV^2 and $\sin^2 2\theta_{13} = 0.1$. The left panel shows standard interactions (SM), while the right panel includes non-standard interactions in the $\mu - \tau$ sector.

In the right panel of the figure (1), we present $P_{\mu\tau}$ at 9700 km, including NSI. In presence of NSI, the maxima and the minima are located at different energies as compared to the standard case. The difference between the probabilities with same value of $|\epsilon_{\mu\tau}|$ ($\equiv |\epsilon|$) but different sign, $\Delta P_{\mu\tau} = P_{\mu\tau}(-\epsilon) - P_{\mu\tau}(\epsilon)$, vanishes at certain baselines L and energies E given as

$$L = \frac{n\pi}{1.27\left(2V_{CC} + \frac{\Delta_{31}}{E} + \sqrt{4V_{CC}^2 + \left(\frac{\Delta_{31}}{E}\right)^2 - 4V_{CC}\frac{\Delta_{31}}{E}\cos 2\theta_{13}}\right)}\,, \tag{8}$$

$$E = \Delta_{31}\frac{1.27L}{n\pi}\left(\frac{2n\pi}{1.27L} - 8V_{CC}\cos^2\theta_{13}\right) \Big/ \left(\frac{n\pi}{1.27L} - 4V_{CC}\right). \tag{9}$$

These baselines and energies are independent of the absolute value of NSI parameter $\epsilon_{\mu\tau}$ and for a fixed baseline, these energies are the same as where maxima and minima of SM probability occur as seen in the right panel of figure (1). In the left panel of the figure (2), we show the difference in $P_{\mu\tau}$ for standard interactions (SI) and NSI taking the value of $\epsilon_{\mu\tau}$ as 0.05 and taking the phase as 0 and π. The red and blue regions denote the baselines and energies for which the differences between SI and NSI are maximum.

In order to see the contribution of the $P_{\mu\tau}$ channel at the probability level, we define a χ^2 as $\chi^2 = (P(\epsilon_{\mu\tau} = x) - P(\epsilon_{\mu\tau} = 0))^2 / P(\epsilon_{\mu\tau} = 0)$. This is shown in the right panel of the figure (2). It is seen that one can get higher contributions for large baselines where there is a higher difference between SI and NSI. Thus, if the tau events can be included in the χ^2 analysis, the sensitivity to NSI parameter $\epsilon_{\mu\tau}$ may increase.

4 Conclusion

The $P_{\mu\tau}$ oscillation probability shows about 70% matter effect at baselines $\sim$ 9700 km. We explore the impact of non-standard interactions in the $P_{\mu\tau}$ channel. We find interesting features at large baselines and energies due to the non-standard matter effects. These baselines and energies are suitable for atmospheric neutrino experiments.

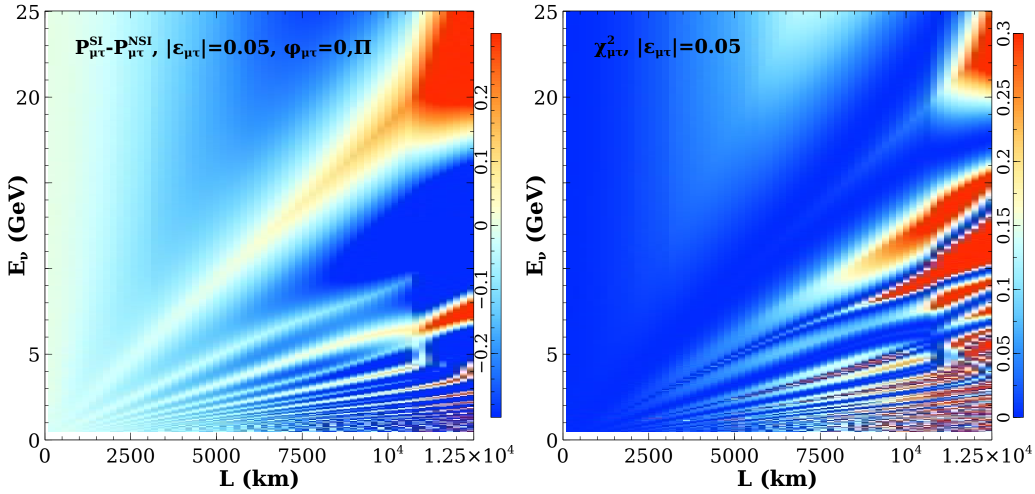

Figure 2: The difference in the probability $P_{\mu\tau}$ for standard case and in presence of NSI (left) and χ^2 (right) has been shown in L-E plane for $\epsilon_{\mu\tau} = 0.05$.

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