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# LFV $\mu$ decays study with neutrino NSI

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Lepton flavor violation (LFV) is known to be a suitable avenue to look for physics beyond the Standard Model. With experiments like LHCb and Belle II running in the flavor sector, we expect to get a lot of data that will help search for the hint of new physics. There exist few anomalies in the quark sector, although there is no clear evidence of new physics. On the other hand, the observation of neutrino oscillation has opened a new window to particle physics, indicating physics beyond the Standard Model. In our work, we study the charged LFV $\mu$ decays such as $\mu \to e\gamma$, $\mu \to eee$, and $(\mu - e)_{\mathrm{Ti}}$ with a vector leptoquark $(U_3)$ by considering the constraints from non-standard neutrino interaction (NSI) sector parameter $\epsilon_{e\mu}$. We consider that these NSIs are attributed to the presence of leptoquarks to account for the difference in the experimental observations of $\delta_{CP}$ measurement by NOvA and T2K. We obtained the branching ratios with uncertainties for three decay modes: $(\mu \to e\gamma) \leq 10^{-18}$, $(\mu \to eee) \leq 10^{-21}$ and $(\mu \to e)_{\mathrm{Ti}} \leq 10^{-19}$. Our results show an improvement in the current limits, which can be explored in future experiments.

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## 1. Introduction

Accelerator-based neutrino experiments offer exciting avenues for exploring neutrino physics and the universe's mysteries. Neutrinos travel long distances—hundreds of kilometers in current long-baseline experiments—and undergo flavor oscillations that hint at physics beyond the Standard Model (SM). As they pass through the Earth, neutrinos experience the Wolfenstein matter effect, influenced by non-standard interactions (NSIs) that can reveal deviations from SM predictions, potentially pointing to new physics models involving heavy states or light mediators. While the SM describes fundamental particles well, it fails to explain neutrino mass origins and lepton flavor violation (LFV). Neutrino oscillations [1] imply flavor mixing, suggesting similar processes could occur in charged leptons. Though no LFV has been observed in charged leptons, many SM extensions, such as models with leptoquarks and supersymmetry, predict LFV processes like $\mu \to e\gamma$ and $\tau \to e\gamma$. Recent experimental discrepancies, particularly in ratios like $\mathcal{R}_{K(K^{(*)})}$ [2] and $\mathcal{R}_{D(D^{(*)})}$ [3], intensify the search for LFV and new physics. Experiments like T2K, NOvA, T2HK, and DUNE are vital for refining measurements of neutrino masses and mixing angles. NOvA [4] and T2K [5] have reported tensions in the CP phase $\delta_{CP}$, with NOvA favoring $\delta_{CP} \approx 0.8\pi$ and T2K suggesting $\delta_{CP} \approx 1.5\pi$. NSIs may help resolve this tension, especially regarding the mixing angle $\theta_{23}$, where NOvA prefers a lower octant and T2K a higher one.

In this study we explore how NSIs influence standard neutrino oscillations and LFV decays of muons, including $\mu \to e\gamma$, $\mu \to eee$, and $\mu - e$ conversion in titanium. We propose that leptoquarks could mediate these NSIs, impacting experimental results. Upcoming experiments like MEG II and Mu3e are well-suited to investigate these LFV decays and further clarify the role of NSIs in neutrino physics.

## 2. Formalism

This study integrates neutrino non-standard interactions (NSI) with lepton flavor violation (LFV) in leptoquark models.

### 2.1 Neutrino Non-Standard Interactions

NSI is characterized by six-dimensional four-fermion operators:

$$\mathcal{L}_{\text{NSI}} = \frac{2}{\sqrt{2}G_F} \sum_f \sum_{\alpha,\beta} C^f_{\alpha\beta} [\nu_\alpha \gamma_\rho P_L \nu_\beta][f \gamma^\rho P_C f] + h.c.,$$

where $\alpha, \beta = e, \mu, \tau$ are neutrino flavors, $C^f_{\alpha\beta}$ are dimensionless parameters, and $f = u, d, e$ are matter fermions. The effective Hamiltonian for neutrino propagation in matter is $H_{\text{eff}} = \frac{1}{2E} U_{\text{PMNS}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger_{\text{PMNS}} + V$, with the NSI potential given by

$$V = 2\sqrt{2} G_F N_e E \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon^*_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon^*_{e\tau} e^{-i\phi_{e\tau}} & \epsilon^*_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}.$$

The parameters $\epsilon_{\alpha\beta}$ represent NSI effects and are defined as $\epsilon_{\alpha\beta} \equiv \sum_f \left(\epsilon^L_{\alpha\beta} + \epsilon^R_{\alpha\beta}\right) \frac{N_f}{N_e}$. Focusing on flavor nondiagonal NSI ($\epsilon_{\alpha\beta}$ with $\alpha \neq \beta$), we examine the conversion probability $P_{\mu e}$ for $\nu_\mu \to \nu_e$.

### 2.2 Lepton Flavor Violation

Lepton flavor violating decays, such as $\mu \to e\gamma$, can occur via one-loop diagrams, but predicted rates are suppressed [6] i.e. $\mathcal{B}(\mu \to e\gamma) < 10^{-54}$. We focus on NSI constraints from leptoquarks using data from T2K and NOvA, by studying $\mu \to e\gamma$, $\mu \to eee$, and $\mu - e$ conversions, with current upper limits reported by MEG [7], SINDRUM [8] and SINDRUM II [9]:

$$\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}, \quad \mathcal{B}(\mu \to eee) < 1.0 \times 10^{-12}, \quad \mathcal{B}(\mu - e)_{Ti} < 4.3 \times 10^{-12}.$$

Leptoquarks, particularly the vector $U_3$, can explain LFV phenomena while conserving baryon and lepton numbers. The effective interactions are $\mathcal{L} \supset \chi^{LL}_{ij} \overline{Q}^{i,a}_L \gamma^\mu (\sigma^k . U^k_{3,\mu})^{ab} L^{j,b}_L + h.c.$ The effective interactions for neutrinos with quarks are

$$\mathcal{L}^{up}_{eff} = \frac{-2}{m^2_{LQ}} \chi^{LL}_{j\beta} \chi^{LL^*}_{i\alpha} (\overline{d}^i \gamma_\mu P_L d^j)(\overline{\nu}_\alpha \gamma^\mu P_L \nu^\beta), \mathcal{L}^{down}_{eff} = \frac{-1}{m^2_{LQ}} \chi^{LL}_{j\beta} \chi^{LL^*}_{i\alpha} (\overline{u}^i \gamma_\mu P_L u^j)(\overline{\nu}_\alpha \gamma^\mu P_L \nu^\beta).$$

The branching ratios for these LFV processes are:

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha_e N_c^2}{64\pi G_F^2} \left[ \frac{|\chi^{LL}_{12} \chi^{LL}_{11}|}{2m^2_{LQ}} \left( \frac{m^2_{q_i}}{m^2_{LQ}} \right) \right]^2, \mathcal{B}(\mu \to eee) = \frac{\alpha_e^2 N_c^2}{96\pi^2 G_F^2} \left[ \frac{|\chi^{LL}_{12} \chi^{LL}_{11}|}{m^2_{LQ}} \left( \frac{m^2_{q_i}}{m^2_{LQ}} \right) \right]^2,$$

$$\mathcal{B}(\mu - e)_{Ti} = \frac{4\alpha_e^2 N_c^2}{96\pi^2} C \frac{\alpha_e^3 m_\mu^5 Z^4_{eff} Z |\overline{F}_p|^2}{\Gamma_{capt}} \frac{2}{3\pi^2} \left[ \sum_{i=1}^{3} \frac{|\chi^{LL}_{i2} \chi^{LL}_{i1}|}{m^2_{LQ}} \left( \frac{m^2_{q_i}}{m^2_{LQ}} \right) \right]^2.$$

## 3. Analysis details

We analyzed data using GLoBES [10] and its additional tool, incorporating standard model parameters from nuFIT v5.1 [11] and PDG [12] to assess sensitivity and oscillation probabilities for DUNE and T2HK, running simulations based on specified durations in both neutrino and antineutrino modes. DUNE will feature a 40-kiloton liquid argon detector using a 1.2 MW proton beam to create neutrino and antineutrino beams from pion decays, located 1300 km from Fermilab, with energies between 0.5 and 20 GeV, peaking around 3.0 GeV. T2HK will have a 225 kt water Cherenkov detector powered by a 30 GeV J-PARC beam at 1.3 MW, situated 295 km from the source.
Fig. 1 (left) presents the analysis results from T2K and NO$\nu$A, showing allowed regions for $\epsilon_{e\mu}$ with $\delta_{CP}$ and NSI phase $\phi_{e\mu}$. Figure 1 (right) shows allowed regions for $\epsilon_{e\tau}$ with $\delta_{CP}$ and NSI phase $\phi_{e\tau}$. Both figures indicate a preference for non-zero couplings $|\epsilon_{e\mu}|$ and $|\epsilon_{e\tau}|$, detailed in Table 1, consistent with global NSI parameter constraints. We found $\delta_{CP} \approx 1.12\pi$ for both the $e - \mu$ and $e - \tau$ sectors.

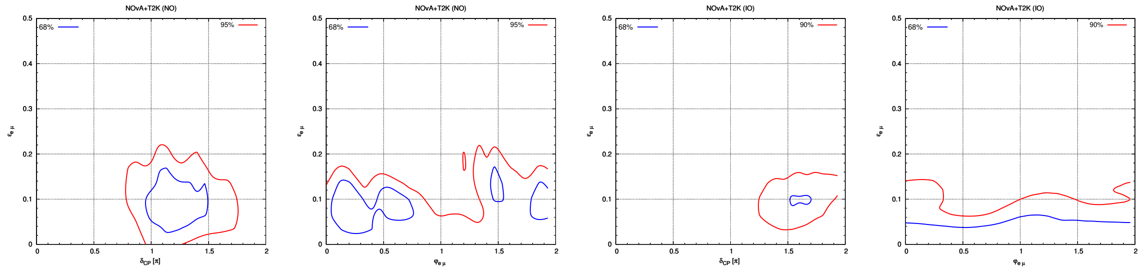


**Figure 1:** Allowed regions for $\epsilon_{e\mu}$ and the CP phase (left); $\epsilon_{e\mu}$ and phase $\phi_{e\mu}$ (right) determined by the combination of T2K and NO$\nu$A for NO (top panel) and IO (bottom panel). The contours are drawn at the 68% and 90% C.L. for 2 d.o.f.

**Table 1:** Best fit points from the allowed region plots, corresponding to the minimum $\chi^2$ values.

| Mass ordering | NSI | $\lvert\epsilon_{\alpha\beta}\rvert$ | $\phi_{\alpha\beta}/\pi$ | $\chi^2$ |
|---|---|---|---|---|
| NO | $\epsilon_{e\mu}$ | 0.1 | 0.2 | 0.518 |
| | $\epsilon_{e\tau}$ | 0.1 | 1.47 | 0.385 |
| IO | $\epsilon_{e\mu}$ | 0.01 | 1.67 | 0.533 |
| | $\epsilon_{e\tau}$ | 0.13 | 0.8 | 1.668 |

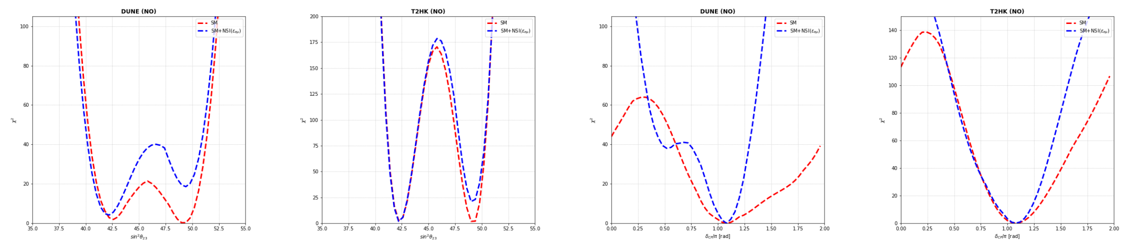


**Figure 2:** One-dimensional projections of $\theta_{23}$ (left) and $\delta_{CP}$ (right) for DUNE and T2HK in the NO case: SM (red dashed) and SM+NSI from $e-\mu$ (blue dashed).

**Lepton Flavor Violation $\mu$ decays:** In the presence of NSI, defined by dimension six four-fermion $(ff)$ operator [13],

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fC}[\overline{\nu_\alpha}\gamma^\rho P_L\nu_\beta][\overline{f}\gamma_\rho P_C f] + h.c. \tag{1}$$

where $G_F$ is Fermi coupling constant, $\epsilon_{\alpha\beta}^{fC}$ are dimensionless parameters that measure the new interaction's strength in relation to the SM, $\alpha, \beta = e, \mu, \tau$ indicate the neutrino flavor, superscript $C = L, R$ refers to the chirality of $ff$ current, $f = u, d, e$ denotes the matter fermions. For neutrino propagation in the Earth, $\epsilon_{\alpha\beta} \equiv \sum_{f,C}\epsilon_{\alpha\beta}^{fC}\frac{N_f}{N_e} \equiv \sum_{f=e,u,d}(\epsilon_{\alpha\beta}^{fL}+\epsilon_{\alpha\beta}^{fR})\frac{N_f}{N_e}$, where $N_e$ is the number density of electrons and $N_f$ being the number density of the $f$ fermion. The effective NSI parameter can be expressed as

$$\epsilon_{\alpha\beta} \simeq \epsilon_{\alpha\beta}^{e} + 3\epsilon_{\alpha\beta}^{u} + 3\epsilon_{\alpha\beta}^{d}\ . \tag{2}$$

$$\epsilon^{uL}_{\alpha\beta} = \frac{1}{2\sqrt{2}G_F}\frac{1}{m^2_{LQ}}\chi^{LL}_{1\beta}\chi^{LL^*}_{1\alpha}, \epsilon^{dL}_{\alpha\beta} = \frac{1}{\sqrt{2}G_F}\frac{1}{m^2_{LQ}}\chi^{LL}_{1\beta}\chi^{LL^*}_{1\alpha}. \quad (3)$$

We assume the discrepancy in $\delta_{CP}$ arises from new physics effects, specifically due to non-standard interactions (NSI). We extract the NSI contribution, particularly $\epsilon_{e\mu}$ from Ref. [14], summarized in Table 1. While other couplings may exist, $\epsilon_{e\mu}$ is the dominant one. In this work, we study the implications of $\epsilon_{e\mu}$ on lepton flavor violating (LFV) decays, including $\mu \to e\gamma$, $\mu \to eee$, and $\mu - e$ conversion. We set $\epsilon^u_{\alpha\beta} + \epsilon^d_{\alpha\beta}$ using Eq. 2, neglecting $\epsilon^e_{e\mu}$ due to its minimal contribution. For $\mu \to e\gamma$, we express it as $\epsilon^u_{e\mu}+\epsilon^d_{e\mu} \simeq \frac{\epsilon_{e\mu}}{3}$. Substituting values from Table 1, $\epsilon^u_{e\mu}+\epsilon^d_{e\mu} \simeq 0.033^{+0.01103}_{-0.01107}$ and the equations for $\epsilon^{uL}_{e\mu}$ and $\epsilon^{dL}_{e\mu}$ become:

$$\epsilon^{uL}_{e\mu} = \frac{1}{2\sqrt{2}G_F m^2_{LQ}}\chi^{LL}_{1\mu}\chi^{LL^*}_{1e}, \epsilon^{dL}_{e\mu} = \frac{1}{\sqrt{2}G_F m^2_{LQ}}\chi^{LL}_{1\mu}\chi^{LL^*}_{1e}. \quad (4)$$

Adding these equations gives $\epsilon^u_{e\mu} + \epsilon^d_{e\mu} = \frac{3}{2\sqrt{2}G_F m^2_{LQ}}\chi^{LL}_{1\mu}\chi^{LL^*}_{1e}$. To obtain the leptoquark coupling, we express it as $\frac{\chi^{LL}_{1\mu}\chi^{LL^*}_{1e}}{m^2_{LQ}} = \frac{2}{3}\sqrt{2}G_F(\epsilon^u_{e\mu} + \epsilon^d_{e\mu})$. Substituting $G_F = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$ and $\epsilon^u_{e\mu} + \epsilon^d_{e\mu} \simeq 0.033^{+0.01103}_{-0.01107}$ yields $\frac{\chi^{LL}_{1\mu}\chi^{LL^*}_{1e}}{m^2_{LQ}} \leq 3.67^{+1.20}_{-1.23} \times 10^{-7}\,\mathrm{GeV}^{-2}$.

- $\mu \to e\gamma$ decay: For the branching ratio calculation with a 2.0 TeV leptoquark, we use values: $\alpha_e = 1/137$, $N_c = 3$, and quark masses $m_d = 4.67$ MeV, $m_s = 93$ MeV, $m_b = 4.18$ GeV [12]. The leptoquark coupling is $\frac{\chi^{LL}_{1\mu}\chi^{LL^*}_{1e}}{m^2_{LQ}} \leq 3.67^{+1.20}_{-1.23} \times 10^{-7}$ GeV$^{-2}$. This gives $\mathcal{B}(\mu \to e\gamma) \leq 4.6^{+3.8}_{-2.6} \times 10^{-18}$. This result is below the current limit of $\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [7].
- $\mu \to eee$ decay: By using $m_d = 4.67$ MeV, $m_s = 93$ MeV and $m_b = 4.18$ GeV, we obtain the branching ratio, $\mathcal{B}(\mu \to eee) \leq 9.57^{+7.43}_{-5.37} \times 10^{-21}$. This is also below the limit of $\mathcal{B}(\mu \to eee) < 1.0 \times 10^{-12}$ [8].
- $\mu - e$ conversion in Nuclei: We use the following values [15] for Ti: $Z^{\mathrm{Ti}} = 22$, $Z^{\mathrm{Ti}}_{eff} = 17.61$, $\overline{F}^{\mathrm{Ti}}_p = 0.55$, $\Gamma^{\mathrm{Ti}}_{\mathrm{capt}} = 2.59\times10^6\ s^{-1}$, and $C^{\mathrm{Ti}} = 1.0$, the obtained the branching ratio is, $\mathcal{B}(\mu \to e)_{\mathrm{Ti}} \leq 6.89^{+5.61}_{-3.89} \times 10^{-19}$. This result is lower than the limit of $\mathcal{B}(\mu \to e)_{\mathrm{Ti}} < 4.3 \times 10^{-12}$ [9].

## 4. Summary

We studied NSI in constraining parameters using NO$\nu$A and T2K datasets. DUNE and T2HK prefer the lower octant with $e - \mu$ NSI, while $e - \tau$ NSI reintroduces degeneracy. Differences in oscillation probabilities between neutrino and anti-neutrino channels may help resolve the neutrino mass ordering issue. Notably, NSI reduces sensitivity, particularly in DUNE. Future NO$\nu$A and T2K data could clarify tensions in $\delta_{CP}$, potentially indicating new physics. We also studied the leptoquark effects on the branching ratios for different LFV processes i.e. $\mu \to e\gamma$, $\mu \to eee$, and $\mu - e$ conversion. Based on NSI constraints from neutrino data, we determined the leptoquark mass to be around 2.0 TeV and the obtained branching ratios are: $\mathcal{B}(\mu \to e\gamma) \leq 4.6^{+3.8}_{-2.6} \times 10^{-18}$, $\mathcal{B}(\mu \to eee) \leq 9.57^{+7.43}_{-5.37} \times 10^{-21}$, $\mathcal{B}(\mu \to e)_{\mathrm{Ti}} \leq 6.89^{+5.61}_{-3.89} \times 10^{-19}$[16]. Recent MEG II results show a sensitivity of $\mathcal{B}(\mu \to e\gamma) < 7.5 \times 10^{-13}$, with future experiments like COMET and Mu2e targeting sensitivities of $< 10^{-14}$ and $< 2.4 \times 10^{-16}$, respectively.



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