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Vector leptoquark U_3: A possible solution to the recent discrepancy between NOvA and T2K results on CP violation

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In the current epoch of neutrino physics, many experiments are aiming for precision measurements of oscillation parameters. Thus, various new physics scenarios which alter the neutrino oscillation probabilities in matter deserve careful investigation. Recent results from NOvA and T2K show a slight tension on their reported values of the CP violating phase δ_{CP}. Since the baseline of NOvA is much larger than the T2K, the neutral current non-standard interactions (NSIs) of neutrinos with the earth matter during their propagation might play a crucial role for such discrepancy. In this context, we study the effect of a vector leptoquark which induces non-standard neutrino interactions that modify the oscillation probabilities of neutrinos in matter. We show that such interactions provide a relatively large value of NSI parameter $\varepsilon_{e\mu}$. Considering this NSI parameter, we successfully explain the recent discrepancy between the observed δ_{CP} results of T2K and NOvA. We also briefly discuss the implication of U_3 leptoquark on lepton flavour violating muon decay mode $\mu \to e\gamma$.

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1. Introduction

Results from various neutrino oscillation experiments firmly established the three flavour mixing framework, where the flavour eigenstates ν_α ($\alpha = e, \mu, \tau$), are related to the corresponding mass eigenstates ν_i ($i = 1, 2, 3$), through the 3×3 unitary PMNS matrix, $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$. The mixing matrix U can be parametrized by three mixing angles, $\theta_{12}, \theta_{23}, \theta_{13}$ and one CP violating phase δ_{CP} and the precise determination of the oscillation parameters is one of the prime objectives of the currently running and the future long-baseline experiments. So far, we know the precise values of all the three mixing angles, except the octant of the atmospheric mixing angle θ_{23}. However, the CP violating phase δ_{CP}, which plays a crucial role in constraining the leptonic CP violation, has not yet been measured. Its measurement is of paramount relevance, as it would provide a feasible explanation for the observed baryon asymmetry of the universe. Recently, the two currently running long-baseline experiments NOvA and T2K reported their first results on the measurement of δ_{CP}. The T2K data suggests $\delta_{CP} \sim 3\pi/2$ [1] along with a preference for normal mass ordering, while NOvA result [2] indicates that $\delta_{CP} \sim \pi$. There is a mild tension at 2σ level between the measurements of these two experiments. This could be because of the limited statistics or systematic errors or more interestingly it could be a first hand hint for a new physics scenario. Recently, two independent groups have shown in their studies that presence of non-standard interaction (NSI) parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ can resolve the current NOvA and T2K tension in the measurement of CP violating phase δ_{CP} [3, 4].

In this context, we follow a model-dependent framework to investigate the effect of NSIs on neutrino oscillations. In particular, we consider the leptoquark (LQ) model [5], which can induce new interactions between the propagating neutrinos and the nucleons in the earth matter. We demonstrate that these interactions can provide large NSI parameter $\varepsilon_{e\mu}$, which can explain the observed discrepancy in the measurement of δ_{CP} between NOvA and T2K.

2. Model Framework

Here, we consider an additional vector leptoquark U_3, on top of the SM particle spectrum, which transforms as $(\overline{3}, 3, 2/3)$ under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. The charge of the vector LQ $U_3(\overline{3}, 3, 2/3)$ is expressed in terms of its isospin and hypercharge as $Q = I_3 + Y$ and thus, the three charged states are denoted as $U_3^{5/3}, U_3^{2/3}, U_3^{-1/3}$. During the propagation, the neutrinos interact with the nucleons (i.e. u and d quarks) of the earth matter through the exchange of the leptoquark as shown in the left panel of Figure-1.

Since the vector leptoquark U_3 transforms as a triplet under $SU(2)_L$, it can couple only to left-handed quark and lepton doublets and the corresponding Lagrangian describing the interaction is given as

$$\mathcal{L} \supset \lambda_{ij}^{LL}\, \overline{Q}_L^{i,a} \gamma^\mu (\tau^k \cdot U_{3,\mu}^k)^{ab} L_L^{j,b} + \text{H.c.}, \tag{1}$$

where $Q_L(L_L)$ are the left-handed quark (lepton) doublets, $\boldsymbol{\tau}$ are the Pauli matrices, $i, j = 1, 2, 3$ are the generation indices while a, b represent the $(SU(2))$ indices. The charged states can be expressed as $U_3^{5/3} = (U_3^1 - iU_3^2)/\sqrt{2}$, $U_3^{-1/3} = (U_3^1 + iU_3^2)/\sqrt{2}$ and $U_3^{2/3} = U_3^3$. Expanding the flavour indices, and using the following transformations for relating the flavor and mass eigenstates,

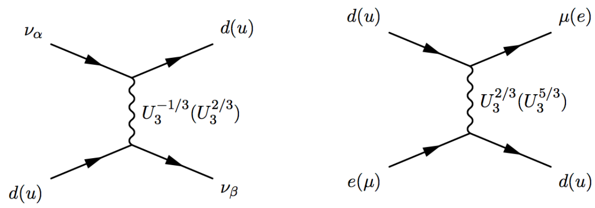

Figure 1: Feynman diagram for the interaction of neutrinos with u/d quarks (left panel) and the decay of $\pi^0 \to \mu^\pm e^\mp$ (right panel) through the exchange of U_3 LQ.

$u_L^j \to V_{jk}^\dagger u_L^k$, $d_L^j \to d_L^j$, $e_L^j \to e_L^j$ and $\nu_L^j \to U_{jk}^\dagger \nu_L^k$, where U and V represent the PMNS and CKM mixing matrices, one can write the effective four-fermion interaction between the neutrinos and *up* or *down*-type quarks as

$$\mathcal{L}_{\rm eff}^{\rm down} = -\frac{2}{m_{LQ}^2}\lambda_{j\beta}^{LL}\lambda_{i\alpha}^{LL*}(\overline{d}^i\gamma_\mu P_L d^j)(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)\,, \mathcal{L}_{\rm eff}^{\rm up} = -\frac{1}{m_{LQ}^2}\lambda_{j\beta}^{LL}\lambda_{i\alpha}^{LL*}(\overline{u}^i\gamma_\mu P_L u^j)(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)\,, \quad (2)$$

where m_{LQ} represents the mass of the leptoquark.

The standard expression for the neutral current non-standard interaction Lagrangian, is generally expressed as

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fX}(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)(\overline{f}\gamma_\mu P_X f)\,, \quad (3)$$

where $\alpha, \beta = e, \mu, \tau$ indicate the neutrino flavor, $f = e, u, d$ represent the matter fermions, the superscript $X = L, R$ refers to the chirality of the fermion current and $\varepsilon_{\alpha\beta}^{fX}$ are the strengths of NSIs. Assuming $n_u \approx n_d = 3n_e$, one can write the effective NSI parameter as $\varepsilon_{\alpha\beta} \simeq \varepsilon_{\alpha\beta}^e + 3\varepsilon_{\alpha\beta}^u + 3\varepsilon_{\alpha\beta}^d$.

Thus, comparing eqns. (2) and (3), we get the relation between the NSI parameter $\varepsilon_{\alpha\beta}$ and LQ parameters as

$$\varepsilon_{\alpha\beta}^{uL} = \frac{1}{2\sqrt{2}G_F}\frac{1}{m_{LQ}^2}\lambda_{1\beta}^{LL}\lambda_{1\alpha}^{LL*}, \qquad \text{and} \qquad \varepsilon_{\alpha\beta}^{dL} = \frac{1}{\sqrt{2}G_F}\frac{1}{m_{LQ}^2}\lambda_{1\beta}^{LL}\lambda_{1\alpha}^{LL*}. \quad (4)$$

In this work, we mainly focus to study the effect of $\varepsilon_{e\mu}$, and constrain the relevant LQ couplings, from the lepton flavour violating decays $\pi^0 \to \mu^\pm e^\mp$, mediated through the exchange of $U_3^{2/3}(U_3^{5/3})$ LQ as shown in the right panel of Fig.1. One can thus obtain the branching ratio of $\pi^0 \to \mu e$ process as

$$\begin{aligned}{\rm BR}(\pi^0 \to \mu^+e^- + \mu^-e^+) &= \frac{1}{64\pi m_\pi^3}\frac{|\lambda_{12}^{LL}\lambda_{11}^{LL*}|^2}{m_{LQ}^4}\tau_\pi f_\pi^2\left(1-2V_{11}^2\right)^2 \\ &\times\sqrt{(m_\pi^2-m_\mu^2-m_e^2)^2-4m_\mu^2m_e^2}\left[m_\pi^2(m_\mu^2+m_e^2)-(m_\mu^2-m_e^2)^2\right]. \quad (5)\end{aligned}$$

Using the values of input parameters from [6], we obtain the bound on the leptoquark parameters as $0 \le \frac{|\lambda_{12}^{LL}\lambda_{11}^{LL*}|}{m_{LQ}^2} \le 3.4\times10^{-6}$ GeV^{-2}. These bounds can be translated into NSI couplings using Eqn (4) as $\varepsilon_{e\mu}^{uL} \le 0.1$, $\varepsilon_{e\mu}^{dL} \le 0.2$, which gives $\varepsilon_{e\mu} \le 0.9$.

Now, we briefly discuss the effect of the NSIs of the neutrinos with the earth matter during their propagation. Due to the presence of NSIs, the effective Hamiltonian of neutrinos gets modified and is represented as

$$\mathcal{H} = \frac{1}{2E}\left[UM^2U^\dagger + V_m\right] , \tag{6}$$

where $M^2 = \mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})$ and V_m represents the matter potential which contains the NSI parameters $\varepsilon_{\alpha\beta}$ can be expressed as

$$V_m = A\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu}e^{i\phi_{e\mu}} & \varepsilon_{e\tau}e^{i\phi_{e\tau}} \\ \varepsilon_{e\mu}e^{-i\phi_{e\mu}} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \varepsilon_{e\tau}e^{-i\phi_{e\tau}} & \varepsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \varepsilon_{\tau\tau} \end{pmatrix}, \tag{7}$$

where, $A \equiv 2\sqrt{2}G_F n_e E$ and n_e stands for the density of electrons. Using matter perturbation theory, the appearance probability $P_{\mu e}$ to first order in A, can be expressed in terms of the off-diagonal $\varepsilon_{e\mu}$ for normal mass hierarchy (NH) as

$$P_{\mu e} = P_{\mu e}(\varepsilon = 0)_{SI} + P_{\mu e}(\varepsilon_{e\mu})_{NSI}, \tag{8}$$

where the expressions for $P_{\mu e}(\varepsilon = 0)_{SI}$ and $P_{\mu e}(\varepsilon_{e\mu})_{NSI}$ can be found in Ref. [5].

2.1 Addressing the T2K, NOvA discrepancy of δ_{CP}

The main difference between the two currently running long-baseline experiments NOvA and T2K is the difference in their baseline lengths. NOvA has a 810 km baseline while T2K has a comparatively shorter baseline of 295 km. Therefore, one possibility is to attribute this tension to the neutrino-nucleus NSIs in earth matter during the propagation of the beam. To explain this discrepancy, here we consider the effect of non-zero NSI parameter $\varepsilon_{e\mu}$ as obtained from the vector leptoquark (U_3) induced interactions between neutrinos and nucleons. Thus, for non-zero $\varepsilon_{e\mu}$, one can find degenerate solutions for Eq. (8) with two different set of oscillation parameters, i.e.,

$$P_{\mu e}(\theta_{12}, \theta_{13}, \theta_{23}, \delta^{\text{true}}_{CP}, \Delta m^2_{21}, \Delta m^2_{31}, \varepsilon_{e\mu}, \phi_{e\mu})_{\text{NSI}} = P_{\mu e}(\theta_{12}, \theta_{13}, \theta_{23}, \delta^{\text{meas}}_{CP}, \Delta m^2_{21}, \Delta m^2_{31})_{\text{SI}}. \tag{9}$$

One can thus, obtain a relationship between the measured and true values of δ_{CP} for NOvA experiment, with normal ordering as [4],

$$\begin{aligned} &-s_{12}c_{12}c_{23}\frac{\pi}{2}\sin\delta^{\text{true}}_{CP} + A|\varepsilon_{e\mu}|\Big(s^2_{23}\cos(\delta^{\text{true}}_{CP}+\phi_{e\mu}) - c^2_{23}\frac{\pi}{2}\sin(\delta^{\text{true}}_{CP}+\phi_{e\mu})\Big) \\ &\approx -s_{12}c_{12}c_{23}\frac{\pi}{2}\sin\delta^{\text{meas}}_{CP} \equiv P^{\delta}_{\mu e} . \end{aligned} \tag{10}$$

Fig. 2 shows the behaviour of $P^{\delta}_{\mu e}$ with respect to the phase $\phi_{e\mu}$ for NOvA experiment. This can be obtained by plotting the l.h.s and r.h.s of eqn (10) separately. The black curve shows the appearance probability ($P^{\delta}_{\mu e}$) for standard neutrino interactions (SI). The red, blue and magenta curves are plotted assuming the presence of non-zero $\varepsilon_{e\mu}$ for $\varepsilon_{e\mu} = 0.2$, $\varepsilon_{e\mu} = 0.15$ and $\varepsilon_{e\mu} = 0.1$ respectively. It can be noticed that when $\varepsilon_{e\mu} = 0.15$ (blue), $\varepsilon_{e\mu} = 0.2$ (red), we can clearly see an overlap between red, blue and black curves demonstrating a degeneracy of the form eq. (9) for different values of $\phi_{e\mu}$. However, in the case of T2K experiment the effect of NSI at a baseline of

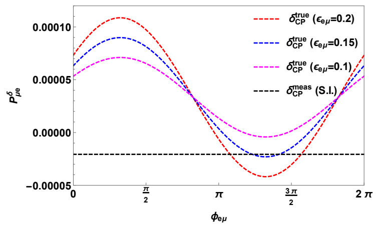

Figure 2: Appearance probability $P^{\delta}_{\mu e}$ versus $\phi_{e\mu}$ assuming standard interactions (black curve) and NSI for different values of $\varepsilon_{e\mu}$.

295 km is not very prominent. We show that the degeneracies of this form led to tension between the δ_{CP} measurement in NOvA and T2K. Therefore, we consider $\varepsilon_{e\mu} = 0.15$ as a representative value through out our analysis.

In this work, we simulated T2K and NOvA experiments according to the specifications given in Refs. [1] and [2] using the GLoBES software package. True values of the oscillation parameters used in the analysis for NOvA are taken from [2] and for T2K from [1] and the NSI parameters as $|\varepsilon_{e\mu}|$=0.15 and $\phi_{e\mu}$=1.53π. Here, we illustrate the predictions of the model in the context of T2K, NOvA experiments. Fig. 3 shows the allowed parameter regions spanned in the $\sin^2\theta_{23}$ - δ_{CP} plane. The red and green curves show the regions allowed at 1σ and 2σ confidence levels for 2 degrees of freedom. In both the cases we have assumed normal hierarchy and the presence of non-zero $\varepsilon_{e\mu}$. Additionally, we have marginalised over Δm^2_{31} and $\phi_{e\mu}$. It can be seen from left and right plots that the allowed values of $\sin^2\theta_{23}$ and δ_{CP} spanned by the contours in both the experiments are in agreement with each other. We can observe from left plot that in the case of NOvA experiment the true point for δ_{CP} has been shifted from 0.8π to 1.5π thus, resolving the tension between the two experiments. In addition, we also noticed that in the presence of NSI there is a degeneracy between the upper and lower octants.

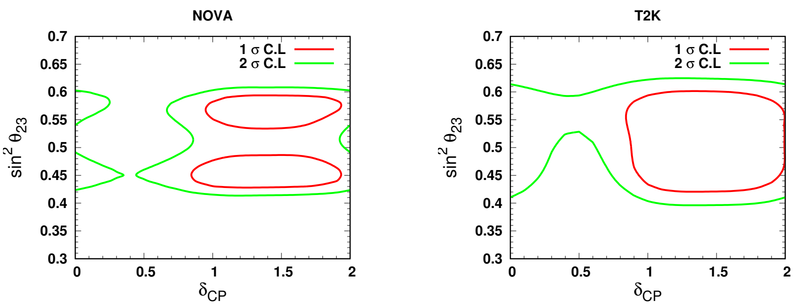

Figure 3: Allowed 1σ and 2σ confidence regions for $\sin^2\theta_{23}$-δ_{CP} parameter space obtained for NOvA (left) and T2K (right) experiments.

2.2 Implications of U_3 LQ on lepton flavour violating μ decays

In this section, we will briefly discuss the implications of the U_3 leptoquark on the lepton flavour violating (LFV) rare decay $\mu \to e\gamma$. This process is strictly forbidden in the Standard

Model and can be induced in models with extended gauge or lepton sectors. The current limit on the branching ratio is $\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ at 90% C.L. from MEG Collaboration [7]. In the presence the U_3 leptoquark, the $\mu \to e\gamma$ process can be mediated through one-loop diagrams with $up/down$ quarks and $U^{2/3}/U^{5/3}$ leptoquarks flowing in the loop, and the branching ratio is given as [5],

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha N_C^2}{64\pi G_F^2}\left[\sum_{i=1}^{3} \frac{|\lambda_{i2}^{LL}\lambda_{i1}^{LL}|}{m_{LQ}^2}\left(\frac{1}{2}\frac{m_{d_i}^2}{m_{LQ}^2} + \frac{m_{u_i}^2}{m_{LQ}^2}\right)\right]^2, \tag{11}$$

where $N_C = 3$ is the number of colors and $m_{d_i}(m_{u_i})$ represent the masses of the $down(up)$-type quarks. The constraints on leptoquark couplings can be scrutinized by assuming the presence of only one generation of quarks flowing in loop at a given time. Thus, it should be noted that $\mu \to e\gamma$ process is not very sensitive to the LQ couplings $\lambda_{12}^{LL}\lambda_{11}^{LL}$, required for obtaining the limit on $\varepsilon_{e\mu}$, as $m_{(u/d)}^2/m_{LQ}^2$ is negligibly small. Now, using the value of leptoquark parameters, constrained by the NOvA and T2K result on δ_{CP}, the quark masses as $m_u = m_d \approx 350$ MeV, we obtain the branching ratio for a TeV scale leptoquark as,

$$\mathrm{BR}(\mu \to e\gamma) \approx 7.35 \times 10^{-20}\,, \tag{12}$$

which is well below the present upper limit $\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$, as expected.

3. Conclusion

There is a slight tension between the recent measurements of the CP violating phase δ_{CP} by NOvA and T2K at the level of 2σ. The simplest and obvious reason for accounting this discrepancy is the presence of non-standard neutrino interactions of neutrinos with the earth matter during their propagation. In this work, we have considered the vector leptoquark model as an example and have shown that it can successfully resolve the observed discrepancy in the measurement of δ_{CP} by T2K and NOvA. We also briefly discussed the implications of U_3 leptoquark on the lepton flavour violating muon decays s $\mu \to e\gamma$.

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