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

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Introduction

- Results from various Neutrino oscillation experiments firmly established the standard three-fravour mixing framework:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- All the mixing angles are measured with relatively large values in contrast to small mixing in quark sector
- This opens up the possibility of observing the CP violation in lepton sector as CP violation effect is quantified in terms of Jarlskog invariant

$$J_{CP} = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP}$$

- δ_{CP} can be searched in long-baseline expts. through oscillation channels involving both Δm^2_{21} and Δm^2_{31}, e.g., $(\nu_\mu \rightarrow \nu_e)$
- Objective of the two currently running LBL expts. (NOvA and T2K) to measure δ_{CP}

NOvA and T2K Experiments in a Nutshell

NOvA Experiment

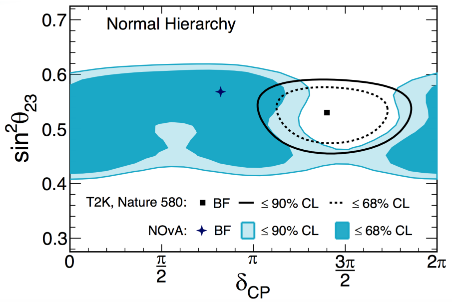
- Uses NuMI beam of Fermilab, with beam power 700 KW
- Aim to observe $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ osc.
- Has two functionally identical detectors: ND (300t) and FD (14kt)
- Both detectors are 14.6 mrad off-axis, corresponding to peak energy of 2 GeV
- Baseline: 810 km
- Matter density: 2.84 g/cc

T2K Experiment

- Uses the beam from J-PARC facility
- primary goal to observe $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\mu$ channels for both neutrinos and antineutrinos
- Has two detectors ND (plastic scintillator) and FD (22.5 kt) water Cherenkov
- Both detectors are at 2.5° off-axial in nature corresponding oscillation peak of 0.6 GeV.
- Baseline: 295 km
- Matter density: 2.3 g/cc

- Primary Physics Goals: To measure the atmospheric sector oscillation parameters (Δm^2_{32}, $\sin^2\theta_{23}$)
- Address some key open questions in oscillation (Neutrino MO, Octant of θ_{23}, CP violating phase δ_{CP}, NSIs, Sterile neutrinos, $\cdots$)

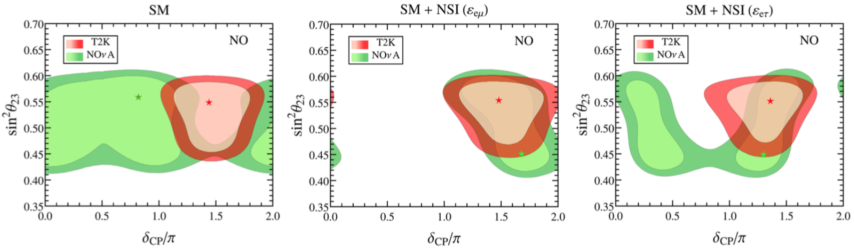
NOvA and T2K results on δ_{CP}



- Both expts. prefer Normal ordering
- No strong preference for CP violation in NOvA: $\delta_{CP} \sim 0.8\pi$
- T2K prefers $\delta_{CP} \simeq 3\pi/2$
- Slight disagreement between the two results at $\sim 2\sigma$ level

NOvA and T2K Tension & NSI (PRL 126, 051802 (2021))

- Difference between NOvA and T2K is the baseline and the matter density
- Neutrinos at NOvA experience stronger matter effect $\Longrightarrow$ New Physics solutions could be related to this differences
- Introduction of NC-NSIs can resolve this ambiguity, shown by two different groups

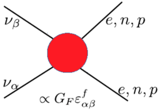


$\varepsilon_{e\mu} = 0.15,\ \delta_{e\mu} = 1.38\pi,\ \delta_{CP} = 1.48\pi\ (2.1\sigma)$; $\varepsilon_{e\tau} = 0.27,\ \delta_{e\tau} = 1.62\pi,\ \delta_{CP} = 1.46\pi\ (1.9\sigma)$

New Physics Effects: Non-Standard Interactions

- Non-Standard interactions (NSIs): Sub-leading effects in neutrino oscillation, usually generated by the exchange of new massive particles and are $\varepsilon \sim \mathcal{O}(M_W^2/M_{NP}^2)$
- NC-NSIs affect the neutrino propagation from source to detector and can be expressed as

$$\mathcal{L}_{\mathrm{NC-NSI}} = \frac{G_F}{\sqrt{2}} \sum_f \varepsilon^f_{\alpha\beta}[\bar{\nu}_\beta \gamma^\mu (1-\gamma_5)\nu_\alpha][\bar{f}\gamma_\mu(1\pm\gamma_5)f]$$



- CC NSIs are important for SBL/Reactor experiments, while NC NSIs are crucial for LBL/Accelerator expts.

Basic Formalism of NSI

- The Hamiltonian for neutrino propagation in matter in the standard paradigm is

$$\mathcal{H}_{SM} = \frac{1}{2E}\left[U \cdot \mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^\dagger + \mathrm{diag}(A, 0, 0)\right], \quad A = 2\sqrt{2}G_F N_e E$$

- The NSI Hamiltonian

$$\mathcal{H}_{NSI} = \frac{A}{2E}\begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}, \quad \text{where} \quad \varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| e^{i\delta_{\alpha\beta}}$$

- For neutrino propagation in the earth, the relevant combinations are

$$\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \varepsilon^f_{\alpha\beta}\frac{N_f}{N_e} = \sum_{f=e,u,d}\left(\varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}\right)\frac{N_f}{N_e}$$

- For $N_u \simeq N_d \simeq 3N_e \Longrightarrow \boxed{\varepsilon_{\alpha\beta} \simeq \varepsilon^e_{\alpha\beta} + 3\varepsilon^u_{\alpha\beta} + 3\varepsilon^d_{\alpha\beta}}$

- Using matter perturbation theory, the appearance probability $P_{\mu e}$, to first order in A expressed in terms of $\varepsilon_{e\mu}$ for NO:

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

$$\begin{aligned}
P_{\mu e}(\varepsilon = 0)_{SI} &= \sin^2 2\theta_{13} s_{23}^2 \sin^2 \Delta_{31} + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right)^2 \Delta_{31}^2 \\
&+ 4 c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23} \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right) \Delta_{31} \left[\cos\delta \sin 2\Delta_{31} - 2\sin\delta \sin^2 \Delta_{31}\right] \\
&+ 2\sin^2 2\theta_{13} s_{23}^2 \left(\frac{AL}{4E}\right) \left[\frac{1}{\Delta_{31}} \sin^2 \Delta_{31} - \frac{1}{2} \sin 2\Delta_{31}\right],
\end{aligned}$$

$$\begin{aligned}
&P_{\mu e}(\varepsilon_{e\mu} \neq 0)_{NSI} = -8\left(\frac{AL}{4E}\right) \\
&\times \left[s_{23} s_{13} \left\{ |\varepsilon_{e\mu}| \cos(\delta + \phi_{e\mu}) \left(s_{23}^2 \frac{\sin^2 \Delta_{31}}{\Delta_{31}} - \frac{c_{23}^2}{2} \sin 2\Delta_{31} \right) + c_{23}^2 |\varepsilon_{e\mu}| \sin(\delta + \phi_{e\mu}) \sin^2 \Delta_{31} \right\} \right. \\
&\left. - c_{12} s_{12} c_{23} \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \left\{ |\varepsilon_{e\mu}| \cos\phi_{e\mu} \left(c_{23}^2 \Delta_{31} + \frac{s_{23}^2}{2} \sin 2\Delta_{31} \right) + s_{23}^2 |\varepsilon_{e\mu}| \sin\phi_{e\mu} \sin^2 \Delta_{31} \right\} \right],
\end{aligned}$$

where $\Delta_{31} \equiv \frac{\Delta m_{31}^2 L}{4E}$.

Model dependent approach: Leptoquark Model

- Leptoquarks are color-triplet bosons which can couple to quarks and leptons simultaneously
- They can be scalar/vector type and are found in many extensions of the SM, e.g., $SU(5)$ GUT, Pati-Salam $SU(4)$ model, Composite model etc.
- Let's consider an additional VLQ U_3 which transforms as $(\bar{3}, 3, 2/3)$ under the SM gauge group $SU(3) \times SU(2) \times U(1)$
- Since U_3 transforms as a triplet under $SU(2)_L$, it can couple only to LH quark and lepton doublets and the corresponding interaction Lagrangian is

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

- The three charged states are:

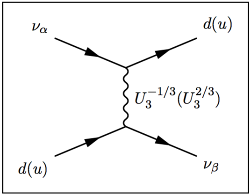
$$\boxed{U_3^{5/3} = (U_3^1 - iU_3^2)/\sqrt{2}, \quad U_3^{-1/3} = (U_3^1 + iU_3^2)/\sqrt{2}, \quad U_3^{2/3} = U_3^3}$$

NSIs due to LQ interactions

- The effective four-fermion interaction between neutrinos and u/d quarks $(q^i + \nu_\alpha \to q^j + \nu_\beta)$

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

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



- Thus, one can obtain the NSI parameters as

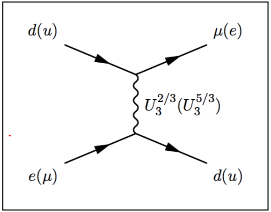
$$\varepsilon_{\alpha\beta}^{uL} = \frac{1}{2\sqrt{2}G_F} \frac{1}{m_{\rm LQ}^2} \lambda_{1\beta}^{LL} \lambda_{1\alpha}^{LL} \ , \quad \text{and} \quad \varepsilon_{\alpha\beta}^{dL} = \frac{1}{\sqrt{2}G_F} \frac{1}{m_{\rm LQ}^2} \lambda_{1\beta}^{LL} \lambda_{1\alpha}^{LL} \ .$$

- LQ parameters are constrained from te LFV decay, $\pi^0 \to \mu e$

Constraints on LQ couplings from LFV decays

- We are mainly interested to study the effect of the NSI parameter $\varepsilon_{e\mu}$, which may be responsible for NOvA and T2K discrepancy on $\delta_{\rm CP}$.
- For constraining the LQ parameters, we consider the LFV decay $\pi^0 \to \mu e$, mediated through the exchange of $U_3^{2/3}(U_3^{5/3})$
- The effective Lagrangian for $\pi^0 \to (\mu^+ e^- + e^+ \mu^-)$ process is given as

$$\mathcal{L}_{\rm eff} = -\Big[\frac{1}{m_{LQ}^2}\lambda_{12}^{LL}\lambda_{11}^{LL*}(\bar{d}_L\gamma^\mu d_L)(\bar{\mu}_L\gamma_\mu e_L) + \frac{2}{m_{LQ}^2}(V\lambda^{LL})_{12}(V\lambda^{LL})_{11}^*(\bar{u}_L\gamma^\mu u_L)(\bar{\mu}_L\gamma_\mu e_L)\Big].$$



- As the CKM matrix elements are strongly hierarchical, i.e., $V_{11} > V_{12} > V_{13}$, we keep only the diagonal element V_{11}

Constraints on LQ couplings from LFV decays

- The branching fraction of $\pi^0 \to \mu e$ process is given as

$$\mathcal{B}(\pi^0 \to \mu^+ e^- + \mu^- e^+) = \frac{1}{64\pi m_\pi^3} \frac{\left|\lambda_{12}^{LL}\lambda_{11}^{LL*}\right|^2}{m_{LQ}^4} \tau_\pi f_\pi^2 \left(1 - 2V_{11}^2\right)^2$$
$$\times \sqrt{(m_\pi^2 - m_\mu^2 - m_e^2)^2 - 4m_\mu^2 m_e^2} \left[m_\pi^2(m_\mu^2 + m_e^2) - (m_\mu^2 - m_e^2)^2\right]$$

- The measured branching ratio of this process at 90% C.L.

$$\mathcal{B}(\pi^0 \to \mu^+ e^- + \mu^- e^+) < 3.6 \times 10^{-10}$$

- Thus, we obtain the bound on the leptoquark parameters as

$$0 \leq \frac{|\lambda_{12}^{LL}\lambda_{11}^{LL*}|}{m_{LQ}^2} \leq 3.4 \times 10^{-6}\ \mathrm{GeV}^{-2}.$$

- These bounds can be translated into NSI couplings as

$$\varepsilon_{e\mu}^{uL} \leq 0.1, \qquad \varepsilon_{e\mu}^{dL} \leq 0.2,$$

which gives $\varepsilon_{e\mu} \leq 0.9$.

Addressing NOvA and T2K discrepancy on δ_{CP}

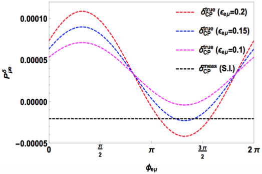
- General Approach: Accurately measure the $P_{\mu e}$ and compare with prediction
- Any mismatch between data and prediction $\Longrightarrow$ Interplay of NP

- To resolve the ambiguity, we consider the effect of $\varepsilon_{e\mu}$ and use its value obtained from U_3, i.e., we consider all other NSI parameters to be zero.
- Due to the presence of nonzero $\varepsilon_{e\mu}$, one can obtain degenerate solutions in $P_{\mu e}$, i.e.,

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

- After a little algebraic manipulation, one can obtain a relationship between the measured and true values of δ_{CP} for the NOvA experiment

$$-s_{12}c_{12}c_{23}\frac{\pi}{2}\sin\delta_{CP}^{\text{true}} + A|\varepsilon_{e\mu}|\left(s_{23}^2\cos(\delta_{CP}^{\text{true}}+\phi_{e\mu}) - c_{23}^2\frac{\pi}{2}\sin(\delta_{CP}^{\text{true}}+\phi_{e\mu})\right)$$
$$\approx -s_{12}c_{12}c_{23}\frac{\pi}{2}\sin\delta_{CP}^{\text{meas}} \equiv P_{\mu e}^{\delta}\ .$$



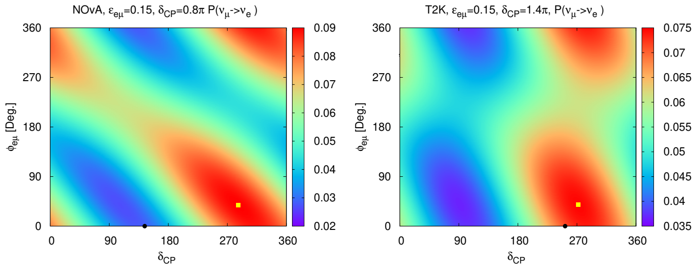
- $\varepsilon_{e\mu} \geq 0.15$, there will be degeneracy between SI and NSI $P_{\mu e}$

Discussion at Probability Level

- For simulation, we used GLoBES and obtained the χ^2

$$\chi^2_{\mathrm{stat}} = 2 \sum_i \left[N_i^{\mathrm{test}} - N_i^{\mathrm{true}} + N_i^{\mathrm{true}} \ln \frac{N_i^{\mathrm{true}}}{N_i^{\mathrm{test}}} \right]$$

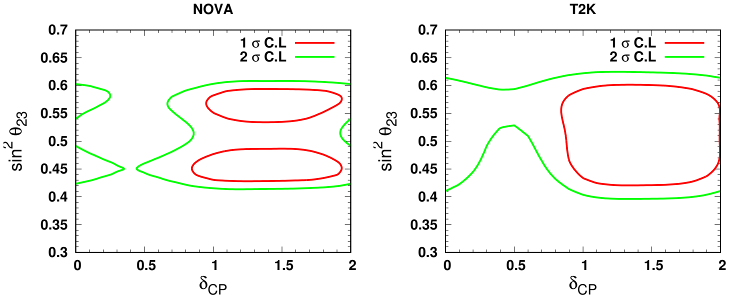
- We show the oscillograms for $P_{\mu e}$ assuming $\varepsilon_{e\mu} = 0.15$ with respect to the variation in δ_{CP} and the NSI phase $\phi_{e\mu}$.



- When one assumes non-zero $\varepsilon_{e\mu}$, both NOvA and T2K are suggesting same value of $\delta_{CP} = 3\pi/2$.

Prediction for Neutrino Oscillation Parameters

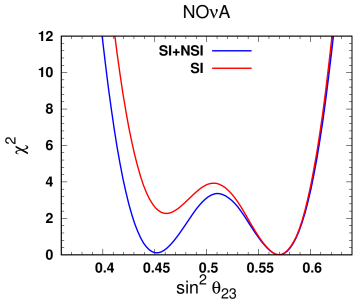
- The true values used in the simulation are taken from NuFit 5.1. In addition, we used $\delta_{CP} = 1.4\pi$, $\varepsilon_{e\mu} = 0.15$, $\phi_{e\mu} = 1.53\pi$
- Marginalization is done over Δm^2_{31} and $\phi_{e\mu}$



- Allowed parameter space in $\sin^2\theta_{23} - \delta_{CP}$ plane in the presence of $\varepsilon_{e\mu}$ for Normal Ordering

Prediction for Neutrino Oscillation Parameters

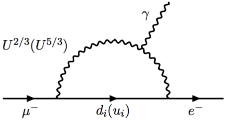
- To get the best-fit value of θ_{23} in the presence of $\varepsilon_{e\mu}$, we show χ^2 vs $\sin^2\theta_{23}$

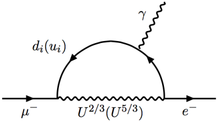


- With NSI, the absolute minima still falls in higher octant, though for values of $\theta_{23} < 45^\circ$ there seems to be a degeneracy with lower octant.

Implications of U_3 LQ on LFV μ decays

- The LQ couplings relevant for constraining the NSI parameter $\varepsilon_{e\mu}$ are intimately connected to $\mu \to e\gamma$.
- The current upper limit: $\mathcal{B}(\mu \to e\gamma < 4.2 \times 10^{-13}$ at 90% CL
- In presence of U_3, $\mu \to e\gamma$ process can be mediated through one-loop





- Including leading order loop functions of order $\mathcal{O}(m_{q_i}^2/m_{LQ}^2)$ as

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

- For a TeV scale leptoquark, the branching fraction is

$$\mathcal{B}(\mu \to e\gamma) \approx 7.35 \times 10^{-20}$$

Conclusion

- There is slight tension between the recent measurements of δ_{CP} by NOvA and T2K at 2σ level
- The simplest and obvious reason for accounting this discrepancy is the presence of NSIs of neutrinos with the earth matter during their propagation.
- We have considered the vector LQ (U_3) 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.
- In addition, we also noticed that in the 3-flavour paradigm, NOvA prefers upper octant for θ_{23}, while in the presence of NSI there is a degeneracy between the upper and lower octants.
- We also showed the implications U_3 in LFV decay $\mu \to e\gamma$

Thank you for your attention!