# 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

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

- CP violation in lepton sector is quite different from quark sector.
- $\delta_{CP}$ can be searched in long-baseline expts. through oscillation channels $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
- Objective of the two currently running LBL expts. (NOvA and T2K) to measure $\delta_{CP}$

# NOvA and T2K Experiments in a Nutshell

**NOvA Experiment**

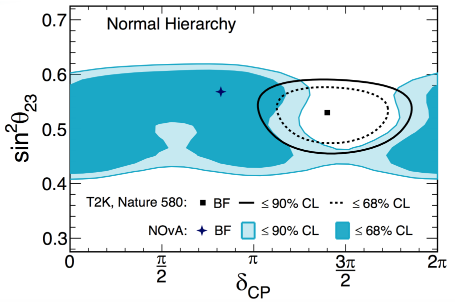
- Uses NuMI beam of Fermilab, with beam power 700 KW
- Aim to observe $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ osc.
- Has two functionally identical detectors: ND (300t) and FD (14kt)
- Both detectors are 14.6 mrad off-axis, corresponding to peak energy of 2 GeV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

**T2K Experiment**

- Uses the beam from J-PARC facility
- primary goal to observe $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ channels for both neutrinos and antineutrinos
- Has two detectors ND (plastic scintillator) and FD (22.5 kt) water Cherenkov
- Both detectors are at $2.5^\circ$ 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 ($\Delta m^2_{32}$, $\sin^2\theta_{23}$)
- Address some key open questions in oscillation (Neutrino MO, Octant of $\theta_{23}$, CP violating phase $\delta_{CP}$, NSIs, Sterile neutrinos, $\cdots$)

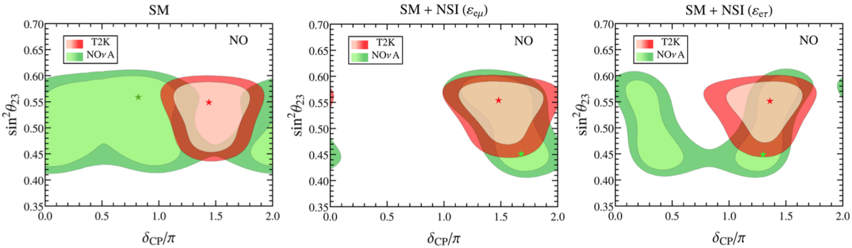
# NOvA and T2K results on $\delta_{CP}$




- 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

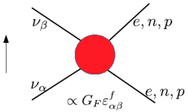



$\varepsilon_{e\mu} = 0.15,\ \delta_{e\mu} = 1.38\pi,\ \delta_{CP} = 1.48\pi\ (2.1\sigma)$; $\varepsilon_{e\tau} = 0.27,\ \delta_{e\tau} = 1.62\pi,\ \delta_{CP} = 1.46\pi\ (1.9\sigma)$

# 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

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




- 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:

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

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

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

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.
- Natural good candidates to coherently address the flavor anomalies while respecting other bounds
- 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

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

- The three charged states are:

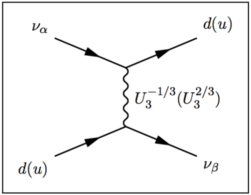
$$\boxed{U_3^{5/3} = (U_3^1 - iU_3^2)/\sqrt{2}, \quad U_3^{-1/3} = (U_3^1 + iU_3^2)/\sqrt{2}, \quad U_3^{2/3} = U_3^3}$$

# NSIs due to LQ interactions

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

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

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




- Comparing with the generalized NC-NSI interaction Lagrangian

$$\mathcal{L} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fL}(\bar{f}\gamma_\mu P_L f)(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)$$

- One can obtain the NSI parameters as

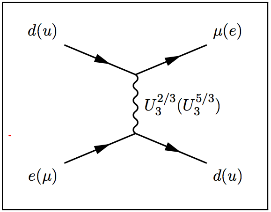
$$\varepsilon_{\alpha\beta}^{uL} = \frac{1}{2\sqrt{2}G_F}\frac{1}{m_{\rm LQ}^2}\lambda_{1\beta}^{LL}\lambda_{1\alpha}^{LL}\ , \quad \text{and} \quad \varepsilon_{\alpha\beta}^{dL} = \frac{1}{\sqrt{2}G_F}\frac{1}{m_{\rm LQ}^2}\lambda_{1\beta}^{LL}\lambda_{1\alpha}^{LL}\ .$$

- 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

$$0 \le \frac{|\lambda_{12}^{LL}\lambda_{11}^{LL*}|}{m_{LQ}^2} \le 3.4 \times 10^{-6}\ \mathrm{GeV}^{-2} \Longrightarrow m_{LQ} \ge 540\ \mathrm{GeV}\ \ \text{for } \lambda_{\rm ij} \sim \mathcal{O}(1).$$

- These bounds can be translated into NSI couplings as

$$\varepsilon_{e\mu}^{uL} \le 0.1, \quad \varepsilon_{e\mu}^{dL} \le 0.2, \quad \Longrightarrow \quad \varepsilon_{e\mu} \le 0.9$$

# Addressing NOvA and T2K discrepancy on $\delta_{CP}$

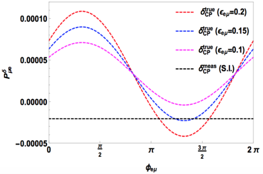
- General Approach: Accurately measure the $P_{\mu e}$ and compare with prediction
- Any mismatch between data and prediction $\Longrightarrow$ Interplay of NP

- 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.,

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

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

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



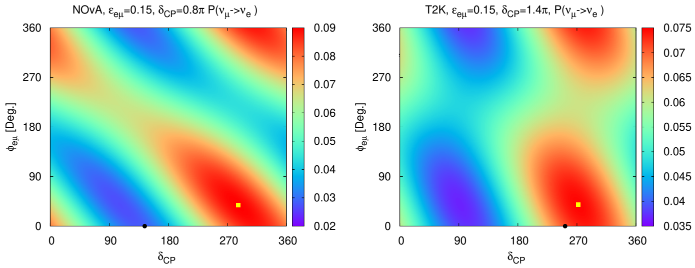

- $\varepsilon_{e\mu} \geq 0.15$, there will be degeneracy between SI and NSI $P_{\mu e}$

# Discussion at Probability Level

- For simulation, we used GLoBES and obtained the $\chi^2$

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

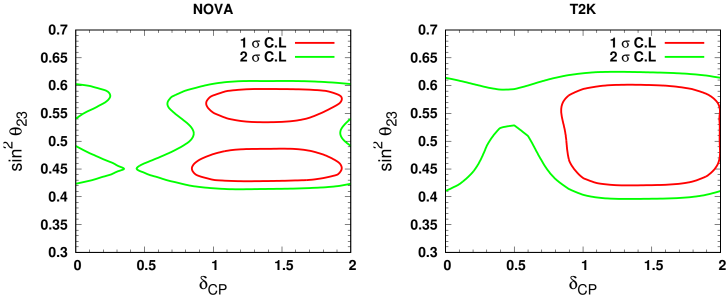
- We show the oscillograms for $P_{\mu e}$ assuming $\varepsilon_{e\mu} = 0.15$ with respect to the variation in $\delta_{CP}$ and the NSI phase $\phi_{e\mu}$.




- 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

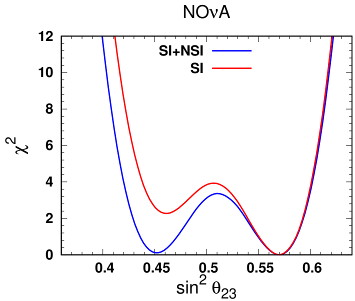
- The true values used in the simulation are taken from NuFit 5.1. In addition, we used $\delta_{CP} = 1.4\pi$, $\varepsilon_{e\mu} = 0.15$, $\phi_{e\mu} = 1.53\pi$
- Marginalization is done over $\Delta m^2_{31}$ and $\phi_{e\mu}$




- 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 $\theta_{23}$ in the presence of $\varepsilon_{e\mu}$, we show $\chi^2$ 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.

# LFV decay mode $\mu \to e\gamma$

- LFV provides an alternate avenue to look for NP
- Though LFV has been observed in $\nu$-oscillation, but so far not detected in $\ell$
- There is $4.2\sigma$ discrepancy between the Expt. and SM prediction of $(g-2)_\mu$ $\Longrightarrow$ potential existence of NP
- The NP models that accommodate $a_\mu$ , in principle could affect LFV decays, i.e., $\mu \to e\gamma$
- The current limit at 90% CL is $\mathcal{B}(\mu \to e\gamma) < 10^{-13}$ from MEG
- The general effective Lagrangian for $\mu \to e\gamma$ is

$$\mathcal{L}_{\rm eff} = \frac{\mu^M_{e\mu}}{2}\,(\bar{e}\sigma^{\mu\nu}\mu)F_{\mu\nu} + \frac{\mu^E_{e\mu}}{2}\,(\bar{e}i\gamma_5\sigma^{\mu\nu}\mu)F_{\mu\nu}\ ,$$

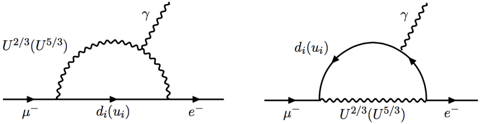
- Neglecting $m_e$, one can express $\mu^{M/E}_{e\mu} = e m_\mu A^{M/E}_{e\mu}/2$, which gives

$$\mathcal{B}(\mu \to e\gamma) = \frac{3(4\pi)^3\alpha}{4G_F^2}\left(|A^M_{e\mu}|^2 + |A^E_{e\mu}|^2\right)$$

- The LFV decay mode $\mu \to e\gamma$ is highly suppressed in the SM with $\mathcal{B}(\mu \to e\gamma) \approx 10^{-54}$

# Implications of $U_3$ LQ on LFV $\mu$ decays

- The LQ couplings relevant for constraining the NSI parameter $\varepsilon_{e\mu}$ are intimately connected to $\mu \to e\gamma$.
- 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

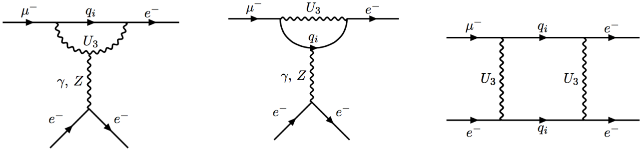
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha N_C^2}{64\pi G_F^2}\left[\sum_{i=1}^{3}\frac{|\lambda_{i2}^{LL}\lambda_{i1}^{LL}|}{m_{LQ}^2}\left(\frac{1}{2}\frac{m_{d_i}^2}{m_{LQ}^2}+\frac{m_{u_i}^2}{m_{LQ}^2}\right)\right]^2$$

- Using $\frac{|\lambda_{12}^{LL}\lambda_{11}^{LL\,*}|}{m_{LQ}^2} = 5.5\times 10^{-7}\ \mathrm{GeV}^{-2}$, corresponding to $\varepsilon_{e\mu} = 0.15$, for $m_{LQ} \sim \mathcal{O}(1)$ TeV, the branching ratio is

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

# LFV process $\mu^+ \to e^+ e^- e^+$

- Another important LFV mode is $\mu \to eee$, receive contributions from off-shell photons, Z-penguins and box diagrams, in addition to photonic penguins.
- The current upper limit is $\mathcal{B}(\mu \to eee) < 1.0 \times 10^{-12}$
- The relevant penguin and box diagrams are




- The branching ratio for this process in the presence of $U_3$ leptoquark is

$$\mathcal{B}(\mu \to eee) = \frac{\alpha^2 N_C^2}{96\pi^2 G_F^2}\left[\sum_{i=1}^{3} \frac{|\lambda_{i2}^{LL}\lambda_{i1}^{LL}|}{m_{LQ}^2} \log\left(\frac{m_{q_i}^2}{m_{LQ}^2}\right)\right]^2.$$

- For a TeV scale LQ, the coupling strengths, constrained by the branching ratio

$$\frac{|\lambda_{12}^{LL}\lambda_{11}^{LL}|}{m_{LQ}^2} < 1.0 \times 10^{-9}\ \mathrm{GeV}^{-2} \Longrightarrow \text{vanishingly small value for } \varepsilon_{e\mu}.$$

# Conclusion

- There is slight tension between the recent measurements of $\delta_{CP}$ by NOvA and T2K at $2\sigma$ 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 $\delta_{CP}$ by T2K and NOvA.
- In addition, we also noticed that in the 3-flavour paradigm, NOvA prefers upper octant for $\theta_{23}$, 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!