Exploration of Physics beyond the Standard Model with Neutrinos

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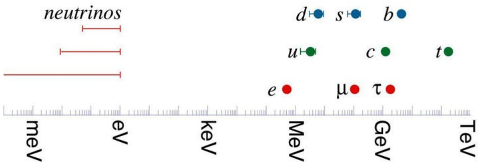
Neutrinos: What we know

- Only neutral fermions in the SM, come with three flavors $(\nu_e, \nu_\mu, \nu_\tau)$
- Flavour eigenstates are not same as mass eigenstates, leading to neutrino oscillations - have been observed
- The lightest massive particles, million times lighter than electron (No direct mass measurement yet)



Mass Generation in the SM

- In the minimal SM, neutrinos do not have mass. The gauge group is $SU(3)_C \times SU(2)_L \times U(1)_Y$
- SM Particle content: ($Q = T_3 + Y/2$)

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix} : (3,2,1/3), \quad U_R : (3,1,4/3) \quad D_R : (3,1,-2/3)$$

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} : (1,2,-1), \quad E_R : (1,1,-2)$$

$$\Phi = \begin{pmatrix} h^+ \\ (v + h^0)/\sqrt{2} \end{pmatrix} : (1,2,1), \quad v \text{ is the vev of Higgs}$$

- Quark and Charged lepton masses are from the following Yukawa couplings

$$\bar{Q}_L \tilde{\Phi} U_R, \quad \bar{Q}_L H D_R, \quad \bar{L}_L \Phi E_R,$$

- Nothing will pair up with $L_L(\nu_L) \Rightarrow$ Neutrinos are masless in SM. Extension of SM is needed for generating neutrino mass

Simplest Neutrino Mass Model

How can we add neutrino masses to the SM?

Simplest way: just replicate what we do with the other fermions.

(1) Add right-handed neutrinos:

Representation	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
ν_R	$\mathbf{1}$	$\mathbf{1}$	0

(2) Write Yukawa couplings:

$$\mathcal{L}_Y^\nu = Y_\nu \, \ell_L \widetilde{\Phi} \nu_R + \text{h.c.}$$

(3) Generate neutrino masses through the Higgs VEV:

$$\mathcal{L}_m^\nu = \mathcal{M}_\nu \, \overline{\nu}_L \nu_R + \text{h.c.}$$

However...

Seesaw Mechanism

- Master Formula: $2 \otimes 2 = 3 \oplus 1$
- Possibility I: SM gauge group: $SU(2)_L \times U(1)_Y$ with $2 \otimes 2 = 3 \oplus 1$: $\Rightarrow$

$$\bar{L}\tilde{\Phi} \sim (2,+1) \otimes (2,-1) = (1,0) \oplus (3,0)$$

- To make a singlet, couple (1,0) or (3,0), because $3 \otimes 3 = 5 \oplus 3 \oplus 1$
- Possibility II:

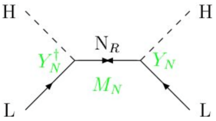
$$\bar{L}L^c \sim (2,+1) \otimes (2,+1) = (1,+2) \oplus (3,+2)$$

- To make a singlet, couple to $(1,-2)$ or $(3,-2)$.
- However, the singlet combination is $\bar{\nu}\ell^c - \bar{\ell}\nu^c$, can not generate neutrino mass term

So, the possibilities are:	$(1,0)$	or	$(3,-2)$	or	$(3,0)$
	type I		type II		type III

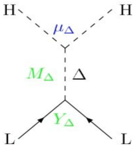
Seesaw Mechanisms

Right-handed singlet:
(type-I seesaw)



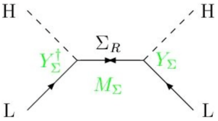
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

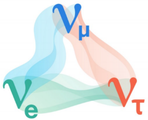
Fermion triplet:
(type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Image Courtesy: T. Hambye

Neutrino Oscillations : Three Neutrino Paradigm



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor Eigenstates

Mixing Matrix

Mass Eigenstates

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

Measured from the following neutrino sources

Solar

Reactor

Accelerator

Atmospheric

Neutrino Mixing Matrix

- 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.

$$J_{CP}^{\rm quark} \sim \mathcal{O}(10^{-5}), \qquad J_{CP}^{\rm lepton} \sim \mathcal{O}(10^{-3})$$

- δ_{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 δ_{CP}

Main Assumptions

- Neutrinos have only Standard $(V - A)$ type Interactions
- There are only three flavours of neutrinos
- The PMNS Matrix is Unitary
- No information regarding the nature of neutrinos, i.e., Dirac or Majorana
- As there are no RH neutrinos in the SM, neutrino masses cann't be generated by the standard Yukawa interactions
- They can be generated via various seesaw mechanisms
  - Type-I : Additional RH Neutrinos
  - Type-II : Additional Scalar triplets
  - Type-III : Additional Fermion triplets
- New heavy particles are inevitable for generating the tiny neutrino masses
- Since neutrinos are special, they can provide the ideal platform to explore various BSM Physics

Current unknowns

- The absolute masses of the neutrinos
- The nature of neutrinos : Dirac or Majorana
- Are there more than 3 flavours: Sterile neutrinos
- Is the PMNS matrix is unitary $\Longrightarrow$ Precise determination of mixing angles
- Mass ordering and CP phases
- Why leptonic mixing is so different from quark mixing

$$V_{CKM} = \begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2, \quad U_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

- The origin of neutrino masses and mixing at a more fundamental level : Beyond Standard Model
- Do neutrinos have Non-standard Interactions ? Is there violation of fundamental symmetries like CPT, Lorentz Invariance, etc.
- Neutrinos give a new perspective on Physics BSM.

New Physics prospects from Neutrino experiments

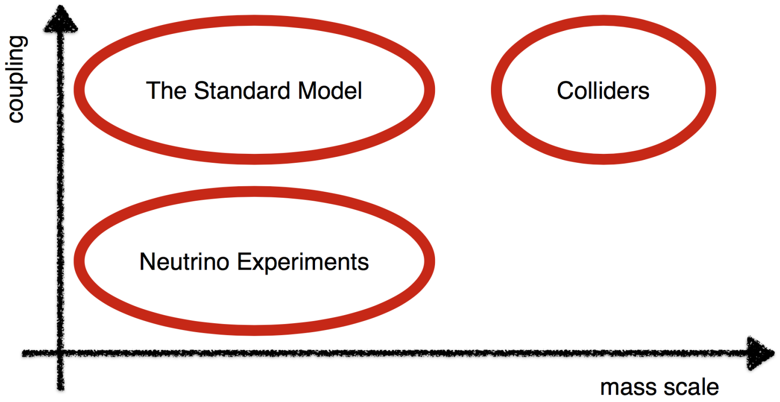
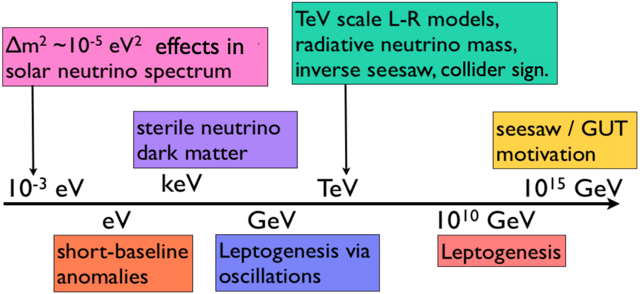


Fig. Courtesy: P. Machado

Sterile Neutrinos: A very simple extension of the SM

- Fermionic singlets under the SM gauge group : Sterile Neutrinos, Right-handed Neutrinos, Heavy Neutral Leptons
- Interact with the SM leptons though Yukawa: $\mathcal{L}_Y = -Y\bar{L}_L\tilde{\phi}N_R + \text{h.c.}$ (How Many ?)
- Majorana Mass term : $\frac{1}{2}\overline{N_R^c}M_R N_R + \text{h.c.}$ (At which mass scale, M_R is not related to Higgs vev)



Number of light neutrino flavours

- The most precise determination of the No. of light neutrino species is obtained from measurements of the visible cross-sections of e^+e^- annihilation at and around the Z resonance,

- The decay modes of Z^0 are :

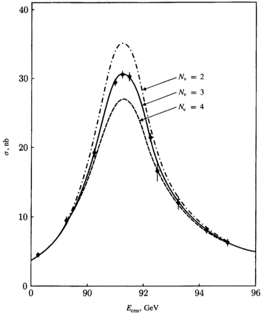
$$Z^0 \to q\bar{q},\ \ell^+\ell^-,\ \nu_\alpha\bar{\nu}_\alpha$$

- The observed width gives for the number of flavours

$$N_\nu = 2.99 \pm 0.01$$

- From Cosmology

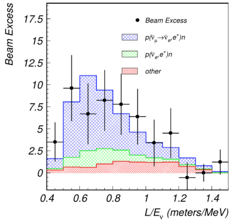
$$N_\nu = 3.0440 \pm 0.0002$$



Dawn of Sterile Neutrino Era: LSND Experiment

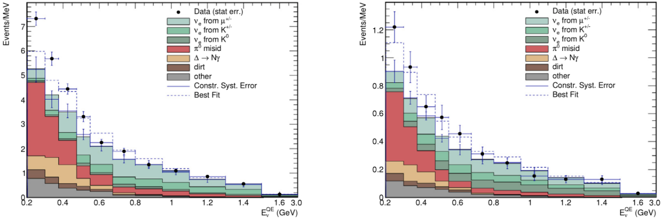
- LSND expt was in operation during (1993-1998) at LANL to look for ν oscillation
- The neutrino flux arises from stopped $\pi^+ \to \nu_\mu \mu^+$ decay followed by $\mu^+ \to \bar{\nu}_\mu \nu_e e^+$, while the π^- were rapidly absorbed by nuclei without producing neutrinos.
- LSND beam was composed of ν_μ, $\bar{\nu}_\mu$ and ν_e without any $\bar{\nu}_e$, making it ideally suited for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation search
- $L/E \sim 1$ m/MeV to probe $\Delta m^2 \sim 1\ \mathrm{eV}^2$

- LSND Expt: Observed an excess of 3.8σ in $\bar{\nu}_e$ events over the backgrounds
- Explanation for this excess in terms of oscillations between SM neutrinos and extra, sterile neutrinos with $\Delta m^2 \approx 1\mathrm{eV}^2$



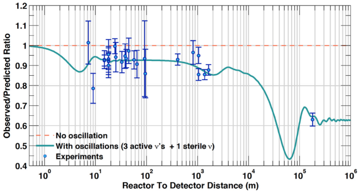
MiniBooNe Anomaly

- The MiniBooNE experiment is designed to test the LSND signal within the two massive neutrino oscillation hypothesis.
- However, ν_μ ad $\bar{\nu}_\mu$ neutrinos are now made by pion DIF at the Fermilab Booster neutrino beamline, and the baseline is 541 m (MiniBooNE can test 1 eV sterile neutrino hypothesis, because of similar L/E with LSND)
- MiniBooNE observed 3.4σ (2.8σ) excess events in ν_e $(\bar{\nu}_e)$ appearance channels



Reactor Anomaly

- Nuclear reactors have been used as neutrino sources ever since the Reines & Cowan experiment that first provided experimental evidence for the existence of neutrinos
- There are large number of SBL experiments with baselines ($\lesssim 100$ m), where no oscillations are expected in the standard three-flavor oscillation
- A discrepancy of 3σ is found, known as the reactor anti-neutrino anomaly



- A new analysis finds that discrepancies between reactor neutrino experiments and theory may be the result of errors in the analysis of electron data (PRL 130, 021801 (2023))

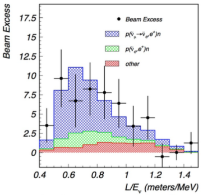
Recent results from MicroBoone

- Recent MicroBooNE results : there is no excess of ν_e events coming from the ν_μ beam.
- Denton, studied the same set of MicroBooNE data and showed that an analysis with the electron disappearance channel is consistent with oscillations governed by sterile neutrinos (PRL 129 (2022) 6, 061801).
- In reply to that, MicroBooNE performed a joined fit taking the ν_e appearance and ν_e disappearance channel and showed that three neutrino fit still gives a better fit than four neutrino fit at 1σ
- In addition, a combined fit of MiniBooNE and MicroBooNE shows that the 3+1 model is still allowed at a significant confidence level
- On the other hand, the atmospheric data from the IceCube experiment is consistent with the no sterile neutrino hypothesis
- The gallium-based experiment BEST and reactor based experiment Neutrino-4 recently reported a positive signal for a light sterile neutrino.

Summary of short-baseline Anomalies

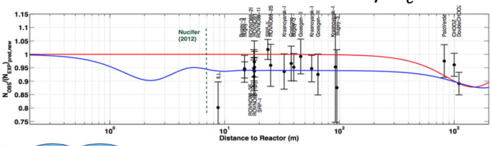
Short Baseline Anomalies

LSND $\bar{\nu}_e$ **Excess**



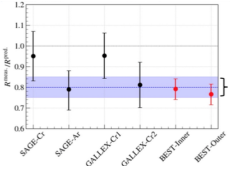
Phys.Rev. D64:112007 (2001)

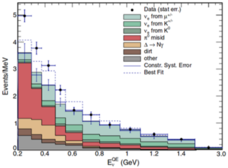
"Reactor Anomaly" $\bar{\nu}_e$ **deficit**



Hint oscillation from additional
"Sterile" neutrino(s)
$m_4 \sim 1\text{eV}$

"Gallium Anomaly"
solar ν_e **deficit**





MiniBooNE
$\nu_e/\bar{\nu}_e$ **Excess**
at low energy

@ Fermilab
On-axis of Booster neutrino beamline

3

3+1 Neutrino Oscillation Framework

- In the presence of a single sterile neutrino ν_s

$$\begin{pmatrix} \nu_{e1} & \nu_{e2} & \nu_{e3} \\ \nu_{\mu 1} & \nu_{\mu 2} & \nu_{\mu 3} \\ \nu_{\tau 1} & \nu_{\tau 2} & \nu_{\tau 3} \end{pmatrix} \Longrightarrow \begin{pmatrix} \nu_{e1} & \nu_{e2} & \nu_{e3} & \nu_{e4} \\ \nu_{\mu 1} & \nu_{\mu 2} & \nu_{\mu 3} & \nu_{\mu 4} \\ \nu_{\tau 1} & \nu_{\tau 2} & \nu_{\tau 3} & \nu_{\tau 4} \\ \nu_{s1} & \nu_{s2} & \nu_{s3} & \nu_{s4} \end{pmatrix}$$

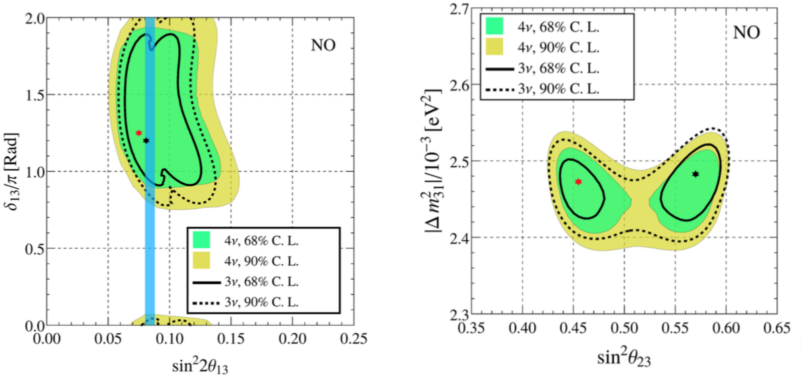
- To parametrize the 4×4 unitary matrix, we need 6 mixing angles (additional $\theta_{14},\ \theta_{24},\ \theta_{34}$) and three CP violating phases ($\delta_{13},\ \delta_{14},\ \delta_{24}$)
- In the limit $\Delta m^2_{31},\ \Delta m^2_{21} \to 0$, the appearance and disappearance probability becomes

$$P^{\mathrm{SBL}}_{\alpha\beta} \approx \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right); \qquad \sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

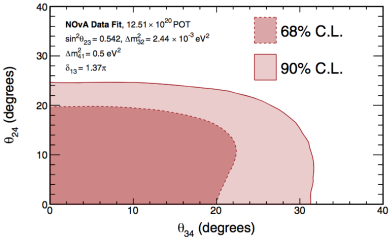
$$P^{\mathrm{SBL}}_{\alpha\alpha} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right); \qquad \sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

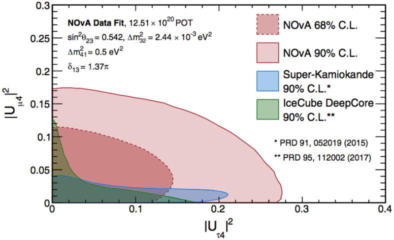
Hints for Light sterile neutrinos from NOvA and T2K

(2005.10338)



Hints for Light sterile neutrinos from NOvA (PRL 127, 201801 (2023))





Hints for Sterile Neutrinos from Flavour sector : $B^+ \to K^+ \nu\bar{\nu}$ Measurement (2311.14647)

- Recently Belle II reported the BR for $B^+ \to K^+ \nu\bar{\nu}$ using 362 fb^{-1} data with Hadronic and Inclusive Tagging

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})) \times 10^{-5}$$

  which has 2.7σ deviation with the SM result.

- Combining this with previous data gives the new world average:

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (1.3 \pm 0.4) \times 10^{-5}$$

- Precise SM prediction, does not suffer much from hadronic uncertainties

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6} \quad (\mathrm{HPQCD\ Collab})$$

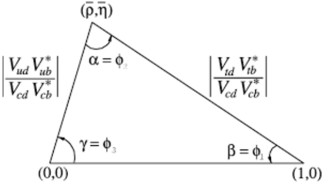
  including the long distance contributions $(0.61 \pm 0.06) \times 10^{-6}$.

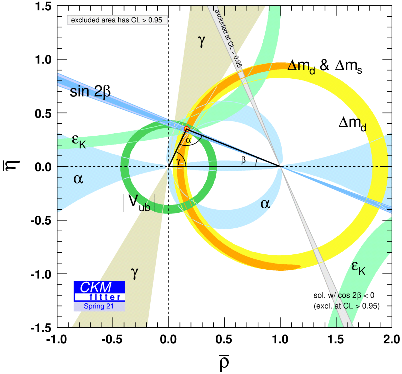
- Attractive scenarios: Additional decay channels with undetected final states, e.g., sterile neutrinos, dark matter, long-lived particles
- Light sterile neutrinos are well motivated and occur numerous minimal extension of SM

Non-unitarity of Neutrino Mixing Matrix

- The unitarity condition of CKM matrix:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$





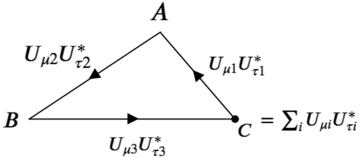
- $s_{12} = 0.225,\ s_{23} = 0.043,\ s_{13} = 0.0037,\ \delta_{CP} = 0.364\pi$ (CKM)
  $s_{12} = 0.55,\ s_{23} = 0.73,\ s_{13} = 0.15,\ \delta_{CP} \sim 1.23\pi$ (PMNS)

No direct way to constrain the Unitarity triangle in lepton sector

Unitarity Triangle in the Lepton sector

- Unitarity triangles are key to access CP violation
- Neutrino oscillation experiments can provide direct tests of LMM unitarity.
- The Unitarity conditions $U^\dagger U = UU^\dagger = I$ gives

$$\sum_i U_{\alpha i} U^*_{\beta i} = 0, \qquad \sum_\alpha U_{\alpha i} U^*_{\alpha j} = 0$$



- Rescaling the sides one can have vertices at the origin, (1,0) and (ρ_{xy}, η_{xy})

$$\rho_{xy} + i\eta_{xy} = -\frac{U_{xi}U^*_{yi}}{U_{xj}U^*_{yj}}$$

$$\rho_{12} = \frac{c_{13}^2}{4}\left(\frac{\sin^2 2\theta_{12}\left(c_{23}^2 - s_{13}^2 s_{23}^2\right) + 4\cos 2\theta_{12}\Delta\cos\delta_{\rm CP}}{\left(s_{12}^2 c_{23}^2 + c_{12}^2 s_{13}^2 s_{23}^2 + 2\Delta\cos\delta_{\rm CP}\right)\left(c_{12}^2 c_{23}^2 + s_{12}^2 s_{13}^2 s_{23}^2 - 2\Delta\cos\delta_{\rm CP}\right)}\right) ,$$

$$\eta_{12} = -c_{13}^2 \frac{\Delta\sin\delta_{\rm CP}}{\left(s_{12}^2 c_{23}^2 + c_{12}^2 s_{13}^2 s_{23}^2 + 2\Delta\cos\delta_{\rm CP}\right)\left(c_{12}^2 c_{23}^2 + s_{12}^2 s_{13}^2 s_{23}^2 - 2\Delta\cos\delta_{\rm CP}\right)} ,$$

$$\rho_{13} = \frac{1}{2}\left(\frac{2s_{23}^2\left(s_{12}^2 - s_{13}^2 c_{12}^2\right) - t_{23} s_{13}\sin 2\theta_{12}\cos 2\theta_{23}\cos\delta_{\rm CP}}{s_{12}^2 s_{23}^2 + c_{12}^2 s_{13}^2 c_{23}^2 - 2\Delta\cos\delta_{\rm CP}}\right) ,$$

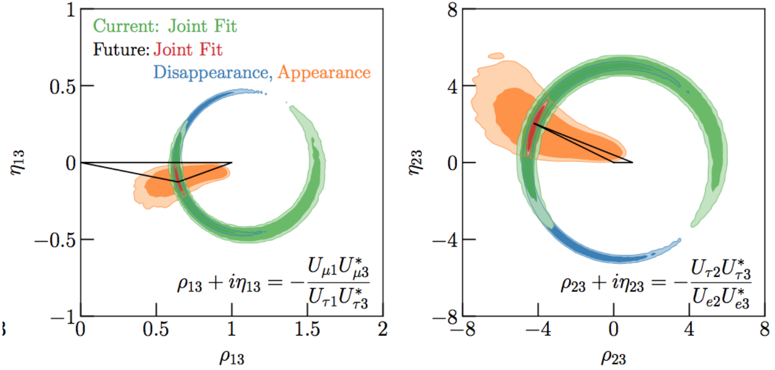
$$\eta_{13} = \frac{1}{2}\left(\frac{t_{23} s_{13}\sin 2\theta_{12}\sin\delta_{\rm CP}}{s_{12}^2 s_{23}^2 + c_{12}^2 s_{13}^2 c_{23}^2 - 2\Delta\cos\delta_{\rm CP}}\right) ,$$

$$\rho_{23} = c_{23}^2\left(1 + \frac{t_{23}\cos\delta_{\rm CP}}{t_{12} s_{13}}\right) ,$$

$$\eta_{23} = -c_{23}^2\left(\frac{t_{23}\sin\delta_{\rm CP}}{t_{12} s_{13}}\right) ,$$

where $4\Delta = s_{13}\sin 2\theta_{12}\sin 2\theta_{23}$.

Rep. LMM Unitarity Trangle (2004.13719)



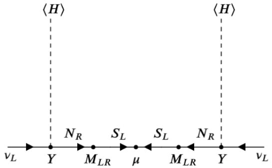
Non-unitarity of Neutrino Mixing Matrix

- A generic characteristic of most models explaining the neutrino mass pattern is the presence of heavy neutrino states
- In the low-scale seesaw like Inverse seesaw the heavy neutrinos could be in the TeV scale
- The SM is extended by three RH (N_{R_i}) and three sterile (S_{Li}) singlet neutrinos
- The Yukawa interaction becomes

$$-\mathcal{L}_{inverse} = Y\bar{N}_R LH + M_{LR}\bar{N}_R S_L + \mu \bar{S}_L^c S_L + h.c.$$

- The mass matrix for inverse seesaw is

$$M_{inverse} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_{LR} \\ M_{LS}^T & M_{LR}^T & \mu \end{pmatrix}$$



- The mass formula for light neutrinos for $\mu \ll m_D \ll M_R$

$$m_{inv} = m_D^T (M_{LR}^T)^{-1} \mu M_{LR}^{-1} m_D + h.c \sim \frac{v^2}{M_{LR}^2}\mu$$

- These additional heavy leptons would mix with the light neutrino states
- As a result, the complete unitary mixing matrix would be a squared $n \times n$ matrix, (n being the total no. of neutrino states)

$$U^{n\times n} = \begin{pmatrix} N & S \\ V & T \end{pmatrix}$$

- N and V describe the mixing between light and heavy states, T contains the mixing among the heavy states
- Hence, the usual 3×3 PMNS matrix (N) will be non-unitary:

$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

- The oscillation probability for $\nu_\alpha \to \nu_\beta$ becomes

$$P_{\alpha\beta} = |(NN^\dagger)_{\alpha\beta}|^2 - 4\sum_{k>j} \Re[N^*_{\alpha k} N_{\beta k} N_{\alpha j} N^*_{\beta j}] \sin^2\left(\frac{\Delta m^2_{kj}}{L} 4E\right)$$

$$+ 2\sum_{k>j} \Im[N^*_{\alpha k} N_{\beta k} N_{\alpha j} N^*_{\beta j}] \sin^2\left(\frac{\Delta m^2_{kj}}{L} 4E\right)$$

- The first term depends only on the values of the α parameters $\Longrightarrow$ in presence of nonunitary neutrino mixing, a zero-distance flavor conversion is possible.
- For short-baseline experiments

$$P_{\mu e}^{\mathrm{SBL}} = \alpha_{11}^2 |\alpha_{21}|^2$$

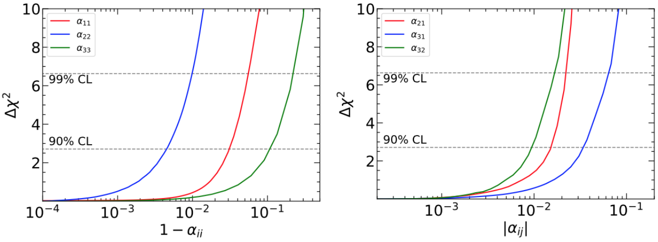
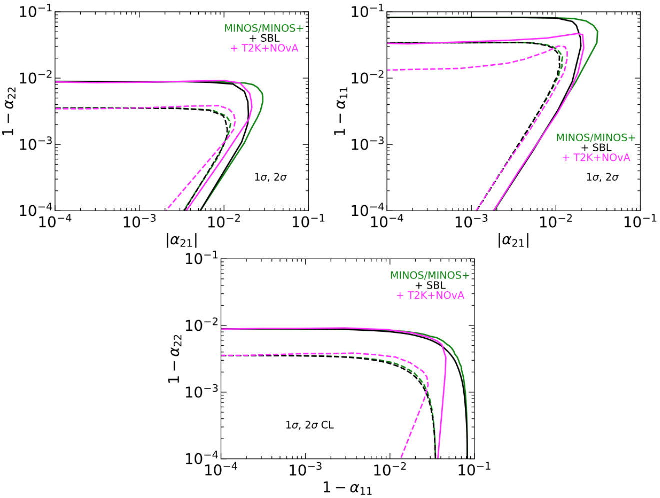


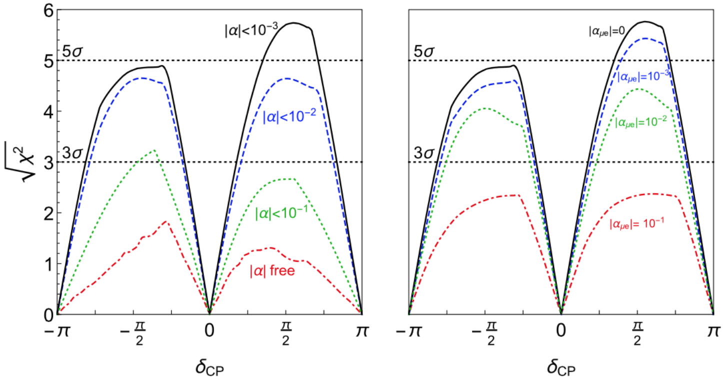
Figure: $\Delta\chi^2$ profiles for the diagonal and nondiagonal nonunitarity parameters obtained from the combined analysis of short and long-baseline neutrino oscillation data. PRD 104, 075030 (2021)

Allowed regions of Nonunitarity parameters



Impact of Non-unitarity on CPV sensitivity of DUNE

(2008.12769)



Allowed regions for DUNE (2008.12769)

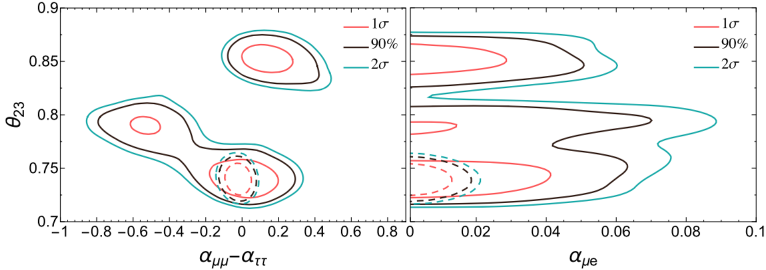


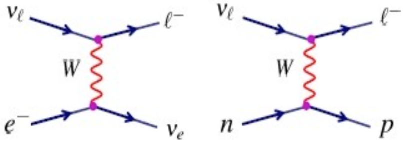
Figure: The solid lines correspond to the analysis of DUNE data alone, while the dashed lines include the present constraints on non-unitarity.

New Physics Effects: Non-Standard Interactions

- The existence of small neutrino mass by itself is a clear signature of New Physics
- Various neutrino mass models proposed to explain ν masses and mixing
- These neutrino mass models come in various categories, e.g.,
  - Familiar seesaw mechanism
  - Radiative mass generation due to presence of extra Higgs
- Structure of the SM electroweak CC and NC interactions affected by these mechanisms
- In the low-energy limit, these effects are known as NSIs, usually generated by the exchange of new massive particles
- NSIs are parametrized in terms of small parameter ε and are $\mathcal{O}(M_W^2/M_{NP}^2)$ and opens the possibility to test neutrino oscillation facilities

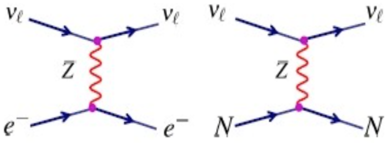
Neutrino Interactions in the SM

- Neutrinos interact with other SM fermions by both CC and NC interactions:
- CC Interaction



Vertex $\propto \frac{g}{\sqrt{2}}\gamma^\mu(1-\gamma_5)$

- NC Interaction



Vertex $\propto \frac{g}{\cos\theta_W}\gamma^\mu(c_V^f - c_A^f\gamma_5)$
where $c_V^f = T_f^3 - 2\sin^2\theta_W Q_f$
and $c_A^f = T_3^f$

Non-Standard Interactions

- Non-Standard interactions (NSIs): Sub-leading effects in neutrino oscillation
- NSI effects may appear at three different states in an expt.
  - Neutrino Production and detection (CC NSIs)
    e.g., $\pi^+ \to \mu^+ + \nu_e$ (Source) $\nu_e + n \to p + \mu^+$ (Detector)
  - Neutrino propagation from source to detector (NC NSIs)
- The Lagrangian for CC and NC interactions:

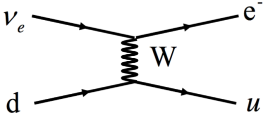
$$\mathcal{L}_{\rm CC-NSI} = -\frac{G_F}{\sqrt{2}} \sum_{f,f'} \varepsilon^{ff'}_{\alpha\beta} [\bar{\nu}_\beta \gamma^\mu (1-\gamma_5) \ell_\alpha][\bar{f}' \gamma_\mu (1 \pm \gamma_5) f]$$

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

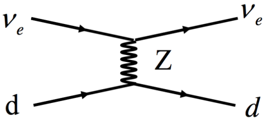
- CC NSIs are important for SBL/Reactor experiments, while NC NSIs are crucial for LBL/Accelerator expts.

Schematic Representation of NSIs

- In the Standard Model,



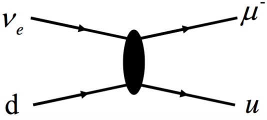
$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma_\mu P_L f')$$



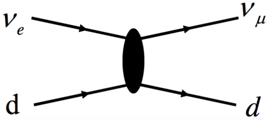
$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma_\mu P_L f')$$

- With new physics, we could have

$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$



$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$



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:

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

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

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

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

Simple Model to generate $\varepsilon_{\alpha\beta}$ (1608.04719)

- Enlarge the SM particle content by two scalars

$$\eta \sim (1,1,1/2)\,, \quad \phi^- \sim (1,1,-1)$$

- These scalar are odd under Z_2 symmetry along with e_R and rest SM particles are even
- To realize NSI, couple SM lepton doublet L_α and e_R through η

$$\mathcal{L}_{int} \supset \lambda_\alpha \overline{L_\alpha} \eta e_R + \text{h.c.}$$

- Neglecting $\eta - \phi$ mixing, the effective $d = 6$ operator after integrating out heavy η

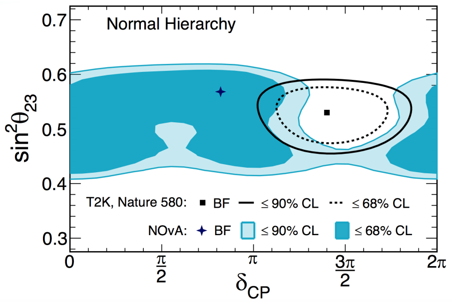
$$\mathcal{L} \supset \frac{\lambda_\alpha \lambda^*_\beta}{m^2_\eta} (\bar{\nu}_\alpha e_R)(\bar{e}\nu_\beta) = -\frac{\lambda_\alpha \lambda^*_\beta}{2m^2_\eta} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\overline{e_R}\gamma_\mu e_R)$$

- Comparing with the CC mediated W boson interaction

$$\mathcal{L} = -2\sqrt{2} G_F (\bar{\nu}_e \gamma^\mu e_L)(\overline{e_R}\gamma_\mu \nu_e) = -2\sqrt{2} G_F (\bar{\nu}_e \gamma^\mu \nu_e)(\bar{e}_L \gamma_\mu e_L)$$

$$\Longrightarrow \varepsilon^\eta_{\alpha\beta} = \frac{\lambda_\alpha \lambda^*_\beta}{4\sqrt{2} m^2_\eta G_F}$$

NOvA and T2K results on δ_{CP}: Hints for NSI



- 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 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

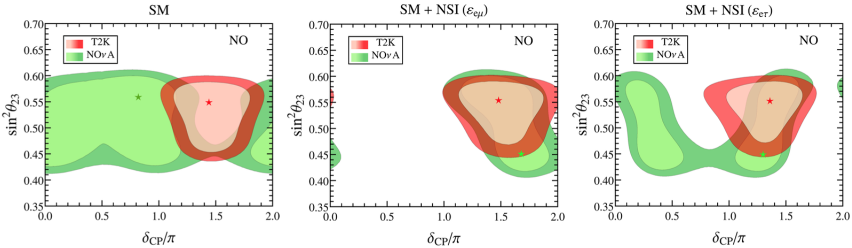
T2K Experiment

- 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 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



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

Model dependent approach: Leptoquark Model (2205.04269)

- Leptoquarks are color-triplet bosons which can couple to quarks and leptons simultaneously
- 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 $SU(3) \times SU(2) \times U(1)$
- The three charged states are: $(Q = T_3 + Y)$

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

- 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

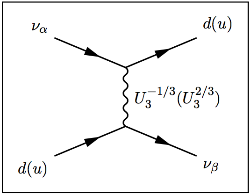
$$\mathcal{L} \supset \lambda_{ij}^{LL} \overline{Q}_L^{i,a} \gamma^\mu (\tau^k \cdot U_{3,\mu}^k)^{ab} L_L^{j,b} + \mathrm{H.c.},$$

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

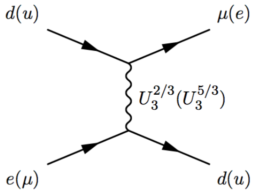
$$\varepsilon_{\alpha\beta}^{uL} = \frac{1}{2\sqrt{2}G_F}\frac{1}{m_{\rm LQ}^2}\lambda_{1\beta}^{LL}\lambda_{1\alpha}^{LL}\ , \quad \text{and} \quad \varepsilon_{\alpha\beta}^{dL} = \frac{1}{\sqrt{2}G_F}\frac{1}{m_{\rm LQ}^2}\lambda_{1\beta}^{LL}\lambda_{1\alpha}^{LL}\ .$$

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

Constraints on LQ couplings from LFV decays

- 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

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



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

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

- These bounds can be translated into NSI couplings as

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

Addressing NOvA and T2K discrepancy on δ_{CP}

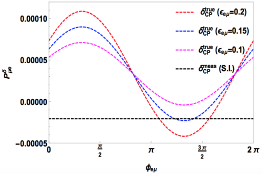
- General Approach: Accurately measure the $P_{\mu e}$ and compare with prediction
- Any mismatch between data and prediction $\Longrightarrow$ Interplay of NP

- 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

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



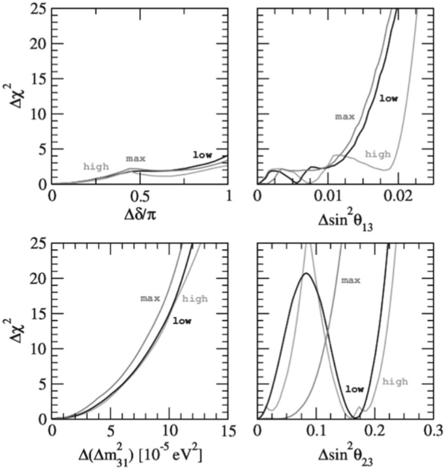
- $\varepsilon_{e\mu} \geq 0.15$, there will be degeneracy between SI and NSI $P_{\mu e}$

CPT and Lorentz violation

- CPT invariance is one of the most fundamental symmetries in nature
- No definitive signal of CPT violation has been observed so far
- Neutrino experiments are expected to provide more stringent bounds on CPT invariance violation when compared to the existing bounds from the Kaon system.
- There exist experimental limits on CPT violating parameters from kaon and the lepton sectors.
- However, the current neutrino oscillation data provides the most stringent constraints on various oscillation parameters:

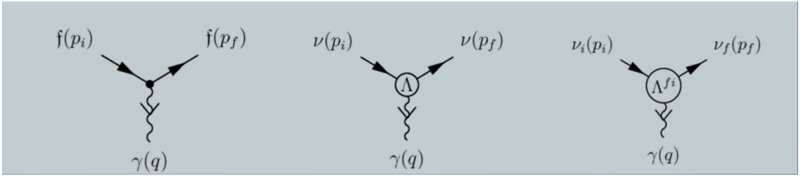
$$
\begin{aligned}
|\Delta m^2_{21} - \Delta \overline{m}^2_{21}| &< 4.7 \times 10^{-5}\ \mathrm{eV}^2, \\
|\Delta m^2_{31} - \Delta \overline{m}^2_{31}| &< 2.5 \times 10^{-4}\ \mathrm{eV}^2, \\
|\sin^2 \theta_{12} - \sin^2 \overline{\theta}_{12}| &< 0.14, \\
|\sin^2 \theta_{13} - \sin^2 \overline{\theta}_{13}| &< 0.029, \\
|\sin^2 \theta_{23} - \sin^2 \overline{\theta}_{23}| &< 0.19.
\end{aligned}
$$

Sensitivities of DUNE to the diff of ν and $\bar{\nu}$ parameters



Electromagnetic properties of neutrinos

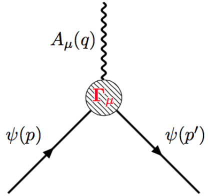
- Exploring EM properties of neutrinos provides an interesting avenue to explore BSM
- They are electrically neutral, so do not couple to γ at tree level, but such ints. can be generated at loop level
- Neutrino em properties can be used to distinguish Dirac and Majorana neutrinos



Neutrino Magnetic moment

- Neutrinos can have electromagnetic interaction at loop level
- The effective interaction Lagrangian

$$\mathcal{L}_{\mathrm{EM}} = \overline{\psi}\Gamma_\mu \psi A^\mu = J_\mu^{EM} A^\mu$$



- The matrix element of J_μ^{EM} between the initial and final neutrino mass states

$$\langle \psi(p')|J_\mu^{EM}|\psi(p)\rangle = \bar{u}(p')\Gamma_\mu(p', p)u(p)$$

- Lorentz invariance implies Γ_μ takes the form

$$\Gamma_\mu(p,p') = f_Q(q^2)\gamma_\mu + if_M(q^2)\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

$f_Q(q^2)$, $f_M(q^2)$, $f_E(q^2)$ and $f_A(q^2)$ are the form factors of charge, magnetic dipole, electric dipole and anapole respectively.

Magnetic moment in minimal extended SM

- For Dirac neutrinos:

$$\left\{\begin{matrix} \mu_{ij}^D \\ \epsilon_{ij}^D \end{matrix}\right. = \frac{eG_F}{8\sqrt{2}\pi^2}(m_i \pm m_j) \sum_{l=e,\mu,\tau} f(x_l) U_{li}^* U_{lj}, \qquad x_l = m_l^2/m_W^2$$

- For small $x_l \ll 1, \quad f(x) \simeq = 3/2\,(1 - x/2)$:

$$\mu_{ii}^D \simeq \frac{3eG_F m_i}{8\sqrt{2}\pi^2}\left(1 - \frac{1}{2}\sum_{l=e,\mu,\tau} x_l |U_{li}|^2\right) \simeq 3.2 \times 10^{-19}\left(\frac{m_i}{eV}\right)\mu_B$$

- For the Majorana neutrinos both electric and magnetic diagonal moments vanish (matrix is antisymmetric)

$$\mu_{ii}^M = \epsilon_{ii}^M = 0$$

Neutrino Transition moments

- Neutrino transition moments are off-diagonal elements of

$$\begin{cases} \mu_{ij}^D \\ \epsilon_{ij}^D \end{cases} \simeq -\frac{3eG_F}{32\sqrt{2}\pi^2}(m_i \pm m_j) \sum_{l=e,\mu,\tau} \left(\frac{m_l}{m_W}\right)^2 U_{li}^* U_{lj}, \quad \text{for } i \neq j$$

- The transition moments are suppressed wrt diagonal moments

$$\begin{cases} \mu_{ij}^D \\ \epsilon_{ij}^D \end{cases} \simeq -4 \times 10^{-23} \left(\frac{m_i \pm m_j}{eV}\right) f_{ij} \mu_B$$

- For Majorana neutrinos transition moments may be non-vanishing
- When ν_i and ν_j have opposite CP phase

$$\mu_{ij}^M = -\frac{3eG_F m_i}{16\sqrt{2}\pi^2} \left(1 + \frac{m_j}{m_i}\right) \sum_{l=e,\mu,\tau} Im(U_{li}^* U_{lj}) \frac{m_l^2}{m_W^2}$$

- Thus we get: $\boxed{\mu_{ij}^M = 2\mu_{ij}^D}$

Neutrino-electron elastic scattering

- Most widely used method to determine ν magnetic moment is $\nu + e^- \rightarrow \nu + e^-$

$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{SM}} = \frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{T_e}{E_\nu}\right)^2 + (g_A^2-g_V^2)\frac{m_e T_e}{E_\nu^2}\right]$$

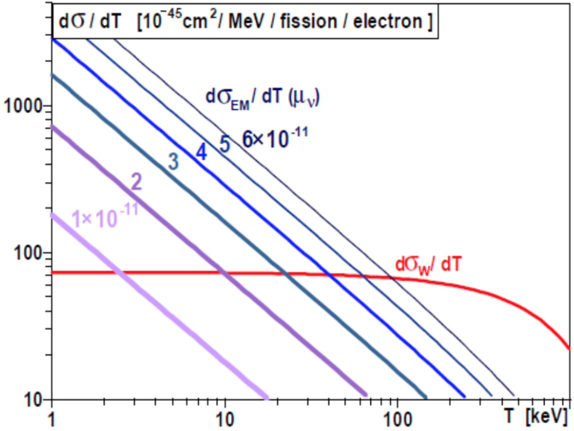
- The $\nu - e$ EM cross section

$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{EM}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_{eff}}{\mu_B}\right)^2$$

- The cross sections are added incoherently

$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{Tot}} = \left(\frac{d\sigma}{dT_e}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT_e}\right)_{\mathrm{EM}}$$

- For low-T_e : EM X-sec will increase ($\propto \frac{1}{T_e}$)



dσ / dT [10^-45 cm^2 / MeV / fission / electron]
dσ_EM / dT (μ_ν)
6×10^-11
5
4
3
2
1×10^-11
dσ_W / dT
1000
100
10
1
10
100
T [keV]

Simple Model with vector-like scalar triplet (2306.14801)

- SM is extended with three vector-like fermion triplets Σ_k, with $k = 1, 2, 3$ and two inert scalar doublets η_j, with $j = 1, 2$.

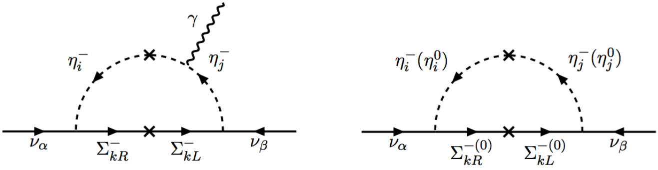
	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
Leptons	$\ell_L = (\nu, e)_L^T$	$(\mathbf{1}, \mathbf{2}, \ -1/2)$	$+$
	e_R	$(\mathbf{1}, \mathbf{1}, \ -1)$	$+$
	$\Sigma_{k(L,R)}$	$(\mathbf{1}, \mathbf{3}, 0)$	$-$
Scalars	H	$(\mathbf{1}, \mathbf{2}, \ 1/2)$	$+$
	η_j	$(\mathbf{1}, \mathbf{2}, \ 1/2)$	$-$

- The $SU(2)_L$ triplet $\Sigma_{L,R} = \left(\Sigma^1, \Sigma^2, \Sigma^3\right)_{L,R}^T$ can be expressed in the fundamental representation as

$$\Sigma_{L,R} = \frac{\sigma^a \Sigma^a_{L,R}}{\sqrt{2}} = \begin{pmatrix} \Sigma^0_{L,R}/\sqrt{2} & \Sigma^+_{L,R} \\ \Sigma^-_{L,R} & -\Sigma^0_{L,R}/\sqrt{2} \end{pmatrix}.$$

- The Lagrangian terms of the model is given by

$$\mathcal{L}_\Sigma = y'_{\alpha k}\overline{\ell_{\alpha L}}\Sigma_{kR}\tilde{\eta}_j + y_{\alpha k}\overline{\ell^c_{\alpha L}} i\sigma_2 \Sigma_{kL}\eta_j + \frac{i}{2}\mathrm{Tr}[\overline{\Sigma}\gamma^\mu D_\mu \Sigma] - \frac{1}{2}\mathrm{Tr}[\overline{\Sigma} M_\Sigma \Sigma] + \mathrm{h.c.}$$

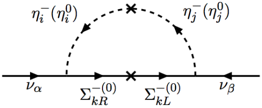


- The νMM arises from one-loop diagram

$$(\mu_\nu)_{\alpha\beta} = \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{8\pi^2} M_{\Sigma_k^+} \left[(1+\sin 2\theta_C)\frac{1}{M_{C2}^2}\left(\ln\left[\frac{M_{C2}^2}{M_{\Sigma_k^+}^2}\right] - 1\right) + (1-\sin 2\theta_C)\frac{1}{M_{C1}^2}\left(\ln\left[\frac{M_{C1}^2}{M_{\Sigma_k^+}^2}\right] - 1\right)\right]$$

Neutrino Mass

- Contribution to neutrino mass can arise at one-loop: with charged/neutral scalars and fermion triplet in the loop



$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{32\pi^2} M_{\Sigma_k^+} \Bigg[(1+\sin 2\theta_C) \frac{M_{C2}^2}{M_{\Sigma_k^+}^2 - M_{C2}^2} \ln\left(\frac{M_{\Sigma_k^+}^2}{M_{C2}^2}\right) + (1-\sin 2\theta_C) \frac{M_{C1}^2}{M_{\Sigma_k^+}^2 - M_{C1}^2} \ln\left(\frac{M_{\Sigma_k^+}^2}{M_{C1}^2}\right) \Bigg]$$
$$+ \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{32\pi^2} M_{\Sigma_k^0} \Bigg[(1+\sin 2\theta_R) \frac{M_{R2}^2}{M_{\Sigma_k^0}^2 - M_{R2}^2} \ln\left(\frac{M_{\Sigma_k^0}^2}{M_{R2}^2}\right) + (1-\sin 2\theta_R) \frac{M_{R1}^2}{M_{\Sigma_k^0}^2 - M_{R1}^2} \ln\left(\frac{M_{\Sigma_k^0}^2}{M_{R1}^2}\right) \Bigg]$$
$$- \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{32\pi^2} M_{\Sigma_k^0} \Bigg[(1+\sin 2\theta_I) \frac{M_{I2}^2}{M_{\Sigma_k^0}^2 - M_{I2}^2} \ln\left(\frac{M_{\Sigma_k^0}^2}{M_{I2}^2}\right) + (1-\sin 2\theta_I) \frac{M_{I1}^2}{M_{\Sigma_k^0}^2 - M_{I1}^2} \ln\left(\frac{M_{\Sigma_k^0}^2}{M_{I1}^2}\right) \Bigg].$$

Conclusion

- Neutrino Experiments provide unique platform to explore variety of New Physics
- Hopefully, we will get some interesting NP signals from the upcoming long-baseline expts.

Thank you for your attention !