Exploring Physics beyond the Standard Model with Neutrinos

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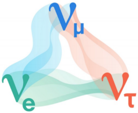
Neutrinos: What we know

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



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

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.

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

- 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}

Current values of Neutrino Oscillation Parameters

NuFIT 5.2 (2022)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{\rm CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

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

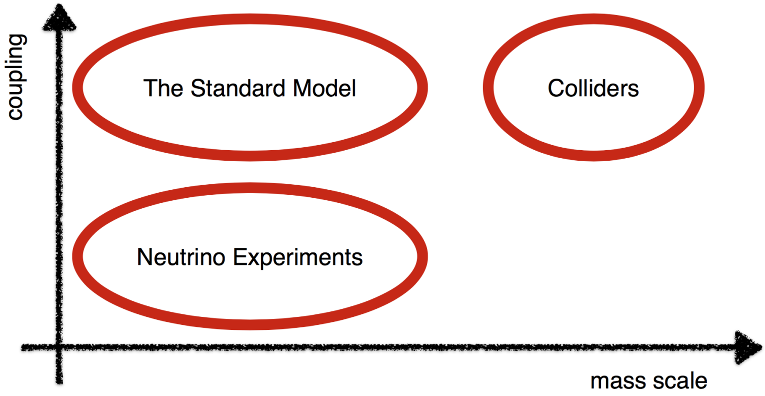
Open Windows on Physics beyond the SM

- Neutrinos give a new perspective on Physics BSM.
- Origin of masses: Why neutrinos have mass and why are they so lighter.
- Why their hierarchy is at most mild
- Problem of flavour:

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

- Why leptonic mixing is so different from quark mixing
- This information is complementary with the one from flavour physics experiments and from colliders.

New Physics prospects from Neutrino experiments



[Fig. Courtesy: P. Machado]

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
- NSIs are parametrized in terms of $\varepsilon \sim \mathcal{O}(M_W^2/M_{NP}^2)$ and open the possibility to test neutrino oscillation facilities
- NSI effects may appear at three different stages in an expt:
  (i) neutrino production, e.g., $\pi^+ \to \mu^+ + \nu_e$ (source)
  (ii) neutrino propagation from the source to the detector
  (iii) neutrino detection e.g., $\nu_e + n \to p + \mu^-$ (detector)

$$\mathcal{L}_{\mathrm{CC-NSI}} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \varepsilon_{\alpha\beta}^{s,d\ ff'} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma_5) l_\alpha\right] \left[\bar{f}' \gamma_\rho (1 \pm \gamma_5) f\right]$$

$$\mathcal{L}_{\mathrm{NC-NSI}} = \frac{G_F}{\sqrt{2}} \sum_{f} \varepsilon_{\alpha\beta}^{m\ ff} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma_5) \nu_\alpha\right] \left[\bar{f} \gamma_\rho (1 \pm \gamma_5) f\right]$$

- Charged Current NSIs: Detection and Production process.
- Neutral Current NSIs: Neutrino propagation.

Basic formalism of NSI

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

$$\begin{aligned} \mathcal{H}_{SM} &= \mathcal{H}_0 + \mathcal{H}_{\rm matter} \\ &= \frac{1}{2E} U \cdot {\rm diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \cdot U^\dagger + {\rm diag}(V_{CC}, 0, 0) \end{aligned}$$

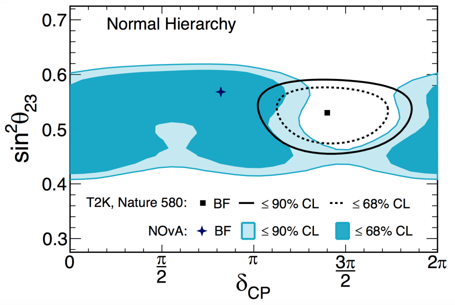
- The NSI Hamiltonian

$$\boxed{\mathcal{H}_{NSI} = V_{CC} \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}} \qquad \text{where} \qquad \varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| e^{i\delta_{\alpha\beta}}$$

- Diagonal elements correspond to LFU violation interations.
- Off-diagonal elements correspond to LFV interactions.
- Neutrino oscillation probability in presence of NSI is given by

$$\boxed{P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | e^{-i(\mathcal{H}_{SM} + \mathcal{H}_{NSI})L} | \nu_\alpha \rangle|^2.}$$

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

Model dependent approach: Leptoquark Model (2205.04269)

- 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:

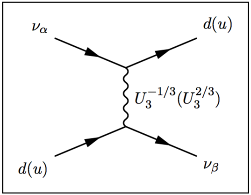
$$\boxed{U_3^{5/3} = (U_3^1 - iU_3^2)/\sqrt{2}, \quad U_3^{-1/3} = (U_3^1 + iU_3^2)/\sqrt{2}, \quad U_3^{2/3} = U_3^3}$$

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

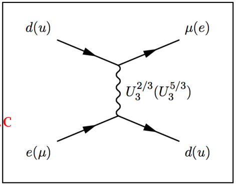
$$\varepsilon_{\alpha\beta}^{uL} = \frac{1}{2\sqrt{2}G_F}\frac{1}{m_{\rm LQ}^2}\lambda_{1\beta}^{LL}\lambda_{1\alpha}^{LL} , \quad \text{and} \quad \varepsilon_{\alpha\beta}^{dL} = \frac{1}{\sqrt{2}G_F}\frac{1}{m_{\rm LQ}^2}\lambda_{1\beta}^{LL}\lambda_{1\alpha}^{LL} .$$

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

Constraints on LQ couplings from LFV decays

- 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

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



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

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

one can obtain the bound on the leptoquark parameters as

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

- These bounds can be translated into NSI couplings as

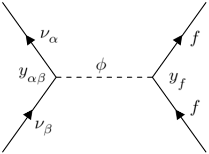
$$\varepsilon_{e\mu}^{uL} \le 0.1, \quad \varepsilon_{e\mu}^{dL} \le 0.2, \quad \Longrightarrow \quad \varepsilon_{e\mu} \le 0.9$$

Scalar mediated NSI

- For NSIs, discussions are mainly focusing on vector currents, either from a vector mediator or with Fierz transformation from a charged scalar
- Neutrinos can couple also to scalar field & scalar NSI can induce rich phenomenology
- In contrast to vector NSI, scalar NSI effect is no longer a matter potential
- Vector NSI always conserves chirality, which is no longer true for SNSI
- The latter can only appear as a correction to neutrino mass term that flips chirality

NSI mediated by the scalar field

- The non-standard interaction between the neutrinos ν and the fermions f, mediated by a scalar field ϕ



$$\mathcal{L}_{\rm eff} = \frac{y_{\alpha\beta} y_f}{m_\phi^2}(\overline{\nu}_\alpha \nu_\beta)(\bar{f} f).$$

- $\mathcal{L}_{\rm eff}$ cann't be transformed into a vector current via Fierz, hence it does not contribute to the matter potential

$$\frac{\partial \mathcal{L}_{\rm eff}}{\partial \overline{\nu}_\alpha} \propto \frac{1}{m_\phi^2}(\bar{f} f) \times \nu_\beta$$

- So it appears as a medium-dependent correction to the neutrino mass.
- Dirac equation in the presence of SNSI becomes

$$\overline{\nu}_\beta \left[i\partial_\mu \gamma^\mu - \left(M_{\beta\alpha} + \frac{\sum_f N_f y_f y_{\alpha\beta}}{m_\phi^2} \right) \right] \nu_\alpha = 0$$

- It can be realized as a mass shift

$$H_{eff} = \frac{1}{2E_\nu}(M + \delta M)^\dagger (M + \delta M) + V_{CC}, \quad \text{where} \quad V_{CC} = \text{diag}(\sqrt{2} G_F N_e, 0, 0)$$

[Ge, Parke: 1812.08376]

Parametrization of Scalar NSI

- In the flavor basis, normalizing to one of the mass splitting, it can be parameterized as

$$\delta M = \sqrt{|\Delta m^2_{31}|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix} , \qquad \eta_{\alpha\beta} = \frac{1}{m^2_\phi \sqrt{|\Delta m^2_{31}|}} \sum_f N_f y_f y_{\alpha\beta} \, .$$

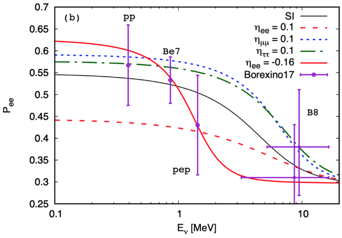
- The modified Hamiltonian becomes

$$H_{eff} \supset M^\dagger \cdot \delta M \supset m_1 \times \eta \times [\text{modulo PMNS elements}]$$

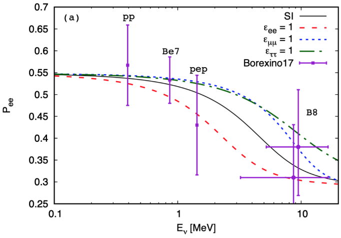
- To have any observable effect, need to have $y_f y_{\alpha\beta}/m^2_\phi \sim 10^{10} G_F$, which is possible for a light scalar mediator
- It depends on the choice of m_1.
- To constrain η, need to fix Δm^2_{ij} to measured values & specify a choice of m_1

Bounds from Borexino: 1812.08376

- Even in the absence of genuine mass matrix, oscillation can still happen due to SNSI
- Essentially there is no difference between M and the one induced by Scalar NSI
- Unlike vector NSI, the scalar NSI is energy independent and hence not suppressed at low energy
- The electron-neutrino survival probability:

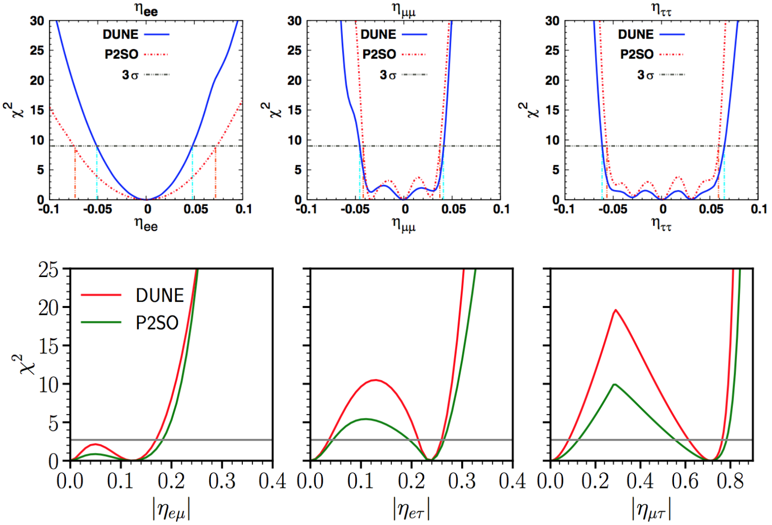


Scalar NSI's

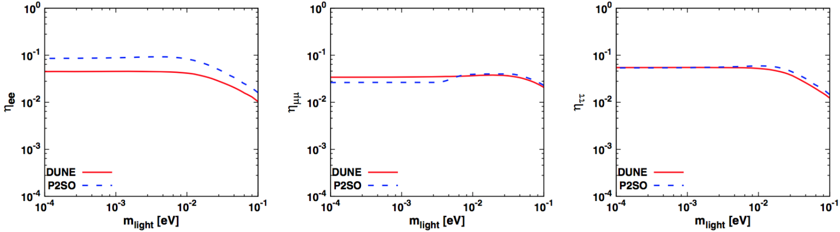


Vector NSI's

Bound on SNSI parameters [PRD 109, 095038]

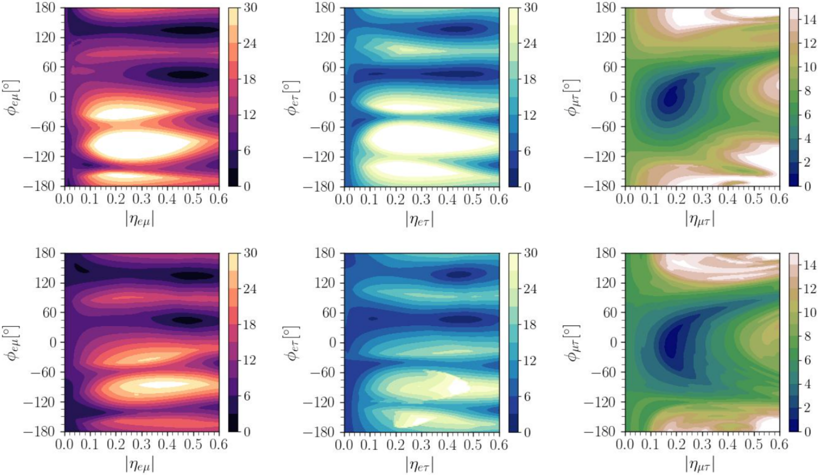


Dependence on the lightest neutrino mass



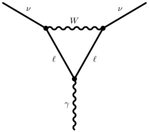
- Best upper limits can be obtained for larger m_1

CPV Sensitivity



Electromagnetic properties of neutrinos

- Exploring EM properties of neutrinos provides an interesting avenue to explore BSM
- Neutrinos being electrically neutral, do not have EM interactions at tree level. However, such ints can be generated at loop-level.



- With the loop suppression factor $\frac{m_\ell^2}{m_W^2}$, the contribution turns out to be

$$\mu_\nu \simeq \frac{3eG_F}{4\sqrt{2}\pi^2} m_\nu \simeq 3.2 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}}\right) \mu_B$$

- Thus, $m_\nu \neq 0$ imply non-zero NMM, which can be used to distinguish Dirac and Majorana neutrinos

Neutrino Magnetic moment: Experimental status

- Limits on NMM come from various experiments

$$\text{Reactor} \begin{cases} \text{TEXONO (2010)} & \mu_\nu < 2.0 \times 10^{-10} \mu_B \,, \\ \text{GEMMA (2012)} & \mu_\nu < 2.9 \times 10^{-11} \mu_B \,, \\ \text{CONUS (2022)} & \mu_\nu < 7.0 \times 10^{-11} \mu_B \,. \end{cases}$$

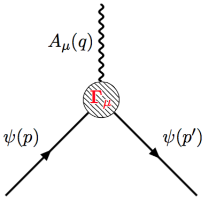
$$\text{Accelerator} \begin{cases} \text{LAPMF (1993)} & \mu_\nu < 7.4 \times 10^{-10} \mu_B \,, \\ \text{LSND (2002)} & \mu_\nu < 6.4 \times 10^{-10} \mu_B \,. \end{cases}$$

$$\text{Solar} \begin{cases} \text{Borexino (2017)} & \mu_\nu < 2.8 \times 10^{-11} \mu_B \,, \\ \text{XENONnT (2022)} & \mu_\nu < 6.4 \times 10^{-12} \mu_B \,. \end{cases}$$

Neutrino Magnetic moment

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

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



- 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

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

$f_Q(q^2)$, $f_M(q^2)$, $f_E(q^2)$ and $f_A(q^2)$ are the form factors

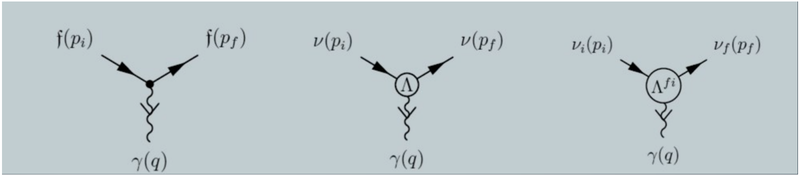
Magnetic moment in minimal extended SM

- For Dirac neutrinos:

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

- The diagonal electric dipole moment vanishes: $\epsilon_{ii}^D = 0$
- 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 become

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

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

Neutrino-electron elastic scattering

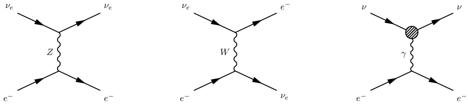
- Most widely used method to determine νMM is $\nu + e^- \to \nu + e^-$

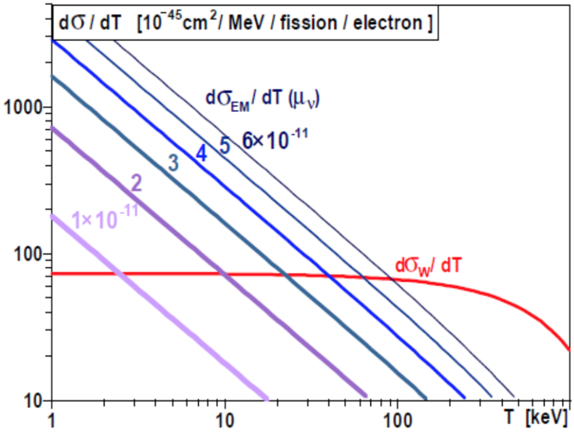
$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{SM}} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T_e}{E_\nu^2}\right]$$

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

- The cross sections are added incoherently

$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{Tot}} = \left(\frac{d\sigma}{dT_e}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT_e}\right)_{\mathrm{EM}} \quad (\mathrm{EM} \propto \frac{1}{T_e}, \quad \mathrm{SM} \propto \frac{m_e T_e}{E_\nu^2} \quad \text{low recoil})$$




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]

Model Description [PRD 108, 095048 (2023)]

- Objective is to address the neutrino mass, magnetic moment and dark matter in a common platform
- SM is extended with three vector-like fermion triplets Σ_k and two inert scalar doublets η_j
- An additional Z_2 symmetry is imposed to realize neutrino phenomenology at one-loop and for the stability of the dark matter candidate.

	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	$(\mathbf{1}, \mathbf{2}, \ 1/2)$	$-$

Table: Fields and their charges in the present model.

Model Description

- The $SU(2)_L$ triplet $\Sigma_{L,R}$ and inert doublets can be expressed as

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

- Charged scalars help in attaining neutrino magnetic moment , while Charged and neutral scalars help in obtaining neutrino mass at one loop.
- Scalar components annihilate via SM scalar and vector bosons and their freeze-out yield constitutes dark matter density of the Universe.
- 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 Lagrangian for the scalar sector takes the form

$$\mathcal{L}_{\mathrm{scalar}} = -\sum_{i=1,2} \left| \left(\partial_\mu + \frac{i}{2} g \, \sigma^a W^a_\mu + \frac{i}{2} g' B_\mu \right) \eta_i \right|^2 - V(H, \eta_1, \eta_2)$$

Mass Spectrum

- The scalar potential is expressed as

$$V(H,\eta_1,\eta_2) = \mu_H^2 H^\dagger H + \mu_1^2\eta_1^\dagger\eta_1 + \mu_2^2\eta_2^\dagger\eta_2 + \mu_{12}^2(\eta_1^\dagger\eta_2 + \mathrm{hc}) + \lambda_H(H^\dagger H)^2 + \lambda_1(\eta_1^\dagger\eta_1)^2$$
$$+ \lambda_2(\eta_2^\dagger\eta_2)^2 + \lambda_{12}(\eta_1^\dagger\eta_1)(\eta_2^\dagger\eta_2) + \lambda_{12}'(\eta_1^\dagger\eta_2)(\eta_2^\dagger\eta_1) + \frac{\lambda_{12}''}{2}\left[(\eta_1^\dagger\eta_2)^2 + \mathrm{h.c.}\right]$$
$$+ \sum_{j=1,2}\left(\lambda_{Hj}(H^\dagger H)(\eta_j^\dagger\eta_j) + \lambda_{Hj}'(H^\dagger\eta_j)(\eta_j^\dagger H) + \frac{\lambda_{Hj}''}{2}\left[(H^\dagger\eta_j)^2 + \mathrm{h.c.}\right]\right).$$

- The mass matrices of the charged and neural scalar components are:

$$\mathcal{M}_C^2 = \begin{pmatrix}\Lambda_{C1} & \mu_{12}^2\\ \mu_{12}^2 & \Lambda_{C2}\end{pmatrix},\quad \mathcal{M}_R^2 = \begin{pmatrix}\Lambda_{R1} & \mu_{12}^2\\ \mu_{12}^2 & \Lambda_{R2}\end{pmatrix},\quad \mathcal{M}_I^2 = \begin{pmatrix}\Lambda_{I1} & \mu_{12}^2\\ \mu_{12}^2 & \Lambda_{I2}\end{pmatrix}$$

$$\Lambda_{Cj} = \mu_j^2 + \frac{\lambda_{Hj}}{2}v^2,$$
$$\Lambda_{Rj} = \mu_j^2 + \left(\lambda_{Hj} + \lambda_{Hj}' + \lambda_{Hj}''\right)\frac{v^2}{2},$$
$$\Lambda_{Ij} = \mu_j^2 + \left(\lambda_{Hj} + \lambda_{Hj}' - \lambda_{Hj}''\right)\frac{v^2}{2}.$$

Mass Spectrum

- The flavor and mass eigenstates can be related by $U_\theta = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

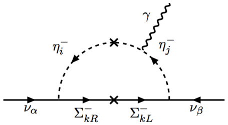
$$\begin{pmatrix} \eta_1^+ \\ \eta_2^+ \end{pmatrix} = U_{\theta_C} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}, \quad \begin{pmatrix} \eta_1^R \\ \eta_2^R \end{pmatrix} = U_{\theta_R} \begin{pmatrix} \phi_1^R \\ \phi_2^R \end{pmatrix}, \quad \begin{pmatrix} \eta_1^I \\ \eta_2^I \end{pmatrix} = U_{\theta_I} \begin{pmatrix} \phi_1^I \\ \phi_2^I \end{pmatrix}.$$

- Invisible decays of Z and $W^\pm$ at LEP, limit the masses as

$$M_{Ci} > M_Z/2, \quad M_{Ri} + M_{Ii} > M_Z, \quad M_{Ci} + M_{Ri,Ii} > M_W.$$

Neutrino Magnetic Moment

- In this model, the magnetic moment arises from one-loop diagram, and the expression of corresponding contribution takes the form

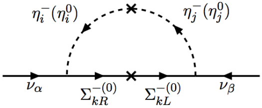


$$(\mu_\nu)_{\alpha\beta} = \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{8\pi^2} M_{\Sigma_k^+} \left[(1+\sin 2\theta_C) \frac{1}{M_{C2}^2} \left(\ln \left[\frac{M_{C2}^2}{M_{\Sigma_k^+}^2} \right] - 1 \right) + (1-\sin 2\theta_C) \frac{1}{M_{C1}^2} \left(\ln \left[\frac{M_{C1}^2}{M_{\Sigma_k^+}^2} \right]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

where $y = y' = Y$ and $(Y^2)_{\alpha\beta} = Y_{\alpha k} Y^T_{k\beta}$.

Neutrino Mass

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



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

Inert scalar doublet dark matter : Relic density

- The model provides scalar dark matter candidates and we study their phenomenology for dark matter mass up to 2 TeV range.
- All the inert scalar components contribute to the dark matter density of the Universe through annihilations and co-annihilations.

$$\phi_i^R \phi_j^R \longrightarrow f\bar{f},\ W^+W^-, ZZ,\ hh \quad \text{(via Higgs mediator)}$$
$$\phi_i^R \phi_j^I \longrightarrow f\bar{f},\ W^+W^-,\ Zh, \quad \text{(via Z boson)}$$
$$\phi_i^\pm \phi_j^{R/I} \longrightarrow f'\overline{f''}, AW^\pm, ZW^\pm, hW^\pm, \quad \text{(through W}^\pm \text{ bosons)}$$

- The abundance of dark matter can be computed by

$$\Omega h^2 = \frac{1.07\times 10^9\ \mathrm{GeV}^{-1}}{M_{\mathrm{Pl}}\ {g_*}^{1/2}}\frac{1}{J(x_f)}, \quad \text{where} \quad J(x_f) = \int_{x_f}^{\infty}\frac{\langle\sigma v\rangle(x)}{x^2}dx$$

$$\langle\sigma v\rangle(x) = \frac{x}{8M_{\mathrm{DM}}^5 K_2^2(x)}\int_{4M_{\mathrm{DM}}^2}^{\infty}\hat{\sigma}\times(s-4M_{\mathrm{DM}}^2)\ \sqrt{s}\ K_1\left(\frac{x\sqrt{s}}{M_{\mathrm{DM}}}\right)ds$$

Dark Matter Direct Searches

- The scalar dark matter can scatter off the nucleus via the Higgs and the Z boson.
- The DM-nucleon cross section in Higgs portal can provide a SI Xsection and the effective interaction Lagrangian takes the form

$$\mathcal{L}_{\text{eff}} = a_q \phi_1^R \phi_1^R q\bar{q}, \quad \text{where}$$

$$a_q = \frac{M_q}{2M_h^2 M_{R1}}(\lambda_{L1}\cos^2\theta_R + \lambda_{L2}\sin^2\theta_R) \text{ with } \lambda_{Lj} = \lambda_{Hj} + \lambda'_{Hj} + \lambda''_{Hj}.$$

- The corresponding cross section is

$$\sigma_{\text{SI}} = \frac{1}{4\pi}\left(\frac{M_n M_{R1}}{M_n + M_{R1}}\right)^2 \left(\frac{\lambda_{L1}\cos^2\theta_R + \lambda_{L2}\sin^2\theta_R}{2M_{R1}M_h^2}\right)^2 f^2 M_n^2$$

- Sensitivity can be checked with stringent upper bound of LZ-ZEPLIN experiment.

Numerical Analysis

- We consider ϕ_1^R to be the lightest inert scalar eigen state and there are five other heavier scalars.
- We consider one parameter M_{R1} and three mass splittings namely δ, $\delta_{\rm IR}$ and $\delta_{\rm CR}$.
- The masses of the rest of the inert scalars can be obtained from:

$$M_{R2} - M_{R1} = M_{I2} - M_{I1} = M_{C2} - M_{C1} = \delta,$$
$$M_{Ri} - M_{Ii} = \delta_{\rm IR}, \quad M_{Ri} - M_{Ci} = \delta_{\rm CR} \ ,$$

- Scanning over model parameters as given below

$$100 \text{ GeV} \leq M_{R1} \leq 2000 \text{ GeV}, \quad 0 \leq \sin\theta_R \leq 1,$$
$$0.1 \text{ GeV} \leq \delta < 200 \text{ GeV}, \quad 0.1 \text{ GeV} \leq \delta_{\rm IR}, \delta_{\rm CR} \leq 20 \text{ GeV}.$$

Some Results

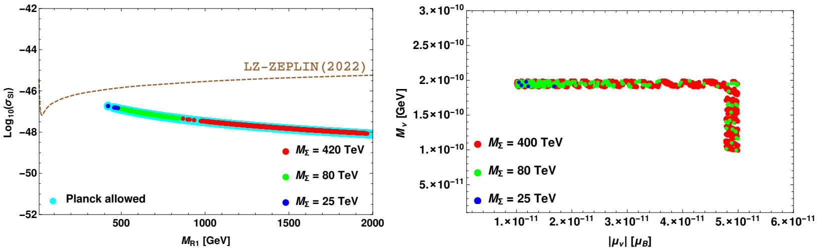
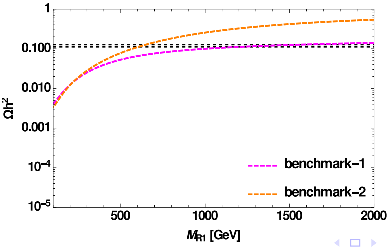


Figure: Left panel: Projection of SI WIMP-nucleon cross section as a function M_{R1}. Right panel: νMM and and light neutrino mass for suitable Yukawas.

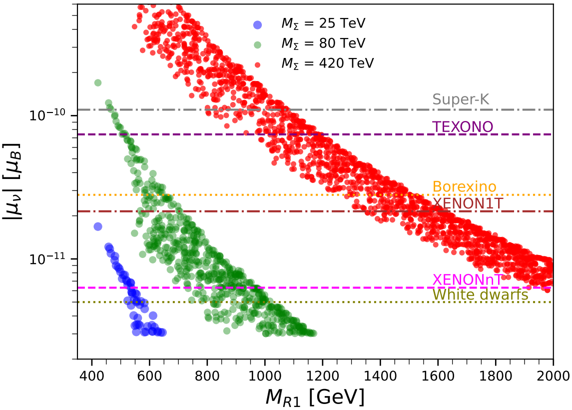
Benchmark values of parameters

	M_{R1} [GeV]	δ [GeV]	$\delta_{\rm CR}$ [GeV]	$\delta_{\rm IR}$ [GeV]	M_Σ [TeV]	Yukawa	$\sin\theta_R$
benchmark-1	1472	101.69	9.03	0.35	420	$10^{-4.89}$	0.09
benchmark-2	628	36.40	4.38	3.45	80	$10^{-4.85}$	0.06

	$\lvert\mu_\nu\rvert$ $[\mu_B]$	$\mathcal{M}_\nu$ [GeV]	$\mathrm{Log}_{10}^{[\sigma_{\rm SI}]}$ cm^{-2}	Ωh^2
benchmark-1	2.73×10^{-11}	1.99×10^{-10}	-47.78	0.123
benchmark-2	3.03×10^{-11}	1.92×10^{-10}	-47.04	0.119



Variation of ν Magnetic Moment with DM Mass



Conclusion

- Neutrino Physics provides a unique platform to explore variety of New Physics
- Various BSM Physics scenarios, e.g, NSIs, Lorentz Violation, CPT violation, Non-unitarity can be explored with Neutrinos
- Combining with other sectors, like Flavor and Dark matter will help to identify the nature of New Physics
- Hopefully, we will get some interesting NP signals from the upcoming long-baseline expts.

Thank you for your attention !