Exploring Physics beyond the Standard Model with Neutrinos

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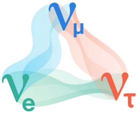
Neutrinos: What we know

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



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

Mixing Matrix

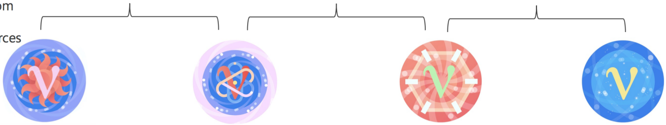
Flavor Eigenstates

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



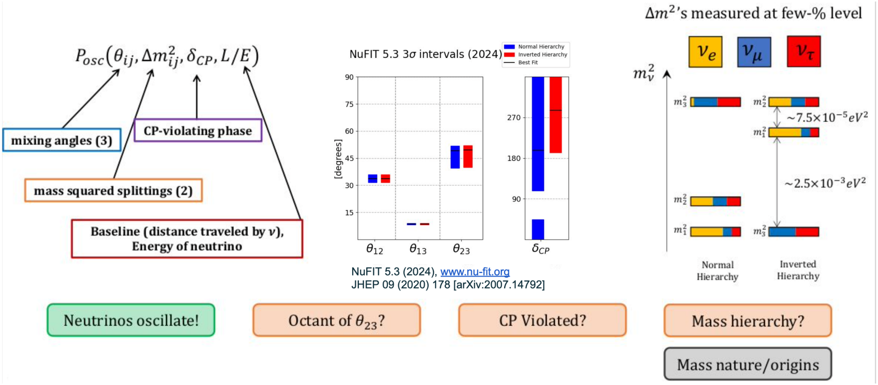
Solar

Reactor

Accelerator

Atmospheric

Current Status



K.Wood, CoSSURF-2024

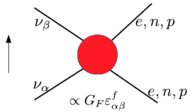
Main Assumptions

- 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

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
- NC-NSIs affect the neutrino propagation from source to detector and can be expressed as

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



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

NOvA and T2K Experiments in a Nutshell

NOvA Experiment

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

T2K Experiment

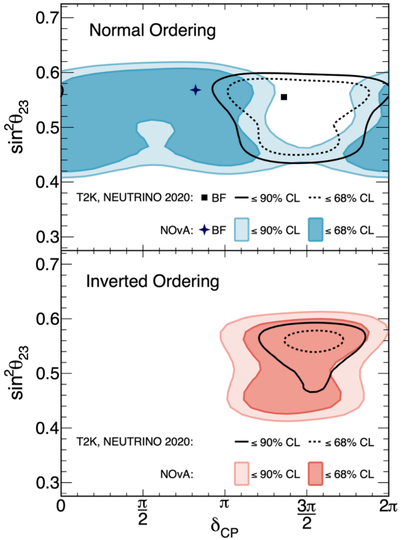
- Uses the beam from J-PARC facility
- primary goal to observe $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\mu$ channels for both neutrinos and antineutrinos
- Has two detectors ND (plastic scintillator) and FD (22.5 kt) water Cherenkov
- Both detectors are at 2.5° off-axial in nature corresponding oscillation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

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

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

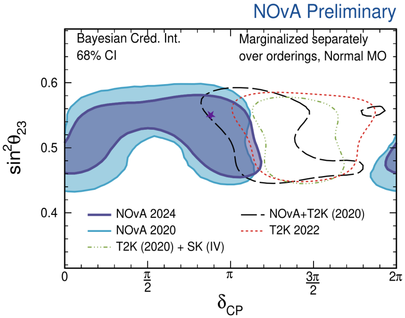
NEUTRINO 2022

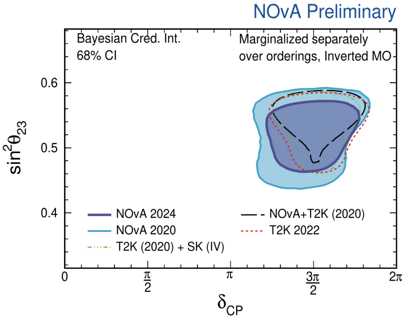
- Both expts. prefer Normal ordering
- No strong preference for CP violation in NOvA: $\delta_{CP} \sim 0.8\pi$
- T2K prefers $\delta_{CP} \simeq 3\pi/2$
- Slight disagreement between the two results at $\sim 2\sigma$ level



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

NEUTRINO 2024

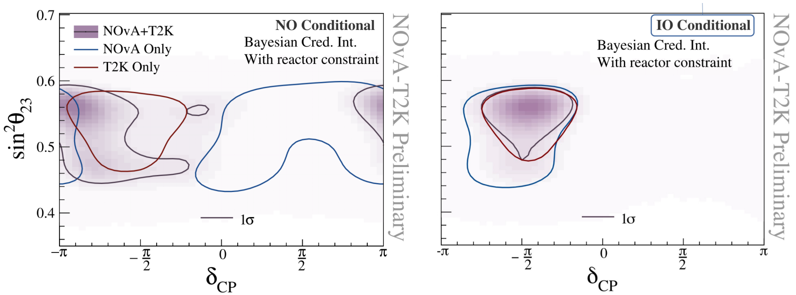




NOvA vs. other data favor different regions in NO,
same region in IO

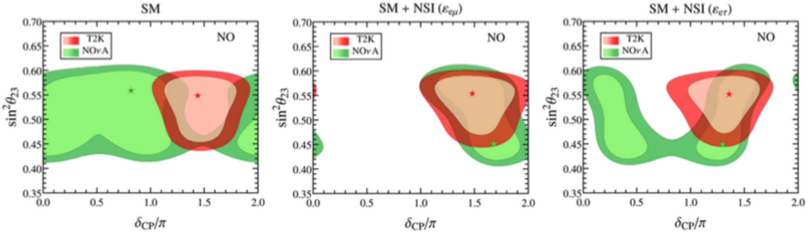
NOvA and T2K Joint-fit Results

NEUTRINO 2024



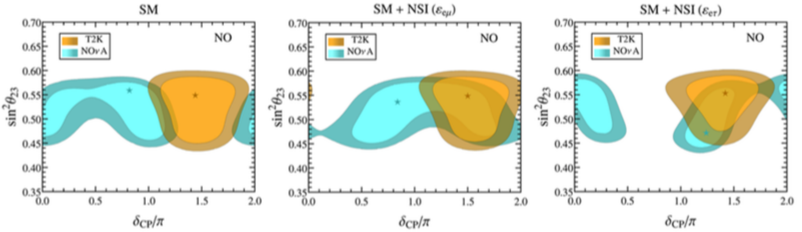
Joint fit splits the difference b/w NOvA-only & T2K-only in NO;
Improves constraint in IO

NOvA and T2K Tension & NSI



[Chatterjee, Palazzo, 2008.04161 (PRL); see also Denton, Gehrlein, Pestes , 2008.01110 (PRL)]

T2K-NOνA anomaly persists in 2024 data!



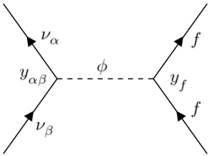
[Chatterjee, Palazzo, 2409.10599]

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

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

- 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

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

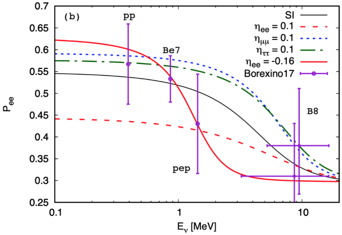
- The modified Hamiltonian becomes

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

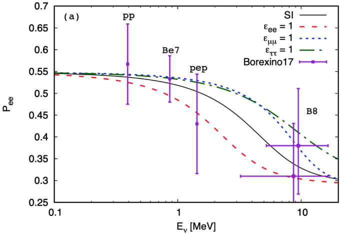
- To have any observable effect, need to have $y_f y_{\alpha\beta}/m^2_\phi \sim 10^{10} G_F$, which is possible for a light scalar mediator
- It depends on the choice of m_1.
- To constrain η, need to fix Δm^2_{ij} to measured values & specify a choice of m_1

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:

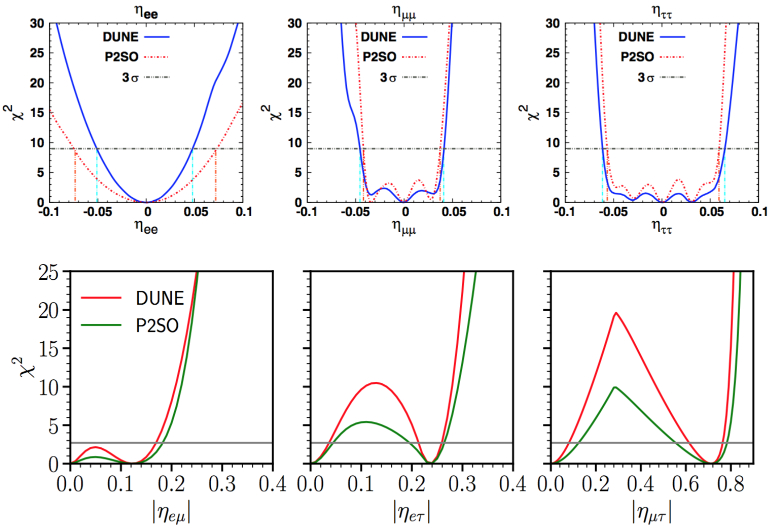


Scalar NSI's

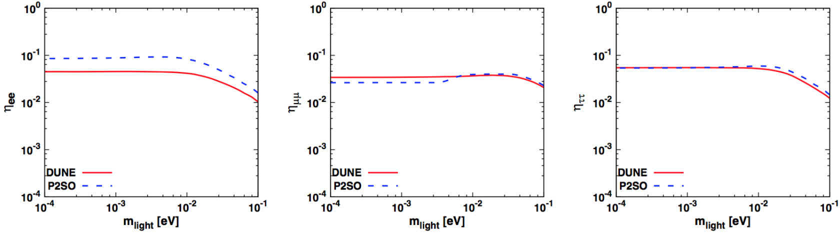


Vector NSI's

Bound on SNSI parameters [PRD 109, 095038]

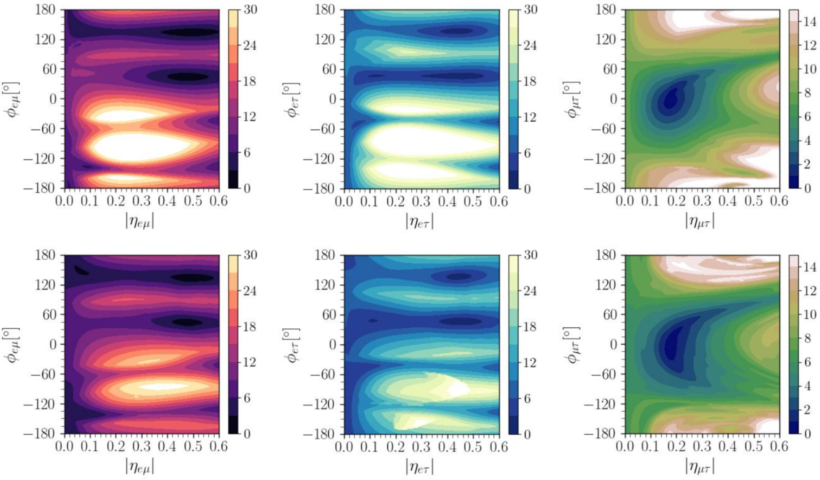


Dependence on the lightest neutrino mass



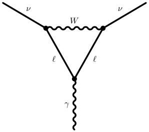
- Best upper limits can be obtained for larger m_1

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

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

- 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

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

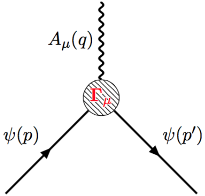
$$
\text{Accelerator} \begin{cases} \text{LAPMF (1993)} & \mu_\nu < 7.4 \times 10^{-10} \mu_B \,, \\ \text{LSND (2002)} & \mu_\nu < 6.4 \times 10^{-10} \mu_B \,. \end{cases}
$$

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

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

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

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

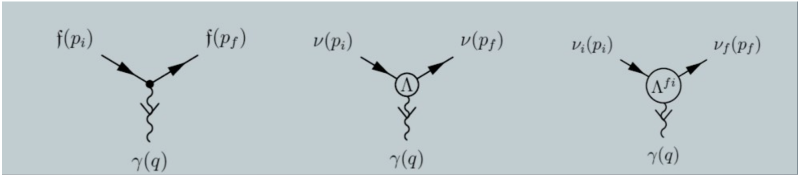
Magnetic moment in minimal extended SM

- 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

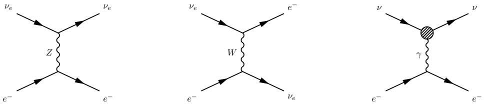
- Most widely used method to determine νMM is $\nu + e^- \to \nu + e^-$

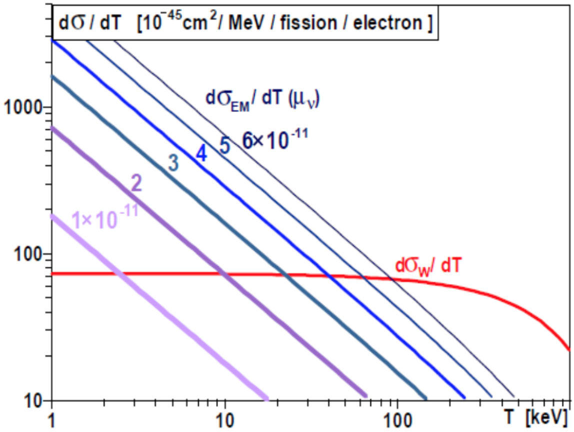
$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{SM}} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T_e}{E_\nu^2}\right]$$

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

- The cross sections are added incoherently

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




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

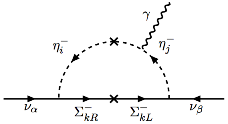
$$\Sigma_{L,R} = \frac{\sigma^a \Sigma^a_{L,R}}{\sqrt{2}} = \begin{pmatrix} \Sigma^0_{L,R}/\sqrt{2} & \Sigma^+_{L,R} \\ \Sigma^-_{L,R} & -\Sigma^0_{L,R}/\sqrt{2} \end{pmatrix},$$

$$\eta_j = \begin{pmatrix} \eta_j^+ \\ \eta_j^0 \end{pmatrix}; \quad \eta_j^0 = \frac{\eta_j^R + i\eta_j^I}{\sqrt{2}}$$

- 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.

Neutrino Magnetic Moment

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

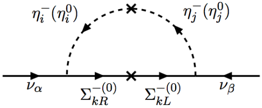


$$(\mu_\nu)_{\alpha\beta} = \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{8\pi^2} M_{\Sigma_k^+} \left[(1+\sin 2\theta_C) \frac{1}{M_{C2}^2} \left(\ln \left[\frac{M_{C2}^2}{M_{\Sigma_k^+}^2} \right] - 1 \right) + (1-\sin 2\theta_C) \frac{1}{M_{C1}^2} \left(\ln \left[\frac{M_{C1}^2}{M_{\Sigma_k^+}^2} \right]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

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

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

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

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

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

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

- The corresponding cross section is

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

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

Some Results

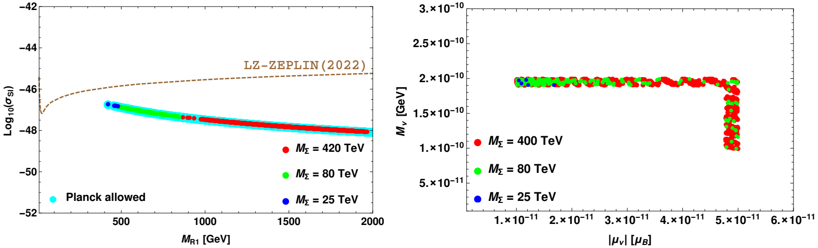
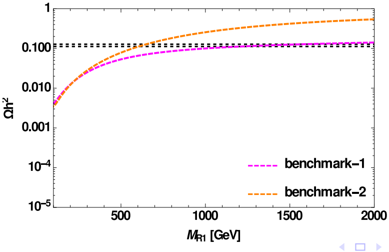


Figure: Left panel: Projection of SI WIMP-nucleon cross section as a function M_{R1}. Right panel: νMM and and light neutrino mass for suitable Yukawas.

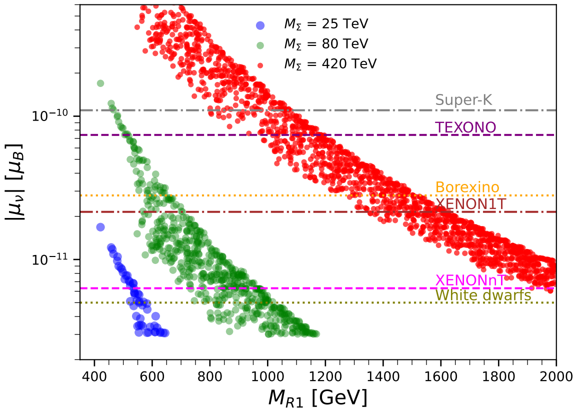
Benchmark values of parameters

	M_{R1} [GeV]	δ [GeV]	δ_{CR} [GeV]	δ_{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

	$\lvert\mu_\nu\rvert$ [μ_B]	$\mathcal{M}_\nu$ [GeV]	$\mathrm{Log}_{10}^{[\sigma_{SI}]}$ 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 !