Neutrino magnetic moment and inert doublet dark matter in a radiative seesaw scenario

Rukmani Mohanta

University of Hyderabad, Hyderabad-500046, India

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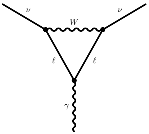
22ND CONFERENCE ON FLAVOR PHYSICS AND CP VIOLATION

Motivation

- Despite its tremendous success, SM can be regarded as a low-energy effective theory of a more fundamental theory
- No direct evidence of NP either in Energy frontier or Intensity frontier
- There are a few open issues, which can not be addressed in the SM
  - Existence of Dark Matter $\Rightarrow$ New weakly interacting particles
  - Non-zero neutrino masses $\Rightarrow$ Right-handed (sterile) neutrinos
  - Observed Baryon Asymmetry of the Universe $\Rightarrow$ Additional CP violating interactions
- It is obvious that SM must be extended.
- As a consequence of $m_\nu \neq 0$, many new avenues beyond SM are expected to exist
- One among them is neutrinos having EM properties, e.g, electric and magnetic moments
- It is extremely hard to measure their EM properties, but limits can be set from various expts.

Neutrino magnetic moment

- 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

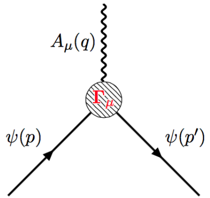
$$\mu_\nu \simeq \frac{3eG_F}{4\sqrt{2}\pi^2} m_\nu \simeq 3.2 \times 10^{-19} \left(\frac{m_\nu}{\mathrm{eV}}\right) \mu_B$$

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

Neutrino Magnetic moment

- 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

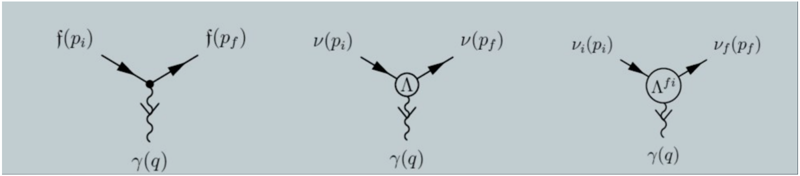
Magnetic moment in minimal extended SM

- 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 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

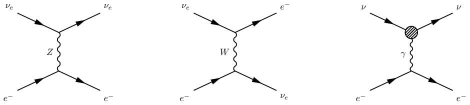
- Most widely used method to determine νMM is $\nu + e^- \to \nu + e^-$

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

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

- The cross sections are added incoherently

$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{Tot}} = \left(\frac{d\sigma}{dT_e}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT_e}\right)_{\mathrm{EM}} \qquad (\propto \tfrac{1}{T_e} \text{ for low recoil})$$



Model Description

- 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:

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

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

Mass Spectrum

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

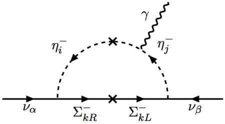
$$\begin{pmatrix} \eta_1^+ \\ \eta_2^+ \end{pmatrix} = U_{\theta_C} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}, \quad \begin{pmatrix} \eta_1^R \\ \eta_2^R \end{pmatrix} = U_{\theta_R} \begin{pmatrix} \phi_1^R \\ \phi_2^R \end{pmatrix}, \quad \begin{pmatrix} \eta_1^I \\ \eta_2^I \end{pmatrix}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

- 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

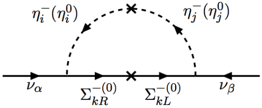


$$(\mu_\nu)_{\alpha\beta} = \sum_{k=1}^{3} \frac{(Y^2)_{\alpha\beta}}{8\pi^2} M_{\Sigma_k^+} \left[(1+\sin 2\theta_C) \frac{1}{M_{C2}^2} \left(\ln \left[\frac{M_{C2}^2}{M_{\Sigma_k^+}^2} \right] - 1 \right) + (1-\sin 2\theta_C) \frac{1}{M_{C1}^2} \left(\ln \left[\frac{M_{C1}^2}{M_{\Sigma_k^+}^2} \right]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

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

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

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

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

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

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

- 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.

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

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

Results on Neutrino oscillations

- For diagonalization of neutrino mass matrix, we take

$$U_\nu = U_{\mathrm{TBM}} \cdot U_{13} = \begin{pmatrix} \cos\Theta & \sin\Theta & 0 \\ -\frac{\sin\Theta}{\sqrt{2}} & \frac{\cos\Theta}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sin\Theta}{\sqrt{2}} & -\frac{\cos\Theta}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \cdot \begin{pmatrix} \cos\varphi & 0 & e^{-i\zeta}\sin\varphi \\ 0 & 1 & 0 \\ -e^{i\zeta}\sin\varphi & 0 & \cos\varphi \end{pmatrix}$$

which gives

$$\mathcal{M}_\nu = Y \cdot \mathrm{diag}(\Lambda_1', \Lambda_2', \Lambda_3') \cdot Y^T, \qquad \mu_\nu = Y \cdot \mathrm{diag}(\Lambda_1, \Lambda_2, \Lambda_3) \cdot Y^T$$

where Y is the 3×3 Yukawa matrix

- Diagonalizing the matrices using U_ν, gives three unique solutions where the Yukawa couplings of different flavors become linearly dependent,

$$Y_{e1/e3} = \left(\frac{\sqrt{2}\,\cos\Theta\,\cos\varphi}{\sin\Theta\,\cos\varphi \mp e^{-i\zeta}\sin\varphi} \right) Y_{\tau 1}, \qquad Y_{e2} = -\frac{\sqrt{2}\,\sin\Theta}{\cos\Theta} Y_{\tau 2},$$

$$Y_{\mu 1/\mu 3} = \left(\frac{e^{-i\zeta}\sin\varphi + \sin\Theta\,\cos\varphi}{e^{-i\zeta}\sin\varphi \mp \sin\Theta\,\cos\varphi} \right) Y_{\tau 1}, \qquad Y_{\mu 2} = -Y_{\tau 2}.$$

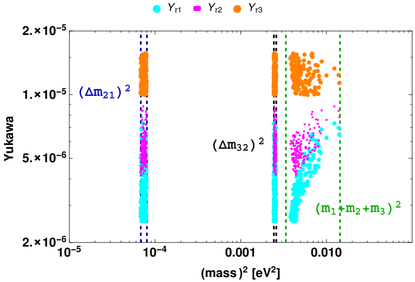
- Thus, the obtained diagonalized matrices are

$$\mathcal{M}_\nu^D/\mu_\nu^D = \begin{pmatrix} a_1 \;\; Y_{\tau 1}^2 \Lambda_1'(\Lambda_1) & 0 & 0 \\ 0 & a_2 \;\; Y_{\tau 2}^2 \Lambda_2' 9 \Lambda_2) & 0 \\ 0 & 0 & a_3 \;\; Y_{\tau 3}^2 \Lambda_3' 9 \Lambda_3) \end{pmatrix},$$

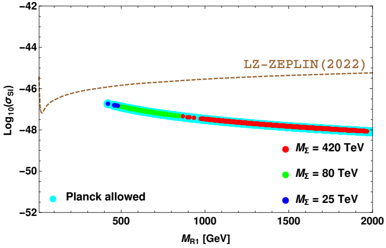
where,

$$a_1 = \frac{2e^{2i\zeta}}{(-e^{i\zeta}\cos\varphi\sin\Theta + \sin\varphi)^2}, \quad a_2 = \frac{2}{\cos^2\Theta}, \quad a_3 = \frac{2e^{-2i\zeta}}{(e^{-i\zeta}\cos\varphi + \sin\Theta\sin\varphi)^2}.$$

- Using the best-fit values on θ_{12}, θ_{13} and θ_{23}, we fix $\Theta = 33.04^\circ$, $\varphi = 10.18^\circ$ and $\zeta = 180^\circ$.



Some Results



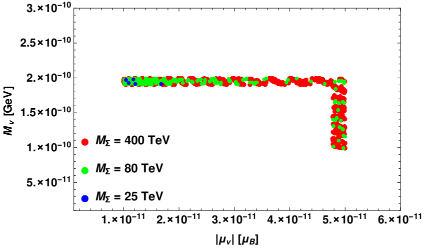


Figure: Left panel: Projection of SI WIMP-nucleon cross section as a function M_{R1}. Right panel: νMM and and light neutrino mass for suitable Yukawas.

Some Results

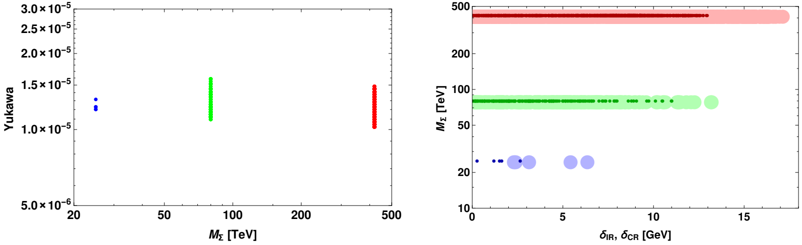
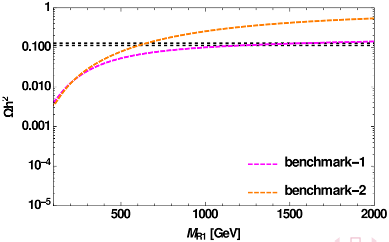


Figure: Left panel: Suitable region for triplet mass and Yukawa to explain neutrino phenomenology. Right panel: allowed region for scalar mass splittings, thick (thin) bands correspond to $\delta_{\rm IR}$ ($\delta_{\rm CR}$) respectively.

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

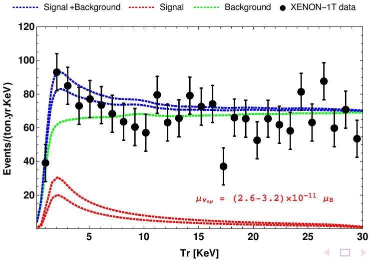


Excess in electron recoil events

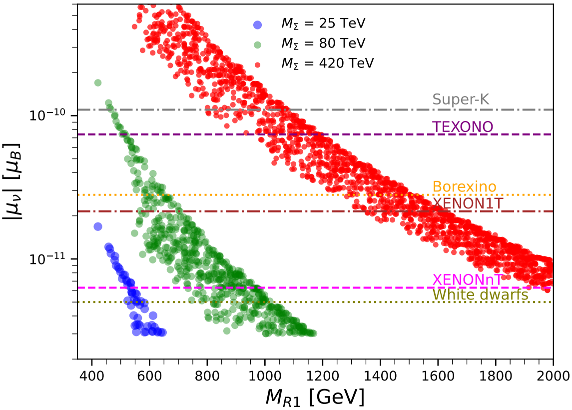
$$\frac{dN}{dT_r} = n_{\rm te} \times \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} dE_\nu \int_{T_{\rm th}}^{T_{\rm max}} dT_e \left(\frac{d\sigma^{\nu_e e}}{dT_e} P_{ee} + \cos^2\theta_{23} \frac{d\sigma^{\nu_\mu e}}{dT_e} P_{e\mu} \right)$$
$$\times \frac{d\phi_s}{dE_\nu} \times \epsilon(T_e) \times G(T_e, T_r).$$

where, $E_\nu^{\rm max} = 420$ KeV and $E_\nu^{\rm min} = [T + (2m_e T + T^2)^{\frac{1}{2}}]/2$.

- $T_{\rm th} = 1$ KeV and $T_{\rm max} = 30$ KeV stand for the threshold and maximum recoil energy of detector.



Variation of ν Magnetic Moment with DM Mass



Conclusion

- Primary objective is to address neutrino mass, magnetic moment and dark matter phenomenology in a common framework.
- SM is extended with three vector-like fermion triplets and two inert scalar doublets to realize Type-III radiative scenario.
- A pair of charged scalars help in obtaining neutrino magnetic moment,
- All charged and neutral scalars come up in getting light neutrino mass at one-loop level.
- All the inert scalars participate in annihilation and co-annihilation channels to provide dark matter relic density consistent with Planck data
- The model is able to provide neutrino magnetic moment in a wide range ($10^{-12}\mu_B$ to $10^{-10}\mu_B$), in the same ball park of Borexino, Super-K, TEXONO, XENONnT and white dwarfs.

Thank you for your attention !