A Radiated Linear Seesaw Model

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Outline

Questions in SM

The Standard model works well but not the end of the story:

- Small but no-zero neutrino mass: $\Delta m_{21}^2 = 7.46 \times 10^{-5}$eV, $\Delta m_{32}^2 = 2.51 \times 10^{-3}$eV and $m_1 + m_2 + m_3 < 0.23$eV.
- Dark matter:$\Omega_{DM} h^2 = 0.1199 \pm 0.0027$[Plank Collaboration(2013)]
- Matter-antimatter asymmetry of our universe
- Hierarchy Problems
- Strong CP problem
- Gauge Unification
- etc

Tiny neutrino mass compared with EW scale:

Figure: Neutrino $m_\nu < 1\text{eV}$

Figure: Top quark $m_t = 173\text{GeV}$

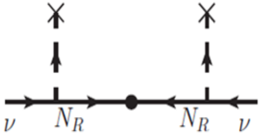
For a Dirac mass term via Yukawa coupling:

$$m_\nu \sim 0.1eV \Rightarrow y_\nu \simeq \frac{m_\nu}{v_{EW}} \simeq 10^{-12}$$

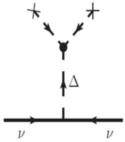
unnatural small Yukawa coupling!

Majorana neutrino mass

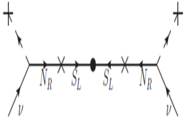
Type-I seesaw: $m_\nu \sim \frac{v^2}{M_R}$



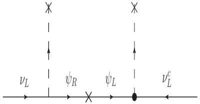
m_ν suppressed by N_R with 10^{14}GeV mass



Type-II seesaw:
$m_\nu \sim \mu \frac{v^2}{M_\Delta^2}$



Inverse seesaw:
$m_\nu \sim \mu \frac{v^2}{M^2}$



Linear seesaw:
$m_\nu \sim \mu \frac{v}{M}$

μ: naturally small parameter breaking L symmetry(by Hooft)
m_ν suppressed by both small μ and heavy state

Linear Seesaw Model

Linear seesaw model:
the SM particles+Ψ_L, Ψ_R

E.Akhmedov, M. Linder, E. Schnapka, J. W. F. Valle, PLB, 368, 270(1996)

M. Malinsky, J. C. Romao, J. W. F. Valle, PRL 95. 161801(2005)

$$L = m_D \overline{\nu}_L \Psi_R + M_R \overline{\Psi}_R \Psi_L + M_L \nu_L \widetilde{\Psi}_L + h.c \quad (1)$$

in the basis of (ν_L, Ψ_R, Ψ_L) is

$$M_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M_R \\ M_L & M_R & 0 \end{pmatrix} \Rightarrow m_\nu = m_D M_L \frac{1}{M_R} + Transpose \quad (2)$$

We want to

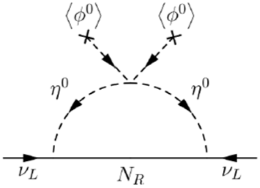
- suppress L-breaking term M_L
- accommodate the neutrino mass and dark matter simultaneously.

  One stone, two birds!

Ma model(2006)

Z_2 symmetry:

- forbid m_ν at tree level
- DM stability



$$(m_\nu)_{ij} \sim -\frac{\lambda}{16\pi^2}\sum \frac{f_{ik}f_{jk}v^2}{M_k} \quad \textit{for} \quad m_\eta \simeq M_k$$

- Inert scalar η as a DM candidate$\Rightarrow$ inert doublet model
- Majorana fermion N_R: two fold constraints from $\Omega_{DM}h^2$ and LFV processes

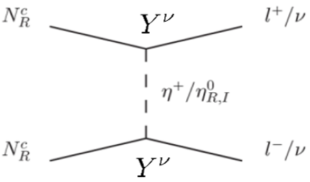


Figure: $\Omega_{DM}h^2 \sim 0.12 \Rightarrow f \sim 1$

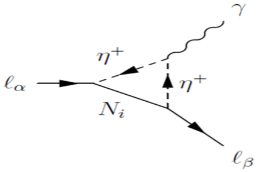
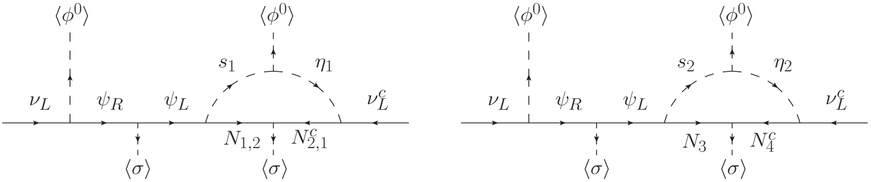


Figure: $\mathrm{BR}(\mu \to e + \gamma) < 5.7 \times 10^{-13} \Rightarrow |f_{\mu i}|, |f_{ei}| < 10^{-2}$

Radiated Linear Seesaw

Feynman Diagrams:



New particles content: $G_{SM} \times B-L$

Particles	Ψ_R	Ψ_L	N_R	N_R'	N_R''	η_1	s_1	η_2	s_2	σ
$SU(2)_L$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{1}$	$\underline{2}$	$\underline{1}$	$\underline{2}$	$\underline{1}$	$\underline{1}$
$U(1)_Y$	0	0	0	0	0	$\frac{1}{2}$	0	$\frac{1}{2}$	0	0
$U(1)_{B-L}$	-1	0	$-\frac{1}{2}$	x	$-1-x$	$-\frac{1}{2}$	$-\frac{1}{2}$	x	x	1

$$-L_Y = y_l\overline{L_l}\psi_R i\tau_2\Phi^* + y'\overline{\psi_L}\psi_R\sigma + h_\alpha\overline{N_{R\alpha}}\psi_L s_1 + f_{\alpha l}\overline{L_l^c}N_{R\alpha}^c i\tau_2\eta_1^* + \boxed{\frac{1}{2}Y_\alpha\overline{N_{R\alpha}^c}N_{R\alpha}\sigma}$$

$$+ h\overline{N_R'}\psi_L s_2 + f_l\overline{L_l^c}N_R''^c i\tau_2\eta_2^* + \boxed{\frac{1}{2}Y\overline{N_R''^c}N_R'\sigma} + h.c$$

no interplay Yukawa terms between N_Rs and (N_R', N_R'').

Charge Assignment

x is fixed by anomalies cancelation for $[U(1)_{B-L}] \times [Gravity]^2$
$[U(1)_{B-L}]^3$:

$$
\begin{aligned}
3 + (-\frac{1}{2})N_1 + xN_2 + (-1-x)N_2 + (-1)N_\psi = 0 \\
3 + (-\frac{1}{2})^3 N_1 + x^3 N_2 + (-1-x)^3 N_2 + (-1)^3 N_\psi = 0
\end{aligned} \tag{3}
$$

Solution:

$$
N_1 = 2, \qquad N_2 = 1, \qquad N_\psi = 1, \qquad x = \frac{\sqrt{2}-1}{2} \tag{4}
$$

partiles with B-L charge $-\frac{1}{2}$ can't decay to SM particles $\Leftarrow$ DM candidates.
particles with irrational B-L charge can't decay to SM particles $\Leftarrow$ DM candidates.

A two-component dark matter model

Scalar Potential

$$
\begin{aligned}
V(\Phi,\sigma,\eta_1,s_1,\eta_2,s_2) = & -\mu_\Phi^2\Phi^\dagger\Phi + \lambda_\Phi(\Phi^\dagger\Phi)^2 - \mu_\sigma^2|\sigma|^2 + \lambda_\sigma|\sigma|^4 \\
& + \mu_{\eta_1}^2\eta_1^\dagger\eta_1 + \lambda_{\eta_1}(\eta_1^\dagger\eta_1)^2 + \mu_{\eta_2}^2\eta_2^\dagger\eta_2 + \lambda_{\eta_2}(\eta_2^\dagger\eta_2)^2 \\
& + \mu_{s_1}^2|s_1|^2 + \lambda_{s_1}|s_1|^4 + \mu_{s_2}^2|s_2|^2 + \lambda_{s_2}|s_2|^4 + \lambda_{s_1s_2}|s_1|^2|s_2|^2 \\
& + \lambda_{\eta_1\Phi}(\Phi^\dagger\Phi)(\eta_1^\dagger\eta_1) + \lambda'_{\eta_1\Phi}(\eta_1^\dagger\Phi)(\Phi^\dagger\eta_1) + \lambda_{\eta_2\Phi}(\Phi^\dagger\Phi)(\eta_2^\dagger\eta_2) + \lambda'_{\eta_2\Phi}(\eta_2^\dagger\Phi)(\Phi^\dagger\eta_2) \\
& + \lambda_{\eta_1\eta_2}(\eta_1^\dagger\eta_1)(\eta_2^\dagger\eta_2) + \lambda'_{\eta_1\eta_2}(\eta_1^\dagger\eta_2)(\eta_2^\dagger\eta_1) \\
& + \lambda_{s_1\Phi}|s_1|^2(\Phi^\dagger\Phi) + \lambda_{s_1\eta_1}|s_1|^2(\eta_1^\dagger\eta_1) + \lambda_{s_1\eta_2}|s_1|^2(\eta_2^\dagger\eta_2) \\
& + \lambda_{s_2\Phi}|s_2|^2(\Phi^\dagger\Phi) + \lambda_{s_2\eta_1}|s_2|^2(\eta_1^\dagger\eta_1) + \lambda_{s_2\eta_2}|s_2|^2(\eta_2^\dagger\eta_2) \\
& + \boxed{\lambda_{\sigma\Phi}|\sigma|^2(\Phi^\dagger\Phi)} + \lambda_{\sigma\eta_1}|\sigma|^2(\eta_1^\dagger\eta_1) + \lambda_{\sigma\eta_2}|\sigma|^2(\eta_2^\dagger\eta_2) \\
& + \lambda_{s_1\sigma}|s_1|^2|\sigma|^2 + \lambda_{s_2\sigma}|s_2|^2|\sigma|^2 + \boxed{(\mu_1 s_1^\dagger\Phi^\dagger\eta_1 + \mu_2 s_2^\dagger\Phi^\dagger\eta_2 + h.c)}
\end{aligned}
$$

- no interplay mass term between (η_1, s_1) and (η_2, s_2)
- blue box: mixing between h and H
- red box: mixing between η_1 and s_1 (η_1 and s_2)

$$
\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi_r^0 \\ \sigma_r^0 \end{pmatrix} \qquad \sin 2\theta = \frac{2\lambda_{\sigma,\Phi} v_\phi v_\sigma}{m_H^2 - m_h^2}
$$

$$
\begin{pmatrix} A_{1,2}^0 \\ H_{1,2}^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_{1,2} & -\sin\theta_{1,2} \\ \sin\theta_{1,2} & \cos\theta_{1,2} \end{pmatrix} \begin{pmatrix} \eta_{1,2}^0 \\ s_{1,2}^0 \end{pmatrix} \quad , \quad \sin 2\theta_{1,2} = \frac{\sqrt{2}\mu_{1,2} v_\phi}{m_{A_{1,2}}^2 - m_{H_{1,2}}^2}
$$

$$
m_h^2 = \lambda_\Phi v_\phi^2 + \lambda_\sigma v_\sigma^2 - \sqrt{(\lambda v_\phi^2 - \lambda_\sigma v_\sigma^2)^2 + \lambda_{\sigma\Phi}^2 v_\phi^2 v_\sigma^2} \qquad m_{A_{1,2}}^2 = \frac{1}{2}\left(m_{\eta_{1,2}}^2 + m_{s_{1,2}}^2 + \sqrt{(m_{\eta_{1,2}}^2 - m_{s_{1,2}}^2)^2 + 2\mu_{1,2}^2 v_\phi^2}\right)
$$

$$
m_H^2 = \lambda_\Phi v_\phi^2 + \lambda_\sigma v_\sigma^2 + \sqrt{(\lambda v_\phi^2 - \lambda_\sigma v_\sigma^2)^2 + \lambda_{\sigma\Phi}^2 v_\phi^2 v_\sigma^2} \qquad m_{H_{1,2}}^2 = \frac{1}{2}\left(m_{\eta_{1,2}}^2 + m_{s_{1,2}}^2 - \sqrt{(m_{\eta_{1,2}}^2 - m_{s_{1,2}}^2)^2 + 2\mu_{1,2}^2 v_\phi^2}\right)
$$

More looks on the model

The spontaneous breaking of B-L symmetry:

$$\sigma = \frac{v_\sigma + \sigma_0 + iG_\sigma}{2} \qquad (5)$$

- The heavy states get masses via Yukawa interactions.
- Z' gets mass via Higgs mechanism.
- The origion of lepton number breaking term μ_L.
- Dark side: $U(1)_{B-L} \xrightarrow{\text{SSB}} Z_2 \times Z_2'$ symmetry

  with all inert particles are odd.

  A residual symmetry stabilizing the DM candidates.

Neutrino Mass

$$m_\nu = m_\nu^I + m_\nu^{II}$$

where

$$M^I_{\nu l l'} = \frac{v_\phi \sin\theta_1 \cos\theta_1}{16\pi^2\sqrt{2}M_\psi} y_l \sum_{i=1}^{2} h_i f_{il'} m_i \Big[\frac{m^2_{A_1}}{m_i^2 - m_{A_1}} \ln\Big(\frac{m^2_{A_1}}{m_i^2}\Big) - \frac{m^2_{H_1}}{m_i^2 - m^2_{H_1}} \ln\Big(\frac{m^2_{H_1}}{m_i^2}\Big)\Big] + (l \leftrightarrow l')$$

$$M^{II}_{\nu l l'} = \frac{v_\phi \sin\theta_2 \cos\theta_2}{16\pi^2\sqrt{2}M_\psi} y_l h_3 f_{l'} m_\chi \Big[\frac{m^2_{A_2}}{m_\chi^2 - m^2_{A_2}} \ln\Big(\frac{m^2_{A_2}}{m_\chi^2}\Big) - \frac{m^2_{H_2}}{m_\chi^2 - m^2_{H_2}} \ln\Big(\frac{m^2_{H_2}}{m_\chi^2}\Big)\Big] + (l \leftrightarrow l')$$

benchmark points:

$$\mu_1 = \mu_2 = 0.1 \text{ GeV}, y = h = f = 0.01, M_\psi = 300 \text{ GeV}$$

$$M_{N_{R1}} = 149.5 \text{ GeV}, M_{N_{R2}} = 200 \text{ GeV}, M_\chi = 150 \text{ GeV}$$

$$M_{A_1^0} = 300 \text{ GeV}, M_{\eta_1^\pm} = 270 \text{ GeV}, M_{H_1^0} = 1000 \text{ GeV}$$

$$M_{A_2^0} = 700 \text{ GeV}, M_{\eta_2^\pm} = 690 \text{ GeV}, M_{H_2^0} = 62 \text{ GeV}$$

$$\Rightarrow m_\nu \sim 0.1 eV$$

LFV process

$\mu \to e\gamma$: η^+ contribution

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha_{em}}{64\pi G_F^2}\left|\sum_{i=1}^{2}\frac{f_{i\mu}f_{ie}^*}{m_{\eta_1^+}^2}F\left(\frac{m_{N_i}^2}{m_{\eta_1^+}^2}\right) + \frac{f_l f_l^*}{m_{\eta_2^+}^2}F\left(\frac{m_{N''}^2}{m_{\eta_2^+}^2}\right)\right|^2$$

where

$$F(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{6(1-x)^4}$$

For our benchmark point

$$BR(\mu \to e\gamma) = 8.8 \times 10^{-14}$$

current bound:

$$BR(\mu \to e\gamma) < 5.7 \times 10^{-13} (90\% CL)$$

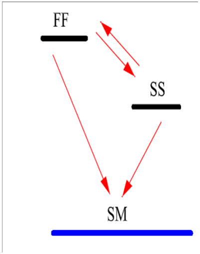
- ”nature” choice: $f_{ei}, f_{\mu i}, f_{\tau i} \sim 0.01$
- hierarchal choice: $f_{ei}, f_{\mu i} \sim 0.01, f_{\tau i} \sim 1$
- special choice: nearly diagonal f matrix

Dark Scalar+ Dark Fermion Scenario

Candidates:

scalar $M_S \simeq 60$GeV

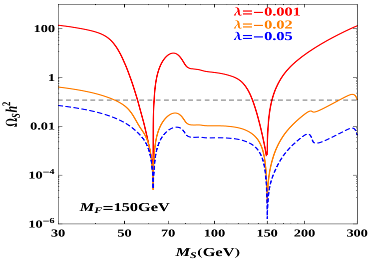
fermion $M_F \simeq 150$GeV

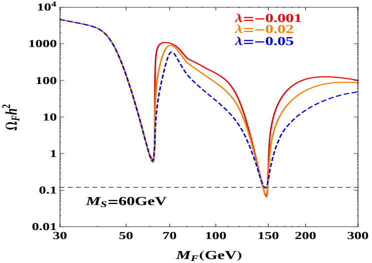


$FF/SS \to l^+l^-/\nu\nu \quad \Rightarrow$ suppressed for natural choice.

Higgs Portal dominate

Relic Density:

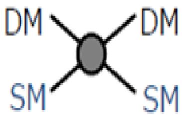


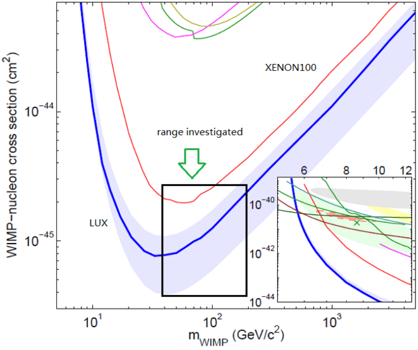


where $\lambda \equiv \lambda_{\sigma\eta_2} = \lambda_{\sigma s_2}$

Direct Detection

DM scattering with nucleus





$\sigma_{DM} \leq 10^{-45}[cm^2] \quad M_D \sim 10^2\mathrm{GeV}$

Event rate

$$R \propto \sum n_i \langle\sigma\rangle_i = \sum \frac{\rho_i}{m_i}\langle\sigma\rangle_i$$

Two component DM:

$$\frac{\epsilon_F}{M_F}\sigma_F + \frac{\epsilon_S}{M_S}\sigma_S < \frac{\sigma_{exp}}{M_{DM}} \qquad (\epsilon_F \equiv \frac{\Omega_F h^2}{0.12}, \quad \epsilon_S \equiv \frac{\Omega_S h^2}{0.12})$$

In our benchmark point

$$\sigma^{SI}_{SN} = 1.62 \times 10^{-44} cm^2, \quad \sigma^{SI}_{FN} = 1.10 \times 10^{-46} cm^2$$

The ϵ_S should be less than 4% to satisfy LUX bound

$1.1 \times 10^{-47} cm^2/GeV$(for $M_{DM} \in [30, 200] GeV$)

Constraints by Collider Machine

- $\sin\theta_0$: $\sin^2\theta_0 = 0.09$
  Current bound: $\sin^2\theta_0 < 0.1$(1505.03831)
  Future perspective: HL-LHC 4×10^{-2}, CEPC 2×10^{-3}.

- Higgs invisible decay:

  $$BR(h\to SS)\simeq 1.7\% \quad (M_s, \simeq 60GeV)$$

  Current bound: $BR_h^{Inv} < 37\%$(1505.05516)
  Future perspective: 14TeV LHC 5%,HL-LHC $2\% - 3\%$

- Z': $M_{Z'} = 4$TeV, $g_{B-L} = 0.5$
  Current bound: LEP-II $M_{Z'}/g_{B-L} \geq 7$TeV,
  LHC $M_{Z'} >$2.95TeV $(g_{B-L}\simeq 0.7)$

Summary

- radiated linear seesaw model
  based on $G_{SM} \times U(1)_{B-L}$
  small M_L generated at 1 loop level
- 2 component DM
  charges restricted by anomaly-free condition
  stability guaranteed by residual $Z_2 \times Z_2'$
- The model can satisfy the current bound from LFV, relic density of DM, direct research of DM and collider machine.
- The detailed phenomenology including research of Z', Ψ and $\eta^{\dagger}_{1,2}$ on collider machine will shows in the paper.