New Radiative Neutrino Mass Model

Vedran Brdar

Faculty of Science, Department of Physics
Zagreb, Croatia

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Scientific experience

- **2012 CERN Summer Student**
  $W\mu\nu$ Zbb vs $W\mu\nu$ Hbb significance observation with CMS experiment simulation

- **Master's thesis at the University of Zagreb**
  Neutrino Masses and Exotic Particles in the LHC Era

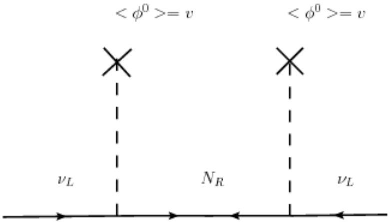
Contents

Introduction

- neutrinos are massless in SM
- oscillation experiments → nonvanishing mass

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta \,|\, \nu_\alpha(t)\rangle|^2 = |\sum_i U_{\beta i} U^*_{\alpha i} e^{-iE_i(t-t_0)}|^2 \quad (1)$$

- $\sum_i m_i < 0.23eV$
- tree-level diagrams (type I,II,III)



- $m_D M_R^{-1} m_D^T$
- experimentally unverifiable

Weinberg Operator

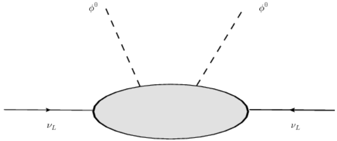
$$
\begin{aligned}
\delta\mathcal{L} &= \frac{f}{\Lambda}(\overline{L_L^C}\tilde{\Phi}^*)(\tilde{\Phi}^\dagger L_L) + h.c \\
&= \frac{f}{\Lambda}[\begin{pmatrix} \overline{\nu_L^C} & \overline{l_L^C} \end{pmatrix} \begin{pmatrix} \phi^0 \\ -\phi^+ \end{pmatrix}]\ [\begin{pmatrix} \phi^0 & -\phi^+ \end{pmatrix} \begin{pmatrix} \nu_L \\ l_L \end{pmatrix}] + h.c. \\
&= \frac{f}{\Lambda}(\overline{\nu_L^C}\phi^0 - \overline{l_L^C}\phi^+)(\phi^0\nu_L - \phi^+ l_L) + h.c. \qquad (2)
\end{aligned}
$$

- symmetry breaking generates Majorana mass term

$$\mathcal{L}_m = -\frac{1}{2}\overline{\psi_L^C} M \psi_L + h.c. \qquad (3)$$

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{d=5} + \mathcal{L}_{eff}^{d=6} + \mathcal{L}_{eff}^{d=7} + ... \qquad (4)$$

- where $\mathcal{L}_{eff}^{d} \sim \frac{1}{\Lambda^{d-4}}\mathcal{O}^d$

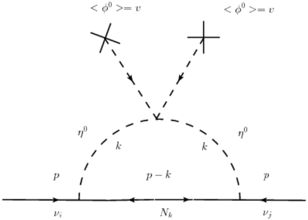


Ma Model

- $\boldsymbol{\eta} \equiv (\eta^+, \eta^0)^T \sim (2, 1, -)$ $\quad N_R \sim (1, 0, -)$
- allowed Yukawa couplings

$$h_{ij}\overline{L_{Li}}\boldsymbol{\eta}^{\mathbf{c}} N_{Rj} + h.c = h_{ij}\overline{\nu_{Li}}\eta^{0*} N_{Rj} - h_{ij}\overline{l_{Li}}\eta^{-} N_{Rj} + h.c. \tag{5}$$

$$V = -\mu_\Phi^2 \Phi^\dagger\Phi + M^2\boldsymbol{\eta}^\dagger\boldsymbol{\eta} + \frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 + \frac{1}{2}\lambda_2(\boldsymbol{\eta}^\dagger\boldsymbol{\eta})^2 + \lambda_3(\Phi^\dagger\Phi)(\boldsymbol{\eta}^\dagger\boldsymbol{\eta}) + \lambda_4(\Phi^\dagger\boldsymbol{\eta})(\boldsymbol{\eta}^\dagger\Phi) + \frac{1}{2}\lambda_5[(\Phi^\dagger\boldsymbol{\eta})^2 + h.c] \tag{6}$$



$$M_{ij} = \frac{1}{8\pi^2} h_{ik} h_{jk} \lambda_5 M_k v^2 \frac{1}{m_0^2 - M_k^2}\left(1 - \frac{M_k^2}{m_0^2 - M_k^2}\ln\frac{m_0^2}{M_k^2}\right) \tag{7}$$

The Model

- particle content

$$\Sigma_R \equiv (\sigma_R^0, \sigma_R^-)^T \sim (2,-1)\ , \quad \Sigma_L \equiv (\sigma_L^0, \sigma_L^-)^T \sim (2,-1) \tag{8}$$

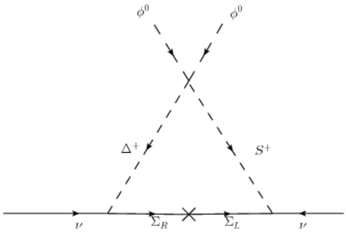
$$\Delta = \frac{1}{\sqrt{2}} \sum_j \tau_j \Delta^j = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^3 & \Delta^1 - i\Delta^2 \\ \Delta^1 + i\Delta^2 & -\Delta^3 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^0 & \Delta^+ \\ \Delta^- & -\frac{1}{\sqrt{2}}\Delta^0 \end{pmatrix} \sim (3,0)\ . \tag{9}$$

$$S^+ \sim (1,2) \tag{10}$$

- potential of scalar sector

$$\begin{aligned} V(\Phi,\Delta,S^+) = & -\mu_\Phi^2(\Phi^\dagger\Phi) + \lambda_1(\Phi^\dagger\Phi)^2 + \mu_S^2 S^- S^+ + \lambda_2(S^- S^+)^2 \\ & + \mu_\Delta^2 Tr(\Delta^2) + \lambda_3(Tr[\Delta^2])^2 + \lambda_4(\Phi^\dagger\Phi)(S^- S^+) + \lambda_5(\Phi^\dagger\Phi)(Tr[\Delta^2]) \\ & + \lambda_6(S^- S^+)(Tr[\Delta^2]) + \lambda_7\Phi^\dagger\Delta\Phi + (\lambda_8\Phi^\dagger\Delta\tilde{\Phi}S^+ + h.c.) \end{aligned} \tag{11}$$

Neutrino Mass from Effective $d = 5$ Operator



- Yukawa coupling

$$g_i \overline{\nu_{Li}^C} \sigma_L^- S^+ + h.c. \qquad f_i \overline{\nu_{Li}} \Delta^+ \sigma_R^- + h.c. \tag{12}$$

$$i\mathcal{L} = (g_i f_j + g_j f_i)\lambda_8 M_\Sigma \overline{\nu_{Li}^C} \nu_{Lj} \phi^0 \phi^0 \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - M_\Sigma^2} \frac{1}{k^2 - m_\Delta^2} \frac{1}{k^2 - m_S^2} \tag{13}$$

$$\mathcal{M}_{ij} = \frac{(g_i f_j + g_j f_i)}{8\pi^2} \lambda_8 v^2 M_\Sigma \frac{M_\Sigma^2 m_S^2 \ln\frac{M_\Sigma^2}{m_S^2} + M_\Sigma^2 m_\Delta^2 \ln\frac{m_\Delta^2}{M_\Sigma^2} + m_S^2 m_\Delta^2 \ln\frac{m_S^2}{m_\Delta^2}}{(m_S^2 - m_\Delta^2)(M_\Sigma^2 - m_S^2)(M_\Sigma^2 - m_\Delta^2)} \tag{14}$$

Model with Z_2 Symmetry

- singet and charged triplet component mix

$$\begin{pmatrix} S^- & \Delta^- \end{pmatrix} \begin{pmatrix} m_S^2 & \lambda_8 v^2 \\ \lambda_8 v^2 & m_\Delta^2 \end{pmatrix} \begin{pmatrix} S^+ \\ \Delta^+ \end{pmatrix} \tag{15}$$

- relation to the mass eigenstates

$$\begin{pmatrix} S^\pm \\ \Delta^\pm \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S_1^\pm \\ S_2^\pm \end{pmatrix} \tag{16}$$

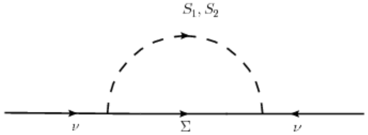
- the diagonalization condition

$$tg(2\theta) = \frac{2\lambda_8 v^2}{m_\Delta^2 - m_S^2} \tag{17}$$

$$\begin{aligned} m_{S_1}^2 &= m_S^2 \cos^2\theta + m_\Delta^2 \sin^2\theta - 2\lambda_8 v^2 \sin\theta\cos\theta \\ m_{S_2}^2 &= m_S^2 \sin^2\theta + m_\Delta^2 \cos^2\theta + 2\lambda_8 v^2 \sin\theta\cos\theta \end{aligned} \tag{18}$$

- relevant Yukawa inteactions

$$\begin{aligned} \mathcal{L} &= g_i \overline{L_{Li}^C} i\sigma_2 \Sigma_L S^+ + f_i \overline{L_{Li}} \Delta \Sigma_R^- + h.c. \\ &= g_i \overline{L_{Li}^C} i\sigma_2 \Sigma_L (\cos\theta S_1^+ + \sin\theta S_2^+) + f_i \overline{\nu_{Li}} (-\sin\theta S_1^- + \cos\theta S_2^-) \sigma_R^- + h.c. \end{aligned} \tag{19}$$



$$-i\Sigma_2 = \int \frac{d^4k}{(2\pi)^4}\overline{\nu_{iL}^C}\nu_{jL}2\{ig_i\cos\theta\frac{i(\not k + M_\Sigma)}{(p-k)^2 - M_\Sigma^2}(-i)\sin\theta f_j\frac{i}{k^2 - m_{S_1}^2} + ig_i\sin\theta\frac{i(\not k + M_\Sigma)}{((p-k)^2 - M_\Sigma^2)}i\cos\theta f_j\frac{i}{k^2 - m_{S_2}^2}\} \quad (20)$$

$$-i\Sigma_2 = -g_i f_j\overline{\nu_{iL}^C}\nu_{jL}2M_\Sigma\sin\theta\cos\theta\int\frac{d^4k}{(2\pi)^4}\{\frac{1}{k^2 - m_{S_1}^2}\frac{1}{k^2 - M_\Sigma^2} - \frac{1}{k^2 - m_{S_2}^2}\frac{1}{k^2 - M_\Sigma^2}\} \quad (21)$$

$$(\mathcal{M}_\nu)_{ij} = -\cos\theta\sin\theta\frac{(g_i f_j + f_i g_j)M_\Sigma}{8\pi^2}\left[\frac{m_{S_1}^2}{m_{S_1}^2 - M_\Sigma^2}\ln\frac{m_{S_1}^2}{M_\Sigma^2} - \frac{m_{S_2}^2}{m_{S_2}^2 - M_\Sigma^2}\ln\frac{m_{S_2}^2}{M_\Sigma^2}\right] \quad (22)$$

- for small value of λ_8 previous result with Weinberg operator is reproduced

Dark Matter

$$\Omega_b h^2 = 0.02264 \pm 0.00050 \qquad \Omega_{DM} h^2 = 0.1138 \pm 0.0045 \tag{23}$$

- CDM ("Cold Dark Matter")
- WIMP
- Dark Matter with minimal SM extension
- Z_2 symmetry

$$Q(Q + \frac{2Y}{\cos\theta_W})\Delta M \tag{24}$$

- **Boltzmann equation**

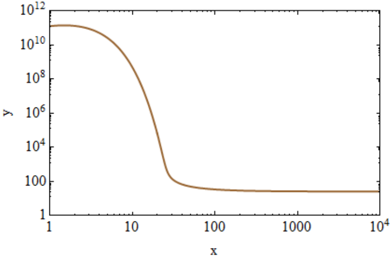
$$\frac{dn_\chi}{dt} = -3Hn_\chi - (n_\chi^2 - n_{eq\chi}^2) < \sigma v > (\chi\chi \to SM) \tag{25}$$

- $\frac{dY}{dt} = -(Y^2 - Y_{eq}^2)s < \sigma v >$ where $Y = \frac{n_\chi}{s}$
- equation in terms of $x = \frac{m}{T}$ variable

$$\frac{dY}{dx} = -\frac{m}{x^2}\sqrt{\frac{\pi g_*}{45G}}(Y^2 - Y_{eq}^2) < \sigma v > \tag{26}$$

- $y = m\sqrt{\frac{\pi g_*}{45G}} < \sigma v > Y$

$$\frac{dy}{dx} = -\frac{1}{x^2}(y^2 - y_{eq}^2) \quad (27)$$

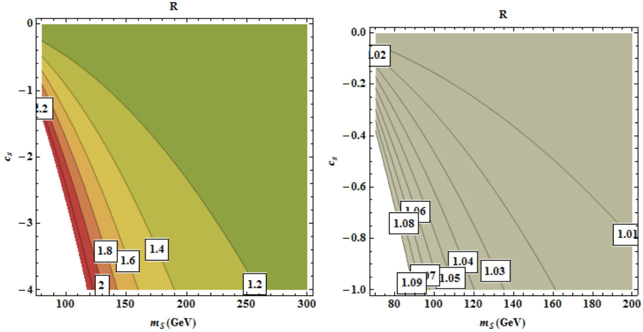


- relic abundance $\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{mY_\infty s_0}{\rho_c}$
- **Coannihilations**
- **Sommerfeld corrections**

$H \to \gamma\gamma$

$$R = \left| 1 + \sum_{S=S_1,S_2} Q_S^2 \frac{c_S}{2} \frac{v^2}{m_S^2} \frac{A_0(\tau_S)}{A_1(\tau_W) + N_C Q_t^2 A_{1/2}(\tau_t)} \right|^2 \quad (28)$$

- significant contribution in $100 - 200 GeV$ range



$$A_1(x) = -x^2\{2x^{-2} + 3x^{-1} + 3(2x^{-1} - 1)\arcsin^2\sqrt{x^{-1}}\} \qquad A_0(x) = -x^{-2}\{x^{-1} - \arcsin^2\sqrt{x^{-1}}\}$$

$$A_{1/2}(x) = 2x^2\{x^{-1} + (x^{-1} - 1)\arcsin^2\sqrt{x^{-1}}\} \quad (29)$$

Model with $U(1)_D$ Gauge Symmetry

- exact or broken to Z_2
- number of degrees of freedom increases
- photon and dark photon mix, same for Higgses
- additional terms in scalar potential

$$\Delta V(\Phi, \Delta) = \lambda_9(\Delta^\dagger \tau_a^{(3)} \Delta)^2 + \lambda_{10}(\Phi^\dagger \tau_a^{(2)} \Phi)(\Delta^\dagger \tau_a^{(3)} \Delta) \qquad (30)$$

- mass splitting can make charged triplet component lighter than neutral
- mixing can raise charged triplet mass which leads to negligible SM coannihilation contribution
- astrophysical results

Conclusions

- neutrinos massless in SM
- our solution : new radiative model

- 1) without Z_2

- 2) with Z_2
- possible Dark Matter candidate?

- 3) with new gauge symmetry

Thank you for your attention

BACKUP SLIDES

Scalar Sector

$$V(\Phi,\Delta,S^+) = -\mu_\Phi^2(\Phi^\dagger\Phi) + \lambda_1(\Phi^\dagger\Phi)^2 + \mu_S^2 S^- S^+ + \lambda_2(S^- S^+)^2 + \mu_\Delta^2 Tr(\Delta^2) + \lambda_3(Tr[\Delta^2])^2 + \lambda_4(\Phi^\dagger\Phi)(S^- S^+) + \lambda_5(\Phi^\dagger\Phi)(Tr[\Delta^2]) + \lambda_6(S^- S^+)(Tr[\Delta^2]) + \lambda_7\Phi^\dagger\Delta\Phi + (\lambda_8\Phi^\dagger\Delta\tilde{\Phi}S^+ + h.c.) \quad (31)$$

- where $Tr[\Delta^2] = \Delta^{0^2} + 2\Delta^+\Delta^-$. Neutral mass matrix :

$$M_0^2 = \begin{pmatrix} 2\lambda_1 v^2 & 2\lambda_5 vu - \frac{1}{\sqrt{2}}\lambda_7 v \\ 2\lambda_5 vu - \frac{1}{\sqrt{2}}\lambda_7 v & 8\lambda_3 u^2 + \frac{\lambda_7}{2\sqrt{2}}\frac{v^2}{u} \end{pmatrix} \quad (32)$$

$$\begin{pmatrix} \phi^0 \\ \Delta^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{pmatrix}\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \quad (33)$$

$$M_{H_1}^2 = \lambda_1 v^2(1+|csc\ 2\theta_0|) + (\frac{2\lambda_7 v^2}{8\sqrt{2}u} + 4\lambda_3 u^2)(1-|csc\ 2\theta_0|)$$

$$M_{H_2}^2 = \lambda_1 v^2(1-|csc\ 2\theta_0|) + (\frac{2\lambda_7 v^2}{8\sqrt{2}u} + 4\lambda_3 u^2)(1+|csc\ 2\theta_0|) \quad (34)$$

Lepton Sector

- Lagrangian mass terms

$$
\begin{aligned}
-\mathcal{L} &= \overline{L_L} Y \phi l_R + \overline{\Sigma_L} \tilde{Y} \phi l_R + M \overline{\Sigma_L} \Sigma_R + \overline{L_L} \tilde{M} \Sigma_R + h.c \\
&= \overline{l_L} \frac{Yv}{\sqrt{2}} l_R + \overline{\sigma_L^-} \frac{\tilde{Y} v}{\sqrt{2}} l_R + M \overline{\sigma_L^-} \sigma_R^- + \overline{l_L} \tilde{M} \sigma_R^- + M \overline{\sigma_L^0} \sigma_R^0 + \overline{\nu_L} \tilde{M} \sigma_R^0 + h.c.
\end{aligned} \tag{35}
$$

- mass term $\tilde{M}$ can be rotated away by field redefinition

$$
-\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\sigma_L^0} & \overline{(\sigma_R^0)^C} \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & M \\ 0 & M & 0 \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ (\sigma_L^0)^C \\ \sigma_R^0 \end{pmatrix} + h.c. \tag{36}
$$

- $m_l \equiv \frac{Yv}{\sqrt{2}} \qquad m' \equiv \frac{\tilde{Y} v}{\sqrt{2}}$

$$
-\begin{pmatrix} \overline{l_L} & \overline{\sigma_L^-} \end{pmatrix} \begin{pmatrix} m_l & 0 \\ m' & M \end{pmatrix} \begin{pmatrix} l_R \\ \sigma_R^- \end{pmatrix} + h.c. \tag{37}
$$

- Grimus/Lavoura diagonalization

$$U = \begin{pmatrix} \sqrt{1 - BB^\dagger} & B \\ -B^\dagger & \sqrt{1 - B^\dagger B} \end{pmatrix} \quad U^\dagger = \begin{pmatrix} \sqrt{1 - BB^\dagger} & -B \\ B^\dagger & \sqrt{1 - B^\dagger B} \end{pmatrix} \tag{38}$$

- $B = B_1 + B_2 + ...$

$$U_L = \begin{pmatrix} 1 & m_l m'^\dagger M^{-2} \\ -M^{-2} m' m_l & 1 \end{pmatrix}$$
$$U_R = \begin{pmatrix} 1 - \frac{1}{2} m'^\dagger M^{-2} m' & m'^\dagger M^{-1} \\ -M^{-1} m' & 1 - \frac{1}{2} M^{-1} m' m'^\dagger M^{-1} \end{pmatrix} \tag{39}$$

$$\begin{aligned}\mathcal{L}_{gauge} &= -e\overline{l_L}\gamma^\mu l_L A_\mu - e\overline{l_R}\gamma^\mu l_R A_\mu - e\overline{\sigma_L^-}\gamma^\mu \sigma_L^- A_\mu - e\overline{\sigma_R^-}\gamma^\mu \sigma_R^- A_\mu \\ &+ \frac{g}{\cos\theta_W}\{\frac{1}{2}\overline{\nu_L}\gamma^\mu \nu_L Z_\mu - (\frac{1}{2} - sin^2\theta_W)\overline{l_L}\gamma^\mu l_L Z_\mu + \frac{1}{2}\overline{\sigma_L^0}\gamma^\mu \sigma_L^0 Z_\mu + \frac{1}{2}\overline{\sigma_R^0}\gamma^\mu \sigma_R^0 Z_\mu \\ &- (\frac{1}{2} - sin^2\theta_W)\overline{\sigma_L^-}\gamma^\mu \sigma_L^- Z_\mu + \overline{l_R} V_{ll}\gamma^\mu l_R Z_\mu + \overline{l_R} V_{l\sigma}\gamma^\mu \sigma_R^- Z_\mu \\ &- \frac{1}{2}\overline{\sigma_R} V_{\sigma l}\gamma^\mu l_R^- Z_\mu + \overline{\sigma_R} V_{\sigma\sigma}\gamma^\mu \sigma_R Z_\mu\} \\ &- \frac{g}{\sqrt{2}}\{\overline{l_L}\gamma^\mu V_{PMNS}\nu_L W_\mu^- + \overline{\sigma_L^-}\gamma^\mu \sigma_L^0 W_\mu^- + \overline{\sigma_R^-}\gamma^\mu \sigma_R^0 W_\mu^- - \overline{l_R^-} m'^\dagger M^{-1}\gamma^\mu \sigma_R^0 W_\mu^-\} + h.c.\end{aligned} \tag{40}$$