Implications of electroweak scale non-sterile ν_R's

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Plan of Talk

- A brief review of the electroweak scale non-sterile right-handed neutrino model: what it is and what it does.

- Pati-Salam extension of the model $\Rightarrow$ Emergence of sterile neutrinos, some of which can have keV masses.

- Constraints on various symmetry breaking scales from $\sin^2\theta_W(M_Z)$.

- Proton decay from color Higgs exchange.

- Extra heavy W's and Z's ($< TeV$) and suggestive connection with the scale governing proton decay.

- Conclusions

A Model of Electroweak scale ν_R's

(hep-ph/0612004, P.L.B**649**, 275 (2007))

- SM with Mirror Fermions.

- Mirror Fermions cannot be much heavier than the electroweak scale.

- ν_R's : Mirror neutral leptons $\Rightarrow$ Not sterile $\Rightarrow$ Can have a "low" mass of O(Λ_{EW}).

Strong Constraints from the Z width and the successful relation $M_W = M_Z \cos\theta_W$ ($\rho = 1$).

SM with Mirror Fermions

- Gauge group: $SU(2)_L \otimes U(1)_Y$. (Actually the subscript L refers to the fact that left-handed SM fermions couple to the W's.)

- Leptonic content:
  - $SU(2)_L$ doublets: SM: $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$; Mirror: $l_R^M = \begin{pmatrix} \nu_R^M \\ e_R^M \end{pmatrix}$

    (In fact the SM $SU(2)_L$ could be called $SU(2)_L \rightarrow SU(2)_V$)

$e_R^M \neq e_R$ because neutral current experiments force e_R to be an $SU(2)_L$ singlet.

- $SU(2)_L$ singlets: SM: e_R ; Mirror: e_L^M

- Quark content:

  - $SU(2)_L$ doublets: SM: $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$; Mirror: $q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}$

  - $SU(2)_L$ singlets: SM: u_R, d_R ; Mirror: u_L^M, d_L^M

Mass terms for neutrinos: (other charged fermions receive masses by coupling to the SM Higgs doublet.)

- Lepton-number conserving Dirac mass:

  Bilinears $\bar{\nu}_L \, \nu_R^M$ can come from $SU(2)_L$ singlet or triplet; $\bar{e}_R \, e_L^M$ (not relevant for neutrinos): $SU(2)_L$ singlet.

  $\Rightarrow$ Simplest possibility: Coupling to a singlet Higgs field

  $$\mathcal{L}_S = g_{Sl} \, \bar{l}_L \, \phi_S \, l_R^M + g'_{Sl} \, \bar{e}_R \, \phi_S \, e_L^M + H.c.$$

  $$\langle \phi_S \rangle = v_S$$

  $\Rightarrow$ Neutrino Dirac mass $m_D = g_{Sl} \, v_S$ $\Rightarrow$ Unrelated to the electroweak scale.

- Lepton-number violating Majorana mass:

  Relevant bilinear $l_R^{M,T} \, \sigma_2 l_R^M$: $SU(2)_L$ singlet or triplet.

Singlet Higgs field with VEV would break charge conservation
$\Rightarrow$ Out!

Only option: an $SU(2)_L$ triplet Higgs $\tilde{\chi} = (3, Y/2 = 1)$.

$$\tilde{\chi} = \frac{1}{\sqrt{2}} \vec{\tau}.\vec{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}}\chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}}\chi^+ \end{pmatrix}$$

$\Rightarrow$ $\mathcal{L}_M = g_M \, l_R^{M,T} \sigma_2 \tau_2 \tilde{\chi} \, l_R^M$

$\langle \chi^0 \rangle = v_M$ breaks $SU(2)_L$!

$\Rightarrow$ Right-handed neutrino Majorana mass $M_R = g_M v_M$

- Seesaw: M_R ; $-m_D^2/M_R$

A $U(1)_M$ global symmetry is imposed to avoid a Majorana mass term for the L-H neutrinos at the lowest order. Other options are possible. The Pati-Salam extension of the model (next) $\Rightarrow$ No need for the global $U(1)_M$!

SM with $SU(2)_L$ Higgs doublets $\Rightarrow$ The successful relation $M_W = M_Z \cos\theta_W$ ($\rho = 1$). Additional triplets $\Rightarrow$ $\rho \neq 1$ unless $v_M \ll \Lambda_{EW}$. Trouble!! Why? BECAUSE the Z-width constraint requires $M_R > M_Z/2$ since ν_R's couple to the Z boson.

Elegant solution (Chanowitz and Golden, Georgi and Machacek):

$\rho \approx 1$ is a manifestation of an approximate custodial global $SU(2)$ symmetry of the Higgs potential. (Recall: In the SM with Higgs doublets, the W mass term is $\frac{1}{2}M_W^2\vec{W}_\mu\vec{W}^\mu$ with $M_W^2 = \frac{1}{4}g^2v^2$, reflecting that custodial symmetry.) How do we obtain $\rho = 1$?

Add $\xi = (3, Y/2 = 0)$ which can be grouped with $\tilde{\chi} = (3, Y/2 = 1)$ to form

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}$$

$\Rightarrow$ Global $SU(2)_L \otimes SU(2)_R$ symmetry of the Higgs potential with:

$\chi = (3, 3)$ and $\Phi = \begin{pmatrix} \phi^0 & -\phi^+ \\ \phi^- & \phi^{0,*} \end{pmatrix} = (2, 2)$

$$\langle \chi \rangle = \begin{pmatrix} v_M & 0 & 0 \\ 0 & v_M & 0 \\ 0 & 0 & v_M \end{pmatrix}$$

and

$$\langle \Phi \rangle = \begin{pmatrix} v_2 & 0 \\ 0 & v_2 \end{pmatrix}$$

$SU(2)_L \otimes SU(2)_R \rightarrow SU(2) \Rightarrow M_W = g\, v/2$ and $M_Z = M_W / \cos\theta_W$, where $v = \sqrt{v_2^2 + 8\, v_M^2}$.

$\Rightarrow$ $\rho = 1$! even if $v_M \sim \Lambda_{EW}$!!

$\Rightarrow$ $M_R \sim O(\Lambda_{EW})$!

(The potential is such that the $U(1)_M$ symmetry is broken explicitely so that there are no NG bosons.)

- How low can M_R be?

  Answer: $M_Z/2$ from the constraint of the Z width.

  $\Rightarrow$ $M_Z/2 < M_R < \Lambda_{EW}$

- m_D or v_S?

  $m_\nu \leq 1\,eV$ + $M_R \sim O(\Lambda_{EW}) \Rightarrow$ $m_D \sim 10^5\,eV$ $\Rightarrow v_S \sim 10^5\,eV$ if $g_{Sl} \sim O(1)$ or e.g. $v_S \sim 10^8\,eV$ if $g_{Sl} \sim 10^{-3}$.

- Some kind of "see-saw" among the charged leptons and their mirror counterparts as well as in the quark sector. However, the mass eigenvalues are, e.g. the charged leptons:

  $$\tilde{m}_l = m_l - \frac{m_D^2}{m_{lM} - m_l} \sim m_l$$

  $$\tilde{m}_{lM} = m_{lM} - \frac{m_D^2}{m_{lM} - m_l} \sim m_{lM}$$

  because $m_D \ll m_{lM} - m_l \Rightarrow$ Practically impossible to detect SM and mirror mixing among the charged sectors.

Two important questions:

- Looking at the $SU(2)_L$ singlets: Mistmatch between quarks and leptons!. More quarks than leptons. How can one complete the assignment?

- Why does one need to impose the global $U(1)_M$ to prevent a Majorana mass term for the left-handed neutrinos?

Natural answers found in quark-lepton unification $\grave{a}$ la Pati-Salam
$\Rightarrow$ Emergence of sterile neutrinos, new heavy W's and Z's, etc...

Quark-lepton unification $\grave{a}$ la Pati-Salam and consequences

p.q.h, arXiv: [hep-ph]

Pati-Salam: quarks and leptons grouped into a quartet of $SU(4)_{PS}$.

Model: $SU(4)_{PS} \otimes SU(2)_L \otimes SU(2)_R \otimes SU(2)'_L \otimes SU(2)'_R$ (similar to the group considered by Hung, Buras, Bjorken (82) and Buras and Hung (2003): Petite Unification)

with

$SU(4)_{PS} \to SU(3)_c \otimes U(1)_S$

$$SU(2)_L \otimes SU(2)_R \to SU(2)_V$$

$$SU(2)'_L \otimes SU(2)'_R \otimes U(1)_S \to U(1)_Y$$

$$Q = T_{3V} + \frac{Y}{2}$$

$$T_{3V} = T_{3L} + T_{3R}$$

$$\frac{Y}{2} = T'_{3L} + T'_{3R} + \sqrt{\frac{2}{3}} T_{15}$$

Fermion representations:

$$\Psi_L = (\begin{pmatrix} u_L \\ d_L \end{pmatrix}_i , \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_i) = (4, 2, 1, 1, 1)$$

$$\Psi_R^M = (\begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}_i, \begin{pmatrix} \nu_R^M \\ e_R^M \end{pmatrix}_i) = (4, 1, 2, 1, 1)$$

$$\Psi_R = (\begin{pmatrix} u_R \\ d_R \end{pmatrix}_i, \begin{pmatrix} N_R \\ e_R \end{pmatrix}_i) = (4, 1, 1, 1, 2)$$

$$\Psi_L^M = (\begin{pmatrix} u_L^M \\ d_L^M \end{pmatrix}_i, \begin{pmatrix} N_L \\ e_L^M \end{pmatrix}_i) = (4, 1, 1, 2, 1)$$

Emergence of sterile ($SU(2)_V$ singlet) neutrinos of both helicities: N_L and N_R!!

Generalized "see-saw" involving N_L and N_R

- Dirac mass terms involve

$$\bar{\Psi}_L \times \Psi_R = (1 + 15, 2, 1, 1, 2),$$

$$\bar{\Psi}^M_R \times \Psi^M_L = (1 + 15, 1, 2, 2, 1),$$

$$\bar{\Psi}_L \, \Psi^M_R = (1 + 15, 2, 2, 1, 1),$$

$$\bar{\Psi}_R \times \Psi^M_L = (1 + 15, 1, 1, 2, 2)$$

Higgs fields:

$$\Phi_S = (1,2,1,1,2)\,;\;\Phi_A = (15,2,1,1,2),$$

$$\Phi_S^M = (1,1,2,2,1)\,;\;\Phi_A^M = (15,1,2,2,1),$$

$$\tilde{\Phi}_S = (1,2,2,1,1),$$

$$\Phi_S^N = (1,1,1,2,2).$$

- Majorana mass terms involve

$$\Psi_R^{M,T}\,\sigma_2\,\Psi_R^M = (4 \times 4 = 6 + 10, 1, 1 + 3, 1, 1)$$

$$\Psi_R^T\sigma_2\,\Psi_R = (4 \times 4 = 6 + 10, 1, 1, 1, 1 + 3)$$

Higgs fields

$$\Phi_{10} = (\bar{10} = 1 + \bar{3} + \bar{6}, 1, 3, 1, 1)$$

$$\Phi_{10N} = (\bar{10} = 1 + \bar{3} + \bar{6}, 1, 1, 1, 3)$$

- VEV's:

$$\langle \phi^{0}_{S,u} \rangle = v_u \,;\, \langle \phi^{0}_{S,d} \rangle = v_d$$

$$\langle \phi^{0,M}_{S,u} \rangle = v^M_u \,;\, \langle \phi^{0,M}_{S,d} \rangle = v^M_d$$

$$\frac{\langle \phi^{15}_{A,u} \rangle}{2\sqrt{6}} = v_{15,u} \,;\, \frac{\langle \phi^{15}_{A,d} \rangle}{2\sqrt{6}} = v_{15,d}$$

$$\frac{\langle \phi^{M,15}_{A,u} \rangle}{2\sqrt{6}} = v^M_{15,u} \,;\, \frac{\langle \phi^{M,15}_{A,d} \rangle}{2\sqrt{6}} = v^M_{15,d}$$

$$\langle \tilde{\Phi}_S \rangle = \begin{pmatrix} v_S & 0 \\ 0 & v_S \end{pmatrix}$$

$$\langle \Phi_S^N \rangle = \begin{pmatrix} v_S^N & 0 \\ 0 & v_S^N \end{pmatrix}$$

- Generalized see-saw:

$$M_4 = \begin{pmatrix} 0 & m_D & 0 & m_{\nu_L N_R} \\ m_D & M_R & m_{\nu_R^M N_L} & 0 \\ 0 & m_{\nu_R^M N_L} & 0 & m_D^N \\ m_{\nu_L N_R} & 0 & m_D^N & M_R^N \end{pmatrix}$$

- One numerical example (there are several) with e.g. $M_R = 100\, GeV$:

$$\frac{M_4}{M_R} = \begin{pmatrix} 0 & 10^{-6} & 0 & 10^{-8} \\ 10^{-6} & 1 & 10^{-8} & 0 \\ 0 & 10^{-8} & 0 & 1.8.10^{-4} \\ 10^{-8} & 0 & 1.8.10^{-4} & 1 \end{pmatrix}$$

$$m_1 \approx -0.1\, eV$$

$$\tilde{\nu}_1 \approx -\nu_L + 10^{-6}\,\nu_R^M + 5.6 \times 10^{-5}\,N_L - 5.6 \times 10^{-11}\,N_R$$

$$m_2 \approx 100\, GeV$$

$$\tilde{\nu}_2 \approx 10^{-6}\,\nu_L + \nu_R^M + 10^{-8}\,N_L - 2 \times 10^{-12}\,N_R$$

$$m_{S1} \approx -3.24\, keV$$

$$\tilde{\nu}_{S1} \approx 5.6 \times 10^{-5}\,\nu_L + 10^{-8}\,\nu_R^M - N_L 1.8 \times 10^{-4}\,N_R$$

$$m_{S2} \approx 100\, GeV$$

$$\tilde{\nu}_{S2} \approx 10^{-8}\, \nu_L + 0\, \nu_R^M + 1.8 \times 10^{-4}\, N_L + N_R$$

- One can find examples where N_L and N_R have masses of order $O(keV)'s$ and $O(MeV)'s$ respectively.

Constraint from $\sin^2\theta_W(M_Z)$

$$G \xrightarrow{M} G_1 \xrightarrow{\tilde{M}} G_2 \xrightarrow{M_{LR}} SU(3)_c \otimes SU(2)_V \otimes U(1)_Y$$

$$G = SU(4)_{PS} \otimes SU(2)_L \otimes SU(2)_R \otimes SU(2)'_L \otimes SU(2)'_R$$

$$G_1 = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes SU(2)'_L \otimes SU(2)'_R \otimes U(1)_S$$

$$G_2 = SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$$

- We require

$$0.2308 \leq \sin^2 \theta_W(M_Z^2) \leq 0.2314$$

- Basic formulae:

$$sin^2\tilde{\theta}_W(M_{LR}^2) = sin^2\tilde{\theta}_W^0\{1 - C_S^2\frac{\tilde{\alpha}(M_{LR}^2)}{\alpha_S(M_{LR}^2)} - 8\pi\tilde{\alpha}(M_{LR}^2)$$

$$[K \ln(\frac{\tilde{M}}{M_{LR}}) + K' \ln(\frac{M}{\tilde{M}})]\}$$

$$sin^2\tilde{\theta}_W^0 = \frac{1}{3}$$

$$K = b_1 - 2\,b_2 - \frac{2}{3}b_3$$

$$K' = C_S^2\,(\tilde{b} - b_3)$$

- From $\sin^2\theta_W(M_{LR}^2) = \frac{2\sin^2\tilde{\theta}_W(M_{LR}^2)}{1+\sin^2\tilde{\theta}_W(M_{LR}^2)}$ $\Rightarrow$ $\sin^2\theta_W(M_Z)$.

- For $\frac{M_{LR}}{M_Z} = 5 - 10$ $\Rightarrow$ $\tilde{M} \sim 10^7 - 10^8\, GeV$ and $M \sim 10^{15} - 10^{17}\, GeV$.

- M_{LR}: "mass" of the heavy W's and Z.

  M: quark-lepton unification mass.

Implications

- Electroweak scale non-sterile right-handed neutrinos can be produced and detected (through e.g. like-sign dilepton events) at the LHC.

- A Pati-Salam extension of the electroweak scale non-sterile ν_R model completes the particle assignment $\Rightarrow$ Introduction of the sterile N_L and N_R.

  keV N_L: Warm dark matter? Molecular hydrogen and early star formation? Pulsar kicks??

What about the heavier N_R?

- W's and Z's (orthogonal states of SM W's and Z) "light" enough to be detected at the LHC? Its mass is correlated to the PS mass M. Through the color-non-singlet scalars, proton decay can occur and is governed in parts by M.

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Backup slide:

Phenomenology of Electroweak Scale ν_R's

Majorana neutrinos with electroweak scale masses

$\Rightarrow$ lepton-number violating processes at electroweak scale energies.

One can produce ν_R's and observe their decays at colliders (Tevatron(?), LHC,ILC...) $\Rightarrow$ Characteristic signatures: like-sign dilepton events (first examined in the context of L-R models by Keung and Senjanovic). $\Rightarrow$ A high-energy equivalent of neutrinoless double beta decay. That could be the smoking gun for Majorana neutrinos!

- Production of ν_R's (Tevatron, LHC, ILC):

  $$q + \bar{q} / e^+ + e^- \longrightarrow Z \longrightarrow \nu_R + \nu_R$$

  and e.g.

  $$u + \bar{d} \longrightarrow W^+ \longrightarrow \nu_R + l_R^{M,+}$$

- Decays:
  - ν_R's are Majorana and can have transitions $\nu_R \longrightarrow l_R^{M,\mp} + W^{\pm}$.
  - A heavier ν_R can decay into a lighter l_R^M and
    - $q + \bar{q} / e^+ + e^- \longrightarrow Z \longrightarrow \nu_R + \nu_R \longrightarrow l_R^{M,\mp} + l_R^{M,\mp} + W^{\pm} + W^{\pm}$

$\rightarrow l_L^{\mp} + l_L^{\mp} + W^{\pm} + W^{\pm} + \phi_S + \phi_S$, where ϕ_S would be missing energy.

* $u + \bar{d} \rightarrow W^{+} \rightarrow \nu_R + l_R^{M,+} \rightarrow l_R^{M,+} + l_R^{M,+} + W^{-}$

  $\rightarrow l_L^{+} + l_L^{+} + W^{-} + \phi_S + \phi_S$

Interesting like-sign dilepton events! One can look for like-sign dimuons for example.

Careful with background! For example one of such backgound could be a production of $W^{\pm}W^{\pm}W^{\mp}W^{\mp}$ with 2 like-sign W's decaying into a charged lepton plus a neutrino ("missing energy"), O(α_W^2) in amplitude.

In addition, depending on the lifetime of the mirror leptons, the SM leptons appear at a displaced vertex. Detailed phenomenological analyses are in preparation: SM background, event reconstructions, etc...