Electroweak scale right-handed neutrinos

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Fermilab, 2007

Plan of Talk

- Highlights of the Seesaw Mechanism: $\frac{m_D^2}{M_R}$, M_R with $M_R \gg m_D$.

- Implications of mirror fermions: Why M_R can be of the order of the electroweak scale $\Lambda_{EW} = 246\, GeV$, i.e. $M_Z/2 < M_R < \Lambda_{EW}$.

- A probe of electroweak-scale neutrinos $\Rightarrow$ a probe of the electroweak symmetry breaking sector.

- Implications of electroweak scale ν_R's: Lepton-number violating processes at electroweak scale energies; production ν_R's at colliders and their decays into like-sign dileptons..

- Further implications of the model: the role of mirror fermions in $\mu \to e\,\gamma$ e.g.

- Conclusions

Seesaw Mechanism

The Seesaw mechanism in a nutshell:

- In "standard scenarios", ν_R's are SM singlets (sterile) $\Rightarrow$ Implications on the sizes of the Dirac and Majorana masses.

- Dirac mass term:

  $\mathcal{L}_D = g_L \bar{l}_L \phi \nu_R + H.c.$

  $l_L = (\nu_L, e_L)$ and $\phi = (\phi^0, \phi^-)$ are $SU(2)_L$ doublets.

$\langle \phi \rangle = (\Lambda_{EW}/\sqrt{2}, 0)$ with $\Lambda_{EW} \approx 246\, GeV \Rightarrow m_D = g_L \Lambda_{EW}/\sqrt{2}$

$\Rightarrow$ Dirac mass $\propto$ Electroweak scale Λ_{EW}.

- Majorana mass term:

  $\mathcal{L}_M = M_R \nu_R^T \sigma_2 \nu_R$

  It violates lepton number by two units i.e. $\Delta L = 2$.

- Seesaw:

  For $M_R \gg m_D \Rightarrow$ One small eigenvalue: $-\frac{m_D^2}{M_R}$ and one large: M_R.

  Since $m_D \propto \Lambda_{EW}$, a light neutrino mass of O($< 1\, eV$) implies $M_R \gg \Lambda_{EW}$. Typically, $M_R \sim 10^{13}\, GeV$.

- Implications:
  - Neutrinos are Majorana particles i.e. $\nu = \nu^c$.
  - Tests of Majorana nature of ν?
    - Neutrinoless double beta decay ($\Delta L = 2$): $< m_{\beta\beta} >= [\sum |U_{ei}|^2 m_i^2]^{1/2} < 0.35\, eV$. Much more to be done!

      This only probes the light neutrino sector.

      Where else can one probe the Majorana nature of the neutrinos?

    - $\Delta L = 2$ processes might be probed at colliders (see e.g. Han and Zhang) if the sterile ν is light enough i.e. 10-400 GeV (But why so light? Fine tuning? Kersten and Smirnov). (They only appear in intermediate states and cannot be directly produced, being sterile.) See also works by de Gouvea and collaborators.

– In the "standard" seesaw scenarios, one cannot directly probe the heavy (practically right-handed) neutrino sector because of: (1) sterility and (2) $M_R \gg \Lambda_{EW}$.

- Since the only thing we more or less "know" is that the light neutrino masses are less than 1 eV or so (and of course part of the leptonic mixing matrix), is it possible to construct a model in which $M_R \leq \Lambda_{EW}$? Can ν_R be non-sterile i.e. they can interact directly with W and Z?

  If so...

Advantages: One can directly produce ν_R's at colliders and see if they exist or not. One can test the see-saw mechanism and the Majorana nature of neutrinos by looking at the heavy sector directly.

The role of mirror fermions: Introduction of heavy mirror fermions which could also be tested either directly by collider searches or indirectly in e.g. $\mu \rightarrow e\,\gamma$.

A Model of Non-sterile Electroweak scale ν_R's

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

Objective: Construct a model in which ν_R's are not sterile i.e. non-singlet under $SU(2)_L \otimes U(1)_Y$, and have a "low" mass of O(Λ_{EW}).

Constraints:

- A non-sterile ν_R will couple to the Z boson $\Rightarrow$ Strong constraint from the Z width!

- A Majorana bilinear $\nu_R^T \sigma_2 \nu_R$ will transform non-trivially under $SU(2)_L \Rightarrow$ Strong constraint on the $SU(2)_L$ Higgs field which couples to that bilinear and which develops a non-zero vacuum expectation value, in particular one has to preserve the successful relation $M_W = M_Z \cos\theta_W$ ($\rho = 1$)!

Possibilities: Mirror Fermions

- Simplest possibility: ν_R as part of a doublet of $SU(2)_L$. Who is the partner? A right-handed mirror charged lepton.

- $SU(2)_L$ doublets:

SM: $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

Mirror: $l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}$

(Notice this is different from $l_R^c = i\sigma_2 l_L^*$)

$e_R^M \neq e_R$ 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

- In addition to heavy mirror leptons, the model also contains heavy mirror quarks. It is amusing to note that anomaly cancellation can be done between SM fermions and their mirror counterparts. One does not need the usual cancellation between quarks and leptons. Charge quantization: sign of GUT?

- Also the requirement of the vanishing of the non-perturbative Witten anomaly for $SU(2)_L \Rightarrow$ Even number of doublets can be accomplished with just leptons or just quarks!

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

- Lepton-number conserving Dirac mass:

  It is proportional to the bilinear $\bar{l}_L\, l_R^M$ which could be an $SU(2)_L$ singlet or triplet. One also has (for the charged leptons) the bilinear involving $SU(2)_L$ singlets, $\bar{l}_L^M\, l_R$ (not relevant for neutrinos). $\Rightarrow$ Simplest possibility: Coupling to a singlet Higgs field

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

  $\langle \phi_S \rangle = v_S \Rightarrow m_D = g_{Sl}\, v_S \Rightarrow$ Unrelated to the electroweak scale.

  Since neutrino masses are so different from their charged counterparts, why should the Dirac masses be related to the electroweak scale anyway!

- Lepton-number violating Majorana mass:

  The relevant bilinear is $l_R^{M,T}\,\sigma_2 l_R^M$. This cannot couple to a singlet Higgs field since its VEV would break charge conservation $\Rightarrow$ Only option: an $SU(2)_L$ triplet Higgs $\tilde{\chi} = (3, Y/2 = 1)$.

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

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

  $$\langle\chi^0\rangle = v_M \Rightarrow M_R = g_M\, v_M$$

  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.

This VEV also breaks $SU(2)_L$!

The successful relation $M_W = M_Z \cos\theta_W$ ($\rho = 1$) which relies primarily on $SU(2)_L$ Higgs fields being doublets would be spoiled unless $v_M \ll \Lambda_{EW}$. Trouble!!

With just $\tilde{\chi}$, $\rho = 1/2$. ρ can be significantly different from 1 at tree-level when both doublet and triplet with comparable V.E.V's are present!

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.) To maintain that custodial symmetry, one can add an additional Higgs triplet $\xi = (3, Y/2 = 0)$ 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 χ being $(3,3)$ of that global symmetry. The complex Higgs doublet belong to a $(2,2)$ representation: $\Phi = \begin{pmatrix} \phi^0 & -\phi^+ \\ \phi^- & \phi^{0,*} \end{pmatrix}$

With

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

and

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

breaking global $SU(2)_L \otimes SU(2)_R$ down to a custodial $SU(2)$ symmetry with $M_W = g\,v/2$ 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.)

Two questions:

- How low can M_R be?

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

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

  A rather “narrow” range!

- Actually, since $v = \sqrt{v_2^2 + 8\, v_M^2} \sim 246\, GeV$, this can have a quite interesting implication on the form of the quark mass matrices themselves since the top quark mass is $\sim 171\,GeV$ and quarks couple only to the Higgs doublet. In fact, with $v_M > M_Z/2 \sim 46\,GeV$, the scale that appears in front of the Up-quark mass matrix, namely $g_U\, v_2/\sqrt{2}$ is constrained such that, for $g_U \sim O(1)$, $v_2/\sqrt{2} < 147\,GeV$ $\Rightarrow$ the mass matrix of the Up-quark sector might be of the almost democratic type for example. This also would imply that mirror fermions cannot be too heavy.

- What about m_D or rather the VEV v_S of the singlet Higgs field?

  Answer: With the light neutrino mass $m_\nu \leq 1\,eV$ and $M_R \sim O(\Lambda_{EW})$ $\Rightarrow$ $m_D \sim 10^5\,eV$ $\Rightarrow$ $v_S \sim 10^5\,eV$ if we assume $g_{Sl} \sim O(1)$ or e.g. $v_S \sim 10^8\,eV$ if $g_{Sl} \sim 10^{-3}$.

(Possible cosmological implications of a singlet scalar field e.g. the possibility of of the link between Mass-Varying Neutrinos (MaVans) and Dark Energy: Hung; Gu, Wang and Zhang; Fardon, Nelson and Weiner. Also, constraints from CMB? Other astrophysical implications?)

- 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.

- Last but not least: It is possible to avoid the imposition of the $U(1)_M$ global symmetry. The see-saw mechanism will look however very different from the above $\Rightarrow$ Interesting implications concerning the see-saw matrix $\Rightarrow$ Possibility of dynamical electroweak symmetry breaking. Work in preparation.

Phenomenology of Electroweak Scale ν_R's

Since we are dealing with Majorana neutrinos with electroweak scale masses, it is not surprising that we should expect lepton-number violating processes at electroweak scale energies. (For singlet ν_R's, the issue is much more complex, involving delicate cancellations to keep the light neutrinos light.) In particular, we should be able to produce ν_R's and observe their decays at colliders (LHC, etc...) $\Rightarrow$ Characteristic signatures: like-sign dilepton events $\Rightarrow$ A high-energy equivalent of neutrinoless double beta decay. That could be the smoking gun for Majorana neutrinos!

- From $l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}$, ν_R's interact with the Z and W bosons! They are not sterile any more.

  Recall $M_Z/2 < M_R < \Lambda_{EW}$.

- Production of ν_R's:

  $q + \bar{q} \rightarrow Z \rightarrow \nu_R + \nu_R$

  and e.g.

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

  – ν_R's are Majorana and can have transitions $\nu_R \rightarrow l_R^{M,\mp} + W^{\pm}$.

  – A heavier ν_R can decay into a lighter l_R^M and

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

$\nu_R + l_R^{M,+} \rightarrow l_R^{M,+} + l_R^{M,+} + W^{-} \rightarrow l_L^{+} + l_L^{+} + W^{-} + \phi_S + \phi_S$,

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

Since this involves missing energies $\Rightarrow$ 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").

But...This is of O(α_W^2) in amplitude smaller than the above process. Another background: $H + W \rightarrow WWW$. In addition, depending on the lifetime of the mirror leptons, the SM leptons appear at a displaced vertex.

- Lepton-number violating process with like-sign dileptons can also occur with ν_R's in the intermediate state (from $W^{\pm} W^{\pm} \rightarrow l_L^{\pm} + l_L^{\pm}$) but that involves very small mixing angles of the order $\frac{m_\nu}{M_R}$.

- Detailed phenomenological analyses are in preparation: SM background, event reconstructions, etc...

Other phenomenological consequences

- Triplet Higgs scalars:
  - Doubly charged scalars in $\tilde{\chi}$!
  - $\tilde{\chi}$ can be produced at colliders.
  - $\tilde{\chi}$ couples to W and Z and to right-handed neutrinos and mirror charged leptons which subsequently decay into SM leptons.
  - ξ does not couple to fermions but to W and Z. Can look for them through W and Z.

- Mirror fermions:

  The charged mirror fermions decay into SM charged fermions plus (missing energy) ϕ_S. The decay length will depend primarily on the coupling g_{Sl}!

- Singlet scalar ϕ_S:

  ϕ_S can be as light as few hundreds keV's. Possible cosmological and astrophysical implications? e.g. $\phi_S + \phi_S^* \rightarrow l^+ + l^-$ with a charged mirror lepton in the t-channel.

- LFV processes such as $\mu \rightarrow e\,\gamma$ are being investigated.

  For $\mu \rightarrow e\,\gamma$, we make the following observations:

- Dominant contribution from the couplings:

  Doublets: $g_{Sl}\,\bar{E}_L^0\,E_R^{0,M}\,\phi_S + H.c.$, with $E_L^0 = (e,\mu,\tau)_L^0$ and $E_R^{0,M} = (e^M,\mu^M,\tau^M)_R^0$.

  Singlets: $g_{Sl}\,\bar{E}_R^0\,E_L^{0,M}\,\phi_S + H.c.$, with $E_R^0 = (e,\mu,\tau)_R^0$ and $E_L^{0,M} = (e^M,\mu^M,\tau^M)_L^0$.

- In terms of mass eigenstates:

  $E_L^0 = U_L^l E_L$

  $E_R^{0,M} = U_R^M E_R^M$

  $E_R^0 = U_R^l E_R$

  $E_L^{0,M} = U_L^M E_L^M$

  $\Rightarrow g_{Sl}\,\bar{E}_L\,U_{lM,D}\,E_R^M\,\phi_S + H.c.$

  Similarly:

$$g_{Sl}\,\bar{E}_R\,U_{lM,S}\,E_L^M\,\phi_S + H.c.$$

$$U_{lM,D} = U_L^{l,\dagger}\,U_R^M$$

$$U_{lM,S} = U_R^{l,\dagger}\,U_L^M$$

- One loop contribution to $\mu \to e\,\gamma$ with ϕ_S and $E_{R,L}^M$ propagating in the loop.

- Amplitudes of decay rate depends on

  1) $\sum_i \frac{U_{\mu\,i,D}\,U^*_{e\,i,D}}{m_i}$ with m_i the masses of the mirror charged leptons.

  2) $\sum_i \frac{U_{\mu\,i,S}\,U^*_{e\,i,S}}{m_i}$.

  3) g_{Sl}^2.

- The decay rate vanishes if the mirror charged leptons are degenerate $m_i = m$ since then $\sum_i U_{\mu\, i,(D,S)}\, U^*_{e\, i,(D,S)} = 0$ by unitarity $\Rightarrow$ the branching ratio for $\mu \rightarrow e\,\gamma$ will depend on the mirror charged lepton mass differences besides the mixing angles and g_{Sl}^2: B($\mu \rightarrow e\,\gamma$) $\sim 10^{-3}\, \frac{M_W^4}{m^4}\, g_{Sl}^4\, (|\epsilon_2 U_{\mu\, 2,D}\, U^*_{e\, 2,D} + \epsilon_3 U_{\mu\, 3,D}\, U^*_{e\, 3,D}|^2 + |\epsilon_2 U_{\mu\, 2,S}\, U^*_{e\, 2,S} + \epsilon_3 U_{\mu\, 3,S}\, U^*_{e\, 3,S}|^2)/m_\mu^2$, where $m_1 = m$; $m_2 = m + \epsilon_2$; $m_3 = m + \epsilon_3$.

– B($\mu \rightarrow e\,\gamma$) can be reachable and can provide interesting glimpses on e.g. the product of the matrices that diagonalize the SM charged lepton mass matrix and that of the mirror charged leptons.

– Connection between low energy : $\mu \rightarrow e\,\gamma$ and high energy: the decay length of the charged mirror lepton, through the coupling g_{Sl}.

- The mass splitting between different mirror generations cannot be large. Constraint from $\mu \to e\,\gamma$: They are close in mass $\Rightarrow$ Intersting implications concerning their searches!

- Last but not least: The addition of mirror generations to the S parameter can be offset by a negative contribution from the triplet scalar sector.

The extra Higgses and heavy mirror fermions could, in principle, be searched for at future colliders: LHC, ILC, etc...

Conclusions

- It is possible to have a seesaw mechanism in which the Majorana mass of the right-handed neutrinos can be of the order of the electroweak scale. There is no reason why it should be close to some GUT scale.

- The lepton-number violating processes coming from the "heavy" non-sterile ν_R's can now be accessible experimentally at colliders!

- Rich spectrum of particles which can be tested in a not-too-distant future.

- Interesting implications concerning $\mu \rightarrow e\,\gamma$.