Electroweak scale right-handed neutrinos

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Aspen, 2007

Plan of Talk

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

- 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..

- 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: $< m_{\beta\,\beta} >= [\sum |U_{ei}|^2 m_i^2]^{1/2} < 0.35\, eV$. Much more to be done!

      This probes the light neutrino sector.
    - $\Delta\, L\ =\ 2$ 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?

  If so...

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

  Prices (or rewards?): Introduction of heavy mirror fermions which could also be tested.

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 and have a "low" mass of O(Λ_{EW}).

Constraints:

- A non-sterile ν_R will couple to the Z boson ⇒ 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 Higgs field which couples to that bilinear and which develops a non-zero vacuum expectation value, namely one has to preserve the successful relation $M_W = M_Z \cos\theta_W$!

Possibilities:

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

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

- $e_R^M \neq e_R$ because neutral current experiments force e_R to be an $SU(2)_L$ singlet. Equivalently, the mirror singlet charged lepton will be e_L^M.

Mass terms:

- 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). ⇒ 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.)

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!!

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. 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

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

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 $v = \sqrt{v_2^2 + 8\,v_M^2}$ and $\langle\Phi\rangle = v_2/\sqrt{2}$. Φ is a doublet.

$\Rightarrow$ $\rho = 1$ 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!

- 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 $M_R \sim O(\Lambda_{EW}) \Rightarrow v_S \sim 10^5\,eV$

  (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?)

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.

- 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:

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

  - 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.

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

Since this involves missing energies ⇒ 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. 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.

- 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.

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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.