Electroweak scale right-handed neutrinos

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Plan of Talk

- The question of parity restoration at high energies: Gauge Left-Right symmetric model vs SM with mirror fermions.

- Implications of mirror fermions: Why the right-handed neutrinos can have electroweak-scale masses.

- 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 $\mu \to e\,\gamma$ and electroweak precision constraints.

- Conclusions

The question of parity restoration at high energies

- Observed parity violation at low energies well described by the SM $SU(2)_L \otimes U(1)_Y$: Left-handed fermions in doublets; Right-handed fermions being singlets. No Right-handed neutrinos.

  Parity violation: an intrinsic feature of nature or is it just a low energy effect?

- Intrinsic: No right-handed neutrinos $\Rightarrow$ No neutrino masses, in principle. (Efforts to generate Majorana neutrino masses with only left-handed neutrinos seem to be disfavoured by experiments.)

IF NOT...?

- Low energy effect: Parity restoration at high energies. How and how high?

  - Most popular model: The left-right symmetric model $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ with $M_{W_R} \gg M_{W_L}$ (Mohapatra, Pati, Senjanovic).

    PARITY VIOLATION: $E \ll M_{W_R}$.

    PARITY RESTORATION: $E \gg M_{W_R}$.

    $\Rightarrow$ Implications concerning neutrino masses:

Tiny neutrino masses linked to large suppression of V+A interactions.

- Mirror Fermions in $SU(2)_L \otimes U(1)_Y$: (Earlier mention by Lee and Yang, 1957)

  SM fermions: left-handed doublets; right-handed singlets.

  Mirrors: right–handed doublets; left-handed singlets.

  Manifest parity violation in the weak interactions of SM fermions (at tree level)!

  PARITY "RESTORATION": $E \gg M_{mirror} > M_{SM}$.

  $\Rightarrow$ Very different implications concerning neutrino masses! But one common feature:

Tiny neutrino masses linked to large suppression of V+A interactions

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 $O(\Lambda_{EW})$.

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

$e_R^M \neq e_R$ 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?

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 $\tilde{\chi} = (3, Y/2 = 1)$.

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

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

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

$\Rightarrow$ Right-handed neutrino Majorana mass $\boxed{M_R = g_M \, v_M}$

- Seesaw: $\boxed{M_R}$; $\boxed{-m_D^2/M_R}$

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.

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

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

$SU(2)_L \otimes SU(2)_R \to SU(2) \Rightarrow M_W = g\,v/2$ 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.

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

- m_D or v_S?

  $m_\nu \leq 1\,eV$ + $M_R \sim O(\Lambda_{EW}) \Rightarrow \boxed{m_D \sim 10^5\,eV} \Rightarrow v_S \sim 10^5\,eV$ 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.

- 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 $\Rightarrow$ Possibility of dynamical electroweak symmetry breaking. Work in preparation.

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):

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

  and e.g.

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

- Decays:
  - 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
    * $q + \bar{q} / e^+ + e^- \rightarrow Z \rightarrow \nu_R + \nu_R \rightarrow l_R^{M,\mp} + l_R^{M,\mp} + W^\pm + W^\pm$

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

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

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

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...

Other phenomenological consequences

- Triplet Higgs scalars (under investigation with Alfredo Aranda):

  Doubly charged scalars in $\tilde{\chi}$ can be searched at colliders.

  The issue of Electroweak Symmetry Breaking is linked in our scenario to the issue of Electroweak scale right-handed neutrinos!

- 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}!

- $\mu \to e\,\gamma$

  - Dominant contribution from the couplings (assuming $g_{Sl} = g^{'}_{Sl}$):

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

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

  - In terms of mass eigenstates:

    $E^0_L = U^l_L E_L$

    $E^{0,M}_R = U^M_R E^M_R$

    $E^0_R = U^l_R E_R$

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

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

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

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

3) g^2_{Sl}.

– $\Gamma(\mu \to e\,\gamma) = 0$ if $U_D = U_S$ and degenerate $m_i = m$.
  $\Gamma(\mu \to e\,\gamma) \neq 0$ otherwise $\Rightarrow$ Implications concerning mass matrices!

– B($\mu \to e\,\gamma$) 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. The mass splitting between different mirror generations cannot be large.

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

- Vertices similar to that for $\mu \rightarrow e\,\gamma$ are calculated at one loop to put constraints on parameters such as g_{Sl} using electroweak precision quantities. In particular, how large are V+A contributions to the normal weak interactions? Work in preparation with Ha Dai Phuoc.

Conclusions

- SM with Mirror Fermions $\Rightarrow$ Electroweak scale right-handed neutrinos

- The lepton-number violating processes coming from the electroweak scale 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. Potential implications for electroweak symmetry breakin

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