Electroweak scale active ν_R's and implications

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Beyond the 3SM Generation at the LHC era, 4-5 September 2008

Five (surely more) reasons why there is life beyond the 3SM generation

Beyond 3SM generation? Extra fermions (left-handed or right-handed) which are EW non-singlets.

- Why not? What's so special about about 3 generations?

- Not ruled out experimentally. Might even have implications concerning the SM Higgs boson (Kribs et al), EWSB (Holdom,..), rare B decays (Hou, Soni,..), etc...Recent analysis of experimental constraints on a 4th generation $\rightarrow$ more flexible regions of allowed masses and mixings than previously believed (Sher and pqh).

- A 4th generation might even bring about coupling constant unification at 2-loop level without the need for SUSY (pqh '97).

- Mirror replication of SM families: Left-handed $\longrightarrow$ Right-handed. Active right-handed neutrinos $\longrightarrow$ Possibility of electroweak-scale ν_R's $\longrightarrow$ Electroweak-scale see-saw mechanism. Directly testing it at the LHC finally?

- Quark-lepton unification à la Pati-Salam $\longrightarrow$ Extra EW singlet neutrinos with astrophysical implications $\longrightarrow$ Further embedding into $SO(2m+4)$ groups leads to an argument in favor of 4 (SM and mirror) generations.

The last 2 items: Focus of this talk.

Mirror fermions and electroweak scale ν_R's

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

Suppose there is a mirror replication of the SM fermions.

Questions:

- What fundamental roles could mirror fermions play in our understanding of the SM?

- Would the existence of mirror fermions necessitate an extended Higgs sector?

- If they exist, how do we detect them?

- Constraints from EW precision data?

- Could there be theoretical motivations for such mirror fermions?

- If yes, is there anything else?

- If yes, could there be some insight into the fundamental question of the number of generations itself?

What can mirror fermions do?

I) What do we mean by mirror fermions?

- EW gauge group: $SU(2)_L \otimes U(1)_Y$.

- Leptonic content:

  Mirror fermions: same gauge group, same fermion representations but with opposite chiralities to SM fermions.

  – $SU(2)_L$ 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 a "vector-like" model: $SU(2)_L \rightarrow SU(2)_V$)

$e_R^M \neq e_R$: Neutral current experiments $\rightarrow$ e_R: $SU(2)_L$ 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

II) Now that we have defined what mirror fermions are, what can they do?

Focus first on leptons.

- Mirror fermions have the same EW gauge interactions as SM fermions.

- What kind of mass terms that involve mirror fermions?

  Under $SU(2)_L$:

  $\bar{l}_L \, l_R^M$: 1 or 3

  $\bar{l}_R^M \, e_L^M$: 2

$\bar{e}_R \, e_L^M$: 1

$l_R^{M,T} \sigma_2 l_R^M$: 1 or 3

- What Higgs structure for those bilinears?

  SM Higgs doublet: Φ $(Y/2 = -1/2)$

  (New) Higgs triplet: $\tilde{\chi}$ $(Y/2 = 1)$

  (New) Higgs singlet: ϕ_S $(Y/2 = 0)$

- Couplings:
  - Lepton-number violating: $\mathcal{L}_M = g_M \, l_R^{M,T} \, \sigma_2 \, \tau_2 \, \tilde{\chi} \, l_R^M$

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

Term involving χ^0:

$$g_M \, \nu_R^{M,T} \, \sigma_2 \, \chi^0 \, \nu_R^M$$

Majorana mass of ν_R^M:

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

– Lepton-number conserving: $\mathcal{L}_S = g_{Sl} \, \bar{l}_L \, \phi_S \, l_R^M + g_{Sl}^{'} \, \bar{e}_R \, \phi_S \, e_L^M + H.c.$

Dirac mass of neutrinos:

$\langle \phi_S \rangle = v_S$ $\Rightarrow$ $m_D = g_{Sl} \, v_S$

– Seesaw:

M_R ; $-m_D^2/M_R$

– Mass scales:

If $v_M \sim O(\Lambda_{EW}) \sim 246\, GeV$ and $g_M \sim O(1)$ (not necessarily so) $\Rightarrow$ $M_R \sim O(\Lambda_{EW})$ and $m_D \sim 10^5\, eV$ for $m_\nu \leq O(1\, eV)$.

Contrast that with generic seesaw: $M_R \sim O(\Lambda_{GUT})$ and $m_D \sim O(\Lambda_{EW})$

- Masses for charged mirror leptons:

$g_{eM} \bar{l}_R^M \, \Phi \, e_L^M + H.c.$ $\Rightarrow$ Masses proportional to SM doublet VEV. (Similar interactions for the SM and mirror quarks.)

- Mass mixing between charged SM and mirror's come from

$\mathcal{L}_S = g_{Sl}\,\bar{l}_L\,\phi_S\,l_R^M + g'_{Sl}\,\bar{e}_R\,\phi_S\,e_L^M + H.c. \Rightarrow$ proportional to $m_D \sim 10^5\,eV \Rightarrow$ Negligible!

- No terms such as $l_L^T\,\sigma_2\,\tau_2\,\tilde{\chi}\,l_L$ because of extra $U(1)_M$ symmetry or forbidden by gauge invariance in a Pati-Salam extension of the model.

III) Problem with and solution to $v_M \sim O(\Lambda_{EW}) \sim 246\,GeV$

- VEV of a Higgs triplet of with $O(\Lambda_{EW})$ breaks badly the relation $\rho = 1$ at tree level!

- Z width $\Rightarrow$ $M_R > M_Z/2$ since ν_R^M's couple to the Z boson at tree level.

- To recover $\rho = 1$ with $v_M \sim O(\Lambda_{EW}) \sim 246\,GeV$, add $\xi = (3, Y/2 = 0)$ such that

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

(Chanowitz and Golden; Georgi and Machacek)

$\Rightarrow$ 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

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

VEV structure dictated by proper vacuum alignment.

$SU(2)_L \otimes SU(2)_R \to SU(2) \Rightarrow M_W = g\, v/2$ and $M_Z = M_W / \cos\theta_W$, where

$$\boxed{v = \sqrt{v_2^2 + 8\, v_M^2} \sim 246\, GeV}.$$

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

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

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

- How large can v_M be?

  Tree unitarity constraint on triplet scalar scattering (Aoki and Kanemura) $\Rightarrow$ $\sin\theta_H = \frac{2\sqrt{2}\, v_M}{v} < 0.9 \Rightarrow v_M < 87\, GeV$

  $\Rightarrow$ Limit on $M_R = g_M\, v_M$!

  For $g_M \sim O(1) \Rightarrow$ $45.6\, GeV < M_R < 87\, GeV$

  Even for $g_M^2/4\pi < O(1) \Rightarrow$ $45.6\, GeV < M_R < 308\, GeV$.

  Interesting connection between the study of the triplet scalar sector and the mass of ν_R^M (Aranda, Hernandez and PQH, in preparation)

Where could the mirror fermions come from?

Natural answer 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

Nucl. Phys. B805, 326 (2008), arXiv: 0805.3486v1 [hep-ph]

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

I) 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

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

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

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

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

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

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

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

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!!

Quark-lepton unification $\grave{a}$ la Pati-Salam of the electroweak-scale non-sterile ν_R model inevitably leads to the existence of sterile neutrinos with possible astrophysical consequences (Warm Dark Matter, Pulsar kicks, etc...)!

II) Generalized "seesaw" involving N_L and N_R:

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

Some (many more) numerical examples (see backup slides):

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

$$\tilde{\nu}_{S1} \approx -2.2 \times 10^{-5}\, \nu_L + 4 \times 10^{-9}\, \nu_R^M - N_L$$
$$+ 1.8 \times 10^{-4}\, N_R$$

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

$$\tilde{\nu}_{S2} \approx 4 \times 10^{-9}\, \nu_L + 0\, \nu_R^M + 1.8 \times 10^{-4}\, N_L$$
$$+ N_R$$

keV sterile neutrinos mix very little ($\sim 10^{-5}$) with active light neutrinos $\Rightarrow$ Right kind of parameter range for the sterile neutrino explanation of WDM and pulsar kicks,...

keV sterile neutrinos are hard to come by when they are the right-handed neutrinos participating in the seesaw mechanism.

III) Constraints on breaking scales from $\sin^2\theta_W(M_Z)$:

Computation of $\sin^2\theta_W(M_Z)$ relates its experimental value to different breaking scales and among each other.

Question: How big is the P-S breaking scale M (and subsequent scale $\tilde{M}$) if the scale M_{LR}, where $SU(2)_L \otimes SU(2)_R \to SU(2)_V$, is less than $1\, TeV$?

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

Proton decay is possible, not by the P-S gauge bosons, but by the mediation of heavy scalars.

Families from spinors: a case for four generations

What if there is a 4th generation? Any guiding principles? Families from spinors.

- Our model contains: $SU(2)_L \otimes SU(2)_R \otimes SU(2)'_L \otimes SU(2)'_R$.
- $SO(4) \approx SU(2) \otimes SU(2)$
- Let $\psi_+ = (2,1)$ and $\psi_- = (1,2)$ under $SU(2) \otimes SU(2)$.

- Spinor of $SO(2m+4) = 2^{m-1}\psi_+ + 2^{m-1}\psi_-$ of $SO(4)$ or 2^{m-1} families.

- Requirement: $SO(2m+4)$ anomaly-free
  - $m = 1$ (one family) $\rightarrow SO(6) \rightarrow$ not anomaly free
  - $m = 2$ (two families) $\rightarrow$ OK but phenomenologically we know there are more than two families
  - $m = 3$ (four families) $\rightarrow SO(10)$
  - $m = 4$ (eight families of SM and mirror fermions) $\rightarrow$ severe problems with asymptotic freedom; QCD rapidly becomes non-asymptotically free at energies above the masses of all fermions.

- In this context, four families appear to be a favored choice!

- One can envision:

  $$SO(10) \rightarrow SU(4)_H \otimes SU(2)_L \otimes SU(2)_R$$

  $$SO(10)' \rightarrow SU(4)'_H \otimes SU(2)'_L \otimes SU(2)'_R$$

- Two separate Horizontal gauge groups: $SU(4)_H$ for $SU(2)_V$ non-singlets and $SU(4)'_H$ for $SU(2)_V$ singlets.

Implications

- Electroweak scale non-sterile right-handed neutrinos can be produced and detected (through e.g. like-sign dilepton events) at the LHC $\Rightarrow$ High energy equivalent of neutrinoless double beta decay!

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

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

  Many more non-SM modes! Details of phenomenology in preparation with Dilip Gosh, Nguyen Nhu Le and PQH.

- LFV processes such as $\mu \to e\gamma$ and $\tau \to \mu\gamma$ put constraints on the model (PQH, P.L.B659, 585 (2008)). Correlation between the observability or non-observability of these processes with how displaced the decay vertices may be.

- A rich Higgs structure, including doubly charged scalars such as χ^{++}, χ^{--}. In addition to a possible production of these scalars, like-sign dilepton events can be generated by first producing the doubly-charged Higgses followed by their decays into like-sign charged mirror leptons which subsequently decay into like-sign SM leptons. (Aranda, Hernandez, PQH)

- 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. Quark-lepton unification in this model requires the existence of the sterile neutrinos with both helicities, in addition to the non-sterile right-handed neutrinos! Some of the sterile neutrinos can have keV masses.

keV N_L:

- Warm Dark Matter: Problems with ΛCDM scenario in explaining structure formation, in particular the number of dwarf galaxies. keV sterile neutrinos appear to alleviate this problem.(For a review see Alex Kusenko papers.)

- Pulsar kicks: keV sterile neutrinos can carry a large amount of supernova energy $\Rightarrow$ could explain the "large" recoil velocities of the neutron stars (pulsar kicks) which could be as much as 10^3 km/s (see Kusenko).

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.

- Families from spinors $\Rightarrow$ Four families appear to be a favored choice!

  Is there a 4th family?

- Electroweak precision parameters such as S and T can be satisfied experimentally with additional chiral families if the

SM is extended in the Higgs sector. SM with two Higgs doublets $\Rightarrow$ up to *three additional chiral families* (He, Polonsky, Su). With additional Higgs *triplets*, one can have negative contributions to S depending on the mass splitting inside the triplets.

THE FLAVOUR QUESTION IS JUST AS IMPORTANT AS THE QUEST FOR THE HIGGS AT THE LHC!

HIGGS SECTOR $\Longleftrightarrow$ FLAVOUR SECTOR

BACKUP SLIDES:

Generalized "see-saw" involving N_L and N_R

A) Active and sterile neutrino mass scales:

- Dirac mass terms involve

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

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

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

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

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

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

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

- VEV's:

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

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

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

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

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

$$\langle \Phi^N_S \rangle = \begin{pmatrix} v^N_S & 0 \\ 0 & v^N_S \end{pmatrix}$$

- Generalized see-saw:

$$M_4 = \begin{pmatrix} 0 & m_D & 0 & m_{\nu_L N_R} \\ m_D & M_R & m_{\nu^M_R N_L} & 0 \\ 0 & m_{\nu^M_R N_L} & 0 & m^N_D \\ m_{\nu_L N_R} & 0 & m^N_D & M^N_R \end{pmatrix}$$

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

$$\frac{M_4}{M_R} = \begin{pmatrix} 0 & 10^{-6} & 0 & 4\times 10^{-9} \\ 10^{-6} & 1 & 4\times 10^{-9} & 0 \\ 0 & 4\times 10^{-9} & 0 & 1.8.10^{-4} \\ 4\times 10^{-9} & 0 & 1.8.10^{-4} & 1 \end{pmatrix}$$

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

$$\tilde{\nu}_1 \approx -\nu_L + 10^{-6}\,\nu_R^M + 2.2\times 10^{-5}\,N_L - 2.2\times 10^{-11}\,N_R$$

$$m_2 \approx 100\,GeV$$

$$\tilde{\nu}_2 \approx 10^{-6}\,\nu_L + \nu_R^M + 10^{-9}\,N_L - 7.3\times 10^{-13}\,N_R$$

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

$$\tilde{\nu}_{S1} \approx -2.2 \times 10^{-5}\,\nu_L + 4 \times 10^{-9}\,\nu_R^M - N_L + 1.8 \times 10^{-4}\,N_R$$

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

$$\tilde{\nu}_{S2} \approx 4 \times 10^{-9}\,\nu_L + 0\,\nu_R^M + 1.8 \times 10^{-4}\,N_L + N_R$$

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

B) Remarks on mirror fermion masses:

Mirror fermions as defined above have not been observed $\Rightarrow$ They must be HEAVY. But why?

One possibility:

$$\mathcal{M}_H = m_3 \begin{pmatrix} 0 & \epsilon^3 & 0 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ 0 & \epsilon^2 & 1 \end{pmatrix}$$

To $O(\epsilon^4)$ the eigenvalues are $-m_3\,\epsilon^4$, $m_3\,\epsilon^2$ and $m_3\,(1+\epsilon^4)$. With $\epsilon_u = 0.07$ and $\epsilon_d = 0.21$ one can reproduce the phenomenological mass hierarchies at the scale M_Z (Rosenfeld and Rosner).

For mirror fermions,

Ansatz:

$$\mathcal{M}_M = m_M \begin{pmatrix} 0 & \epsilon_M^3 & 0 \\ \epsilon_M^3 & \epsilon_M^2 & \epsilon_M^2 \\ 0 & \epsilon_M^2 & 1 \end{pmatrix}$$ with

$$\boxed{\epsilon_M^u \sim \epsilon_M^d \sim \frac{M_{LR}}{M_Z}\,\epsilon_{SM}}$$

Recall: Above M_{LR}, SM and Mirror fermions have separate $SU(2)_L$ and $SU(2)_R$ gauge interactions while below they have the same $SU(2)_V$ gauge interactions.

Example: $\epsilon_{SM} \sim 0.09$, $\frac{M_{LR}}{M_Z} \sim 10$, and $m_M \sim 350\,GeV$ $\Rightarrow$ Eigen-values: $(-196, 179, 651)\,GeV$.

$\Rightarrow$ Heavy mirror quarks.

Similar considerations for the leptons.

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 $\boxed{\sin^2\theta_W(M^2_{LR}) = \frac{2\sin^2\tilde{\theta}_W(M^2_{LR})}{1+\sin^2\tilde{\theta}_W(M^2_{LR})}}$ $\Rightarrow$ $\boxed{\sin^2\theta_W(M_Z)}$.

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

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

  M: quark-lepton unification mass.

  Computations were done for 3 and 4 generations. Why 4?

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):

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

  and e.g.

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

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

$\rightarrow l_L^{\mp} + l_L^{\mp} + W^{\pm} + W^{\pm} + \phi_S + \phi_S$, 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...