Left-Right Models Radiatively Broken by a Doublet

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Breaking Path

- The existing gauge symmetries at low energies, $SU(3)_c \times U(1)_{em}$, are vector-like.
- At higher energies ($\mu \sim \Lambda_{SM}$) there is a parity violation in nature due to the axial nature of $SU(2)_L$.
- Gauge parity can be restored at even higher energies using Left-Right Models, first proposed by Pati and Salam[1] $SU(4)_c \times SU(2)_L \times SU(2)_R$
- We choose to start at:

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$$

Which is broken down into the Standard Model.

[1] Pati, J. C. and Salam, A., Phys. Rev. D 10, 275 (1974)

Particle Contents

To achieve realistic fermion masses, a 2nd higgs bidoublet is added.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
Q	3	2	1	1/3
Q^c	$\bar{3}$	1	2	−1/3
L	1	2	1	−1
L^c	1	1	2	1
h	1	2	2	0
h'	1	2	2	0

(1)

The superpotential is

$$\mathcal{W} = Y_q QhQ^c + Y_q' Qh'Q^c + Y_e LhL^c + Y_e' Lh'L^c + \alpha \mathrm{Tr} hh + \alpha' \mathrm{Tr} h'h' + \beta \mathrm{Tr} hh' + h.c.$$

The soft mass terms are

$$V_{soft} = m_{L^c}^2|\tilde{L}^c|^2 + m_L^2|\tilde{L}|^2 + m_{Q^c}^2|\tilde{Q}^c|^2 + m_Q^2|\tilde{Q}|^2 + m_h^2|h|^2 + m_{h'}^2|h'|^2 + \mathcal{O}(hh') \tag{2}$$

In order to achieve radiative breaking, there needs to be a soft mass splitting at some higher energy, meaning this model does not have matter parity symmetry, only gauge parity symmetry.

Breaking Mechanism

Doublets were initially proposed[2], but after the seesaw was introduced [3] triplet models were introduced to achieve a seesaw mechanism without R-Parity breaking. However to achieve LRM breaking without Q_{em} violation, R-Parity has to be broken as well[4] leading to nonzero VEV of $\langle \tilde{L}^c \rangle = \frac{v_R}{\sqrt{2}}$.

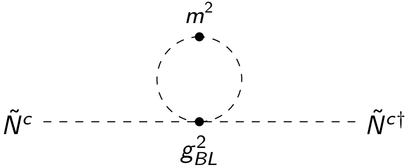


Figure: Soft mass insertions in D-term corrections must be larger than F-term and Gaugino corrections

[2] Mohapatra, R. N. and Pati, J. C., Phys. Rev. D 11, 2558 (1975). ,Senjanovic, G. and Mohapatra, R. N., Phys. Rev. D 12, 1502 (1975)

[3] Minkowski, P., Physics Letters B 67, 421 (1977)

[4] Kuchimanchi, R. and Mohapatra, R. N., Phys. Rev. D 48, 4352 (1993)

Soft Lepton Mass RGEs

$$
\begin{aligned}
8\pi^2 \frac{dm^2_{\tilde{L}_i}}{d\ln\mu} &= \sum_{j,k} |Y_L^{ijh}|^2 \left(m^2_{\tilde{L}_i} + m^2_{\tilde{L}^c_j} + m^2_h \right) - g^2_{BL} \mathrm{Tr}[\mathrm{Q_{BL} m^2}] \\
&\quad - 4g^2_{BL} M^2_{BL} - 3g^2_L M^2_L \\
8\pi^2 \frac{dm^2_{\tilde{L}^c_i}}{d\ln\mu} &= \sum_{j,k} |Y_L^{ijh}|^2 \left(m^2_{\tilde{L}_i} + m^2_{\tilde{L}^c_j} + m^2_h \right) + g^2_{BL} \mathrm{Tr}[\mathrm{Q_{BL} m^2}] \\
&\quad - 4g^2_{BL} M^2_{BL} - 3g^2_R M^2_R
\end{aligned} \tag{3}
$$

The soft slepton mass runnings at one-loop can easily be derived. The $U(1)_{B-L}$ charge dictates sign of the trace:

$$
g^2_{BL} \mathrm{Tr}\left[Q_{BL} m^2 \right] = \sum_i^3 2g^2_{BL} \left(m^2_{\tilde{Q}_i} - m^2_{\tilde{Q}^c_i} - m^2_{\tilde{L}_i} + m^2_{\tilde{L}^c_i} \right). \tag{4}
$$

We only need a single large left handed scalar quark doublet to be large which would dominate over even the gaugino masses.

Soft Quark Mass RGEs

Similar to lepton sector, they get additional gluino term. Due to the large top Yukawa, heavy generations run the risk of running negative as well (breaking electromagnetism). This can be avoided by large gluino mass.

$$\beta_{m^2_{\tilde{Q}}} = 2|Y_q|^2 \left(m^2_{\tilde{Q}} + m^2_{\tilde{Q}^c} + m^2_h + m^2_{h'} \right) - \frac{4}{9} g^2_{BL} M^2_{BL} + \frac{1}{3} g^2_{BL} \mathrm{Tr}[\mathrm{Q_{BL} m^2}] - 3\mathrm{g^2_L M^2_L} - \frac{16}{3}\mathrm{g^2_3 M^2_3} \tag{5}$$

$$\beta_{m^2_{\tilde{Q}^c}} = 2|Y_q|^2 \left(m^2_{\tilde{Q}} + m^2_{\tilde{Q}^c} + m^2_h + m^2_{h'} \right) - \frac{4}{9} g^2_{BL} M^2_{BL} - \frac{1}{3} g^2_{BL} \mathrm{Tr}[\mathrm{Q_{BL} m^2}] - 3\mathrm{g^2_R M^2_R} - \frac{16}{3}\mathrm{g^2_3 M^2_3} \tag{6}$$

With

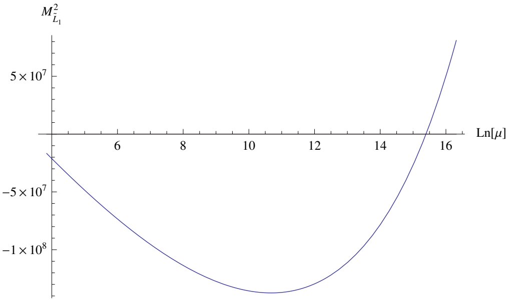
$$g^2_{BL} \mathrm{Tr}\left[Q_{BL} m^2 \right] = \sum_i^3 2 g^2_{BL} \left(m^2_{\tilde{Q}_i} - m^2_{\tilde{Q}^c_i} - m^2_{\tilde{L}_i} + m^2_{\tilde{L}^c_i} \right). \tag{7}$$

Inputs

- $\mu_{GUT} = 10^{16}$ GeV and the breaking is around 7 TeV
- Yukawas and g_y, for one heavy generation, were ran from low energy with $\theta_R \approx 55^\circ$. The couplings are very sensitive to θ_R
- Higgs doublets set at 5 TeV but have minimal influence in runnings
- Values at GUT Scale:

$M_{\tilde{L}^c_1}$	$M_{\tilde{L}^c_2}$	$M_{\tilde{L}^c_3}$	$M_{\tilde{Q}^c_3}$	$M_{\tilde{Q}_3}$	$M_{\tilde{L}_3}$
9000. GeV	10 000. GeV	10 000. GeV	100 000. GeV	150 000. GeV	2000. GeV

Breaking Relations



$$g_Y = g_R \sin\theta_R$$
$$\tan\theta_R = \frac{2g_{BL}}{g_R}$$
$$Y_W = \frac{Y_{BL}}{2} - (T_3)_R$$

$$M_{W_R} = \frac{1}{2} g_R v_{\mathrm{R}}$$
$$M_{Z_R} = \frac{1}{2} v_{\mathrm{R}} \sqrt{4g_{\mathrm{BL}}^2 + g_R^2} \qquad (8)$$
$$M_{A_Y} = 0$$

Tau Lepton constraint and Low Energy

$$\mathcal{L} \supset \tilde{M}_R^{\pm} \lambda_R^{+} \lambda_R^{-} + \frac{g_R v_{BL}}{\sqrt{2}} E^c \lambda_R^{-} + h.c. \tag{9}$$

$$\mathcal{L} \supset \mathcal{M} \xi^{+} \lambda_R^{-} + h.c. \tag{10}$$

- The multiplet has an uneven number in hypercharge$=\pm 1$.
- There is an orthogonal mode present after the LR breaking.
- In order to keep the tau lepton from having too large of a mixing angle and exceeding bounds, $\tilde{M}_R^{\pm} >> M_{W_R}$. Leaving $\delta\Gamma_{\tau\tau} \sim 10^{-2}$

$M^2_{\tilde{L}_1^c}$	$M^2_{\tilde{L}_2^c}$	$M^2_{\tilde{L}_3^c}$	$M^2_{\tilde{Q}_3^c}$	$M^2_{\tilde{Q}_3}$	$M^2_{\tilde{L}_3}$
-1.67675×10^7 GeV^2	1.87069×10^6 GeV^2	1.86795×10^6 GeV^2	3.51217×10^9 GeV^2	1.39674×10^{10} GeV^2	1.32691×10^9 GeV^2

Neutrino Masses

- We define the VEV to be $v_R = \sqrt{\frac{-8m_{L^c}^2}{(g_R^2+g_{BL}^2)}} \sim 20$ TeV
- $M_{W_R} \sim 4.6$ TeV and $M_{Z_R} \sim 8.3$ TeV
- The mass matrix after the LRM breaking is

$$M_{\nu^c,\tilde{\lambda}_{BL},\tilde{\lambda}_R^3} = \begin{pmatrix} M_R & 0 & g_R v_R \\ 0 & M_{BL} & g_{BL} v_R \\ g_R v_R & g_{BL} v_R & 0 \end{pmatrix} \tag{11}$$

- We still get a heavy neutrino but after EW breaking we can still induce a light neutrino spectrum via see-saw.

$$m_\nu \sim \frac{|\tilde{Y}_L|^2 \tilde{v}_u^2}{(2M_{\nu^c})} \tag{12}$$

Quark Masses

- Down Quark sector to be a diagonalized matrix $M_u = D_u$.
- Rotate up quark mass to get a diagonalized mass matrix $V_{km}^{\dagger} M_d V_{km} = D_d$.
- After EWSB

$$m_u = \frac{1}{\sqrt{2}} Y_q v_u$$

$$m_u' = \frac{1}{\sqrt{2}} Y_q' v_u'$$

- Now quark mass matrices can now be expressed as

$$M_u = m_u + m_u' = D_u \tag{13}$$

$$M_d = c m_u + c' m_u' = V_{km} D_d V_{km}^{\dagger}$$

- Where $c = \frac{v_d}{v_u}$ and $c' = \frac{v_d'}{v_u'}$.
- In general, there can be Left and Right KM matrices to rotate the quarks.

Conclusions

- The Left-Right Models offer great parity restoring phenomnology at higher energies
- Minimal LRMs without triplets can be broken via right-handed sneutrino radiatively.
- Due to tau lepton constraint, a very heavy squark is needed.
- Small neutrino masses can still be produced via gaugino mixings
- Some fine tuning is needed