TeV scale Left-Right symmetry

with spontaneous D-parity breaking

Debasish Borah

IIT Bombay

Jaipur 2010

Motivation

- Recently P.S.B. Dev and R.N. Mohapatra have shown the existence of TeV scale left-right symmetry with spontaneous D-parity breaking in a model which can also account for tiny neutrino masses as well as gauge-coupling and $b - \tau$ unification (PRD **81**, 013001 (2010)).

[1] Based on arXiv preprint 1006.2245 with co-authors Sudhanwa Patra and Utpal Sarkar (Physical Research Laboratory, Ahmedabad)

Motivation

- Recently P.S.B. Dev and R.N. Mohapatra have shown the existence of TeV scale left-right symmetry with spontaneous D-parity breaking in a model which can also account for tiny neutrino masses as well as gauge-coupling and $b - \tau$ unification (PRD **81**, 013001 (2010)).
- They, however did not explicitly derive the ground state of the scalar potential in their model. Our purpose is to study all possible Left Right models with spontaneous D-parity breaking and show explicitly whether the ground state of the theory allow a TeV scale intermediate symmetry along with correct order of neutrino masses. [1]

[1] Based on arXiv preprint 1006.2245 with co-authors Sudhanwa Patra and Utpal Sarkar (Physical Research Laboratory, Ahmedabad)

Motivation

- Recently P.S.B. Dev and R.N. Mohapatra have shown the existence of TeV scale left-right symmetry with spontaneous D-parity breaking in a model which can also account for tiny neutrino masses as well as gauge-coupling and $b - \tau$ unification (PRD **81**, 013001 (2010)).
- They, however did not explicitly derive the ground state of the scalar potential in their model. Our purpose is to study all possible Left Right models with spontaneous D-parity breaking and show explicitly whether the ground state of the theory allow a TeV scale intermediate symmetry along with correct order of neutrino masses. [1]
- We also show the gauge coupling unification in the SUSY versions of each such models.

[1] Based on arXiv preprint 1006.2245 with co-authors Sudhanwa Patra and Utpal Sarkar (Physical Research Laboratory, Ahmedabad)

Left-Right Symmetric Models (LRSM)

- The standard model gauge group is extended to $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Left-Right Symmetric Models (LRSM)

- The standard model gauge group is extended to $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Parity is spontaneously broken and smallness of neutrino masses arise automatically by seesaw mechanism.

Left-Right Symmetric Models (LRSM)

- The standard model gauge group is extended to $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Parity is spontaneously broken and smallness of neutrino masses arise automatically by seesaw mechanism.
- Supersymmetric version of such models come with other advantages like stabilizing scalar masses, natural dark matter candidate (LSP), gauge coupling unification etc.

LRSM with spontaneous D-parity breaking

- Usual LRSM also contains a discrete Z_2 symmetry (in addition to the gauge symmetry) under which left-handed fields interchanges with the right handed ones. This discrete symmetry also forces us to take the coupling constants of $SU(2)_R$ and $SU(2)_L$ same $g_R = g_L$.

LRSM with spontaneous D-parity breaking

- Usual LRSM also contains a discrete Z_2 symmetry (in addition to the gauge symmetry) under which left-handed fields interchanges with the right handed ones. This discrete symmetry also forces us to take the coupling constants of $SU(2)_R$ and $SU(2)_L$ same $g_R = g_L$.
- In usual LRSM, this Z_2 symmetry as well as the $SU(2)_R$ gauge symmetry breaks simultaneously.

LRSM with spontaneous D-parity breaking

- Usual LRSM also contains a discrete Z_2 symmetry (in addition to the gauge symmetry) under which left-handed fields interchanges with the right handed ones. This discrete symmetry also forces us to take the coupling constants of $SU(2)_R$ and $SU(2)_L$ same $g_R = g_L$.
- In usual LRSM, this Z_2 symmetry as well as the $SU(2)_R$ gauge symmetry breaks simultaneously.
- As considered by Chang and Mohapatra'1983, addition of a singlet field η which transform as $\eta \rightarrow -\eta$ under this Z_2 symmetry called the D-parity breaks this discrete symmetry first leaving the gauge symmetry unbroken.

LRSM with spontaneous D-parity breaking

- The D-parity breaking introduces an asymmetry between left and right handed Higgs fields and makes the coupling constants of $SU(2)_R$ and $SU(2)_L$ evolve separately under the renormalization group.

LRSM with spontaneous D-parity breaking

- The D-parity breaking introduces an asymmetry between left and right handed Higgs fields and makes the coupling constants of $SU(2)_R$ and $SU(2)_L$ evolve separately under the renormalization group.
- This D-parity breaking is different from the low energy parity breaking observed in the weak interactions which arises as a result of $SU(2)_R$ gauge symmetry breaking at a scale higher than the electroweak scale.

LRSM with spontaneous D-parity breaking

- The D-parity breaking introduces an asymmetry between left and right handed Higgs fields and makes the coupling constants of $SU(2)_R$ and $SU(2)_L$ evolve separately under the renormalization group.
- This D-parity breaking is different from the low energy parity breaking observed in the weak interactions which arises as a result of $SU(2)_R$ gauge symmetry breaking at a scale higher than the electroweak scale.
- In such models although the type I seesaw term still remains sensitive to the $U(1)_{B-L}$ breaking scale M_R, the other seesaw terms namely type II and type III becomes sensitive to the D-parity breaking scale.

LRSM with Higgs doublets

Particle Content of the model

The particle content of the Left-Right symmetric model with Higgs doublet is

$$Q_L \equiv (3,2,1,1/3), \quad Q_R \equiv (3,1,2,1/3)$$

$$\Psi_L \equiv (1,2,1,-1), \quad \Psi_R \equiv (1,1,2,-1)$$

$$\Phi \equiv (1,2,2,0), \quad H_L \equiv (1,2,1,1), \quad H_R \equiv (1,1,2,1)$$

where the numbers in the brackets are the quantum numbers corresponding to the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. To the above particle content we add a parity odd singlet scalar field $\eta(1,1,1,0)$. We denote the vacuum expectation values of the neutral components of the Higgs fields as

$$\langle \Phi_1 \rangle = v_1, v_2, \quad \langle H_L \rangle = v_L, \quad \langle H_R \rangle = v_R, \quad \langle \eta \rangle = s$$

Scalar potential minimization

Minimizing the scalar potential gives

$$\frac{\partial V}{\partial v_L} = \mu_L^2 v_L + \lambda_5 v_L^3 + \frac{\lambda_6}{2} v_L v_R^2 + \mu_{h\phi}(v_1 + v_2) v_R = 0 \quad (1)$$

$$\frac{\partial V}{\partial v_R} = \mu_R^2 v_R + \lambda_5 v_R^3 + \frac{\lambda_6}{2} v_R v_L^2 + \mu_{h\phi}(v_1 + v_2) v_L = 0 \quad (2)$$

where μ_L^2 and μ_R^2 are effective mass terms of H_L and H_R given by

$$\mu_L^2 = \mu_h^2 + Ms + \lambda_8 s^2 + (\alpha_4 + \alpha_4^*) v_1 v_2 + \alpha_1 (v_1^2 + v_2^2) + \alpha_2 v_2^2 + \alpha_3 v_1^2$$

$$\mu_R^2 = \mu_h^2 - Ms + \lambda_8 s^2 + (\alpha_4 + \alpha_4^*) v_1 v_2 + \alpha_1 (v_1^2 + v_2^2) + \alpha_2 v_2^2 + \alpha_3 v_1^2 \quad (3)$$

Scalar potential minimization

From equations (1), (2) we get

$$v_L v_R(2Ms) + (\lambda_5 - \frac{\lambda_6}{2})(v_L^2 - v_R^2)v_L v_R + \mu_{h\phi}(v_1 + v_2)(v_R^2 - v_L^2) = 0$$

Thus a non-zero value of $\langle\eta\rangle = s$ does not allow a solution with $v_L = v_R$. Assuming $v_L \ll v_R \ll s, M$ will give

$$v_L = \frac{-\mu_{h\phi}(v_1 + v_2)v_R}{2Ms} \qquad (4)$$

If we set $\mu_{h\phi} = M = s = 10^8$ GeV, and $v_{1,2} \sim M_Z$ then $\frac{v_L}{v_R}$ comes out to be of the order 10^{-6} which is desired for type III seesaw. Unlike LRSM without D-parity breaking, here v_R need not be very high but can be as low as TeV.

LRSM with Higgs triplets

Particle content of the model

The particle content of LRSM with Higgs triplets is

$$Q_L \equiv (3, 2, 1, 1/3), \quad Q_R \equiv (3, 1, 2, 1/3)$$

$$\Psi_L \equiv (1, 2, 1, -1), \quad \Psi_R \equiv (1, 1, 2, -1)$$

$$\Phi \equiv (1, 2, 2, 0), \quad \triangle_L \equiv (1, 3, 1, 2), \quad \triangle_R \equiv (1, 1, 3, 2)$$

To the above field content we add a parity odd singlet scalar η like in the previous case. We denote the vacuum expectation values of the neutral components of the Higgs fields $\Phi_1, \triangle_L, \triangle_R, \eta$ as

$$\langle \Phi_1 \rangle = v_1, v_2, \quad \langle \triangle_L \rangle = v_L, \quad \langle \triangle_R \rangle = v_R, \quad \langle \eta \rangle = s$$

Scalar potential minimization

Minimizing the scalar potential gives

$$\frac{\partial V}{\partial v_L} = \mu_L^2 v_L + 2\rho_1 v_L^3 + \rho_3 v_L v_R^2 + (\beta_1 v_1 v_2 + \beta_2 v_1^2 + \beta_3 v_2^2) v_R = 0 \quad (5)$$

$$\frac{\partial V}{\partial v_R} = \mu_R^2 v_R + 2\rho_1 v_R^3 + \rho_3 v_R v_L^2 + (\beta_1 v_1 v_2 + \beta_2 v_1^2 + \beta_3 v_2^2) v_L = 0 \quad (6)$$

where μ_L^2 and μ_R^2 are effective mass terms of $\triangle_L$ and $\triangle_R$ given by

$$\mu_L^2 = \mu_\triangle^2 + Ms + \lambda_6 s^2 + 2(\alpha_2 + \alpha_2^*) v_1 v_2 + \alpha_1 (v_1^2 + v_2^2) + \alpha_3 v_2^2$$
$$\mu_R^2 = \mu_\triangle^2 - Ms + \lambda_6 s^2 + 2(\alpha_2 + \alpha_2^*) v_1 v_2 + \alpha_1 (v_1^2 + v_2^2) + \alpha_3 v_2^2$$

Scalar potential minimization

Equations (5), (6) gives

$$(2Ms + (v_R^2 - v_L^2)(\rho_3 - 2\rho_1))v_L v_R = (v_L^2 - v_R^2)(\beta_1 v_1 v_2 + \beta_2 v_1^2 + \beta_3 v_2^2)$$

Thus a nonzero vev of η disallows those solutions for which $v_L = v_R$. Assuming $v_L \ll v_R \ll s, M$ will give

$$v_L = \frac{-v_R(\beta_1 v_1 v_2 + \beta_2 v_1^2 + \beta_3 v_2^2)}{2Ms} \tag{7}$$

Here if we take v_R of TeV scale then the scale of parity breaking M, s should be low ($\sim 10^8 - 10^9$ GeV) so as to give $v_L \sim eV$ needed to account for neutrino masses by type II seesaw.

SUSYLR model with Higgs doublets [2]

[2] P.S.B. Dev and R. N. Mohapatra, Phys. Rev. **D81**, 013001(2010)

Field content of SUSYLR model with Higgs doublets

The particle content of Supersymmetric Left-Right model with Higgs doublet is

$$Q_L \equiv (3,2,1,1/3), \quad Q_R \equiv (3,1,2,-1/3)$$

$$\Psi_L \equiv (1,2,1,-1), \quad \Psi_R \equiv (1,1,2,1)$$

$$\Phi_1 \equiv (1,2,2,0), \quad \Phi_2 \equiv (1,2,2,0) \quad H_L \equiv (1,2,1,1)$$

$$\bar{H}_L \equiv (1,2,1,-1) \quad H_R \equiv (1,1,2,-1), \quad \bar{H}_R \equiv (1,1,2,1)$$

We add a parity odd singlet superfield ρ to the above particle content. We denote the vev of the neutral components of $\Phi_1, \Phi_2, H_L, \bar{H}_L, H_R, \bar{H}_R$ and ρ as

$$\langle(\Phi_1)_{11}\rangle = v_1, \quad \langle(\Phi_2)_{22}\rangle = v_2, \quad \langle H_L, \bar{H}_L\rangle = v_L, \quad \langle H_R, \bar{H}_R\rangle = v_R, \quad \langle\rho\rangle = s$$

Superpotential

The Higgs part of the superpotential is

$$W = \mu_{ij} \mathrm{Tr}[\tau_2 \Phi_i^T \tau_2 \Phi_j] + M\rho\rho + f_1(H_L^T \Phi_i H_R + \bar{H}_L^T \Phi_i \bar{H}_R)$$
$$+ m_h(H_L^T \tau_2 \bar{H}_L + H_R^T \tau_2 \bar{H}_R) + \lambda_1 \rho (H_L^T \tau_2 \bar{H}_L - H_R^T \tau_2 \bar{H}_R)$$

The scalar potential is $V = V_F + V_D + V_{soft}$ where $V_F = |F_i|^2, F_i = -\frac{\partial W}{\partial \phi}$ is the F-term scalar potential, $V_D = D^a D^a/2, D^a = -g(\phi_i^* T_{ij}^a \phi_j)$ and V_{soft} is the soft supersymmetry breaking scalar potential.

Scalar potential minimization

The effective mass terms of the doublet Higgs fields after ρ acquires vev are

$$\mu^2_{H_L} = \frac{1}{4}[(m_h + s\lambda_1)^2 + f_1^2 v_1^2], \quad \mu^2_{\bar{H}_L} = \frac{1}{4}[(m_h + s\lambda_1)^2 + f_1^2 v_2^2]$$

$$\mu^2_{H_R} = \frac{1}{4}[(m_h - s\lambda_1)^2 + f_1^2 v_2^2] \quad \mu^2_{\bar{H}_L} = \frac{1}{4}[(m_h - s\lambda_1)^2 + f_1^2 v_2^2]$$

Minimizing the potential with respect to v_L, v_R, we get the relation

$$(A_1 v_1 + 4(f_1^2 + \lambda_1^2) v_L v_R + 2f_1(v_1 + v_2)(m_h + 4\mu))(v_R^2 - v_L^2) + (4sA_2$$
$$+8\lambda_1 s(M - m_h)) v_L v_R = 0$$

which shows that the minimization disallows the solutions where $v_L = v_R$.

Scalar potential minimization

- Assuming $v_L \ll v_R \ll s, M$ the above expression gives rise to

$$v_L = \frac{v_R(2f_1 m_h(v_1 + v_2) + 4(f_1^2 + \lambda_1^2)v_L v_R + A_1 v_1)}{8(m_h - M)s\lambda_1 + 4sA_2} \tag{8}$$

Scalar potential minimization

- Assuming $v_L \ll v_R \ll s, M$ the above expression gives rise to

$$v_L = \frac{v_R(2f_1 m_h(v_1+v_2) + 4(f_1^2+\lambda_1^2)v_L v_R + A_1 v_1)}{8(m_h - M)s\lambda_1 + 4sA_2} \tag{8}$$

- If we set

$$m_h \sim M \sim s \sim 10^{16}\,\text{GeV} \quad \text{D-parity breaking scale}$$

and allow $m_h - M \sim 10^8$ GeV by appropriate fine tuning then the above relation will give rise to the desired ratio $v_L/v_R \sim 10^{-6}$. For such a choice of scales we can fine tune the parameters to get a light H_R having mass $\mu_R \sim v_R \sim$ TeV and a heavy H_L having mass $\mu_L \sim s, M \sim 10^{16}$ GeV.

Neutrino Masses

Introduce fermion triplets Σ_L, Σ_R. The relavant Yukawa terms that gives masses (for the *double* seesaw mass matrix) to the three generations of leptons are given by

$$\begin{aligned} \mathcal{L}_\nu^{III} &= h_{ij} \ell_{iL}^T \, C \, i\sigma_2 \, \Sigma_{jL} \, H_L \; + g_{ij} \, \ell_{iR}^T \, C \, i\sigma_2 \, \Sigma_{jR} \, H_R \\ &+ M_\Sigma \, Tr \left(\Sigma_L^T \, C \, \Sigma_L \, + \, \Sigma_R^T \, C \Sigma_R \right) + h.c. \end{aligned} \tag{9}$$

Now the mass matrix in the basis $\left(\nu_L, \; \nu_R, \; \Sigma_R^0, \; \Sigma_L^0\right)$ reads as:

$$M_\nu^{III} = \begin{pmatrix} 0 & m_\nu^D & 0 & h v_L \\ (m_\nu^D)^T & 0 & g v_R & 0 \\ 0 & g^T v_R & M_\Sigma & 0 \\ h^T v_L & 0 & 0 & M_\Sigma \end{pmatrix}. \tag{10}$$

Neutrino Masses

If one assumes $M_\Sigma >> g\, v_R >> m_\nu^D, h\, v_L$ one gets

$$m_{\nu_L} = \frac{1}{v_R^2\,(g^T g)}\left[m_\nu^D\, M_\Sigma\,(m_\nu^D)^T - v_R\, v_L\, m_\nu^D\,(g\, h)^T - v_R\, v_L\,(g\, h)\,(m_\nu^D)^T\right] \quad (11)$$

with right handed neutrino masses

$$M_R = v_R^2\, g\, \left(M_\Sigma\right)^{-1}\, g^T. \quad (12)$$

- If we assume that the first term of [11] will dominate then the seesaw relations will become $m_\nu = \frac{m_e^2}{M_R}$. As $m_e = 0.5$ MeV, we need the values of the right handed Majorana neutrino as: $M_R = 10^3$ GeV to have 0.1 eV light neutrino mass.

Neutrino Masses

If one assumes $M_\Sigma >> g\, v_R >> m_\nu^D, h\, v_L$ one gets

$$m_{\nu_L} = \frac{1}{v_R^2\,(g^T g)}\left[m_\nu^D\, M_\Sigma\,(m_\nu^D)^T - v_R\, v_L\, m_\nu^D\,(g\, h)^T - v_R\, v_L\,(g\, h)\,(m_\nu^D)^T\right] \qquad (11)$$

with right handed neutrino masses

$$M_R = v_R^2\, g\;(M_\Sigma)^{-1}\; g^T. \qquad (12)$$

- If we assume that the first term of [11] will dominate then the seesaw relations will become $m_\nu = \frac{m_e^2}{M_R}$. As $m_e = 0.5$ MeV, we need the values of the right handed Majorana neutrino as: $M_R = 10^3$ GeV to have 0.1 eV light neutrino mass.
- The second and the third term in the equation [11] can also contribute to the neutrino masses if $v_L/v_R \sim 10^{-6}$.

Gauge coupling unification

- Minimal field content above does not give rise to exact unification. For required unification purposes we add two copies of $\delta(1,1,1,2)$, $\bar{\delta}(1,1,1,-2)$ at the $SU(2)_R$ breaking scale.

Gauge coupling unification

- Minimal field content above does not give rise to exact unification. For required unification purposes we add two copies of $\delta(1,1,1,2)$, $\bar{\delta}(1,1,1,-2)$ at the $SU(2)_R$ breaking scale.
- For desired seesaw $M_\Sigma \sim v_R$, but such light triplet fermions will ruin the gauge coupling unification for a TeV scale $SU(2)_R$ breaking scale v_R.

Gauge coupling unification

- Minimal field content above does not give rise to exact unification. For required unification purposes we add two copies of $\delta(1,1,1,2)$, $\bar{\delta}(1,1,1,-2)$ at the $SU(2)_R$ breaking scale.
- For desired seesaw $M_\Sigma \sim v_R$, but such light triplet fermions will ruin the gauge coupling unification for a TeV scale $SU(2)_R$ breaking scale v_R.
- Unification and small neutrino mass are possible only if $SU(2)_R$ breaking scale as well as mass of the triplet fermions are close to the unification scale.

Gauge coupling unification

- Minimal field content above does not give rise to exact unification. For required unification purposes we add two copies of $\delta(1,1,1,2)$, $\bar{\delta}(1,1,1,-2)$ at the $SU(2)_R$ breaking scale.
- For desired seesaw $M_\Sigma \sim v_R$, but such light triplet fermions will ruin the gauge coupling unification for a TeV scale $SU(2)_R$ breaking scale v_R.
- Unification and small neutrino mass are possible only if $SU(2)_R$ breaking scale as well as mass of the triplet fermions are close to the unification scale.
- Adding a fermion singlet however allows the possibility of TeV scale M_R, tiny neutrino masses and unification simultaneously.

Gauge coupling unification

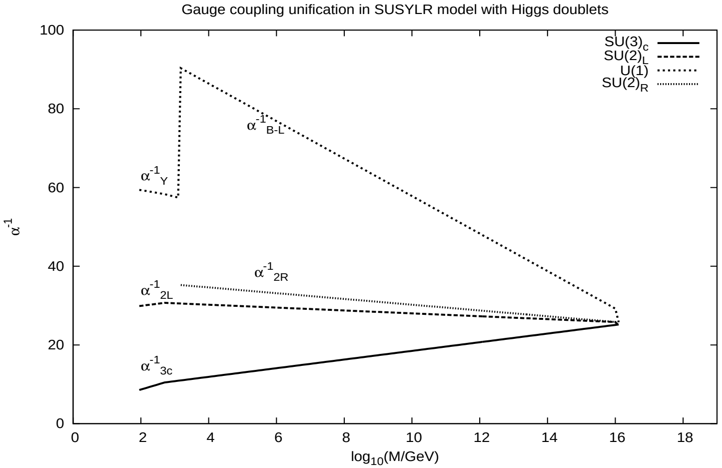

Figure: Gauge coupling unification with $M_{susy} = 500$ GeV, $M_R = 1.5$ TeV, $M_\rho = 10^{16}$ GeV

SUSYLR model with Higgs triplets

- SUSYLR model with Higgs triplets and added parity odd singlet leads to charge breaking vacua as was studied by Kuchimanchi and Mohapatra in 1993.

SUSYLR model with Higgs triplets

- SUSYLR model with Higgs triplets and added parity odd singlet leads to charge breaking vacua as was studied by Kuchimanchi and Mohapatra in 1993.
- We also find that the minimization of the scalar potential does not allow a TeV scale M_R with correct order of neutrino mass.

SUSYLR model with Higgs triplets and bitriplet [3]

[3] S. Patra, A. Sarkar, U. Sarkar, and U. Yajnik, Phys. Lett. **B679**, 386(2009)

Particle Content of the Model

$$Q_L \equiv (3,2,1,1/3), \quad Q_R \equiv (3,1,2,-1/3)$$

$$\Psi_L \equiv (1,2,1,-1), \quad \Psi_R \equiv (1,1,2,1)$$

$$\Phi_1 \equiv (1,2,2,0), \quad \Phi_2 \equiv (1,2,2,0), \quad \triangle \equiv (1,3,1,2)$$

$$\bar{\triangle} \equiv (1,3,1,-2), \quad \triangle^c \equiv (1,1,3,-2), \quad \bar{\triangle}^c \equiv (1,1,3,2)$$

$$\eta(1,3,3,0), \quad \rho(1,1,1,0)$$

We denote the vev's as $\langle \triangle_- \rangle = \langle \bar{\triangle}_+ \rangle = v_L, \langle \triangle^c_+ \rangle = \langle \bar{\triangle}^c_- \rangle = v_R, \langle \Phi_{+-} \rangle = v, \langle \Phi_{-+} \rangle = v', \langle \eta_{+-} \rangle = u_1, \langle \eta_{-+} \rangle = u_2, \langle \eta_{00} \rangle = u_0$

Scalar potential minimization

$$\frac{\partial V}{\partial v_L} = \mu_L^2(2v_L) + 2\lambda_2^2 v_L(v_L^2 - v_R^2) + 2(fu_1 + f^* u_2)M_\triangle v_R + v_R(f + f^*)[2m_\eta(u_1 + u_2 + u_3) + \lambda_1 v^2 + v_L v_R(f + f^*)] + 4v_L m_\delta^2 + 2Av_L s + A_3 v_R(u_1 + u_2 + u_3) = 0 \quad (13)$$

$$\frac{\partial V}{\partial v_R} = \mu_R^2(2v_R) - 2\lambda_2^2 v_R(v_L^2 - v_R^2) + 2(fu_1 + f^* u_2)M_\triangle v_L + v_L(f + f^*)[2m_\eta(u_1 + u_2 + u_3) + \lambda_1 v^2 + v_L v_R(f + f^*)] + 4v_R m_\delta^2 - 2Av_R s + A_3 v_L(u_1 + u_2 + u_3) = 0 \quad (14)$$

Where the effective mass terms μ_L^2, μ_R^2 are given by

$$\mu_L^2 = (M_\triangle + \lambda_2 s)^2 + \lambda_2 m_\rho s + \frac{1}{2}(f^2 u_1^2 + f^{*2} u_2^2) \quad (15)$$

$$\mu_R^2 = (M_\triangle - \lambda_2 s)^2 - \lambda_2 m_\rho s + \frac{1}{2}(f^2 u_1^2 + f^{*2} u_2^2) \quad (16)$$

Scalar potential minimization

Assuming $v_L \ll v_R \ll m_\rho, s$ we get from equations (14), (15):

$$v_L = \frac{-v_R[M_\triangle u_2 f^* + m_\eta(u_2+u_3)(f+f^*) + u_1(fM_\triangle + m_\eta(f+f^*))]}{2m_\rho s\lambda_2 + 4M_\triangle s\lambda_2 + 2As} \tag{17}$$

- For $v_R \sim 1$ TeV and $v_L \sim$ eV, the D-parity breaking scale has to be as low as $s \sim m_\rho \sim M_\triangle \sim 10^{10}$ GeV.

Scalar potential minimization

Assuming $v_L \ll v_R \ll m_\rho, s$ we get from equations (14), (15):

$$v_L = \frac{-v_R[M_\triangle u_2 f^* + m_\eta(u_2+u_3)(f+f^*) + u_1(fM_\triangle + m_\eta(f+f^*)]}{2m_\rho s\lambda_2 + 4M_\triangle s\lambda_2 + 2As} \qquad (17)$$

- For $v_R \sim 1$ TeV and $v_L \sim$ eV, the D-parity breaking scale has to be as low as $s \sim m_\rho \sim M_\triangle \sim 10^{10}$ GeV.
- In such a type II seesaw dominated case, the right handed triplets $\triangle^c$ will be as light as $\mu_R \sim v_R \sim 1$ TeV and the left handed triplets $\triangle$ as heavy as $\mu_L \sim 10^{10}$ GeV.

Scalar potential minimization

Assuming $v_L \ll v_R \ll m_\rho, s$ we get from equations (14), (15):

$$v_L = \frac{-v_R[M_\triangle u_2 f^* + m_\eta(u_2+u_3)(f+f^*) + u_1(fM_\triangle + m_\eta(f+f^*)]}{2m_\rho s\lambda_2 + 4M_\triangle s\lambda_2 + 2As} \tag{17}$$

- For $v_R \sim 1$ TeV and $v_L \sim$ eV, the D-parity breaking scale has to be as low as $s \sim m_\rho \sim M_\triangle \sim 10^{10}$ GeV.
- In such a type II seesaw dominated case, the right handed triplets $\triangle^c$ will be as light as $\mu_R \sim v_R \sim 1$ TeV and the left handed triplets $\triangle$ as heavy as $\mu_L \sim 10^{10}$ GeV.
- However such light Higgs triplets with $B-L$ charge 2 spoils the gauge coupling unification.

Neutrino Masses

$$\begin{aligned} \mathcal{L}_\nu^{II} &= y_{ij}\ell_{iL}\Phi\ell_{jR} + y'_{ij}\ell_{iL}\tilde{\Phi}\ell_{jR} + h.c. \\ &+ f'_{ij}\ \left(\ell_{iR}^T\ C\ i\sigma_2\Delta_R\ell_{jR} + (R \leftrightarrow L)\right) + h.c. \end{aligned} \quad (18)$$

After symmetry breaking, the effective mass matrix of the neutrinos is

$$m_\nu = \frac{-f\ v^2\ v_R}{2\ m_\sigma\ s} - \frac{v^2}{v_R} h\, f^{-1}\, h^T = m_\nu^{II} + m_\nu^{I}$$

As discussed before, the type II term can become dominant (even if $v_R \sim 1$ TeV) if we take $m_\sigma \sim s \sim 10^8 - 10^{10}$ GeV. But such a low D-parity breaking scale does not favor unification and we have to keep this scale very close to the unification scale.

Gauge coupling unification

The minimal particle content above does not give rise to exact unification. For unification purposes we add two copies of heavy colored particles $\chi(3,1,1,0), \bar{\chi}(\bar{3},1,1,0)$ which decouple after the $SU(2)_R$ breaking scale M_R.

Gauge coupling unification

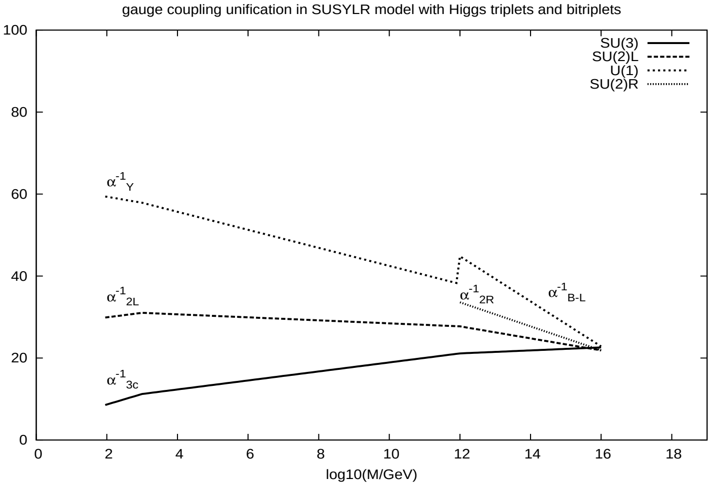

FIGURE: Gauge coupling unification with $M_R = 10^{12}$ GeV, $M_\rho = 10^{16}$ GeV

Results and Conclusion

- After taking into account of spontaneous D-parity breaking, the minimization of the scalar potential also allows the possibility of $M_R \sim$ TeV, $v_L \sim$ eV in LRSM with Higgs triplets and SUSYLR models with Higgs triplets and Higgs bitriplet. It also allows $M_R \sim$ TeV, $v_L/v_R \sim 10^{-6}$ in both susy and non-susy LR models with Higgs doublets.

Results and Conclusion

- After taking into account of spontaneous D-parity breaking, the minimization of the scalar potential also allows the possibility of $M_R \sim$ TeV, $v_L \sim$ eV in LRSM with Higgs triplets and SUSYLR models with Higgs triplets and Higgs bitriplet. It also allows $M_R \sim$ TeV, $v_L/v_R \sim 10^{-6}$ in both susy and non-susy LR models with Higgs doublets.
- In SUSYLR models with Higgs doublets, gauge coupling unification is possible even for a TeV scale M_R as also shown by Bhupal Dev et al (2010).

Results and Conclusion

- After taking into account of spontaneous D-parity breaking, the minimization of the scalar potential also allows the possibility of $M_R \sim$ TeV, $v_L \sim$ eV in LRSM with Higgs triplets and SUSYLR models with Higgs triplets and Higgs bitriplet. It also allows $M_R \sim$ TeV, $v_L/v_R \sim 10^{-6}$ in both susy and non-susy LR models with Higgs doublets.
- In SUSYLR models with Higgs doublets, gauge coupling unification is possible even for a TeV scale M_R as also shown by Bhupal Dev et al (2010).
- However if we add fermion triplets for seesaw, then unification is not possible with TeV scale $SU(2)_R$ breaking scale. Adding fermion singlet for seesaw purposes can evade this difficulty.

Results and Conclusion

- In D-parity breaking SUSYLR model with Higgs triplets, the minimization conditions do not allow the possibility of a TeV scale M_R and eV scale v_L simultaneously.

Results and Conclusion

- In D-parity breaking SUSYLR model with Higgs triplets, the minimization conditions do not allow the possibility of a TeV scale M_R and eV scale v_L simultaneously.
- In SUSYLR model with Higgs triplets and bitriplet, we can have TeV scale M_R and eV scale v_L only if we keep the D-parity breaking scale as low as 10^{10} GeV.

Results and Conclusion

- In D-parity breaking SUSYLR model with Higgs triplets, the minimization conditions do not allow the possibility of a TeV scale M_R and eV scale v_L simultaneously.
- In SUSYLR model with Higgs triplets and bitriplet, we can have TeV scale M_R and eV scale v_L only if we keep the D-parity breaking scale as low as 10^{10} GeV.
- However such a choice of parity breaking scale spoils the gauge coupling unification. The gauge couplings unify if we take $M_R = 10^{12}$ GeV and the D-parity breaking scale as 10^{16} GeV with inclusion of two extra pairs of colored superfields.

Realization within SO(10) framework

- There are two SUSYLR models with spontaneous D-parity breaking: one with Higgs doublets and the other with Higgs triplets and bitriplet.

Realization within SO(10) framework

- There are two SUSYLR models with spontaneous D-parity breaking: one with Higgs doublets and the other with Higgs triplets and bitriplet.
- P.S.B. Dev and Mohapatra had shown that the Higgs doublet model can be realized within SO(10) Grand Unified Theory (GUT) framework with $\mathbf{16}, \overline{\mathbf{16}}, \mathbf{10}, \mathbf{45}$ Higgs representations (PRD **81**, 013001 (2010)).

Bitriplet model within SO(10) framework

- The SUSYLR model with Higgs triplets and bitriplet can be realized by simple extension of MSGUT (Minimal Supersymmetric GUT) with a **54** Higgs.

Bitriplet model within SO(10) framework

- The SUSYLR model with Higgs triplets and bitriplet can be realized by simple extension of MSGUT (Minimal Supersymmetric GUT) with a **54** Higgs.
- MSGUT contains $\mathbf{10}, \mathbf{126}, \overline{\mathbf{126}}, \mathbf{210}$ Higgs representations and it was shown (PRD **70**, 035007 (2004)) that SUSYLR with broken D-parity can not be realized as an intermediate symmetry.

Bitriplet model within SO(10) framework

- The SUSYLR model with Higgs triplets and bitriplet can be realized by simple extension of MSGUT (Minimal Supersymmetric GUT) with a **54** Higgs.
- MSGUT contains $\mathbf{10}, \mathbf{126}, \overline{\mathbf{126}}, \mathbf{210}$ Higgs representations and it was shown (PRD **70**, 035007 (2004)) that SUSYLR with broken D-parity can not be realized as an intermediate symmetry.
- We check that in MSGUT+ **54** it is possible to realize SUSYLR with broken D-parity as an intermediate symmetry.

Bitriplet model within SO(10) framework

- The SUSYLR model with Higgs triplets and bitriplet can be realized by simple extension of MSGUT (Minimal Supersymmetric GUT) with a **54** Higgs.
- MSGUT contains $\mathbf{10}, \mathbf{126}, \overline{\mathbf{126}}, \mathbf{210}$ Higgs representations and it was shown (PRD **70**, 035007 (2004)) that SUSYLR with broken D-parity can not be realized as an intermediate symmetry.
- We check that in MSGUT+ **54** it is possible to realize SUSYLR with broken D-parity as an intermediate symmetry.
- However, the scale of this intermediate symmetry with correct fit to observed fermion masses is still under investigation.

$b - \tau$ Unification in the Bitriplet Model

$b - \tau$ Unification for the doublet model shown by Dev and Mohapatra (PRD **81**, 013001 (2010)) can also be shown for the Bitriplet Model. [4]

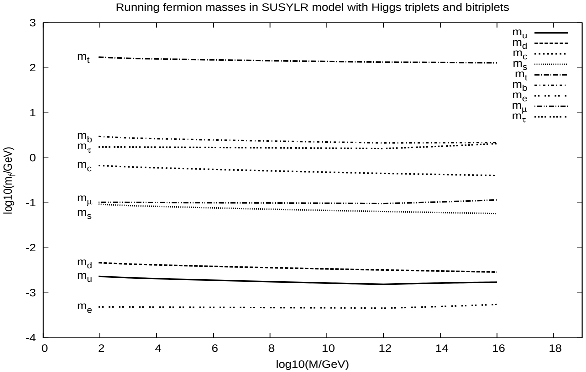

Figure: Fermion masses evolution in the bitriplet model with $M_{susy} = 1$ TeV, $M_R = 10^{12}$ GeV, $M_\rho = 10^{16}$ GeV and $|f| = 0.79, \tan\beta = 10$ at $M = M_Z$

[4] from arXiv:1010.6289 with U.A.Yajnik (IIT Bombay)

THANK YOU