"Neutrino Masses in the Supersymmetric $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ Model with right-handed neutrinos"

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Motivation to study 331 Models

1. At low energies they coincide with the SM;

2. These sort of model are anomally free only if the family number is 3 or any multiple of 3;

3. They have bileptons charged vector bosons;

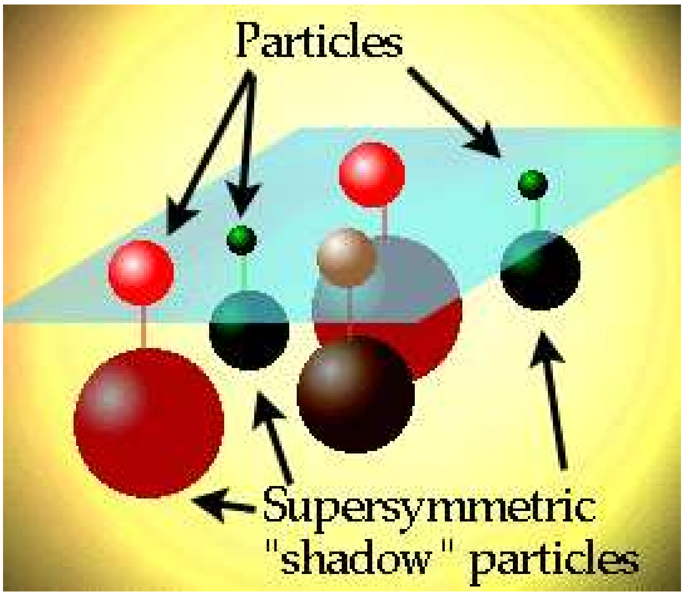
4. They have new heavy quarks;

5. Since one generation of quarks is treated differently from the others this may be lead to a natural explanation for the large mass of the top quark;

Motivation to study SUSY

- Unify bosons and fermions

$$Q|\text{boson}> = |\text{fermion}>$$
$$Q|\text{fermion}> = |\text{boson}>$$

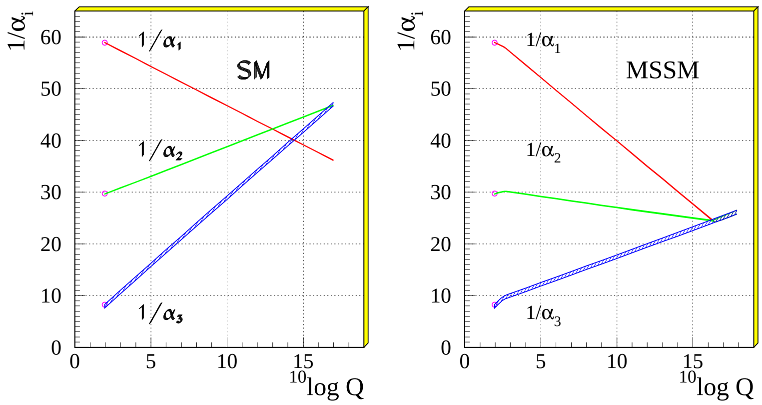


- SUSY local unify with Gravity (Supergravity)

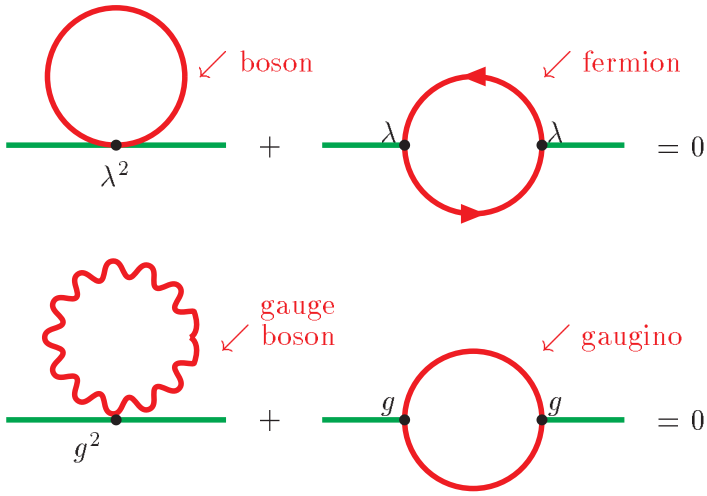
$$\text{spin}2 \longrightarrow \text{spin}\frac{3}{2} \longrightarrow \text{spin}1 \longrightarrow \text{spin}\frac{1}{2} \longrightarrow \text{spin}0$$

- Unify all the gauge constants

Unification of the Coupling Constants
in the SM and the minimal MSSM



- Solve the hierarchy problem



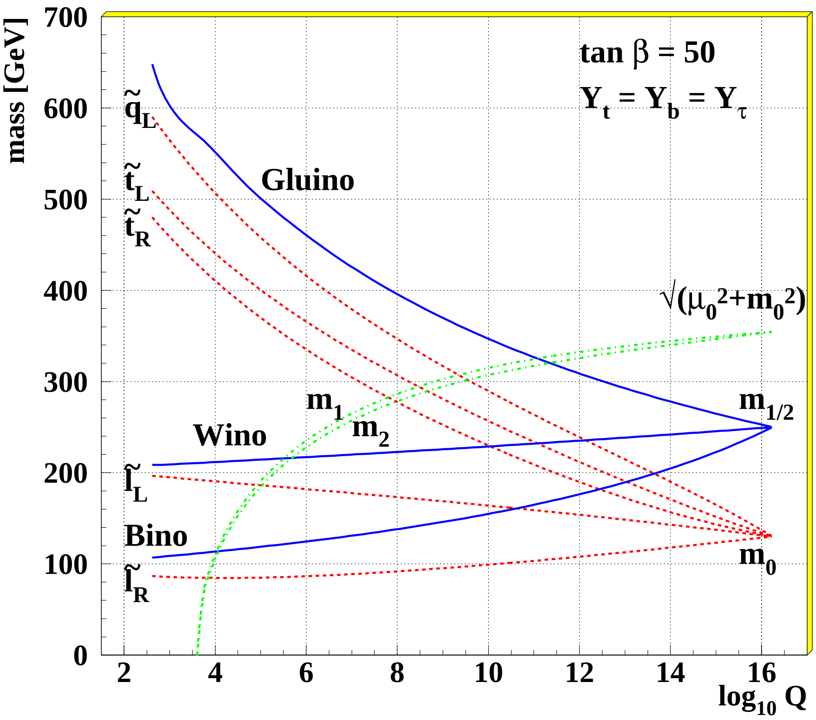
cancel same if susy is broken

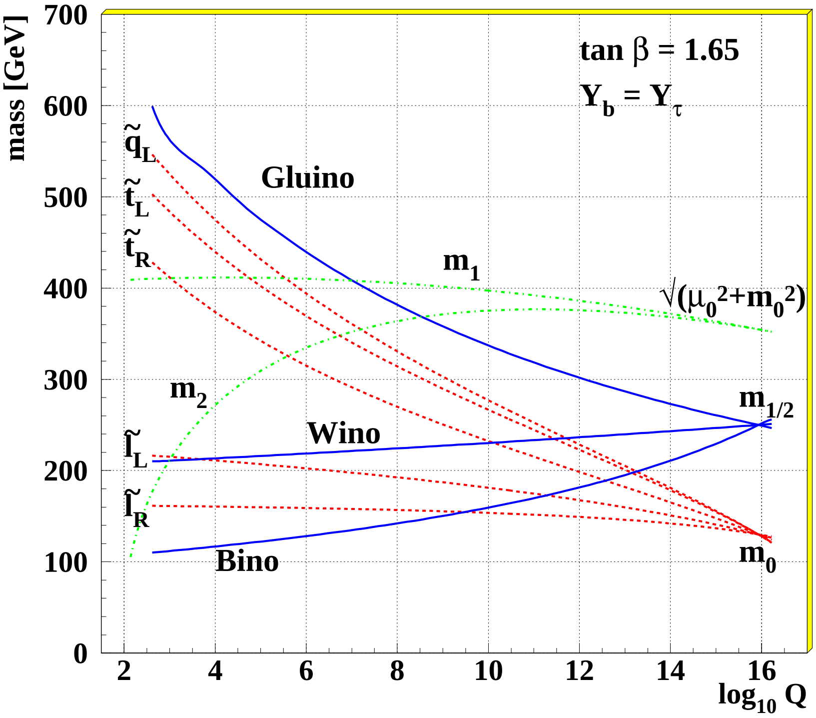
$$\sum_{bosons} m^2 - \sum_{fermions} m^2 = M^2_{SUSY} \leq 1\text{TeV} \quad (1)$$

Higgs Boson

$$\delta M_h^2 \sim g^2 M^2_{SUSY} \sim M_h^2 \quad (2)$$

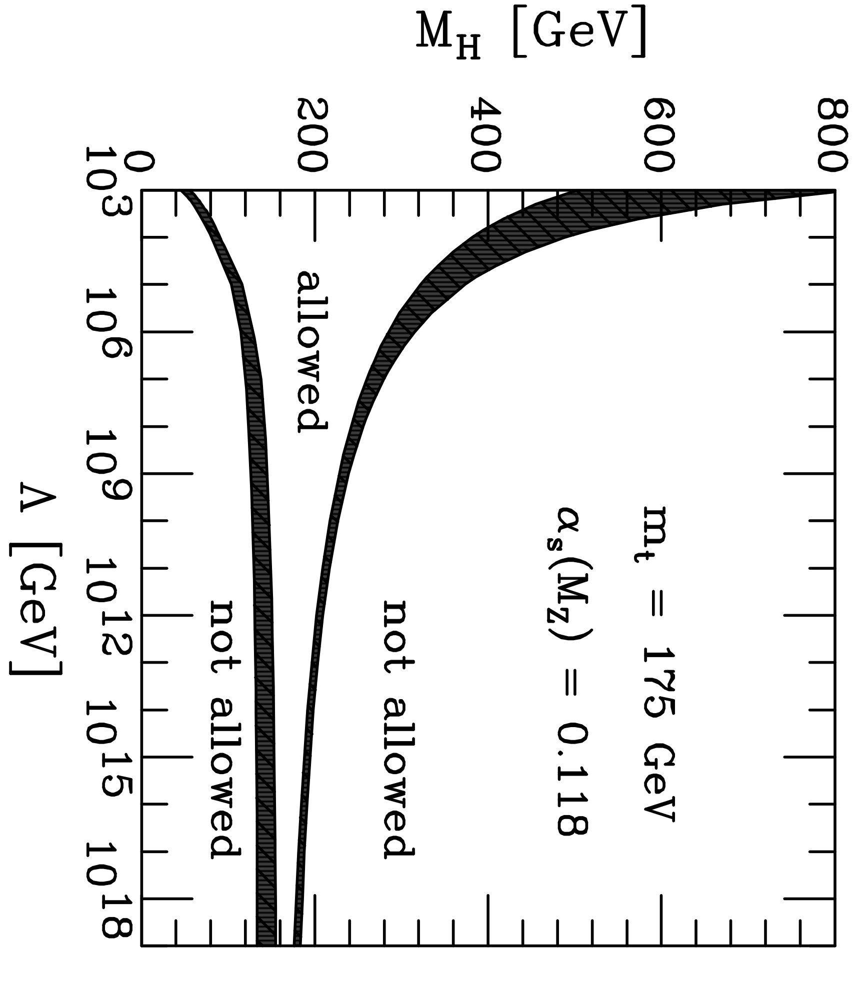
Understood Spontaneous Symmetry Breaking mechanism $\mu > 0 \rightarrow \mu < 0$





mass [GeV]
700
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16
log10 Q
tan β = 1.65
Yb = Yτ
Gluino
m1
√(μ0²+m0²)
m2
Wino
m1/2
Bino
m0
q̃L
t̃L
t̃R
l̃L
l̃R

$m_t \sim 175$ GeV imply $M_h \sim 200$GeV



The Model

Lepton sector

- Triplets

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \\ \nu_a^c \end{pmatrix}_L \sim (\mathbf{1}, \mathbf{3}, -1/3), \qquad (3)$$

$a = e, \mu, \tau$

- Singlets

$$l_{aL}^c \sim (\mathbf{1}, \mathbf{1}, 1). \qquad (4)$$

Quark sector

- Antitriplets

$$Q_{\alpha L} = \begin{pmatrix} d_\alpha \\ u_\alpha \\ D_\alpha \end{pmatrix}_L \sim (\mathbf{3}, \mathbf{3}^*, 0)\,, \quad \alpha = 1, 2; \tag{5}$$

- Triplets

$$Q_{3L} \;=\; \begin{pmatrix} u_3 \\ d_3 \\ T \end{pmatrix}_L \sim (\mathbf{3}, \mathbf{3}, 1/3), \tag{6}$$

- Singlets

$$u^c_{\alpha L} \sim (\mathbf{3}^*, \mathbf{1}, -2/3)\,, \;\; d^c_{\alpha L},\; D^c_{\alpha L} \sim (\mathbf{3}^*, \mathbf{1}, 1/3)\,. \tag{7}$$

$$u^c_{3L},\; T^c_L \sim (\mathbf{3}^*, \mathbf{1}, -2/3), \;\; d^c_{3L} \sim (\mathbf{3}^*, \mathbf{1}, 1/3). \tag{8}$$

- triplets

$$\eta = \begin{pmatrix} \eta_1^0 \\ \eta^- \\ \eta_2^0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi_1^0 \\ \chi^- \\ \chi_2^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, -1/3),$$
$$\rho = \begin{pmatrix} \rho_1^+ \\ \rho^0 \\ \rho_2^+ \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, 2/3), \qquad (9)$$

- Antitriplets

$$\eta' = \begin{pmatrix} \eta_1'^0 \\ \eta'^+ \\ \eta_2'^0 \end{pmatrix}, \quad \chi' = \begin{pmatrix} \chi_1'^0 \\ \chi'^+ \\ \chi_2'^0 \end{pmatrix} \sim \left(\mathbf{1}, \mathbf{3}^*, \frac{1}{3}\right);$$
$$\rho' = \begin{pmatrix} \rho_1'^- \\ \rho'^0 \\ \rho_2'^- \end{pmatrix} \sim \left(\mathbf{1}, \mathbf{3}^*, -\frac{2}{3}\right). \qquad (10)$$

vev

$$
\begin{aligned}
< \eta > &= \begin{pmatrix} v \\ 0 \\ 0 \end{pmatrix}, \ \ < \chi >= \begin{pmatrix} 0 \\ 0 \\ w \end{pmatrix}, \\
< \rho > &= \begin{pmatrix} 0 \\ u \\ 0 \end{pmatrix}, \\
< \eta' > &= \begin{pmatrix} v' \\ 0 \\ 0 \end{pmatrix}, \ \ < \chi' >= \begin{pmatrix} 0 \\ 0 \\ w' \end{pmatrix}, \\
< \rho' > &= \begin{pmatrix} 0 \\ u' \\ 0 \end{pmatrix}.
\end{aligned} \tag{11}
$$

Squarks, Sleptons

$$\tilde{Q}_{\alpha L} = \begin{pmatrix} \tilde{d}_\alpha \\ \tilde{u}_\alpha \\ \tilde{D}_\alpha \end{pmatrix}_L \sim (\mathbf{3}, \mathbf{3}^*, 0), \quad \alpha = 1, 2$$

$$\tilde{Q}_{3L} = \begin{pmatrix} \tilde{u}_3 \\ \tilde{d}_3 \\ \tilde{T} \end{pmatrix}_L \sim (\mathbf{3}, \mathbf{3}, 1/3),$$

$$\tilde{L}_{aL} = \begin{pmatrix} \tilde{\nu}_a \\ \tilde{l}_a \\ \tilde{\nu}_a^c \end{pmatrix}_L \sim (\mathbf{1}, \mathbf{3}, -1/3), \quad a = e, \mu, \tau$$

$$\tilde{l}^c_{aL} \sim (\mathbf{1}, \mathbf{1}, 1),$$

$$\tilde{u}^c_{iL}, \tilde{T}^c_L \sim (\mathbf{3}^*, \mathbf{1}, -2/3), \quad i = 1, 2, 3$$

$$\tilde{d}^c_{iL}, \tilde{D}^c_{\alpha L} \sim (\mathbf{3}^*, \mathbf{1}, 1/3),$$

higgsinos

$$\tilde{\eta} = \begin{pmatrix} \tilde{\eta}_1^0 \\ \tilde{\eta}^- \\ \tilde{\eta}_2^0 \end{pmatrix}, \; \tilde{\chi} = \begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}^- \\ \tilde{\chi}_2^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, -1/3),$$
$$\tilde{\rho} = \begin{pmatrix} \tilde{\rho}_1^+ \\ \tilde{\rho}^0 \\ \tilde{\rho}_2^+ \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, 2/3),$$
$$\tilde{\eta}' = \begin{pmatrix} \tilde{\eta}_1'^0 \\ \tilde{\eta}'^+ \\ \tilde{\eta}_2'^0 \end{pmatrix}, \tilde{\chi}' = \begin{pmatrix} \tilde{\chi}_1'^0 \\ \tilde{\chi}'^+ \\ \tilde{\chi}_2'^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}^*, 1/3),$$
$$\tilde{\rho}' = \begin{pmatrix} \tilde{\rho}_1'^- \\ \tilde{\rho}'^0 \\ \tilde{\rho}_2'^- \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}^*, -2/3). \qquad (12)$$

Boson Sector

Particle	Spin	Superpartner	Spin
(U(1)) V'_m	1	λ_B	$\frac{1}{2}$
(SU(3)) V^a_m	1	λ^a_A	$\frac{1}{2}$
(SU(3)) g^a_m	1	λ^a_C	$\frac{1}{2}$

Lagrangian

$$\mathcal{L}_{331S} = \mathcal{L}_{SUSY} + \mathcal{L}_{\text{soft}},$$

supersymmetric Lagrangian

$$\mathcal{L}_{SUSY} = \mathcal{L}_{\text{Lepton}} + \mathcal{L}_{\text{Quark}} + \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Scalar}}$$

$$\mathcal{L}_{\text{Leptons}} = \int d^4\theta \left[\hat{\bar{L}}_{aL} e^{2g\hat{V} - \frac{g'}{3}\hat{V}'} \hat{L}_{aL} + \hat{\bar{l}}^c_{aL} e^{g'\hat{V}'} \hat{l}^c_{aL} \right],$$

$$\begin{aligned}
\mathcal{L}_{\text{Quarks}} &= \int d^4\theta \Big[\hat{\bar{Q}}_{\alpha L} e^{[2(g_s \hat{V}_C + g\hat{\bar{V}})]} \hat{Q}_{\alpha L} \\
&+ \hat{\bar{Q}}_{3L} e^{[2(g_s \hat{V}_C + g\hat{V}) + \frac{g'}{3}\hat{V}']} \hat{Q}_{3L} \\
&+ \hat{\bar{u}}^c_{iL} e^{[2g_s \hat{\bar{V}}_C - \frac{2g'}{3}\hat{V}']} \hat{u}^c_{iL} \\
&+ \hat{\bar{d}}^c_{iL} e^{[2g_s \hat{\bar{V}}_C + \frac{g'}{3}\hat{V}']} \hat{d}^c_{iL} \\
&+ \hat{\bar{T}}^c_{L} e^{[2g_s \hat{\bar{V}}_C - \frac{2g'}{3}\hat{V}']} \hat{T}^c_{L} \\
&+ \hat{\bar{D}}^c_{\alpha L} e^{[2g_s \hat{\bar{V}}_C + \frac{g'}{3}\hat{V}']} \hat{D}^c_{\alpha L} \Big],
\end{aligned}$$

$$
\begin{aligned}
\mathcal{L}_{\text{Gauge}} &= \frac{1}{4}\int d^2\theta\ \left[\mathcal{W}_{\mathcal{C}}\mathcal{W}_{\mathcal{C}} + \mathcal{W}\mathcal{W} + \mathcal{W}'\mathcal{W}'\right] \\
&+ \frac{1}{4}\int d^2\bar{\theta}\ \left[\bar{\mathcal{W}}_{C}\bar{\mathcal{W}}_{C} + \bar{\mathcal{W}}\bar{\mathcal{W}} + \bar{\mathcal{W}}'\bar{\mathcal{W}}'\right],
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{W}_{\zeta\mathcal{C}} &= -\frac{1}{8g_s}\bar{D}\bar{D}e^{-2g_s\widehat{V}_C}D_\zeta e^{2g_s\widehat{V}_C}, \\
\mathcal{W}_{\zeta} &= -\frac{1}{8g}\bar{D}\bar{D}e^{-2g\widehat{V}}D_\zeta e^{2g\widehat{V}}, \\
\mathcal{W}'_{\zeta} &= -\frac{1}{4}\bar{D}\bar{D}D_\zeta\widehat{V}',\ \ \zeta = 1, 2.
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\text{Escalar}} &= \int d^4\theta\ \left[\bar{\widehat{\eta}}\, e^{[2g\widehat{V} - \frac{g'}{3}\widehat{V}']}\widehat{\eta} + \bar{\widehat{\chi}}\, e^{[2g\widehat{V} - \frac{g'}{3}\widehat{V}']}\widehat{\chi}\right. \\
&+ \bar{\widehat{\rho}}\, e^{[2g\widehat{V} + \frac{2g'}{3}\widehat{V}']}\widehat{\rho} + \bar{\widehat{\eta}}'\, e^{[2g\bar{\widehat{V}} + \frac{g'}{3}\widehat{V}']}\widehat{\eta}' \\
&+ \left.\bar{\widehat{\chi}}'\, e^{[2g\bar{\widehat{V}} + \frac{g'}{3}\widehat{V}']}\widehat{\chi}' + \bar{\widehat{\rho}}'\, e^{[2g\bar{\widehat{V}} - \frac{2g'}{3}\widehat{V}']}\widehat{\rho}'\right] \\
&+ \int d^2\theta W + \int d^2\bar{\theta}\bar{W},
\end{aligned}
$$

W is the superpotential

$$W = \frac{W_2}{2} + \frac{W_3}{3},\ \bar{W} = \frac{\bar{W}_2}{2} + \frac{\bar{W}_3}{3},$$

$$\begin{aligned}
W_2 &= \mu_{0a}\hat{L}_a\hat{\eta}' + \mu_{1a}\hat{L}_a\hat{\chi}' + \mu_\eta\hat{\eta}\hat{\eta}' + \mu_\chi\hat{\chi}\hat{\chi}' + \mu_1\hat{\eta}\hat{\chi}' \\
&+ \mu_2\hat{\chi}\hat{\eta}' + \mu_\rho\hat{\rho}\hat{\rho}', \\
W_3 &= \lambda_{1ab}\hat{L}_a\hat{\rho}'\hat{l}^c_b + \lambda_{2a}\epsilon\hat{L}_a\hat{\chi}\hat{\rho} + \lambda_{3a}\epsilon\hat{L}_a\hat{\eta}\hat{\rho} \\
&+ \lambda_{4ab}\epsilon\hat{L}_a\hat{L}_b\hat{\rho} + \kappa_{1i}\hat{Q}_3\hat{\eta}'\hat{u}^c_i + \kappa'_1\hat{Q}_3\hat{\eta}'\hat{T}^c \\
&+ \kappa_{2i}\hat{Q}_3\hat{\chi}'\hat{u}^c_i + \kappa'_2\hat{Q}_3\hat{\chi}'\hat{T}^c + \kappa_{3\alpha i}\hat{Q}_\alpha\hat{\eta}\hat{d}^c_i \\
&+ \kappa'_{3\alpha\beta}\hat{Q}_\alpha\hat{\eta}\hat{D}^c_\beta + \kappa_{4\alpha i}\hat{Q}_\alpha\hat{\rho}\hat{u}^c_i + \kappa'_{4\alpha}\hat{Q}_\alpha\hat{\rho}\hat{T}^c \\
&+ \kappa_{5i}\hat{Q}_3\hat{\rho}'\hat{d}^c_i + \kappa'_{5\beta}\hat{Q}_3\hat{\rho}'\hat{d}^c_\beta + \kappa_{6\alpha i}\hat{Q}_\alpha\hat{\chi}\hat{d}^c_i \\
&+ \kappa'_{6\alpha\beta}\hat{Q}_\alpha\hat{\chi}\hat{D}^c_\beta + f_1\epsilon\hat{\rho}\hat{\chi}\hat{\eta} + f'_1\epsilon\hat{\rho}'\hat{\chi}'\hat{\eta}' \\
&+ \zeta_{\alpha\beta\gamma}\epsilon\hat{Q}_\alpha\hat{Q}_\beta\hat{Q}_\gamma + \lambda'_{\alpha a i}\hat{Q}_\alpha\hat{L}_a\hat{d}^c_i + \lambda''_{ijk}\hat{d}^c_i\hat{u}^c_j\hat{d}^c_k \\
&+ \xi_{1ij\beta}\hat{d}^c_i\hat{u}^c_j\hat{D}^c_\beta + \xi_{2\alpha a\beta}\hat{Q}_\alpha\hat{L}_a\hat{D}^c_\beta + \xi_{3i\beta}\hat{d}^c_i\hat{T}^c\hat{D}^c_\beta \\
&+ \xi_{4ij}\hat{d}^c_i\hat{T}^c\hat{d}^c_j + \xi_{5\alpha i\beta}\hat{D}^c_\alpha\hat{u}^c_i\hat{D}^c_\beta + \xi_{6\alpha\beta}\hat{D}^c_\alpha\hat{T}^c\hat{D}^c_\beta
\end{aligned}$$

$$
\begin{aligned}
W_{RC} &= \frac{\mu_\eta}{2}\hat{\eta}\hat{\eta}' + \frac{\mu_\chi}{2}\hat{\chi}\hat{\chi}' + \frac{\mu_\rho}{2}\hat{\rho}\hat{\rho}' + \frac{\mu_2}{2}\hat{\eta}\hat{\chi}' + \frac{\mu_3}{2}\hat{\chi}\hat{\eta}' \\
&+ \frac{1}{3}\Big[\lambda_{1ab}\hat{L}_a\hat{\rho}'\hat{l}^c_b + \kappa_{1i}\hat{Q}_3\hat{\eta}'\hat{u}^c_i + \kappa'_1\hat{Q}_3\hat{\eta}'\hat{u}'^c \\
&+ \kappa_{2i}\hat{Q}_3\hat{\chi}'\hat{u}^c_i + \kappa'_2\hat{Q}_3\hat{\chi}'\hat{u}'^c + \kappa_{3\alpha i}\hat{Q}_\alpha\hat{\eta}\hat{d}^c_i \\
&+ \kappa'_{3\alpha\beta}\hat{Q}_\alpha\hat{\eta}\hat{d}'^c_\beta + \kappa_{4\alpha i}\hat{Q}_\alpha\hat{\rho}\hat{u}^c_i + \kappa'_{4\alpha}\hat{Q}_\alpha\hat{\rho}\hat{u}'^c \\
&+ \kappa_{5i}\hat{Q}_3\hat{\rho}'\hat{d}^c_i + \kappa'_{5\beta}\hat{Q}_3\hat{\rho}'\hat{d}^c_\beta + \kappa_{6\alpha i}\hat{Q}_\alpha\hat{\chi}\hat{d}^c_i \\
&+ \kappa'_{6\alpha\beta}\hat{Q}_\alpha\hat{\chi}\hat{d}'^c_\beta + f_1\epsilon\hat{\rho}\hat{\chi}\hat{\eta} + f'_1\epsilon\hat{\rho}'\hat{\chi}'\hat{\eta}'\Big]
\end{aligned}
$$

$$
\text{R-parity} = (-1)^{2S}(-1)^{3(\mathcal{B}+\mathcal{L})}, \qquad (13)
$$

quarks ans charged leptons get their masses
neutrinos remain massless

Triplet	L	Q_3	χ	η	ρ
$\mathcal{B}$ *charge*	0	$\frac{1}{3}$	0	0	0
$\mathcal{L}$ *charge*	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{4}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$

(14)

Anti − Triplet	Q_α	χ'	η'	ρ'
$\mathcal{B}$ *charge*	$\frac{1}{3}$	0	0	0
$\mathcal{L}$ *charge*	$\frac{2}{3}$	$-\frac{4}{3}$	$\frac{2}{3}$	$\frac{2}{3}$

(15)

Singlet	l^c	u^c	d^c	u'^c	d'^c
$\mathcal{B}$ *charge*	0	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
$\mathcal{L}$ *charge*	−1	0	0	2	−2

(16)

Discrete Symmetry for Proton Stability and Neutrino Masses in SUSY331RN

$$\begin{aligned} n_L &= n_\eta = n_\chi = \frac{1}{2}, \\ n_{\eta'} &= n_{\chi'} = n_u = n_{u'} = -\frac{1}{2}, \\ n_{Q_3} &= n_{\rho'} = 1,\ n_d = n_{d'} = -2, \\ n_\rho &= -1,\ n_{Q_\alpha} = \frac{3}{2},\ n_l = -\frac{3}{2}, \end{aligned} \quad (17)$$

$$\begin{aligned} W &= W_{RC} + \frac{1}{2}\left(\mu_{0a}\hat{L}_a\hat{\eta}' + \mu_{1a}\hat{L}_a\hat{\chi}'\right) + \frac{1}{3}\left(\lambda_{1ab}\hat{L}_a\hat{\rho}'\hat{l}^c_b \right. \\ &+ \lambda_{2a}\epsilon\hat{L}_a\hat{\chi}\hat{\rho} + \lambda_{3a}\epsilon\hat{L}_a\hat{\eta}\hat{\rho} + \lambda_{4ab}\epsilon\hat{L}_a\hat{L}_b\hat{\rho} \\ &+ \left. \lambda'_{\alpha ai}\hat{Q}_\alpha\hat{L}_a\hat{d}^c_i + \xi_{2\alpha a\beta}\hat{Q}_\alpha\hat{L}_a\hat{d}'^c_\beta\right) \end{aligned} \quad (18)$$

mixing between leptons and higgsinos

$$
\begin{aligned}
&- \frac{\mu_{0a}}{2} L_a \tilde{\eta}' - \frac{\mu_{1a}}{2} L_a \tilde{\chi}' - \frac{\mu_2}{2} \tilde{\eta}\tilde{\chi}' - \frac{\mu_3}{2} \tilde{\chi}\tilde{\eta}' \\
&- \frac{\lambda_{2a}}{3}(L_a \tilde{\chi}\rho + \tilde{\rho} L_a \chi) - \frac{\lambda_{3a}}{3}(L_a \tilde{\eta}\rho + \tilde{\rho} L_a \eta) \\
&- \frac{\lambda_{4ab}}{3} L_a L_b \rho + hc, \qquad (19)
\end{aligned}
$$

Ψ^0

$$
\begin{aligned}
&\nu_1 \; \nu_2 \; \nu_3 \nu_1^c \; \nu_2^c \; \nu_3^c - i\lambda_A^3 - i\lambda_{X^0} - i\lambda_{X^{0*}} - i\lambda_A^8 - i\lambda_B \\
&\tilde{\eta}_1^0 \tilde{\eta}_1'^0 \; \tilde{\eta}_2^0 \; \tilde{\eta}_2'^0 \; \tilde{\chi}_1^0 \; \tilde{\chi}_1'^0 \; \tilde{\chi}_2^0 \tilde{\chi}_2'^0 \; \tilde{\rho}^0 \; \tilde{\rho}'^0 \qquad (20)
\end{aligned}
$$

$$
-\frac{1}{2}(\Psi^0)^T Y^0 \Psi^0 + h.c. \qquad (21)
$$

$$
\tilde{\chi}_i^0 = N_{ij} \Psi_j^0, \;\; j = 1, \cdots, 21. \qquad (22)
$$

$$Y^0 = \begin{pmatrix} (M_\nu)_{6\times 6} & (M_{\nu N}) \\ \left(M_{\nu N}^T\right) & (M_N)_{15\times 15} \end{pmatrix} \tag{23}$$

M_ν three Dirac eigenstates

$$0 \;\; m_\nu \;\; m_\nu \tag{24}$$

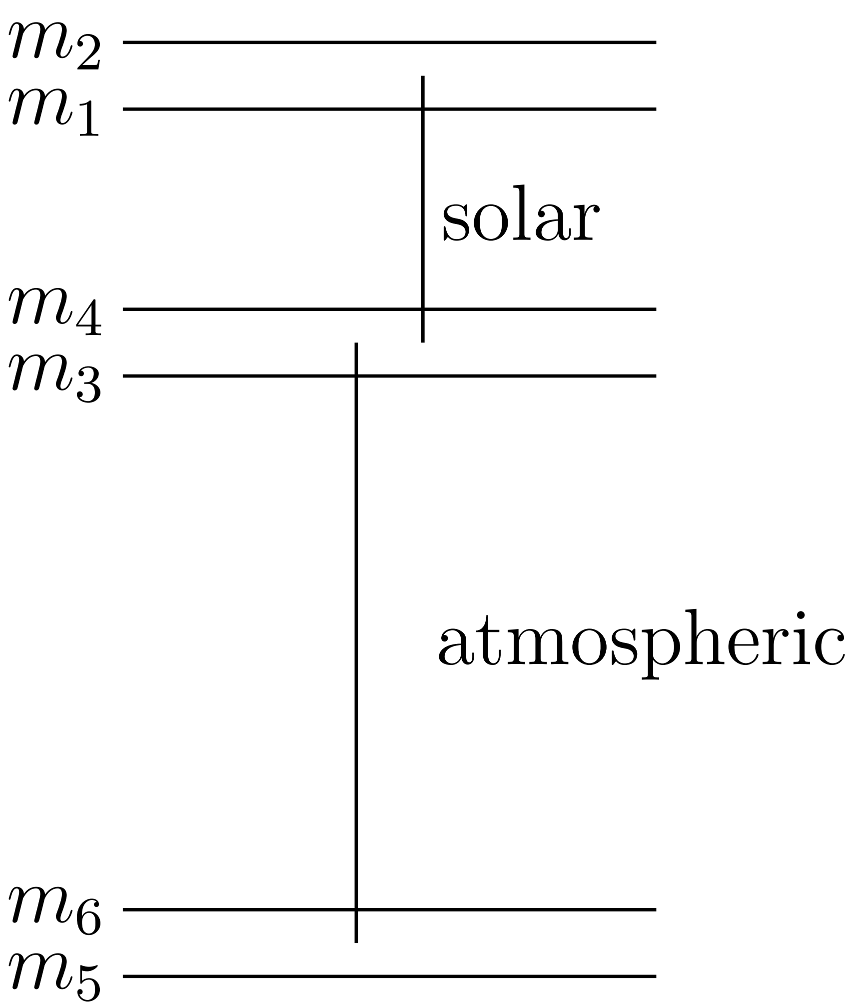
atmospheric neutrino mass difference

$$m_\nu = \frac{2u}{3}\sqrt{\lambda_{412}^2 + \lambda_{413}^2 + \lambda_{423}^2} \tag{25}$$

$$\begin{aligned} \lambda_{412} &= \lambda_{413} = \lambda_{423} = 2 \times 10^{-13}, \\ \lambda_{421} &= \lambda_{431} = \lambda_{432} = -2 \times 10^{-13}. \end{aligned} \tag{26}$$

$$\Delta m_{atm} \sim 5 \times 10^{-2} \text{ eV} \tag{27}$$

mixing terms turn on, this inverted spectrum will not only give rise to mass splitting between the two degenerate Dirac states, it will also split each Dirac pairs into two non-degenerate Majorana states



The inverted hierarchy mass pattern of neutrinos in the model

Conclusion

The famous relation for the R-parity in the MSSM has been generalized to this kind of the 3-3-1 models. In this case it relates to the new conserved charge $\mathcal{L}$. A simple mechanism for the mass generation of the neutrinos has been explored. We have showed that the model naturally gives rise to the neutrinos an inverted hierarchy mass pattern.

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