R-symmetric flipped SU(5)

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Motivation

- Doublet-triplet splitting problem
- Forbidding all the dangerous terms directly from the symmetry
- The SU(5) models require huge representations.

Symmetry Breaking

- H and $\bar{H}$ break the SU(5)xU(1) into the SM gauge group. (ν_H^c and $\nu_{\bar{H}}^c$)
- $\nu_H^c = \nu_{\bar{H}}^c = \Phi$ and S develop VEVs.

R-symmetric Flipped SU(5) Model

- Superpotential

$$W = W_{\text{Yukawa}} + W_{\text{DT}} + W_{\text{neutrino}} + W_{HS} \cdots ,$$

- $W_{\text{Yukawa}} = \frac{1}{4}\lambda_1^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}F_i^{\alpha\beta}F_j^{\gamma\delta}h^{\epsilon} + \sqrt{2}\lambda_2^{ij}F_i^{\alpha\beta}\bar{f}_{j\alpha}\bar{h}_{\beta} + \lambda_3^{ij}\bar{f}_{i\alpha}\ell_j^c h^{\alpha}$,
- $W_{\text{DT}} = \frac{\lambda_4}{4\Lambda_{\text{DT}}^8}\epsilon_{\alpha\beta\gamma\delta\epsilon}S^8 H^{\alpha\beta}H^{\gamma\delta}h^{\epsilon} + \frac{1}{4}\lambda_5\epsilon^{\alpha\beta\gamma\delta\epsilon}\bar{H}_{\alpha\beta}\bar{H}_{\gamma\delta}\bar{h}_{\epsilon}$,
- $W_{\text{neutrino}} = \frac{c_{ij}}{2\Lambda_N^2}S(F_i^{\alpha\beta}\bar{H}_{\alpha\beta})(F_j^{\gamma\delta}\bar{H}_{\gamma\delta})$,
- $W_{HS} = \frac{\lambda_H}{4\Lambda_{HS}^5}(H^{\alpha\beta}\bar{H}_{\alpha\beta})^4 + \frac{\lambda_{HS}}{18\Lambda_{HS}^{10}}(H^{\alpha\beta}\bar{H}_{\alpha\beta})^2 S^9 + \frac{\lambda_S}{18\Lambda_{HS}^{15}}S^{18}$,

- Additional structure in our model:
  - Global $U(1)_R$ symmetry
  - Singlet field S
- $H\bar{H}$ and $h\bar{h}$ terms are both forbidden by the U(1)R symmetry.

Fields	Components	SU(5)	U(1)	$U(1)_R$
F_i	d_i^c, Q_i, ν_i^c	**10**	+1	17/36
$\bar{f}_i$	u_i^c, L_i	$\bar{\mathbf{5}}$	−3	17/36
ℓ_i^c	e_i^c	**1**	+5	17/36
H	d_H^c, Q_H, ν_H^c	**10**	+1	1/36
$\bar{H}$	$d_{\bar{H}}^c$, $Q_{\bar{H}}$, $\nu_{\bar{H}}^c$	$\overline{\mathbf{10}}$	−1	17/36
h	D, H_d	**5**	−2	19/18
$\bar{h}$	$\bar{D}$, H_u	$\bar{\mathbf{5}}$	+2	19/18
S	S	**1**	0	1/9

SU(5)

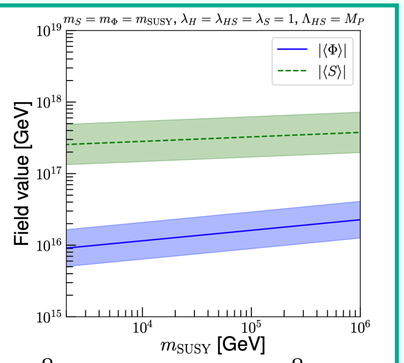
Triplet pair

Mass Spectrum

- Doublet-triplet splitting problem is solved by the Missing partner mechanism.
- Intermediate scale: Light color-triplet Higgs
- $M_{H_C} = \lambda_4 |\langle\Phi\rangle| \left(\frac{\langle S\rangle}{\Lambda_{\text{DT}}}\right)^8$

$$\simeq \lambda_4 \times 7 \times 10^{11} \times \left(\frac{|\langle\Phi\rangle|}{10^{16}\ \text{GeV}}\right)\left(\frac{\langle S\rangle}{3\times 10^{17}\ \text{GeV}}\right)^8\left(\frac{\Lambda_{\text{DT}}}{10^{18}\ \text{GeV}}\right)^{-8}\ \text{GeV}$$

- $M_{\bar{H}_C} = \lambda_5 |\langle\Phi\rangle|$.

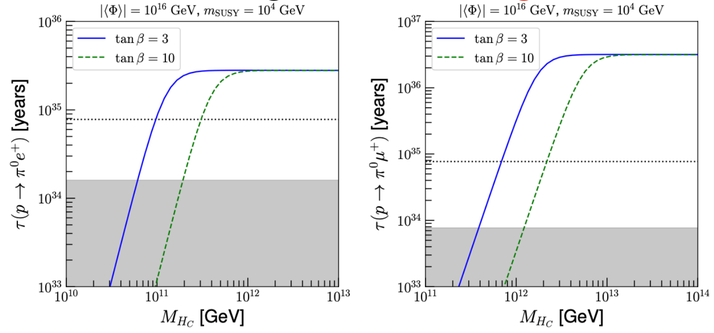


Proton Decay

- The color-triplet Higgs exchange process: induced by the Yukawa interactions —> Main contribution: containing the second generations

Main contribution modes:

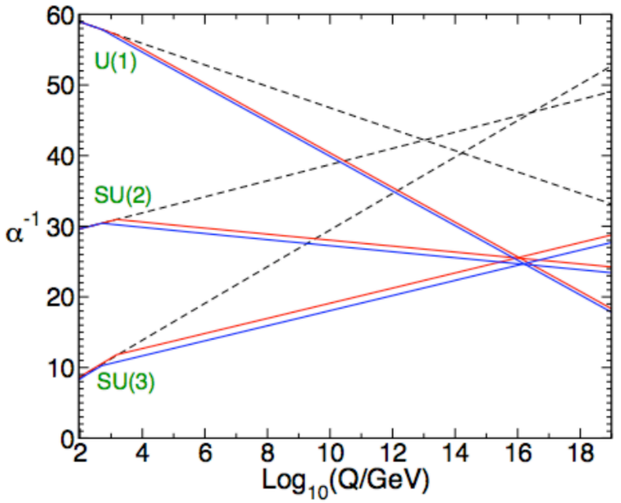
- The minimal SUSY SU(5)
  - $p \to K^+\bar{\nu}$ or $p \to \pi^0 e^+$
- Our model:
  - $p \to \pi^0\mu^+$ and $p \to K^0\mu^+$



(a) $p \to \pi^0 e^+$ (b) $p \to \pi^0 \mu^+$

Grand unified theories

- Unification of quarks and leptons
- Coupling unification
  - $g_1(M_{\rm GUT}) = g_2(M_{\rm GUT}) = g_3(M_{\rm GUT})$
- Charge quantization
- Anomaly cancelation
- SUSY GUT
  - Gauge coupling unification



Minimal SUSY SU(5)

- $$F_i = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u^c_{i3} & -u^c_{i2} & u^1_i & d^1_i \\ -u^c_{i3} & 0 & u^c_{i1} & u^2_i & d^2_i \\ u^c_{i2} & -u^c_{i1} & 0 & u^3_i & d^3_i \\ -u^1_i & -u^2_i & -u^3_i & 0 & e^c_i \\ -d^1_i & -d^2_i & -d^3_i & -e^c_i & 0 \end{pmatrix}, \qquad \bar{f}_i = \begin{pmatrix} d^c_{i1} \\ d^c_{i2} \\ d^c_{i3} \\ e_i \\ -\nu_i \end{pmatrix}, \qquad l^c_i = \begin{pmatrix} \nu^c_i \end{pmatrix}$$

Doublet-triplet splitting problem

- MSSM Higgs: embedded in 5 and $\bar{5}$ in SU(5) theory
  - $$H = \begin{pmatrix} \zeta_u \\ H_u \end{pmatrix}, \qquad \bar{H} = \begin{pmatrix} \bar{\zeta}_d \\ H_d \end{pmatrix}$$
- Superpotential $W \supset \lambda(H\Phi\bar{H} + MH\bar{H})$
  - VEV of $\Phi = 24$ breaks SU(5) into the SM
  - $$< \Phi > = \mathrm{diag}(b, b, b, -\frac{3}{2}b, -\frac{3}{2}b)$$
  - $$W_{\rm eff} = \lambda(b + M)\zeta_u\bar{\zeta}_d + \lambda(-\frac{3}{2}b + M)H_uH_d$$

GUT scale EW scale → Fine-tuning

Dimension-five proton decay operators

- Exchange of the color-triplet Higgs
  - $$W_5^{\rm eff} = \frac{\mu_H}{M_{H_C} M_{\bar{H}_C}} \left[\frac{1}{2} (V^* P \lambda_{1,D} V^\dagger)^{ij} (\lambda_{2,D} U_\ell^*)^{kl} \epsilon_{abc} (Q_i^a \cdot Q_j^b)(Q_k^c \cdot L_l) - (\lambda_{2,D} V P^*)^{ij} (U_\ell \lambda_{3,D})^{kl} \epsilon^{abc} u_{ia}^c d_{jb}^c u_{kc}^c e_l^c \right]$$
- Cut-off suppressed operators
  - $$W_5' = \frac{c_1^{ijkl}}{\Lambda^2} \epsilon_{\alpha\beta\gamma\delta\epsilon} S F_i^{\alpha\beta} F_j^{\gamma\delta} F_k^{\epsilon\tau} \bar{f}_{l\tau} + \frac{c_2^{ijkl}}{\Lambda^2} S F_i^{\alpha\beta} \bar{f}_{j\alpha} \bar{f}_{k\beta} \bar{\ell}_l^c$$
- Dimension-five proton decay does not give the main contribution.

R-axion

- U(1)R symmetry breaking
  - Nambu-Goldstone boson: R-axion
- U(1)R is explicitly violated by a constant term (cosmological constant)
  - $W = W_0 + W_{\rm const}$
- Supergravity effect
- R-axion mass $m_a^2 \simeq \frac{8}{f_a^2 M_P^2} \left| \left\langle W_{\rm const} \left[K^i (K^{-1})_i^{\ j} W_{0j}^* - 3 W_0^* \right] \right\rangle \right|$,
- $$m_a \simeq 1 \times 10^5 \times \left(\frac{\langle S \rangle}{3 \times 10^{17}\ {\rm GeV}} \right)^8 \left(\frac{m_{3/2}}{10^4\ {\rm GeV}} \right)^{1/2} {\rm GeV}$$
- R-axion: as heavy as other SUSY particles