

Proton decay in
SUSY GUT

Da-Xin Zhang
(Peking Univ.)

Review: the
Minimal SUSY
SU(5) GUT

A Realistic
SUSY SU(5)
GUT

Beyond MSSM:
SUSYLR

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- **Higgs fields:**

$$24(\Sigma), 5(H^\alpha), \bar{5}(\bar{H}_\alpha) \quad (1)$$

- **Higgs superpotential**

$$W_{Higgs} = \frac{f}{3} \text{Tr} \Sigma^3 + \frac{1}{2} f V \text{Tr} \Sigma^2 + \lambda \bar{H}_\alpha (\Sigma_\beta^\alpha + 3\kappa \delta_\beta^\alpha) H^\beta \quad (2)$$

- **Matter fields:**

$$10(\psi_i)^{\alpha\beta}, \bar{5}(\varphi_j)_\alpha \quad (3)$$

- **Yukawa couplings**

$$W_F = \frac{h^{ij}}{4} \varepsilon_{\alpha\beta\gamma\delta} \psi_i^{\alpha\beta} \psi_j^{\gamma\delta} H^\epsilon + \sqrt{2} f^{ij} \psi_i^{\alpha\beta} \varphi_{j\alpha} \bar{H}_\beta \quad (4)$$

RGE and Threshold Effects

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- **RGE for $SU(3) \times SU(2) \times U(1)$**

$$\alpha_i^{-1}(E) = \alpha_i^{-1}(M_Z) - \frac{b_i}{2\pi} \ln \frac{E}{M_Z} \quad (5)$$

- **Unification requirement: threshold effects**

$$\begin{aligned} & (3\alpha_2^{-1} - 2\alpha_3^{-1} - \alpha_1^{-1})(m_Z) \\ &= \frac{1}{2\pi} \left(\frac{12}{5} \ln \frac{M_{Hc}}{m_Z} - 2 \ln \frac{m_{SUSY}}{m_Z} \right) \end{aligned} \quad (6)$$

- **The RGE's use those at the 2-loop numerically**

$$3.5 \times 10^{14} GeV \leq M_{Hc} \leq 3.6 \times 10^{15} GeV \quad (7)$$

Proton decay: Dim-5 operator

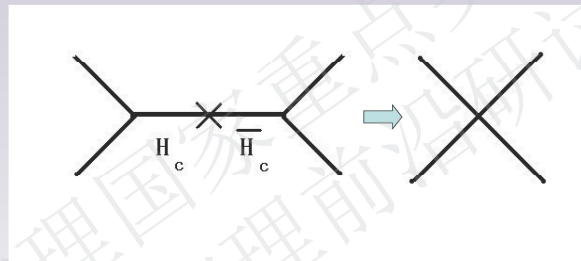
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$$W_5 = \frac{1}{M_T} C_{ijkl} \left[\frac{1}{2} (Q_i Q_j) (Q_k L_l) + (u_i^c d_j^c) (u_k^c e_l^c) \right], \quad (8)$$

Proton decay: dressing

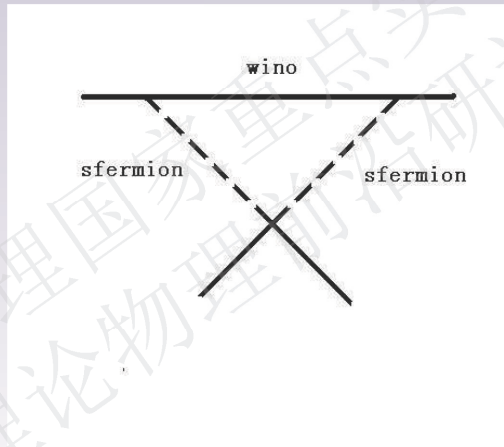
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- Dressing by the charginos:

$$I(f_1, f_2; W) = \frac{\alpha_2}{4\pi} \frac{m_{\tilde{W}}}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \left(\frac{m_{\tilde{f}_1}^2}{m_{\tilde{f}_1}^2 - m_{\tilde{W}}^2} \ln \frac{m_{\tilde{f}_1}^2}{m_{\tilde{W}}^2} - \frac{m_{\tilde{f}_2}^2}{m_{\tilde{f}_2}^2 - m_{\tilde{W}}^2} \ln \frac{m_{\tilde{f}_2}^2}{m_{\tilde{W}}^2} \right). \quad (9)$$

- Experimental requirement by proton decay:

$$M_{H_C} \geq 7.6 \times 10^{16} \text{ GeV}$$

Problems in the Minimal SUSY SU(5)

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- **Fermion masses:**

$$m_b = m_\tau, m_s = m_\mu, m_d = m_e \quad (10)$$

- **Doublet-triplet splitting:**

$$\mu \ll M_{H_C} \quad (11)$$

- **Proton lifetime:
From RGE**

$$3.5 \times 10^{14} GeV \leq M_{H_C} \leq 3.6 \times 10^{15} GeV \quad (12)$$

- From proton decay:**

$$M_{H_C} > 7.6 \times 10^{16} GeV \quad (13)$$

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Jun-hui Zheng and D-X Zhang

Motivation:

- **Fermion masses:**
Georgi-Jarlskog mechanism (PLB86, 297)
not Froggatt-Nielsen mechanism (NPB147, 277)
- **Doublet-triplet splitting:**
Missing Partner Model
(e.g., Altarelli et al, JHEP11, 040)
- **Proton lifetime:**
Weaken the link between fermion masses and
dim.-5 operators (Hisano et al, PLB342, 138)

Higgs Sector: The quantum numbers

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$U_S(1)$ and $U_P(1)$ charges for Higgs superfields.

Higgs	5	$\bar{5}$	45	$\bar{45}$	5'	$\bar{5}'$
$U_S(1)$	h	$-q - h$	$q + h$	$-q - h$	$q + h$	$-h$
$U_P(1)$	τ	$-\sigma$	σ	$-\sigma$	τ	$-\sigma$
50	$\bar{50}$	50'	$\bar{50}'$	75	S	P
$q + h$	$-h$	h	$-q - h$	0	$-q$	0
σ	$-\tau$	σ	$-\tau$	0	$-\tau + \sigma$	$\tau - \sigma$

Superpotential

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$$\begin{aligned}
 W = & -\frac{\sqrt{2}}{6} \lambda A 75_{kl}^{ij} 75_{ij}^{kl} + \lambda 75_{kl}^{ij} 75_{in}^{km} 75_{mj}^{nl} \\
 & + \frac{m}{2} 45_k^{ij} \overline{45}_{ij}^k + \frac{3}{2\sqrt{2}} e \bar{5}_i 75_{jk}^{im} 45_m^{jk} + \frac{\Delta}{\langle S \rangle} S 5^i \bar{5}^i \\
 & + \frac{\sqrt{3}}{4\sqrt{2}} a 5^i 75_{lm}^{jk} \overline{50}_{ijk}^{lm} + \frac{\sqrt{3}}{4\sqrt{2}} b \bar{5}_i 75_{jk}^{lm} 50_{lm}^{ijk} \\
 & + \frac{\sqrt{3}}{4\sqrt{2}} b' 5^i 75_{lm}^{jk} \overline{50}_{ijk}^{lm} + \frac{\sqrt{3}}{4\sqrt{2}} a' \bar{5}^i 75_{jk}^{lm} 50_{lm}^{ijk} \\
 & + \frac{3\sqrt{3}}{2\sqrt{2}} f 45_{ij}^n 75_{kl}^{im} 50_{nm}^{jkl} \\
 & + \frac{M_1}{12\langle P \rangle} P 50_{lm}^{ijk} \overline{50}_{ijk}^{lm} + \frac{M_2}{12\langle P \rangle} P 50_{lm}^{ijk} \overline{50}_{ijk}^{lm},
 \end{aligned} \tag{14}$$

The Higgs spectrum

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Higgs	Repres.	Mass
T^a, \bar{T}_a	$(3, 1, -\frac{1}{3}), (\bar{3}, 1, \frac{1}{3})$	(M_T)
H^α, \bar{H}_α	$(1, 2, \frac{1}{2}), (1, 2, -\frac{1}{2})$	(M_2)
$H_b^{a\alpha}, H_{a\alpha}^b$	$(8, 2, \frac{1}{2}), (8, 2, -\frac{1}{2})$	m
$H^{a\alpha}, H_{a\alpha}$	$(3, 2, \frac{7}{6}), (\bar{3}, 2, -\frac{7}{6})$	m
$H_{ab(s)}, H_{(s)}^{ab}$	$(\bar{6}, 1, -\frac{1}{3}), (6, 1, \frac{1}{3})$	m
$H_\beta^{a\alpha}, H_{a\alpha}^\beta$	$(3, 3, -\frac{1}{3}), (\bar{3}, 3, \frac{1}{3})$	m
H^a, \bar{H}_a	$(3, 1, -\frac{4}{3}), (\bar{3}, 1, \frac{4}{3})$	m
Σ_b^a	$(8, 1, 0)$	$-\frac{2\sqrt{2}}{3}\lambda\Lambda$
$\Sigma_{b\beta}^{a\alpha}$	$(8, 3, 0)$	$-\frac{10\sqrt{2}}{3}\lambda\Lambda$
Σ_0	$(1, 1, 0)$	$\frac{4\sqrt{2}}{3}\lambda\Lambda$
$\Sigma_{\alpha(s)}^{ab}, \Sigma_{ab(s)}^\alpha$	$(6, 2, \frac{5}{6}), (\bar{6}, 2, -\frac{5}{6})$	$-\frac{4\sqrt{2}}{3}\lambda\Lambda$
$\Sigma^a, \bar{\Sigma}_a$	$(3, 1, \frac{5}{3}), (\bar{3}, 1, -\frac{5}{3})$	$\frac{8\sqrt{2}}{3}\lambda\Lambda$

The Higgs spectrum II

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- **The weak-doublets**

$$M_2 = \begin{array}{c|ccc} & H_5 & H_{45} & H_{5'} \\ \hline \overline{H}_5 & 0 & \sqrt{3}eA & 0 \\ \overline{H}_{45} & 0 & m & 0 \\ \overline{H}_{5'} & 0 & 0 & \Delta. \end{array} \quad (15)$$

- **Diagonalizing M_2 gives two pair of heavy weak-doublets with masses**

$$M_+ = \sqrt{m^2 + (\sqrt{3}eA)^2}, \quad M_- = \Delta \quad (16)$$

The Higgs spectrum III

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- The color-triplet Higgs

$$M_T = \begin{array}{c|ccc} & T_5 & T_{45} & T_{5'} \\ \hline \overline{T}_5 & 0 & -eA & -\frac{bb'A^2}{M_1} \\ \hline \overline{T}_{45} & 0 & m & -\frac{fb'A^2}{M_1} \\ \hline \overline{T}_{5'} & -\frac{aa'A^2}{M_2} & 0 & \Delta, \end{array} \quad (17)$$

RGE and threshold effects

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$$\begin{aligned} (3\alpha_2^{-1} - 2\alpha_3^{-1} - \alpha_1^{-1})(m_z) = & \\ \frac{1}{2\pi} \left\{ -2 \ln \frac{m_{SUSY}}{m_z} + \frac{12}{5} \ln \frac{x |\det M_T|}{m_z M_+ M_-} \right. & \\ \left. - \frac{1}{2} \sum_{j=1}^3 \frac{1}{b_j} (3b_{2j} - 2b_{3j} - b_{1j}) \ln \frac{\alpha_j(m_z)}{\alpha_5(\Lambda)} \right\}, & \\ (5\alpha_1^{-1} - 3\alpha_2^{-1} - 2\alpha_3^{-1})(m_z) = & \\ \frac{1}{2\pi} \left\{ 8 \ln \frac{m_{SUSY}}{m_z} + 12 \ln \frac{y m_V^2 M_\Sigma}{m_z^3} \right. & \\ \left. - \frac{1}{2} \sum_{j=1}^3 \frac{1}{b_j} (5b_{1j} - 3b_{2j} - 2b_{3j}) \ln \frac{\alpha_j(m_z)}{\alpha_5(\Lambda)} \right\}, & \end{aligned} \quad (18)$$

$x \sim 0.00006$, $y \sim 2.73$: **splitting in 75; Σ for (8, 3, 0).**

An effective Higgsino mass

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$$M_{H_c} = \frac{|\det M_T|}{M_+ M_-}, \quad (19)$$

Numerically

$$\begin{aligned} 5.8 \times 10^{18} GeV &\leq M_{H_c} \leq 6.0 \times 10^{19} GeV, \\ 1.2 \times 10^{16} GeV &\leq \Lambda_{GUT} \leq 1.4 \times 10^{16} GeV, \end{aligned} \quad (20)$$

Prediction on proton decay

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Proton partial lifetimes. The experimental lower limits are typically around 10^{32-33} years.

Decay mode	lifetime of proton
$\tau(p \rightarrow K^+ + \bar{\nu}_\mu)$	$2.3 \times 10^{35} \sim 2.5 \times 10^{37} \text{ yrs}$
$\tau(p \rightarrow K^+ + \bar{\nu}_e)$	$4.7 \times 10^{36} \sim 5.0 \times 10^{38} \text{ yrs}$
$\tau(p \rightarrow \pi^+ + \bar{\nu}_\mu)$	$4.7 \times 10^{35} \sim 5.0 \times 10^{37} \text{ yrs}$
$\tau(p \rightarrow \pi^+ + \bar{\nu}_e)$	$9.8 \times 10^{36} \sim 1.0 \times 10^{39} \text{ yrs}$
$\tau(p \rightarrow K^0 + \mu^+)$	$3.4 \times 10^{38} \sim 3.6 \times 10^{40} \text{ yrs}$
$\tau(p \rightarrow \pi^0 + \mu^+)$	$6.7 \times 10^{38} \sim 7.2 \times 10^{40} \text{ yrs}$

Motivation

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(Jun Yan, Yun-Fei Wu and D-X Zhang)

Lessons from literature: Proton decay depends on

- **Yukawa couplings**
- **Colored Higgsino mass**
- **Chargino sector, especially wino mass**

Chargino sector in SUSYLR:

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$$X = \begin{pmatrix} M_L & 0 & 0 & \sqrt{2}M_W \cos \beta \\ 0 & M_R & 0 & \sqrt{2}M_W \cos \beta \\ \sqrt{2}M_W \sin \beta & \sqrt{2}M_W \sin \beta & 0 & -\mu \\ 0 & 0 & -\mu' & 0 \end{pmatrix}, \quad (21)$$

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- **Dim.-5 operators:**

$$W_5 = C_{ijkl}(Q_i Q_j)(Q_k L_l) + D_{ijkl}(Q_i^c Q_j^c)(Q_k^c L_l^c), \quad (22)$$

- **Decay rate:**

$$\Gamma(p \rightarrow Ml) = \frac{m_p}{32\pi m_T^2 f_\pi^2} |C|^2 |\beta|^2 [4A_L^2 A_{eL}^2 + xA_R^2 A_{eR}^2] |f(D, F)|^2. \quad (23)$$

- **Ratio of the rates in Model with universal gaugino mass**

$$\frac{\Gamma_R}{\Gamma_L} = 0.31 - 1.24, \quad (24)$$

Without gaugino mass universality

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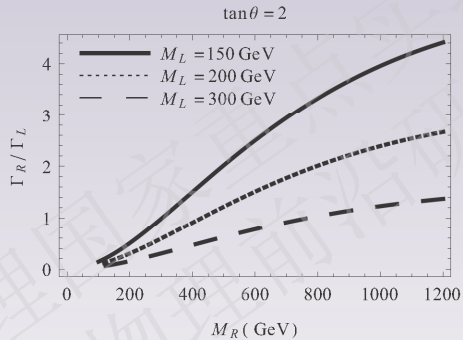


Figure: The ratio of decay rates varying with M_R for $\mu = 200\text{GeV}$ and $M_{\tilde{f}} = 500\text{GeV}$.