GUT SCALE THRESHOLD EFFECTS ON PROTON DECAY

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Based on

arXiv:1503.08561 NPB 898 (2015)

with J.Hisano and Y.Omura (Nagoya U.)

arXiv:1603.03568 NPB 910 (2016)

with B.Bajc (J.Stefan inst.), J.Hisano and Y.Omura (Nagoya U.)

Introduction

Discovery of the 126GeV Higgs boson (in 2012)

- Success of the Standard Model (SM)
- Approach to Beyond SM (BSM) more realistically,

treat all SM parameters as known values

We can prepare theoretical predictions of BSM more precisely.

Intensity Frontier

Flavor Physics
CP violation
etc..

=> Indirect measurement,
but accessible to high-energy

The promising extension of the SM

Supersymmetric Grand Unified Theories (SUSY GUTs)

Unified description of
- strong and electro-weak interactions
- quarks and leptons

⋮

=> Predicting Baryon-Number Violating Processes (Proton Decay etc..)

* B# is accidentally preserved in SM
* Signature of BSM if we find

Precise prediction towards discovery

- Introduction
- SUSY SU(5) GUTs
- Proton Decay
- Procedure & Results
- Summary

SUSY SU(5) GUTs

SUSY SU(5) GUTs

N. Sakai (1981) S.Dimopoulos H.Georgi (1981)

Matter and Gauge sectors are almost universal in the SUSY SU(5) GUTs

Matter Sector: completely embedded in 5* (Φ) and 10 (Ψ)

$$D^C, L \in \Phi, \quad U^C, Q, E^C \in \Psi$$

Gauge Sector

$$V(\mathbf{24}) = \begin{pmatrix} G & X^\dagger \\ X & W \end{pmatrix} - \frac{1}{2\sqrt{15}} \begin{pmatrix} 2 & \\ & -3 \end{pmatrix} B$$

Higgs Sector

MSSM Higgs doublets are embedded in fields in (anti-)fundamental reps.

$$\overline{H}(\overline{\mathbf{5}}) = \begin{pmatrix} H_{\overline{C}} \\ H_d \end{pmatrix}, \quad H(\mathbf{5}) = \begin{pmatrix} H_C \\ H_u \end{pmatrix}$$

+ GUT breaking Higgs, and etc..

So, Higgs sector depends on models

Higgs Sector (besides $5+5^*$ Higgs containing MSSM Higgses)

Minimal SU(5)	Adjoint (24-dimensional) Higgs
Missing Partner Model Masiero, Nanopoulos, Tamvakis, Yanagida (1982) Grinstein (1982)	$50+50^*$ 75-dimensional Higgs
Models for Yukawa Realization Georgi, Jarlskog (1979) et al.	additional $45+45^*$
etc..	

Blue Higgses: GUT breaking one

Higgs Sector (besides 5+5* Higgs containing MSSM Higgses)

In this talk, I focus on

Minimal SU(5)

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Missing Partner Model

Minimal SU(5):

* Simple
* Still valid in high-scale SUSY Scenario (D=5 decay)
* with fine-tuning in doublet-triplet splitting

Missing Partner Model:

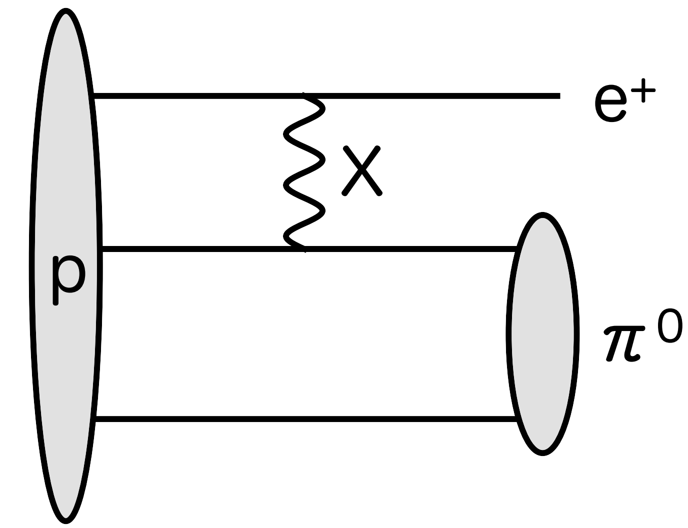
* Solving doublet-triplet splitting without fine-tuning
* Models requiring huge number of fields

  => prospect for large quantum correction to proton decay prediction
* Free from D=5 proton decay (if imposing Peccei-Quinn symmetry)

Proton Decay

X bosons give rise to baryon-number violating process!

$$V(\mathbf{24}) = \begin{pmatrix} G & X^\dagger \\ X & W \end{pmatrix} - \frac{1}{2\sqrt{15}} \begin{pmatrix} 2 & \\ & -3 \end{pmatrix} B$$



➡ Main decay mode: $p \to \pi^0 + e^+$

Proton Decay induced by gauge-interaction:
in general, model (= Higgs sector) independent decay

Current lower bound (future sensitivity) on proton decay.

	CURRENT	FUTURE
$p \to \pi^0 + e^+$	1.67×10^{34} yrs	1.0×10^{35} yrs
	Super-K Result 2016 Moriond	Hyper-K Prospect 10-years exposure

Theoretical progress (Higher-order corrections to Wilson coeff. of D=6 operators)

- ☑ QCD correction (2-loop) — Arafune, Nihei (1994)
- ☑ RGE in SM (2-loop) — Daniel, Penarrocha (1984)
- ☑ RGE in SUSY SM (2-loop) — Hisano, Kobayashi, Nagata, Muramatsu (2013)
- ☐ Threshold Corrections

RGE effects are computed @ 2-loop order (Gauge interaction)

1-loop threshold corrections are also expected as the same order

In addition,

Hadron Matrix Elements @ 2GeV are calculated by lattice simulation with 30% errors

Aoki, Shintani, Soni (2013)

Results

Analytic formula for Threshold Corrections

$$C_1^{(0)} = C_2^{(0)} = -\frac{g_5^2}{M_X^2}$$

$$\mathcal{O}_1^{(0)} = \epsilon_{\alpha\beta\gamma}\epsilon_{rs} U^{C\dagger\alpha} D^{C\dagger\beta} Q^{r\gamma} L^s$$

$$\mathcal{O}_2^{(0)} = \epsilon_{\alpha\beta\gamma}\epsilon_{rs} E^{C\dagger} U^{C\dagger\alpha} Q^{\beta r} Q^{s\gamma}$$

In the Effective theory (~ MSSM),

$$\mathcal{L}_{\mathrm{dim.6}} = \int d^4\theta \sum_{I=1,2} (1-\lambda^{(I)}) C_I^{(0)} \mathcal{O}_I^{(0)} + \mathrm{h.c.}$$

Threshold corrections to Wilson coeff. $\lambda^{(I)}$

For each threshold corrections, we obtain;

Hisano, TK, Omura (2015)

$$\lambda^{(1)} = \frac{\Sigma(0)}{M_X^2 + \Sigma(0)} + \frac{g_5^2}{16\pi^2}\frac{16}{5}\left(1 - \ln\frac{M_X^2}{\mu^2}\right),$$

$$\lambda^{(2)} = \frac{\Sigma(0)}{M_X^2 + \Sigma(0)} + \frac{g_5^2}{16\pi^2}\frac{18}{5}\left(1 - \ln\frac{M_X^2}{\mu^2}\right).$$

Vacuum polarization Vertex + Box

Vacuum polarization strongly depends on GUT mass spectrum

Comparing with the previous study

$$(\text{Ratio}) \equiv \frac{\Gamma(p \to \pi^0 + e^+)|_{\rm w}}{\Gamma(p \to \pi^0 + e^+)|_{\rm w/o}}$$

Ratio of decay rate
with and without threshold corrections

Numerical Results: among the GUT models ($M_X = 2\times10^{16}$GeV)

Bajc, Hisano, TK, Omura (2015)

	Minimal SU(5)	Missing-Partner
Ratio	0.994	0.394
τ ($p\to e^+\pi^0$)	2.23×10^{36}yrs	7.09×10^{35}yrs

Suppressed rate
<= thanks to threshold effects
Short lifetime
<= Large unified coupling @GUT scale due to many fields

Determination of GUT Mass Spectrum

$$\alpha_i^{-1}(\mu) = \alpha_G^{-1}(\mu) + \lambda_i(\mu)$$

MSSM couplings　　Unified coupling

Depends on GUT Scale Masses

Constraining on
* Color-triplet Mass
* $M_X^2 M_\Sigma$

Summary

- ☑ We have derived 1-loop threshold correction to Wilson coefficients of Dim.-6 operators at GUT scale.

- ☑ Proton lifetime becomes longer about a few % due to threshold corrections in the minimal SUSY SU(5).

- ☑ Large suppression of decay rate in the missing-partner SU(5) model (due to many fields and mass splitting)

Backups

SUSY SU(5) GUTs and Its Spectrum

Minimal SUSY SU(5) GUT

Matter Sector

$$\Phi_A(\bar{\mathbf{5}}) = \begin{pmatrix} D^C_a \\ \epsilon_{rs} L^s \end{pmatrix}, \quad \Psi^{AB}(\mathbf{10}) = \begin{pmatrix} \epsilon^{abc} U^C_c & Q^{as} \\ -Q^{br} & \epsilon^{rs} E^C \end{pmatrix}$$

Gauge Sector

$$V(\mathbf{24}) = \begin{pmatrix} G & X^\dagger \\ X & W \end{pmatrix} - \frac{1}{2\sqrt{15}} \begin{pmatrix} 2 & \\ & -3 \end{pmatrix} B$$

Higgs Sector

$$\overline{H}(\bar{\mathbf{5}}) = \begin{pmatrix} H_{\overline{C}} \\ H_d \end{pmatrix}, \quad H(\mathbf{5}) = \begin{pmatrix} H_C \\ H_u \end{pmatrix}$$

$$\Sigma_{24} = \begin{pmatrix} \Sigma_8 & \Sigma_{(3,2)} \\ \Sigma_{(3^*,2)} & \Sigma_3 \end{pmatrix} + \frac{1}{2\sqrt{15}} \begin{pmatrix} 2 & 0 \\ 0 & -3 \end{pmatrix} \Sigma_S$$

Minimal SUSY SU(5) GUT

$$\langle(\Sigma_{24})^r_s\rangle = -3v_{\mathbf{24}}\delta^r_s, \qquad \left\langle(\Sigma_{24})^\alpha_\beta\right\rangle = 2v_{\mathbf{24}}\delta^\alpha_\beta$$

$$\mathcal{K}_{\mathbf{24}} = (\Sigma^\dagger_{24})^A_B(e^{2g_5V})^B_C(e^{-2g_5V})^D_A(\Sigma_{24})^C_D, \qquad \to \quad M_X = 5g_5v_{\mathbf{24}}$$

$$W = \lambda\overline{H}(\Sigma_{24}+3v_{\mathbf{24}})H, \qquad \to \quad M_{H_C} = 5\lambda v_{\mathbf{24}}$$

$$W = \frac{f}{3}\mathrm{Tr}(\Sigma_{24})^3 + \frac{m_{24}}{2}\mathrm{Tr}(\Sigma_{24})^2$$

$$\to \quad W = \frac{m_8}{2}\Sigma^A_8\Sigma^A_8 + \frac{m_3}{2}\Sigma^A_3\Sigma^A_3 + \frac{m_S}{2}\Sigma_S\Sigma_S + \cdots$$

$$\begin{aligned} m_8 : m_3 : m_S &= 5m_{24}/2 : 5m_{24}/2 : m_{24}/2 \\ &= 5:5:1 \end{aligned}$$

Missing-Partner SU(5)

$$\left\langle (\Sigma_{75})^{[rs]}_{[tu]} \right\rangle = \frac{3}{2} v_{\mathbf{75}} (\delta^r_t \delta^s_u - \delta^r_u \delta^s_t), \quad \left\langle (\Sigma_{75})^{[\alpha\beta]}_{[\gamma\delta]} \right\rangle = \frac{1}{2} v_{\mathbf{75}} (\delta^\alpha_\gamma \delta^\beta_\delta - \delta^\alpha_\delta \delta^\beta_\gamma),$$

$$\left\langle (\Sigma_{75})^{[\alpha r]}_{[\beta s]} \right\rangle = -\frac{1}{2} v_{\mathbf{75}} \delta^\alpha_\beta \delta^r_s,$$

$$\mathcal{K}_{\mathbf{75}} = (\Sigma^\dagger_{75})^{[AB]}_{[CD]} (e^{2g_5 V})^C_E (e^{2g_5 V})^D_F (e^{-2g_5 V})^G_A (e^{-2g_5 V})^H_B (\Sigma_{75})^{[EF]}_{[GH]}.$$

$$\rightarrow \quad M_X = 2\sqrt{6} g_5 v_{\mathbf{75}}$$

after integrating out 50+50*

$$W = M_{H_C} H_C \overline{H}'_C + M_{H'_C} H'_C \overline{H}_C,$$

with $M_{H_C} \equiv \frac{48 v^2_{\mathbf{75}}}{M_{\rm Pl}} g_H g'_{\overline{H}}, \quad M_{\overline{H}_C} \equiv \frac{48 v^2_{\mathbf{75}}}{M_{\rm Pl}} g'_H g_{\overline{H}}.$

typically, ~10^{15} GeV

Missing-Partner SU(5)

$$\left\langle (\Sigma_{75})^{[rs]}_{[tu]} \right\rangle = \frac{3}{2} v_{\mathbf{75}} (\delta^r_t \delta^s_u - \delta^r_u \delta^s_t), \quad \left\langle (\Sigma_{75})^{[\alpha\beta]}_{[\gamma\delta]} \right\rangle = \frac{1}{2} v_{\mathbf{75}} (\delta^\alpha_\gamma \delta^\beta_\delta - \delta^\alpha_\delta \delta^\beta_\gamma),$$

$$\left\langle (\Sigma_{75})^{[\alpha r]}_{[\beta s]} \right\rangle = -\frac{1}{2} v_{\mathbf{75}} \delta^\alpha_\beta \delta^r_s,$$

$$W = m_{75} (\Sigma_{75})^{[CD]}_{[AB]} (\Sigma_{75})^{[AB]}_{[CD]} - \frac{1}{3} \lambda_{75} (\Sigma_{75})^{[AB]}_{[EF]} (\Sigma_{75})^{[CD]}_{[AB]} (\Sigma_{75})^{[EF]}_{[CD]}$$

$$75 = (\mathbf{1},\mathbf{1})_0 \oplus (\mathbf{3},\mathbf{1})_{-\frac{5}{3}} \oplus (\overline{\mathbf{3}},\mathbf{1})_{\frac{5}{3}} \oplus (\mathbf{3},\mathbf{2})_{\frac{5}{6}} \oplus (\overline{\mathbf{3}},\mathbf{2})_{-\frac{5}{6}} \oplus (\overline{\mathbf{6}},\mathbf{2})_{\frac{5}{6}} \oplus (\mathbf{6},\mathbf{2})_{-\frac{5}{6}} \oplus (\mathbf{8},\mathbf{1})_0 \oplus (\mathbf{8},\mathbf{3})_0$$

= 2 : 4 : (NG Mode) : 2 : 1 : 5

with $M_{(\mathbf{8},\mathbf{3})_0} = 5 m_{75}$

Constrained Mass Spectra

By using central values for couplings (& sparticles around 1 TeV)

Minimal SU(5)

$$\frac{3}{g_2^2(\mu)} - \frac{2}{g_3^2(\mu)} - \frac{1}{g_1^2(\mu)} = \frac{1}{8\pi^2}\frac{12}{5}\ln\frac{M_{H_C}}{\mu},$$

$$\frac{5}{g_1^2(\mu)} - \frac{3}{g_2^2(\mu)} - \frac{2}{g_3^2(\mu)} = \frac{1}{8\pi^2}12\ln\frac{M_X^2 M_{\Sigma_{24}}}{\mu^3}.$$

$$M_{H_C} = 6.4 \times 10^{15}\ \text{GeV}$$

$$(M_X^2 M_{\Sigma_{24}})^{1/3} = 1.5 \times 10^{16}\ \text{GeV}$$

MP SU(5)

$$\frac{3}{g_2^2(\mu)} - \frac{2}{g_3^2(\mu)} - \frac{1}{g_1^2(\mu)} = \frac{1}{8\pi^2}\left(\frac{12}{5}\ln\frac{M_{H_C}M_{\overline{H}_C}}{M_{H_f'}\mu} + 6\ln\frac{2^6}{5^5}\right),$$

$$\frac{5}{g_1^2(\mu)} - \frac{3}{g_2^2(\mu)} - \frac{2}{g_3^2(\mu)} = \frac{1}{8\pi^2}\left(12\ln\frac{M_X^2 M_{\Sigma_{75}}}{\mu^3} + 54\ln\frac{5}{4}\right).$$

$$\frac{M_{H_C}M_{\overline{H}_C}}{M_{H_f'}} = 1.1 \times 10^{20}\ \text{GeV}$$

$$(M_X^2 M_{\Sigma_{75}})^{1/3} = 5.4 \times 10^{15}\ \text{GeV}$$