SU(5) GUT and Proton decay with High-scale SUSY

based on

J.Hisano, TK, N.Nagata : Phys. Lett. B **723** (2013) 324

J.Hisano, D.Kobayashi, TK, N.Nagata : JHEP **1307** (2013) 038

Takumi Kuwahara

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Motivation

High-Scale SUSY

- The SM Higgs whose mass is about 126GeV was found at LHC in 2012.
- In minimal SUSY models, Higgs mass tend to be lighter than Z boson at tree level. Therefore, we need large quantum corrections to Higgs mass.
- One possible scenario : Heavy sparticle mass! (high-scale SUSY)

Proton decay

- Dim.5 proton decay rate can be small in this scenario.

which is forbidden in low-energy SUSY scenario due to too short lifetime

Outline

- Motivation
- Introduction
- SUSY SU(5) GUT & GUT particle mass spectrum
- Proton decay from dimension 5 operator
- Summary & Future work

High-scale SUSY

-without singlet-

If the ~~SUSY~~ messengers Z are not gauge singlet...

- the sfermion mass terms can be produced

$$\int d^4\theta \frac{1}{M_*^2} Z Z^\dagger \Phi \Phi^\dagger \to \frac{|\langle F_Z \rangle|^2}{M_*^2} \phi \phi^*$$

- the gaugino mass terms and the A terms can not be produced

$$\int d^2\theta \frac{1}{M_*} Z \, \mathrm{tr} \mathcal{W} \mathcal{W} \qquad \int d^2\theta \frac{1}{M_*} Z \Phi_i \Phi_j \Phi_k$$

Leading terms of the gaugino mass and the scalar trilinear can be induced w/ 1-loop suppression.

High-scale SUSY

-gaugino mass-

Leading terms of the gaugino mass and the scalar trilinear can be induced w/ 1-loop suppression.

G.F.Giudice, M.A.Luty, H.Murayama and R.Rattazzi, JHEP **9812** (1998) 027

the gaugino mass

$$M_\lambda = -\frac{\beta_g(\mu)}{g(\mu)} m_{3/2} \qquad \left(\beta_g(\mu) \simeq -\frac{b g^3(\mu)}{16\pi^2} \right)$$

the Scalar trilinear coupling (A-term)

$$W = \lambda \Phi_1 \Phi_2 \Phi_3 \to A \phi_1 \phi_2 \phi_3 \in \mathcal{L}_{\rm soft}$$

$$A(\mu) = -m_{3/2} \beta_\lambda(\mu) = -m_{3/2} \mu \frac{d\lambda}{d\mu}$$

High-scale SUSY

-split mass spectrum and Higgs mass-

Mass scale

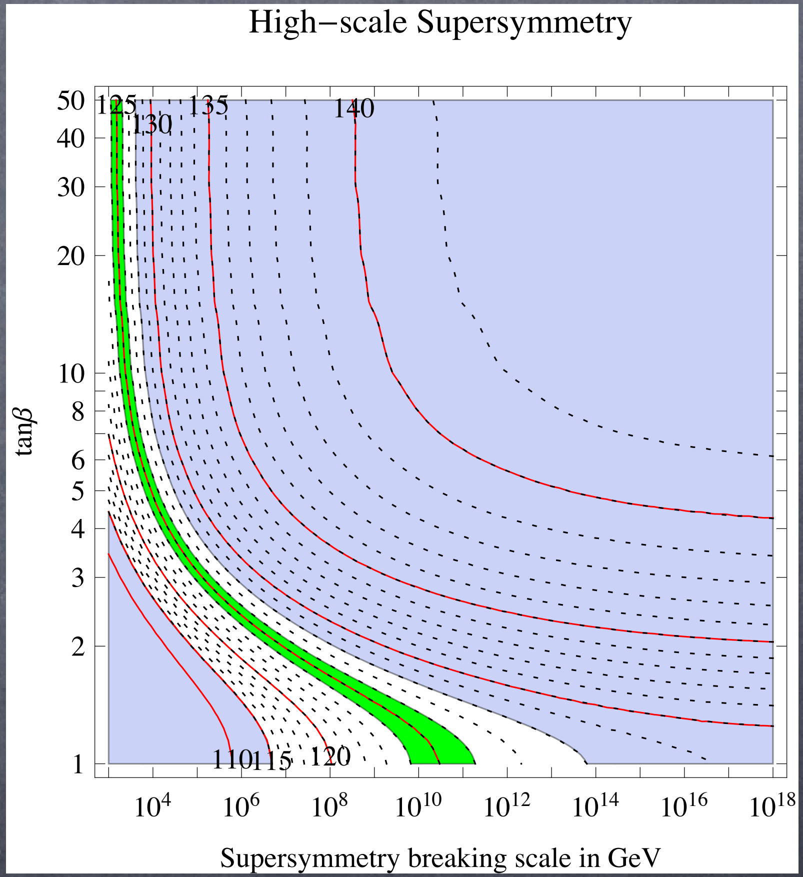
squark
slepton
Heavy Higgs etc...

>> O(10TeV)

Split

gluino
bino
wino

~ O(1TeV)



G.F.Giudice and A.Strumia,
Nucl. Phys. B 858 (2012) 63

SUSY SU(5) GUT

-particle contents-

The MSSM superfields are embedded in SU(5) multiplets.

matter

$$\psi^{\alpha\beta}(\mathbf{10}) = \begin{pmatrix} \epsilon^{abc}U^C_c & Q^{ar} \\ -Q^{sa} & \epsilon^{sr}E^C \end{pmatrix}, \quad \phi_\alpha(\mathbf{5}^*) = \begin{pmatrix} D^C_a \\ \epsilon_{rs}L^s \end{pmatrix}$$

Higgs

$$H(\mathbf{5}) = \begin{pmatrix} H_C \\ H_u \end{pmatrix}, \quad \overline{H}(\mathbf{5}^*) = \begin{pmatrix} \overline{H}_C \\ \overline{H}_d \end{pmatrix}$$

Gauge

$$\mathcal{V}_5 = \sum_{a=1}^{24} \mathcal{V}_5^a T^a = \frac{1}{\sqrt{2}} \begin{pmatrix} G^\alpha{}_\beta - \frac{2}{\sqrt{30}} B\delta^\alpha{}_\beta & X^{\dagger\alpha}{}_r \\ X^s{}_\beta & W^s{}_r + \frac{3}{\sqrt{30}} B\delta^s{}_r \end{pmatrix}$$

Gauge group SU(5) is broken by VEV of the adjoint Higgs Σ.

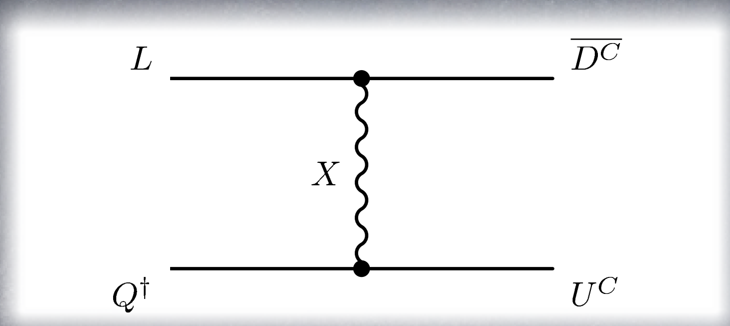
→ X-boson, H_C and Σ have heavy masses.

SUSY SU(5) GUT

-dim.5 vs dim.6-

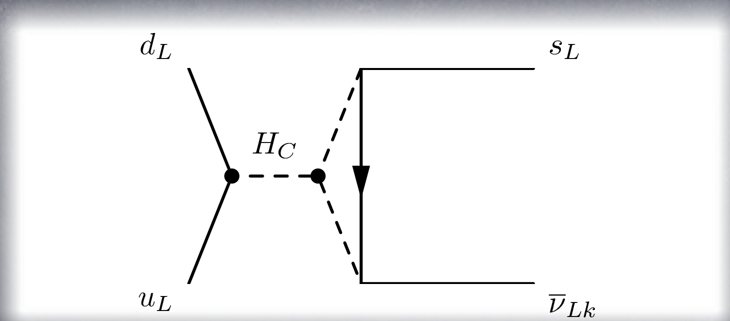
Proton Decay in SUSY SU(5) GUT

is caused by exchanging
* X-boson
* Colored Higgs



* X-boson exchange

$$\tau_p(p \to \pi e^+) \propto (M_X)^4$$



* Colored Higgs exchange

$$\tau_p(p \to K^+ \overline{\nu}) \propto (M_{H_C} M_S)^2$$

This can cause short lifetime for proton!!

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RGE analysis

-threshold correction-

After integrating out the heavy particles

$\longrightarrow$ the gauge coupling relations between full and eff. theory

$$\mathcal{L}_{\text{full}} = -\frac{1}{4}F^{\alpha}_{\mu\nu}F^{\alpha\mu\nu} + \cdots$$

where $l_i = g_i^2(\lambda_i(\mu) + \lambda'_i(\mu)/\epsilon')$

$$\mathcal{L}_{\text{eff}} = \sum_i -\frac{1}{4}(1-l_i)F^{a_i}_{\mu\nu}F^{a_i\mu\nu} + \cdots$$

- "i" means residual symmetries.
- The effects of heavy particles are included as "l_i" in L_{eff}.

By redefining fields and couplings to be canonical kinetic terms,

we obtain the couplings in the effective theory.

$$-\frac{1}{4}(1-l_i)F^{a_i}_{\mu\nu}F^{a_i\mu\nu} \longrightarrow -\frac{1}{4}F'^{a_i}_{\mu\nu}F'^{a_i\mu\nu}$$

by using

$$A'_{a_i\mu} \equiv \sqrt{1-l_i}A_{a_i\mu}$$
$$g_i \equiv g/\sqrt{1-l_i}$$

RGE analysis

-threshold correction-

We have already determined the relation between bare couplings of full theory and those of eff. theory.

Next, we consider renormalized couplings

$$g\mu^{\epsilon/2} = g(\mu) - b_G g^3(\mu)/\epsilon' + \dots$$
$$g_i\mu^{\epsilon/2} = g_i(\mu) - b_i g_i^3(\mu)/\epsilon' + \dots$$

$$g_i \equiv g/\sqrt{1 - l_i}$$

where $l_i = g_i^2(\lambda_i(\mu) + \lambda_i'(\mu)/\epsilon')$

then we can obtain the relation @ 1-loop

$$\alpha_i^{-1}(\mu) = \alpha^{-1}(\mu) - 4\pi\lambda_i(\mu)$$

including the contributions from heavy particles

GUT mass spectrum

-RGE analysis-

We assume that there are three thresholds.

- GUT scale
- SUSY breaking scale (squarks,sleptons,higgsinos and heavy Higgs)
- Gaugino threshold

By using these threshold corrections w/ the solution of 1-loop RGEs, we have

$$\frac{3}{\alpha_2(m_Z)} - \frac{2}{\alpha_3(m_Z)} - \frac{1}{\alpha_1(m_Z)} = \frac{1}{2\pi}\left[\frac{12}{5}\ln\frac{M_{H_C}}{m_Z} - 2\ln\frac{M_S}{m_Z} + 4\ln\frac{M_3}{M_2}\right]$$

$$\frac{5}{\alpha_1(m_Z)} - \frac{3}{\alpha_2(m_Z)} - \frac{2}{\alpha_3(m_Z)} = \frac{1}{2\pi}\left[12\ln\frac{M_V^2 M_\Sigma}{m_Z^3} + 4\ln\frac{M_3 M_2}{m_Z^2}\right]$$

GUT mass spectrum

-w/ 1-loop RGEs-

$$\frac{3}{\alpha_2(m_Z)} - \frac{2}{\alpha_3(m_Z)} - \frac{1}{\alpha_1(m_Z)} = \frac{1}{2\pi}\left[\frac{12}{5}\ln\frac{M_{H_C}}{m_Z} - 2\ln\frac{M_S}{m_Z} + 4\ln\frac{M_3}{M_2}\right]$$

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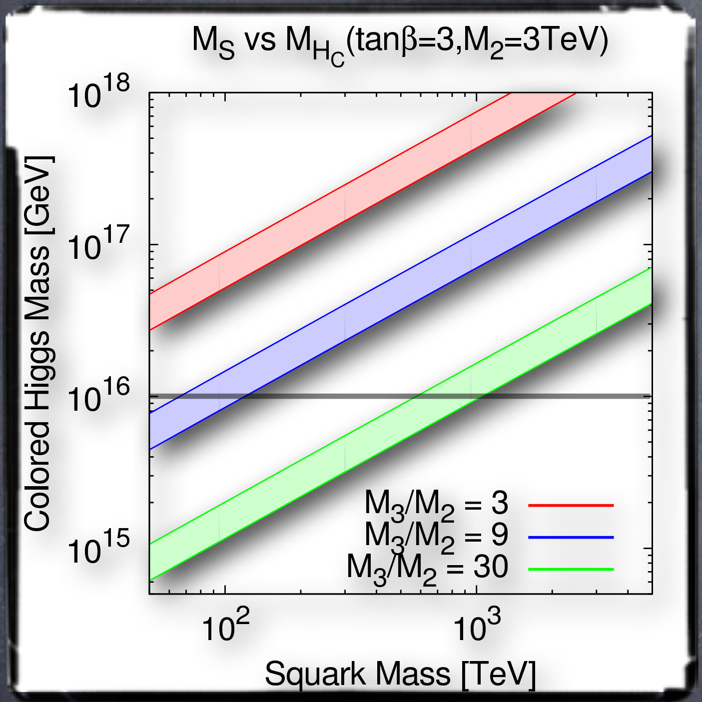
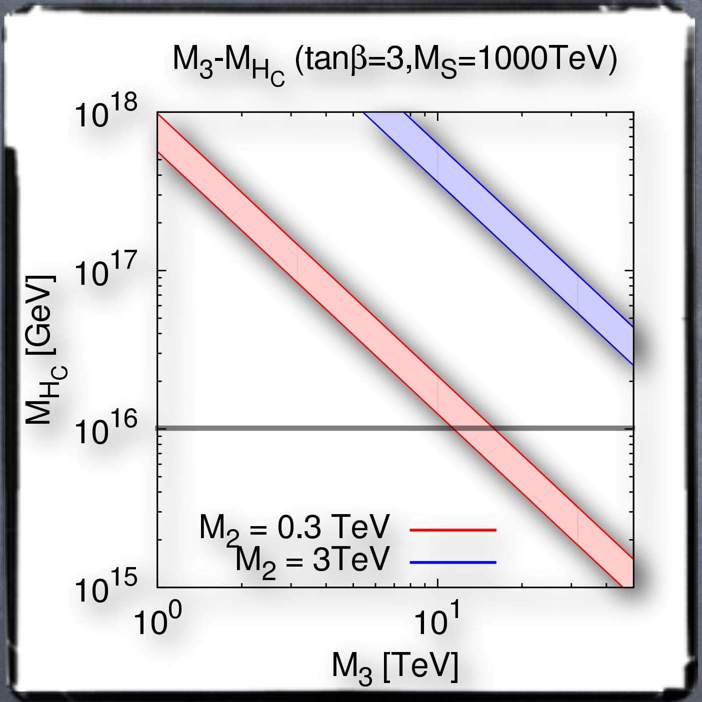
- The higher the SUSY breaking scale becomes, the heavier color-triplet Higgs becomes.
- This triplet mass depends on the ratio of the gaugino mass.
- $M^3_{GUT} \equiv M^2_V M_\Sigma$ becomes lighter if the gauginos are heavy.

Numerical results

Colored Higgs mass from 2-loop RGEs and Threshold corrections





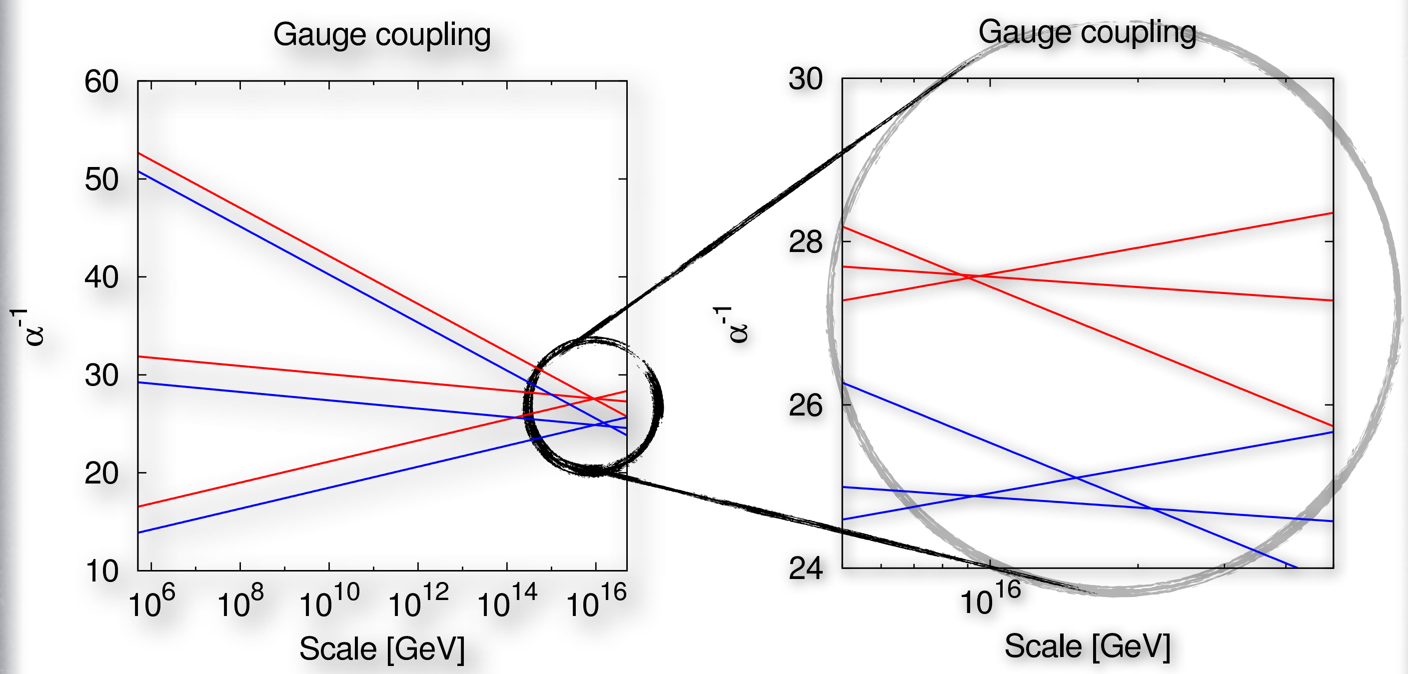
Colored Higgs can have 10^{16} GeV mass !!!

Error bar ⇒
the uncertainty of the strong coupling.
$\alpha_s(M_Z)$=0.1184(7)

M_S=1TeV,M_3=1TeV,M_2=0.3TeV

$$M_{H_C} = (8.774 \pm 2.251) \times 10^{14}\mathrm{GeV}$$

Improvement in gauge coupling unification



Red: High-scale SUSY
$M_S = 10^2$TeV
$M_2 = 3$TeV
$M_3/M_2 = 9$

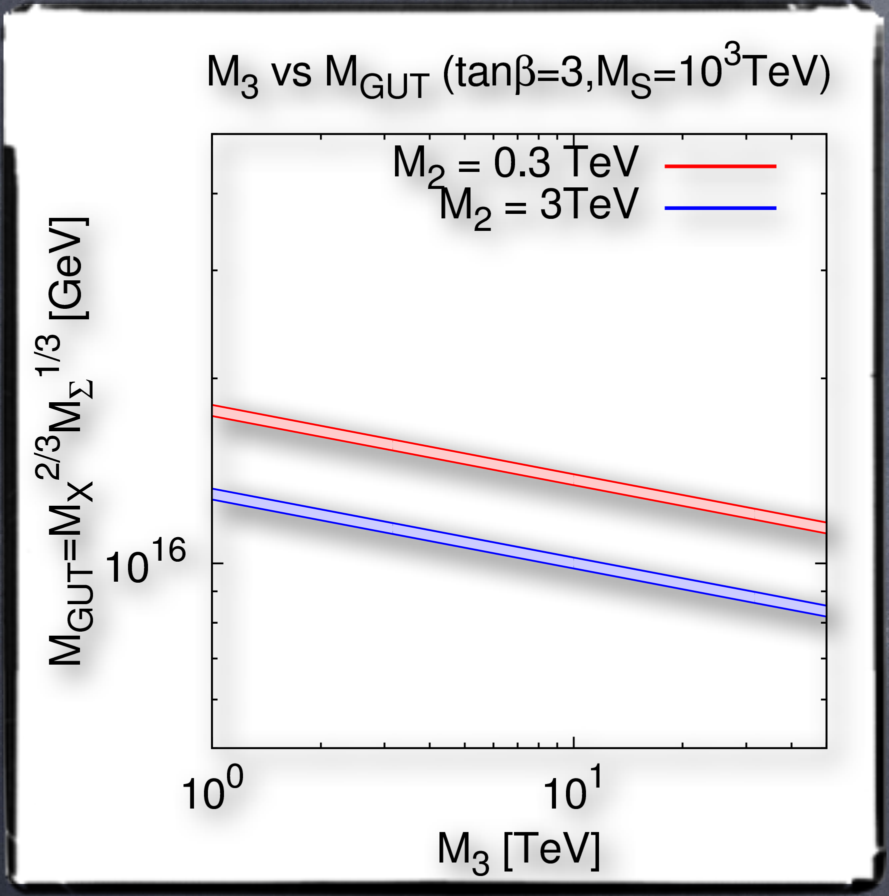
Blue: Low-scale SUSY
$M_S = 1$TeV
$M_2 = 300$GeV
$M_3/M_2 = 3$

If Colored-Higgs can have 10^{16} GeV mass
=> threshold correction becomes small @ GUT scale.
=> gauge couplings unify accurately

Numerical results

GUT scale ($M^3_{GUT} \equiv M^2_X M_\Sigma$) from 2-loop RGEs

and Threshold corrections



Error: $\alpha_S(M_Z)=0.1184(7)$

X-boson can be lighter than 10^{16}GeV.

This result implies that Dim.6 Proton decay rate may be enhanced slightly...

If... $M_X = 0.8 \times 10^{16}$GeV

$\tau(p \to \pi^0 e^+) \sim 5\times10^{34}$ yrs

Current experimental limit

$\tau_{exp}(p \to \pi^0 e^+) \sim 1.3\times10^{34}$ yrs

Brief summery for threshold correction

The Colored-Higgs can have mass around GUT scale($\sim 10^{16}$GeV).

2 possibilities.

1. Gauge coupling unification can be improved in High-scale SUSY.

2. The proton decay by intermediating H_C can be evaded from exp. limits.

X-boson can be lighter than 10^{16}GeV slightly.

The proton decay (due to X) can be caught by next generation detector??

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Proton decay

-problems for dim.5-

The minimal SUSY SU(5) GUT(+ low-scale SUSY) has predicted that proton lifetime is too short.

$$\tau_p(p \to K + \overline{\nu}) \sim 10^{30} \text{ yrs}$$

T.Goto and T.Nihei, Phys. Rev. D **59** (1999) 115009

Current experimental limit

$$\tau_{exp}(p \to K + \overline{\nu}) > 4 \times 10^{33} \text{ yrs}$$

To solve this problem...

- Forbid or Suppress the dim.5 operator by symmetry.

- "high-scale SUSY" can revive the minimal SUSY SU(5).

Proton decay

Superpotential in SUSY SU(5)

$$W = \frac{f}{3}\mathrm{Tr}\Sigma^3 + \frac{fV}{2}\mathrm{Tr}\Sigma^2 + \lambda\overline{H}_\alpha(\Sigma^\alpha_\beta + 3V\delta^\alpha_\beta)H^\beta$$
$$+ \frac{h^{ij}}{4}\epsilon_{\alpha\beta\gamma\delta\epsilon}\psi_i^{\alpha\beta}\psi_j^{\gamma\delta}H^\epsilon + \sqrt{2}f^{ij}\psi_i^{\alpha\beta}\phi_{j\alpha}\overline{H}_\beta$$

α,β,γ,δ,ε,... = 1,2,...,5 (SU(5) indices)

i,j = 1,2,3 (gen. indices)

SU(5) → SU(3)×SU(2)×U(1) by VEV of adjoint Higgs Σ

Assumptions

- R-parity
- the third term (doublet-triplet splitting)

Proton decay

We can reparameterize h^{ij} and f^{ij} by using flavor rot. U(3)×U(3)

d.o.f. : (6+9)×2 　　　　　　　　　　d.o.f. : 9×2

⟶ net d.o.f. : 12

Yukawa terms in superpotential in terms of MSSM superfields

$$W = h^i V_{ij} U_i^C E_j^C H_C + \frac{1}{2} h^i e^{i\varphi_i} (Q_i Q_i) H_C$$
$$+ h^i U_i^C (Q_i H_f) + V_{ij}^* f^j e^{-i\varphi_i} U_i^C D_j^C \overline{H}_C$$
$$+ V_{ij}^* f^j Q_i L_j \overline{H}_C + V_{ij}^* f^j Q_i \overline{H}_f D_j^C + f^i E_i^C L_i \overline{H}_f$$

V : CKM matrix

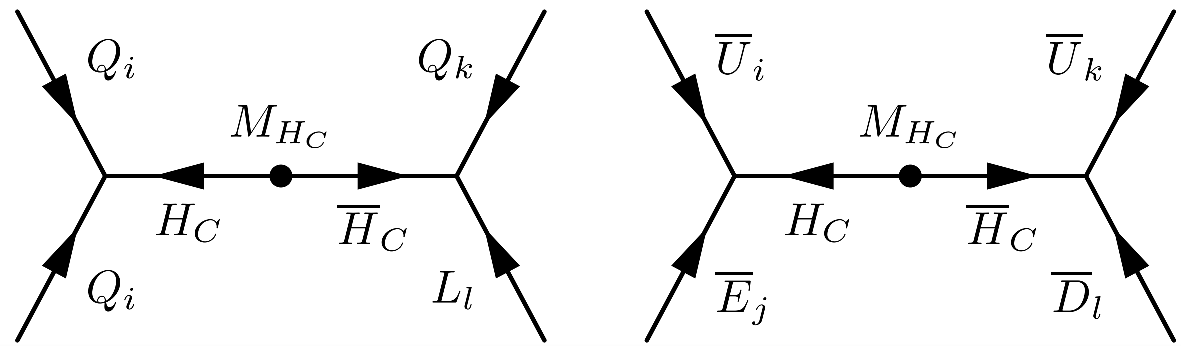
h,f : Yukawa couplings @ GUT scale

φ : additional phases w/ $\varphi_1+\varphi_2+\varphi_3=0$

Proton decay

-p decay in mSUSY GUT-

dim.5 operator



By integrating out the heavy colored Higgs, we can obtain the superpotential for the dim.5 operators

$$W_5 = -\frac{1}{M_{H_C}}\left\{\frac{1}{2}C_L^{ijkl}Q_kQ_lQ_iL_j + C_R^{ijkl}E_k^CU_l^CU_i^CD_j^C\right\}$$

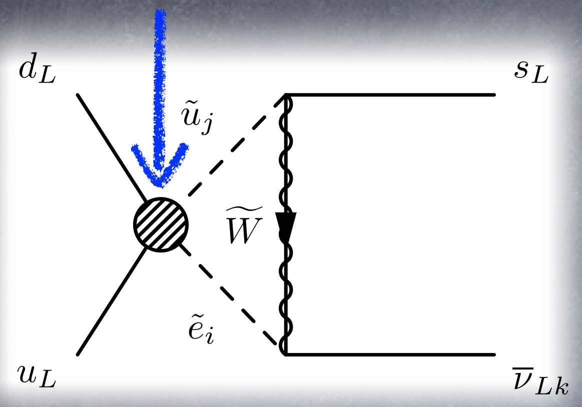
colored Higgs mass LLLL operator RRRR operator

$$C_L^{ijkl} = h^iV_{kl}^*f_le^{i\varphi_i} \qquad C_R^{ijkl} = V_{kl}^*f_lh^iV_{ij}e^{-i\varphi_k}$$

Proton decay

-p-decay from dim.5 operator-

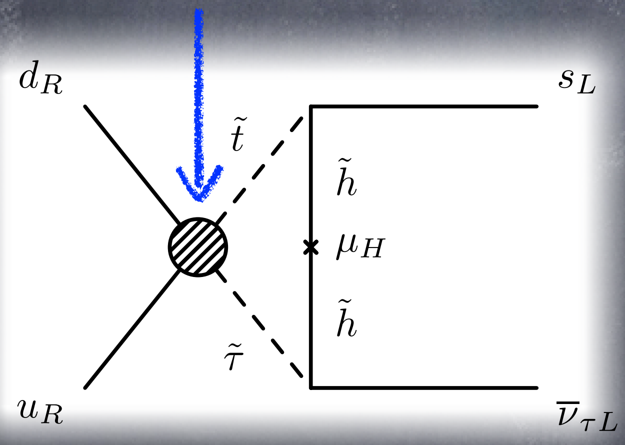
LLLL operator



$$W_{LLLL} = -\frac{h^i f^l}{2M_{H_C}} V_{kl}^* e^{i\varphi_i} Q_i Q_i Q_k L_l$$

The charged winos contribute to proton decay dominantly.

RRRR operator



$$W_{RRRR} = -\frac{f^l h^i}{M_{H_C}} V_{kl}^* V_{ij} e^{-i\varphi_k} U_i^C E_j^C U_k^C D_l^C$$

higgsino-dressed diagrams need the Yukawa coupling.
$\rightarrow$ the contribution of third gen. is only large.

Full Lagrangian for proton decay

4-Fermi operator from wino-dressed diagram

$$\frac{2}{M_{H_C}}\frac{\alpha_2(M_S)\alpha_2(m_Z)}{m_W^2\sin 2\beta}\sum_{i,l} m_{u_i}m_{d_l}A_{S_W}^{(i,l)}e^{i\varphi_i}V_{ul}^*V_{is}V_{id}$$

$$\times F(M_2,M_S)\epsilon_{\alpha\beta\gamma}\left[(d_L^\beta u_L^\alpha)(s_L^\gamma \nu_{lL})+(s_L^\beta u_L^\alpha)(d_L^\gamma \nu_{lL})\right]$$

from higgsino-dressed diagram

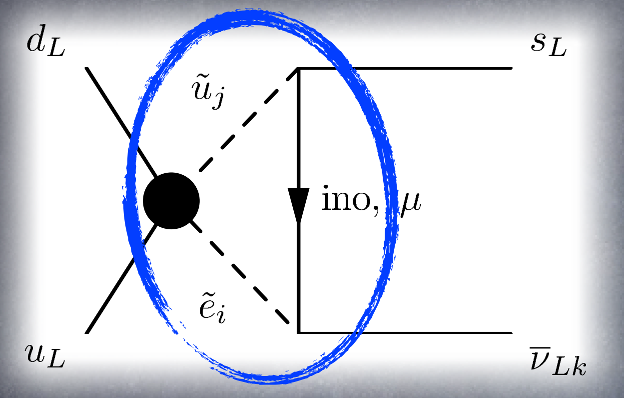
$$-\frac{1}{M_{H_C}}\frac{\alpha_2^2 e^{i\varphi_1}}{m_W^4\sin^2 2\beta}F(\mu_H,M_S)(m_t)^2 m_\tau V_{tb}^*\epsilon^{\alpha\beta\gamma}$$

$$\left[m_d V_{ud}V_{ts}A_{S_h}^1(d_{R\gamma}u_{R\alpha})(s_{L\beta}\nu_{L\tau})+m_s V_{us}V_{td}A_{S_h}^2(s_{R\gamma}u_{R\alpha})(d_{L\beta}\nu_{L\tau})\right]$$

It is important to understand

the behavior of the loop-function F

Sparticle Mass dependence



$$F(\mu, M_S) = \frac{\mu}{M_S^2 - \mu^2}\left[1 - \frac{\mu^2}{M_S^2 - \mu^2}\ln\frac{M_S^2}{\mu^2}\right]$$
$$\sim \begin{cases} \dfrac{\mu}{M_S^2} & (M_S \gg \mu) \\ \dfrac{1}{2M_S} & (M_S \sim \mu) \end{cases}$$

In a splitting case (μ << M_S)

F << $1/M_S$ i.e. dim.5 proton lifetime can be longer.

Approximately, proton lifetime given as,

$$\tau_p \sim (4\times 10^{35}) \times \sin^4 2\beta \left(\frac{0.1}{A_R}\right)^2 \left(\frac{M_S}{10^2\ \mathrm{TeV}}\right)^2 \left(\frac{M_{H_C}}{10^{16}\ \mathrm{GeV}}\right)^2 \quad [\mathrm{yrs}]$$

for $M_S \sim \mu_H$

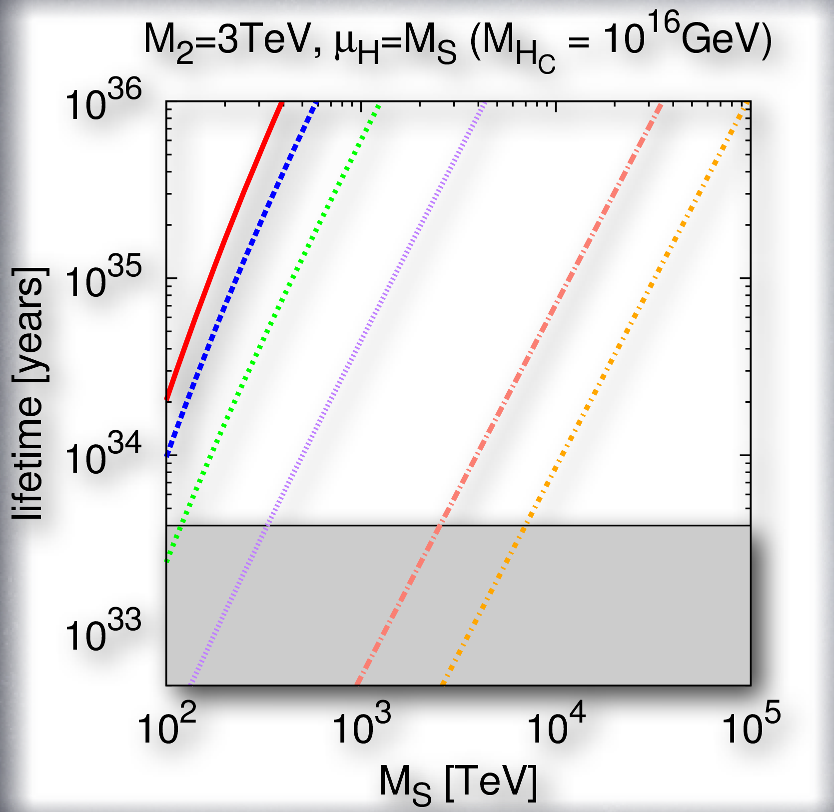
Setups for calc.

-p-decay from dim.5 operator-

- Squarks and Sleptons are degenerated(M_S)
- Gaugino masses are lighter than M_S.
- Higgsino mass is model-dependent

  (→degenerated to M_S or lighter than M_S)
- A-terms are negligible due to the 1-loop suppressed coupling.
- the Colored Higgs mass is set to be 10^{16}GeV
- We choose the additional phase as the proton lifetime is short.

Results



the shaded region is excluded by
the Super-Kamiokande experiment

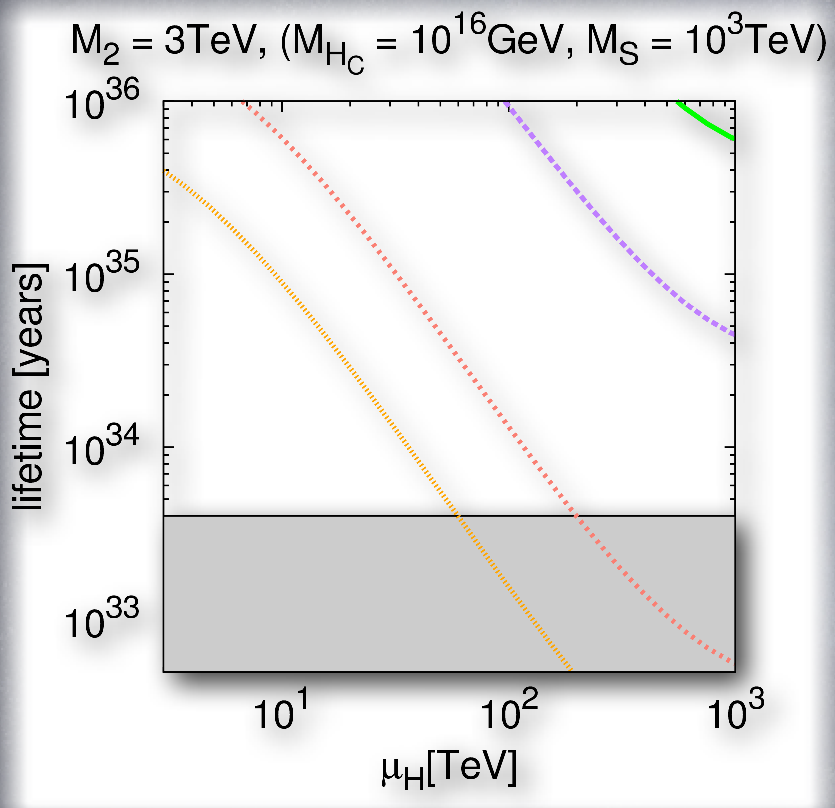
case : $\mu_H = M_S$

From left top to right bottom,
tanβ is 2,3,5,10,30 and 50,respectively.

$$\tau_p \propto \frac{1}{\tan^4 \beta}$$

The proton lifetime can be consistent with experimental result even the sfermion mass is about 100TeV.

Results



the shaded region is excluded by
the Super-Kamiokande experiment

case : $\mu_H < M_S$

From right top to left bottom,
$\tan\beta$ is 5,10,30 and 50,respectively.

$$\tau_p \propto \frac{1}{\tan^4\beta}$$

The lighter Higgsino mass becomes,
the longer lifetime proton has.

Corresponding to Splitting case

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Summary

- high-scale SUSY may be fascinating.
- The gauge coupling unification will be improved in high-scale SUSY.
- The dim.5 proton decay w/ high-scale SUSY can be evaded from experimental limits(Super-K).
- This decay modes ($p \to K^+ + \nu$) may be discovered by next generation detector(Hyper-K : $\tau > 2.5 \times 10^{34}$ yrs).