Doublet-Triplet Mass Splitting and Proton Decay in SU(5) SUSY GUT with Horizontal Symmetry SU(1,1)

Naoki Yamatsu

Department of Physics, Osaka University

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This talk is based on Ref. [1, N.Y.,PTEP,2013,123B01]

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1. Motivation

How to understand Nature

Hints of Physics beyond the Standard Model

Matter sector: Quarks and Leptons

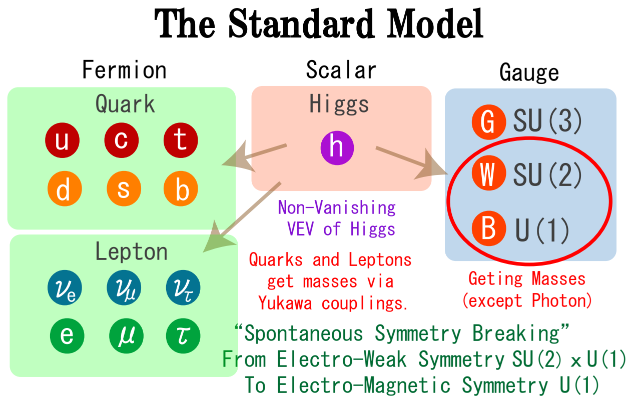
Three Chiral Generations
Hierarchical Mass Structures } ⇒ ①

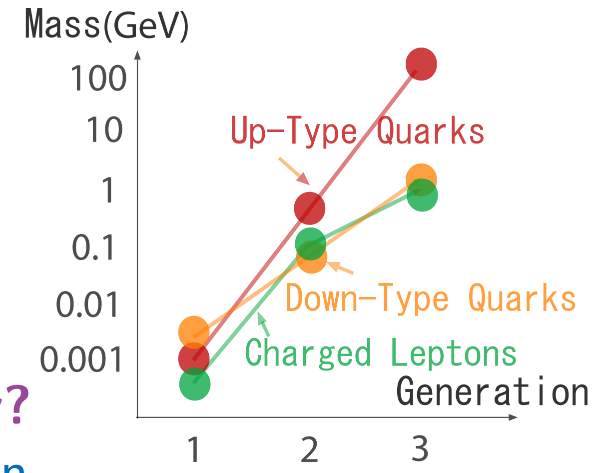
Charge Quantization
Anomaly Cancellations } ⇒ ②

Only Fundamental Representations ⇒ ③

⇒ **How can we understand these questions in a four dimensional effective field theory?**

① Horizontal Symmetry, ② GUT, ③ Unknown.





Approaches to understand generations using horizontal symmetry

Non-Abelian (e.g.,$SU(3)$, A_4)

Naturally explaining three generations.

[2, 3, S.F.King, G.G.Ross,PLB'01;H. Ishimori et al.; $\cdots$]

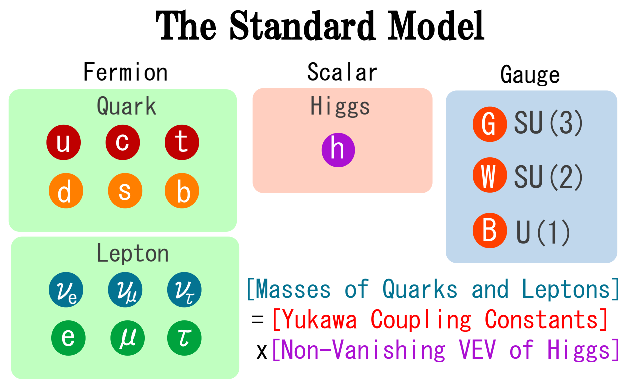
Abelian $U(1)$

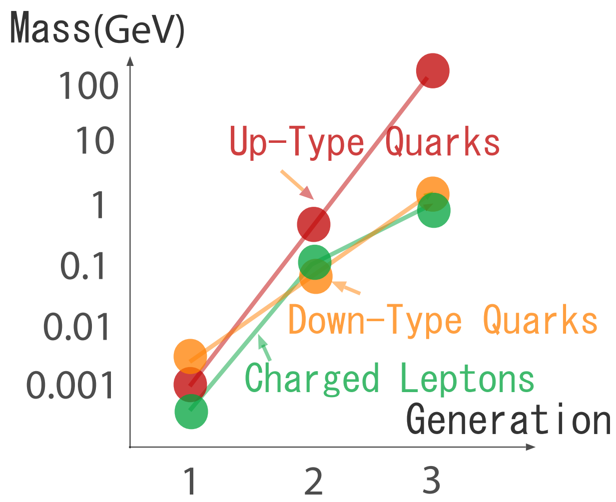
Naturally explaining the mass hierarchies.
Froggatt-Nielsen mechanism

[4, 5, C.D.Froggatt, H.B.Nielsen,NPB'79; N.Maekawa,PTP'01;$\cdots$]

Noncompact Non-Abelian $SU(1,1)$

[6–8, K.Inoue, PTP'95; K.Inoue, N.Y.,PTP'08; N.Yamatsu, PTEP'12;$\cdots$]





Noncompact Non-Abelian Group (minimal $SU(1,1)$)

Noncompact Model ∼ A Vectorlike MSSM with Horizontal Symmetry

[6–8, K.Inoue,PTP'95; K.Inoue, N.Y.,PTP'08; N.Y., PTEP'13]

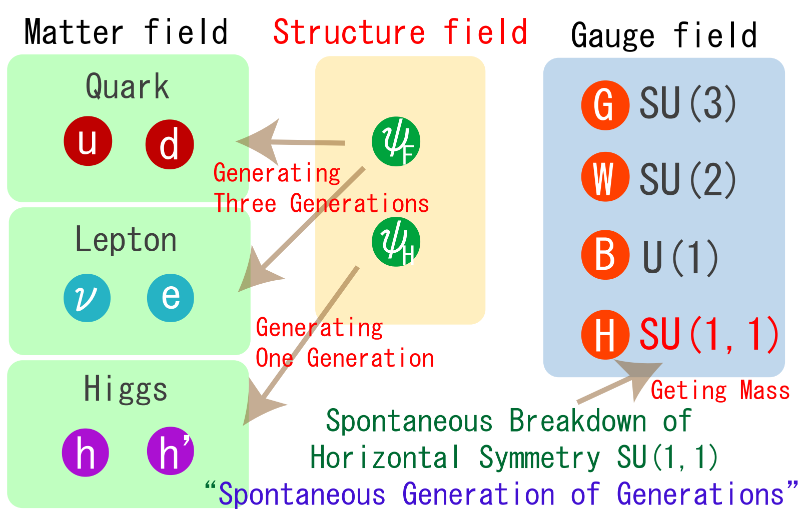
Three Chiral Generations

Chiral matters produced from Vectorlike matters via "**Spontaneous Generation of Generations**"

Hierarchical Mass Structures

Hierarchical structure of Clebsch-Gordan coefficients

Noncompact Model



$\mathcal{N} = 1$ Supersymmetry [9, K.Inoue, H.Kubo & N.Y.,NPB'10]

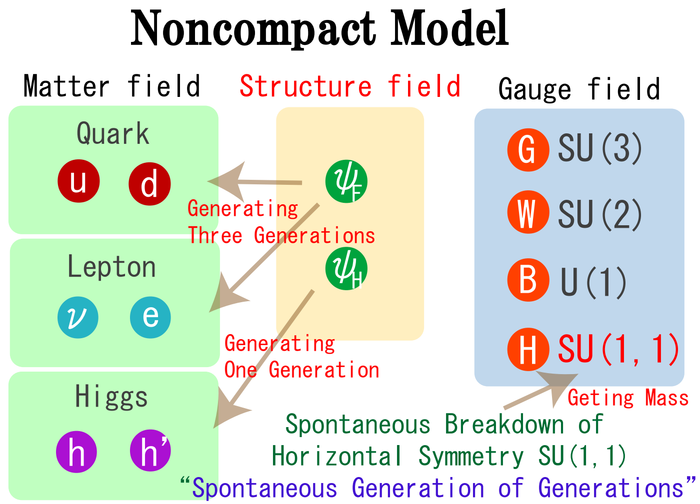
Chirality of Scalar Fields and Stability of Vacuum Structures

Definition of terms in the Noncompact Model

Matter field = infinite-dim. unitary reps. of the noncompact group

$$\begin{cases} \hat{F} = \{\hat{f}_{+\alpha}, \hat{f}_{+\alpha+1}, \hat{f}_{+\alpha+2}, \cdots\}, \\ \hat{F}^c = \{\hat{f}^c_{-\alpha}, \hat{f}^c_{-\alpha-1}, \hat{f}^c_{-\alpha-2}, \cdots\}, \end{cases}$$

α =[real and positive].



Structure field = finite-dim. reps.

$$\hat{\boldsymbol{\Psi}} = \{\hat{\psi}_{-S}, \hat{\psi}_{-S+1}, \cdots, \hat{\psi}_{S-1}, \hat{\psi}_{S}\},$$

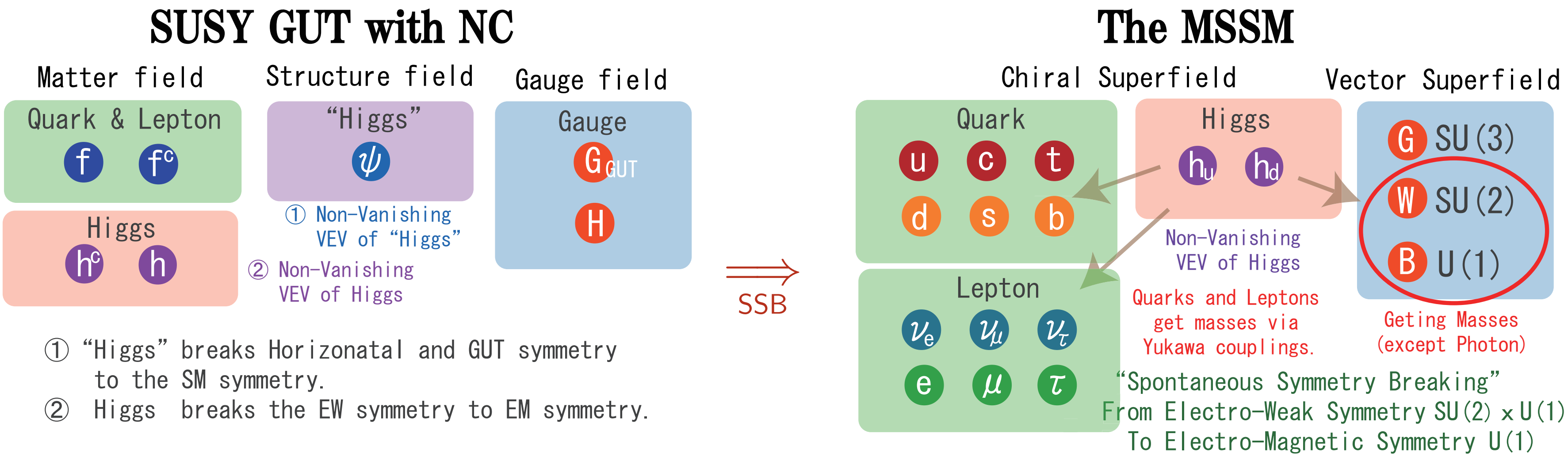
S =[Integer or half-integer], called $SU(1,1)$ spin.

Subscripts, such as α, S, stand for the eigenvalue of τ_3.

All Matter and Structure fields are chiral superfields in $\mathcal{N} = 1$ SUSY.

[8, N.Y., PTEP'13]

2. $SU(5)$ SUSY GUT with $SU(1,1)$



Assuming the following:

- The structure fields get nonvanishing VEVs $M_{\rm GUT} \sim O(10^{16})$ GeV.
- The structure fields break $SU(5) \times SU(1,1)$ to $G_{\rm SM}$.

$\Rightarrow$ Through spontaneous generation of generations, chiral matter fields appear.

2-1 Doublet-Triplet Mass Splitting [7, 10, K.Inoue, N.Yamashita, PTP'00;K.Inoue, N.Y., PTP'08]

(1) Matter fields $SU(5)$ $\mathbf{5}^{(*)}$-plets $\hat{H}_{\mathbf{5}} + \hat{H}^c_{\mathbf{5}^*}$

$$\hat{H}_{\mathbf{5}} = \{\hat{h}_{-\gamma}, \hat{h}_{-\gamma-1}, \cdots\}, \quad \hat{H}^c_{\mathbf{5}^*} = \{\hat{h}^c_{\gamma}, \hat{h}^c_{\gamma+1}, \cdots\}$$

Structure fields $\hat{\Phi}_{\mathbf{1}}$, $\hat{\Phi}'_{\mathbf{24}}$ (S:a highest weight of $SU(1,1)$)

$$\hat{\Phi}_{\mathbf{1}} = \{\hat{\phi}_{-S}, \hat{\phi}_{-S+1}, \cdots, \hat{\phi}_{S}\}, \quad \hat{\Phi}'_{\mathbf{24}} = \{\hat{\phi}'_{-S}, \hat{\phi}'_{-S+1}, \cdots, \hat{\phi}'_{S}\}.$$

(2) Superpotential of Matter-Structure Couplings (x, x': coupling constant)

$$W = x\hat{H}_{\mathbf{5}}\hat{H}^c_{\mathbf{5}^*}\hat{\Phi}_{\mathbf{1}} + x'\hat{H}_{\mathbf{5}}\hat{H}^c_{\mathbf{5}^*}\hat{\Phi}'_{\mathbf{24}}.$$

(3) Nonvanishing VEV of the structure fields $\hat{\Phi}_{\mathbf{1}}$, $\hat{\Phi}'_{\mathbf{24}}$

$$\langle\hat{\Phi}_{\mathbf{1}}\rangle = \{\cdots, 0, \langle\phi_{\mathbf{0}}\rangle, 0, \cdots\}, \ \langle\hat{\Phi}'_{\mathbf{24}}\rangle = \{\cdots, 0, \langle\phi'_{+\mathbf{1}}\rangle_{\mathbf{SU(5)}\to\mathbf{G_{SM}}}, \cdots\}.$$

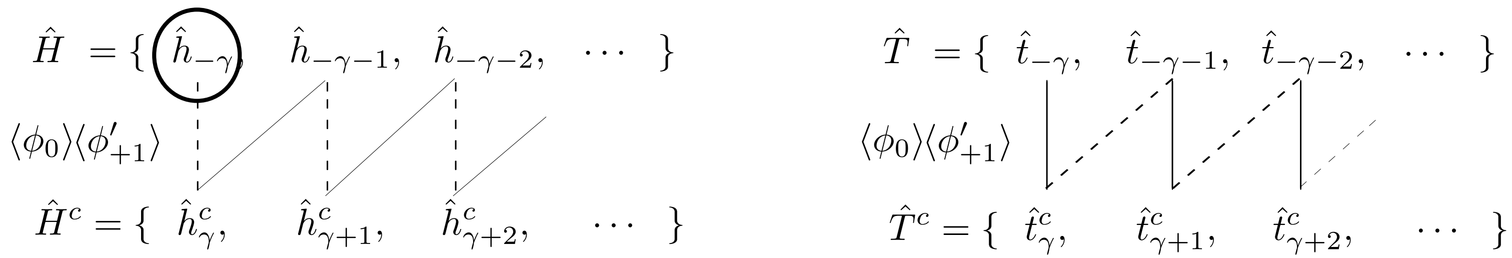
To determine the massless modes, we need to calculate mixing between states.

Normalizable condition for massless modes leads to the following:

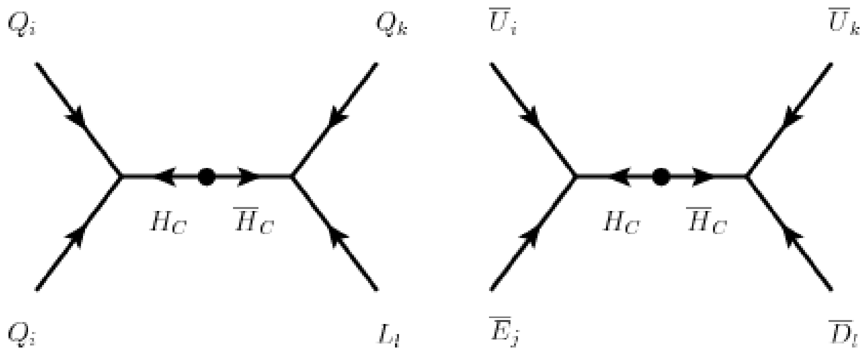
	Condition for ϵ's	Massless Modes
①	$\epsilon_{cr} < \lvert\epsilon_{\mathbf{2}}\rvert < \lvert\epsilon_{\mathbf{3}}\rvert$	~~doublet $\hat{H}$~~, ~~triplet $\hat{T}$~~
②	$\lvert\epsilon_{\mathbf{2}}\rvert < \epsilon_{cr} < \lvert\epsilon_{\mathbf{3}}\rvert$	doublet $\hat{H}$, ~~triplet $\hat{T}$~~
③	$\lvert\epsilon_{\mathbf{2}}\rvert < \lvert\epsilon_{\mathbf{3}}\rvert < \epsilon_{cr}$	doublet $\hat{H}$, triplet $\hat{T}$

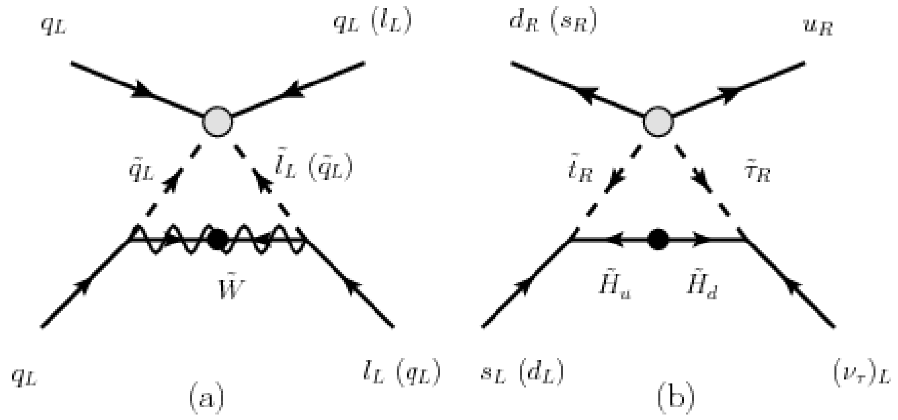
$$\epsilon_{\mathbf{3}} = (-3/2)\epsilon_{\mathbf{2}},\ \epsilon_{\mathbf{2}} := x\langle\phi_0\rangle/x'\langle\phi'_{+1}\rangle,\ \epsilon_{cr} := \sqrt{S!S!/(S+1)!(S-1)!}$$

For the case ②, the lightest doublet higgs has no Dirac mass, while the lightest colored higgs has a Dirac mass $O(M_{\rm GUT}) \sim O(10^{16})$ GeV.



2-2 Proton Decay (via colored higgses)

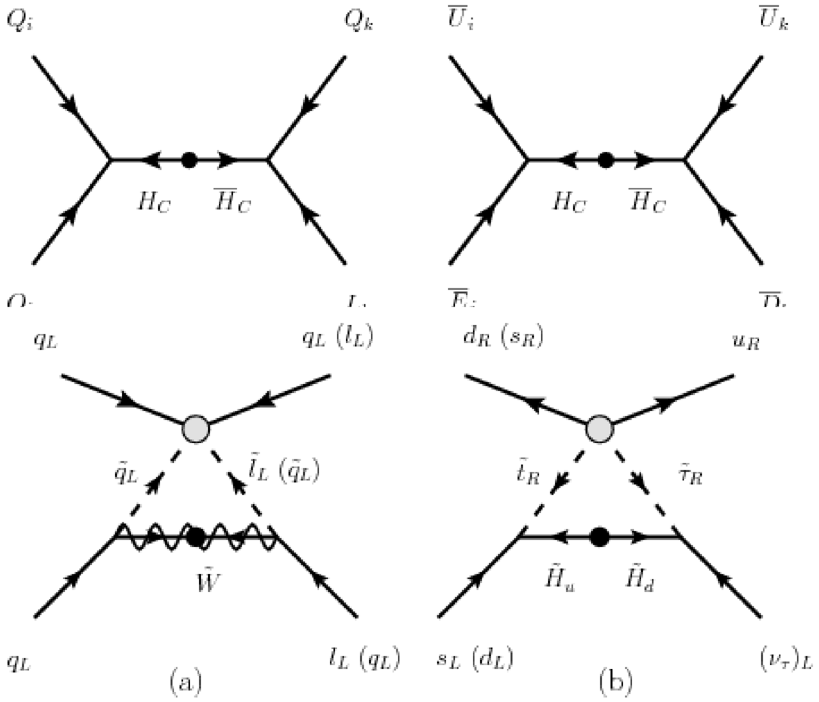




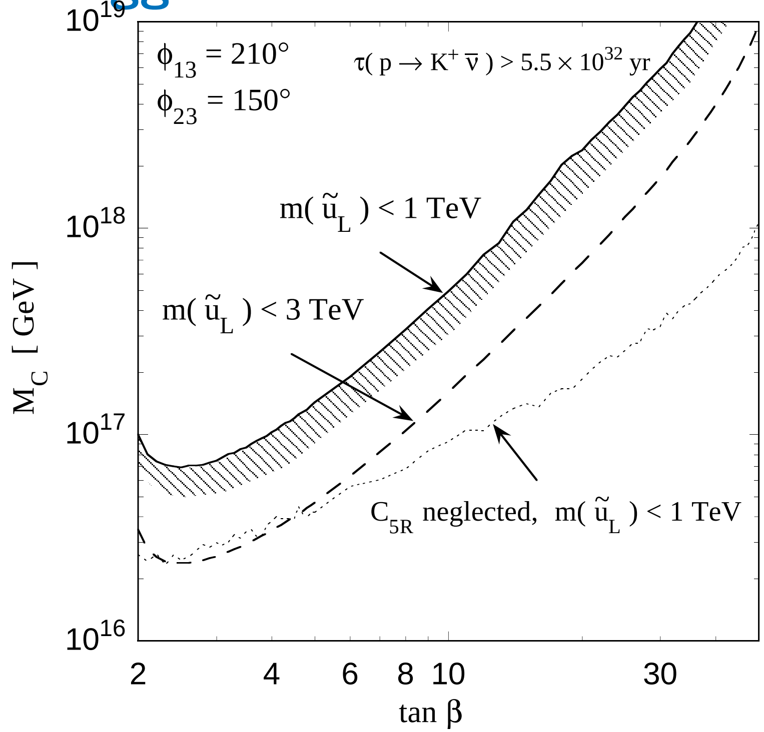
From Ref. [11, J.Hisano et al.,'13]

Superpotential quartic terms $\hat{Q}\hat{Q}\hat{Q}\hat{L}$ and $\hat{U}^c\hat{U}^c\hat{D}^c\hat{E}^c$ are generated by colored higgses, and lead to dimension-6 operators causing proton decays.

Proton decays mediated by colored higgses



From Ref. [11, J.Hisano et al.,'13]



From Ref. [12, T.Goto, T.Nihei,PRD'99]

$$W \sim -\frac{1}{M_C}\left(\hat{Q}\hat{Q}\hat{Q}\hat{L} + \hat{U}^c\hat{U}^c\hat{D}^c\hat{E}^c\right).$$

(Recent Super-Kamiokande result $\tau(p \to K^+\bar{\nu}) > 3.3 \times 10^{33}$ yr [13, M.Miura,PoS'2010])

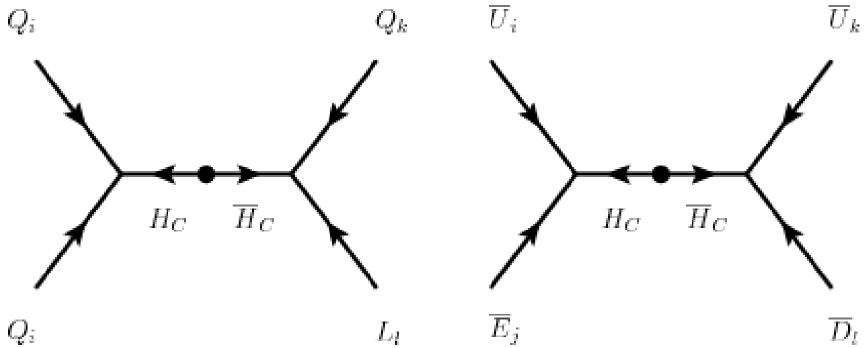
Some known methods suppressing proton decays via colored higgses

- ♯ SUSY particle's masses are much heavier than 1 TeV. [11, J.Hisano, et al.'arXiv'13;· · ·]
- ♯ In an orbifold extra dimension model $S^1/Z^2 \times Z^2$, when only doublet higgses have zero modes and colored higgses have no zero modes [14, Y.Kawamura,PTP'01], the colored higgses have Dirac mass terms. The contribution to proton decay via colored higgses is strongly suppressed [15, L.J.Hall, Y.Nomura,PRD'01;· · ·].

The $SU(5) \times SU(1,1)$ Model

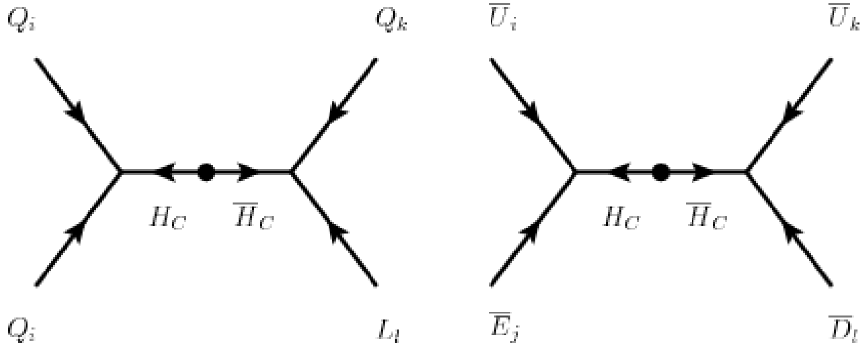
- ♯ When only doublet higgses are chiral and colored higgses are vectorlike via spontaneous generation of generations [7, 10, K.Inoue,N.Yamashita,PTP'00;K.Inoue,N.Y.,PTP'08], the colored higgses have Dirac mass terms. The contribution to proton decay via colored higgses is strongly suppressed [1, N.Y.,PTEP'13].

The $SU(5) \times SU(1,1)$ Model



- μ-term $\hat{H}_u \hat{H}_d$, $\hat{Q}\hat{Q}\hat{Q}\hat{L}$ and $\hat{U}^c\hat{U}^c\hat{D}^c\hat{E}^c$ are forbidden by the horizontal symmetry $SU(1,1)$. (They are allowed by ordinary R-parity.)
- Spontaneous horizontal symmetry breaking can produce nonzero μ-parameter $O(m_{\mathrm{SUSY}})$, and then $\hat{Q}\hat{Q}\hat{Q}\hat{L}$ and $\hat{U}^c\hat{U}^c\hat{D}^c\hat{E}^c$ are also generated.
- The masses of the colored higgses come from mass terms $O(M_{\mathrm{GUT}})$ between the colored higgses and their conjugate fields as well as the effective μ-term $O(m_{\mathrm{SUSY}})$ between up- and down-type colored higgses.

The $SU(5) \times SU(1,1)$ Model



$$W \sim -\frac{\mu}{M_{T_u} M_{T_d}} \left(\hat{Q}\hat{Q}\hat{Q}\hat{L} + \hat{U}^c \hat{U}^c \hat{D}^c \hat{E}^c \right), \quad {}''M_C'' := \frac{M_{T_u} M_{T_d}}{\mu},$$

where $\mu = O(m_{\rm SUSY})$ and $M_{T_u} \simeq M_{T_d} = O(M_{\rm GUT})$.

$$\Rightarrow \quad {}''M_C'' = O(M_{\rm GUT}^2 / m_{\rm SUSY}) \sim O(10^{29}) \text{ GeV}.$$

- The contribution to proton decay via colored higgses ($p \to K^+ \bar{\nu}$) is highly suppressed. Thus the main contribution comes from the GUT gauge bosons ($p \to \pi^0 e^+$).

3. Summary

- $SU(5)$ SUSY GUT with $SU(1,1)$

Through the spontaneous generation of generations, the doublet higgses can appear and the colored higgses can disappear naturally.

We found that once the doublet-triplet mass splitting is realized naturally, proton decay via colored higgses are highly suppressed.

- Other Topics

How to realize three chiral generations of quarks and leptons

How to explain hierarchical structure of Yukawa coupling constants

How and When we identify R-parity as a discrete subgroup of $SU(1,1)$.

If you are interested in them, please read a paper [1, N.Y., PTEP'13]

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