

R-Symmetric Flipped SU(5)

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[arXiv: 2008.08940]

Shihwen Hor

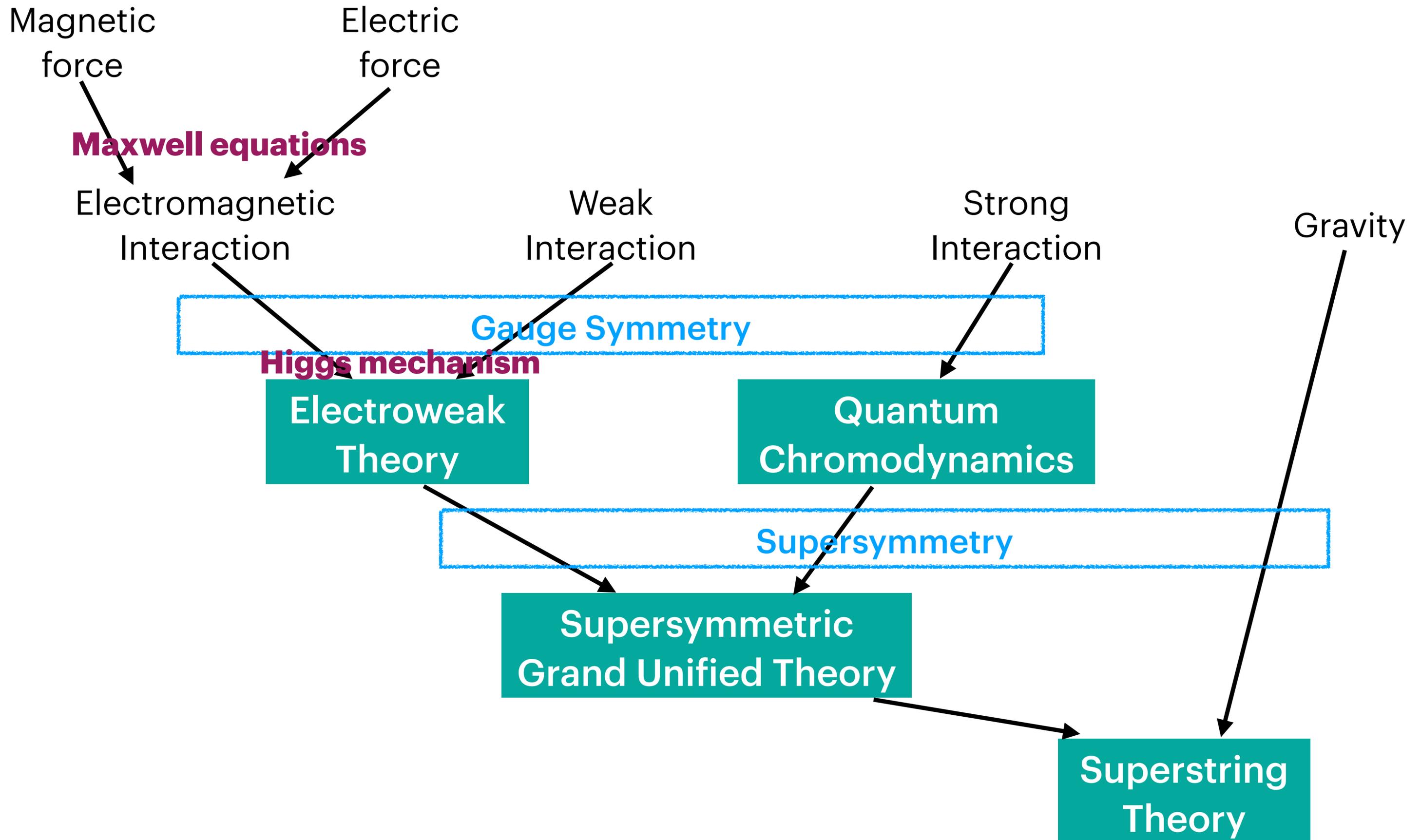
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Outline

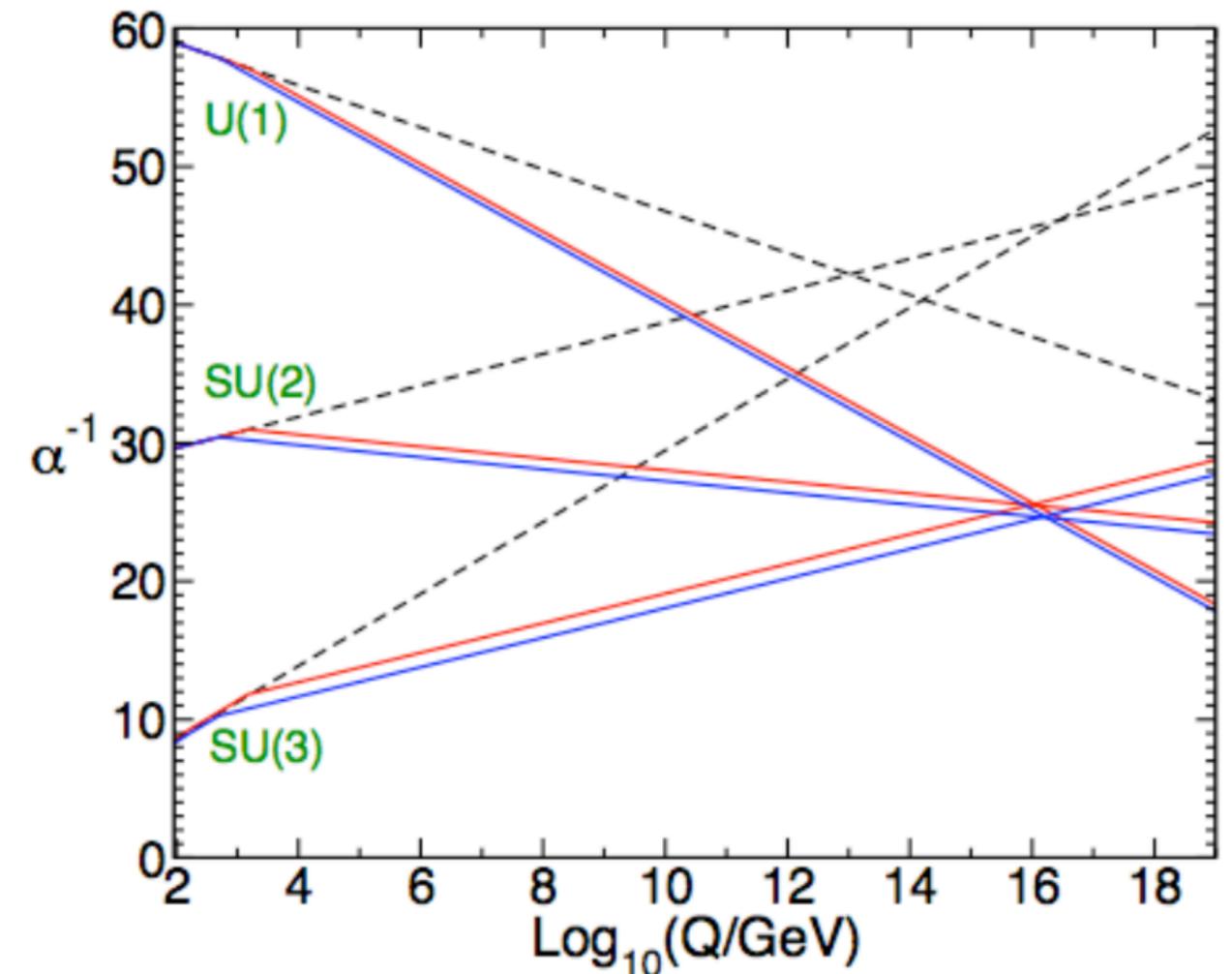
- 1. Introduction
- 2. R-symmetric flipped SU(5)
 - Symmetry breaking
 - Doublet-triplet splitting
 - Proton decay
- 3. Conclusion

1. Introduction



Grand unified theories

- Coupling unification
 - $g_1(M_{\text{GUT}}) = g_2(M_{\text{GUT}}) = g_3(M_{\text{GUT}})$
 - **SUSY GUT** [P. Langacker, Phys. Rept. 72 (1981) 185]
- Unification of quarks and leptons
- Charge quantization
- **Proton decay**



[S. P. Martin, A Supersymmetry primer. (1997)]

Grand unified theories

SU(5) v.s. flipped SU(5) GUT

- SU(5) GUT

$$F_i = \mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_{i3}^c & -u_{i2}^c & u_i^1 & d_i^1 \\ -u_{i3}^c & 0 & u_{i1}^c & u_i^2 & d_i^2 \\ u_{i2}^c & -u_{i1}^c & 0 & u_i^3 & d_i^3 \\ -u_i^1 & -u_i^2 & -u_i^3 & 0 & e_i^c \\ -d_i^1 & -d_i^2 & -d_i^3 & -e_i^c & 0 \end{pmatrix}, \quad \bar{f}_i = \bar{\mathbf{5}} = \begin{pmatrix} d_{i1}^c \\ d_{i2}^c \\ d_{i3}^c \\ e_i \\ -\nu_i \end{pmatrix}, \quad l_i^c = \mathbf{1} = (\nu_i^c)$$

- Flipped SU(5) GUT: **SU(5)xU(1)** gauge theory

$$F_i = \mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & d_{i3}^c & -d_{i2}^c & u_i^1 & d_i^1 \\ -d_{i3}^c & 0 & d_{i1}^c & u_i^2 & d_i^2 \\ d_{i2}^c & -d_{i1}^c & 0 & u_i^3 & d_i^3 \\ -u_i^1 & -u_i^2 & -u_i^3 & 0 & \nu_i^c \\ -d_i^1 & -d_i^2 & -d_i^3 & -\nu_i^c & 0 \end{pmatrix}, \quad \bar{f}_i = \bar{\mathbf{5}} = \begin{pmatrix} u_{i1}^c \\ u_{i2}^c \\ u_{i3}^c \\ e_i \\ -\nu_i \end{pmatrix}, \quad l_i^c = \mathbf{1} = (e_i^c)$$

Grand unified theories

Doublet-triplet splitting problem

- Minimal SUSY SU(5)
- MSSM Higgs: embedded in $\mathbf{5}$ and $\bar{\mathbf{5}}$ in SU(5) theory

$$H = \begin{pmatrix} \zeta_u \\ H_u \end{pmatrix}, \quad \bar{H} = \begin{pmatrix} \bar{\zeta}_d \\ H_d \end{pmatrix}$$

$\zeta_u, \bar{\zeta}_d$: colored Higgs \rightarrow need to be heavy
 H_u, H_d : MSSM Higgs \rightarrow need to be light

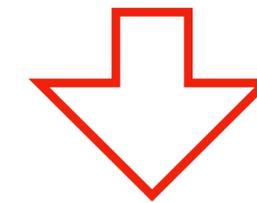
- Superpotential $W \supset \lambda(H\Phi\bar{H} + MH\bar{H})$

- VEV of $\Phi = 24$ breaks SU(5) into the SM

$$\langle \Phi \rangle = \text{diag}(b, b, b, -\frac{3}{2}b, -\frac{3}{2}b)$$

$$W_{\text{eff}} = \lambda \overset{\text{Heavy}}{(b + M)} \zeta_u \bar{\zeta}_d + \lambda \left(-\frac{3}{2}b + M\right) H_u H_d$$

Light



Doublet-triplet splitting problem



Missing partner mechanism

2. R-symmetric flipped SU(5)

2.1 Model

R-symmetric flipped SU(5)

[K. Hamaguchi, S. Hor and N. Nagata, JHEP 11 (2020) 140]

- Standard flipped SU(5) GUT
- **MSSM Higgs reside in h and \bar{h}**
- **H and \bar{H} break the SU(5)xU(1)** down to the SM gauge group
- Newly introduced in our model
 - **Global U(1)R symmetry** (The superpotential has the U(1)R charge +2)
 - Additional **singlet field S**

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	$\bar{5}$	-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}	$u_{\bar{H}}^c, Q_{\bar{H}}, \nu_{\bar{H}}^c$	$\bar{10}$	-1	17/36
h	D, H_d	5	-2	19/18
\bar{h}	\bar{D}, H_u	$\bar{5}$	+2	19/18
S	S	1	0	1/9

The field content and the charge assignments in our model.
 The U(1) charges are given in units of $1/\sqrt{40}$

2.1 Model

Superpotential

$$- W_{\text{Yukawa}} = -\frac{1}{4}\lambda_1^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}F_i^{\alpha\beta}F_j^{\gamma\delta}h^\epsilon + \sqrt{2}\lambda_2^{ij}F_i^{\alpha\beta}\bar{f}_{j\alpha}\bar{h}_\beta + \lambda_3^{ij}\bar{f}_{i\alpha}\ell_j^c h^\alpha,$$

$$- W_{\text{DT}} = \frac{\lambda_4}{4\Lambda_{\text{DT}}^8}\epsilon_{\alpha\beta\gamma\delta\epsilon}S^8 H^{\alpha\beta}H^{\gamma\delta}h^\epsilon + \frac{1}{4}\lambda_5\epsilon^{\alpha\beta\gamma\delta\epsilon}\bar{H}_{\alpha\beta}\bar{H}_{\gamma\delta}\bar{h}_\epsilon,$$

$$- W_{\text{neutrino}} = \frac{c_{ij}}{2\Lambda_N^2}S(F_i^{\alpha\beta}\bar{H}_{\alpha\beta})(F_j^{\gamma\delta}\bar{H}_{\gamma\delta}),$$

$$- W_{\text{HS}} = \frac{\lambda_H}{4\Lambda_{\text{HS}}^5}(H^{\alpha\beta}\bar{H}_{\alpha\beta})^4 + \frac{\lambda_{\text{HS}}}{18\Lambda_{\text{HS}}^{10}}(H^{\alpha\beta}\bar{H}_{\alpha\beta})^2S^9 + \frac{\lambda_S}{18\Lambda_{\text{HS}}^{15}}S^{18},$$

- Unwanted bilinear terms, $H\bar{H}$ and $h\bar{h}$, are both **forbidden** by the **U(1)R** symmetry.
- Right-handed neutrino masses: **non-renormalizable operator**
- U(1)R symmetry highly **restricts possible forms of operators in W_{HS}** .

2.2 Symmetry breaking and mass spectrum

The scalar potential

- The potential minimum at which $\nu_H^c, \nu_{\bar{H}}^c$ and S develop VEVs.

- D-flat direction

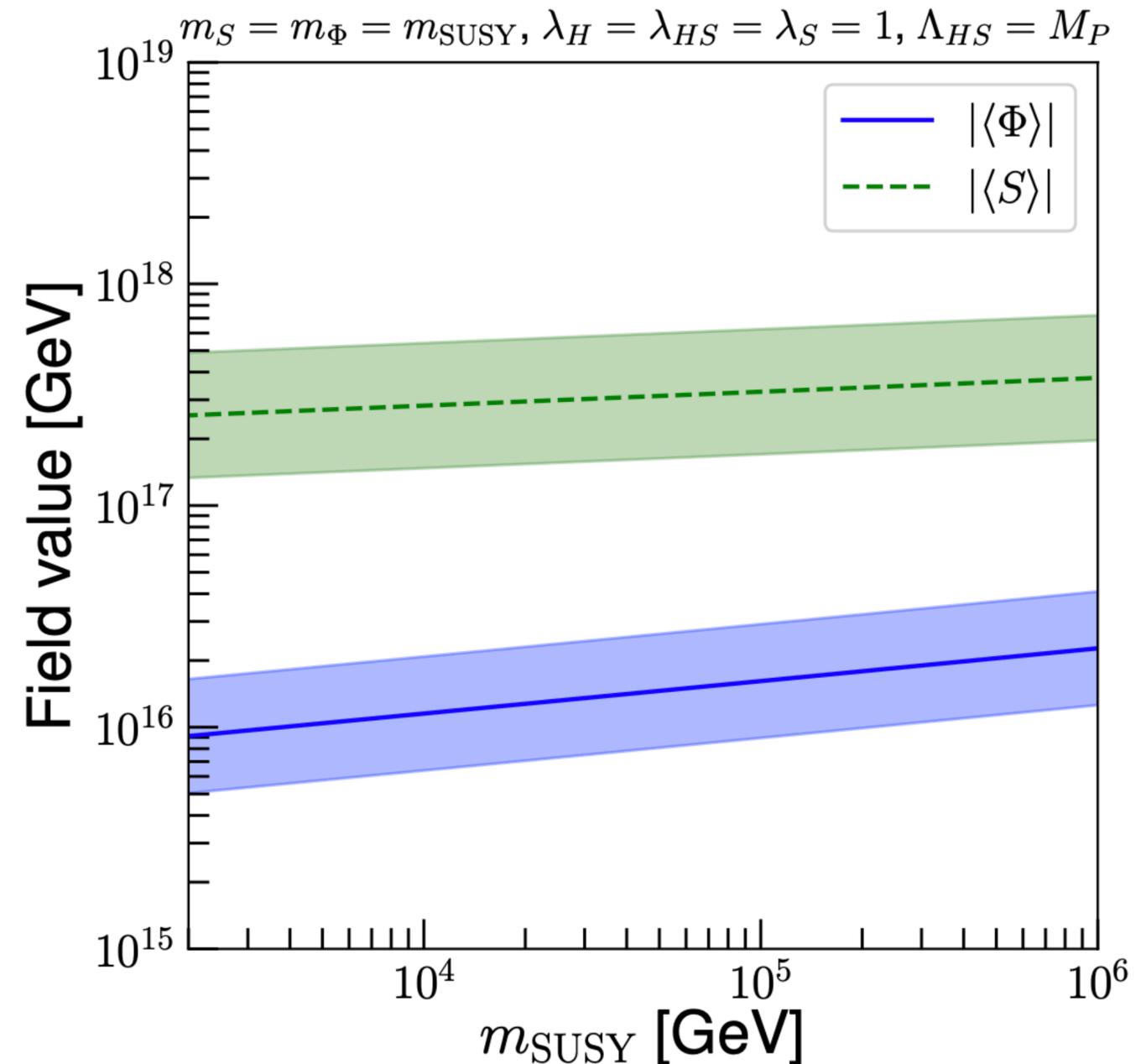
$$\langle \nu_H^c \rangle = \langle \nu_{\bar{H}}^c \rangle = \Phi \equiv |\Phi| e^{i\theta}$$

- Φ breaks the $SU(5) \times U(1)$ into the SM gauge group.

- $m_\Phi^2 \equiv m_H^2 + m_{\bar{H}}^2$

- $|\langle \Phi \rangle| \simeq 10^{16}$ GeV

- $|\langle S \rangle| \simeq \text{a few} \times 10^{17}$ GeV



2.2 Symmetry breaking and mass spectrum

Doublet-triplet splitting

- **Doublet-triplet splitting problem is solved** by the **Missing partner mechanism**.

$$W_{\text{DT}} = \frac{\lambda_4}{4\Lambda_{\text{DT}}^8} \epsilon_{\alpha\beta\gamma\delta\epsilon} S^8 H^{\alpha\beta} H^{\gamma\delta} h^\epsilon + \frac{1}{4} \lambda_5 \epsilon^{\alpha\beta\gamma\delta\epsilon} \bar{H}_{\alpha\beta} \bar{H}_{\gamma\delta} \bar{h}_\epsilon ,$$

$$\bullet 10_{+1} \rightarrow (\bar{3}, 1)_{+1/3} + (3, 2)_{+1/6} + (1, 1)_0$$

$$\bullet 5_{-2} \rightarrow (3, 1)_{-1/3} + (1, 2)_{-1/2}$$

$$- M_{H_C} = \lambda_4 |\langle \Phi \rangle| \left(\frac{\langle S \rangle}{\Lambda_{\text{DT}}} \right)^8$$

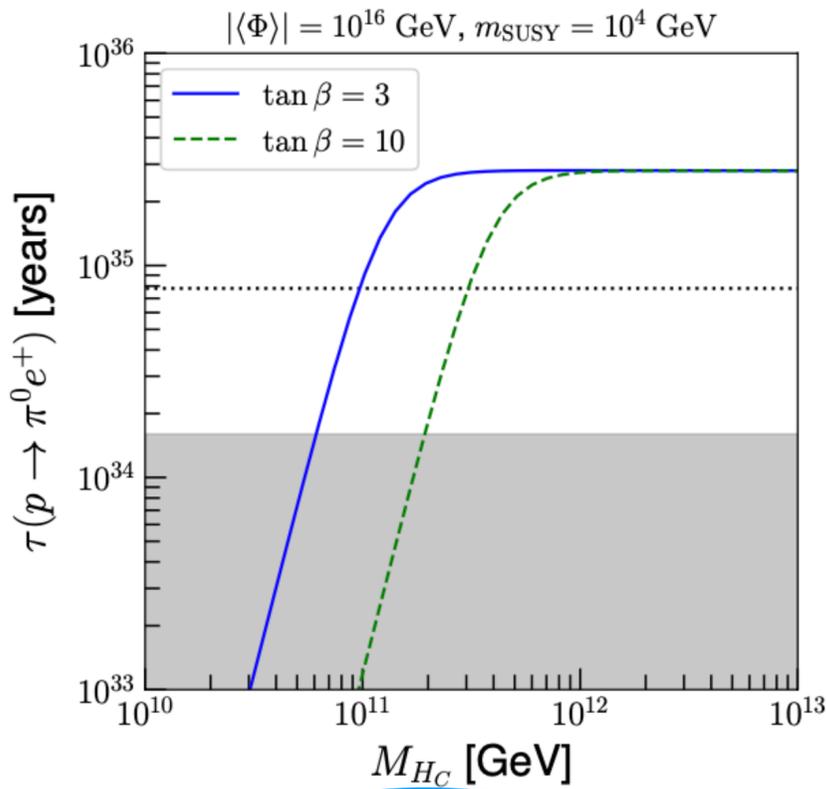
light color-triplet Higgs

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

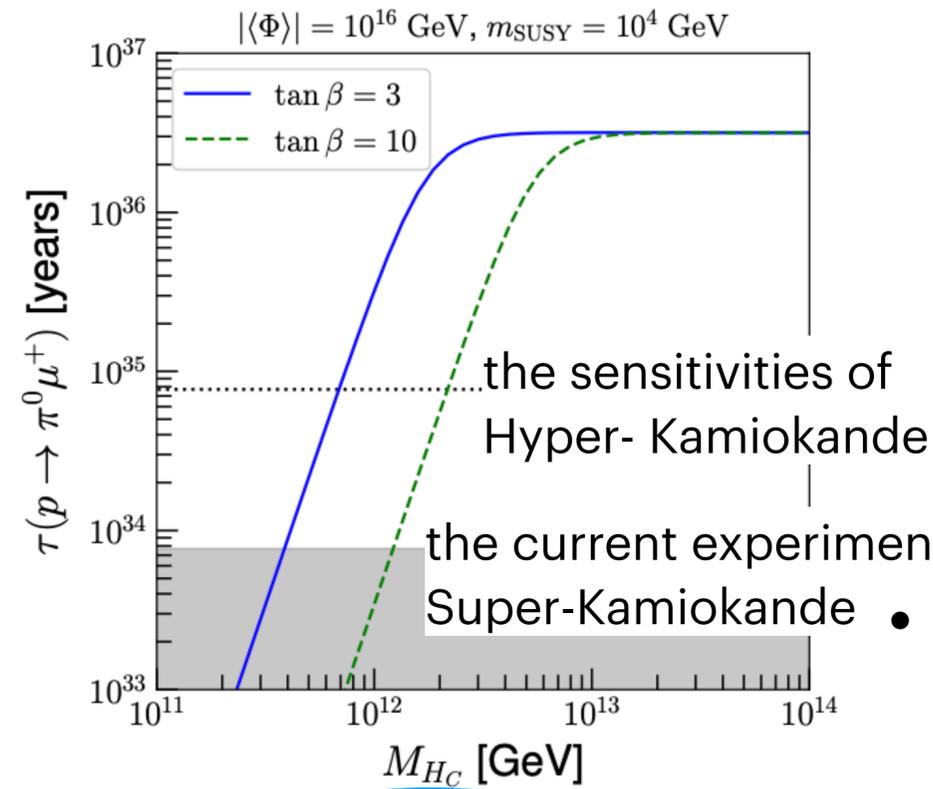
$$- M_{\bar{H}_C} = \lambda_5 |\langle \Phi \rangle| .$$

2.3 Proton decay

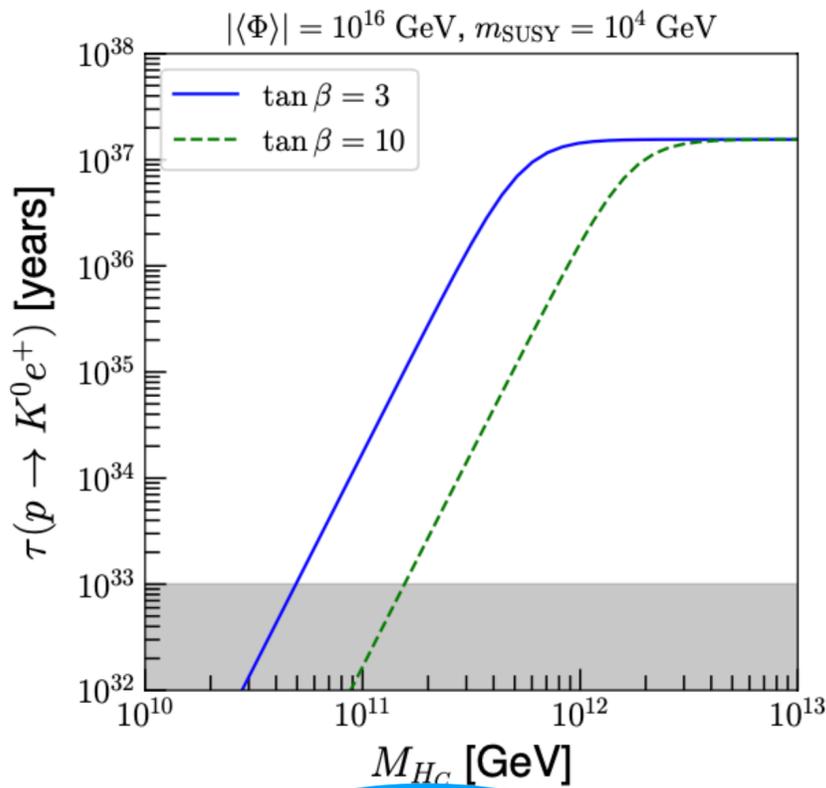
- Dimension-five proton decay operators (**negligible**)
 - Exchange of color-triplet Higgs
- **Dimension-six** proton decay operators
 - Exchange of **SU(5) gauge boson** and the **light color-triplet Higgs**



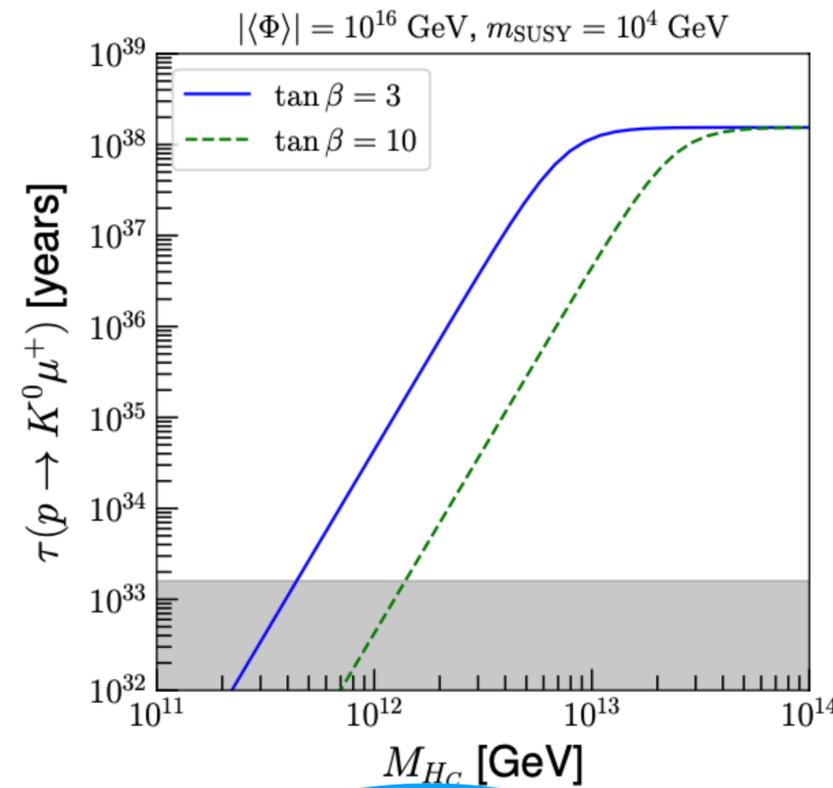
(a) $p \rightarrow \pi^0 e^+$



(b) $p \rightarrow \pi^0 \mu^+$



(c) $p \rightarrow K^0 e^+$



(d) $p \rightarrow K^0 \mu^+$

- The branching is larger for the decay mode containing a **second-generation** quark or lepton.

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

3. Conclusion

- We constructed a flipped SU(5) SUSY GUT model which is invariant under **a global U(1)R symmetry**
 - The SU(5)-breaking Higgs fields acquire a VEV in the flat direction after SUSY is broken.
 - The μ -**terms of the Higgs fields are forbidden** by the U(1)R symmetry.
 - **Light color-triplet Higgs** at intermediate scale
 - **Missing partner mechanism**
 - Right-handed neutrino masses: **non-renormalizable operators**
- Proton decay
 - Channel $p \rightarrow \pi^0 \mu^+$ and $p \rightarrow K^0 \mu^+$

Thank you for your attention.

Appendix

A. Symmetry breaking and mass spectrum

The scalar potential

- Symmetry breaking pattern
- The scalar potential: $V = V_F + V_D + V_{\text{soft}}$,

$$- V_D = \left(\frac{3g_5^2}{10} + \frac{g_X^2}{80} \right) \left[\left| \nu_H^c \right|^2 - \left| \nu_{\bar{H}}^c \right|^2 \right]^2 ,$$

$$- V_F = \left| \frac{\lambda_H}{\Lambda_{HS}^5} (\nu_H^c \nu_{\bar{H}}^c)^2 + \frac{\lambda_{HS}}{9\Lambda_{HS}^{10}} S^9 \right|^2 \left| \nu_H^c \nu_{\bar{H}}^c \right|^2 \left(\left| \nu_H^c \right|^2 + \left| \nu_{\bar{H}}^c \right|^2 \right) + \left| \frac{\lambda_{HS}}{2\Lambda_{HS}^{10}} (\nu_H^c \nu_{\bar{H}}^c)^2 + \frac{\lambda_S}{\Lambda_{HS}^{15}} S^9 \right|^2 |S|^{16} ,$$

$$- V_{\text{soft}} = -m_H^2 \left| \nu_H^c \right|^2 - m_{\bar{H}}^2 \left| \nu_{\bar{H}}^c \right|^2 - m_S^2 |S|^2 .$$

B. R-axion

- **U(1)R symmetry breaking**

- Nambu-Goldstone boson: **R-axion**

- U(1)R is explicitly violated by a constant term (cosmological constant)

- $W = W_0 + W_{\text{const}}$

- Supergravity effect

- **R-axion mass** $m_a^2 \simeq \frac{8}{f_a^2 M_P^2} \left| \left\langle W_{\text{const}} \left[K^i (K^{-1})^j{}_i W_{0j}^* - 3W_0^* \right] \right\rangle \right|$,

$$f_a = \left[2K_i^j r_i r_j \langle \phi_i \rangle \langle \phi_j \rangle \right]^{1/2}, \quad K^i \equiv \frac{\partial K}{\partial \phi_i}, \quad K_i^j \equiv \frac{\partial^2 K}{\partial \phi^{*i} \phi_j}, \quad W_{0j}^* \equiv \frac{\partial W_0^*}{\partial \phi^{*j}}.$$

B. R-axion

$$- f_a \simeq \frac{\sqrt{2}}{9} \langle S \rangle = 5 \times 10^{16} \times \left(\frac{\langle S \rangle}{3 \times 10^{17} \text{ GeV}} \right) \text{ GeV} .$$

$$- \Lambda_{\text{hid}}^3 = (m_{\text{SUSY}} M_P)^{3/2} \simeq 4 \times 10^{33} \times \left(\frac{m_{\text{SUSY}}}{10^4 \text{ GeV}} \right)^{3/2} \text{ GeV}^3 .$$

$$- \left| \left\langle S \frac{\partial W_{HS}^*}{\partial S^*} - 3 W_{HS}^* \right\rangle \right| \simeq 5 \times 10^{38} \times \left(\frac{\langle S \rangle}{3 \times 10^{17} \text{ GeV}} \right)^{18} \text{ GeV}^3 .$$

$$- W_{\text{const}} \simeq |\langle W \rangle| = m_{3/2} M_P^2 = 6 \times 10^{40} \times \left(\frac{m_{3/2}}{10^4 \text{ GeV}} \right) \text{ GeV}^3$$

$$\bullet m_a \simeq 1 \times 10^5 \times \left(\frac{\langle S \rangle}{3 \times 10^{17} \text{ GeV}} \right)^8 \left(\frac{m_{3/2}}{10^4 \text{ GeV}} \right)^{1/2} \text{ GeV}$$

- R-axion: as heavy as other SUSY particles

C. Neutrino

- Right-handed neutrino mass term
 - Non-renormalizable operator

$$- W_{\text{neutrino}} = \frac{c_{ij}}{2\Lambda_N^2} S(F_i^{\alpha\beta} \bar{H}_{\alpha\beta})(F_j^{\gamma\delta} \bar{H}_{\gamma\delta}) ,$$

- See-saw mechanism

- Right-handed neutrino masses are generated after the symmetry breaking.

$$- (M_R)_{ij} = c_{ij} \frac{\langle S \rangle |\langle \Phi \rangle|^2}{\Lambda_N^2}$$

$$\simeq c_{ij} \times 3 \times 10^{13} \times \left(\frac{\langle S \rangle}{3 \times 10^{17} \text{ GeV}} \right) \left(\frac{|\langle \Phi \rangle|}{10^{16} \text{ GeV}} \right)^2 \left(\frac{\Lambda_N}{10^{18} \text{ GeV}} \right)^{-2} \text{ GeV}$$

C. Neutrino

- $(M_R)_{ij}$ too small for the third generation
 - Two singlet chiral superfields: ϕ ($U(1)_R$ charge : 19/18) and $\bar{\phi}$ ($U(1)_R$ charge : 17/18)
 - $W_{\text{ex}} = \lambda_6^i F_i \bar{H} \phi + \mu_\phi \phi \bar{\phi} + \frac{1}{2} \kappa_\phi S \bar{\phi} \bar{\phi}$
 - Integrating out ϕ and $\bar{\phi}$
 - Effective operator $W'_{\text{neutrino}} = \frac{\lambda_6^i \lambda_6^j \kappa_\phi}{2\mu_\phi^2} S (F_i^{\alpha\beta} \bar{H}_{\alpha\beta}) (F_j^{\gamma\delta} \bar{H}_{\gamma\delta}) \rightarrow \mathcal{O}(10^{14})$ mass

D. Difficulty of missing partner in SUSY SU(5)

- Needed to introduce a few additional fields
- Having some **problems in the running couplings unification** due to the **large representations**
- [S. Pokorski, K. Rolbiecki, G.G. Ross and K. Sakurai, JHEP 04 (2019) 161]
- Additional gauge singlet with an additional global U(1) symmetry
 - [G. Altarelli, F. Feruglio and I. Masina, JHEP 11 (2000) 040]
 - Standard missing partner mechanism
- A new set of chiral multiplets and Peccei-Quinn U(1) symmetry
 - [J. Hisano, T. Moroi, K. Tobe and T. Yanagida, Phys. Lett. B 342 (1995) 138]

E. Dimension-five proton decay

- Dimension-five proton decay operators

- Exchange of the color-triplet Higgs

- $$W_5^{\text{eff}} = \frac{\mu_H}{M_{H_C} M_{\bar{H}_C}} \left[\frac{1}{2} (V^* P \lambda_{1,D} V^\dagger)^{ij} (\lambda_{2,D} U_\ell^*)^{kl} \epsilon_{abc} (Q_i^a \cdot Q_j^b) (Q_k^c \cdot L_l) - (\lambda_{2,D} V P^*)^{ij} (U_\ell \lambda_{3,D})^{kl} \epsilon^{abc} u_{ia}^c d_{jb}^c u_{kc}^c e_l^c \right]$$

- Suppression $\frac{\mu_H}{M_{H_C}} \rightarrow$ negligible

- Cut-off suppressed operators

- $$W'_5 = \frac{c_1^{ijkl}}{\Lambda^2} \epsilon_{\alpha\beta\gamma\delta\epsilon} S F_i^{\alpha\beta} F_j^{\gamma\delta} F_k^{\epsilon\tau} \bar{f}_{l\tau} + \frac{c_2^{ijkl}}{\Lambda^2} S F_i^{\alpha\beta} \bar{f}_{j\alpha} \bar{f}_{k\beta} \ell_l^c$$

- c_1^{ijkl} and c_2^{ijkl} : suppressed by the same mechanism as that explains the Yukawa hierarchies

- Dimension-five proton decay does not give the main contribution.

F. Proton decay

- $$\Gamma(p \rightarrow \pi^0 e^+) = \frac{m_p}{32\pi} \left(1 - \frac{m_\pi^2}{m_p^2}\right)^2 |V_{ud}|^2 |(U_\ell)_{11}|^2 (\langle \pi^0 | (ud)_{R} u_L | p \rangle_e)^2 \times \left[\frac{(A_1^H)^2 (A_1^R)^2}{|\langle \Phi \rangle|^4} + \frac{(A_2^R)^2}{M_{H_C}^4} \left\{ y_d(M_{H_C}) y_e(M_{H_C}) \right\}^2 \right],$$
- $$\Gamma(p \rightarrow \pi^0 \mu^+) = \frac{m_p}{32\pi} \left(1 - \frac{m_\pi^2}{m_p^2}\right)^2 |V_{ud}|^2 |(U_\ell)_{12}|^2 (\langle \pi^0 | (ud)_{R} u_L | p \rangle_\mu)^2 \times \left[\frac{(A_1^H)^2 (A_1^R)^2}{|\langle \Phi \rangle|^4} + \frac{(A_2^R)^2}{M_{H_C}^4} \left\{ y_d(M_{H_C}) y_\mu(M_{H_C}) \right\}^2 \right],$$
- $$\Gamma(p \rightarrow K^0 e^+) = \frac{m_p}{32\pi} \left(1 - \frac{m_K^2}{m_p^2}\right)^2 |V_{us}|^2 |(U_\ell)_{11}|^2 (\langle K^0 | (us)_{R} u_L | p \rangle_e)^2 \times \left[\frac{(A_1^H)^2 (A_1^R)^2}{|\langle \Phi \rangle|^4} + \frac{(A_2^R)^2}{M_{H_C}^4} \left\{ y_s(M_{H_C}) y_e(M_{H_C}) \right\}^2 \right],$$
- $$\Gamma(p \rightarrow K^0 \mu^+) = \frac{m_p}{32\pi} \left(1 - \frac{m_K^2}{m_p^2}\right)^2 |V_{us}|^2 |(U_\ell)_{12}|^2 (\langle K^0 | (us)_{R} u_L | p \rangle_\mu)^2 \times \left[\frac{(A_1^H)^2 (A_1^R)^2}{|\langle \Phi \rangle|^4} + \frac{(A_2^R)^2}{M_{H_C}^4} \left\{ y_s(M_{H_C}) y_\mu(M_{H_C}) \right\}^2 \right],$$
- The color-triplet Higgs exchange process is induced by the **Yukawa interactions**, so its contribution tends to be more significant for the decay modes that contain the **second generations**.