ON $d = 6$ PROTON DECAY OPERATORS*

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HAPPY BIRTHDAY GORAN!

PERFECT!

Goran
Nassfeld, 2009

OUTLINE

•MOTIVATION

•EXPERIMENTAL STATUS

• $d = 6$ **PROTON DECAY OPERATORS**
VECTOR (GAUGE) AND SCALAR CONTRIBUTION

•CONCLUSIONS

MOTIVATION

PROTON DECAY ≡ NEW PHYSICS

$p \rightarrow (K^+, \pi^+, \rho^+)\bar{\nu}_i$	$p \rightarrow (K^0, \pi^0, \rho^+, \eta, \omega)e_j^+$	PROTON*
$n \rightarrow (K^0, \pi^0, \rho^0, \omega, \eta)\bar{\nu}_i$	$n \rightarrow (K^-, \pi^-, \rho^-)e_j^+$	NEUTRON*
$i = 1, 2, 3$	$j = 1, 2$	

HOW ROBUST ARE PROTON DECAY SIGNATURES?

*TWO BODY DECAYS…

EXPERIMENTAL RESULTS

PROCESS	τ_p (10^{33} years)	
$p \to \pi^0 e^+$	8.2	*
$p \to \pi^0 \mu^+$	6.6	
$p \to K^+ \bar{\nu}$	2.3	@
$p \to K^0 e^+$	1.0	
$p \to K^0 \mu^+$	1.3	
$p \to \eta e^+$	0.313	
$p \to \eta \mu^+$	0.126	
$p \to \pi^+ \bar{\nu}$	0.025	
$\vdots$	$\vdots$	
$p \to \pi^0 e^+$	10.1	¶

*[Super-Kamiokande Collaboration], arXiv:0903.0676.

@[Super-Kamiokande Collaboration], arXiv:hep-ex/0502026.

¶ www-sk.icrr.u-tokyo.ac.jp/whatsnew/new-20091125-e.html

$d = 6$ PROTON DECAY OPERATORS

VECTOR CONTRIBUTIONS

SCALAR CONTRIBUTIONS

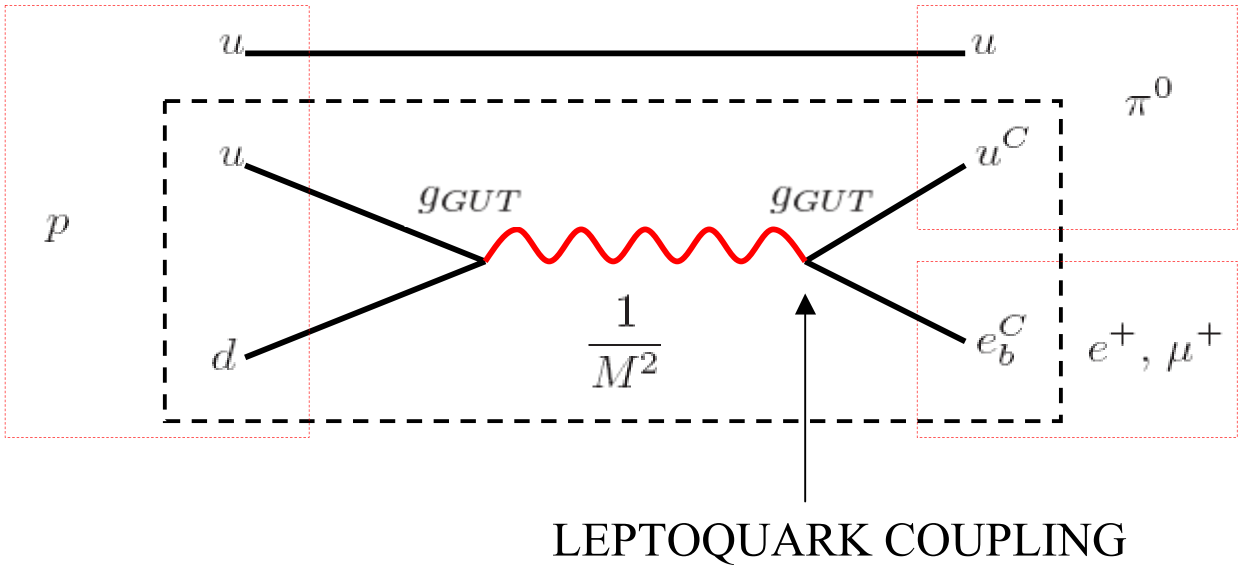
VECTOR CONTRIBUTIONS	SCALAR CONTRIBUTIONS	
$p \rightarrow (K^+, \pi^+, \rho^+)\bar{\nu}_i$	$p \rightarrow (K^0, \pi^0, \rho^+, \eta, \omega)e_j^+$	PROTON*
$n \rightarrow (K^0, \pi^0, \rho^0, \omega, \eta)\bar{\nu}_i$	$n \rightarrow (K^-, \pi^-, \rho^-)e_j^+$	NEUTRON*
$i = 1, 2, 3$	$j = 1, 2$	

*TWO BODY DECAYS…

$d = 6$ PROTON DECAY OPERATORS

VECTOR CONTRIBUTIONS

$$\frac{g_{GUT}^2}{M^2}\ \epsilon_{ijk}\ \epsilon_{\alpha\beta}\ \overline{u_{ia}^C}\ \gamma^\mu\ Q_{j\alpha a}\ \overline{e_b^C}\ \gamma_\mu\ Q_{k\beta b}$$



WHERE DO g_{GUT} AND M COME FROM?

STANDARD MODEL FERMIONS

$SU(3) \times SU(2) \times U(1)$

$$L_a \equiv (\mathbf{1}, \mathbf{2}, -1/2)_a = (\nu_a \quad e_a)^T$$

$$e_a^C \equiv (\mathbf{1}, \mathbf{1}, 1)_a$$

LEPTONS

$$Q_a \equiv (\mathbf{3}, \mathbf{2}, 1/6)_a = (u_a \quad d_a)^T$$

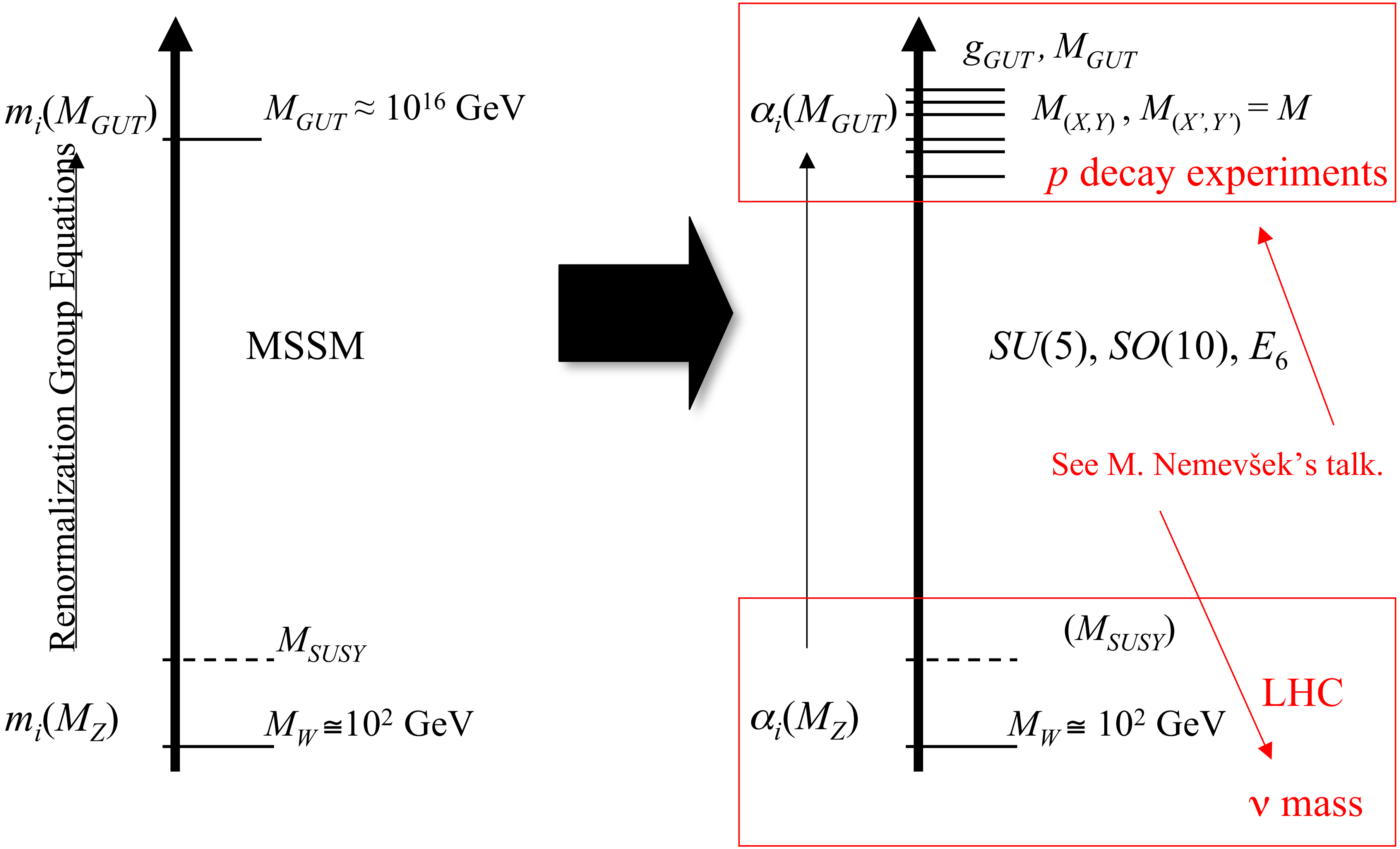
$$u_a^C \equiv (\overline{\mathbf{3}}, \mathbf{1}, -2/3)_a$$

$$d_a^C \equiv (\overline{\mathbf{3}}, \mathbf{1}, 1/3)_a$$

QUARKS

$$a = 1, 2, 3$$

GRAND UNIFIED THEORIES



$SU(5)$ MATTER ASSIGNMENT*
MATTER UNIFICATION

$$\overline{\mathbf{5}}_a = (\mathbf{1}, \mathbf{2}, -1/2)_a + (\overline{\mathbf{3}}, \mathbf{1}, 1/3)_a$$

$$(\overline{\mathbf{5}}_i)_a = \begin{pmatrix} d_1^C \\ d_2^C \\ d_3^C \\ e \\ \nu \end{pmatrix}_a$$

$$\mathbf{10}_a = (\mathbf{1}, \mathbf{1}, 1)_a + (\mathbf{3}, \mathbf{2}, 1/6)_a + (\overline{\mathbf{3}}, \mathbf{1}, -2/3)_a$$

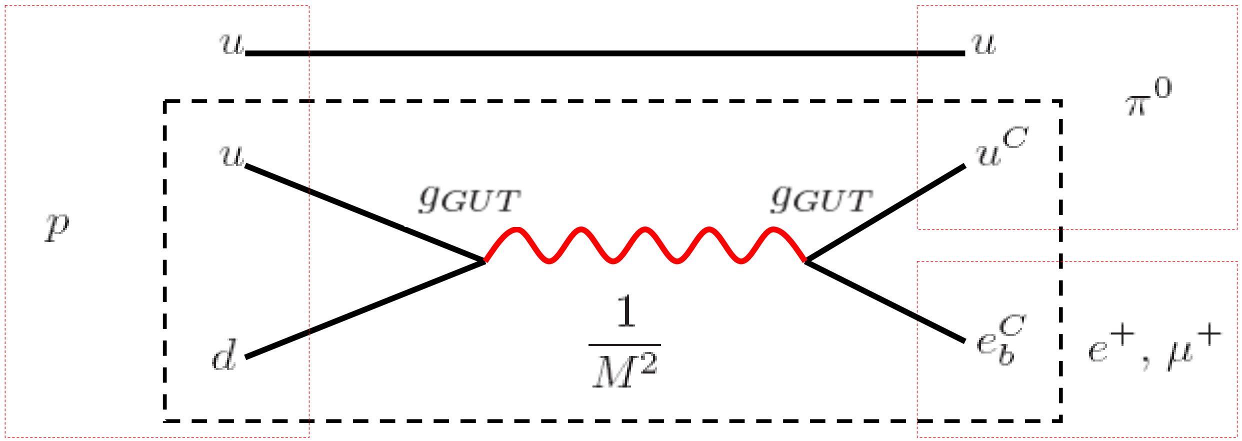
$$(\mathbf{10}^{ij})_a = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^C & -u_2^C & -u^1 & -d^1 \\ -u_3^C & 0 & u_1^C & -u^2 & -d^2 \\ u_2^C & -u_1^C & 0 & -u^3 & -d^3 \\ u^1 & u^2 & u^3 & 0 & -e^C \\ d^1 & d^2 & d^3 & e^C & 0 \end{pmatrix}_a$$

*H. Georgi and S.L. Glashow (1974).

$d = 6$ PROTON DECAY OPERATORS

VECTOR CONTRIBUTIONS

$$\frac{g_{GUT}^2}{M^2}\ \epsilon_{ijk}\ \epsilon_{\alpha\beta}\ \overline{u_{ia}^C}\ \gamma^\mu\ Q_{j\alpha a}\ \overline{e_b^C}\ \gamma_\mu\ Q_{k\beta b}$$



MINIMAL SUPERSYMMETRIC *SO*(10) MODEL*

REPRESENTATIONS: $16_{F\,i}, (i = 1, 2, 3)$ 210_H 126_H $\overline{126}_H$ 10_H

PARAMETERS§: $m,\ \alpha,\ \overline{\alpha},\ |\lambda|,\ |\eta|,\ x = \mathrm{Re}(x) + i\mathrm{Im}(x),\ g_{GUT},\ M_{SUSY}$

(9+3+12) Y_{10} $Y_{\overline{126}}$

See C. S. Aulakh's talk.

OR MINIMAL *SU*(5) MODELS¶

See S. Fajfer's and M. Nemevšek's talks.

*T. E. Clark, T. K. Kuo and N. Nakagawa, Phys. Lett. B 115 (1982) 26; K. S. Babu and R. N. Mohapatra, Phys. Rev. Lett. 70 (1993) 2845; C. S. Aulakh, B. Bajc, A. Melfo, G. Senjanović and F. Vissani, Phys. Lett. B 588 (2004) 196; …

§C. S. Aulakh, B. Bajc, A. Melfo, G. Senjanović and F. Vissani, Phys. Lett. B 588 (2004) 196.

¶I.D. and P. Fileviez Perez, 2006; B. Bajc and G. Senjanović, 2008.

$d = 6$ PROTON DECAY OPERATORS*

$(10\,10)^\dagger\,(10\,10)$ $\quad O^{B-L}_{SU(5)} = k_1^2\,\epsilon_{ijk}\,\epsilon_{\alpha\beta}\,\overline{u^C_{ia}}\,\gamma^\mu\,Q_{j\alpha a}\,\overline{e^C_b}\,\gamma_\mu\,Q_{k\beta b}$

$(10\,\overline{5})^\dagger\,(10\,\overline{5})$ $\quad O^{B-L}_{SU(5)} = k_1^2\,\epsilon_{ijk}\,\epsilon_{\alpha\beta}\,\overline{u^C_{ia}}\,\gamma^\mu\,Q_{j\alpha a}\,\overline{d^C_{kb}}\,\gamma_\mu\,L_{\beta b}$

SU(5) THEORY

FLIPPED *SU*(5) THEORY

$O^{B-L}_{SU(5)'} = k_2^2\,\epsilon_{ijk}\,\epsilon_{\alpha\beta}\,\overline{d^C_{ia}}\,\gamma^\mu\,Q_{j\beta a}\,\overline{\nu^C_b}\,\gamma_\mu\,Q_{k\alpha b}$ $\quad (10\,10)^\dagger\,(10\,10)$

$O^{B-L}_{SU(5)'} = k_2^2\,\epsilon_{ijk}\,\epsilon_{\alpha\beta}\,\overline{d^C_{ia}}\,\gamma^\mu\,Q_{j\beta a}\,\overline{u^C_{kb}}\,\gamma_\mu\,L_{\alpha b}$ $\quad (10\,\overline{5})^\dagger\,(10\,\overline{5})$

$$O^{B-L}_{SU(5)} \to O^{B-L}_{SU(5)'}:\ u \to d,\ u^C \to d^C,\ d \to u,\ d^C \to u^C,\ \nu \to e,\ e^C \to \underline{\nu^C}$$

*S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566; Phys. Rev. D 22 (1980) 1694; Phys. Rev. D 26 (1982) 287; F. Wilczek and A. Zee, Phys. Rev. Lett. 43 (1979) 1571; N. Sakai and T. Yanagida, Nucl. Phys. B 197 (1982) 533.

$d = 6$ PROTON DECAY OPERATORS*

$$k_1 = \frac{g_5}{\sqrt{2} M_V} \qquad V = (X, Y) = (\mathbf{3}, \mathbf{2}, -5/6)$$

SU(5) THEORY

FLIPPED *SU*(5) THEORY

$$k_2 = \frac{g_5'}{\sqrt{2} M_{V'}} \qquad V' = (X', Y') = (\mathbf{3}, \mathbf{2}, 1/6)$$

FLIPPED *SU*(5) + *SU*(5) = SO(10) THEORY

ALL IN ALL, THERE ARE TWENTY FOUR (24) PROTON DECAY MEDIATING GAUGE BOSONS!

*S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566; Phys. Rev. D 22 (1980) 1694; Phys. Rev. D 26 (1982) 287; F. Wilczek and A. Zee, Phys. Rev. Lett. 43 (1979) 1571; N. Sakai and T. Yanagida, Nucl. Phys. B 197 (1982) 533.

$d = 6$ OPERATORS IN THE MASS BASIS[†]

$$O(e_\alpha^C, d_\beta) = c(e_\alpha^C, d_\beta)\ \epsilon_{ijk}\ \overline{u_i^C}\ \gamma^\mu\ u_j\ \overline{e_\alpha^C}\ \gamma_\mu\ d_{k\beta}$$
$$O(e_\alpha, d_\beta^C) = c(e_\alpha, d_\beta^C)\ \epsilon_{ijk}\ \overline{u_i^C}\ \gamma^\mu\ u_j\ \overline{d_{k\beta}^C}\ \gamma_\mu\ e_\alpha$$
$$O(\nu_l, d_\alpha, d_\beta^C) = c(\nu_l, d_\alpha, d_\beta^C)\ \epsilon_{ijk}\ \overline{u_i^C}\ \gamma^\mu\ d_{j\alpha}\ \overline{d_{k\beta}^C}\ \gamma_\mu\ \nu_l$$

$$c(e_\alpha^C, d_\beta) = k_1^2 \left[V_1^{11} V_2^{\alpha\beta} + (V_1 V_{UD})^{1\beta} (V_2 V_{UD}^\dagger)^{\alpha 1} \right]$$
$$c(e_\alpha, d_\beta^C) = k_1^2 V_1^{11} V_3^{\beta\alpha}$$
$$c(\nu_l, d_\alpha, d_\beta^C) = k_1^2 (V_1 V_{UD})^{1\alpha} (V_3 V_{EN})^{\beta l},\ \ \alpha = 1 \text{ or } \beta = 1$$

SU(5)

See R. Mohapatra's and F. Nesti's talks.

$$U_C^T\ Y_U\ U = Y_U^{\text{diag}} \qquad D_C^T\ Y_D\ D = Y_D^{\text{diag}} \qquad E_C^T\ Y_E\ E = Y_E^{\text{diag}}$$

$$V_1 = U_C^\dagger U \qquad V_2 = E_C^\dagger D \qquad V_3 = D_C^\dagger E \qquad V_4 = D_C^\dagger D \qquad V_{UD} = U^\dagger D \qquad V_{EN} = E^\dagger N$$

[†]P. Fileviez Pérez, Phys. Lett. B 595 (2004) 476.

PROTON DECAY

$$\Gamma(p \to K^0 e_\beta^+) \;=\; C(p, K^0)\,\left[1 + \frac{m_p}{m_B}(D - F)\right]^2 \left\{ A_r^2\, \left|c(e_\beta, s^C)\right|^2 + A_l^2\, \left|c(e_\beta^C, s)\right|^2 \right\}$$

GUT PHYSICS

PROTON DECAY

$$\Gamma(p \to \pi^0 e^+) = \frac{C(p,\pi^0)}{2}(1+D+F)^2\left\{A_r^2\,\left|c(e,d^C)\right|^2 + A_l^2\left|c(e^C,d)\right|^2\right\}$$

$$(A_r \approx A_l) \equiv A$$

$m_B \approx m_\Sigma \approx m_\Lambda$ $\quad m_B = 1150\,\mathrm{MeV}$ $\quad D \simeq 0.81$ $\quad F \simeq 0.44$

$$C(A,B) = \frac{(m_A^2 - m_B^2)^2}{8\pi m_p^3 f_\pi^2} A_L^2\,|\alpha|^2 \qquad A_L = 1.25$$

$|\alpha| = (0.003\text{–}0.015)\,\mathrm{GeV}^3$

LATTICE QCD

PROTON DECAY

$$\Gamma(p \to \pi^0 e^+) = \frac{C(p,\pi^0)}{2} (1+D+F)^2 \left\{ A_r^2 \left| c(e, d^C) \right|^2 + A_l^2 \left| c(e^C, d) \right|^2 \right\}$$

$$\left| c(e, d^C) \right|^2_{max} = 4 \qquad \left| c(e^C, d) \right|^2_{max} = 1 \qquad SU(5)$$

FLIPPED $SU(5)$ $\quad \left| c(e, d^C) \right|^2_{max} = 1 \qquad \left| c(e^C, d) \right|^2_{max} = 0$

$$\Gamma_{SU(5)}(p \to \pi^0 e^+)/\Gamma_{SU(5)'}(p \to \pi^0 e^+) = 5$$ *

*S. M. Barr, Phys. Lett. B 112 (1982) 218.

UNIFICATION WITHOUT PROTON DECAY†

FLIPPED
SU(5)

$$\begin{aligned} c(e^C_\alpha, d_\beta) &= 0 \\ c(e_\alpha, d^C_\beta) &= k_2^2 (V_4 V^\dagger_{UD})^{\beta 1} (V_1 V_{UD} V_4^\dagger V_3)^{1\alpha} \\ c(\nu_l, d_\alpha, d^C_\beta) &= k_2^2 V_4^{\beta\alpha} (V_1 V_{UD} V_4^\dagger V_3 V_{EN})^{1l}, \;\; \alpha = 1 \text{ or } \beta = 1 \end{aligned}$$

$$V_4^{\alpha\beta} = (D_C^\dagger D)^{\alpha\beta} = 0 \qquad \alpha = 1 \text{ or } \beta = 1$$

$$(V_1 V_{UD} V_4^\dagger V_3)^{1\alpha} = (U_C^\dagger E)^{1\alpha} = 0$$

⬇

NO GAUGE *d* = 6 PROTON DECAY!

$$V_1 = U_C^\dagger U \qquad V_2 = E_C^\dagger D \qquad V_3 = D_C^\dagger E \qquad V_4 = D_C^\dagger D \qquad V_{UD} = U^\dagger D \qquad V_{EN} = E^\dagger N$$

† I. D. and P. Fileviez Pérez, Phys. Lett. B 606:367-370, 2005.

WHAT ABOUT PROTON DECAY IN *SU*(5)?*

$$
\begin{aligned}
c(e^C_\alpha, d_\beta) &= k_1^2\left[V_1^{11}V_2^{\alpha\beta} + (V_1V_{UD})^{1\beta}(V_2V_{UD}^\dagger)^{\alpha 1}\right] \\
c(e_\alpha, d^C_\beta) &= k_1^2 V_1^{11} V_3^{\beta\alpha} \\
c(\nu_l, d_\alpha, d^C_\beta) &= k_1^2 (V_1V_{UD})^{1\alpha}(V_3V_{EN})^{\beta l}, \ \alpha = 1 \text{ or } \beta = 1
\end{aligned}
$$

SU(5)

$$V_1^{11} = 0 \qquad (V_1V_{UD})^{1\alpha} = 0$$

$$V_1 = \begin{pmatrix} 0 & \star & \star \\ \star & \star & \star \\ \star & \star & \star \end{pmatrix} \qquad V_1V_{UD} = \begin{pmatrix} 0 & 0 & e^{i\phi} \\ \star & \star & 0 \\ \star & \star & 0 \end{pmatrix}$$

$$(V_1)^\dagger V_1 V_{UD} \sim V_{CKM} = \begin{pmatrix} \star & \star & 0 \\ \star & \star & \star \\ \star & \star & \star \end{pmatrix} \qquad \Rightarrow \underline{V_{ub} = 0}$$

$$V_1 = U_C^\dagger U \qquad V_2 = E_C^\dagger D \qquad V_3 = D_C^\dagger E \qquad V_4 = D_C^\dagger D \qquad V_{UD} = U^\dagger D \qquad V_{EN} = E^\dagger N$$

*S. Nandi, A. Stern and E. C. G. Sudarshan (1982).

WHAT ARE THE EXPERIMENTAL LIMITS?[†]

$$c(e^C_\alpha, d_\beta) = k_1^2 \left[V_1^{11} V_2^{\alpha\beta} + (V_1 V_{UD})^{1\beta} (V_2 V_{UD}^\dagger)^{\alpha 1} \right]$$
$$c(e_\alpha, d^C_\beta) = k_1^2 V_1^{11} V_3^{\beta\alpha}$$
$$c(\nu_l, d_\alpha, d^C_\beta) = k_1^2 (V_1 V_{UD})^{1\alpha} (V_3 V_{EN})^{\beta l}, \quad \alpha = 1 \text{ or } \beta = 1$$

SU(5) or *SO*(10)

~~$V_1^{11} = 0$~~ $\quad$ $(V_1 V_{UD})^{1\alpha} = 0$ $\quad$ $V_2^{\beta\alpha} = V_2^{\beta\alpha} = 0 \qquad (\alpha + \beta \leq 3)$

PROTON DECAYS EXCLUSIVELY INTO *s*-MESON AND ANTIMUON!

$$|V_1^{11}| = |V_{ub}| \quad \Rightarrow \quad \left\{ \left|c(e_2, s^C)\right|^2 + \left|c(e_2^C, s)\right|^2 \right\} \rightarrow 2|V_{ub}|^2 \qquad |V_{ub}| \simeq 0.004$$

[†] I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

WHAT ARE THE RELEVANT LIMITS?†

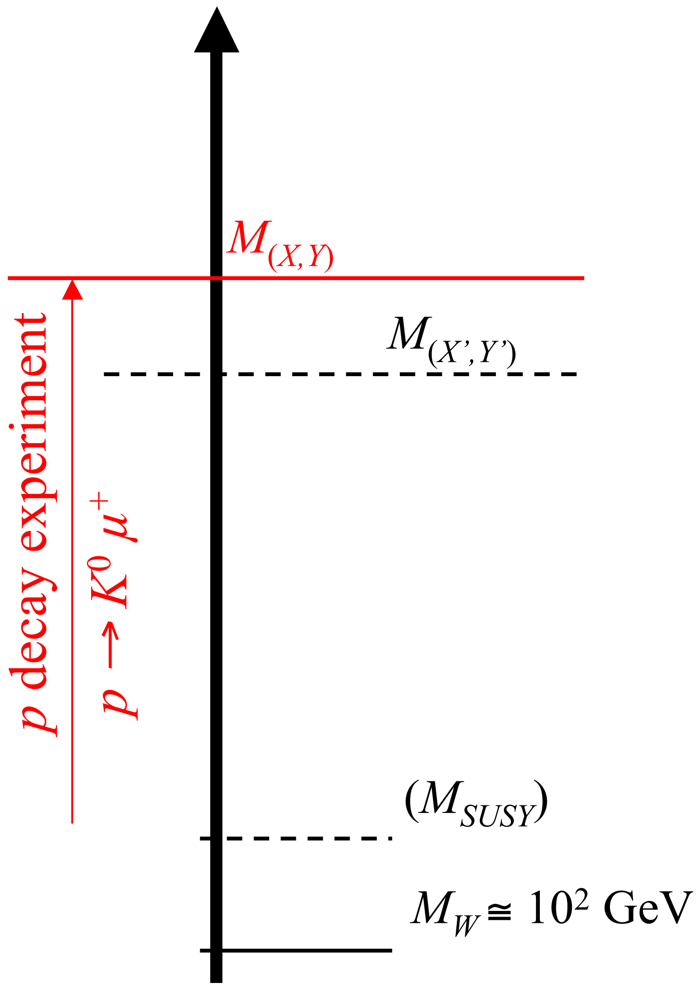
$$\tau_{p \to K^0 \mu^+} \leq 6 \times 10^{38} \; (M_{(X,Y)}/10^{16}\,\mathrm{GeV})^4 \; \alpha_{GUT}^{-2} \; (0.01\,\mathrm{GeV}^3/|\alpha|)^2 \; A^{-2}\,\mathrm{years}$$

$$M_{(X,Y)} > 3.8 \times 10^{14}\,\mathrm{GeV} \; \alpha_{GUT}^{1/2} \; A^{1/2} \; \left(\frac{|\alpha|}{0.01\,\mathrm{GeV}^3}\right)^{1/2} \; \left(\frac{\tau_{p \to K^0 \mu^+}}{1.3 \times 10^{33}\,\mathrm{years}}\right)^{1/4}$$

$$A = \sqrt{A_r^2 + A_l^2}$$

† I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

WHAT ARE THE RELEVANT LIMITS?*



*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

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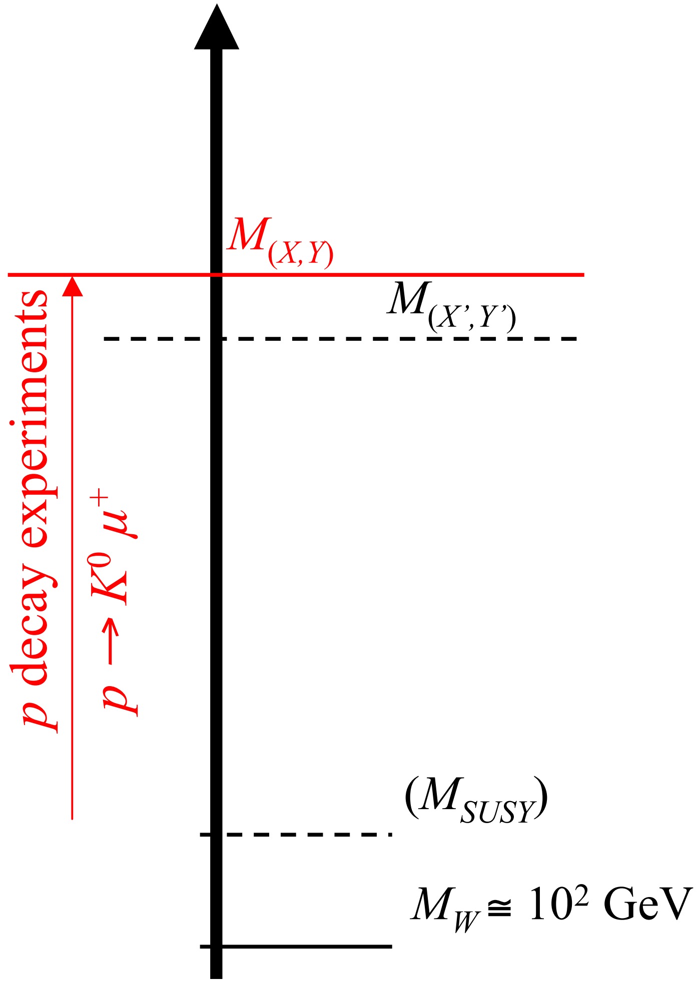

*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

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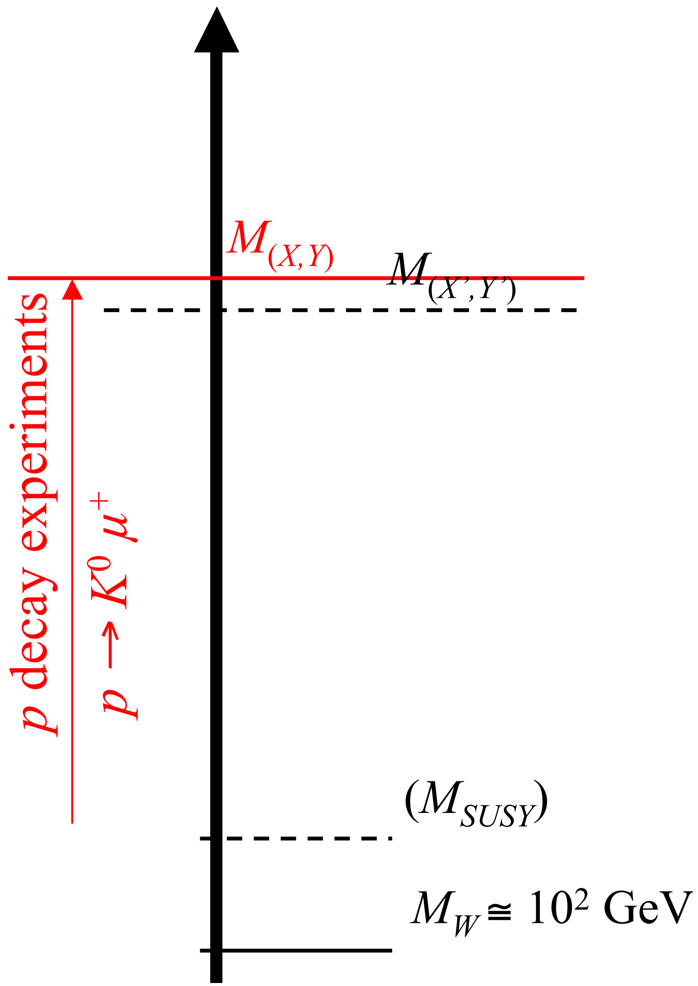

*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

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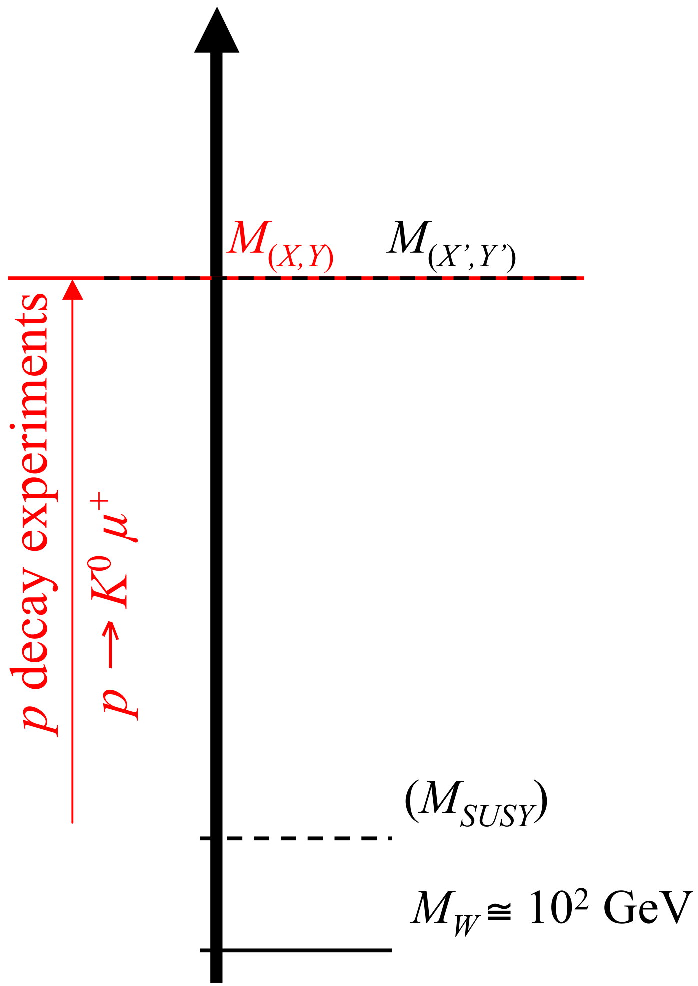
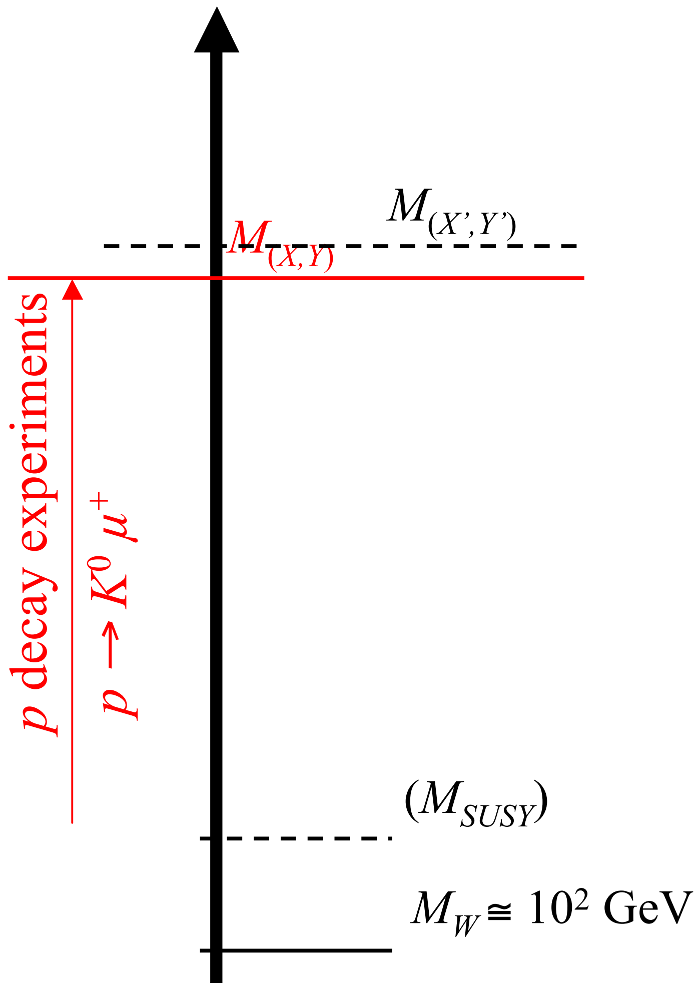


*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

WHAT ARE THE RELEVANT LIMITS?*



*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

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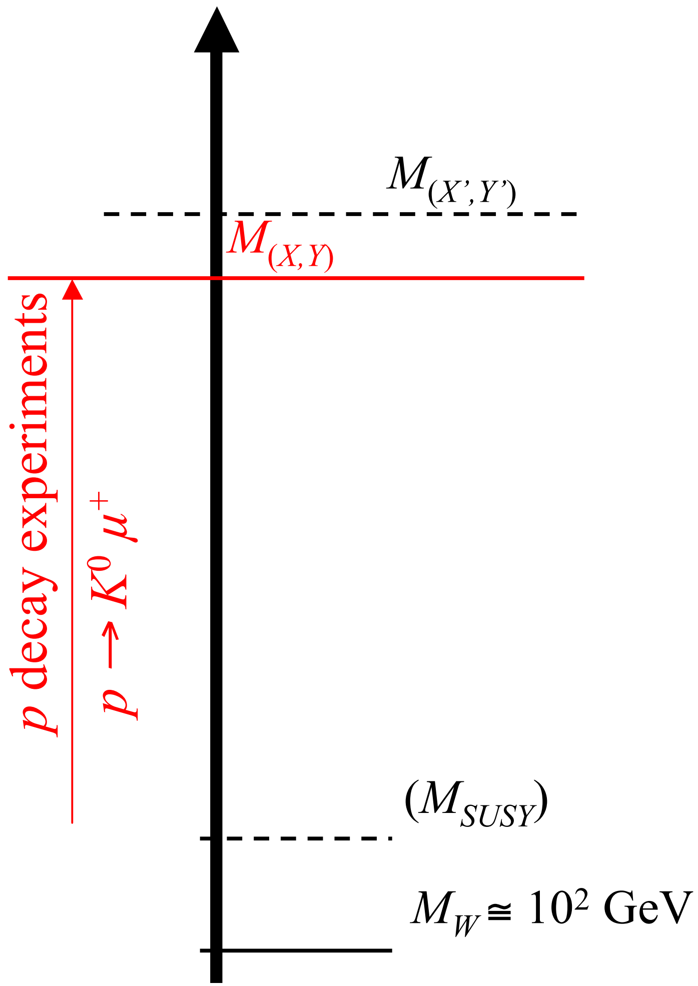
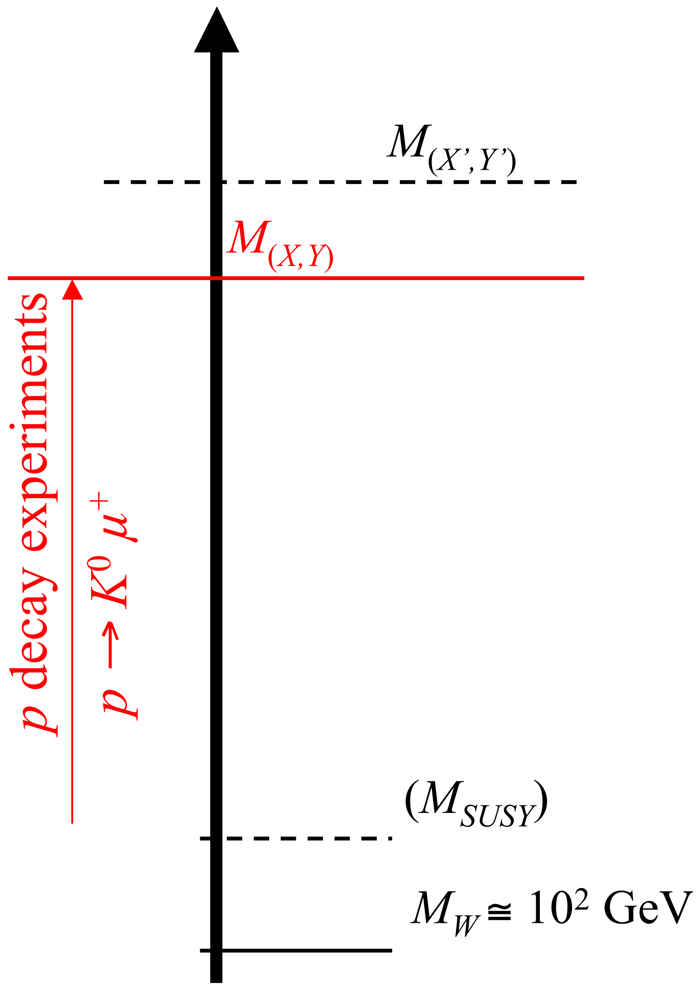


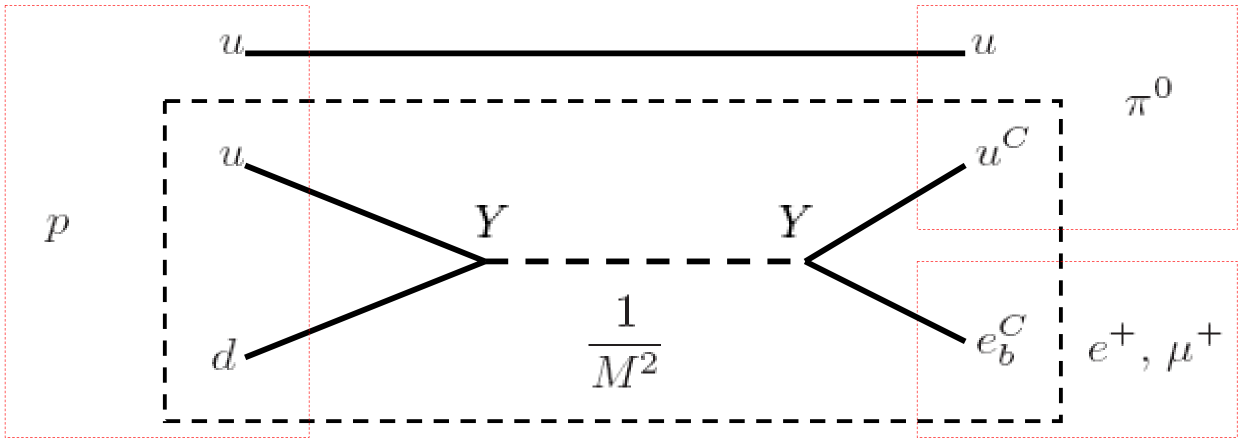
*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

WHAT ARE THE RELEVANT LIMITS?*



*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

d=6 PROTON DECAY OPERATORS
SCALAR CONTRIBUTIONS



Y = Yukawa coupling(s)

FERMION MASSES

SU(5)

$$\mathbf{10} \times \overline{\mathbf{5}} = \mathbf{5} \oplus \mathbf{45}$$

M_E, M_D

$$\mathbf{10} \times \mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \overline{\mathbf{50}}$$

M_U

$$\mathbf{5} = (D, T)$$

$$D = (\mathbf{1}, \mathbf{2}, 1/2)$$

$$T = (\mathbf{3}, \mathbf{1}, -1/3)$$

$$\mathbf{45} = (\Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6, \Delta_7)$$

$$\Delta_1 = (\mathbf{8}, \mathbf{2}, 1/2)$$

$$\Delta_2 = (\overline{\mathbf{6}}, \mathbf{1}, -1/3)$$

$$\Delta_3 = (\mathbf{3}, \mathbf{3}, -1/3)$$

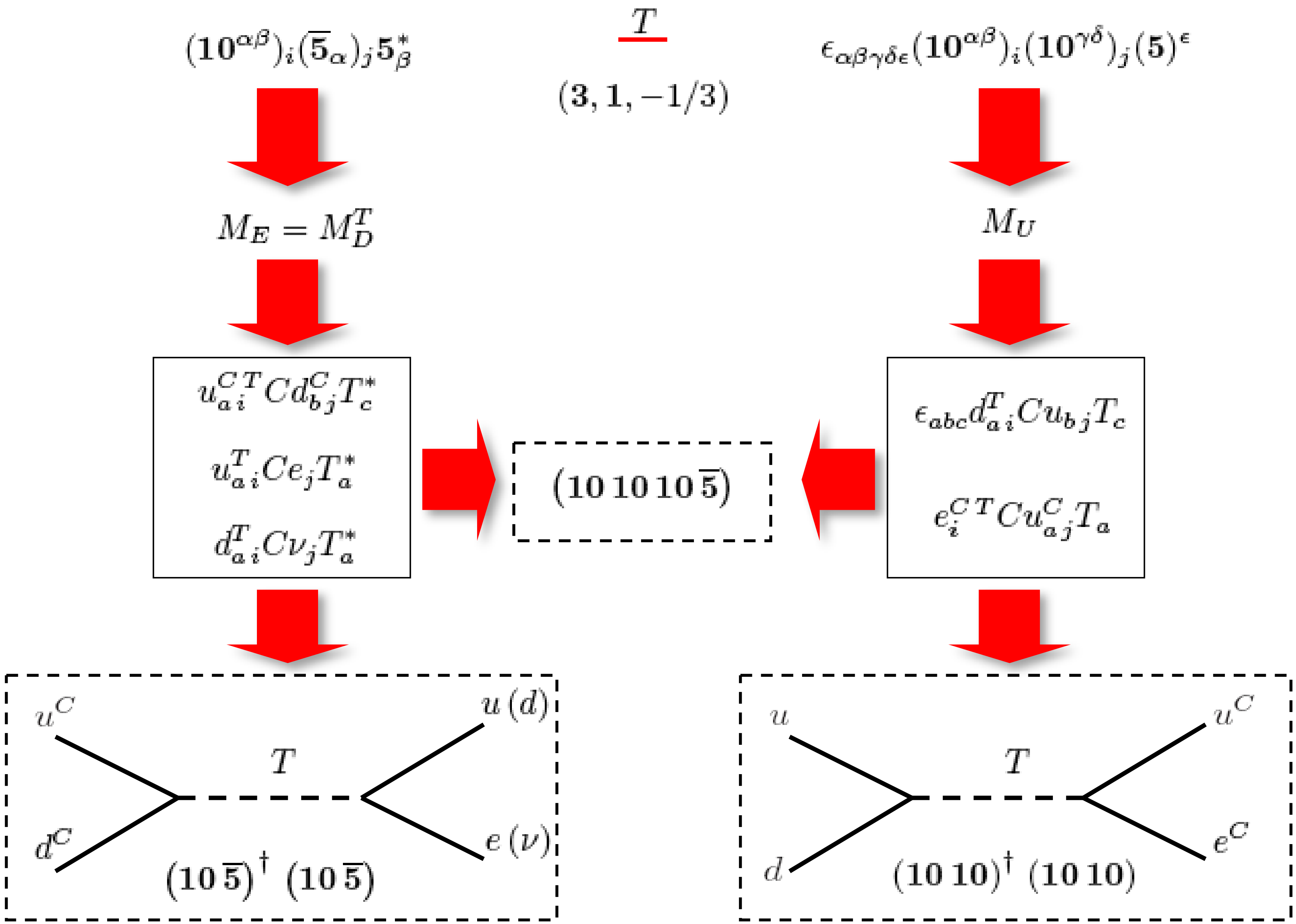
$$\Delta_4 = (\overline{\mathbf{3}}, \mathbf{2}, -7/6)$$

$$\Delta_5 = (\mathbf{3}, \mathbf{1}, -1/3)$$

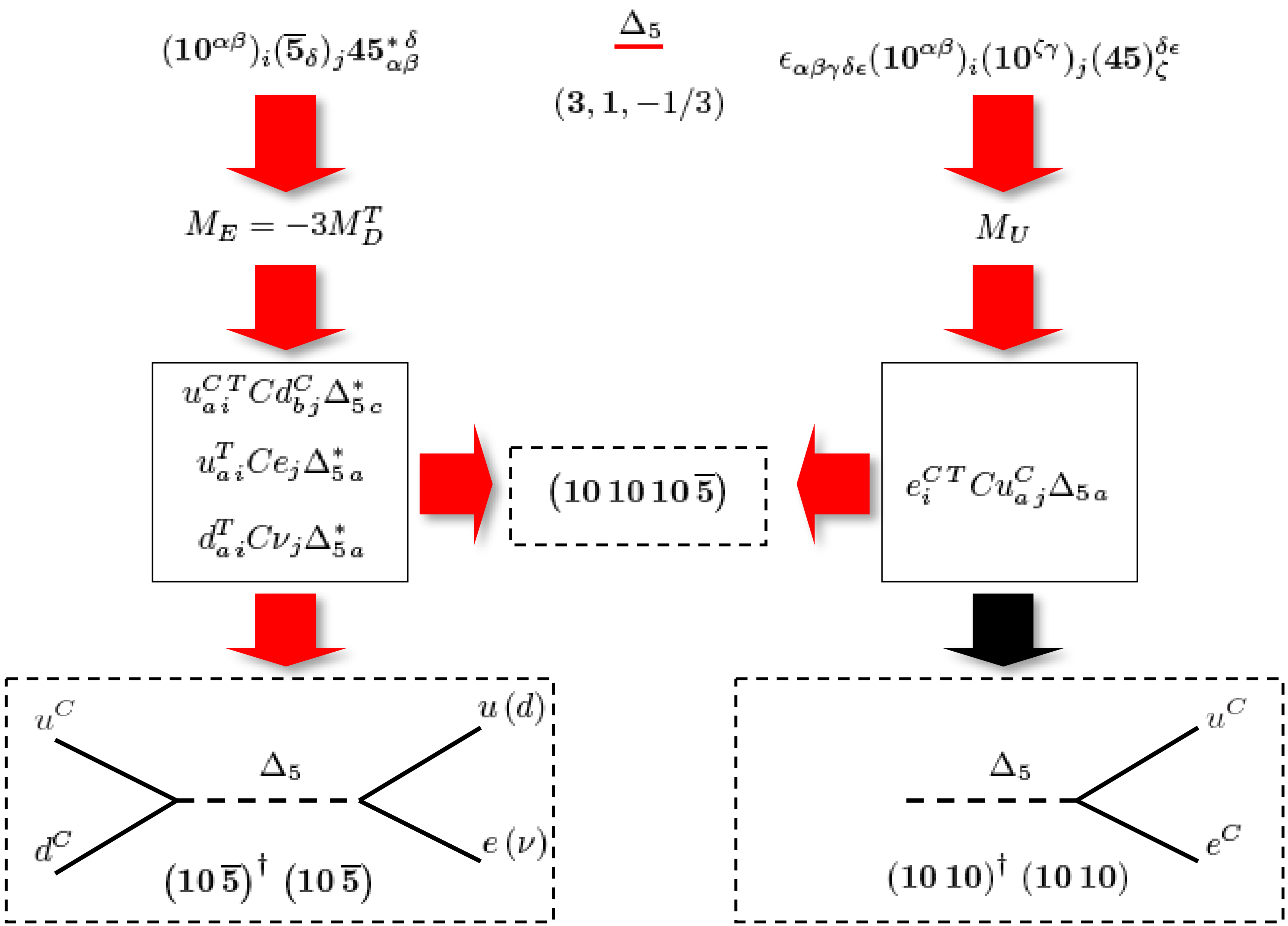
$$\Delta_6 = (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$$

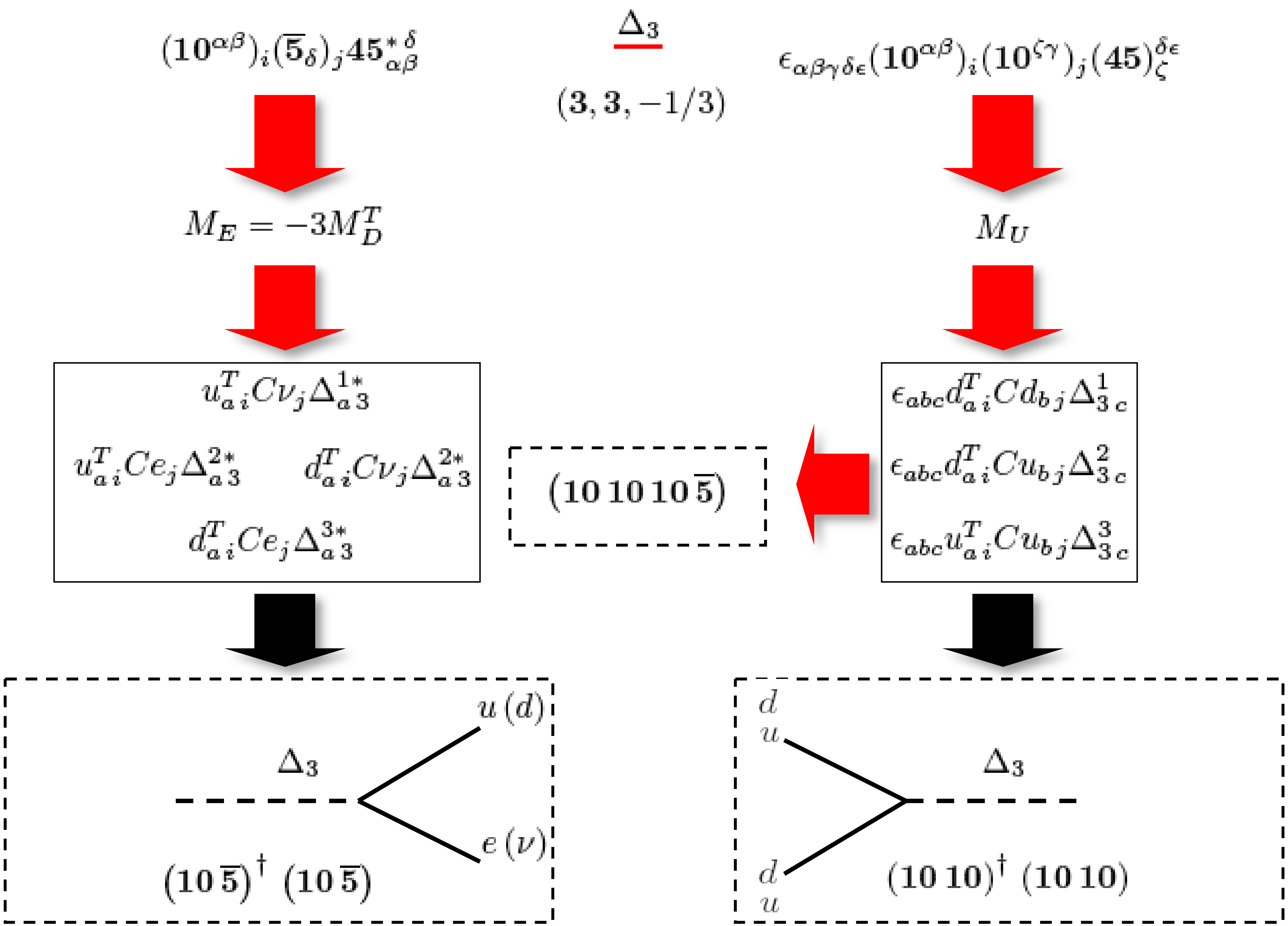
$$\Delta_7 = (\mathbf{1}, \mathbf{2}, 1/2)$$

There are 5 *SU*(3) triplet scalars s that can directly contribute to *p* decay.



T
(3, 1, −1/3)
$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\alpha)_j\mathbf{5}^*_\beta$
$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\gamma\delta})_j(\mathbf{5})^\epsilon$
$M_E = M_D^T$
M_U
$u^{C\,T}_{a\,i}Cd^C_{b\,j}T^*_c$
$u^T_{a\,i}Ce_jT^*_a$
$d^T_{a\,i}C\nu_jT^*_a$
$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$
$\epsilon_{abc}d^T_{a\,i}Cu_{b\,j}T_c$
$e^{C\,T}_iCu^C_{a\,j}T_a$
u^C
d^C
$u\,(d)$
$e\,(\nu)$
T
$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\;(\mathbf{10}\,\overline{\mathbf{5}})$
u
d
u^C
e^C
T
$(\mathbf{10}\,\mathbf{10})^\dagger\;(\mathbf{10}\,\mathbf{10})$


$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\delta)_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$
Δ_5
$(\mathbf{3},\mathbf{1},-\mathbf{1/3})$
$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_\zeta$
$M_E = -3M_D^T$
M_U
$u^{C\,T}_{a\,i}Cd^C_{b\,j}\Delta^*_{5\,c}$
$u^T_{a\,i}Ce_j\Delta^*_{5\,a}$
$d^T_{a\,i}C\nu_j\Delta^*_{5\,a}$
$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$
$e^{C\,T}_iCu^C_{a\,j}\Delta_{5\,a}$
u^C
d^C
Δ_5
$u\,(d)$
$e\,(\nu)$
$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\,(\mathbf{10}\,\overline{\mathbf{5}})$
Δ_5
u^C
e^C
$(\mathbf{10}\,\mathbf{10})^\dagger\,(\mathbf{10}\,\mathbf{10})$



Δ_3
$(\mathbf{3},\mathbf{3},-1/3)$
$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\delta)_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$
$M_E=-3M_D^T$
$u^T_{a\,i}C\nu_j\Delta^{1*}_{a\,3}$
$u^T_{a\,i}Ce_j\Delta^{2*}_{a\,3}$
$d^T_{a\,i}C\nu_j\Delta^{2*}_{a\,3}$
$d^T_{a\,i}Ce_j\Delta^{3*}_{a\,3}$
$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_\zeta$
M_U
$\epsilon_{abc}d^T_{a\,i}Cd_{b\,j}\Delta^1_{3\,c}$
$\epsilon_{abc}d^T_{a\,i}Cu_{b\,j}\Delta^2_{3\,c}$
$\epsilon_{abc}u^T_{a\,i}Cu_{b\,j}\Delta^3_{3\,c}$
$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$
Δ_3
$u\,(d)$
$e\,(\nu)$
$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\;(\mathbf{10}\,\overline{\mathbf{5}})$
d
u
Δ_3
d
u
$(\mathbf{10}\,\mathbf{10})^\dagger\;(\mathbf{10}\,\mathbf{10})$

$\underline{\mathbf{45}}$ *

$$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_{\zeta}$$

$$\cancel{(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_{\delta})_j\mathbf{45}^{*\,\delta}_{\alpha\beta}}$$

⬇

NO SCALAR $d = 6$ PROTON DECAY![†]

BUT $M_E = M_D^T$ RELATION REMAINS![§]

[*] I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, Phys. Lett. B 682:67-73, 2009, arXiv:0906.5585.
[§] E. Tsedenbaljir, arXiv:0909.5597.

$\mathbf{45}$ *

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_{\zeta}$

$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_{\delta})_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$

$\Delta_3 = (\mathbf{3}, \mathbf{3}, -1/3)$ COULD BE ARBITRARILY LIGHT![†]

*I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, Phys. Lett. B 682:67-73, 2009, arXiv:0906.5585.

FLIPPED *SU*(5)*

$$\mathbf{16} = \mathbf{10}^{+1} + \bar{\mathbf{5}}^{-3} + \mathbf{1}^{+5}$$

$$\mathbf{10} = \bar{\mathbf{5}}^{-2} + \bar{\mathbf{5}}^{+2}$$

$$u \to d,\ u^C \to d^C,\ d \to u,\ d^C \to u^C,\ \nu \to e,\ e^C \to \nu^C$$

~~*p* decay~~

$$(\mathbf{10}^{+1})_i(\mathbf{10}^{+1})_j\ \mathbf{5}^{-2}$$

$$(\mathbf{10}^{+1})_i(\mathbf{10}^{+1})_j\ \mathbf{45}^{-2}$$

→ M_D

$$(\bar{\mathbf{5}}^{-3})_i(\mathbf{1}^{+5})_j\ \mathbf{5}^{-2}$$

→ M_E

p decay

$$(\mathbf{10}^{+1})_i(\bar{\mathbf{5}}^{-3})_j\ \bar{\mathbf{5}}^{+2}$$

$$(\mathbf{10}^{+1})_i(\bar{\mathbf{5}}^{-3})_j\ \overline{\mathbf{45}}^{+2}$$

→ M_U

[*] S. M. Barr, Phys. Lett. B 112 (1982) 218.

WHAT IS THIS GOOD FOR?

LIGHT LEPTOQUARKS*

See, for example, S. Fajfer's talk.

*I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, Phys. Rev. D 81:055009, 2010, arXiv:0912.0972.

CONCLUSIONS

Proton can be stable in flipped $SU(5)$! (There is a way to suppress $d = 5$ proton decay operators.)

There exists a lower bound on $M_{(X,Y)}$ in GUTs based on simple groups such as $SU(5)$, $SO(10)$ and E_6 proportional to $|V_{ub}|^2$!

However, even in a well-defined scenarios there exist an uncertainty of seven orders of magnitude when it comes down to the proton decay predictions due to gauge boson exchange.

CONCLUSIONS

Proton decay operators induced via scalar exchange exhibit strong model dependence.

This opens up possibilities for existence of light scalar leptoquark states with interesting phenomenological consequences.

THANK YOU!

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