# ON $d = 6$ PROTON DECAY OPERATORS*

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# 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…

# MOTIVATION

BARYON NUMBER IS CONSERVED IN THE STANDARD MODEL OF ELEMENTARY PARTICLE PHYSICS. THE LIGHTEST OF BARYONS – **PROTON** – SHOULD THUS BE STABILE.

You feel it in your bones it is stable because if it lived less than $10^{16}$ years it would kill you.*

Experimentally, you can only say, “ It lives longer than... ” Theoretically you say you do not know but you believe it is stable. So it good to teach it correctly.*

*Interview of Maurice Goldhaber on January 10, 1967, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.

# EXPERIMENTAL RESULTS

| PROCESS | $\tau_p$ ($10^{33}$ 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 |
| $\vdots$ | $\vdots$ |

*

@

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

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

# $d = 6$ PROTON DECAY OPERATORS

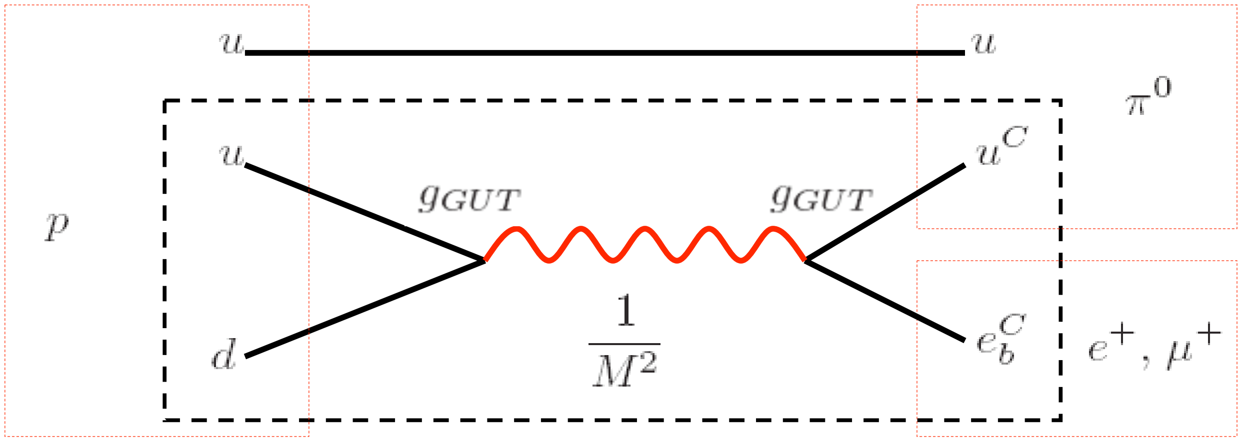
| | | |
|---|---|---|
| $p \rightarrow (K^+, \pi^+, \rho^+)\bar{\nu}_i$ | $p \rightarrow (K^0, \pi^0, \rho^+, \eta, \omega)e_j^+$ | PROTON* |
| $n \rightarrow (K^0, \pi^0, \rho^0, \omega, \eta)\bar{\nu}_i$ | $n \rightarrow (K^-, \pi^-, \rho^-)e_j^+$ | NEUTRON* |
| $i = 1, 2, 3$ | $j = 1, 2$ | |

*TWO BODY DECAYS…

# $d = 6$ PROTON DECAY OPERATORS

## VECTOR CONTRIBUTIONS

$$\frac{g^2_{GUT}}{M^2}\ \epsilon_{ijk}\ \epsilon_{\alpha\beta}\ \overline{u^C_{ia}}\ \gamma^\mu\ Q_{j\alpha a}\ \overline{e^C_b}\ \gamma_\mu\ Q_{k\beta b}$$ *




*PROTON DECAY DUE TO THE VECTOR BOSON EXCHANGE.

# FERMION MASSES

## THE STANDARD MODEL

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

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

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

$$(Y_U)_{ab}\, u_a^{C\,T}\, C\, H^T\, Q_b = (Y_U)_{ab}\, u_a^{C\,T}\, C\, \langle H \rangle\, u_b$$

$$\boxed{U_C^T\, Y_U\, U = Y_U^{\text{diag}}}$$

$$U^\dagger D = V_{CKM}$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$a = 1, 2, 3$$

# STANDARD MODEL FERMIONS

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

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

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

LEPTONS

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

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

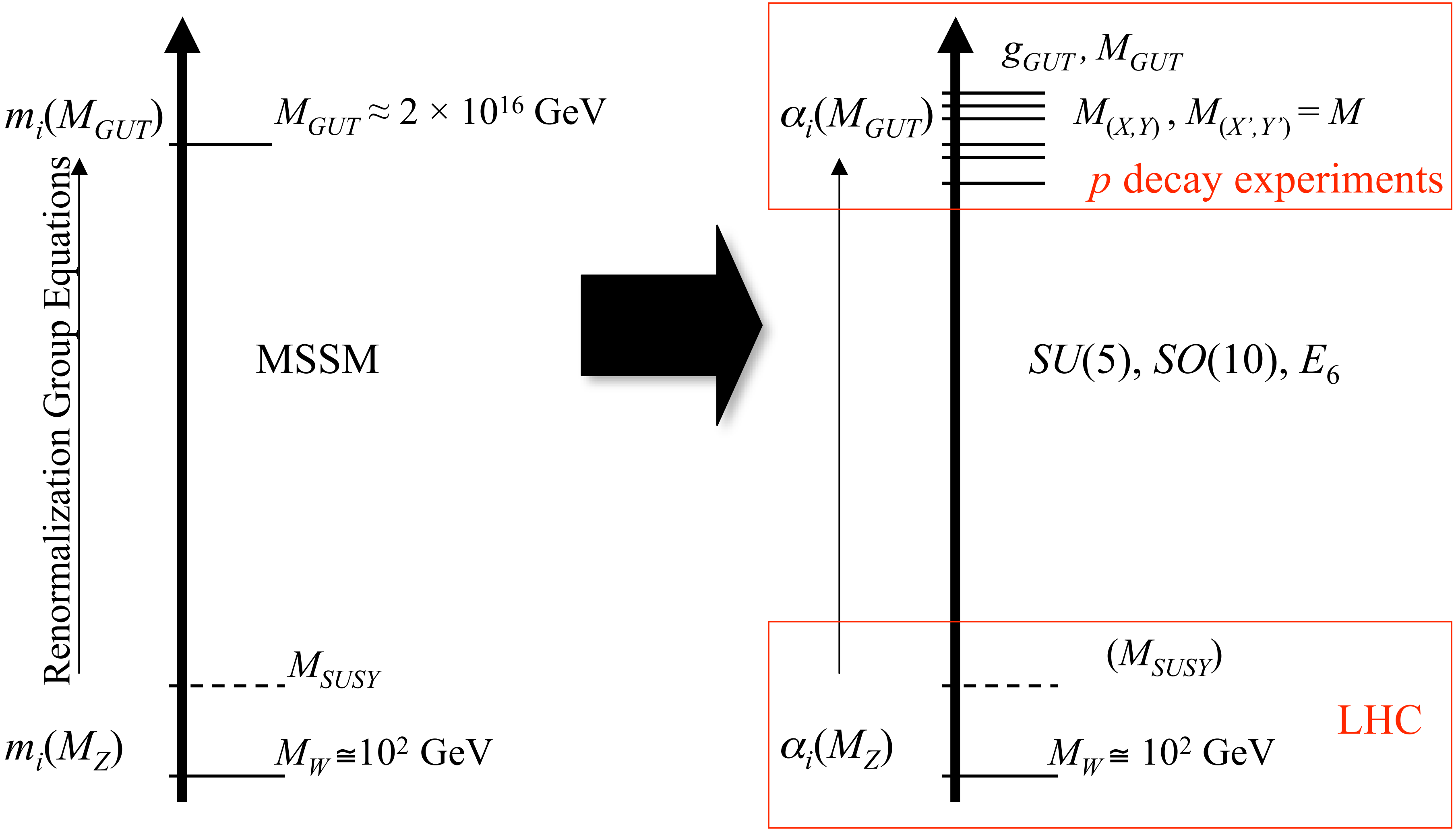
$$d_a^C \equiv (\overline{\mathbf{3}}, 1, 1/3)_a$$

QUARKS

$$a = 1, 2, 3$$

# GRAND UNIFIED THEORIES

## GAUGE COUPLING UNIFICATION



# *SU*(5) MATTER ASSIGNMENT*
## MATTER UNIFICATION

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

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

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

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

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

# $d = 6$ PROTON DECAY OPERATORS*

$(\mathbf{10}\,\mathbf{10})^\dagger\,(\mathbf{10}\,\mathbf{10})$

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

$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\,(\mathbf{10}\,\overline{\mathbf{5}})$

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

*SU*(5) THEORY

FLIPPED *SU*(5) THEORY

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

$(\mathbf{10}\,\mathbf{10})^\dagger\,(\mathbf{10}\,\mathbf{10})$

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

$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\,(\mathbf{10}\,\overline{\mathbf{5}})$

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

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*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[†]

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

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

*SU*(5)

FLIPPED *SU*(5)

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

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

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

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

# PROTON DECAY

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

GUT PHYSICS

# PROTON DECAY

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

---

$$\boxed{(A_r \approx A_l) \equiv A}$$

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

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

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

LATTICE QCD

# PROTON DECAY

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

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

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

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

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

# UNIFICATION WITHOUT PROTON DECAY[†]

FLIPPED $SU(5)$

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

$$\boxed{V_4^{\alpha\beta} = (D_C^\dagger D)^{\alpha\beta} = 0 \qquad \alpha = 1 \text{ or } \beta = 1} \quad \boxed{(V_1 V_{UD} V_4^\dagger V_3)^{1\alpha} = (U_C^\dagger E)^{1\alpha} = 0}$$

$$\Downarrow$$

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)?*

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

*SU*(5)

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

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

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

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

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

# WHAT ARE THE EXPERIMENTAL LIMITS?[†]

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

*SU*(5)
or
*SO*(10)

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

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

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

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

# WHAT ARE THE RELEVANT LIMITS?[†]

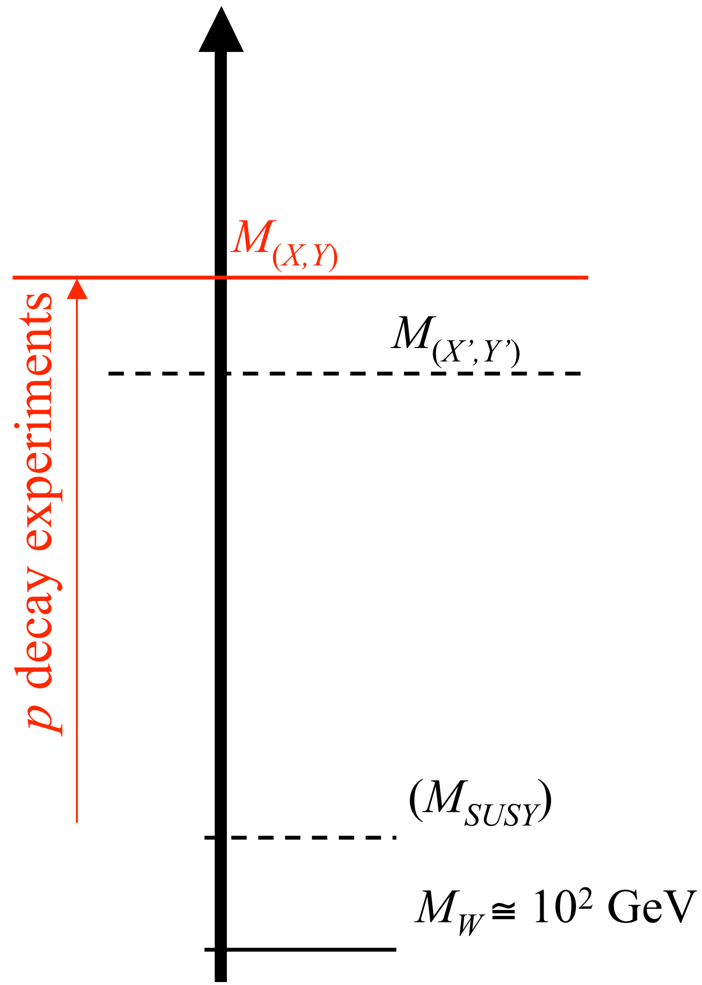
$$\tau_{p\to K^0\mu^+} \leq 6\times 10^{38}\ (M_{(X,Y)}/10^{16}\,\mathrm{GeV})^4\ \alpha_{GUT}^{-2}\ (0.01\,\mathrm{GeV}^3/|\alpha|)^2\ A^{-2}\,\mathrm{years}$$

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

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

[†]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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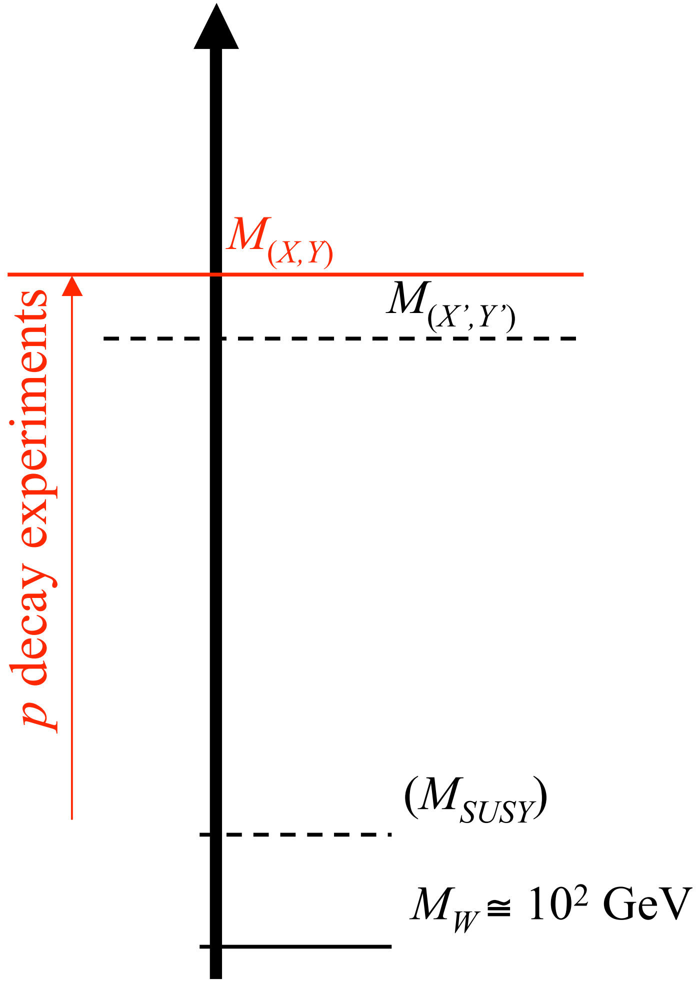


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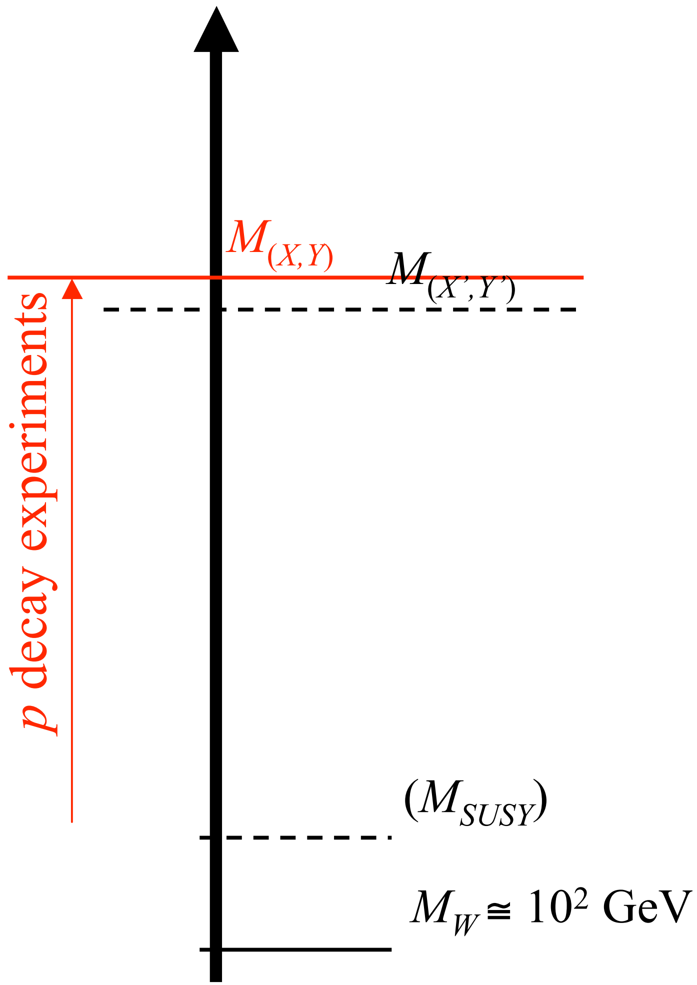


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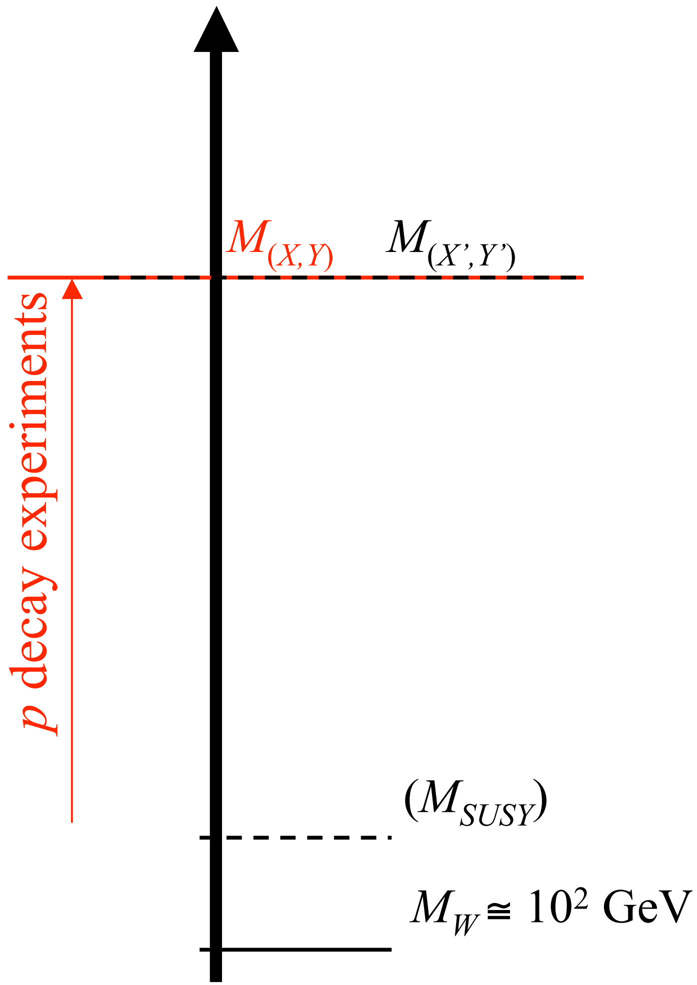


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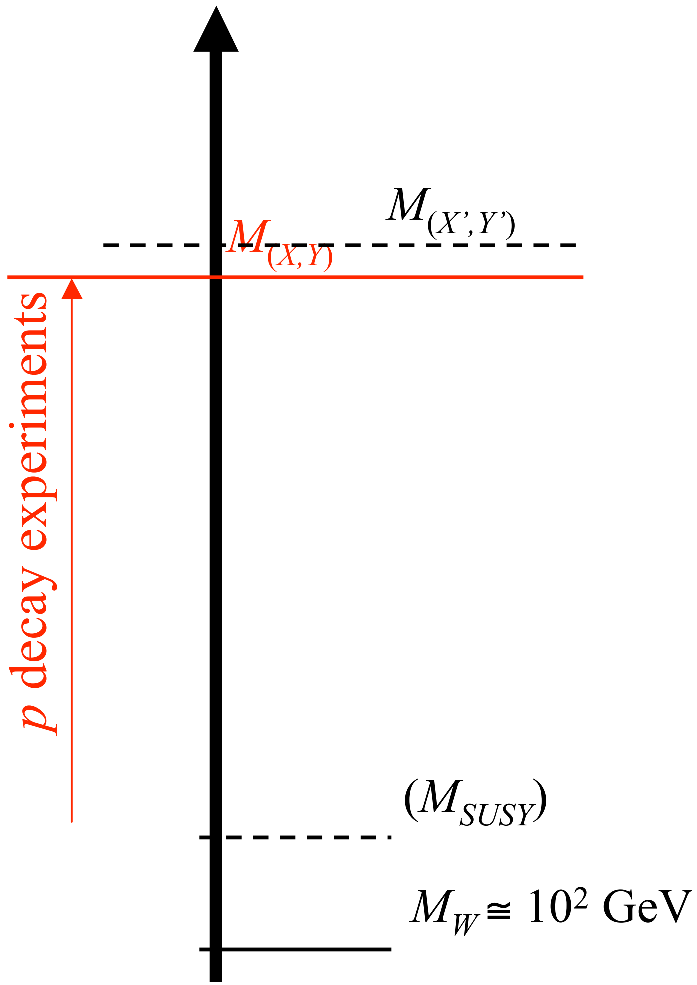


*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

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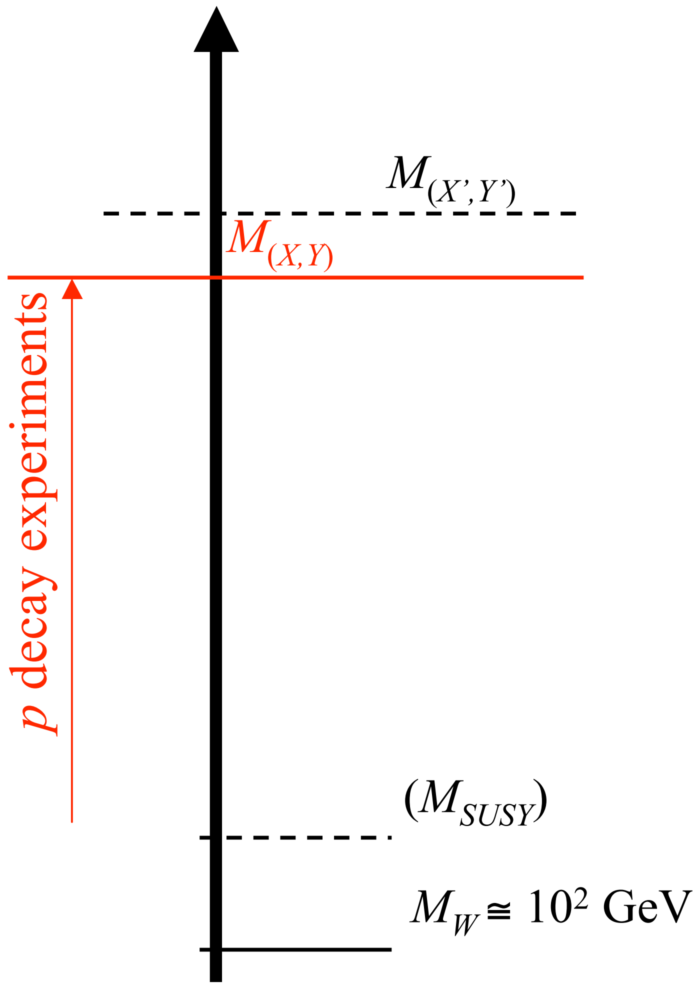


*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

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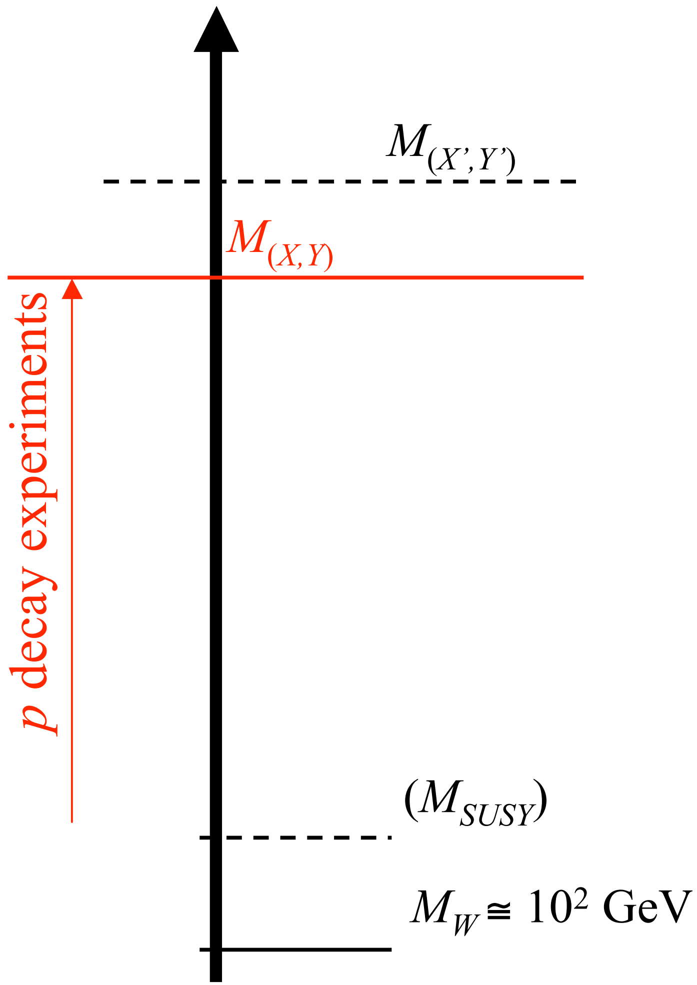
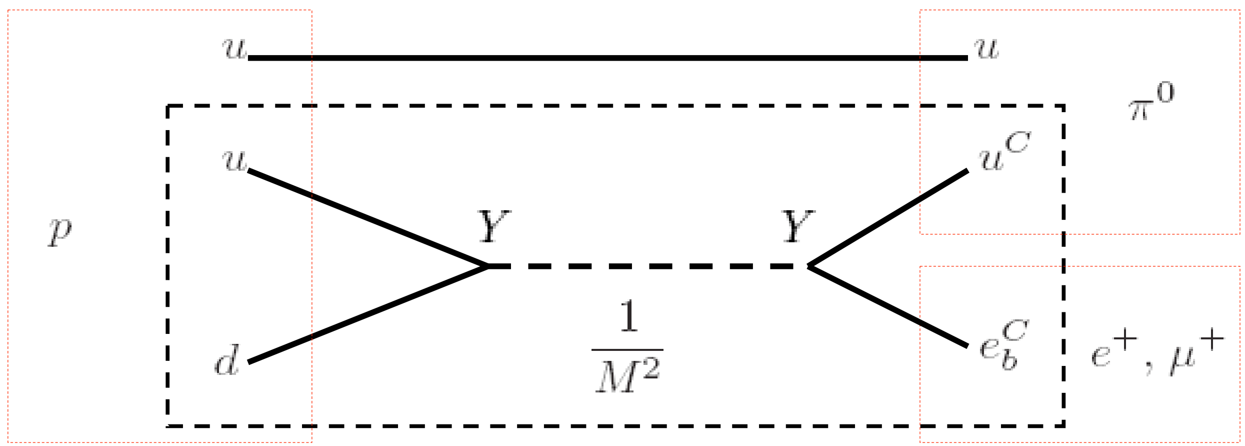



*I. D. and P. Fileviez Pérez, Phys. Lett. B 625:88-95, 2005.

# $d$=6 PROTON DECAY OPERATORS
## SCALAR CONTRIBUTIONS



# FERMION MASSES

## RENORMALIZABLE *SU*(5)

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

$M_E, M_D$

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

$M_U$

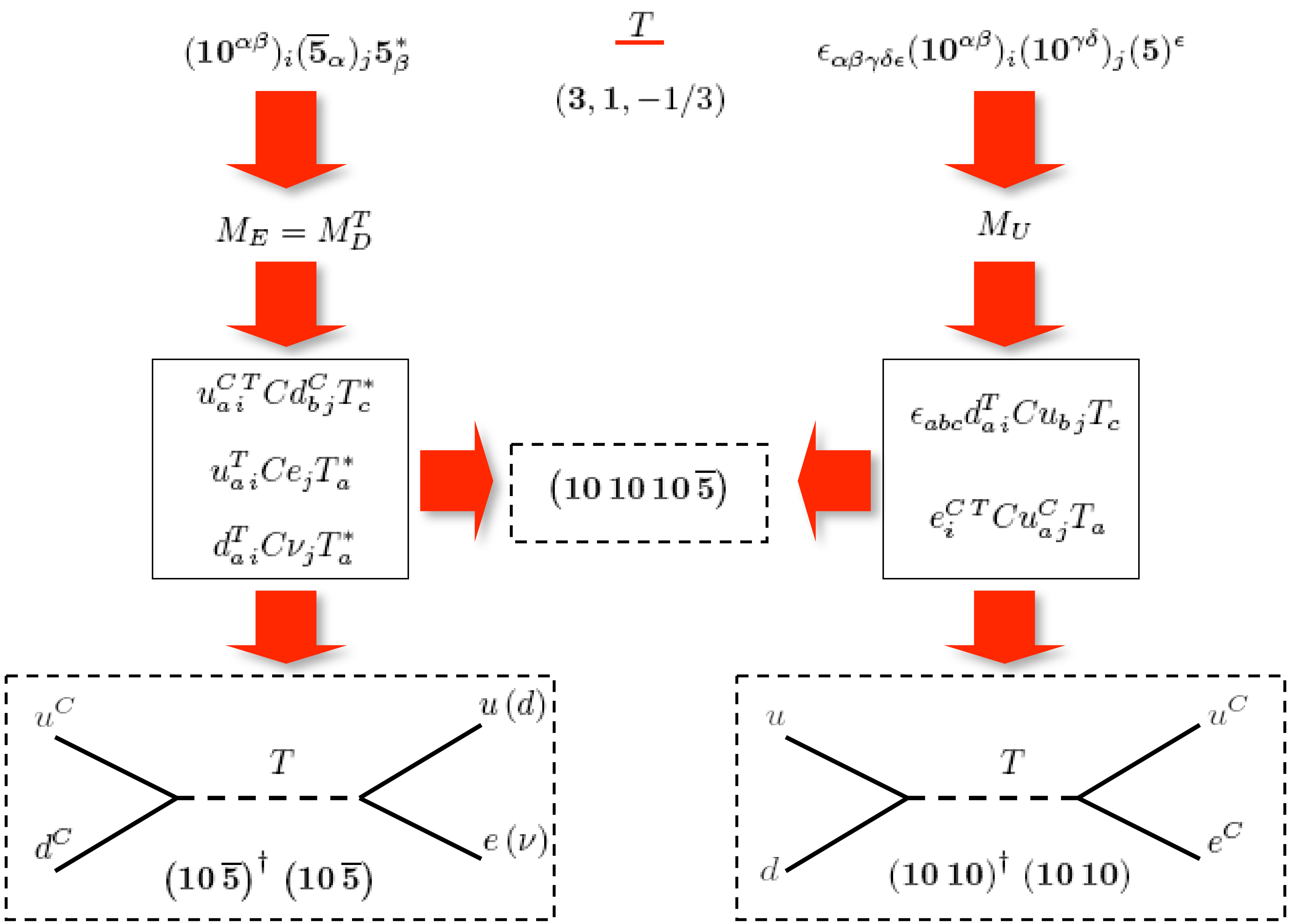
$$\mathbf{5} = (D, T)$$

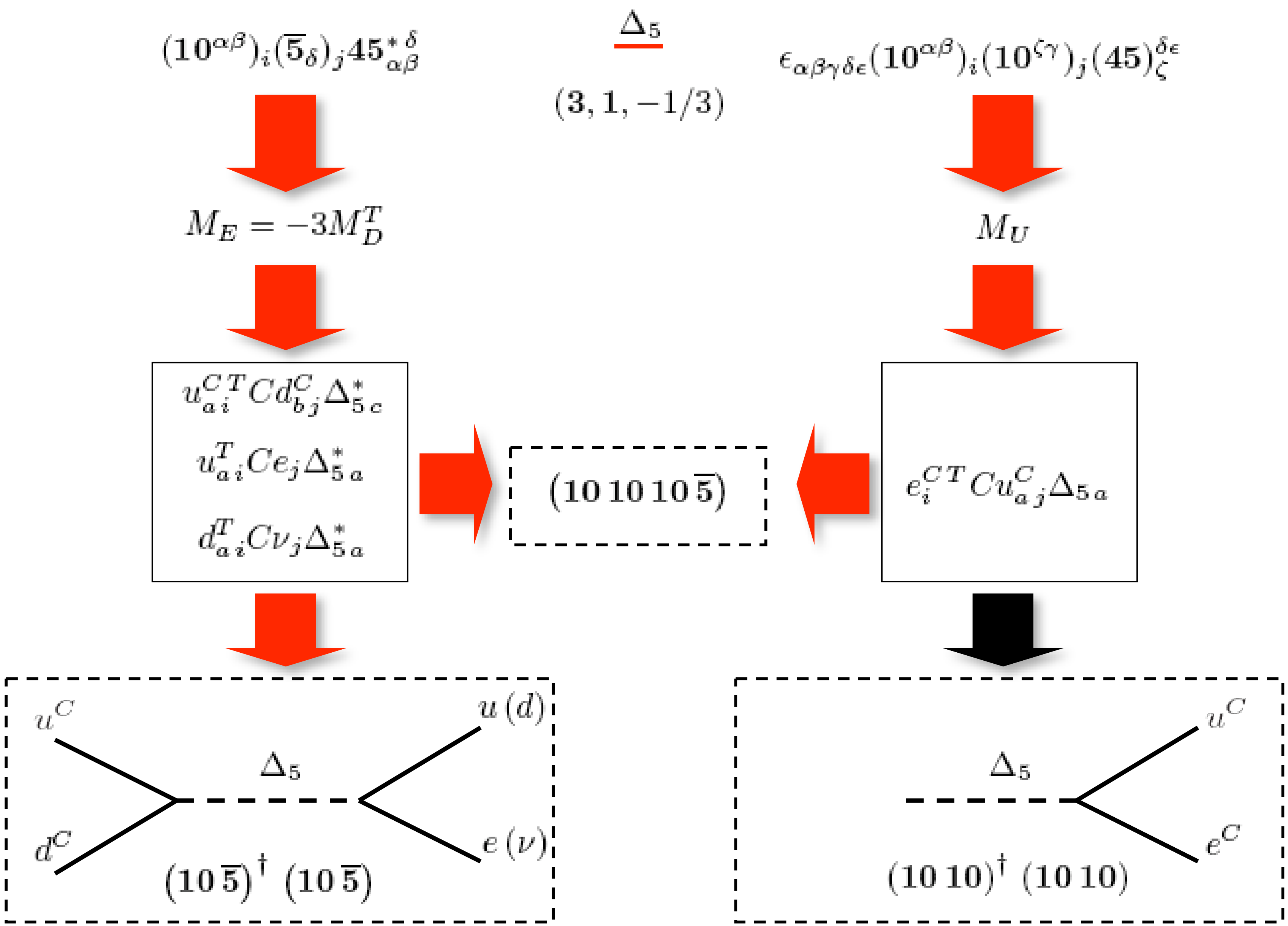
$$\underline{D \;=\; (\mathbf{1}, \mathbf{2}, 1/2)}$$

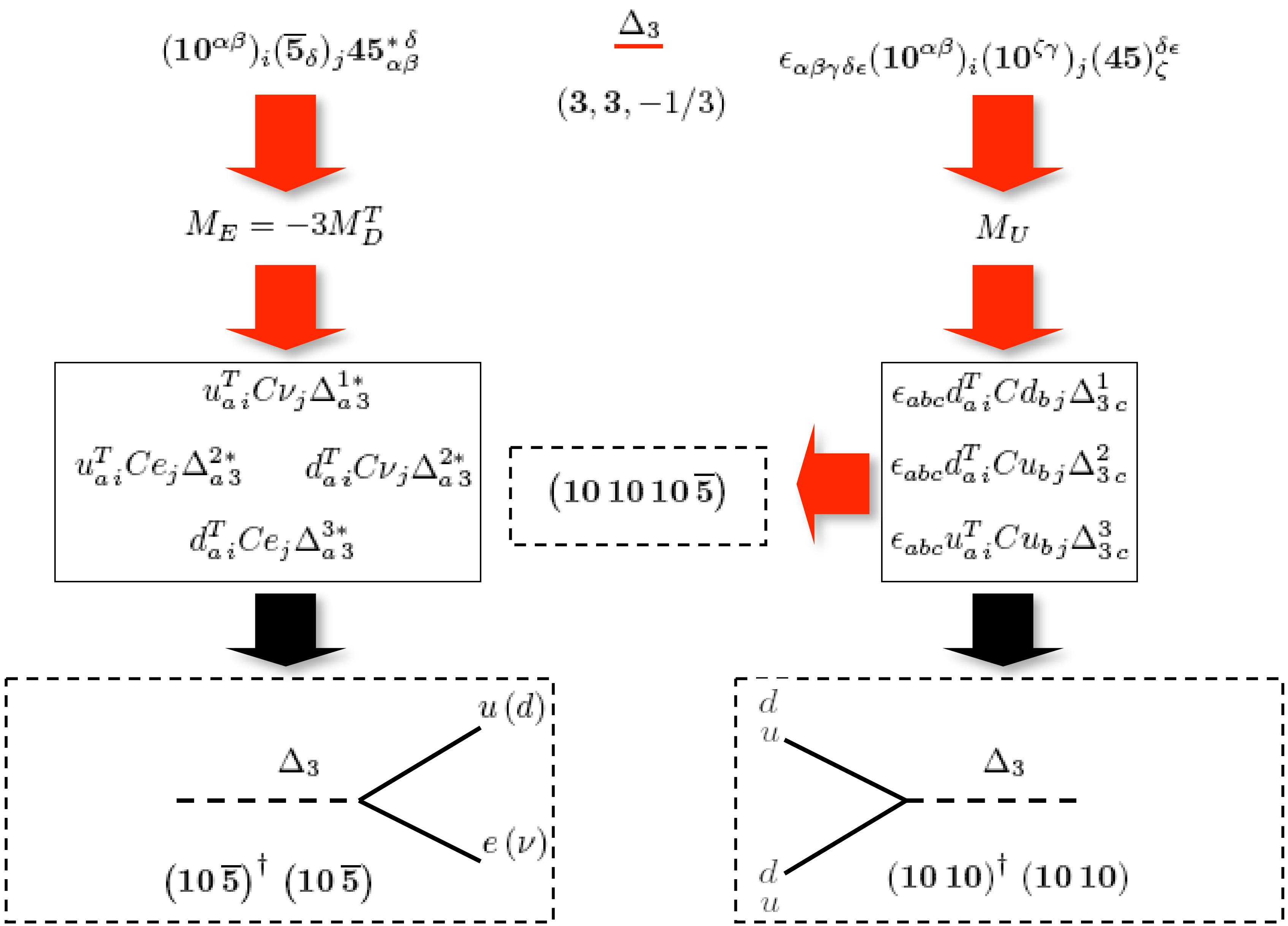
$$\underline{T \;=\; (\mathbf{3}, \mathbf{1}, -1/3)}$$

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

$$\begin{aligned}
\Delta_1 &= (\mathbf{8}, \mathbf{2}, 1/2) \\
\Delta_2 &= (\overline{\mathbf{6}}, \mathbf{1}, -1/3) \\
\underline{\Delta_3} &\underline{= (\mathbf{3}, \mathbf{3}, -1/3)} \\
\Delta_4 &= (\overline{\mathbf{3}}, \mathbf{2}, -7/6) \\
\underline{\Delta_5} &\underline{= (\mathbf{3}, \mathbf{1}, -1/3)} \\
\Delta_6 &= (\overline{\mathbf{3}}, \mathbf{1}, 4/3) \\
\underline{\Delta_7} &\underline{= (\mathbf{1}, \mathbf{2}, 1/2)}
\end{aligned}$$


$\underline{T}$
$(\mathbf{3}, \mathbf{1}, -1/3)$
$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\alpha)_j\mathbf{5}^*_\beta$
$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\gamma\delta})_j(\mathbf{5})^\epsilon$
$M_E = M_D^T$
$M_U$
$u^{C\,T}_{a\,i} C d^C_{b\,j} T^*_c$
$u^T_{a\,i} C e_j T^*_a$
$d^T_{a\,i} C \nu_j T^*_a$
$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$
$\epsilon_{abc} d^T_{a\,i} C u_{b\,j} T_c$
$e^{C\,T}_i C u^C_{a\,j} T_a$
$u^C$
$d^C$
$T$
$u\,(d)$
$e\,(\nu)$
$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\ (\mathbf{10}\,\overline{\mathbf{5}})$
$u$
$d$
$T$
$u^C$
$e^C$
$(\mathbf{10}\,\mathbf{10})^\dagger\ (\mathbf{10}\,\mathbf{10})$


$\Delta_5$
$(\mathbf{3}, \mathbf{1}, -1/3)$
$(\mathbf{10}^{\alpha\beta})_i (\overline{\mathbf{5}}_\delta)_j \mathbf{45}^{*\,\delta}_{\alpha\beta}$
$\epsilon_{\alpha\beta\gamma\delta\epsilon} (\mathbf{10}^{\alpha\beta})_i (\mathbf{10}^{\zeta\gamma})_j (\mathbf{45})^{\delta\epsilon}_{\zeta}$
$M_E = -3 M_D^T$
$M_U$
$u^{C\,T}_{a\,i} C d^C_{b\,j} \Delta^*_{5\,c}$
$u^T_{a\,i} C e_j \Delta^*_{5\,a}$
$d^T_{a\,i} C \nu_j \Delta^*_{5\,a}$
$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$
$e^{C\,T}_i C u^C_{a\,j} \Delta_{5\,a}$
$u^C$
$d^C$
$\Delta_5$
$u\,(d)$
$e\,(\nu)$
$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\ (\mathbf{10}\,\overline{\mathbf{5}})$
$\Delta_5$
$u^C$
$e^C$
$(\mathbf{10}\,\mathbf{10})^\dagger\ (\mathbf{10}\,\mathbf{10})$


$\Delta_3$
$(\mathbf{3}, \mathbf{3}, -1/3)$
$(\mathbf{10}^{\alpha\beta})_i (\overline{\mathbf{5}}_\delta)_j \mathbf{45}^{*\,\delta}_{\alpha\beta}$
$M_E = -3 M_D^T$
$u^T_{a\,i} C \nu_j \Delta^{1*}_{a\,3}$
$u^T_{a\,i} C e_j \Delta^{2*}_{a\,3}$
$d^T_{a\,i} C \nu_j \Delta^{2*}_{a\,3}$
$d^T_{a\,i} C e_j \Delta^{3*}_{a\,3}$
$\epsilon_{\alpha\beta\gamma\delta\epsilon} (\mathbf{10}^{\alpha\beta})_i (\mathbf{10}^{\zeta\gamma})_j (\mathbf{45})^{\delta\epsilon}_{\zeta}$
$M_U$
$\epsilon_{abc} d^T_{a\,i} C d_{b\,j} \Delta^1_{3\,c}$
$\epsilon_{abc} d^T_{a\,i} C u_{b\,j} \Delta^2_{3\,c}$
$\epsilon_{abc} u^T_{a\,i} C u_{b\,j} \Delta^3_{3\,c}$
$(\mathbf{10}\,\mathbf{10}\,\mathbf{10}\,\overline{\mathbf{5}})$
$u\,(d)$
$\Delta_3$
$e\,(\nu)$
$(\mathbf{10}\,\overline{\mathbf{5}})^\dagger\ (\mathbf{10}\,\overline{\mathbf{5}})$
$d$
$u$
$\Delta_3$
$d$
$u$
$(\mathbf{10}\,\mathbf{10})^\dagger\ (\mathbf{10}\,\mathbf{10})$

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

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

NO SCALAR $d = 6$ PROTON DECAY![†]

[*] I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, arXiv:0906.5585.

$\mathbf{45}$ [*]

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

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

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

[*] I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, arXiv:0906.5585.

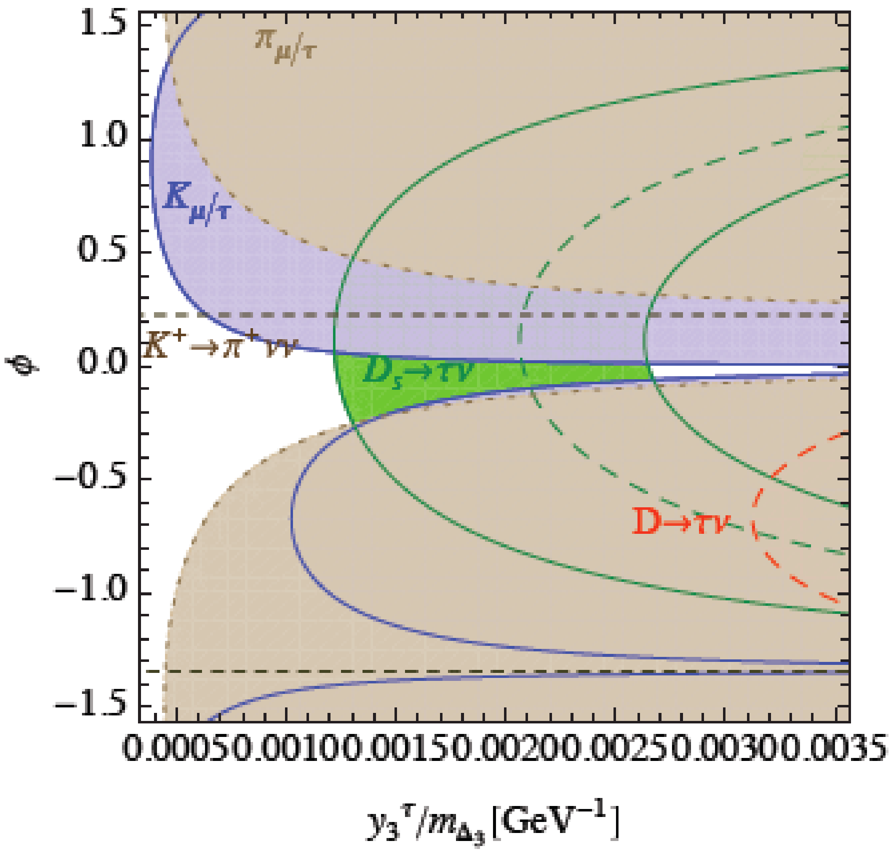
# <u>WHAT IS THIS GOOD FOR?</u>
## LIGHT LEPTOQUARKS

IF $\Delta_3$ OR $T$ ARE LIGHT, THEY COULD ADDRESS ACCOMULATING EVIDENCE FOR NONSTANDARD LEPTONIC DECAYS OF $D_s$ MESONS…[*]

[*]B. A. Dobrescu and A. S. Kronfeld, Phys. Rev. Lett. 100, 241802 (2008).

# WHAT IS THIS GOOD FOR?

## LIGHT LEPTOQUARKS

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*I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, arXiv:0906.5585.

# CONCLUSIONS

Proton can be stable in flipped $SU(5)$!

There exist a lower bound on $M_{(X,Y)}$ in GUTs based on simple groups such as $SU(5)$, $SO(10)$ and $E_6$!

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 also exhibit strong model dependence.

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

**<u>THANK YOU!</u>**

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