Upper bound on the proton lifetime and a minimal grand unified theory

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SUSY'06, Irvine, California, USA.

References

I. Dorsner, P. F. P, Physics Letters B **625** (2005) 88.
I. Dorsner, P. F. P, Nuclear Physics B **723** (2005) 53.
I. Dorsner, P. F. P, R. Gonzalez Felipe, hep-ph/0512068.
I. Dorsner, P. F. P, hep-ph/0606062.

Aim

The decay of the proton is the most dramatic prediction coming from matter unification!

Is there an upper bound on the proton lifetime?

The Georgi Glashow model based on $SU(5)$ is the simplest GUT!

What is the minimal realistic extension of the Georgi Glashow model?

How can we test a minimal realistic non-SUSY GUT?

Contents

Weinberg, 1979-1982; Wilczek, Zee,'79; Sakai, Yanagida,'82

Baryon number violating effective operators

$$\mathcal{L}_{eff} = c_d \frac{\mathcal{O}^d}{M^{d-4}}$$

Supersymmetric Models

$$\Longrightarrow \quad d = 4$$

$$\Longrightarrow \quad d = 5$$

Non-Supersymmetric Contributions

$$\Longrightarrow \quad \textbf{Gauge } d = 6$$

$$\Longrightarrow \quad \textbf{Higgs } d = 6$$

For details see

P. Nath, P. F. P, "Proton stability in grand unified theories, in strings, and in branes", Physics Reports (2006), hep-ph/0601023

P. F. P, Physics Letters **B** 595 (2004) 476-483

Gauge $d=6$ nucleon decay in $SU(5)$ and $SO(10)$

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

$$
\begin{aligned}
c(e^C_\alpha, d_\beta) &= k_1^2 \left[V_1^{11} V_2^{\alpha\beta} + (V_1 V_{UD})^{1\beta} (V_2 V_{UD}^\dagger)^{\alpha 1} \right] \\
c(e_\alpha, d^C_\beta) &= k_1^2\ V_1^{11} V_3^{\beta\alpha} + \ k_2^2\ (V_4 V_{UD}^\dagger)^{\beta 1} (V_1 V_{UD} V_4^\dagger V_3)^{1\alpha} \\
c(\nu_l, d_\alpha, d^C_\beta) &= k_1^2\ (V_1 V_{UD})^{1\alpha} (V_3 V_{EN})^{\beta l} \\
&+ \ \ k_2^2\ V_4^{\beta\alpha} (V_1 V_{UD} V_4^\dagger V_3 V_{EN})^{1l}
\end{aligned}
$$

$\alpha = \beta = 1, 2.\quad l = 1, 2, 3.\quad k_{1,2} = g_{GUT}/\sqrt{2} M_{V,V'}.$

$$V_1 = U_C^\dagger U,\ V_2 = E_C^\dagger D,\ V_3 = D_C^\dagger E,\ V_4 = D_C^\dagger D,$$

$$V_{EN} = E^\dagger N = K_3 V_{PMNS},\quad V_{UD} = U^\dagger D = K_1 V_{CKM} K_2.$$

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

$(X, Y) = (\mathbf{3}, \mathbf{2}, 5/3),\ (X', Y') = (\mathbf{3}, \mathbf{2}, -1/3).$

I. Dorsner, P. F. P, Physics Letters B **625** (2005) 88-95

Upper bound on the proton lifetime in GUTs

$$k_2 = 0 \Longrightarrow \text{GUTs based on } SU(5)$$

Gauge Bosons:

$$A(24) = G_{ij} \bigoplus (X_i, Y_i) \bigoplus (\bar{X}_i, \bar{Y}_i) \bigoplus (W^+, W^3, W^-) \bigoplus B^0$$

$$c(e^C_\alpha, d_\beta) = k_1^2 \left[V_1^{11} V_2^{\alpha\beta} + (V_1 V_{UD})^{1\beta} (V_2 V_{UD}^\dagger)^{\alpha 1} \right]$$

$$c(e_\alpha, d^C_\beta) = k_1^2 \; V_1^{11} V_3^{\beta\alpha}$$

$$c(\nu_l, d_\alpha, d^C_\beta) = k_1^2 \; (V_1 V_{UD})^{1\alpha} (V_3 V_{EN})^{\beta l}$$

Case 1. There are no decays into a meson-antineutrino
Case 2. There are no decays into a meson-charged antilepton

$$(V_1 V_{UD})^{1\alpha} = (U_C^\dagger D)^{1\alpha} = 0 \Longrightarrow U_C = D A^\dagger \quad \text{(C.I)}$$

$$V_2^{\beta\alpha} = (E_C^\dagger D)^{\beta\alpha} = 0 \Longrightarrow E_C = D B_1 \quad \text{(C.II)}$$

$$V_3^{\beta\alpha} = (D_C^\dagger E)^{\beta\alpha} = 0 \Longrightarrow D_C = E B_2 \quad \text{(C.III)}$$

$$A = \begin{pmatrix} 0 & 0 & e^{i\alpha} \\ \dots & \dots & 0 \\ \dots & \dots & 0 \end{pmatrix}, \quad B_i = \begin{pmatrix} 0 & 0 & e^{i\beta_i} \\ 0 & e^{i\gamma_i} & 0 \\ e^{i\delta_i} & 0 & 0 \end{pmatrix}$$

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$$\Gamma_p = \Gamma(p \to K^0 \mu^+) \quad = \quad 8\pi^2 C(p, K^0)\ |V_{CKM}^{13}|^2\ \alpha_{GUT}^2\ M_V^{-4}$$

where:

$$C(p, K^0) = \frac{(m_p^2 - m_K^2)^2}{8\pi m_p^3 f_\pi^2}\ A_L^2\ |\beta|^2 \times \left[1 + \frac{m_p}{m_B}(D - F)\right]^2$$

The upper bound on the proton lifetime corresponds to the total lifetime of **Case 1.** We find it to be:

In the case of Majorana neutrinos

$$\tau_p \leq 6.0 \times 10^{39}\ \frac{(M_V/10^{16}\,\mathrm{GeV})^4}{\alpha_{GUT}^2}\ (0.003\,\mathrm{GeV}^3/\beta)^2\,\mathrm{years}$$

Using ($\tau_p \geq 50 \times 10^{32}$ years) and $\beta = 0.003$ GeV^3:

$$M_V \ > \ 3.04 \times 10^{14} \sqrt{\alpha_{GUT}}\,\mathrm{GeV}$$

if $\alpha_{GUT} = 1/39 - 1/25$:

$$M_V \ > \ (4.9 - 6.1) \times 10^{13}\,\mathrm{GeV}$$

I. Dorsner, P. F. P, Physics Letters B **625** (2005) 88-95

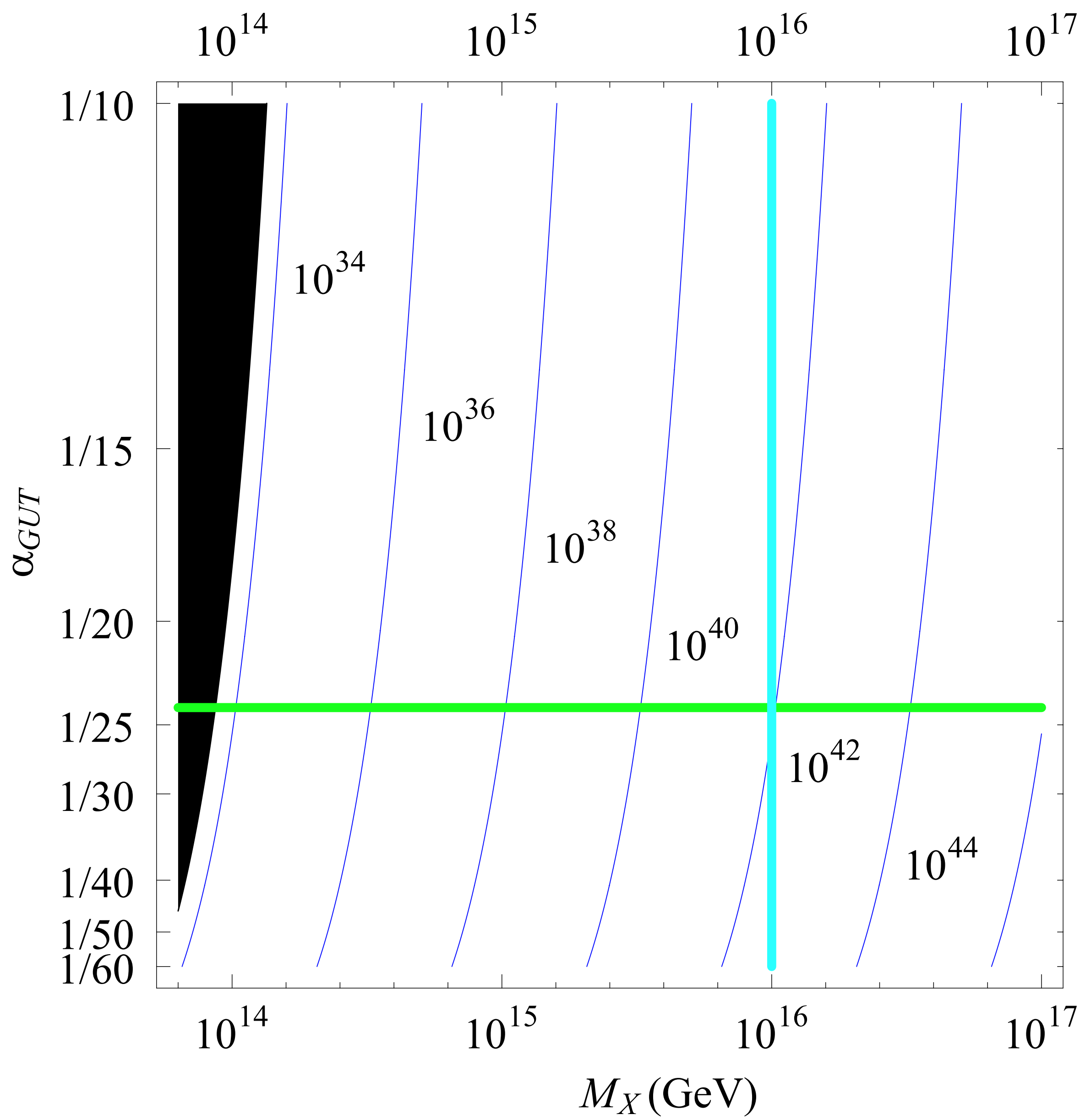


Figure 1: Isoplot for the upper bounds on the total proton in years in the Majorana neutrino case in the M_X–α_{GUT} plane. The value of the unifying coupling constant is varied from 0.02 to 1.

I. Dorsner, P. F. P, Physics Letters B **605** (2005) 367-370

Could we rotate proton decay away?

In flipped $SU(5)$

$$c(e^C_\alpha, d_\beta) = 0$$

$$c(e_\alpha, d^C_\beta) = k_2^2 \, (V_4 V_{UD}^\dagger)^{\beta 1} (V_1 V_{UD} V_4^\dagger V_3)^{1\alpha}$$

$$c(\nu_l, d_\alpha, d^C_\beta) = k_2^2 \, V_4^{\beta\alpha} (V_1 V_{UD} V_4^\dagger V_3 V_{EN})^{1l}$$

$$(X', Y') = (\mathbf{3}, \mathbf{2}, -1/3), \quad \alpha, \beta = 1, 2, \quad l = 1, 2, 3$$

Solution:

$$V_4^{\beta\alpha} = (D_C^\dagger D)^{\beta\alpha} = 0, \;\; \alpha = 1 \;\text{ or }\; \beta = 1 \;\; \& \;\; (U_C^\dagger E)^{1\alpha} = 0.$$

What these two conditions that remove $d = 6$ operators imply for the structure of the fermion sector?

$$\begin{aligned} Y_U &= Y_U^{diag} \\ Y_D &= K_1^* \, V_{CKM}^* \, K_2^* \, B \, Y_D^{diag} \, K_2^* \, V_{CKM}^\dagger \, K_1^*, \\ Y_E &= E_C^* \, Y_E^{diag} \, E^\dagger, \\ Y_N &= E^* K_3^* \, V_{PMNS}^* \, Y_N^{diag} \, V_{PMNS}^\dagger \, K_3^* E^\dagger. \end{aligned}$$

where: $|E^{13}| = 1$, & $|B^{13}| = |B^{22}| = |B^{31}| = 1$.

Is there an upper bound on the proton lifetime?

There is a conservative model independent upper bound on the total proton decay lifetime:

$$\tau_p^M \leq 6.0 \times 10^{39} \, \frac{(M_V/10^{16}\,\mathrm{GeV})^4}{\alpha_{GUT}^2} \, (0.003\,\mathrm{GeV}^3/\beta)^2 \,\mathrm{years}$$

The Georgi Glashow model based on $SU(5)$ is the simplest GUT!

What is the minimal realistic extension of the Georgi Glashow model?

How can we test a minimal realistic non-SUSY GUT?

H. Georgi & S. L. Glashow, 1974.

Georgi-Glashow model

Gauge Group: $SU(5)$

Gauge Bosons:

$$A(24) = G_{ij} \bigoplus (X_i, Y_i) \bigoplus (\bar{X}_i, \bar{Y}_i) \bigoplus (W^+, W^3, W^-) \bigoplus B^0$$

Matter Unification:

$$\mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^C & -u_2^C & u_1 & d_1 \\ -u_3^C & 0 & u_1^C & u_2 & d_2 \\ u_2^C & -u_1^C & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^C \\ -d_1 & -d_2 & -d_3 & -e^C & 0 \end{pmatrix}_L \qquad \bar{\mathbf{5}} = \begin{pmatrix} d_1^C \\ d_2^C \\ d_3^C \\ e \\ -\nu \end{pmatrix}_L$$

Higgs Sector:

$$\mathbf{5_H} = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ H^+ \\ H^0 \end{pmatrix}$$

$$\mathbf{24_H} = \begin{pmatrix} \Sigma_8 & \Sigma_{(3,2)} \\ \Sigma_{(\bar{3},2)} & \Sigma_3 \end{pmatrix} + \frac{\mathbf{1}}{\mathbf{2\sqrt{15}}} \begin{pmatrix} 2 & 0 \\ 0 & -3 \end{pmatrix} \mathbf{\Sigma_{24}}$$

PROBLEMS:

- It does not incorporate massive neutrinos.

  Possible solutions:

  - Higher-dimensional operators (M_{GUT}/M_{Pl}).
    (Barbieri, Ellis, Gaillard'80)
  - ν_R (Type I see-saw)
    (Minkowski; Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra, Senjanović'79-80)
  - $\mathbf{15}_H$ (Type II see-saw)
    (Lazarides, Shafi, Wetterich; Mohapatra, Senjanović '81)

- Relation $Y_D = Y_E^T$ in disagreement with the experimental observed values.

  Possible solutions:

  - Higher-dimensional operators (Ellis, Gaillard '79)
  - $\mathbf{45}_H$ (Georgi, Jarlskog '79)

- It is not possible to achieve gauge coupling unification.

- Doublet-Triplet splitting. (in SUSY $SU(5)$)

  (Grinstein'82, Masiero, Nanopoulos, Tamvakis, Yanagida'82)

I. Dorsner, P. F. P, Nucl. Phys. B **273**(2005)53

A minimal realistic non-supersymmetric GUT

Matter: $\bar{5}, \mathbf{10}$

Higgs Sector: $5_H,\ \mathbf{24}_H,\ \mathbf{15}_H.$

$$\mathbf{15}_H = \Phi = (\Phi_a, \Phi_b, \Phi_c) = (\mathbf{1}, \mathbf{3}, 1) + (\mathbf{3}, \mathbf{2}, 1/6) + (\mathbf{6}, \mathbf{1}, -2/3)$$

$$V_{\text{Yukawa}} = \ 10\ Y_u\ 10\ 5_H\ +\ 10\ Y_d\ \overline{5}\ 5_H^* + \ \overline{5}\ Y_\nu\ \overline{5}\ 15_H$$

$$+ \text{ higher-dimensional terms}$$

$$V_{\text{Higgs}} = V_{\text{Higgs}}^{SU(5)}\ +\ c_3\ 5_H^\dagger\ 15_H\ 5_H^*\ +\ b_8\ 5_H^\dagger\ 24_H\ 15_H\ 5_H^*\ +\ h.c.$$

$$-\ \frac{\mu_\Phi^2}{2} Tr\ 15_H^\dagger 15_H\ +\ \frac{a_\Phi}{4}(Tr\, 15_H^\dagger 15_H)^2\ + ...$$

For previous studies in non-minimal $SU(5)$ models see Ruegg'80; Buccella,Gelmini, Masiero, Roncadelli '84.

Unification constraints

At the one-loop level:

$$\alpha_i^{-1}|_{M_Z} \;=\; \alpha_{GUT}^{-1} \;+\; \tfrac{1}{2\pi}\, B_i \;\ln\; \tfrac{M_{GUT}}{M_Z}$$

where $i = 1, 2, 3$ for $U(1)$, $SU(2)$, and $SU(3)$, respectively.

$$\alpha_{GUT} = g_{GUT}^2/(4\pi)$$

$$B_i \;=\; b_i + \sum_I b_{iI} r_I, \qquad r_I = \frac{\ln M_{GUT}/M_I}{\ln M_{GUT}/M_Z}$$

$$(M_Z \le M_I \le M_{GUT})$$

$$b_1^{SM} \;=\; \frac{40}{10} + \frac{n}{10} \qquad b_2^{SM} \;=\; -\frac{20}{6} + \frac{n}{6} \qquad b_3^{SM} \;=\; -7$$

$$\frac{B_{23}}{B_{12}} \;=\; \frac{5}{8}\frac{\sin^2\theta_w(M_Z) - \alpha_{em}(M_Z)/\alpha_s(M_Z)}{3/8 - \sin^2\theta_w(M_Z)},$$

$$\ln\frac{M_{GUT}}{M_Z} \;=\; \frac{16\pi}{5\alpha_{em}(M_Z)}\frac{3/8 - \sin^2\theta_w(M_Z)}{B_{12}}.$$

I. Dorsner, P. F. P, Nucl. Phys. B **273**(2005)53

with $B_{ij} = B_i - B_j$ (See for example: Giveon, Hall, Sarid'91).

using $\sin^2\theta_w(M_Z) = 0.23120 \pm 0.00015$,

$\alpha_{em}^{-1}(M_Z) = 127.906 \pm 0.019$ and $\alpha_s(M_Z) = 0.1187 \pm 0.002$.

$$\frac{B_{23}}{B_{12}} = 0.719 \pm 0.005; \qquad \ln\frac{M_{GUT}}{M_Z} = \frac{184.9 \pm 0.2}{B_{12}}$$

$$\tau_p = C\ M_V^4\ \alpha_{GUT}^{-2}\ m_p^{-5}; \qquad M_V\ >\ (4.9 - 6.1)\ 10^{13}\ \mathrm{GeV}$$

In the Standard Model: $(B_{23}^{SM}/B_{12}^{SM} = 0.53)$

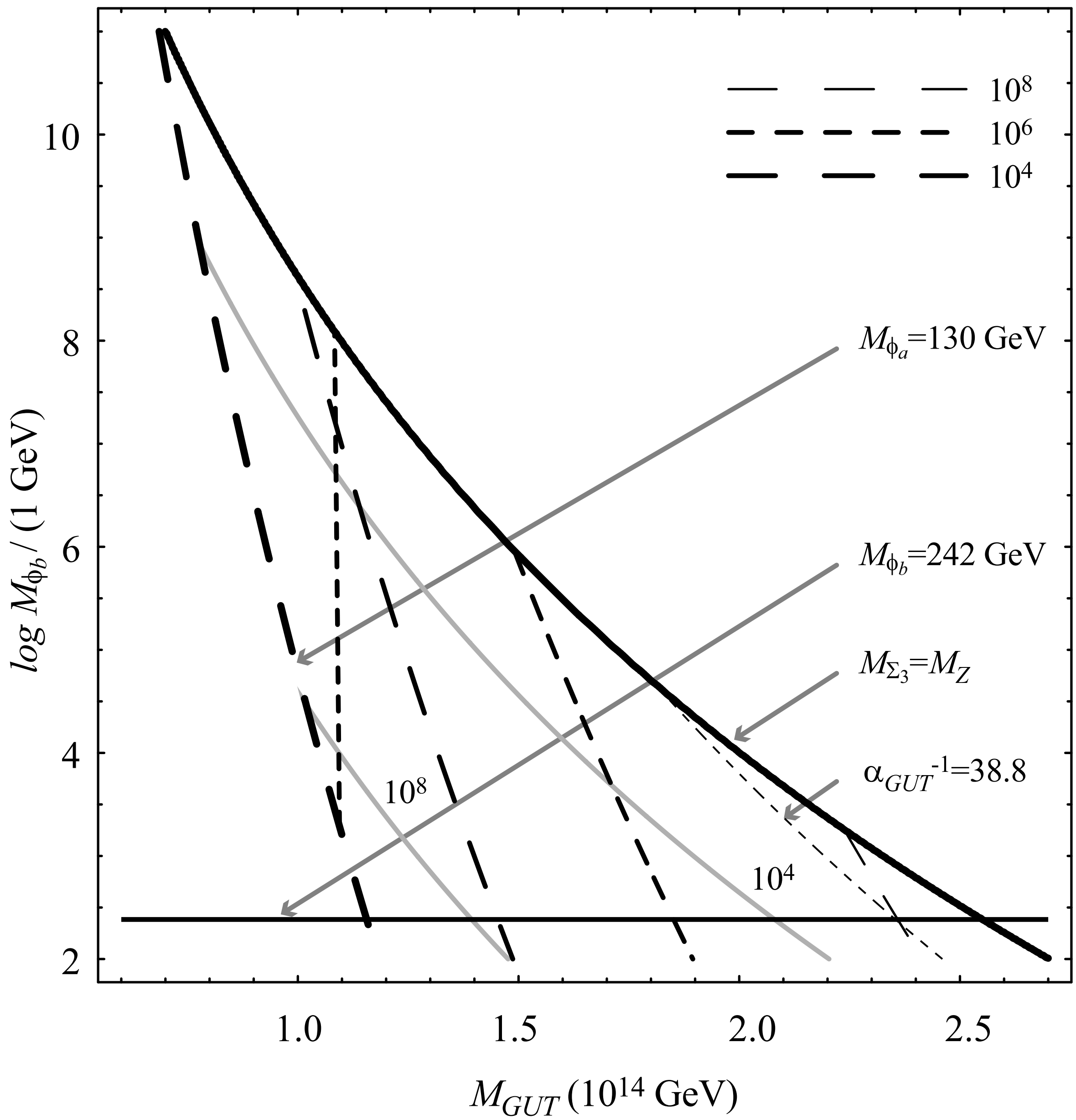
Contributions to the B_{ij} coefficients
(The mass of the SM Higgs doublet is taken to be at M_Z)

SM	Ψ_T	V	Σ_8	Σ_3	Φ_a	Φ_b	Φ_c
$\frac{23}{6}$	$-\frac{1}{6}r_{\Psi_T}$	$-\frac{7}{2}r_V$	$-\frac{1}{2}r_{\Sigma_8}$	$\frac{1}{3}r_{\Sigma_3}$	$\frac{2}{3}r_{\Phi_a}$	$\frac{1}{6}r_{\Phi_b}$	$-\frac{5}{6}r_{\Phi_c}$
$\frac{109}{15}$	$\frac{1}{15}r_{\Psi_T}$	$-7r_V$	0	$-\frac{1}{3}r_{\Sigma_3}$	$-\frac{1}{15}r_{\Phi_a}$	$-\frac{7}{15}r_{\Phi_b}$	$\frac{8}{15}r_{\Phi_c}$

$(M_I = M_{GUT})\ \ 0\ \leq r_I \leq\ 1\ \ (M_I = M_Z)$

Fields capable of improving unification are: $\Sigma_3(\subset \mathbf{24}_H)$, $\Phi_a(\subset \mathbf{15}_H)$, $\Phi_b(\subset \mathbf{15}_H)$, and $V = (X, Y)$.

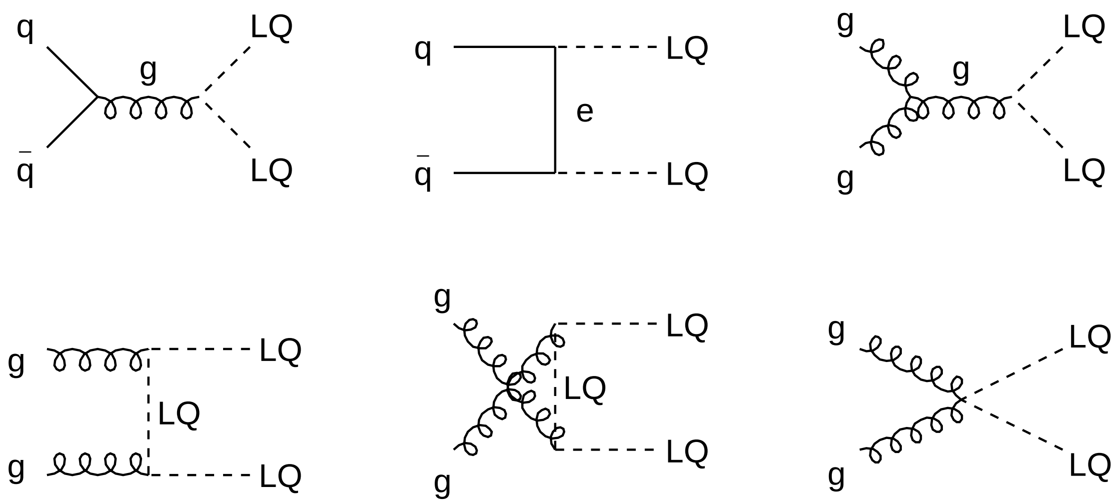
I. Dorsner, P. F. P, R. Gonzalez Felipe, Nucl. Phys. B (2006), hep-ph/0512068



$\tau_p \leq 1.4 \times 10^{36}$ years

$\tau_p > 10^{33}$ years

Light Leptoquarks



Production channels at the LHC

$$\Phi_b = (\mathbf{3}, \mathbf{2}, 1/6) \quad \text{Light Leptoquarks}$$

$$(d^C)_L^T \, C^{-1} \, Y_\nu \, \Phi_b \, l_L \;=\; (d^C)_L^T \, C^{-1} \, Y_\nu \, (\phi_b^1 \, e_L \;-\; \phi_b^2 \, \nu_L),$$

Tevatron experiments have set limits on scalars leptoquarks with couplings to eq of $M_{LQ} > 242$ GeV. **Preliminary studies by the LHC experiments ATLAS and CMS indicate that clear signals can be established for masses up to about $M_{LQ} \approx 1.3$ TeV.**(Abdullin, Charles, hep-ph/9905396; Mitsou, Benekos, Panagoulias, Papadopoulou, hep-ph/0411189)

Summary

Is there an upper bound on the proton lifetime?

$$\tau_p \leq 6.0 \times 10^{39} \, \frac{(M_V/10^{16}\,\mathrm{GeV})^4}{\alpha_{GUT}^2} \, (0.003\,\mathrm{GeV}^3/\beta)^2 \,\mathrm{years}$$

if $\alpha_{GUT} = 1/39 - 1/25$: $M_V \; > \; (4.9 - 6.1) \times 10^{13}\,\mathrm{GeV}$

What is the minimal realistic extension of the Georgi Glashow model?

- It is possible to achieve unification in the context of a minimal non-SUSY $SU(5)$, where the Higgs sector is composed of $\mathbf{5}_H$, $\mathbf{15}_H$ and $\mathbf{24}_H$.

How can we test a minimal realistic non-SUSY GUT?

- This GUT model can be tested at the next generation of proton decay experiments $\tau_p \; < \; 1.4 \times 10^{36}$ years.

- In order to achieve unification the theory predicts light leptoquarks. Therefore, it could be a possibility to test the GUT idea at future colliders, particularly at the LHC.