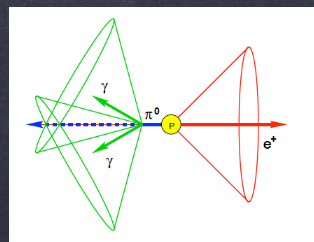
New Physics and Proton Decay

Pavel Fileviez Perez

CASE WESTERN RESERVE UNIVERSITY EST. 1826

NNN16, Beijing, Nov 2016



Main References

P. F. P., Physics Reports 597 (2015) 1

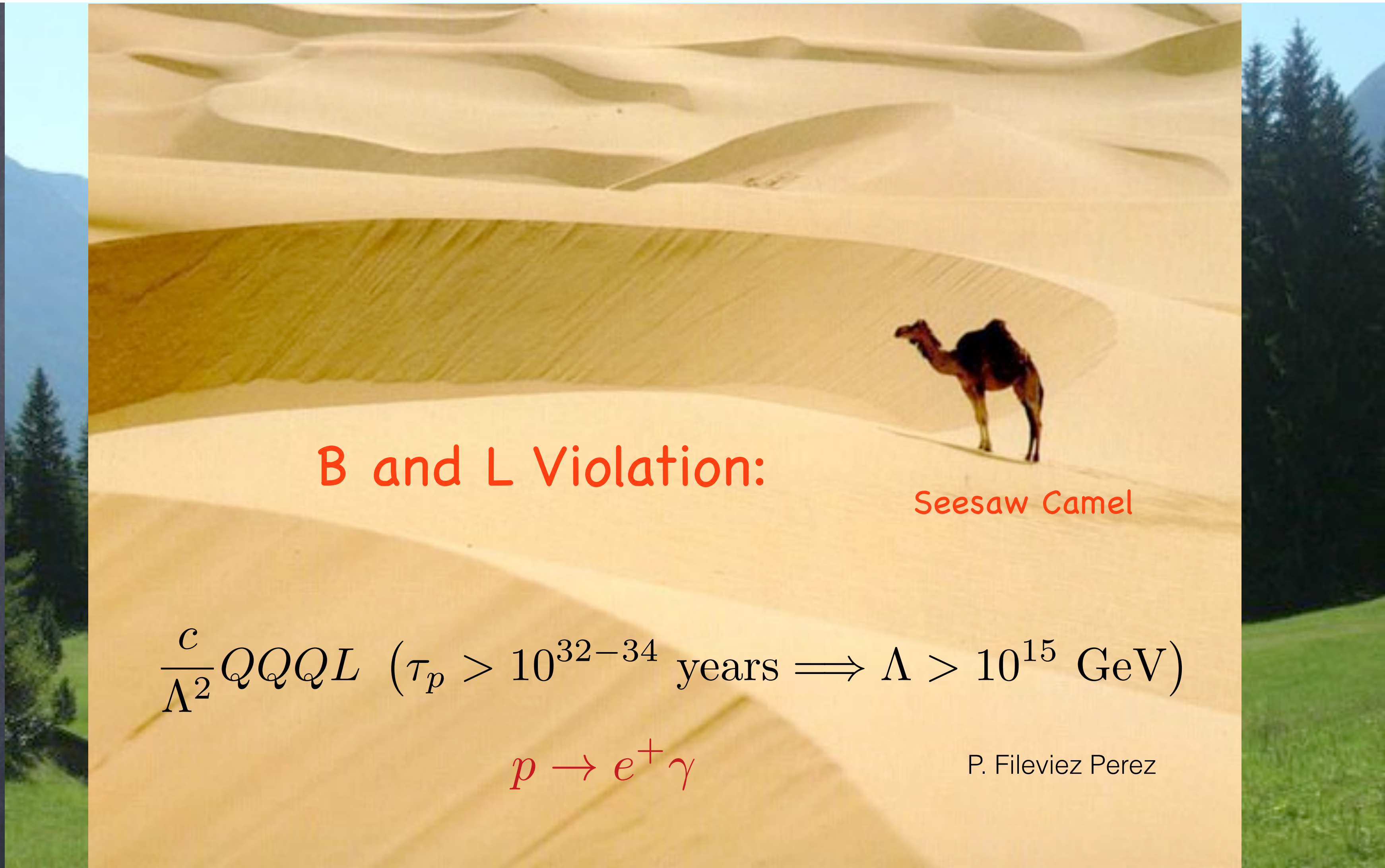
P. Nath, P. F. P., Physics Reports 441 (2007) 191

P. F. P., C. Murgui, Phys.Rev. D94 (2016) 7, 075014

The Desert Hypothesis in Particle Physics

LOW SCALE

HIGH SCALE



Standard Model

$\Lambda_{\text{Weak}} \sim 100 \text{ GeV}$

GUTs, Strings ?

$\Lambda \sim 10^{15-19} \text{ GeV}$

Georgi-Glashow Model SU(5)

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

Our starting point is the assumption that *weak and electromagnetic forces are mediated by the vector bosons of a gauge-invariant theory with spontaneous symmetry breaking.* A model describing the interactions of leptons using the gauge group SU(2) $\otimes$ U(1) was first proposed by Glashow, and was improved by Weinberg and Salam who incorporated spontaneous symmetry breaking.[1] This scheme can also describe had-

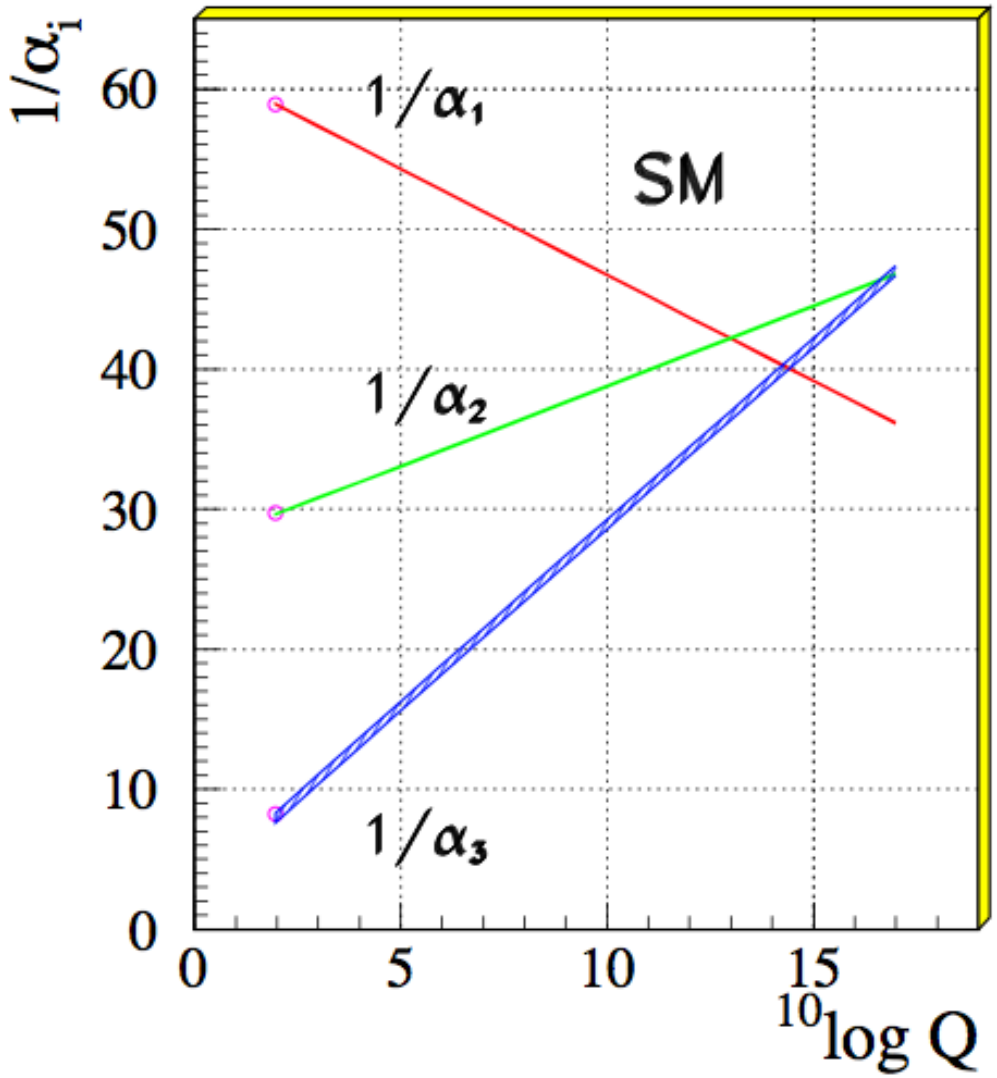
of the GIM mechanism with the notion of colored quarks[4] keeps the successes of the quark model and gives an important bonus: Lepton and hadron anomalies cancel so that the theory of weak and electromagnetic interactions is renormalizable.[5]

The next step is to include strong interactions. We assume that *strong interactions are mediated by an octet of neutral vector gauge gluons* associated with local color SU(3) symmetry, and

actions are associated with a non-Abelian theory, they may be asymptotically free.[9]

Running of the gauge couplings in the SM

Lyman L ... *tts 02138*

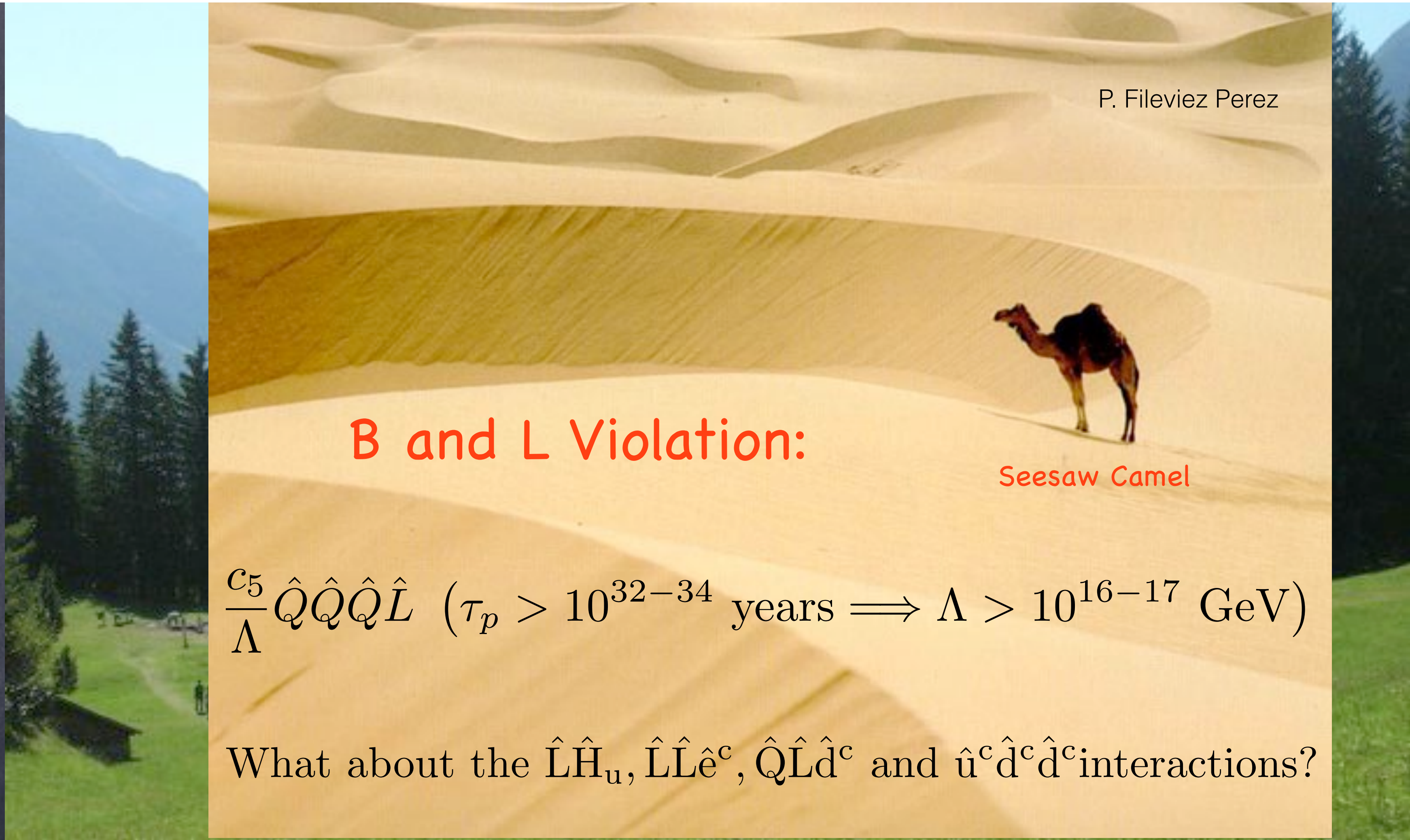


We pres ... which make
strong int ... , and weak
interactio ... ontaneous
breakdow ... almost the
Planck ma

The scaling observ ... is. In order to sup-
scattering suggests t ... ns, Georgi and Gla-
the strong interactio ... sumption[7] that some
energies. Asymptoti ... ry.
the strong interactio ... nple gauge group unit-
planation: The gluon ... romagnetic interac-
fined as the value of ... ive. However, as
mion-fermion vertex ... lashow, the success
ized by a mass μ) is ... n an understanding
GeV or larger, but b ... the obvious disparity
small, through the p ... ng and the weak and
countered in perturb ... at ordinary ener-
calculation[2] a fit was ... present in this paper
[in a color SU(3) mod ... calculation of such
$\mu \simeq 2$ GeV. ... effects. This will lead us to an estimate of the

The Desert Hypothesis and Supersymmetry

LOW SCALE



B and L Violation:

$$\frac{c_5}{\Lambda}\hat{Q}\hat{Q}\hat{Q}\hat{L} \ \ (\tau_p > 10^{32-34} \text{ years} \Longrightarrow \Lambda > 10^{16-17} \text{ GeV})$$

What about the $\hat{\mathrm{L}}\hat{\mathrm{H}}_{\mathrm{u}}, \hat{\mathrm{L}}\hat{\mathrm{L}}\hat{\mathrm{e}}^{\mathrm{c}}, \hat{\mathrm{Q}}\hat{\mathrm{L}}\hat{\mathrm{d}}^{\mathrm{c}}$ and $\hat{\mathrm{u}}^{\mathrm{c}}\hat{\mathrm{d}}^{\mathrm{c}}\hat{\mathrm{d}}^{\mathrm{c}}$interactions?

HIGH SCALE

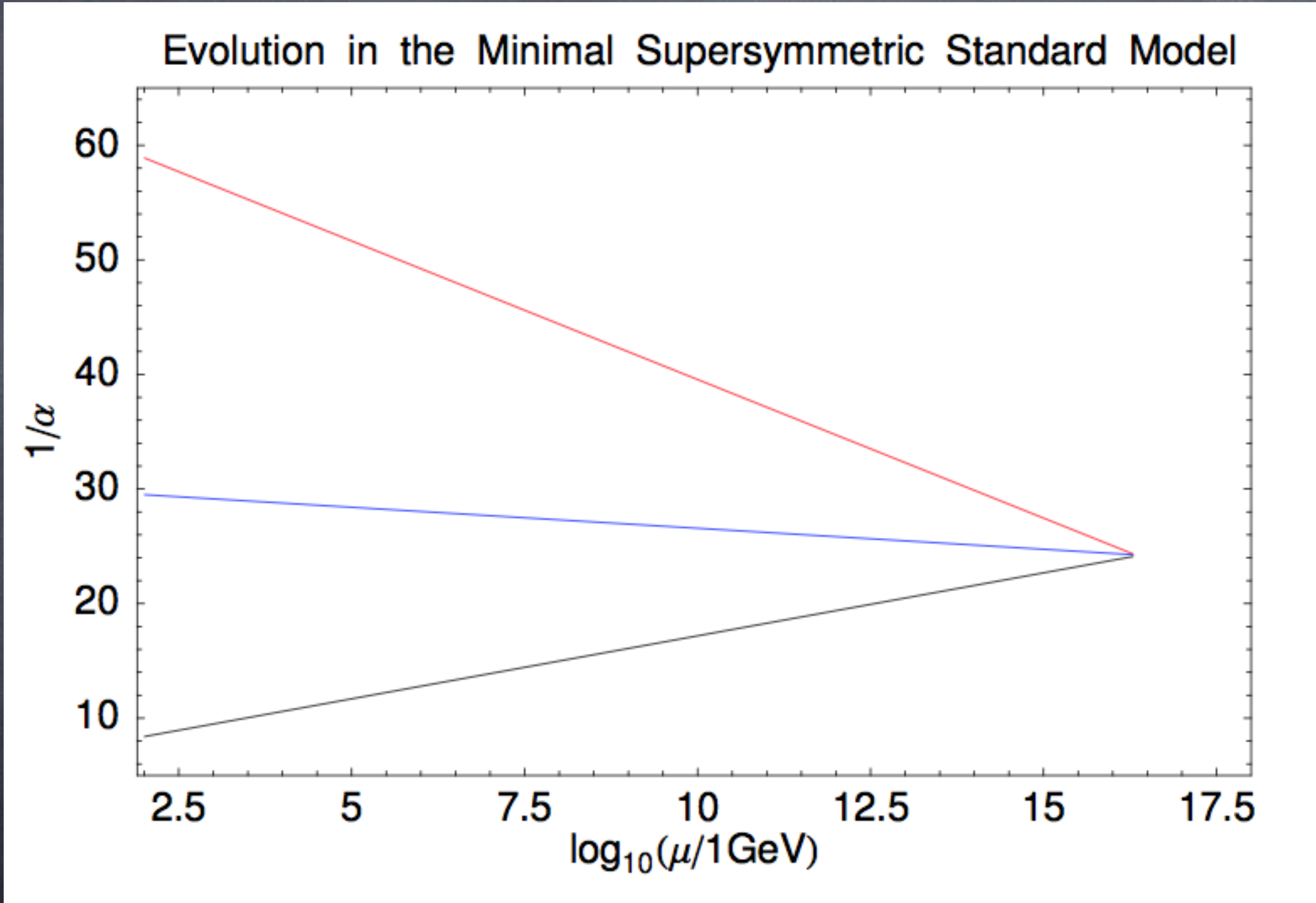
Unification of Gauge Couplings !

MSSM

10 TeV ? 100 TeV ? ...

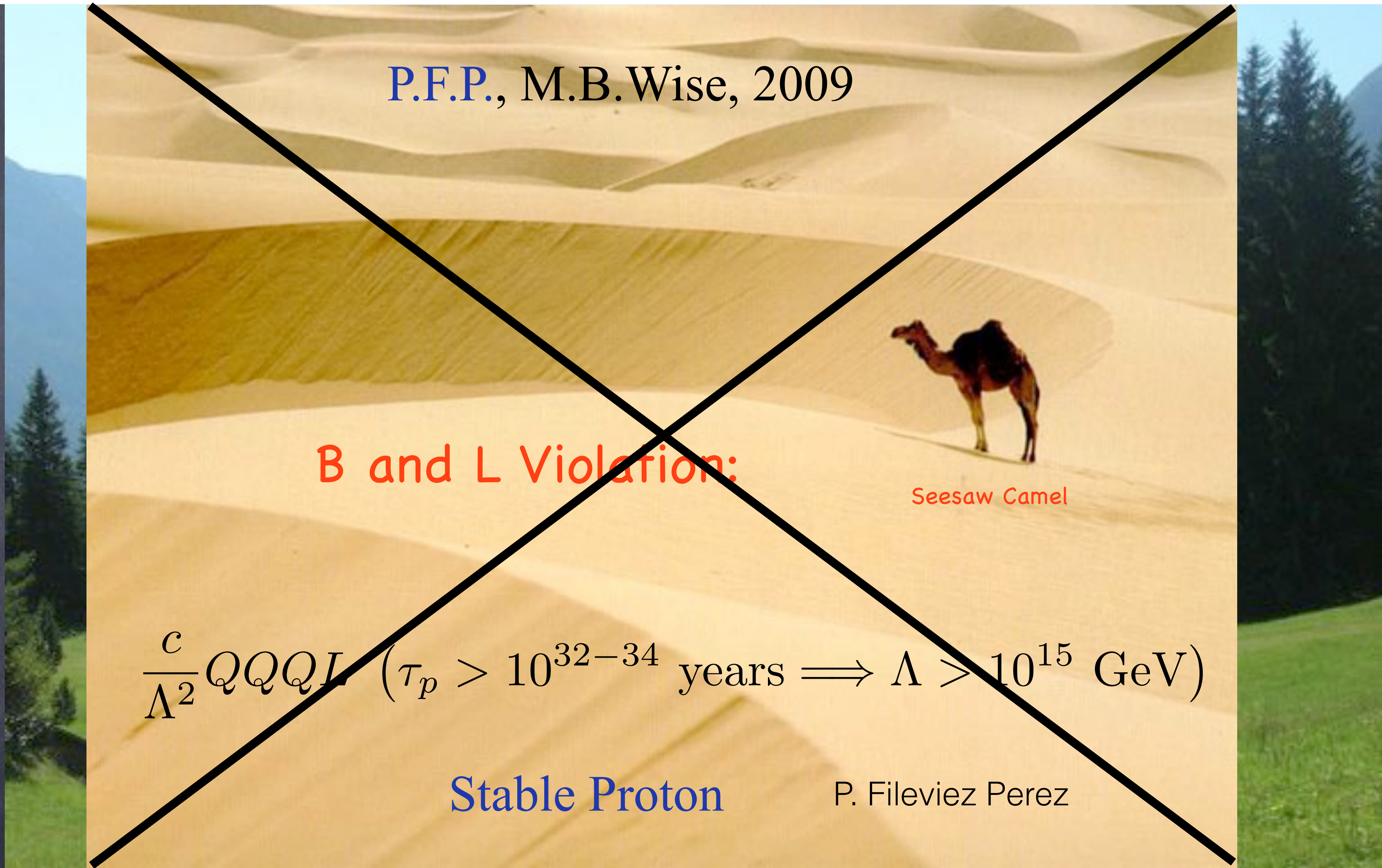
GUTs, Strings ?

Running of the gauge couplings in the MSSM



The Desert Hypothesis in Particle Physics

L O W S C A L E



H I G H S C A L E

Standard Model

$\Lambda_{\text{Weak}} \sim 100 \text{ GeV}$

GUTs, Strings ?

$\Lambda \sim 10^{15-19} \text{ GeV}$

Aim

Physics beyond the SM vs. Proton Decay

Proton Decay in Grand Unified Theories

Maybe the proton is stable and the great Desert is not needed

Main focus of this talk !

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Outline

- Introduction
- Grand Unification vs. Proton Decay
- Nucleon Decay in Supersymmetry
- Summary

Introduction

Proton Stability

SM: In the renormalizable SM the proton is stable !
Baryon number is a global symmetry broken at the quantum level by SU(2) instanton processes in 3 units $(\Delta B = 3)$

Matter Unification: In theories where quarks and leptons are unified one could have B violating interactions which mediate proton decay (Pati, Salam, 1973)

$$p \to \gamma \; e^+, \pi^0 \; e^+, ...(\Delta B = 1)$$

GUTs: In grand unified theories (SU(5), SO(10),..) B is explicitly broken at the high scale and generically one predicts proton decay.

SUSY: In the MSSM B and L are explicitly broken at the renormalizable level by RpV interactions and generically one predicts proton decay.

$$R = (-1)^{3(B-L)+2S}$$

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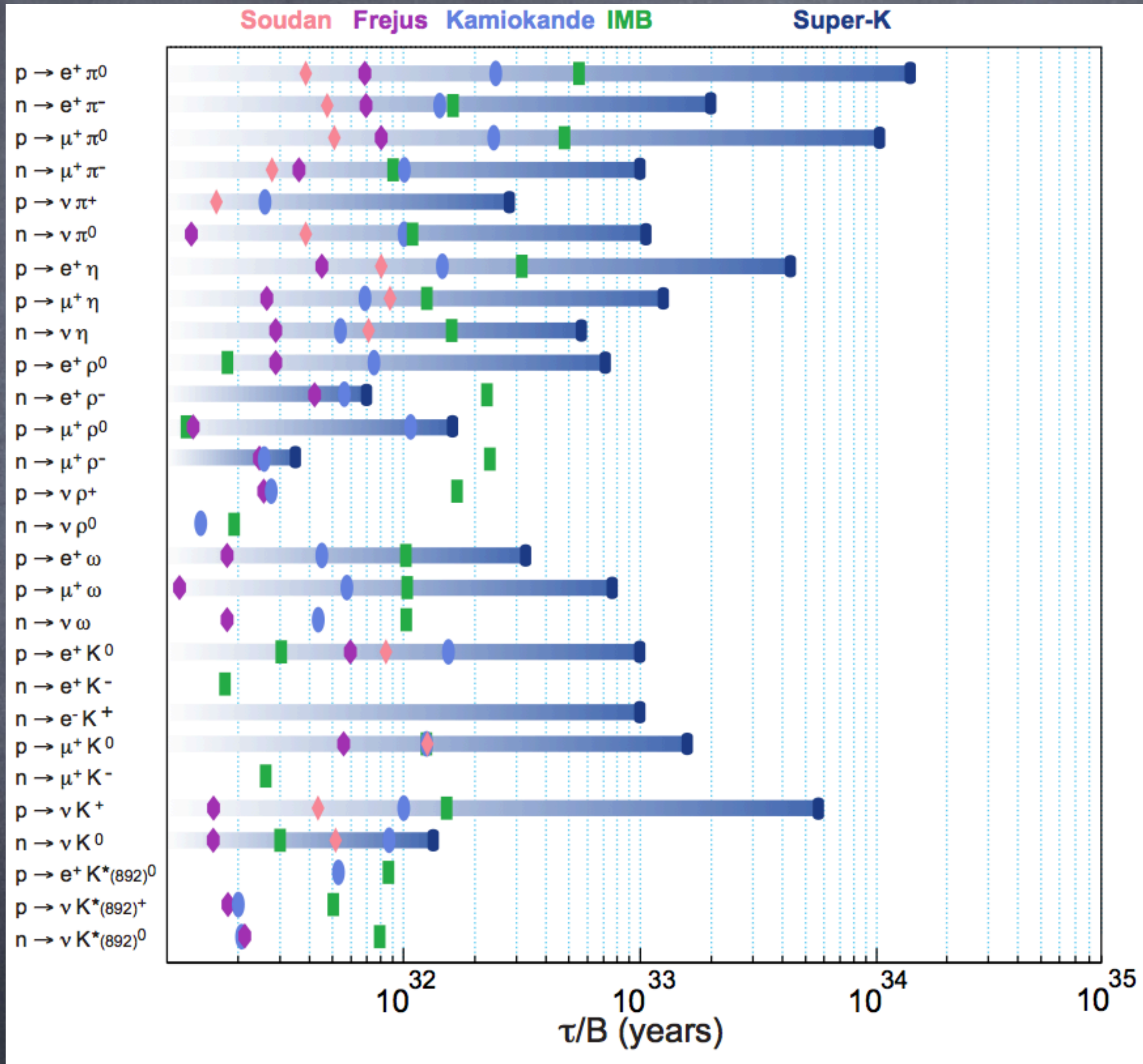
Experimental Results: $\Delta B = 1, \ \Delta L = \text{odd}$



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Grand Unification vs. Proton Decay

Non-SUSY GUTs

d=6 gauge:

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

after integrating out the superheavy gauge bosons.

$$c(e^c, d),\;\; c(e, d^c)\; \&\; c(\nu, d, d^c) \;\sim\; g_{GUT}^2 / M_V^2$$

$$M_V > 10^{14-15}\ \text{GeV}$$ naive !

in agreement with gauge coupling unification at the high scale.

Unfortunately, the values of the Wilson coefficients can change dramatically in different models !

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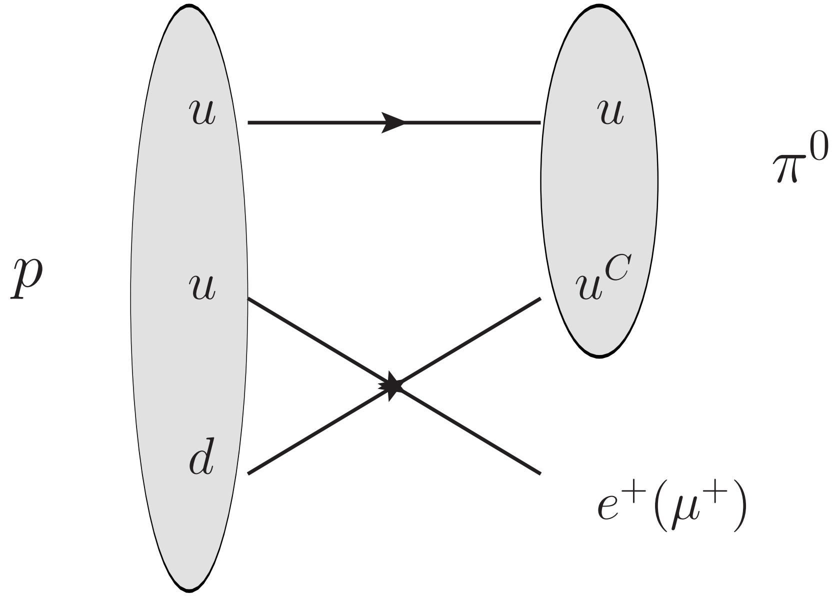

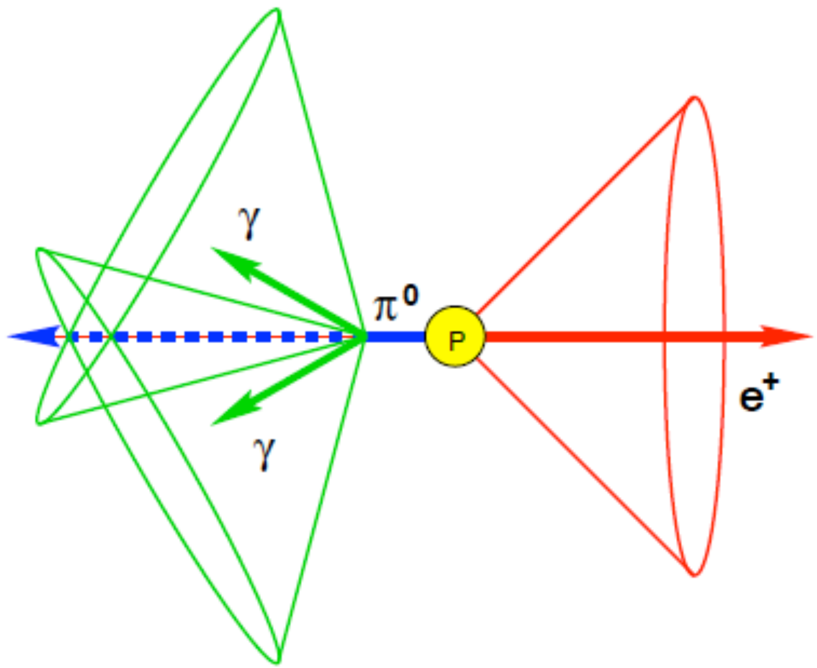

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Georgi-Glashow Model

Georgi, Glashow, Phys.Rev.Lett.32:438-441,1974

$$G_{SM} \;=\; SU(3) \bigotimes SU(2) \bigotimes U(1) \subset SU(5)$$

$$\alpha_3 \qquad \alpha_2 \qquad \alpha_1 \quad \longrightarrow \quad \alpha_5$$

Matter Assignment

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

Higgs Bosons

$$\mathbf{5_H} = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ H^+ \\ H^0 \end{pmatrix} \qquad \mathbf{24_H} = \begin{pmatrix} \Sigma_8 & \Sigma_{(3,2)} \\ \Sigma_{(\bar{3},2)} & \Sigma_3 \end{pmatrix} + \frac{1}{2\sqrt{15}} \begin{pmatrix} 2 & 0 \\ 0 & -3 \end{pmatrix} \Sigma_{24}$$

Georgi-Glashow Model

Georgi, Glashow, Phys.Rev.Lett.32:438-441,1974

$$A_\mu = \frac{1}{2}\lambda_a A_\mu^a = \frac{1}{2}\begin{pmatrix} G_\mu, B_\mu & V_\mu \\ V_\mu^* & W_\mu, B_\mu \end{pmatrix} \quad V_\mu = \sqrt{2}\begin{pmatrix} X_{1\mu} & Y_{1\mu} \\ X_{2\mu} & Y_{2\mu} \\ X_{3\mu} & Y_{3\mu} \end{pmatrix}$$

– New B violating interactions $\rightarrow$ THE PROTON IS UNSTABLE !!!

$$\bar{5}^\dagger \gamma^0 i \gamma^\mu D_\mu \bar{5} \rightarrow g_5 \, \overline{(d^C)}_L \, \gamma^\mu \, (X_\mu e_L - Y_\mu \nu_L)/\sqrt{2}$$

$$Tr\overline{10} i \gamma^\mu D_\mu 10 \rightarrow g_5 \, \overline{(e^C)}_L \, \gamma^\mu \, (X_\mu d_L - Y_\mu u_L)/\sqrt{2} +$$

$$g_5 \left(\overline{u}_L \, \gamma^\mu \, X_\mu (u^C)_L + \overline{d}_L \, \gamma^\mu \, Y_\mu (u^C)_L \right) /\sqrt{2}$$

$$\mathcal{O}(e_\alpha^C, d_\beta) = k_1^2 \, c(e_\alpha^C, d_\beta) \, \epsilon_{ijk} \, \overline{u_i^C} \, \gamma^\mu \, u_j \, \overline{e_\alpha^C} \, \gamma_\mu \, d_{k\beta}$$

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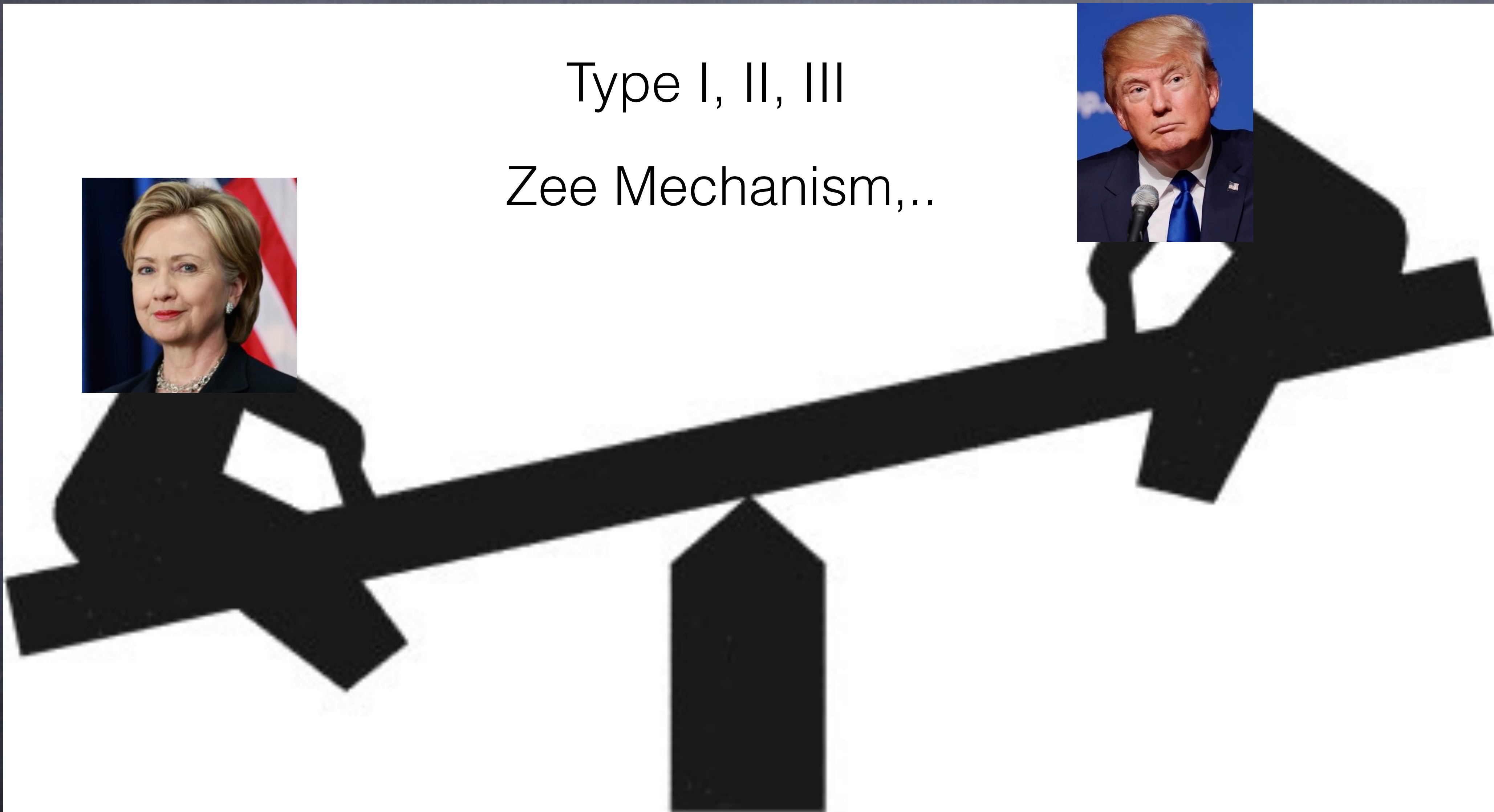
Why the Georgi-Glashow model is ruled out ?

- The unification of gauge couplings in disagreement with the experiments
- $M_E = M_D^T$ at the GUT scale in disagreement with the experiments
- $M_\nu = 0$

What are the simplest realistic extensions of the Georgi-Glashow Model ?

Type II-SU(5)	I. Dorsner, **P. F. P.**, Nucl. Phys. B723 (2005)53
Type III-SU(5)	B. Bajc, G. Senjanovic, Nucl. Phys. B723 (2005)53
Minimal Renormalizable SU(5)	**P. F. P.**, C. Murgui, Phys.Rev. D94 (2016) 7, 075014

Seesaw Mechanism



I. Dorsner, P.F.P Nucl.Phys.B723:53-76,2005

Type II-SU(5)

Matter: $\bar{5} = (d^C, e, \nu)$, $10 = (u^C, Q, e^C)$

$\tau_p < 2 \times 10^{36}$ years

Higgs Sector: 5_H, 24_H, 15_H

$$15 = \underbrace{(1,3,1)}_{\Delta} \bigoplus \underbrace{(3,2,1/6)}_{\Phi_b} \bigoplus \underbrace{(6,1,-2/3)}_{\Phi_c}$$

Neutrino Mass through the Type II seesaw mechanism:

$Y_\nu \, \bar{5} \, \bar{5} \, 15_H \; + \; \mu \, 5_H^* \, 5_H^* \, 15_H + \text{h.c.}$

$$M_\nu = Y_\nu < \Delta >= Y_\nu \, \mu \, v_W^2 / M_\Delta^2$$

Charged Fermion Masses: $Y_E \neq Y_D^T$ higher-dimensional operators

Unification: O.K. The theory predicts a light scalar leptoquark Φ_b

See also: I. Dorsner, P.F.P, R. González Felipe, Nucl.Phys.B747:312-327,2006
I. Dorsner, P.F.P, G. Rodrigo, Phys. Rev. D75 (2007) 125007

Type III seesaw and Non-SUSY Unification

B. Bajc, G. Senjanović, hep-ph/0612029

Matter: $\bar{5} = (d^C, e, \nu)$, $10 = (u^C, Q, e^C)$, 24

$\tau_p < 10^{36-37}$ years

Higgs Sector: 5_H, 24_H

$$24 = \underbrace{(8,1,0)}_{\rho_8} \oplus \underbrace{(1,3,0)}_{\rho_3} \oplus \underbrace{(3,2,-5/6)}_{\rho_{(3,2)}} \oplus \underbrace{(\bar{3},2,5/6)}_{\rho_{(\bar{3},2)}} \oplus \underbrace{(1,1,0)}_{\rho_0}$$

Neutrino Mass:

$$Y_0^i\, \bar{5}_i\, 24\, 5_H \;+\; \frac{1}{\Lambda}\, \bar{5}_i \times (\, Y_1^i\, 24\, 24_H \;+\; Y_2^i\, 24_H\, 24 \;+\; Y_3^i\, Tr(24\, 24_H))\, 5_H$$

Charged Fermion Masses: $Y_E \neq Y_D^T$ using higher-dimensional operators

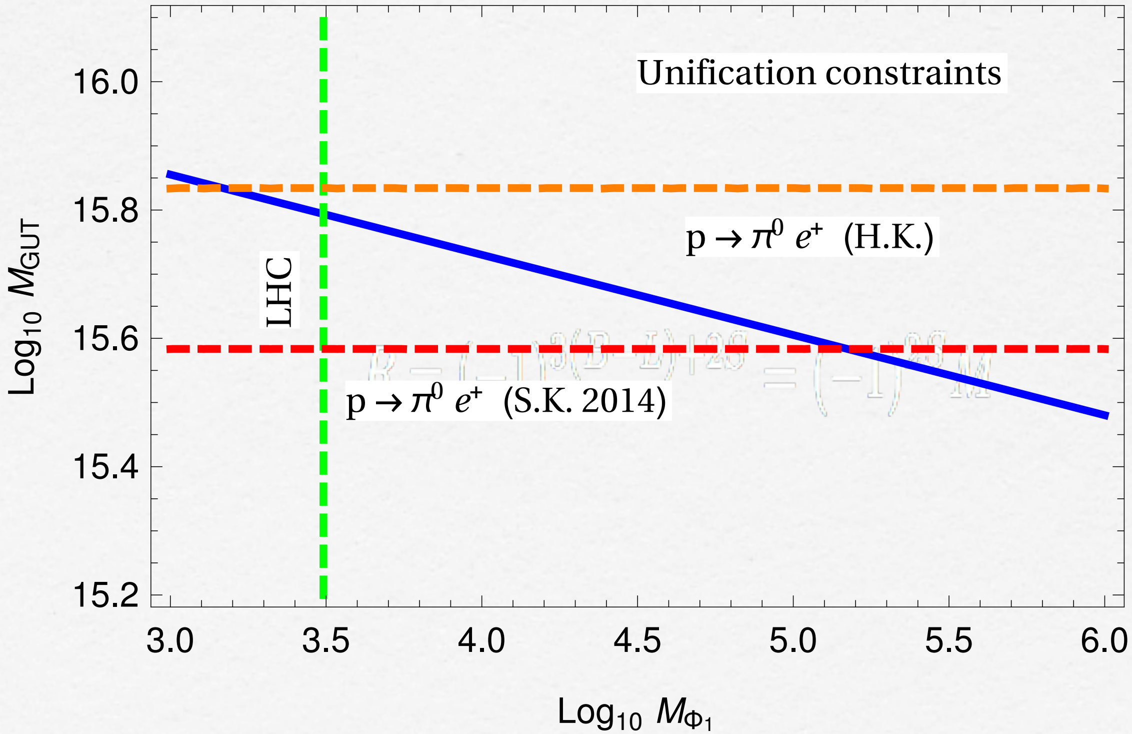
Unification: O.K. The theory predicts a light fermionic SU(2) triplet ρ_3

See also: I. Dorsner, P.F.P, JHEP 0706:029,2007.

Renormalizable SU(5)

P. F. P., C. Murgui, Phys.Rev. D94 (2016) 7, 075014

$$5_H, 24_H, 45_H$$



$$45_H \subset \Phi_1 \sim (8, 2, 1/2)$$

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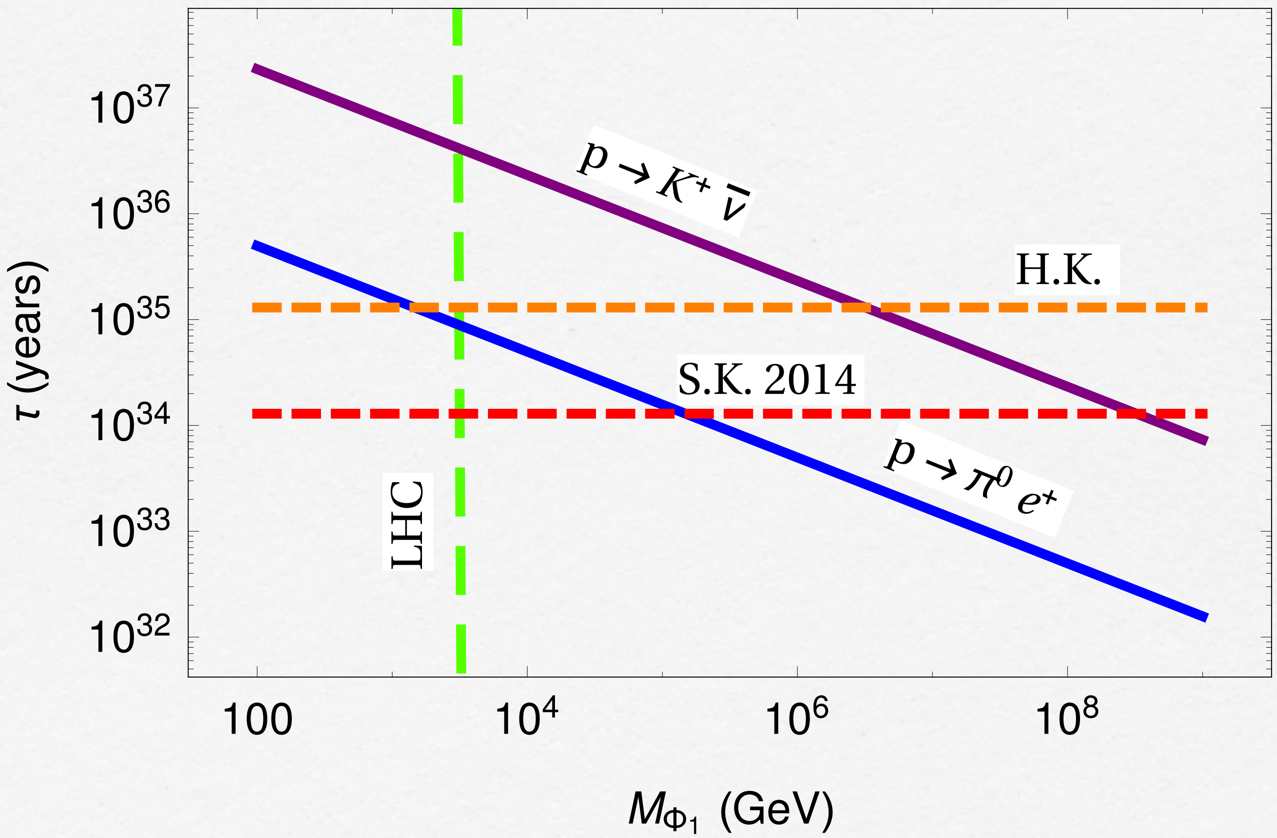
Proton decay in Minimal Renormalizable SU(5)

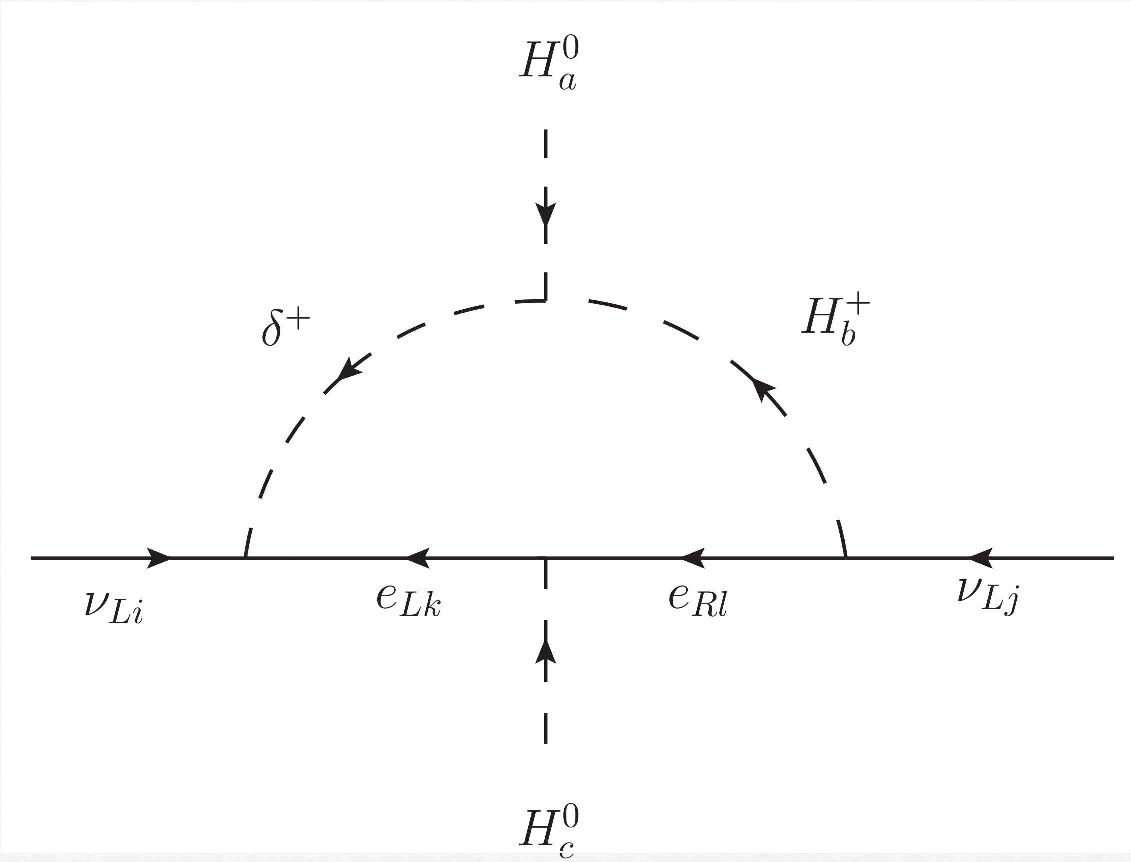
P. F. P., C. Murgui, Phys.Rev. D94 (2016) 7, 075014



$$45_H \subset \Phi_1 \sim (8, 2, 1/2)$$

Neutrino Mass - Minimal Renormalizable SU(5)

P. F. P., C. Murgui, Phys.Rev. D94 (2016) 7, 075014



Nucleon Decay in Supersymmetry

MSSM Interactions

$$\mathcal{W}_{RpC} = Y_u Q H_u u^c + Y_d Q H_d d^c + Y_e L H_d e^c + \mu H_u H_d$$

$$\mathcal{W}_{RpV} = \epsilon L H_u + \lambda L L e^c + \lambda^{'} Q L d^c + \lambda^{''} u^c d^c d^c$$

$$R = (-1)^{3(B-L)+2S} = (-1)^{2S} M$$

LSP $\tilde{\chi}_1^0 = \left(\tilde{B}, \tilde{W}, \tilde{H}_u^0, \tilde{H}_d^0\right)$ ⇒ **Cold Dark Matter !**

ν_i ⇒ **Massless Neutrinos !**

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B and L Violation in the MSSM

$$\mathcal{W}_{RpV} = \epsilon L H_u + \lambda L L e^c + \lambda^{'} Q L d^c + \lambda^{''} u^c d^c d^c$$

$$\mathcal{W}^5_{RPC} = \frac{\lambda_\nu}{\Lambda} L L H_u H_u + \frac{\lambda_L}{\Lambda} Q Q Q L + \frac{\lambda_R}{\Lambda} u^c d^c u^c e^c$$

Missing energy at the LHC (DM) vs Neutrino Masses ?

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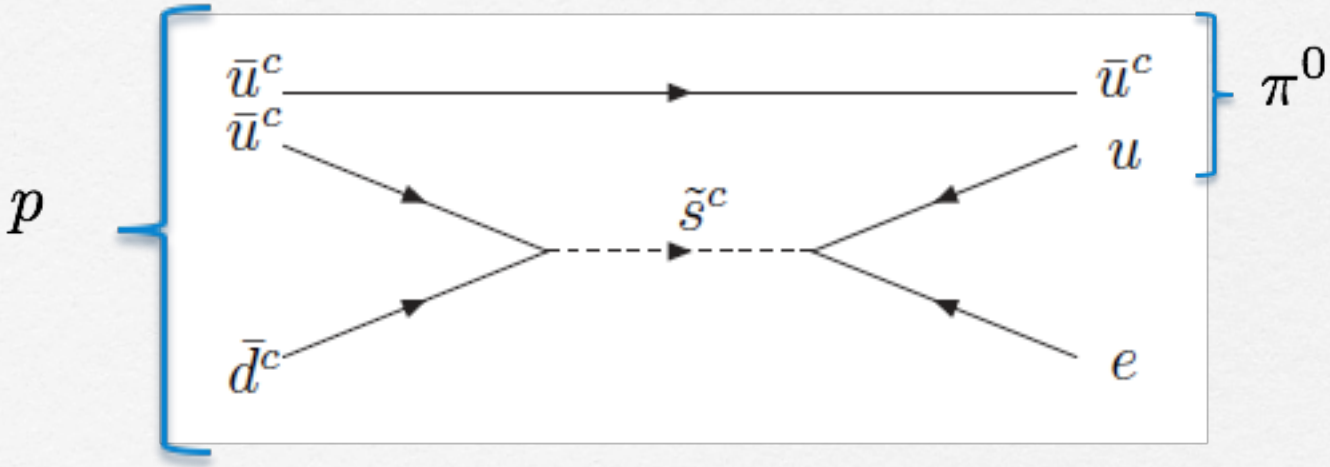
See e.g. P. Nath, P. Fileviez Perez, Physics Reports 441:191,2007

Proton Decay and M-Parity

$\lambda' Q L d^c$

$\lambda'' u^c d^c d^c$



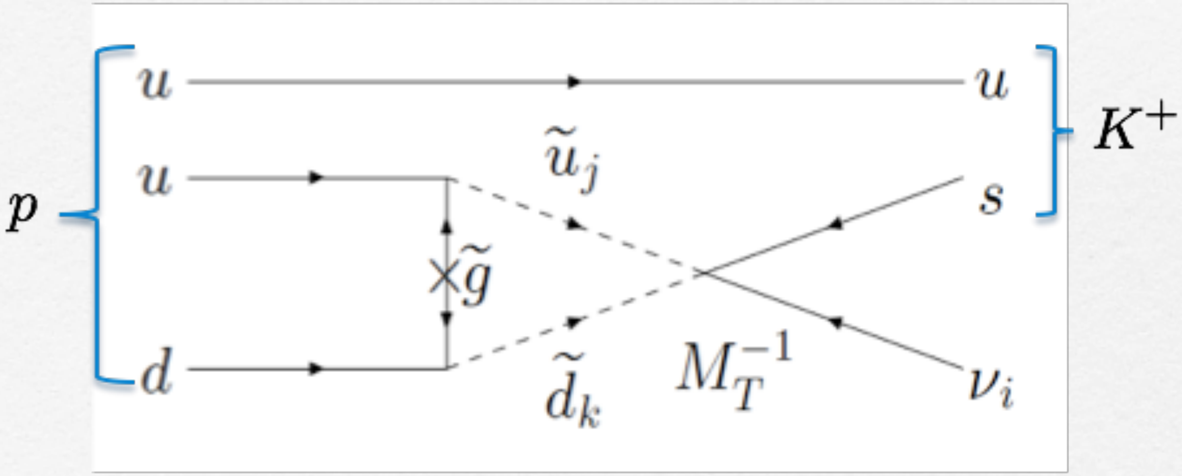
Channel : $\tau_{p \to \pi^0 e^+} > 10^{33}$ years

$M_{\tilde{q}} \sim 10^3$ GeV $\Rightarrow$ $\tau_4 \sim 10^{-20}$ years

d=5 operators

Example: $p \to K^+ \bar{\nu} \quad (\tau > 2.3 \times 10^{33} \text{years})$

$\frac{\lambda_L}{M_T} QQQL$

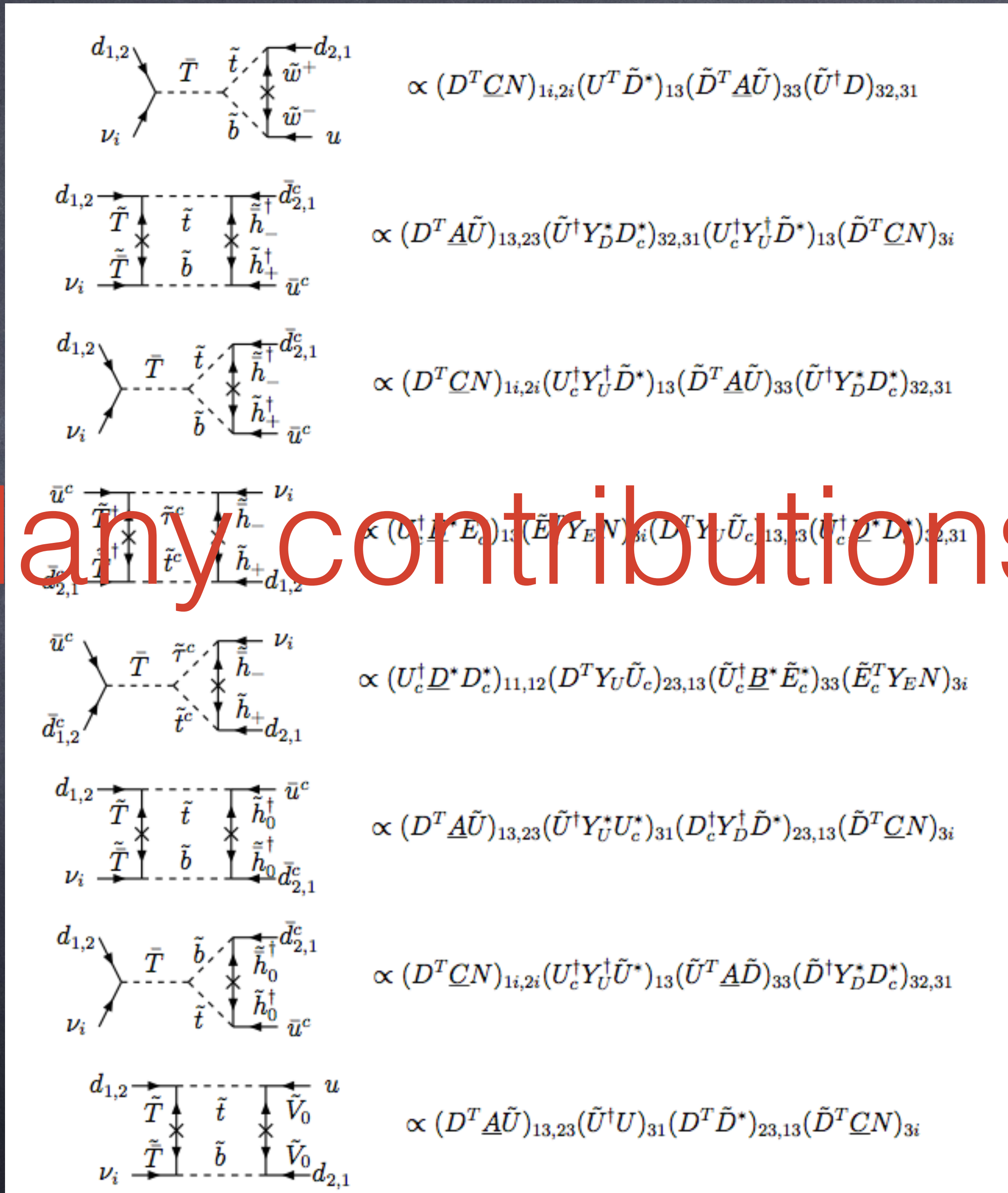


$M_T > 10^{17} \text{GeV (NAIVE)}$

Dimopoulos, Raby, Wilczek; Arnowitt, Chamseddine, Nath; Goto, Nihei; Lucas, Raby; Bajc, P.F.P., Senjanovic

d=5 contributions

Bajc, P.F.P., Senjanovic



Many contributions !

Minimal Supersymmetric $SU(5)$

S. Dimopoulos and H. Georgi NPB(1981); N. Sakai Z. Phys. C (1981)

Chiral Superfields: $\hat{\bar{5}}_i$, $\hat{10}_i$, $\hat{5}_H$, $\hat{\bar{5}}_H$, $\hat{24}_H$

Vector Superfields: $\hat{24}_G$

$$\hat{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & U_3^C & -U_2^C & U_1 & D_1 \\ -U_3^C & 0 & U_1^C & U_2 & U_2 \\ U_2^C & -U_1^C & 0 & U_3 & D_3 \\ -U_1 & -U_2 & -U_3 & 0 & E^C \\ -D_1 & -D_2 & -D_3 & -E^C & 0 \end{pmatrix}_L$$

$$\hat{\bar{5}} = \begin{pmatrix} D_1^C \\ D_2^C \\ D_3^C \\ E \\ -N \end{pmatrix}_L \qquad \hat{5}_H = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ H_2^+ \\ H_2^0 \end{pmatrix} \qquad \hat{\bar{5}}_H = \begin{pmatrix} \bar{T}_1 \\ \bar{T}_2 \\ \bar{T}_3 \\ H_1^- \\ -H_1^0 \end{pmatrix}$$

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

- Unification: O.K.
- $M_E = M_D^T$ $(b - \tau$ unification O.K.)
- $M_\nu = 0$ if R-parity is conserved

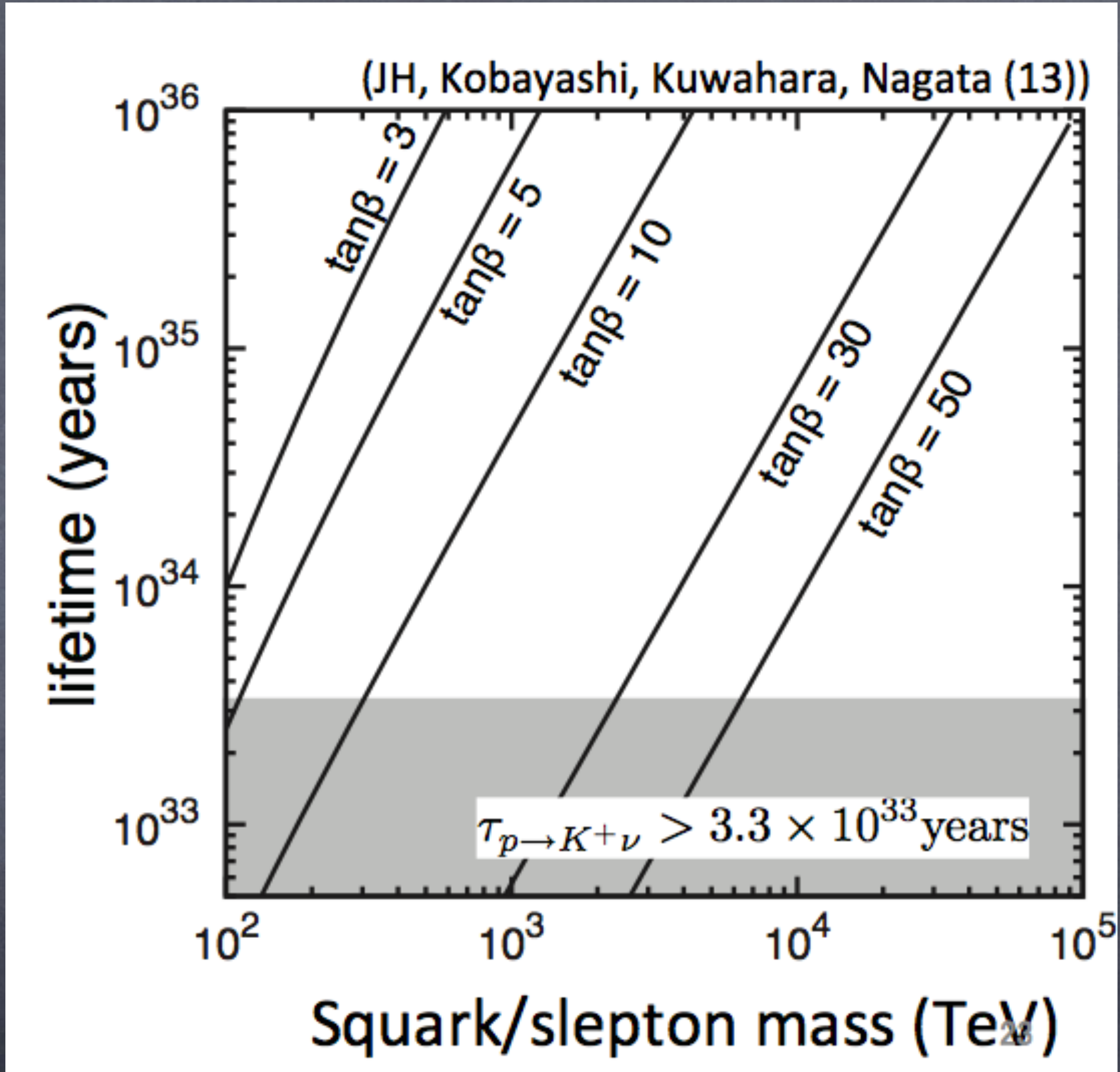
The Minimal Renormalizable SUSY $SU(5)$ is ruled out !!

The non-renormalizable SUSY SU(5) model is OK, see: Bajc, P.F.P., Senjanovic, 0210374; 0204311.

Unfortunately, the proton decay lifetime cannot be predicted in SUSY because one needs to know the full spectrum of supersymmetric particles !

In minimal SUSY $SU(5)$, assuming $m_{\tilde{q},\tilde{l}} \sim 1$ TeV: $M_T > 10^{17}$ GeV

Note that in general we do not know $(\widetilde{U}^\dagger\, U)_{j1}(\widetilde{D}^\dagger\, D)_{k1}$!!!



J. Hisano @ BLV2013

SO(10) GUTs and proton decay

$$16_F, \ 10_H, 126_H, 210_H, ...$$

These theories are considered very appealing because the fermions are unified in the 16 representation. However, one has different breaking scales and it is very difficult to predict the lifetime of the proton.

For recent studies see:

K.S. Babu, S. Khan, 2015
H. Kolesova, M. Malinsky, 2014
Mohapatra et al, 2012
Babu, Pati, Tavartkiladze, 2010

Summary

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The idea of grand unification is one of the most appealing ideas we have for new physics.

One can predict the lifetime of the proton in the simplest non-supersymmetric grand unified theories.

The minimal renormalizable SU(5) predictions could be tested at Hyper-Kamiokande or other experiments.

More experimental effort is needed to search for proton decay in the near future. Young people, new ideas and new techniques are needed in this field.

非常感謝你

Fēicháng gǎnxiè nǐ