Grand Unified Theories, Nucleon Decay and Flavor Physics

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GIAN Course on Electrowak Symmetry Breaking, Flavor Physics and BSM

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Unification of Forces and Matter

Electromagnetic, weak and strong forces share identical structure: all belong to gauge theories with unitary symmetry

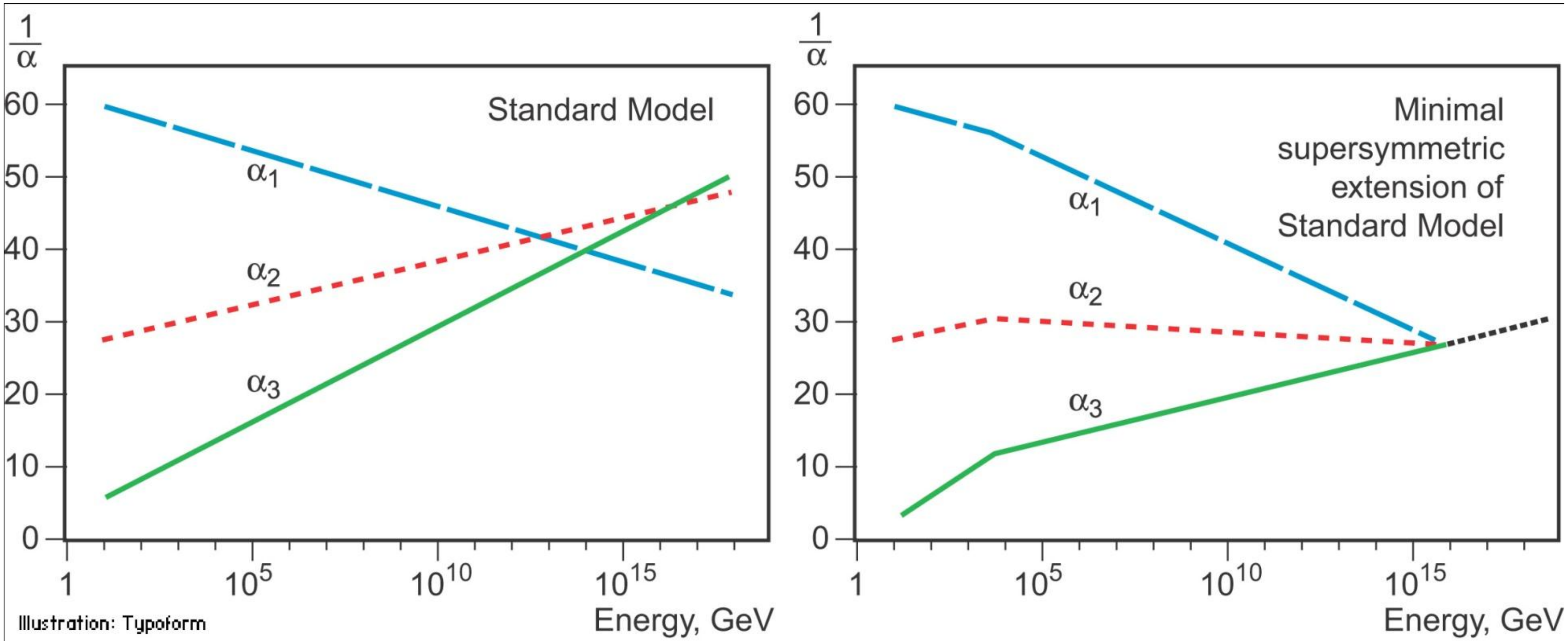
The high energy behavior of these theories support unification idea

Ordinary matter – quarks and leptons – fit neatly within multiplets of the unified symmetry

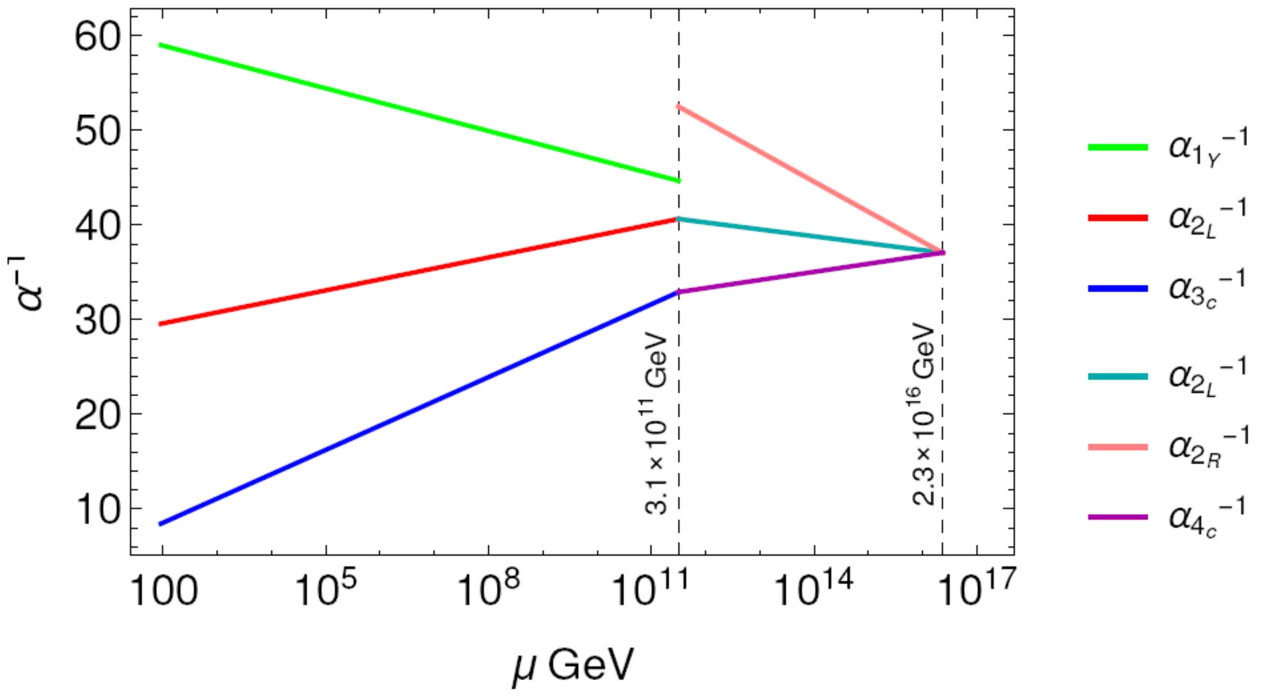
Unified theories are more predictive, many predictions agree with observations

Nucleon decay is the missing link; its discovery would be monumental

Evolution of gauge couplings with energy



Gauge coupling unification without supersymmetry



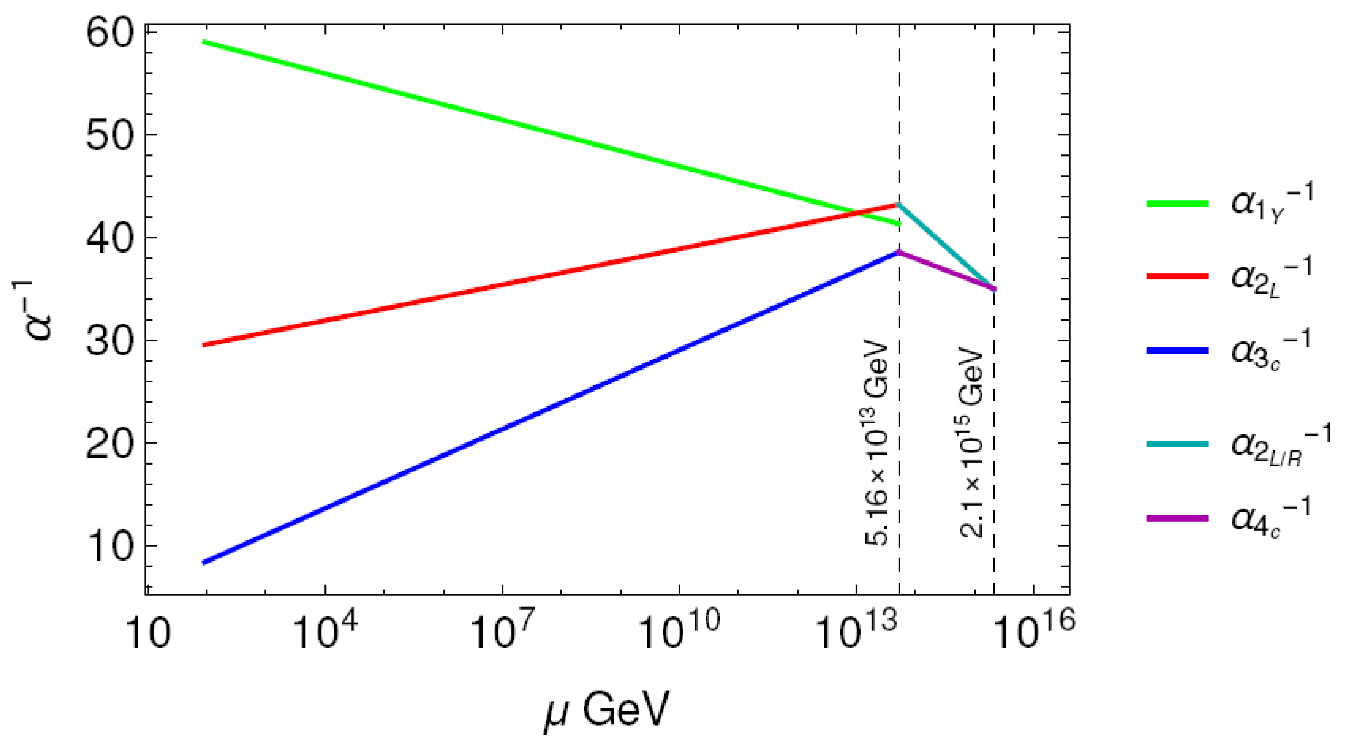
Non-SUSY $SO(10)$ GUTs allow intermediate gauge symmetry

Intermediate Pati-Salam symmetry: $SU(2)_L \times SU(2)_R \times SU(4)_c$

(without discrete Parity)

From: KSB, Bajc, Saad (2017)

Gauge coupling unification: Non-SUSY SO(10)



Intermediate Pati-Salam symmetry: $SU(2)_L \times SU(2)_R \times SU(4)_c \times P$

(with discrete Parity)

More Hints in favor of Unification

- Electric charge quantization
  - $Q_p = -Q_e$ to better than 1 part in 10^{21}
- Miraculous cancellation of anomalies
- Quantum numbers of quarks and leptons
- Existence of ν_R and thus neutrino mass
- Unification of gauge couplings with low energy SUSY
- $b - \tau$ unification
- Baryon asymmetry of the universe

Unifying Forces and Matter

First successful attempt by Pati and Salam (1973)

Based on $SU(4)_c \times SU(2)_L \times SU(2)_R$ gauge symmetry

$$\psi_L = \begin{pmatrix} u_1 & u_2 & u_3 & e \\ d_1 & d_2 & d_3 & \nu \end{pmatrix}_L, \quad \psi_R = \begin{pmatrix} u_1 & u_2 & u_3 & e \\ d_1 & d_2 & d_3 & \nu \end{pmatrix}_R$$

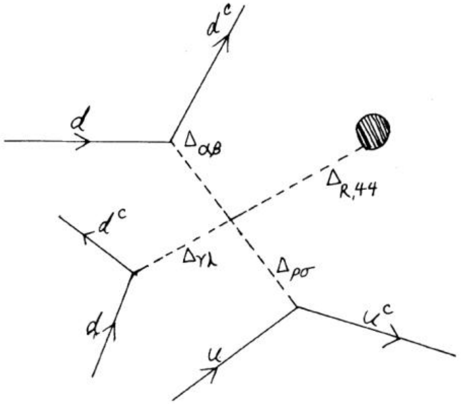
Lepton number identified as fourth color

Scale of $SU(4)_c$ breaking > 2300 TeV $(K_L \to \mu e)$

Baryon number violation occurs via scalar exchange with $|\Delta B| = 2$ selection rule

$n - \overline{n}$ oscillation occurs without proton decay

$$\mathcal{L}_{\rm eff} = \frac{uddudd}{\Lambda^5}$$



Marshak, Mohapatra (1980)

Unification in SU(5)

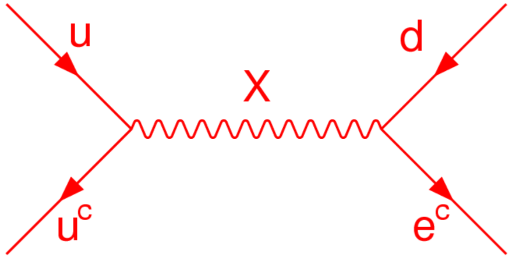
More complete unification of forces and matter discovered in SU(5) by Georgi and Glashow (1974)

$$\mathbf{10} : \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix} \qquad \bar{\mathbf{5}} : (d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

Quarks and leptons are unified

Particles unify with antiparticles $\Rightarrow$ Matter is unstable

$p \rightarrow e^+\pi^0$ decay



Symmetry Breaking in SU(5)

- The symmetry breaking sector consists of two types of Higgs fields. One is an adjoint $\mathbf{24}_H$–plet Σ, which acquires vacuum expectation value and breaks $SU(5)$ down to the SM gauge symmetry.
- The VEV of this traceless hermitian matrix is chosen as

$$\langle \Sigma \rangle = V.\text{diag}\left\{1,\, 1,\, 1,\, -\frac{3}{2},\, -\frac{3}{2}\right\} .$$

- Under $SU(5)$ gauge transformation $\Sigma \to U \Sigma U^{\dagger}$.

Fermion Masses in SU(5)

- The Yukawa couplings of fermions and the $(H\,,\overline{H})$ fields are obtained from the superpotential

$$W_{\rm Yuk} = \frac{(Y_u)_{ij}}{4}\psi_i^{\alpha\beta}\psi_j^{\gamma\delta}H^\rho\epsilon_{\alpha\beta\gamma\delta\rho} + \sqrt{2}\,(Y_d)_{ij}\psi_i^{\alpha\beta}\chi_{j\alpha}\overline{H}_\beta\,.$$

- Here (i,j) are family indices, and $(\alpha,\,\beta\ldots)$ are $SU(5)$ indices with ϵ being the completely antisymmetric Levi–Cevita tensor. The $\overline{H}$ field has components similar to χ , so that its fifth component is neutral and acquires a VEV: $\langle\overline{H}_5\rangle = v_d$.
- Similarly, the fifth component of H acquires a VEV: $\langle H_5\rangle = v_u$.
- When these VEVs are inserted, the following mass terms for quarks and leptons are generated:

$$\mathcal{L}_{\rm mass} = \frac{1}{2}(Y_u)_{ij}\,v_u\,(u_iu_j^c + u_ju_i^c) + (Y_d)_{ij}\,v_d\,(d_id_j^c + e_i^ce_j) + h.c.$$

$$M_u = Y_u\,v_u\,,\quad M_d = Y_d\,v_d\,,\quad M_\ell = Y_d^T\,v_d\,.$$

B-Tau Mass Unification in SU(5)

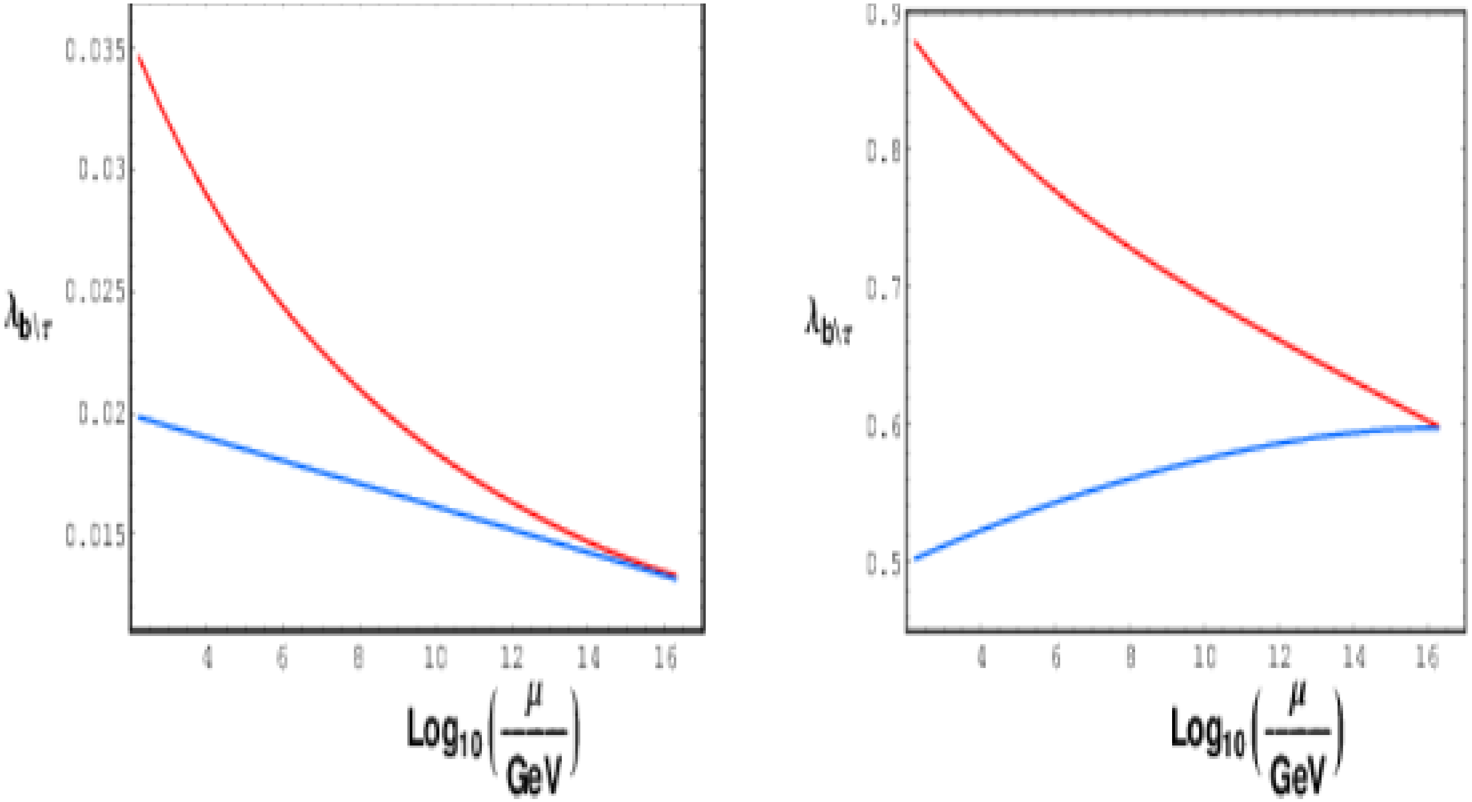


Figure: Evolution of the b–quark and τ–lepton Yukawa couplings in the MSSM for $\tan\beta = 1.7$ (left panel) and 50 (right panel). $m_b(m_b) = 4.65$ GeV has been used here.

Matter Fields in SO(10)

$SO(10)$ theories contain Pati-Salam and $SU(5)$ features

All particles and antiparticles are unified in **16**

SO(10)

$u_r : \{-++\ +-\}$	$d_r : \{-++\ -+\}$	$u_r^c : \{+--\ ++\}$	$d_r^c : \{+--\ --\}$
$u_b : \{+-+\ +-\}$	$d_b : \{+-+\ -+\}$	$u_b^c : \{-+-\ ++\}$	$d_b^c : \{-+-\ --\}$
$u_g : \{++-\ +-\}$	$d_g : \{++-\ -+\}$	$u_g^c : \{--+\ ++\}$	$d_g^c : \{--+\ --\}$
$\nu : \{---\ +-\}$	$e : \{---\ -+\}$	$\nu^c : \{+++\ ++\}$	$e^c : \{+++\ --\}$

Frist 3 spins refer to color, last 2 are weak spins

$$Y = \tfrac{1}{3}\Sigma(C) - \tfrac{1}{2}\Sigma(W)$$

ν^c state crucial for neutrino mass generation

Standard Model

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$u^c = (\, u_1^c \quad u_2^c \quad u_3^c \,) \sim (\bar{3}, 1, -\frac{2}{3})$$

$$d^c = (\, d_1^c \quad d_2^c \quad d_3^c \,) \sim (\bar{3}, 1, \frac{1}{3})$$

$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, -\frac{1}{2})$$

$$e^c \sim (1, 1, +1)$$

$$\nu^c \sim (1, 1, 0)$$

Georgi (1975); Fritzsch, Minkowski (1975)

SO(10) Unification (without SUSY)

Unlike $SU(5)$, $SO(10)$ allows an intermediate symmetry

$$SO(10) \rightarrow SU(4)_c \times SU(2)_L \times SU(2)_R \times P$$ **Pati-Salam symmetry**

Unification of gauge couplings consistent with data

Intermediate scale may be identified as Peccei-Quinn scale to solve strong CP problem

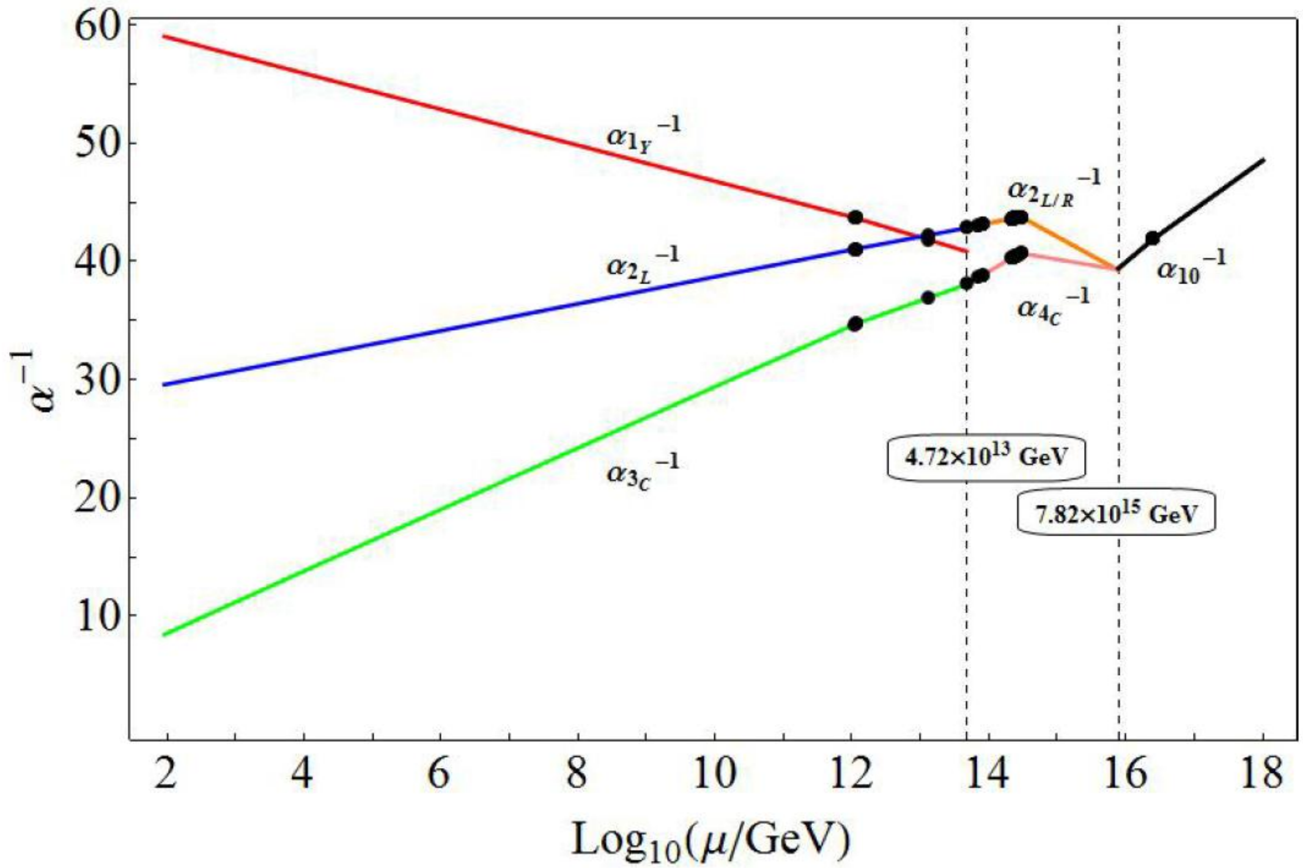
Proton decays via exchange of $SO(10)$ gauge bosons

Lifetime within reach of currently envisioned experiments

Rich literature:

Rizzo, Senjanovic (1980)
Mohapatra, Parida (1993)
Deshpande, Keith, Pal (1995)
Lee, Mohapatra, Parida, Rani (1995)
Bertolini, Luzio, Malinsky (2012)
Altarelli, Meloni (2013)
Babu, Khan (2015)

Gauge coupling evolution in non-SUSY SO(10)



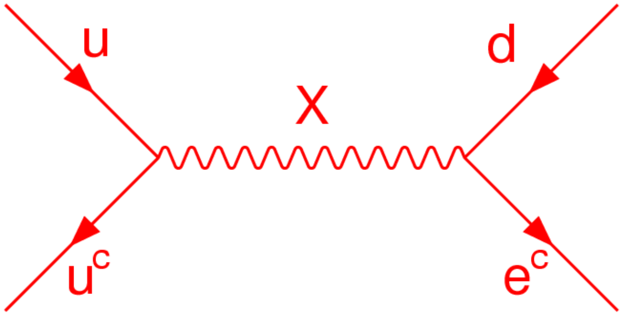
Intermediate symmetry: $SO(10) \rightarrow SU(4)_c \times SU(2)_L \times SU(2)_R \times P$

KSB, S. Khan (2015)

Nucleon Decay in non-SUSY SO(10)

$SO(10)$ breaks to an intermediate Pati–Salam symmetry
$SU(2)_L \times SU(2)_R \times SU(4)_c \times P$

Proton decays to $e^+\pi^0$ via GUT scale X, Y gauge boson exchange



$$\Gamma^{-1}(p \to e^+\pi^0) \approx (8.2 \times 10^{34}\ \text{yr}) \times \left(\frac{\alpha_H}{0.0122\ \text{GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/34.7}\right)^{-2} \left(\frac{A_R}{3.35}\right)^{-2} \left(\frac{M_X}{10^{16}\ \text{GeV}}\right)^{4}$$

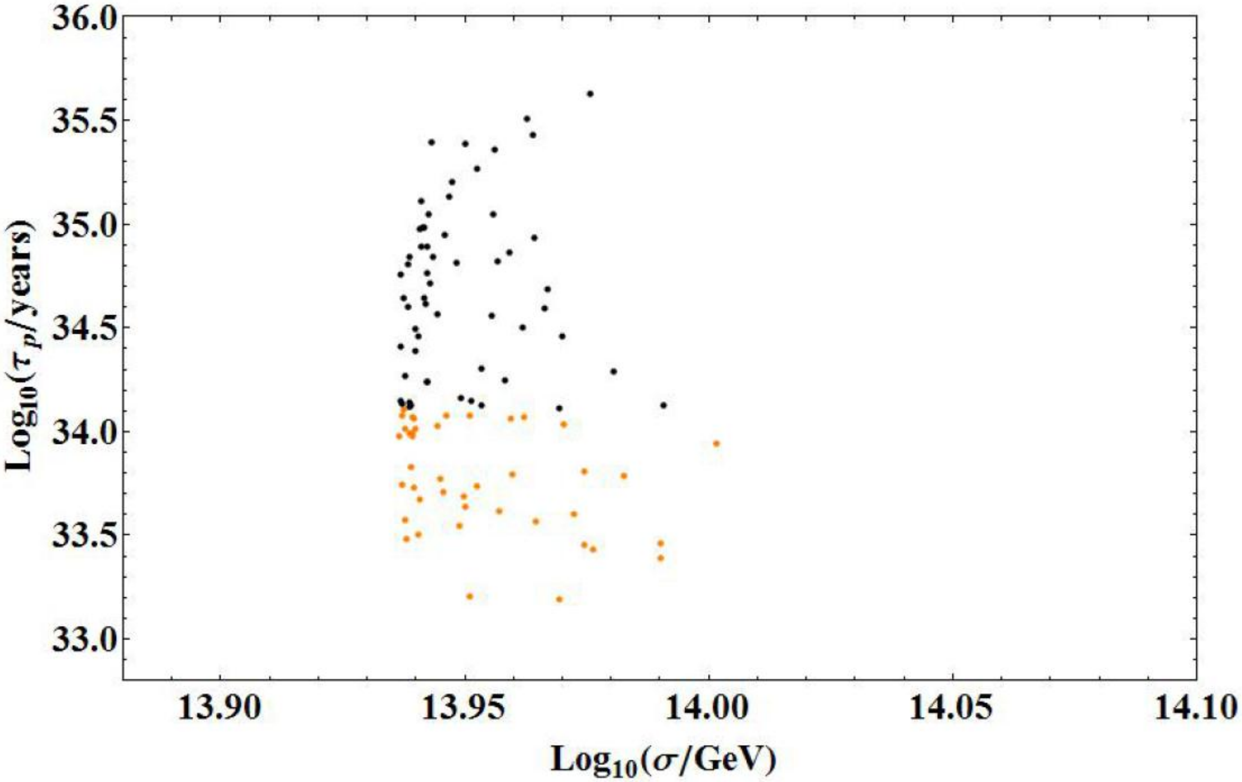
Threshold corrections play important role

GUT symmetry breaking via **126** and **54**

α_H: Hadronic matrix element

Aoki, Izubuchi, Shintani, Soni (2017)

Proton lifetime versus intermediate scale



$\tau_p < 3 \times 10^{35}$ yrs.

KSB, S. Khan (2015)

Proton decay branching ratios

$$\begin{aligned}
\Gamma(p \to \overline{\nu}\pi^+) &: \quad 48\% \\
\Gamma(p \to e^+\pi^0) &: \quad 47\% \\
\Gamma(p \to \mu^+K^0) &: \quad 3.62\% \\
\Gamma(p \to \mu^+\pi^0) &: \quad 1\% \\
\Gamma(p \to e^+\eta^0) &: \quad 0.20\% \\
\Gamma(p \to e^+K^0) &: \quad 0.16\% \\
\Gamma(p \to \overline{\nu}K^+) &: \quad 0.22\%
\end{aligned}$$

Fermion masses and mixings fit with a minimal Yukawa sector

$$\mathcal{L}_{\text{Yuk}} = 16 \left(Y_{10} 10_H + Y_{126} \overline{126}_H \right) 16$$

Minimal SO(10) Model

$$\mathcal{L}_{\text{Yukawa}} = Y_{10}\,\mathbf{16}\,\mathbf{16}\,\mathbf{10}_H + Y_{126}\,\mathbf{16}\,\mathbf{16}\,\overline{\mathbf{126}}_H$$

Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$\begin{aligned} M_u &= \kappa_u Y_{10} + \kappa'_u Y_{126} \\ M_d &= \kappa_d Y_{10} + \kappa'_d Y_{126} \\ M_\nu^D &= \kappa_u Y_{10} - 3\kappa'_u Y_{126} \\ M_l &= \kappa_d Y_{10} - 3\kappa'_d Y_{126} \end{aligned}$$

$$\begin{aligned} M_{\nu R} &= \langle \Delta_R \rangle Y_{126} \\ M_{\nu L} &= \langle \Delta_L \rangle Y_{126} \end{aligned}$$

Model has only 11 real parameters plus 7 phases to fit 18 observables

Babu, Mohapatra (1993)
Bajc, Melfo, Senjanovic, Vissani (2002, 2004)
Fukuyama, Okada (2002)
Fukuyama, Ilakovac, Kikuchi, Meljanac, Okada (2004)
Aulakh et al (2004)
Bertolini, Frigerio, Malinsky (2004)
Babu, Macesanu (2005)
Bertolini, Malinsky, Schwetz (2006)
Dutta, Mimura, Mohapatra (2007)
Bajc, Dorsner, Nemevsek (2009)
Joshipura, Patel (20121
Dueck, Rodejohann (2013)

Specific Example: Type I Seesaw

Input at the GUT scale:

$$\begin{aligned}
m_u &= 0.0006745 & m_c &= 0.3308 & m_t &= 97.335 \\
m_d &= 0.0009726 & m_s &= 0.02167 & m_b &= 1.1475 \\
m_e &= 0.000344 & m_\mu &= 0.0726 & m_\tau &= 1.350 \text{ GeV} \\
s_{12} &= 0.2248 & s_{23} &= 0.03278 & s_{13} &= 0.00216 \\
& & \delta_{CKM} &= 1.193 \,.
\end{aligned}$$

Output for neutrinos:

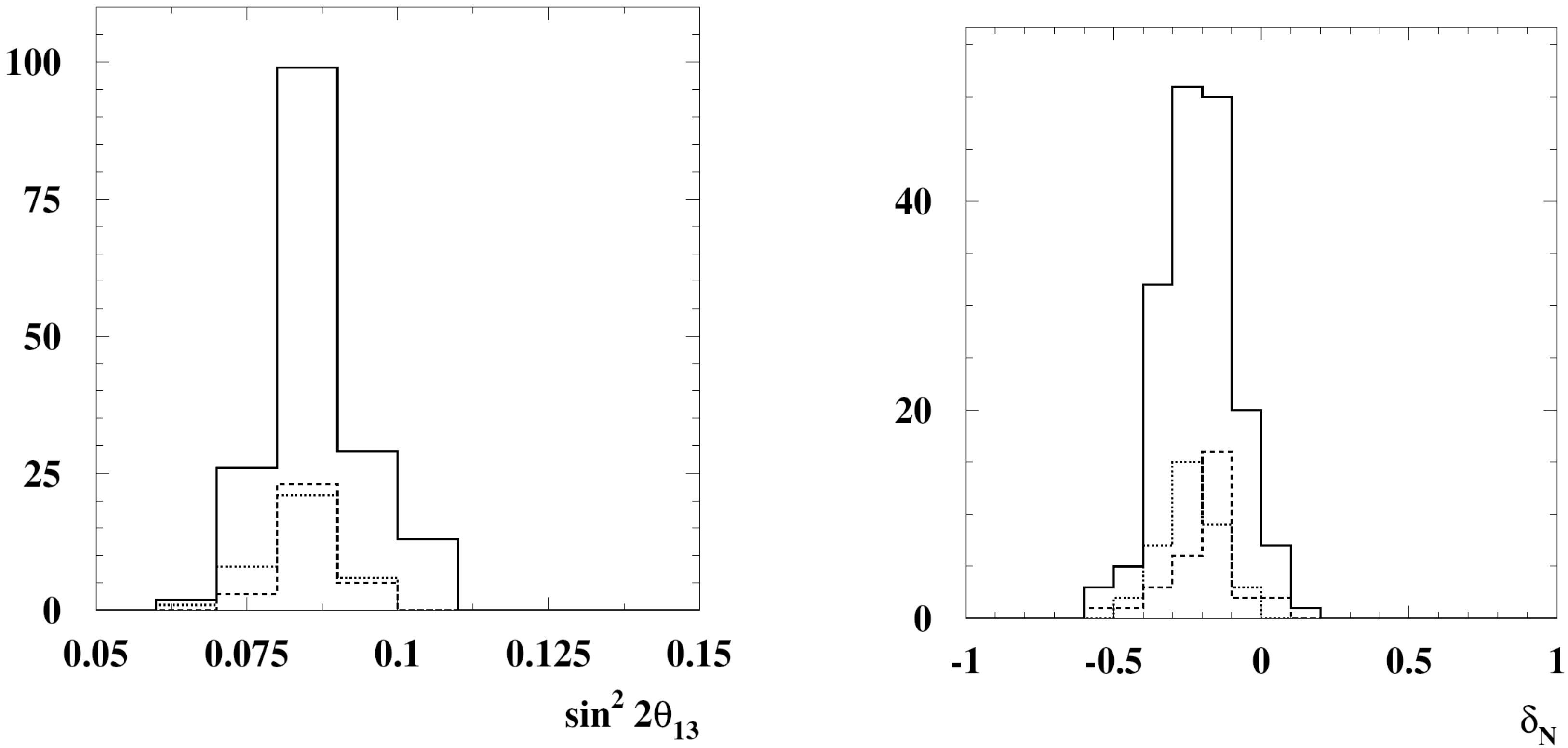
$$\sin^2\theta_{12} \simeq 0.27, \quad \sin^2 2\theta_{23} \simeq 0.90, \quad \sin^2 2\theta_{13} \simeq 0.08$$

$$m_i = \{0.0021 e^{0.11 i},\ 0.0098 e^{-3.08 i},\ 0.048\} \text{ eV}$$

$$\Delta m^2_{23} / \Delta m^2_{12} \simeq 24$$

K.S. Babu and C. Macesanu (2005)

Theta(13) in Minimal SO(10)



$\sin^2 2\theta_{13}$ and CP violating phase δ_N

K.S. Babu and C. Macesanu (2005)

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$ Daya Bay (2012)

Alternative Minimal Yukawa sector for SO(10)

In $SO(10)$, three types of Higgs can have Yukawa couplings:

$$\mathcal{L}_{\text{Yuk}} = 16_F(Y_{10}10_H + Y_{120}120_H + Y_{126}\overline{126}_H)16_F.$$

10_H and 120_H are *real* representations of $SO(10)$, while $\overline{126}_H$ is complex

Often complex 10_H is employed with additional symmetries to reduce Yukawa parameters

A good fit to fermion masses and mixing angles, including neutrino oscillation parameters is obtained with a *real* 10_H and a *real* 120_H, along with a complex $\overline{126}_H$

KSB, Bajc, Saad (2017)

Best fit values for fermion masses and mixings

Masses (in GeV) and Mixing parameters	Inputs (at $\mu = M_{GUT}$)	Fitted values (**type-I**) (at $\mu = M_{GUT}$)	pulls (**type-I**)	Fitted values (**type-I+II**) (at $\mu = M_{GUT}$)	pulls (**type-I+II**)
$m_u/10^{-3}$	0.442±0.149	0.444	0.009	0.442	-0.0002
m_c	0.238±0.007	0.238	-0.002	0.238	0.0001
m_t	74.51±0.65	74.52	0.009	74.52	-0.005
$m_d/10^{-3}$	1.14±0.11	1.14	-0.0002	1.14	-0.00006
$m_s/10^{-3}$	21.58±1.14	21.60	0.007	21.59	0.0001
m_b	0.994±0.009	0.994	0.002	0.994	0.000005
$m_e/10^{-3}$	0.470692±0.000470	0.470674	-0.03	0.470675	-0.003
$m_\mu/10^{-3}$	99.3658±0.0993	99.3618	-0.04	99.3621	-0.003
m_τ	1.68923±0.00168	1.68925	0.01	1.68925	0.001
$\|V_{us}\|/10^{-2}$	22.54±0.06	22.54	0.002	22.54	0.00008
$\|V_{cb}\|/10^{-2}$	4.856±0.06	4.856	0.001	4.856	0.0007
$\|V_{ub}\|/10^{-2}$	0.420±0.013	0.420	-0.007	0.420	-0.0001
δ_{CKM}	1.207±0.054	1.207	0.01	1.207	0.005
$\Delta m^2_{sol}/10^{-4}(\text{eV}^2)$	1.29±0.04 $(1 \times 10^{15}\text{GeV})$ 1.27±0.04 $(7.3 \times 10^{12}\text{GeV})$	1.27	-0.48	1.27	0.04
$\Delta m^2_{atm}/10^{-3}(\text{eV}^2)$	4.12±0.13 $(1 \times 10^{15}\text{GeV})$ 4.05±0.13 $(7.3 \times 10^{12}\text{GeV})$	4.06	- 0.46	4.06	0.04
$\sin^2\theta_{12}^{\text{PMNS}}$	0.308±0.017	0.308	-0.01	0.308	0.00001
$\sin^2\theta_{23}^{\text{PMNS}}$	0.387±0.0225	0.387	-0.01	0.387	-0.00006
$\sin^2\theta_{13}^{\text{PMNS}}$	0.0241±0.0025	0.0241	0.01	0.0241	-0.0003

Total $\chi^2 = 0.45$ (type I) and 0.004 (type I + II)

(15 real parameters and a few phases to fit 18 observables)

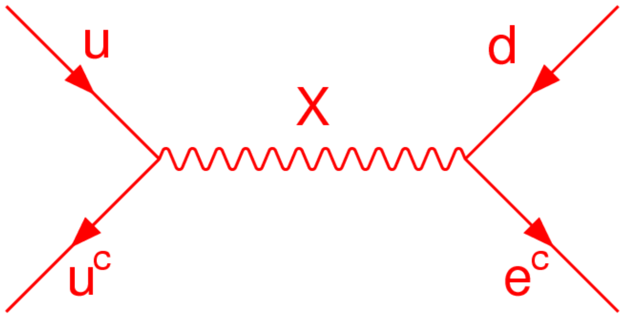
Proton Decay Branching Ratios

p decay modes	**type-I**	**type-I+II**
$p \to \overline{\nu} + \pi^+$	49.07%	48.77%
$p \to e^+\pi^0$	42.57%	35.16%
$p \to \mu^+K^0$	4.13%	5.12%
$p \to \mu^+\pi^0$	1.60%	5.62%
$p \to \overline{\nu}K^+$	1.19%	2.64%
$p \to e^+K^0$	0.99%	2.28%
$p \to e^+\eta$	0.40%	0.33%
$p \to \mu^+\eta$	0.01%	0.05%

KSB, Bajc, Saad (2017)

Nucleon Decay in SUSY GUTs

Gauge boson exchange



$$\Gamma^{-1}(p \to e^+\pi^0) = (2.0 \times 10^{35}\ \text{yr})$$
$$\times \left(\frac{\alpha_H}{0.01\ \text{GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/25}\right)^{-2} \left(\frac{A_R}{2.5}\right)^{-2} \left(\frac{M_X}{10^{16}\ \text{GeV}}\right)^4$$

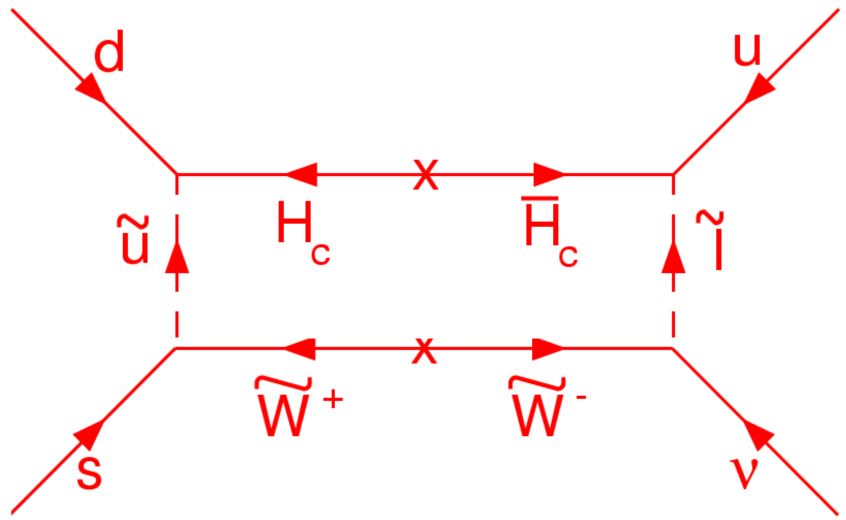
$$(-2\alpha_3^{-1} - 3\alpha_2^{-1} + 3\alpha_Y^{-1})(M_Z) = \frac{1}{2\pi}\left\{36 \ln\left(\frac{M_X}{M_Z}\left(\frac{M_\Sigma}{M_X}\right)^{1/3}\right) + 8 \ln\left(\frac{M_{\text{SUSY}}}{M_Z}\right)\right\}$$

M_Σ: Heavy color octet mass, uncertain: Threshold effect

$\frac{M_\Sigma}{M_X} \leq 1.8$ (perturbation theory)

Hisano, Murayama, Yanagida (1993)
Nath, Perez, Phys. Rept. (2007)

Supersymmetric nucleon decay mode



Sakai, Yanagida (1982)

Weinberg (1982)

$$p \rightarrow \bar{\nu} K^+$$

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{32} yr]^{-1}$$

Murayama, Pierce (2002)

Proton decay tension in minimal SUSY SU(5)

$SU(5)$ symmetry broken by an adjoint **24** Higgs

Electroweak Higgs doublets are contained in $\mathbf{5} + \overline{\mathbf{5}}$

$\mathbf{5} + \overline{\mathbf{5}}$ Higgs contain color triplet components which mediate proton decay

Gauge coupling unification prefers color triplet mass $< 7 \times 10^{14}$ GeV

$$\Gamma^{-1}_{d=5}(p \to \bar{\nu} K^+) \simeq 1.7 \cdot 10^{30}\,\mathrm{yrs} \times \left(\frac{0.012\,\mathrm{GeV}^3}{\beta_H}\right)^2 \left(\frac{7}{\bar{A}^{\alpha}_{S}}\right)^2 \left(\frac{1.25}{R_L}\right)^2 \times \left(\frac{M_T}{2 \cdot 10^{16}\mathrm{GeV}}\right)^2 \left(\frac{m_{\tilde{q}}}{1.5\mathrm{TeV}}\right)^4 \left(\frac{500\,\mathrm{GeV}}{M_{\tilde{W}}}\right)^2$$

β_H: Hadronic matrix element

Super-Kamiokande Limit: $\tau > 5.9 \times 10^{33}$ yr.

Proton Lifetime in Realistic SUSY SU(5)

Minimal SUSY $SU(5)$ provides a benchmark point for proton lifetime

Minimal $SU(5)$ predicts some wrong mass relations

$$m_b^0 = m_\tau^0, \; m_s^0 = m_\mu^0, \; m_d^0 = m_e^0 \text{ (at GUT scale)}$$

$$\Rightarrow \frac{m_d}{m_s} = \frac{m_e}{m_\mu}$$

Off by an order of magnitude

This problem should be fixed before discussing $p \to \overline{\nu} K^+$ rate

Simplest way is to add $5 + \overline{5}$ fermion at GUT scale

Mixing of $5 + \overline{5}$ fermions with normal fermions correct wrong mass relations, and improves proton lifetime

Babu, Bajc, Tavartkiladze (2012)

Proton Lifetime in Realistic SUSY SU(5)

$\Gamma^{-1}_{d=5}(p \to \bar{\nu} K^+)$	$4 \cdot 10^{33}$ yrs.
$\Gamma^{-1}_{d=5}(n \to \bar{\nu} K^0)$	$2 \cdot 10^{33}$ yrs.
$\Gamma^{-1}_{d=5}(p \to \mu^+ K^0)$	$1.0 \cdot 10^{34}$ yrs.
$\Gamma^{-1}_{d=5}(p \to \mu^+ \pi^0)$	$1.8 \cdot 10^{34}$ yrs.
$\Gamma^{-1}_{d=5}(p \to \bar{\nu} \pi^+)$	$7.3 \cdot 10^{33}$ yrs.
$\Gamma^{-1}_{d=5}(n \to \bar{\nu} \pi^0)$	$1.5 \cdot 10^{34}$ yrs.

Babu, Bajc, Tavartkiladze (2012)

Nucleon lifetime cannot exceed 2×10^{34} yrs in this realistic SUSY $SU(5)$ model if SUSY masses are < 3 TeV

SUSY SO(10) with Natural Doublet-Triplet Splitting

Babu, Pati, Tavartkiladze (2010)

Higgs sector: $\{45_H + 10_H + 16_H + \overline{16}_H + 16'_H + \overline{16}'_H\}$

$$W_{D-T} = \lambda(\mathbf{10}_H \mathbf{45}_H \mathbf{10}'_H) + M' \mathbf{10}'_H \mathbf{10}'_H$$

$$\langle 45_H \rangle = \begin{pmatrix} a & 0 & 0 & 0 & 0 \\ 0 & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \otimes i\tau_2 \quad \propto B - L$$

Adjoint VEV along $B - L$ gives mass only to color triplets and not to doublets

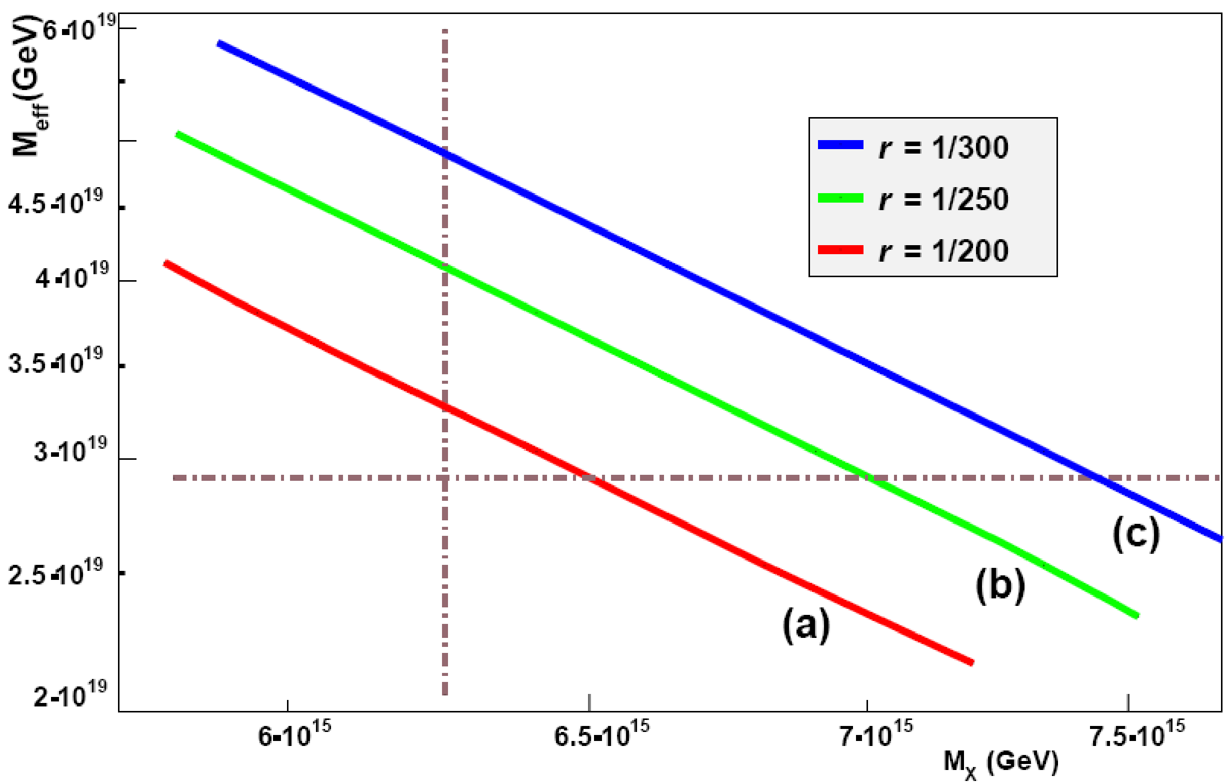
(Dimopoulos-Wilczek mechanism)

Dimopoulos, Wilczek (1981)
Babu, Barr (1993)
Barr, Raby (2000)

Correlation between proton decay modes

$$M_{\text{eff}} \simeq 10^{19}\text{GeV}\cdot\left(\frac{10^{16}\text{GeV}}{M_X}\right)^3\left(\frac{3}{\tan\beta}\right)\left(\frac{1/100}{r}\right)\frac{\exp[2\pi(\Delta^{(2)}_{2,w}-\Delta^{(2)}_{3,w}-\delta\alpha_3^{-1})]}{2.54\cdot 10^{-2}}\,.$$

$$r \equiv \frac{M_\Sigma}{M_X} \approx \left(\frac{1}{100}-\frac{1}{300}\right)$$



Proton Lifetime Predictions

$$\Gamma^{-1}_{d=6}(p \to e^+\pi^0) \simeq 1.0\times 10^{34}\,\text{yrs}\left(\frac{0.012\text{GeV}^3}{\alpha_H}\right)^2\left(\frac{2.78}{A_R}\right)^2\left(\frac{5.12}{f(p)}\right)\left(\frac{1/20}{\alpha_G(M_X)}\right)^2\left(\frac{M_X}{6.24\times 10^{15}\text{GeV}}\right)^4$$

$$\Gamma^{-1}_{d=5}(p \to \bar{\nu}K^+) = 3.5\times 10^{33}\text{yrs}\left(\frac{0.012\text{GeV}^3}{|\beta_H|}\right)^2\left(\frac{6.91}{\bar{A}_S^\alpha}\right)^2\left(\frac{1.25}{R_L}\right)^2\left(\frac{M_{\text{eff}}}{3.38\times 10^{19}\text{GeV}}\right)^2\times$$
$$\times\left(\frac{m_{\tilde{q}}}{1.5\text{TeV}}\right)^4\left(\frac{130}{m_{\tilde{W}}}\right)^2\left(\frac{3.1}{K^\nu_{d=5}}\right)\,.$$

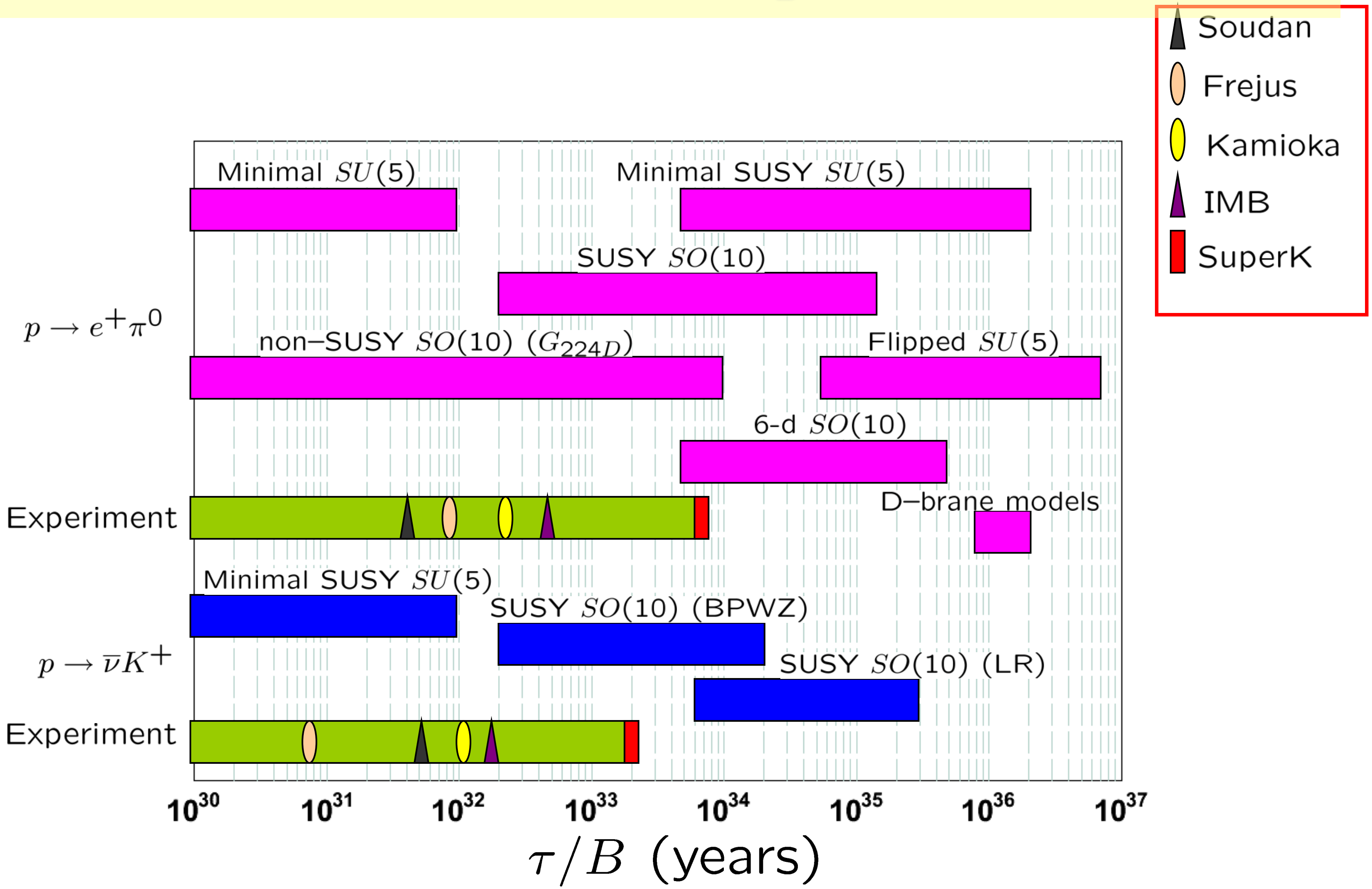
Imposing the correlation equation we obtain the predictions:

$$\Gamma^{-1}_{d=6}(p \to e^+\pi^0) \lesssim 5.3\times 10^{34}\ \text{yrs}$$

$$\Gamma^{-1}(p \to \bar{\nu}K^+) \lesssim (3.1\times 10^{34}\ \text{yrs})\times\left(\frac{m_{\tilde{q}}}{1.5\ \text{TeV}}\right)^4\left(\frac{130\ \text{GeV}}{m_{\tilde{W}}}\right)^2\ (3/\tan\beta)^2$$

Both modes should be within reach of experiments!

Proton Lifetime Expectations



Neutron-antineutron Oscillations

In presence of baryon number violation neutron can spontaneously convert into antineutron

Kuzmin (1970), Glashow (1979), Marshak, Mohapatra (1980)

Violates B by two units: Likely analog of L violation by two units in neutrino Majorana mass

Generated by effective dimension 9 operatos such as

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^5}(u_R d_R u_R d_R d_R d_R)$$

Experiments sensitive to cut-off scale $\Lambda \sim 10^5 - 10^6$ GeV

Probes a different sector of B violation compared to proton decay which tests $|\Delta B| = 1$

$n - \overline{n}$ oscillations may be the source of baryon asymmetry of the Universe

Discovery of $n - \overline{n}$ oscillations would likely rule out high scale models of baryon asymmetry generation (e.g: leptogenesis)

Neutron-antineutron Oscillations Phenomenology

Time evolution of a neutron in presence of $\Delta B = 2$ interactions:

$$i\hbar \frac{\partial}{\partial t} \begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix} \begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

Probablility of n oscillating into $\overline{n}$ at time t is

$$P_{n \to \bar{n}}(t) = \frac{(\delta m)^2}{\Delta E_n^2 + (\delta m)^2} \sin^2\{\sqrt{\Delta E_n^2 + 4(\delta m)^2}\, t\}$$

$$E_n = m_n - \vec{\mu}_n.\vec{B} + V_n, \qquad E_{\overline{n}} = m_n + \vec{\mu}_n.\vec{B} + V_{\overline{n}}$$

$$\Delta E_n = E_n - E_{\overline{n}} = -2\vec{\mu}_n.\vec{B} + V_n - V_{\overline{n}}$$

For $\delta m \ll \Delta E_n$, this expression reduces to:

$$P_{\bar{n}} \simeq \left(\frac{\delta m}{\Delta E_n}\right)^2 \sin^2(\Delta E_n t)$$

D.G. Phillips II et. al, Phys. Rept. (2016)

Case (i): $\Delta E_n t \ll 1$: In this case

$$P_{n\to\bar{n}}(t) \simeq (\delta m \cdot t)^2 \equiv \left(\frac{t}{\tau_{n-\bar{n}}}\right)^2$$

This case corresponds to free neutron oscillation in vacuum

Case (ii): $\Delta E_n \cdot t \gg 1$:

$$P_{n\to\bar{n}}(t) \simeq \frac{1}{2}\left(\frac{\delta m}{\Delta E_n}\right)^2$$

This is realized when bound neutrons inside nucleus "oscillates" to antineutrons

$$\tau_{Nuc.} = R(\tau_{n-\bar{n}})^2 \qquad R \simeq 0.3 \times 10^{24} \text{ sec.}^{-1}$$

Friedman, Gal (2008)

Expt	source of neutrons	$\tau_{Nucl.}(yrs)$	$\tau_{osc.}$(sec)
Soudan	^{56}Fe	0.72×10^{32}	1.3×10^{8}
Frejus	^{56}Fe	0.65×10^{32}	1.2×10^{8}
Kamiokande	^{16}O	0.43×10^{32}	1.2×10^{8}
Super-K	^{16}O	1.77×10^{32}	2.3×10^{8}

Free neutrons: $\tau_{n-\bar{n}} > 0.86 \times 10^{8}$ sec. (ILL, 1994)

Discussions ongoing for free neutron oscillation experimnet at ESS

Baryogenesis and n-nbar oscillations in SO(10)

In $SU(5)$ decays of heavy gauge bosons of color triplet scalars can generate baryon asymmetry

This asymmetry is however washed out by electroweak sphalerons since $(B-L)$ is preserved

In $SO(10)$, color sextet scalar decays can lead to sphaleron-proof baryon asymmetry via $\Delta(B-L)=2$ processes

K.S. Babu, R.N. Mohpatra (2012)

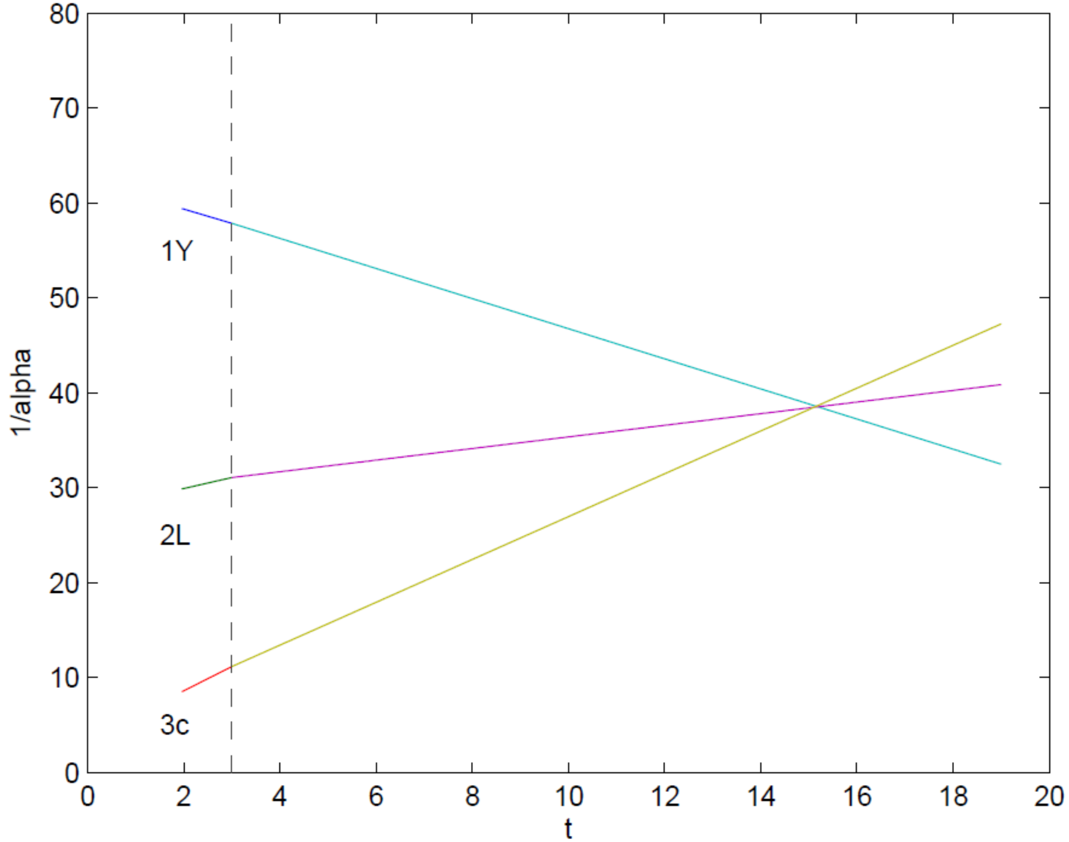
Non-SUSY SO(10) provides a natural dark matter candidate due to $B-L$ symmetry

Kadastik, Kannike, Raidal (2009);
Mambrini, Nagata, Olive, Quivillon, Zheng (2015)

Proton decay via $\Delta(B-L)=2$ processes have $n \to e^- \pi^+$ as a leading mode

Minimal SO(10) can provide dark matter, n-nbar oscillations, proton decay, and LHC signals for colored scalars!

TeV-scale Color Sextet scalar and unification

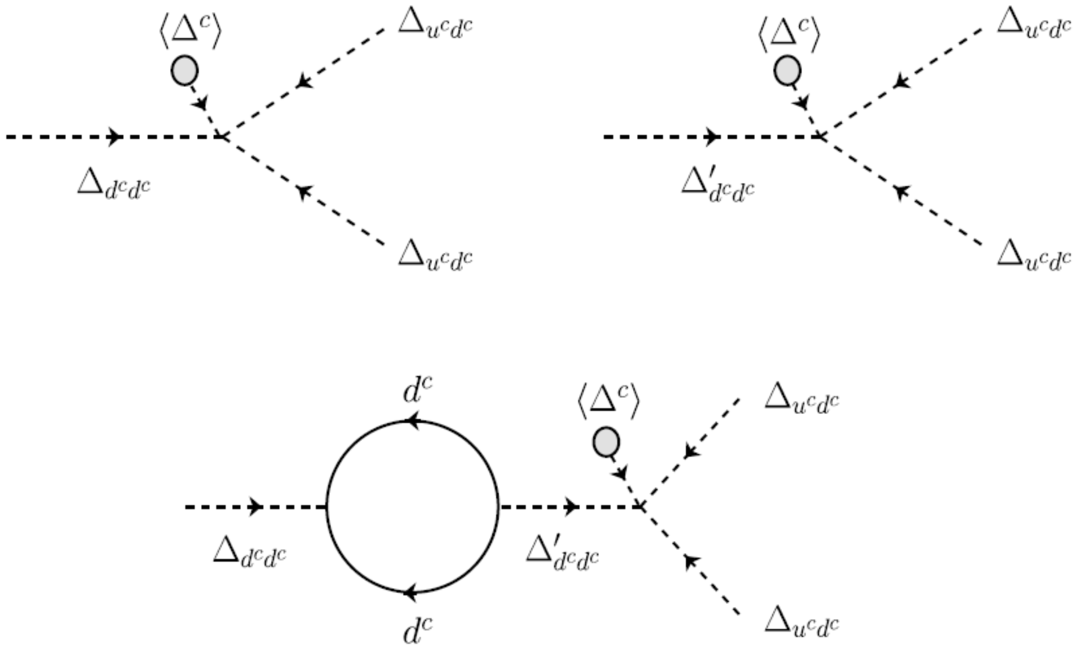


$\Delta_{u^c d^c}(6^*, 1, 1/3)$ scalar and a $(1,3,0)$ fermion at 1 TeV

$(1,3,0)$ fermion stable dark matter with mass $2.7 - 3$ TeV

K.S. Babu, R.N. Mohpatra (2012)

Baryongenesis via Color sextet decay



$\Delta_{d^c d^c}$: GUT mass; $\Delta_{u^c d^c}$: TeV mass

Minimal $SO(10)$ models have two $\Delta_{d^c d^c}$ (from **126** and **54**) and one $\Delta_{u^c d^c}$

$(B-L)$ asymmetry of the right order induced

Baryongenesis via Color sextet decay (cont.)

$(B-L)$ asymmetry parameter ϵ_{B-L}:

$$\epsilon_{B-L} = (r - \bar{r})(B_1 - B_2)$$

r is branching ratio for $\Delta_{d^c d^c} \to \Delta^*_{u^c d^c} \Delta^*_{u^c d^c}$
$\bar{r}$ is branching ratio for $\Delta^*_{d^c d^c} \to \Delta_{u^c d^c} \Delta_{u^c d^c}$

$B_1 = -4/3, \quad B_2 = 4/3$ ($B-L$ of two final states)

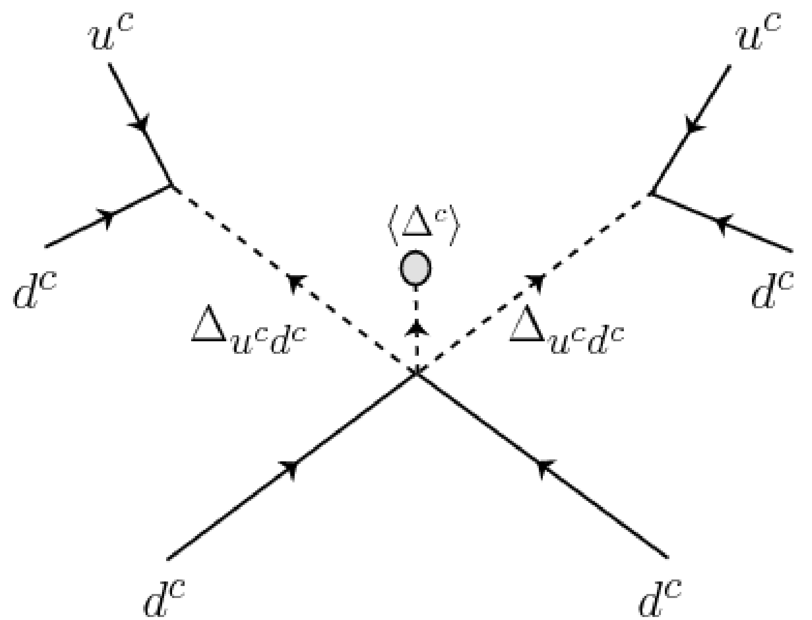
$$\eta = \frac{n_B}{s} \simeq \frac{\epsilon_{B-L}}{g^*} d$$

$$\epsilon_{B-L} \simeq \frac{2}{\pi |\lambda v_R|^2} \mathrm{Tr}(f^\dagger f) \mathrm{Im}[(\lambda v_R)(\lambda' v_R)^*] F \cdot \mathrm{Br}$$

$$F = \frac{M^2_{d^c d^c}}{M^2_{d^c d^c} - M'^2_{d^c d^c}}$$

$\eta_B \approx 10^{-10}$ naturally generated

Baryogenesis and n-nbar oscillations



$$M_{\delta_{u^c d^c}} = 1 \text{ TeV}, \; M_{\Delta_{d^c d^c}} = 10^{14} \text{ GeV}, \; f_{11} = 10^{-3}$$

$$\Rightarrow \qquad \tau_{n-\bar{n}} = (10^9 - 10^{11}) \text{ sec.}$$