Baryon number violation

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Introduction

An appealing framework for baryon number violation is given by Grand Unified Theories (GUTs):

- unify gauge interactions (couplings)
- unify matter
- quantize U(1) charge

$\Delta B = 2$

Unfortunately such processes are less important for low energy physics coming from GUTs.

The reason is the large dimensionality of the $\Delta B = 2$ operator in SM

$$\mathcal{L}_{\Delta B=2} = \frac{1}{M^5} u^c u^c d^c d^c d^c d^c$$

If $M = v_{B-L}$

$$\rightarrow \quad \tau_{n-\bar{n}} \sim \frac{M^5}{\Lambda^4_{QCD}}$$

far too small!

Conclusion different if extra light states

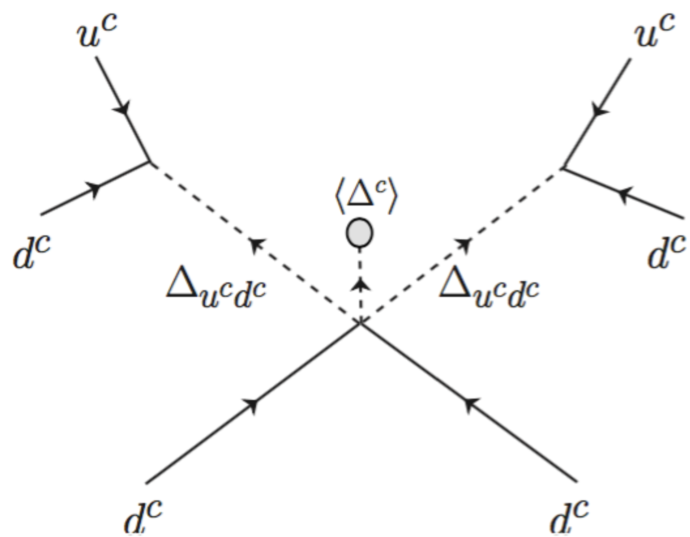


Fig. taken from Babu, Mohapatra, '12

$$M^5 \sim M^4_{\Delta_{u^c d^c}} v_{B-L}$$

So with a light $M_{\Delta_{u^c d^c}} \sim \mathcal{O}(1 \text{ TeV})$ even a heavy $v_{B-L} \sim M_{GUT}$

$$\tau_{n-\bar{n}} \sim 10^8 s$$

These same states makes single step unification possible

Babu, Mohapatra, '12

Similar considerations with MSSM plus extra vectorlike $5 + \bar{5}$ and/or $10 + \overline{10}$ plus singlets and use RPV couplings

Ajaib, Gogoladze, Mimura, Shafi, '09

Instead of

$$\Delta B = 2$$

I will consider in this talk

$$\Delta B = 1 \quad , \quad \Delta L = 1$$

In some GUTs - SO(10) - we have automatic also (Majorana neutrino mass)

$$\Delta L = 2$$

In this sense these theories are connected to the main topic of this workshop $\Delta B = 2$ due to the sphaleron connection mentioned on monday by R. Mohapatra.

$\Delta B = 1$

The lowest dimensional operators that describe nucleon decay are of the form (schematically)

$$\mathcal{L}_{d=6} = \frac{\kappa}{M^2} qqql + h.c.$$

Weinberg, 79

Wilczek, Zee, 79

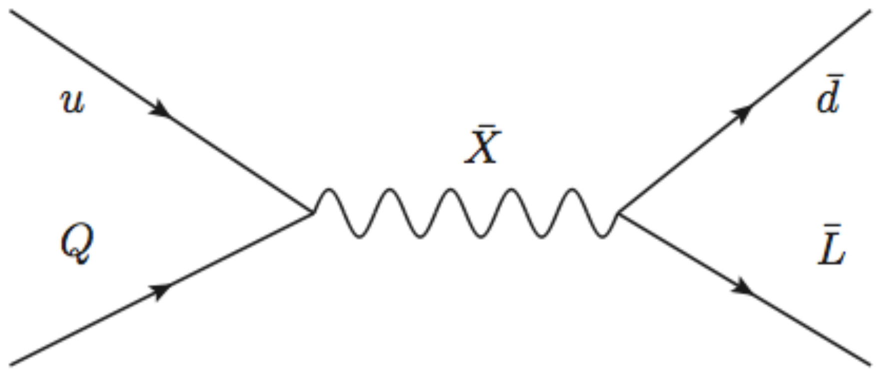
$q \ldots$ left-handed (Q) or right-handed (u_R, d_R) quark

$l \ldots$ left-handed (L) or right-handed (e_R) lepton

Accidentally $(B - L)-$preserving, follows just from gauge symmetry and particle content of SM

Non-supersymmetric GUTs

in non-susy d=6 decay (gauge boson mediating) modes only.
predictions are neater and typically can be consistent with exp



$$\text{amplitude} \propto \frac{1}{M_{GUT}^2} \to \tau \propto M_{GUT}^4$$

Strong dependence on M_{GUT}

Unification constraints $\to$ M_{GUT} and particle spectrum

SU(5)

In SU(5) all fermions of one generations live in two representations

$$5_F = d_R(3) + L(2) \quad , \quad 10_F = u_R(3) + Q(6) + e_R(1)$$

There are 24 SU(5) gauge bosons

$$24_V = gluons(8) + W^{\pm}(2) + Z(1) + \gamma(1) + X(6) + \bar{X}(6)$$

$X(3, 2, -5/6)$, $\bar{X}(\bar{3}, 2, 5/6)$ gauge bosons have mass M_{GUT} (where three SM gauge couplings unify) and mediate proton decay

The original minimal Georgi-Glashow SU(5) model

$$3 \times (10_F + \bar{5}_F) + 5_H + 24_H$$

does not work, because

- SM gauge couplings do not unify
- neutrino mass vanishes

One need to add some other representation to make it realistic add 24_F

BB, Senjanović, '06; BB, Nemevšek, Senjanović, '07

- new states in 24_F contribute to RGE's:

$$\begin{aligned} 24 &= S(1,1,0) + T(1,3,0) + O(8,1,0) \\ &+ X(3,2,-5/6) + \bar{X}(\bar{3},2,5/6) \end{aligned}$$

- unification occurs iff

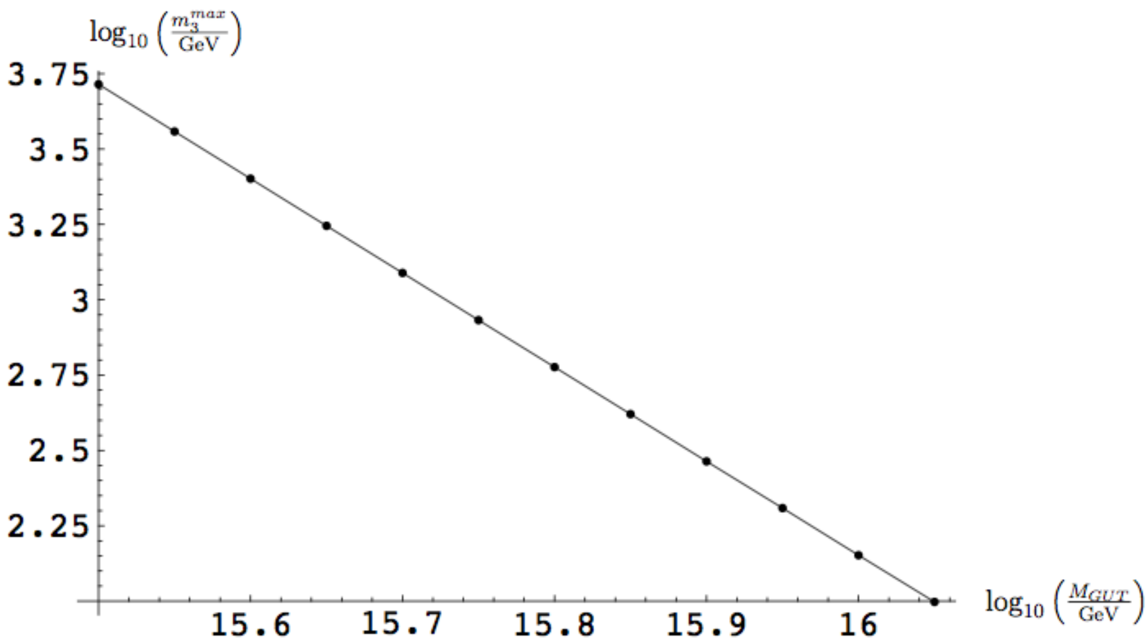
$$m_T \approx 10^3 \text{ GeV} \ , \ m_O \approx 10^8 \text{ GeV} \ , \ m_{X,\bar{X}} \approx 10^{13} \text{ GeV}$$

→ prediction of a light (TeV) weak fermionic triplet

- neutrino mass from mixed type I (S) and III (T) see-saw
- same Yukawa that describe neutrino mass appear in triplet decay (to check at LHC)

- proton decay faster if triplet heavier

$m_3^{max} - M_{GUT}$ at two loops



large $m_T \approx 5$ TeV $\rightarrow M_{GUT} \approx 10^{15.5}GeV\rightarrow \tau_p \approx 10^{34}$yrs

small $m_T \approx 100$ GeV $\rightarrow M_{GUT} \lesssim 10^{16}GeV\rightarrow \tau_p \lesssim 10^{36}$yrs

We have already some data:

ATLAS (2015) at 95% CL: $m_T \gtrsim 300 - 500$ GeV (depending on the Yukawas - triplet branching ratios)

If LHC will not find the triplet:

$m_T \gtrsim 700$ GeV $\rightarrow \tau_p \lesssim 10^{35}$ yrs (or the model is ruled out)

SO(10)

In SO(10) possible Yukawas are as usual with 10, 120, 126:

$$\mathcal{L}_{Yukawa} = 16_F \left(Y_{10} 10_H + Y_{120} 120_H + Y_{126} 126_H \right) 16_F$$

10_H and 120_H real representations (different from susy)

$\rightarrow$ only 1 doublet in 10:

$$H_u(10) = H_d^*(10)$$

$\rightarrow$ only $10 + 126$ not enough

One possibility:

introduce a PQ symmetry $\to$ 10_H promoted complex

$\to$ only one Y_{10}

(without PQ instead of one complex 10_H one should consider two real 10_H and so 2 Yukawa matrices $Y_{10}^{(1)}$ and $Y_{10}^{(2)}$)

unfortunately one and the same 126_H cannot break both rank of SO(10) and PQ U(1)

$\to$ introduce two 126_H with different PQ charges so that only one has Yukawa couplings

BB, Melfo, Vissani, Senjanović, '05

Another possibility is to have 3 Yukawas matrices, but minimal:

$$10_H + 126_H + 120_H \quad (10_H, 120_H \quad \text{real})$$

minimal because 120 is antisymmetric and so have only 3 complex non-zero components

The model has been analyzed recently and can fit the fermion masses and mixings both assuming type I seesaw dominance or the mixed type I+II.

Dominant channels are $\bar{\nu}\pi^+$ and $\pi^0 e^+$.

Babu, BB, Saad, '16

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%

Supersymmetric GUTs

Three big extra uncertainties here:

- R-parity violation → makes susy GUTs quite non-predictive for p-decay (unless R-parity predicted, like in SO(10) with 126). Usually assumed to vanish.
- typically too large operators

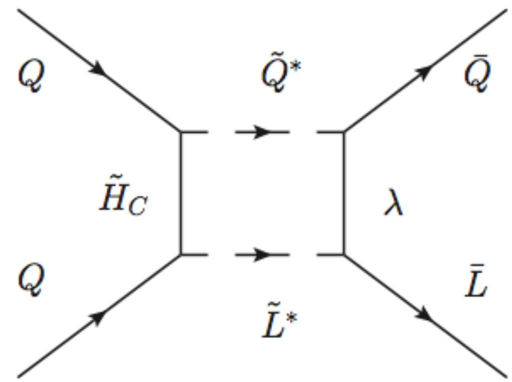
$$\frac{1}{M_{Planck}} QQQL$$

  $B + L$ violating operators (unless they are forbidden, like in E_6 GUTs). Usually assumed to vanish.
- susy breaking terms

→ we can give in many cases at most upper limits to proton decay lifetime, assuming no further cancellation occur

The rate for nucleon decay in low-energy susy models is typically dominated by $d = 5$ operators (schematically)

$$\tau^{-1} \approx \left| \left(\frac{Y^2}{M_C} \right) \left(\frac{\alpha}{4\pi} \frac{m_\lambda}{m_{\tilde{f}}^2} \right) \right|^2 m_p^5$$



Weinberg, '82; Sakai, Yanagida, '82

Hisano,Murayama,Yanagida, '92 ; Lucas,Raby, '96; Goto,Nihei, '98

$Y^2 \dots$ product of two Yukawa couplings

$M_C \dots$ color triplet mass

$(\alpha \dots)$ MSSM loop factor (λ gaugino or higgsino, $\tilde{f}$ sfermion)

$m_p^5 \dots$ from strong QCD dynamics (lattice)

Lifetime strongly model dependent

Supersymmetric SU(5)

$3 \times (10_F + \overline{5}_f) + 5_H + \overline{5}_H + 24_H$

If

- renormalizable
- low energy susy
- sfermion mixing $\sim$ fermion mixing

gauge coupling unification needs threshold correction of a light color triplet $\rightarrow$ $\tau \approx 10^{29}$ years

Murayama, Pierce, '01

Too fast, since $\tau_{exp}(p \to K^+ \bar{\nu}) \gtrsim 4 \cdot 10^{33}$ yrs

However no real reason for all these assumptions.

The same SU(5) (with the above assumptions) is anyway ruled out by bad fermion mass relations ($M_D = M_E$). Different cures:

1. non-renormalizable operators
2. sfermion mixing $\neq$ fermion mixing
3. extra representations ($5_F + \overline{5}_F$, $45_H + \overline{45}_H$, etc)
4. MSSM threshold corrections + susy scale higher

With these corrections proton decay can change drastically.

1. Non-renormalizable operators

- Yukawas Y^2 not necessarily the low-energy ones

Ellis, Gaillard, '79; Emmanuel-Costa, Wiesenfeldt, '03

- Particle spectrum arbitrary. If $T = (1, 3, 0) \subset 24$ and $O = (8, 1, 0) \subset 24$ lighter than M_{GUT}
$\rightarrow$ RGE change and M_{GUT} and M_C could increase :

$$M_{GUT}^{new} = M_{GUT} \left(\frac{M_{GUT}}{\sqrt{m_T m_O}} \right)^{1/2} \quad , \quad M_C^{new} = M_C \left(\frac{m_T}{m_O} \right)^{5/2}$$

Bachas, Fabre, Yanagida, '96; Chkareuli, Gogoladze, '98

2. sfermion mixings $\neq$ fermion mixings

BB, Fileviez Perez, Senjanović, '02

3. extra vectorlike $5_F + \overline{5}_F$:

- weak doublets from extra $5_F + \overline{5}_F$ correct the wrong relation $Y_D = Y_E$

- color triplets from extra $5_F + \overline{5}_F$ are lighter to satisfy RGE constraint on unification, while color triplet from $5_H + \overline{5}_H$ mediate nucleon decay

$\rightarrow$ theoretical proton lifetime longer than experimental

at least one p decay mode not slower than $2 \cdot 10^{34}$ yrs

providing all spartners lighter than 3 TeV

Babu, BB, Tavartkiladze, '12

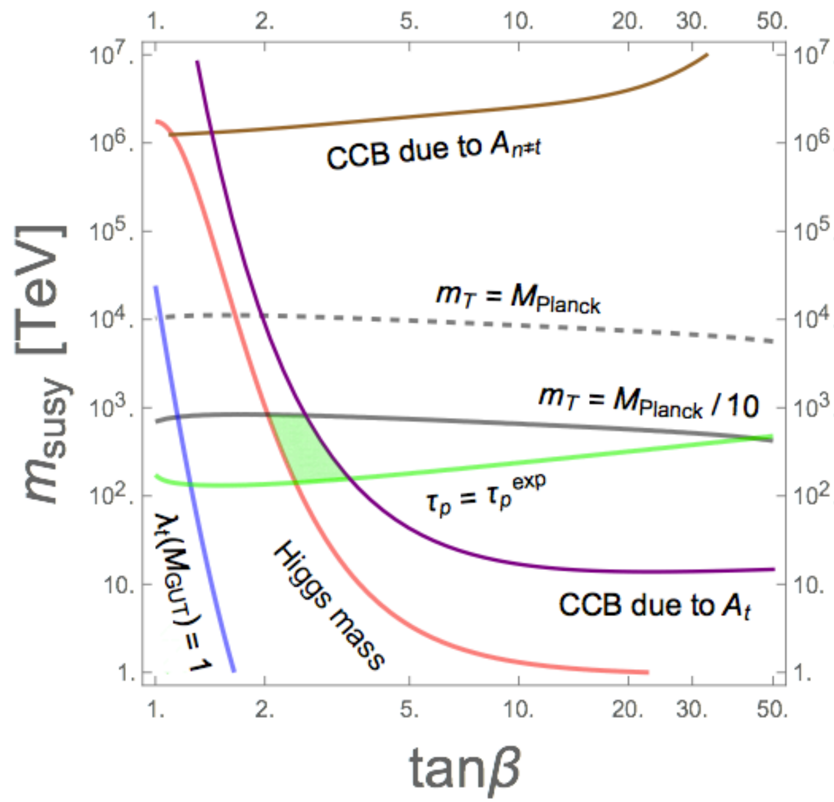
decay mode	$\tau_{d=5}^{max}$ (yrs)	exp. lower limit (90 % CL)
$p \to \bar{\nu} K^+$	$2 \cdot 10^{34}$	$6 \cdot 10^{33}$
$p \to \mu^+ K^0$	$4 \cdot 10^{34}$	$2 \cdot 10^{33}$
$p \to \mu^+ \pi^0$	$7 \cdot 10^{34}$	$8 \cdot 10^{33}$
$p \to \bar{\nu} \pi^+$	$3 \cdot 10^{34}$	$4 \cdot 10^{32}$
$n \to \bar{\nu} K^0$	$8 \cdot 10^{33}$	$1 \cdot 10^{32}$
$n \to \bar{\nu} \pi^0$	$6 \cdot 10^{34}$	$1 \cdot 10^{33}$

4. MSSM threshold corrections + higher scale susy

With approximation of degenerate susy spectrum the constraints on $\tan\beta$ and common m_{susy}:

- gauge couplings unification: $m_{susy} \propto m_T^{5/6}$
- proton decay: $\tau \propto m_{susy}^{11/3} / \tan^2\beta$
- Higgs mass
- vacuum metastability (from large threshold corrections)

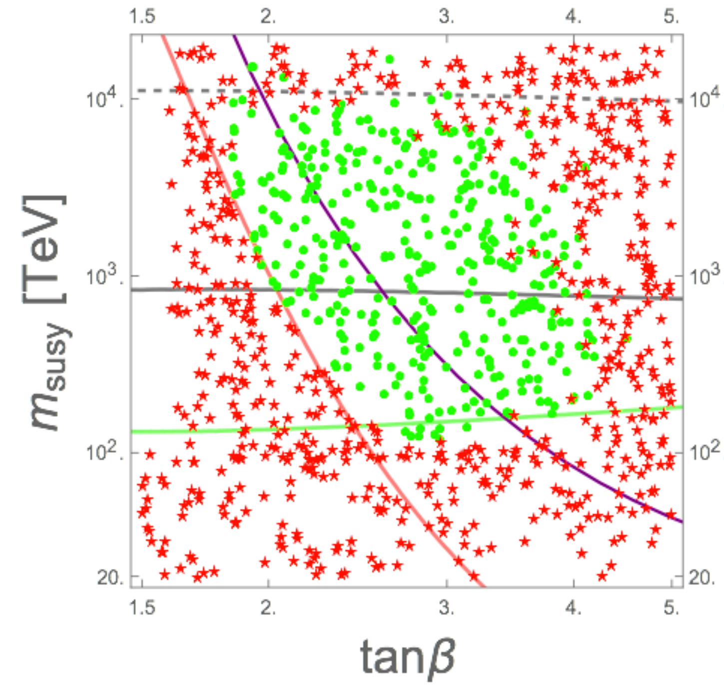
Putting all together:



Green region allowed

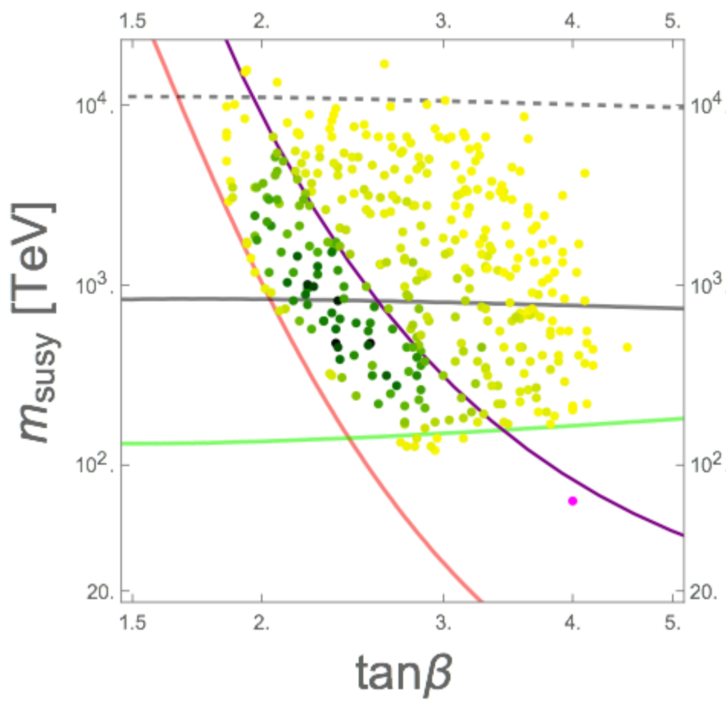
This is our expectation: bounded and non-empty region

Realistic non-degenerate spectrum:



green dot: at least 1 valid point in 1000 tries

red star: not even 1 valid point in 1000 tries



Number of solutions found increases from light yellow to dark green

A single point in $(\tan\beta, m_{susy})$ plane hides 15 susy breaking parameters $(m_{\tilde{5}_i}, m_{\tilde{10}_i}, m_{H_{u,d}}, M_{1/2}, A_{5_i}, A_{10_i})(M_{GUT})$ on top of some heavy masses $(m_T, m_{8,3}, m_X)$ and $sign(\mu)$.

Working hard possible to find solutions with a bit decreased m_{susy}.

Magenta point:

$$\begin{aligned} m_{susy} &= 63.0 \text{ TeV} \\ m_{\tilde{B}}(m_{susy}) &= 16.9 \text{ TeV} \\ m_{\tilde{u}^c,\tilde{c}^c}(m_{susy}) &= 22.3 \text{ TeV} \end{aligned}$$

Supersymmetric SO(10)

Renormalizable $3 \times 16_F + 10_H + 210_H + 126_H + \overline{126}_H$

Clark, Kuo, Nakagawa, '82; Aulakh, Mohapatra, '83

Babu, Mohapatra, '92; Aulakh, BB, Melfo, Senjanović, Vissani, '03

1. The model:
   - to break rank and predict R-parity use $126_H + \overline{126}_H$

     Mohapatra, '86; Forn, Ibañez, Quevedo, '89; Martin, '92

     Aulakh,Benakli,Senjanović,'97; Aulakh,Melfo,Senjanović,'98

     Aulakh, Melfo, Rašin, Senjanović, '99
   - to get main contribution to fermion masses use 10_H
   - to break SO(10) and correct bad mass relations use 210_H

     Babu, Mohapatra, '92

2. Comparing with experiment:

- good fit of fermion masses

  Goh, Ng, Mohapatra, '03; Bertolini, Malinsky, '04;

  Babu, Macesanu, '04; Bertolini, Malinsky, Schwetz, '05

- to get right absolute neutrino mass $\rightarrow$ split susy scenario

  $m_\lambda \approx 100$ TeV, $m_{\tilde{f}} \approx 10^{14}$ GeV

  BB, Doršner, Nemevšek, '08

  $\rightarrow$ no $d = 5$ p-decay modes, no uncertainties with soft terms, no MSSM threshold corrections to fermion masses

- borderline $d = 6$ p-decay mode: $\tau(p \rightarrow \pi^0 e^+) \lesssim 1.2 \cdot 10^{34}$ yrs;

  $BR(p \rightarrow \pi^+ \bar{\nu}) = 0.49$, $BR(p \rightarrow \pi^0 e^+) = 0.44$,

  $BR(p \rightarrow K^0 \mu^+) = 0.05$

3. Some important problems:
   - $\theta_{13}^{leptons}$ too low (but not known at the time so only upper limit considered in χ^2);
   - Higgs mass wrong (not known at the time);
   - sfermion scale too high. In fact

   (a) for vacuum metastable $\tilde{m}_s \lesssim 10^{12}$ GeV

   Giudice, Strumia, '12

   (b) for stability under radiative corrections $\tilde{m}_s \lesssim 10^{10}$ GeV

   Haba, Okada, '07

   (c) for correct Higgs mass $\tilde{m}_s \lesssim 10^{8}$ GeV

   Giudice, Strumia, '12

(a) and (c) above can be relaxed if some SM singlet (from SO(10) fields) coupled to $H_u H_d$ is lighter than 10^{10} GeV

Can a new fit be found with $\tilde{m}_s \lesssim 10^{10}$ GeV?

Possible to have a better fit with extra 54

- this has been done in the past to make the SU(5) 15 of 126 light without making light partners (and thus destroy perturbativity)

Goh, Mohapatra, Nasri, '04

- Another possibility is to search for solution

$$v_R << M_{GUT}$$

v_R becomes an input, independent of the other parameters, so possible to choose right order of magnitude for neutrino mass.

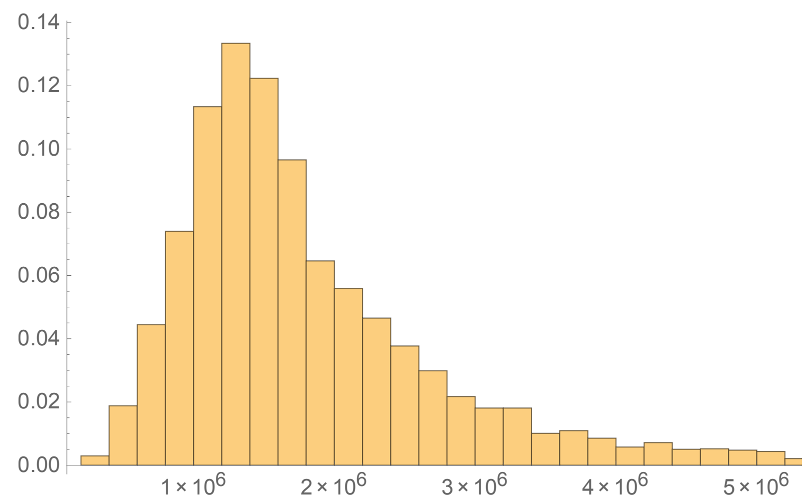
This possible only because of extra 54. But proton decay tends still to be too fast with low energy susy. Order 100 TeV or more needed.

Babu, BB, Saad, in progress

The way this is done is

- choose randomly initial values for parameters
- vary them continuously until all measurable quantities are reproduced (1st approx.: Yukawa RG for low energy susy)

Histogram for 7135 different inputs:



The minimal $m_{susy} = 232$ TeV

Babu, BB, Saad, in progress

Conclusions

Several hints that grand unification is around. These are good theories of proton decay and fermion masses.

- Ordinary SU(5):

  light fermionic weak triplet $m_T \lesssim 700$ GeV or $\tau_p \lesssim 10^{35}$ yrs

- Ordinary SO(10):

  $BR(\bar{\nu}\pi^+) \approx 0.5 \quad , \quad BR(e^+\pi^0) \approx 0.40$

- supersymmetric SU(5):

  heavy spartners $m \gtrsim \mathcal{O}(20$ TeV), vacuum metastable

- supersymmetric SO(10):

  slightly split susy with $m_\lambda \approx 1$ TeV, $\tilde{m}_s \approx \mathcal{O}(100$ TeV)