Perspectives on Proton Decay and GUTs

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BLV2011
Gatlinberg, September 22-24, 2011

Outline

Perspectives on

- GUTs: R parity, conventional GUTs, new more unified GUTs.
- Proton decay: Status, implications of LHC-7 data for predictions of susy proton decay lifetimes.
- Conclusions

R parity

- Within GUTs proton stability and for dark matter need R parity

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

  Within MSSM it is ad hoc

- R parity as a global symmetry is not desirable since it can be broken by wormhole effects (Gilbert (1989))

  This problem can be evaded if MSSM is embedded in a larger gauge symmetry so that R parity arises as a discrete remnant of a local gauge symmetry (Krauss, Wilczek (1989)).

- The obvious extended symmetry is

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

  In this case the $U(1)_{B-L}$ gauge symmetry will forbid R parity violating interactions such as $u^c d^c d^c, L\bar{H}, QLd^c, LLe^c$.

- Of course $U(1)_{B-L}$ cannot be an unbroken gauge symmetry because it would have a massless gauge boson associated with it which will produce additional long range forces which are undesirable.

Breaking the $B - L$ gauge symmetry

- While R parity is guaranteed as long as an unbroken $B - L$ gauge symmetry exists, this is not necessarily the case when the $B - L$ gauge symmetry is spontaneously broken. In this case there are two possibilities
  1. 3(B-L)= even integer, R parity is preserved.
  2. 3(B-L)=odd integer, R parity is no preserved.
- Example: Consider an extension of MSSM with a $U(1)_{B-L}$ symmetry. Here for anomaly cancellation one needs three right handed neutrino fields N. The extended superpotential in this case is

$$\mathcal{W} = \mathcal{W}_{\text{MSSM}} \; + \; h_\nu \; L H_u \nu^c + h_{\nu^c} \nu^c \nu^c \Phi + \mu_\Phi \Phi \bar{\Phi}$$

The $B - L$ quantum numbers of the new fields are $(\nu^c, \Phi.\bar{\Phi}) : (-1, -2, 2)$. The VEV of Φ does not break R parity but the VEV growth of ν^c does. A VEV growth for the field ν^c will break $B - L$ invariance and generate a mass for the $B - L$ gauge boson. Renormalization group analysis shows that radiative breaking of R parity symmetry can indeed occur when ν^c develops a VEV. [1]

[1] Khalil, Masiero (2008); Barger, Fileviez Perez, Spinner (2009); Early work: Aulakh and Mohapatra (1982); Masiero, Valle (1990)

Mass growth for B-L gauge boson via the Stueckelberg Mechanism

Feldman, Fileviez Perez, PN: arXiv: 1109.2901

- One can show that if the mass growth of the $B-L$ gauge boson occurs by the Stueckelberg mechanism then R -parity is not violated by radiative breaking in the minimal $U(1)_{B-L}$ extension of MSSM assuming charge conservation.
- Stueckelberg mechanism
  Kors and PN (2004); Feldman, Kors, Liu, PN (2006)

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(mA_\mu + \partial_\mu\sigma)^2 + gA_\mu J^\mu$$

Invariance with J_μ conserved

$$\delta A_\mu = \partial_\mu \epsilon, \quad \delta\sigma = -m\epsilon.$$

$$\textbf{SUSY}: \; L_{St} = (M_{BL}C + S_{St} + \bar{S}_{st})^2|_{\theta^2\bar{\theta}^2},$$

where

$$C = (C_\mu, \lambda_C, D_C), \quad S_{St} = (\rho + i\sigma, \psi_{St}, F_S)$$

The gauge transformations under $U(1)_{B-L}$ are

$$\delta_{BL}C = \Lambda_{BL} + \bar{\Lambda}_{BL}, \quad \delta S_{St} = -M_{BL}\Lambda_{BL}$$

The scalar potential

- Assumption of charge conservation gives

$$\langle \tilde{q} \rangle = 0, \ \langle \tilde{e}_L \rangle = 0 = \langle \tilde{e}^c \rangle$$

- Now the RG evolution of $M_{\tilde{e}_L}$ and of $M_{\tilde{\nu}_L}$ and since $\tilde{e}_L$ does not get a VEV so also $\tilde{\nu}_L$ does not get a VEV

$$< \tilde{\nu}_L >= 0$$

- Integration on the Stueckelberg ρ field gives

$$V_{\nu^c} = M^2_{\tilde{\nu}^c} \tilde{\nu}^{c\dagger} \tilde{\nu}^c + \frac{g^2_{BL} M^2_\rho}{2(M^2_{BL} + M^2_\rho)} (\tilde{\nu}^{c\dagger} \tilde{\nu}^c)^2.$$

  Now in RG analysis there are no beta functions to turn $M^2_{\tilde{\nu}^c}$ negative. Consequently the potential cannot support spontaneous breaking to generate a VEV $\tilde{\nu}^c$ and

$$\langle \tilde{\nu}^c \rangle = 0$$

  Thus with the Stueckelberg mechanism $B - L$ gauge boson gains a mass but R parity remains unbroken.

- Inclusion of nonuniversalites could modify the results: Ambroso, Ovrut (2010)

Implications of $B - L$ Breaking

Feldman talk

- Experiment

$$M_{Z'}^{B-L}/g_{BL} \geq 6\ \text{TeV} \tag{3}$$

This may be difficult to detect at the LHC.

- The mass limits can be lowered in a $U(1)_{B-L} \times U(1)_X$ extension
$U(1)_X$ lies in the hidden sector and the gauge field does not couple to matter fields in the visible sector. The only coupling between the two comes from mixing of the $U(1)_{B-L}$ and $U(1)_X$ gauge fields.

$$X_\mu = -\cos\theta_{BL} Z'_\mu + \sin\theta_{BL} Z''_\mu$$

$$C_\mu = -\sin\theta_{BL} Z'_\mu + \cos\theta_{BL} Z''_\mu$$

In this case two separate conditions arise

$$M_{Z'}/g_{BL} > \sin\theta_{BL} \times 6\text{TeV}, \quad M_{Z''}/g_{BL} > \cos\theta_{BL} \times 6\text{TeV}$$

For small mixing the Z' could lie much lower than 6 TeV and within the range of LHC.

Spontaneous Breaking vs Stueckelberg for B-L

- $B-L$ breaks spontaneously and R parity is broken
  - A massive Z'_{BL}.
  - Neutralino is no longer a dark matter candidate.
  - Normal SUSY signatures with χ^0 as missing energy do not hold.
- $B-L$ breaks spontaneously and R parity is preserved
  - A massive Z'_{BL}.
  - Neutralino is a dark matter candidate.
  - Normal SUSY signatures with χ^0 as missing energy.
  - Additional neutral particles from Φ and $\bar{\Phi}$.
- Mass growth of the $B-L$ gauge boson by Stueckelberg mechanism MSSM.
  - A massive Z'_{BL}.
  - Neutralino is a dark matter candidate.
  - Normal SUSY signatures with χ^0 as missing energy.
  - In the version two of this model one can have a Z'_{BL} as low as a TeV with reduced couplings. If a B-L massive vector boson is observed in the region substantially below 6 TeV, it is most likely of Stueckelberg origin. This distinguishes it from the spontaneous breaking case.

Perspectives on GUTS

Conventional $SO(10)$ models

For $SO(10)$ two steps are needed to break the gauge group

- 16+$\overline{\mathbf{16}}$ or 126+$\overline{\mathbf{126}}$ to reduce the rank
- $\mathbf{45}$, $\mathbf{54}$, $\mathbf{210}$ to break it further to $SU(3)_C \times SU(2)_L \times U(1)_Y$. 10-plet to break it to $SU(3)_C \times U(1)_{em}$.
- One typically has two different scales, one associated with the breaking of the rank and the other to accomplish the rest of the breaking down to the Standard Model gauge group.

A new path to SO(10) unfication

Babu, Gogoladze, PN, Syed PRD 72, 095011(2005); PRD 74, 075004 (2006)

- Quite remarkably it is possible to break $SO(10)$ with a single irreducible rep. This is done by use of a vector-spinor 144 which decomposes under $SU(5) \times U(1)$ as:

  $$144 = \bar{5}_3 + 5_7 + 10_{-1} + 15_{-1} + 24_{-5} + 40_{-1} + \overline{45}_{-3}$$

  The 24-plet has a $U(1)$ charge which means that once the 24-plet gets a VEV, there is a change in the rank.

- Thus giving a VEV to the 24-plet will break the gauge group to the SM gauge group.

  $$SO(10) \to SU(3)_c \times SU(2)_L \times U(1)_Y, \quad < 24(-5) > \neq 0$$

  The 144-plet and $\overline{144}$ contain SM Higgs doublets. One can arrange on pair of Higgs doublets to be light while the Higgs triplets remain heavy.

  This allows one to break SO(10) down to $SU(3)_C \times U(1)_{em}$ using just the $144 + \overline{144}$ plets of Higgs.

- There are three different possibilities for getting the light Higgs doublet. We label these possibilities as D_1, D_2, D_3.

Couplings with fermions

Matter-Higgs couplings are at least quartic (suppressed by $1/\Lambda$)

$$\begin{aligned}
&(\mathbf{16}\times\mathbf{16})_{\mathbf{10}}(\mathbf{144}\times\mathbf{144})_{\mathbf{10}}, \qquad (\mathbf{16}\times\mathbf{16})_{\mathbf{10}}(\overline{\mathbf{144}}\times\overline{\mathbf{144}})_{\mathbf{10}}\\
&(\mathbf{16}\times\mathbf{16})_{\mathbf{120}}(\mathbf{144}\times\mathbf{144})_{\mathbf{120}}, \qquad (\mathbf{16}\times\mathbf{16})_{\mathbf{120}}(\overline{\mathbf{144}}\times\overline{\mathbf{144}})_{\mathbf{120}}\\
&(\mathbf{16}\times\mathbf{16})_{\overline{\mathbf{126}}}(\mathbf{144}\times\mathbf{144})_{\mathbf{126}}, \qquad (\mathbf{16}\times\mathbf{16})_{\overline{\mathbf{126}}}(\overline{\mathbf{144}}\times\overline{\mathbf{144}})_{\mathbf{126}}, \cdots
\end{aligned}$$

Quark- lepton masses for the first two generations arise as follows

$$\begin{aligned}
\mathbf{up-quarks:}\quad & \mathbf{10}_M\mathbf{10}_M < \mathbf{24}_H\mathbf{5}_H >,\\
\mathbf{down-quark-lepton:}\quad & \mathbf{10}_M\bar{\mathbf{5}}_M < \mathbf{24}_H\bar{\mathbf{5}}_H >\\
\mathbf{RR}-\nu\ \mathbf{mass:}\quad & \mathbf{1}_M\mathbf{1}_M < \mathbf{24}_H\mathbf{24}_H >\\
\mathbf{LR}-\nu\ \mathbf{mass:}\quad & \bar{\mathbf{5}}_M\mathbf{1}_M < \mathbf{24}_H\mathbf{5}_H, \mathbf{24}_H\mathbf{45}_H >\\
\mathbf{LL}-\nu\ \mathbf{mass:}\quad & \bar{\mathbf{5}}_M\bar{\mathbf{5}}_M < \mathbf{5}_H\mathbf{5}_H >
\end{aligned}$$

For the third generation one needs cubic interactions which involve 10, 45, 120 plets of matter [2]

[2] Babu, Gogoladze, PN, Syed: PRD 74, 075004 (2006); PN, Syed: PRD 81, 037701 (2010).

Doublet Triplet Splitting

GUT theories typically have the doublet-triplet problem. Some possible solutions are

- Missing VEV: SO(10) breaks in the B-L direction.
- Flipped $SU(5) \times U(1)$
- Missing partner mechanism
- Orbifold GUTs

The missing partner mechanism and the orbifold GUTs are rather compelling in that some doublets are forced to be massless. We will discuss how it works in $SU(5)$ and then discuss how one can extend to $SO(10)$.

Missing partner mechanism in SU(5) Models

- In SU(5) to obtain Higgs doublets which are naturally light one uses an array of light and heavy Higgs multiplets[3]

$$\begin{aligned} \textbf{Heavy}: &\quad \mathbf{50}, \overline{\mathbf{50}}, \mathbf{75} \\ \textbf{Light}: &\quad \mathbf{5}, \bar{\mathbf{5}} \end{aligned}$$

  i.e,, mass terms for $\mathbf{75}, \mathbf{50}, \overline{\mathbf{50}}$ and no mass terms for $\mathbf{5} + \bar{\mathbf{5}}$.
- $\mathbf{75}$ plets breaks the GUT symmetry to $SU(3) \times SU(2) \times U(1)$.
- Doublet pairs (D) and triplet/anti-triplet pairs (T)

$$\begin{aligned} \mathbf{50} + \overline{\mathbf{50}} &\quad 0D + 1T \\ \mathbf{5} + \bar{\mathbf{5}} &\quad 1D + 1T \end{aligned}$$

- The Higgs triplets/anti-triplets of $\mathbf{50} + \overline{\mathbf{50}}$ mix with the Higgs triplets/anti-triplets of $\mathbf{5} + \bar{\mathbf{5}}$ to become heavy. This is accomplished via the superpotential

$$W_0(\mathbf{75}) + M\mathbf{50}.\overline{\mathbf{50}} + \lambda_1 \mathbf{50}.\mathbf{75}.\bar{\mathbf{5}} + \lambda_2 \overline{\mathbf{50}}.\mathbf{75}.\mathbf{5}$$

  The doublets in $\mathbf{5} + \bar{\mathbf{5}}$ have nothing to pair up with and remain light.

[3] Grinstein (1982); Masiero, Nanopoulos, Tamvakis, Yanagida (1982)

A More Unified $SO(10)$ Model: $560 + \overline{560}$

Babu, Gogoladze, PN, Syed (in progress)

A missing partner mechansim can also be implemented in SO(10). One example is a model with $\mathbf{126} + \overline{\mathbf{126}} + \mathbf{210}$ (heavy sector) and $\mathbf{2} \times \mathbf{10} + \mathbf{120}$ (light sector) (Babu, Gogoladze, Tavartkiladze (2007). Here the $\mathbf{50} + \overline{\mathbf{50}}$ of $SU(5)$ arise from $\mathbf{126} + \overline{\mathbf{126}}$ while the $\mathbf{75}$ plet of $SU(5)$ arise from the $\mathbf{210}$ multiplet. It would be nice if one could get a single representation which contains both $\mathbf{50} + \overline{\mathbf{50}}$ and $\mathbf{75}$. This is precisely what happens in 560.

$$\begin{aligned} \mathbf{560} = \mathbf{1(-5)} + \mathbf{\bar{5}(3)} + \overline{\mathbf{10}}\mathbf{(-9)} + \mathbf{10(-1)} + \mathbf{10(-1)} + \mathbf{24(-5)} + \mathbf{40(-1)} \\ + \mathbf{45(7)} + \overline{\mathbf{45}}\mathbf{(3)} + \overline{\mathbf{50}}\mathbf{(3)} + \overline{\mathbf{70}}\mathbf{(3)} + \mathbf{75(-5)} + \mathbf{175(-1)} \end{aligned}$$

$$\begin{aligned} \mathbf{Heavy\ sector:} &\quad \mathbf{D - T\ count} \\ \mathbf{560} + \overline{\mathbf{560}}: &\quad \mathbf{4}\boldsymbol{D} + \mathbf{5}\boldsymbol{T} \\ \\ \mathbf{Light\ sector:} &\quad \mathbf{D - T\ count} \\ \mathbf{2 \times 10}: &\quad \mathbf{2}\boldsymbol{D} + \mathbf{2}\boldsymbol{T} \\ \mathbf{320}: &\quad \mathbf{3}\boldsymbol{D} + \mathbf{3}\boldsymbol{T} \\ \mathbf{Total}: &\quad \mathbf{5}\boldsymbol{D} + \mathbf{5}\boldsymbol{T} \end{aligned} \tag{1}$$

Thus all the Higgs triplets and anti-triplets from the light sector pair up with the ones in the heavy sector while only 4 doublet pairs from the light sector pair up with the ones in the heavy sector leaving one Higgs doublet pair light.

The 560 Multiplet

The $\mathbf{560}$ multiplet is an irreducible tensor spinor. An ordinary $SO(10)$ spinor has $\mathbf{16}$ components. So consider a spinor with two $SO(10)$ tensor indices which are anti-symmetric, i.e.,

$$\mathbf{16 \times 45 = 16 + 144 + 560}$$

We represent the $\mathbf{16 \times 45}$ tensor by $\chi^{720}_{\mu\nu}$. The $\mathbf{560}$ multiplet is a reduction of it by the imposition of a constraint

$$\Gamma_\mu \theta^{560}_{\mu\nu} = 0.$$

where the Γ_μ are the $SO(10)$ gamma's which satisfy the Clifford algebra

$$\{\Gamma_\mu, \Gamma_\nu\} = 2\delta_{\mu\nu} I.$$

Light-Heavy Mixing

Symmetric decomposition

$$(\mathbf{560}\times\mathbf{560})_s = \mathbf{10} + \mathbf{126}_1 + \mathbf{126}_2 + \mathbf{1\bar{2}6} + \mathbf{320} + \mathbf{210}' + \mathbf{1728}_1$$
$$+\mathbf{1728}_2 + \mathbf{2970}_1 + \mathbf{2970}_2 + \mathbf{3696} + \mathbf{4410} + \mathbf{4950}$$
$$+\mathbf{4\bar{9}50} + \mathbf{10560} + \mathbf{6930}' + \mathbf{36750} + \mathbf{27720} + \mathbf{46800}.$$

Anti-symmetric decomposition

$$(\mathbf{560}\times\mathbf{560})_a = \mathbf{120}_1 + \mathbf{120}_2 + \mathbf{320} + \mathbf{1728}_1 + \mathbf{1728}_2 + \mathbf{2970} + \mathbf{3696}_1$$
$$+\mathbf{3696}_2 + \mathbf{4312}_1 + \mathbf{4312}_2 + \mathbf{10560} + \mathbf{36750} + \mathbf{34398} + \mathbf{48114}$$

The $\mathbf{560} + \overline{\mathbf{560}}$ multiplet is heavy. The mixing of the light multiplet with the heavy multiplet comes about as follows

$$M\mathbf{560}.\overline{\mathbf{560}} + \mathbf{560}.\mathbf{560}.\mathbf{320} + \overline{\mathbf{560}}.\overline{\mathbf{560}}.\mathbf{320}$$

$$+\mathbf{560}.\mathbf{560}.\mathbf{10}_1 + \overline{\mathbf{560}}.\overline{\mathbf{560}}.\mathbf{10}_2$$

The $\mathbf{320}$ multiplet has thus far not been used in particle theory. It has the decomposition

$$\mathbf{320} = \mathbf{5}(2) + \bar{\mathbf{5}}(-2) + \mathbf{40}(-6) + \overline{\mathbf{40}}(6)$$

$$+\mathbf{45}(2) + \overline{\mathbf{45}}(-2) + \mathbf{70}(2) + \overline{\mathbf{70}}(-2)$$

• All the components of $\mathbf{320}$ that do not enter in the doublet-triplet splitting become superheavy through mixing with the heavy sector.

Exotics

$$\begin{array}{ccc} & 560 & 320 \\ \langle \mathbf{560(-5)} \rangle & \mathbf{40(-1)} \longleftrightarrow & \overline{\mathbf{40}}\mathbf{(6)} \\ \langle \mathbf{560(-5)} \rangle & \overline{\mathbf{70}}\mathbf{(3)} \longleftrightarrow & \mathbf{70(2)} \\ \langle \mathbf{560(-5)} \rangle & \mathbf{45(7)} \longleftrightarrow & \overline{\mathbf{45}}\mathbf{(-2)} \\ \langle \mathbf{560(-5)} \rangle & \overline{\mathbf{45}}\mathbf{(3)} \longleftrightarrow & \mathbf{45(2)} \\ \langle \overline{\mathbf{560}}\mathbf{(5)} \rangle & \mathbf{40(-1)} \longleftrightarrow & \overline{\mathbf{40}}\mathbf{(6)} \\ \langle \overline{\mathbf{560}}\mathbf{(5)} \rangle & \overline{\mathbf{70}}\mathbf{(3)} \longleftrightarrow & \mathbf{70(2)} \\ \langle \overline{\mathbf{560}}\mathbf{(5)} \rangle & \mathbf{45(7)} \longleftrightarrow & \overline{\mathbf{45}}\mathbf{(-2)} \\ \langle \overline{\mathbf{560}}\mathbf{(5)} \rangle & \overline{\mathbf{45}}\mathbf{(3)} \longleftrightarrow & \mathbf{45(2)} \end{array}$$

All the exotics in 320 become massive by mixing with the components in 560 and $\overline{\mathbf{560}}$. The only remaining light field is a pair of light doublets.

Spontaneous Breaking with 560 + 560 Higgs

The simplest superpotential that would break the $SO(10)$ symmetry is

$$W = M_{560}560.\overline{560} + \frac{1}{M_r}(560.\overline{560})_r.(560.\overline{560})_r$$

where r stands for the representation by which contracts. For r a singlet, the Lagrangian will have an $SU(560)$ global symmetry and a VEV formation of a singlet will lead to Goldstone bosons. The simplest non-trivial contraction is when $r = 45$. That is one considers

$$(560.\overline{560})_{45} \cdot (560.\overline{560})_{45}.$$

Now recall that 560 contains a 75 -plet of $SU(5)$ which must develop a VEV to mimic the the breaking in $SU(5)$. However the VEV formation of $\mathbf{75}$ plets leads to VEV formation of $\mathbf{1, 24}$ and also of the bar fields so all of the following fields develop VEVs.

$$\begin{array}{cc} 560 & \overline{560} \\ 1, 24, 75 & \bar{1}, \overline{24}, \overline{75}. \end{array} \tag{2}$$

Spontaneous symmetry breaking then involves six different VEVs.

Table 1: $\mathbf{S}_{(1)} = \overline{\mathbf{S}}_{(1)}$, $\mathbf{S}_{(24)} = \overline{\mathbf{S}}_{(24)}$, $\mathbf{S}_{(75)} = \overline{\mathbf{S}}_{(75)}$

$M_{45} \cdot M_{560}$ (GeV^2)	$\mathbf{S}_{(1)}$ (GeV)	$\mathbf{S}_{(24)}$ (GeV)	$\mathbf{S}_{(75)}$ (GeV)
10^{30}	$(-1.2 + \imath 1.4) \times 10^{16}$	$(27 + \imath 5.7) \times 10^{14}$	$(6.4 + \imath 25) \times 10^{14}$
	$(-5.4 - \imath 5.4) \times 10^{12}$	$(-2.5 + \imath 2.5) \times 10^{14}$	$(2 - \imath 2) \times 10^{15}$
10^{31}	$(4.4 - \imath 3.8) \times 10^{16}$	$(1.8 + \imath 8.4) \times 10^{15}$	$(7.8 + \imath 2) \times 10^{15}$
	$(-1.7 + \imath 1.7) \times 10^{13}$	$(-7.9 + \imath 7.9) \times 10^{14}$	$(6.5 - \imath 6.5) \times 10^{15}$
10^{32}	$(1.2 - \imath 1.4) \times 10^{17}$	$(-27 - \imath 5.7) \times 10^{15}$	$(-6.4 - \imath 25) \times 10^{15}$
	$(-5.4 + \imath 5.4) \times 10^{13}$	$(-2.5 + \imath 2.5) \times 10^{15}$	$(2 - \imath 2) \times 10^{16}$
10^{33}	$(-3.8 + \imath 4.4) \times 10^{17}$	$(8.4 + \imath 1.8) \times 10^{16}$	$(2 + \imath 7.9) \times 10^{16}$
	$(1.7 - \imath 1.7) \times 10^{14}$	$(7.9 - \imath 7.9) \times 10^{15}$	$(-6.5 + \imath 6.5) \times 10^{16}$
10^{34}	$(1.4 - \imath 1.2) \times 10^{18}$	$(5.7 + \imath 27) \times 10^{16}$	$(25 + \imath 6.4) \times 10^{16}$
	$(-5.4 + \imath 5.4) \times 10^{14}$	$(-2.5 + \imath 2.5) \times 10^{16}$	$(2 - \imath 2) \times 10^{17}$

Non-minimal Models

One can also generate non-minimal missing partner models. This can done as follows: One can have two generations of heavy $\mathbf{560} + \overline{\mathbf{560}}$ and one generation of light $\mathbf{560} + \mathbf{560}$. Introducing a light along with a heavy generation does not change the DT splitting count. Since we have more than one generation of $\mathbf{560} + \overline{\mathbf{560}}$ one can now introduce a light and a heavy 120-plet which also leaves the DT count unchanged. Then the following models can be constructed

- Model 1: $\mathbf{2} \times \mathbf{120}_{a} + \mathbf{10}$
- Model 2: $\mathbf{120}_{a} + \mathbf{3} \times \mathbf{10}$
- Model 3: $\mathbf{320}_{s} + \mathbf{120}_{a} + \mathbf{10}_{LH}$
- Model 4: $\mathbf{320}_{a} + \mathbf{120}_{a} + \mathbf{10}_{LH}$
- Model 5: $\mathbf{320}_{a} + \mathbf{2} \times \mathbf{10} + \mathbf{120}_{LH}$

The subscript LH means that a light + heavy pair is added.

A convenient basis for computation of $SO(2N)$ vertices is to use the $SU(N) \times U(1)$ basis given by[4]

$$\Gamma_{2i} = (b_i + b_i^\dagger), \qquad \Gamma_{2i-1} = -i(b_i - b_i^\dagger), \quad i = 1,..,5$$
$$\{b_i, b_j^\dagger\} = \delta_{ij}, \qquad \{b_i, b_j\} = 0 = \{b_i^\dagger, b_j^\dagger\}$$

Using the above basis it is possible to compute all $SO(2N)$ vertices by field theory techniques [5]

$$\Gamma_\mu \phi_\mu \quad = \qquad b_i^\dagger \phi_{c_i} + b_i \phi_{\bar{c}_i}$$
$$\phi_{ci} = \phi_{2i} + i\phi_{2i-1}, \qquad \phi_{\overline{ci}} = \phi_{2i} - i\phi_{2i-1}$$
$$\phi_{c_i c_j \bar{c}_k \ldots} \quad = \qquad \phi_{2i c_j \bar{c}_k \ldots} + i\phi_{2i-1 c_j \bar{c}_k \ldots} \quad 2^N \text{terms}$$

$\phi_{c_i c_j \bar{c}_k \ldots}$ transforms like a reducible rep of $SU(N)$. Thus if we can express SO(2N) couplings in terms of $\phi_{c_i c_j \bar{c}_k \ldots}$ etc, then we need only to decompose $\phi_{c_i c_j \bar{c}_k \ldots}$ is terms of irreducible reps of $SU(N)$.

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[4] Mohapatra, Sakita PRD D21, 1062 (1980); Wilczek, Zee, PRD 25, 553 (1982).

[5] PN, Raza Syed: PLB 506,68(2001).

The Basic Theorem

In the $SU(N) \times U(1)$ basis on has a vertex expansion for any tensor vertex [6]

$$
\begin{aligned}
\Gamma_\mu \Gamma_\nu \Gamma_\lambda .. \Gamma_\sigma \phi_{\mu\nu\lambda..\sigma} \quad = \quad & b_i^\dagger b_j^\dagger b_k^\dagger .. b_n^\dagger \phi_{c_i c_j c_k ... c_n} \\
& + (b_i b_j^\dagger b_k^\dagger .. b_n^\dagger \phi_{\bar{c}_i c_j c_k ... c_n} + \ perms) \\
& + (b_i b_j b_k^\dagger .. b_n^\dagger \phi_{\bar{c}_i \bar{c}_j c_k .. c_n} + \ perms) \\
& + ... + (b_i b_j b_k .. b_{n-1}^\dagger b_n \phi_{c_i c_j c_k .. c_{n-1} c_n} + \ perms) \\
& + b_i b_j b_k ..... b_n \phi_{\bar{c}_i \bar{c}_j \bar{c}_k ... \bar{c}_n}
\end{aligned}
$$

where all possible permutations of b and $b^\dagger$ are taken. For the vertices involving spinors a similar vertex expansions can be carried out. For vertices including tensor-spinors additional constraints need to be included.

[6] PN, Raza Syed: PLB 506,68(2001); NPB, 618, 138(2001); NPB 676, 64(2004)

B &L violating Dim 6 operators

Proton decay via exchange of vector lepto-quarks

$$\Gamma_p \approx \alpha_{GUT}^2 \, \frac{m_p^5}{M_V^4}$$

The current experimental limit

$$\tau(p \to \pi^0 e^+) \; > 8.2 \times 10^{33} \mathrm{yrs}$$

implies a very rough lower bound on the superheavy gauge boson mass

$$M_V \; > \; 5 \times 10^{15} \; \mathrm{GeV}.$$

- Thus the existence of proton stability at current levels implies the existence of a very high scale, much closer to the Planck scale than the weak scale.

Theoretical predictions of $e^+\pi^0$ mode are model dependent. Most model predictions lie in the range

$$\tau(p \to \pi^0 e^+) \sim (5 \times 10^{34} - 5 \times 10^{36}) \mathrm{yr}$$

Theoretical lifetimes limit on $p \to e^+\pi^0$ mode

Lifetime estimates for $p \to e^+\pi^0$ for various models[7]

Ref	Model	Lifetime estimate in yrs
LMPR[8]	Non-SUSY GUTs	10^{33-38}
DFP [9]	SU(5)	$\sim 10^{37}$
JH[10]	SUSY GUTs	1.6×10^{34}
JCP[11]	SUSY-SO(10)	$\sim 5 \times 10^{35\pm1}$
HM-R[12]	5D models	$\sim 4 \times 10^{36}$
KR[13]	5D -SO(10)	$\sim 7 \times 10^{33\pm2}$
BCEW[14]	6D models	$\sim 5 \times 10^{34\pm1}$
KW[15]	D-brane models	$(0.8 - 1.9) \times 10^{36}$
PR[1]	Black holes, worm holes	$\sim 10^{45}$

7 PN, Fileviez Perez, Physics Reports: (2007)
8 Lee, Mohapatra, Parida, Rani (1995)
9 Dorsner, Fileviez-Perez (2005,2006)
10 J. Hisano (2000)
11 Pati, Berkeley Conf (2007)
12 Hebecker, March-Russel (2002)
13 Kim, Raby (2003)
14 Emmanuel-Costa, Wiesenfeldt (2003)
15 Klebanov, Witten (2003); Cvetic, Richter (2007).

SUSY proton decay

- B&L violating dim 4 operators can appear in SUSY

$$QLD^C, U^C D^C D^C, LLE^C, LH$$

These may be suppressed by the constraint of R parity.

- B&L violating dim 5 operators (Weinberg; Sakai, Yanagida).

$$LLLL : C_{ikl}(Q_i.Q_i)(Q_k.L_l)/M_T$$

$$RRRR : C'_{ijkl} u_i^C e_j^C u_k^C d_l^C / M_T$$

Dressing loops (Arnowitt, Chamseddine, PN; Goto, Nihei; Lucas, Raby) convert dim 5 to dim 6 operators involving quarks and leptons. Further, the quark -lepton lagrangian is converted to the one involving mesons and baryons using effective lagrangian techniques. These give rise to decay modes

$$p \to \bar{\nu}_{e,\mu,\tau} K^+,\ \nu_{e,\mu,\tau}\pi,\ \nu_{e,\mu,\tau}\eta,\ \mu\pi,\ eK,\ \mu K, ..$$

Proton lifetime estimates for $p \to \bar{\nu} K^{+}$ for various models

	Model	Lifetime/ys
AN[16], MP[17]	SUSY SU(5)	$\sim 10^{32-34}$
BPW[18]	SUSY SO(10)	$(1/3 - 2) \times 10^{34}$
LR[19]	SUSY SO(10)	$(6.6 - 3 \times 10^{2}) \times 10^{33}$
DMM[20], NS[21]	SUSY GUTs	$\geq (2 - 3) \times 10^{33}$
PR[17]	Calabi-Yau Strings	$\sim 10^{34-35}$

Proton lifetime estimates for unconventional modes

Ref	Mode	Model	Lifetime/ys
ADPY[22]	$p \to \pi^{+}\pi^{+}l^{-}\nu\nu$	UED -6D	$\geq 10^{35}$
KS[23]	$p \to e^{-}e^{+}\nu\pi^{+}$ etc	Lepto-quark model	suppressed
PR[24]	$p(n) \to \gamma + e^{+}(\bar{\nu})$	SUSY GUTs	$> 10^{38\pm1}$

16 Arnowitt, PN (1985)

17 Murayama, Pierce (2002)

18 Babu, Pati, Wilczek (2000)

19 Lucas, Raby (1997)

20 Dutta, Mimura, Mohapatra (2004)

21 PN, Syed (2001, 2007)

22 Appelquist, Dobrescu, Ponton, Yee (2001)

23 Kovalenko, Schmidt (2003)

24 Physics Reports: PN, Fileviez Perez (2007)

Model dependence of proton decay modes

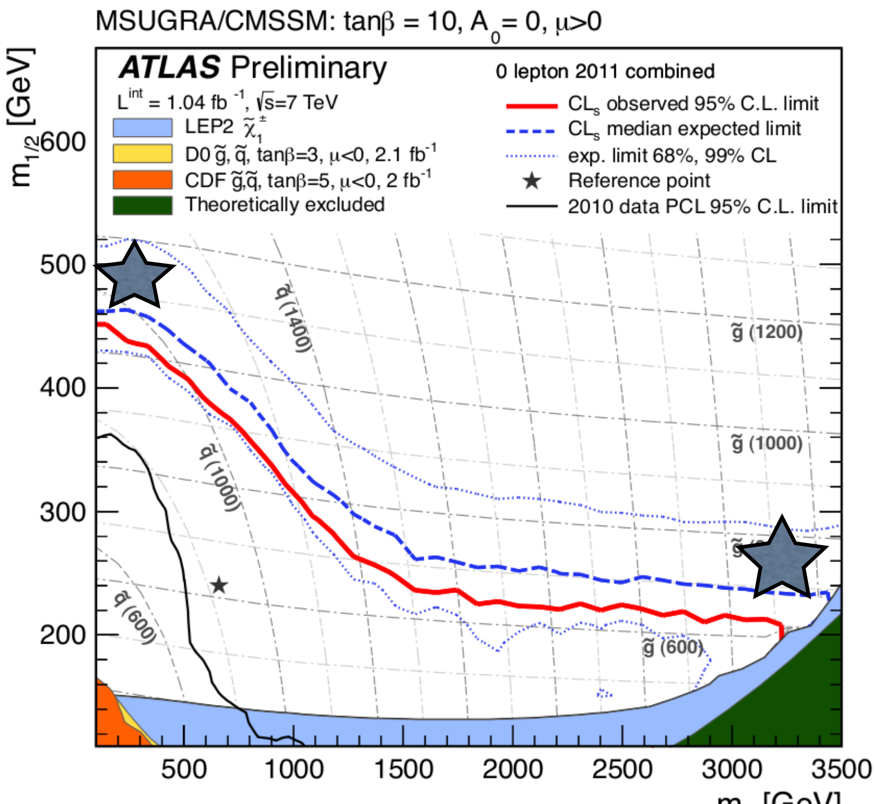
Current experimental limit on $\bar{\nu}K^+$ mode

$\tau(p \to \bar{\nu}K^+) > (2.3) \times 10^{33}$ yrs

K. Kobayashi, at.al. (Super-K), PRD 72, 052007 (2005).
There is significant model dependence in the predictions of the proton decay modes specifically on the SUSY decay modes.

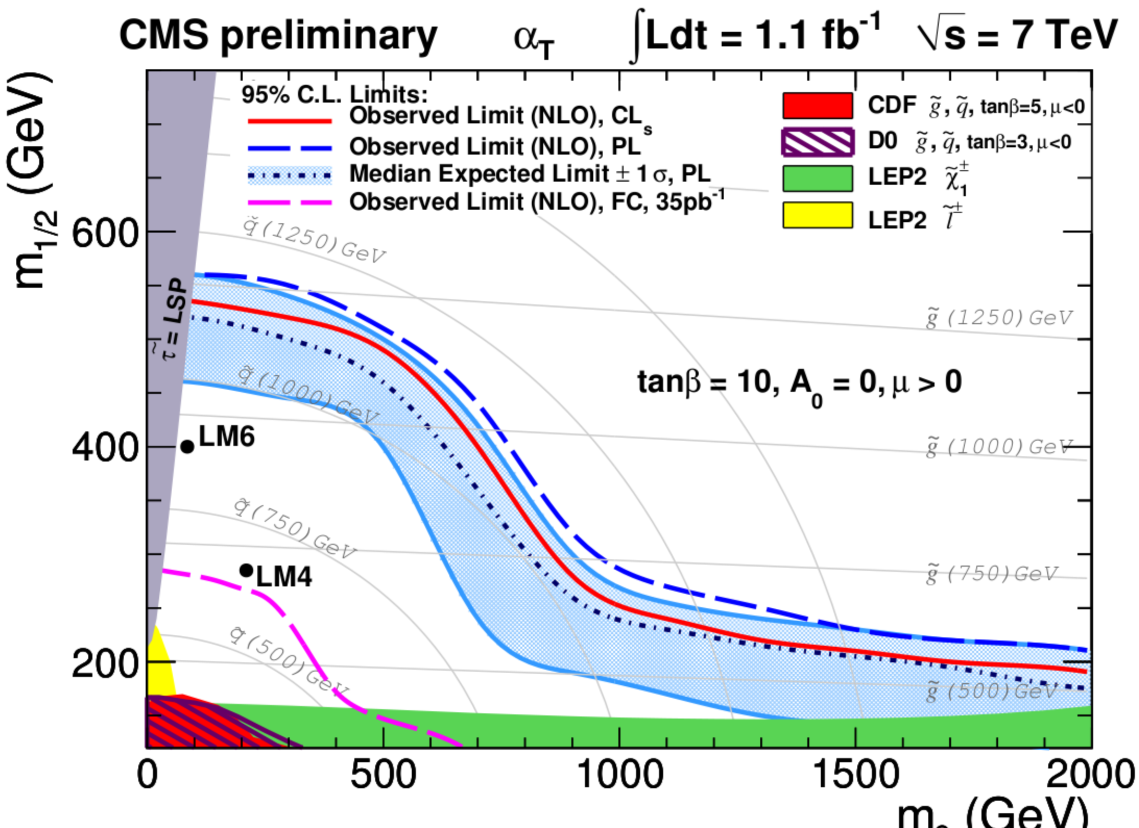
- For many GUT models, the susy proton decay is too fast and needs to be suppressed. This could be done in various ways such as via the cancellation mechanism (PN, Raza Syed) or exploiting the model dependence on inputs which enters via the sparticle mass spectrum including masses of charginos, gluinos, neutralinos, squarks, and sleptons along with their couplings which depend on $m_0, m_{1/2}, A_0, \tan\beta, \mu$.
- LHC is putting new limits in the $m_0 - m_{1/2}$ reach. However, A_0 and $\tan\beta$ are still largely unconstrained. The uncertainty of what exactly the sparticle masses and susy inputs are make precise predictions of the lifetime of SUSY modes difficult.

The ATLAS SUSY constrains on mSUGRA with 1.04 fb^{-1} of data



The specific mSUGRA parameter point $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

The CMS SUSY constrains on mSUGRA with 1.1 fb^{-1} of data



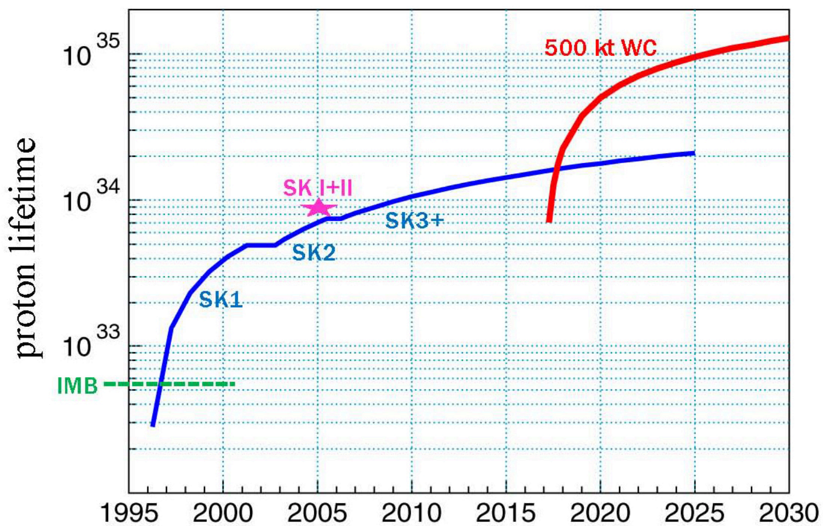
The specific mSUGRA parameter point $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$ and $\mu < 0$.

Conclusion/prospects

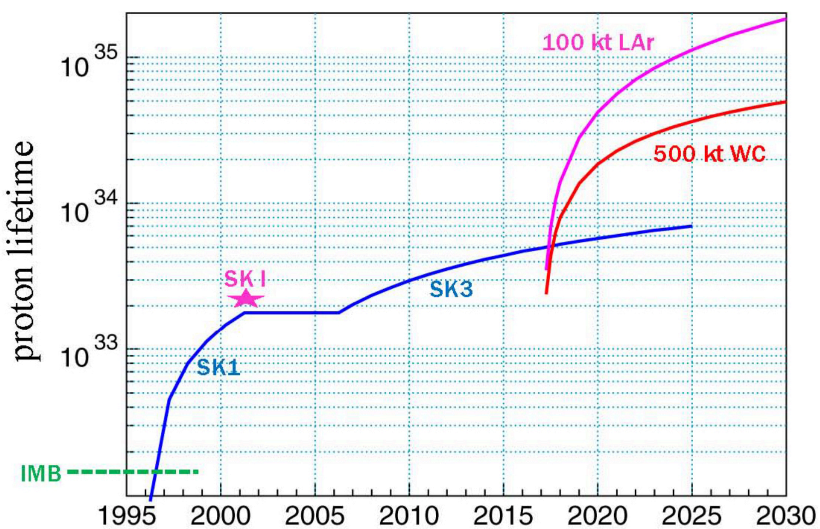
- Proton lifetime experimental limits have played a major role in constraining unified models of particle interactions.
- Proton decay mode $p \to \bar{\nu} K^+$ should have been seen and may be around the corner.
- The LHC results will hopefully provide us with a concrete evidence and measurement of sparticle spectra leading to improved proton lifetime predictions.
- Observation of proton decay would be a definite proof of quark-lepton unification and more generally of the basic idea of grand unification.
- Proton stability experiments should continue as they probe the nature of fundamental interactions at extremely short distances which the accelerators can never hope to reach.

  One needs a large volume detector: 1 mega-ton detector would be ideal. Requires an international effort.

$$p \to e^+\pi^0$$



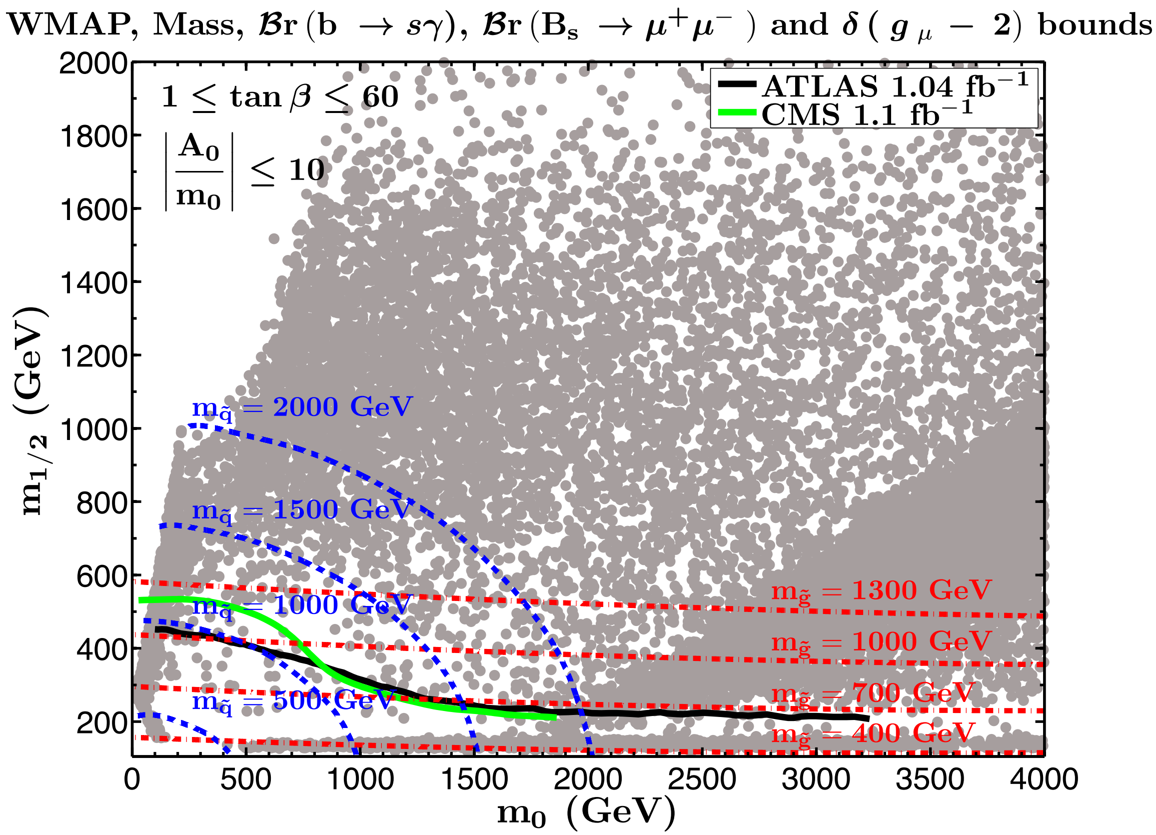
$$p \to K^+\nu$$



Taken from E. Kearns NNN07 talk

LHC and Dark Matter

Some of the region of the parameter space eliminated by CMS and ATLAS was already eliminated by WMAP, flavor and other experimental constraints.



S. Akula, D. Feldman, Z. Liu, PN and G. Peim, arXiv:1103.5061 [hep-ph].