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Workshop on Grand Unification and Proton Decay

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SUSY-breaking in proton decay

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SUSY breaking in proton decay

. . . high scale remnants

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SUSY GUTs

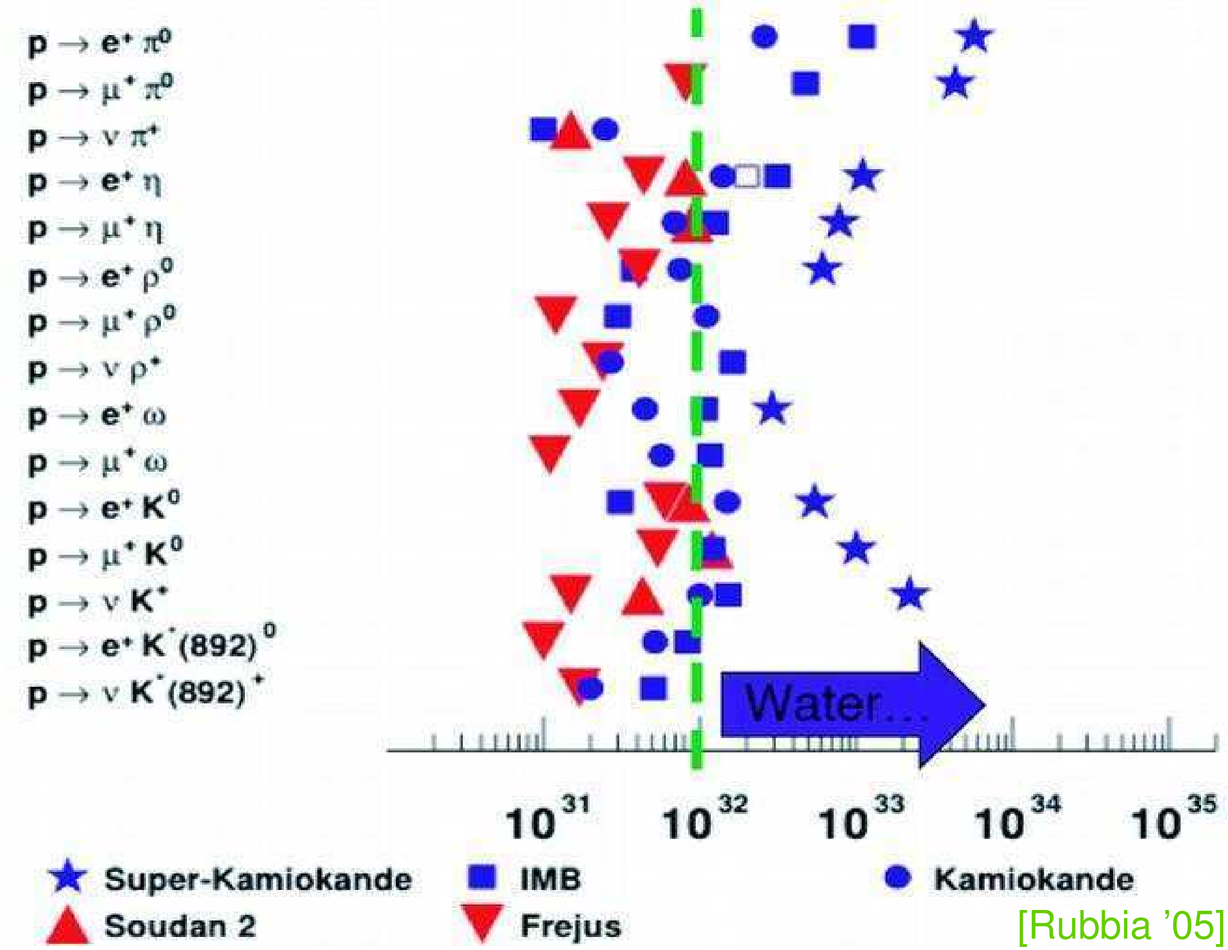
- Understanding the fermion quantum numbers leads to GUTs.
- Gauge couplings also unify.. SUSY GUTs even better.
- Family symmetries can give understanding of masses and mixings.
- Neutrino seesaw is naturally present.
- LSP, lepto-baryogenesys...
- Higgs hierarchy problem solved (the large one).

However:

- In SUSY: proliferation of parameters (and models...).
- In GUTs: proton should decay.

So proton is not forever (?)

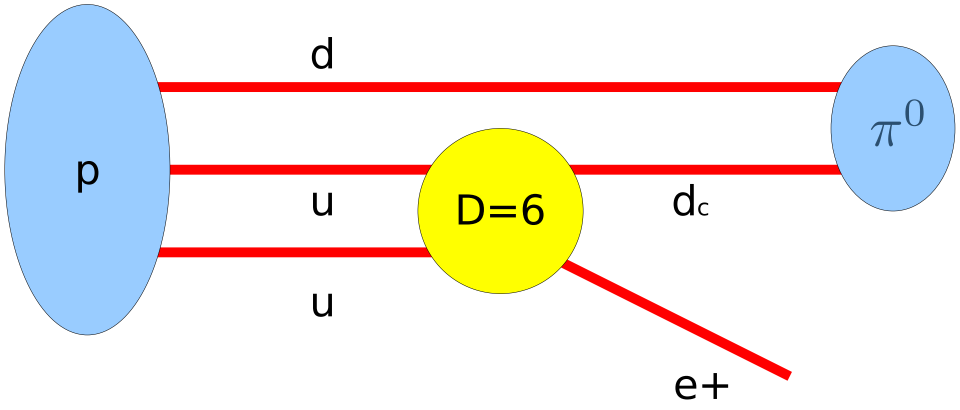
Baryon number nonconservation a natural consequence of Grand-Unified Theories. Probed up to $\sim 10^{33\text{-}34}$y:



[Rubbia '05]

...different channels from different operators.

D=6 operators [Weinberg, Wilczek Zee '79]



Four-fermions operators: (doublets q, l; singlets u^c, d^c, e^c, ν^c)

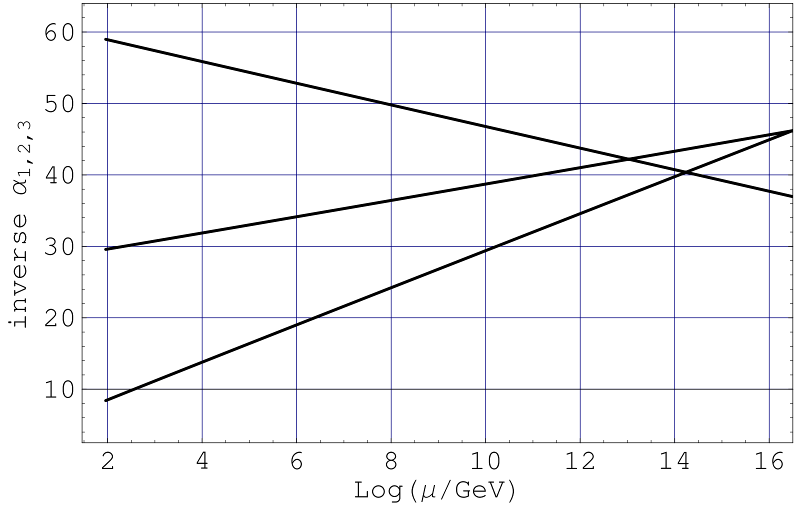
$$O_{\rm gauge} \sim g^2 M_G^{-2}\,(\bar q\, u^c\, \bar l\, d^c)\,, \quad g^2 M_G^{-2}\,(\bar q\, u^c\, \bar q\, e^c)\,,$$

$$O_{\rm higgs} \sim y^2 M_H^{-2}(q\,q\,q\,l)\,, \quad y^2 M_H^{-2}(u^c\,u^c\,d^c\,e^c)\,.$$

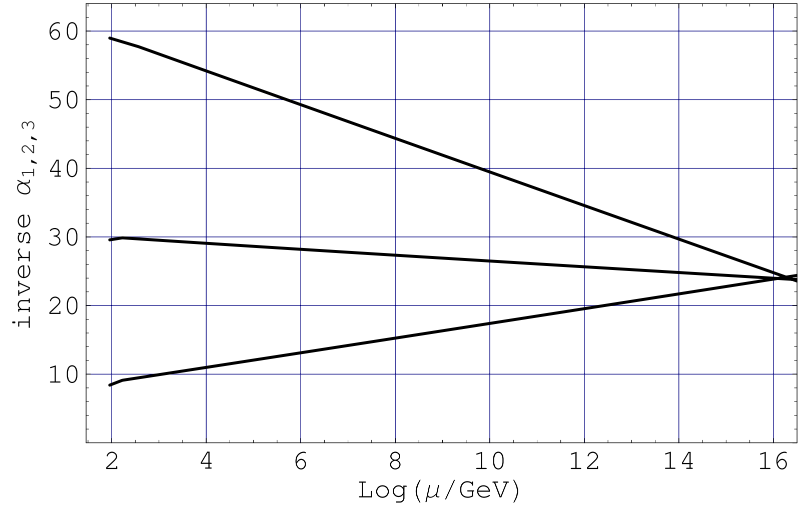
The decay width is very sensitive to M_G, M_H: $\Gamma_p \simeq m_p^5|\mathcal{M}|^2 \sim g^4/M_G^4$.

E.g. for $M_G, M_H \sim 10^{13-15}$ GeV, these are dangerous: $\tau_p \sim 10^{25-33}\,{\rm y}$.

Recall GUT vs SUSY GUT



SM GUT



MSSM GUT

SUSY GUT gives one-shot unification of gauge couplings, in addition to protecting from other issues.

It also sets the GUT scale to 10^{16} GeV, making the D=6 operators safe.

With SUSY new operators *[Weinberg '82]*

With supersymmetry GUT is better, but there are new D=5 and D=4:

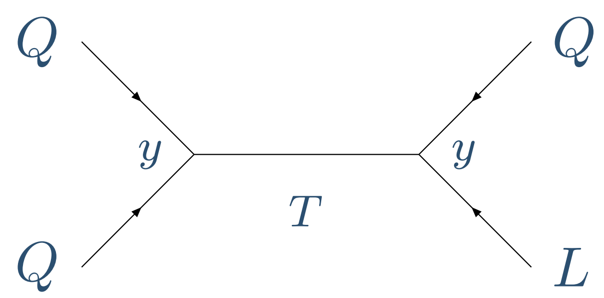
- Most dangerous are D=4 three-superfield operators:

$$UDD^c\,, \qquad QLD^c\,, \qquad E^cLL$$

These are happily eliminated by R-parity ($\Phi \to -\Phi$). This is automatic with some fields content or may be imposed by hand.

- Then there are D=5 operators, mediated by triplet higgsino T:

$$y^2 M_H^{-1} QQQL\,, \qquad y^2 M_H^{-1} Q^cQ^cQ^cL^c$$

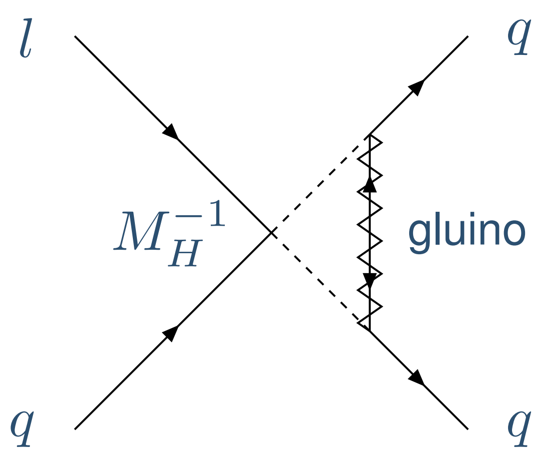


D=5 operators *[Weinberg, Sakai Yanagida '82]*

...two fermions – two scalars

$$O_{\text{higgsino}} \quad \sim \quad y^2 M_H^{-1} (\tilde{q}\, q\, \tilde{q}\, l)\,, \quad y^2 M_H^{-1} (\tilde{u}^c\, u^c\, \tilde{d}^c\, e^c)\,.$$

After dressing they act as D=6:



$$\sim \frac{1}{M_H\, m_{SUSY}}$$

But are suppressed only by $M_G\, m_{SUSY}$, and give $\tau_p \sim 10^{28}\, \mathrm{y}$.

They are very model dependent [e.g. Bajc Filiever-Perez Senjanovic '02]

and in many models can be suppressed

[Coughlan et al '85, Babu Barr '93; Berezhiani F.N. '05]

D=4 operators?

One may ask whether there are also D=4 operators, four-scalars.

$$O_{\rm D=4} \quad \sim \quad g^2(\tilde{q}^*\,\tilde{u}^c\,\tilde{l}^*\,\tilde{d}^c)\,, \quad g^2(\tilde{q}^*\,\tilde{u}^c\,\tilde{q}^*\,\tilde{e}^c)\,,$$

. . . they are unsuppressed, and $\tau_p \sim 10^{-10}\,{\rm s}$!?

. . . and they will be allowed, if scalar partners are discovered at LHC!

We know also that they are already in the lagrangian above GUT: they are the D-terms of the heavy gauge fields:

$$\mathcal{L}_{\rm D-term} = \sum_{A,i} g^2 \left|\phi_i^* \tau_A \phi_i\right|^2 .$$

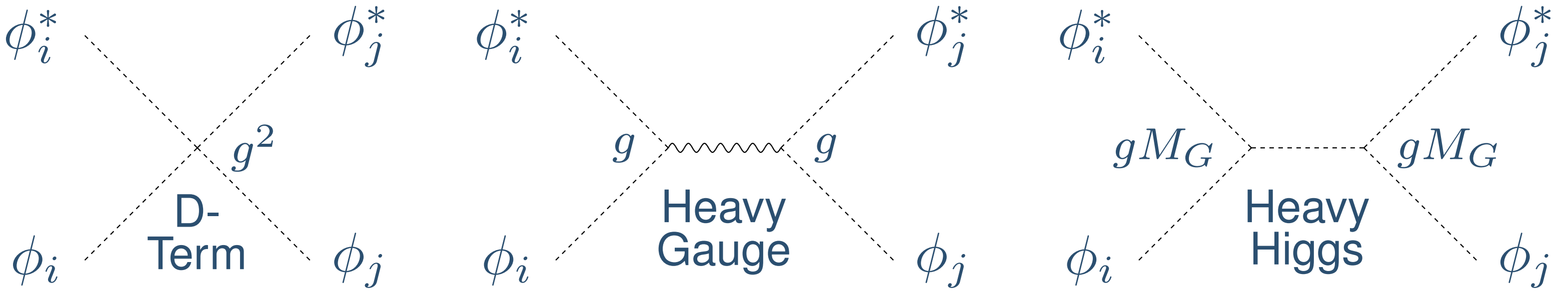
ϕ_i = sfermion multiplets (e.g. $\phi_{\bf 10} = (\tilde{u}^c, \tilde{q}, \tilde{e}^c)$, $\phi_{\bar{\bf 5}} = (\tilde{d}^c, \tilde{l})$ in SU(5))

τ_A = GUT gauge generators (among them τ_X and τ_Y in SU(5))

What happens to these terms at low energy?

SUSY protects

Decoupling theorem should work. . . hence:



$$g^2 \quad + \frac{g^2 p^2}{p^2 - M_G^2} \quad + \frac{g^2 M_G^2}{p^2 - M_G^2} \quad \simeq \frac{g^2 p^2}{M_G^2} \simeq 0$$

Cancellation of D=4 ensured only by SUSY, where all g are equal.

Therefore the discovery of scalar partners will tell us that:

GUT will require SUSY

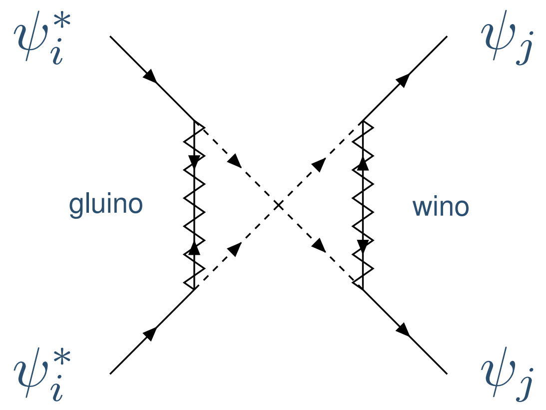
in order to protect us from D=4 operators.

However SUSY is actually broken. . . so?

Proton decay in broken SUSY

We expect partial cancellations, in particular nonzero D=4 operators due to soft terms in the theory: [Derendinger Savoy '82, Sakai '83]

$$\sim g^2 \frac{m_S^2}{M_G^2} \phi\phi^*\phi\phi^*$$



Dressing (double!) gives four-fermions operators:

$$\sim g^2 \frac{m_S^2}{M_G^2} \frac{\alpha^2}{(4\pi)^2 m_{\tilde{g}}^2} \psi\psi^*\psi\psi^*$$

with same strenght as D=6!

$$\sim g^2 \frac{1}{M_G^2} \psi\psi^*\psi\psi^*$$

(but loop factor...)

How to check their relevance and dependence on soft terms?

The calculation...

...is doable in superfields: Chiral $\Phi = \{\Phi_I\}$; Gauge $V = V_A T_A$.

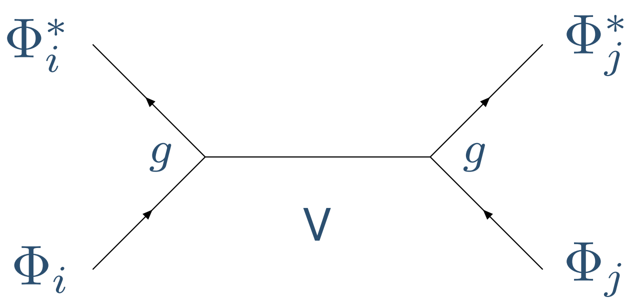
$$\mathcal{L} = \int d^4\theta \left[\Phi^\dagger X e^{2gV} \Phi\right] + \text{superpotential} + \text{gauge kinetic term}$$

Soft masses are in $X_{IJ} = (1 - m_I^2\, \theta^2 \bar{\theta}^2)\delta_{IJ}$. Expand V...

$$\simeq \int d^4\theta \Big[\Phi^\dagger X \Phi + 2 J_A V_A + M_{AB}^2 V_A V_B + \cdots\Big] \qquad J_A = g\,\Phi^\dagger X T_A \Phi\,,$$

$$M_{AB}^2 = 2g^2 \Phi^\dagger X T_A T_B \Phi$$

...and integrate the broken gauge fields V_A between light fields Φ_i:



$$\rightarrow \quad \int d^4\theta\, J_A \frac{g^2}{M_{AB}^2} J_B$$

Four fields operator

$$= \int \mathrm{d}^4\theta \, \frac{g^2}{2g^2 \langle\Phi_H\rangle^\dagger T_A T_A \langle\Phi_H\rangle} \frac{X_i X_j}{X_H} \left(\Phi_i^\dagger T_A \Phi_i\right) \left(\Phi_j^\dagger T_A \Phi_j\right)$$

The soft terms enter via X_i, X_H and via $\langle\Phi_H\rangle$, that also has a nonzero F-term $\langle\Phi_H\rangle = v_H(1 + f_H\theta^2)$.

One can parametrize the result as

$$= \int \lambda_6 \left(1 + \xi\theta^2 + \xi^\dagger\bar{\theta}^2 + \omega_{ij}\theta^2\bar{\theta}^2\right) \left(\Phi_i^\dagger T_A \Phi_i\right) \left(\Phi_j^\dagger T_A \Phi_j\right) \mathrm{d}^4\theta \, ,$$

where $\lambda_6 = g^2/M_A^2$ is the standard D=6 coupling.

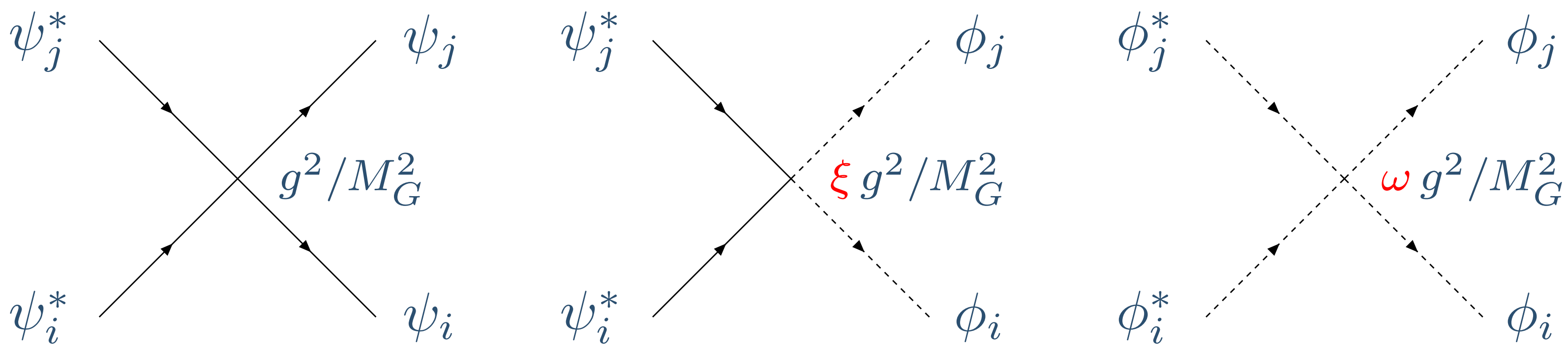
The SUSY breaking coefficients are in general:

$$\xi = -f_H \, , \qquad \omega_{ij} = -m_i^2 - m_j^2 + m_H^2 + |f_H|^2 \, .$$

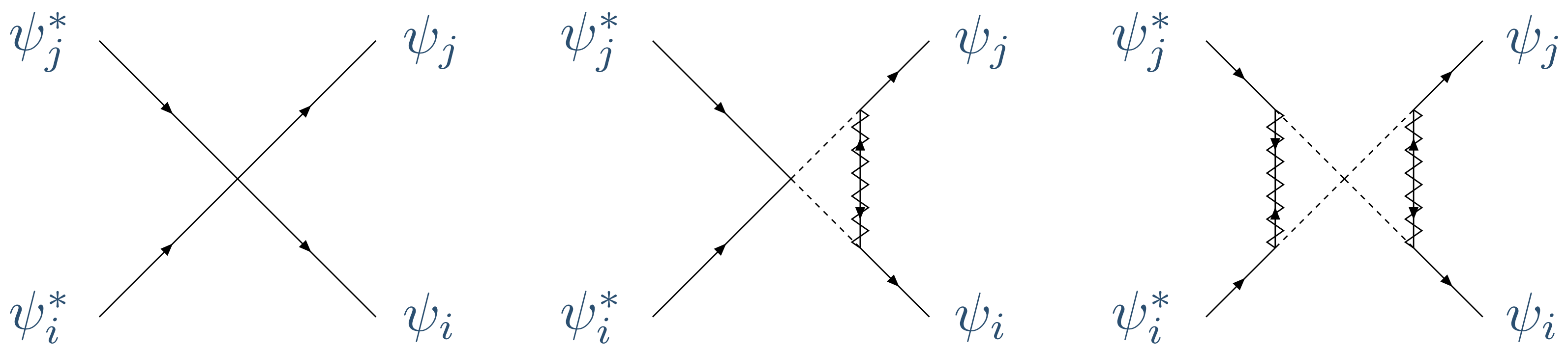
We found standard D=6 plus new D=5 and D=4 operators

New operators

D=6, 5, 4:



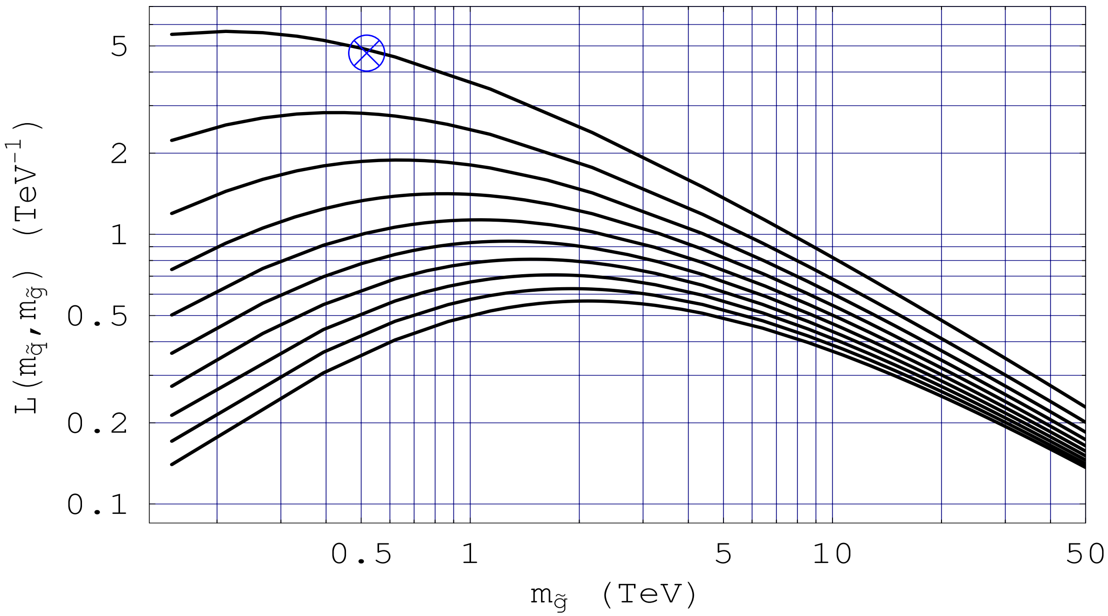
After dressing:



give three competing effects:

$$\lambda_6 \qquad\qquad \lambda_6\, 2\xi \frac{\alpha_3}{4\pi} L(m_{\tilde{q}}, m_{\tilde{g}}) \qquad\qquad \lambda_6\, \omega \frac{\alpha_3}{4\pi}\frac{\alpha_2}{4\pi}[L(m_{\tilde{q}}, m_{\tilde{g}})]^2$$

Loop factor



Loop function L with $m_{\tilde{q}}$ from 0.1 to 2 TeV (upper to lower).

Present limits allow $m_{\tilde{q}} \sim 100$ GeV when $m_{\tilde{g}} \gtrsim 500$ GeV. In this region the loop factor is almost maximal, $L \simeq 5\,\text{TeV}^{-1}$, and one gets:

$$\lambda_6 \left(1 + \frac{\xi}{10\,\text{TeV}} + \frac{\omega}{(30\,\text{TeV})^2}\right)$$

Quite large susy-breaking coefficients are needed ~ 10 TeV!

SU(5) example

$$W(\Sigma) = M_\Sigma(1 - B_\Sigma\theta^2)\,\mathrm{tr}\,\Sigma^2 + \frac{1}{6}\lambda_\Sigma(1 - A_\Sigma\theta^2)\,\mathrm{tr}\,\Sigma^3\,,$$

$$\langle\Sigma\rangle = v_\Sigma\left[1 + (A_\Sigma - B_\Sigma)\theta^2\right]\lambda_{24}\,, \qquad v_\Sigma = 8\sqrt{15}\frac{M_\Sigma}{\lambda_\Sigma}\,.$$

Soft terms are A_Σ, B_Σ, plus all soft masses. $(\Sigma \in \mathbf{24}_H)$

Proton decay can proceed via $\Phi_{\mathbf{10}}\Phi_{\mathbf{10}}\Phi_{\bar{\mathbf{5}}}\Phi_{\bar{\mathbf{5}}}$ or $\Phi_{\mathbf{10}}\Phi_{\mathbf{10}}\Phi_{\mathbf{10}}\Phi_{\mathbf{10}}$ and the standard D=6 coupling is: $\lambda_6(G) = g_5^2/M_A^2$, with $M_A^2 = 5\,g_5^2 v_\Sigma^2/12$.

For the new operators we have:

$$\begin{aligned} \xi &= B_\Sigma - A_\Sigma \\ \omega_{\mathbf{10}\,\bar{\mathbf{5}}} &= -m_{\mathbf{10}}^2 - m_{\bar{\mathbf{5}}}^2 + m_\Sigma^2 + |B_\Sigma - A_\Sigma|^2 \\ \omega_{\mathbf{10}\,\mathbf{10}} &= -2m_{\mathbf{10}}^2 + m_\Sigma^2 + |B_\Sigma - A_\Sigma|^2\,, \end{aligned}$$

Squark masses $m_{\mathbf{10}}$, $m_{\bar{\mathbf{5}}}$ should be small, but:

Could one have large m_Σ^2, A_Σ or B_Σ? ... large B_Σ is not forbidden.

Large B_Σ *easier than* A_Σ

Hierarchy:

$$W_H(\Sigma, H, \bar{H}) = M_H(1 - B_H\theta^2)\bar{H}H + \lambda_H(1 - A_H\theta^2)\bar{H}\Sigma H\,.$$

After the $SU(5)$ breaking, we find $\mu(1 - B_\mu\theta^2)H_uH_d$, with

$$\mu = M_H - \frac{3}{\sqrt{60}}\lambda_H v_\Sigma\,, \qquad \mu B_\mu = \frac{3}{\sqrt{60}}\lambda_H v_\Sigma(A_\Sigma - B_\Sigma - A_H + B_H) + \cdots\,.$$

... two fine tunings needed in general, but ok.

Runnings: B_Σ never appears

$$16\pi^2\frac{\mathrm{d}}{\mathrm{d}t}A_\Sigma = \frac{63}{20}A_\Sigma\lambda_\Sigma^2 + 3A_H\lambda_H^2 - 30\,g_5^2\,m_{\tilde{g}5}$$

$$16\pi^2\frac{\mathrm{d}}{\mathrm{d}t}B_\Sigma = \frac{21}{10}A_\Sigma\lambda_\Sigma^2 + 2A_H\lambda_H^2 - 20\,g_5^2\,m_{\tilde{g}5}\,.$$

Finite corrections! e.g.:

$$\delta B_\mu \sim \frac{\lambda_H^2}{(4\pi)^2}B_\Sigma\,, \qquad \delta m_{\tilde{g}} \sim \frac{g_5^2}{(4\pi)^2}B_\Sigma\,,$$

...effect of heavy higgses soft terms

Large A_Σ, m^2_Σ enter the RG of higgs masses $m^2_{H_{u,d}}$: can destabilize electroweak breaking and whole picture of low energy SUSY.

On the other hand, a large B_Σ of SU(5) is allowed:

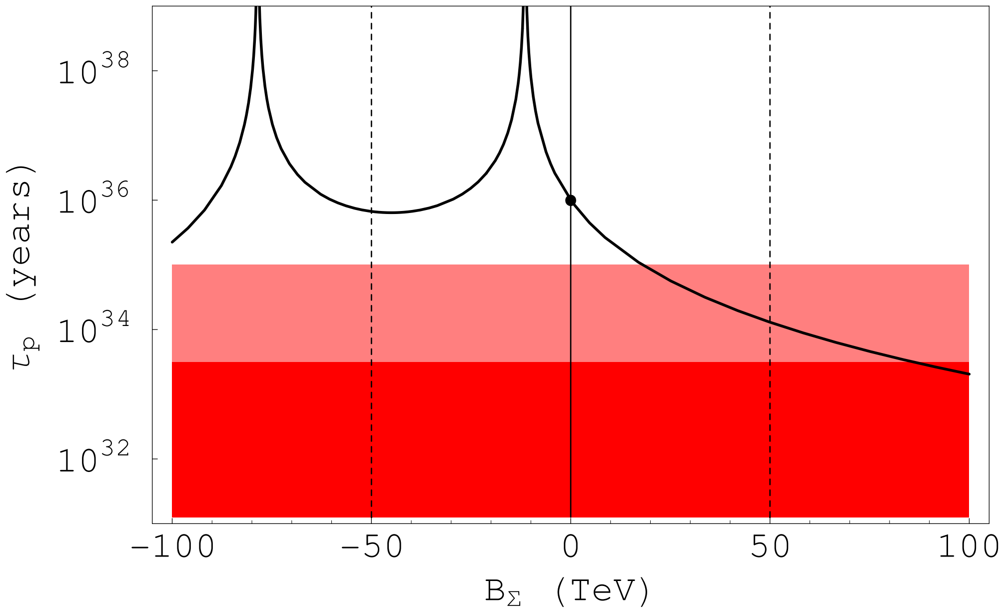
- Hierarchy problem a bit harder, but anyway to be tuned, in minimal SU(5). Usual group-theoretical mechanisms take care.
- B-terms never enter (ruin) the running of any quantity.
- Finite corrections are negligible as far as $B_\Sigma < 50\text{-}100$ TeV.

Effects on proton decay are:

$$\tau^{-1}_{SOFT} = \tau^{-1}_{SUSY} \left(1 + \frac{B_\Sigma}{10\,\text{TeV}} + 0.1 \left| \frac{B_\Sigma}{10\,\text{TeV}} \right|^2 \right)^2$$

So B_Σ may be $< 50\text{-}100$ TeV and still affect proton decay.

Effect of heavy higgses soft terms



Shaded regions represent current and 10-years *hoped* limits on the $p \to \pi^0 e^+$ partial lifetimes, from Water-Cerenkov detectors.
Dashed lines represent the limit of too large B_Σ.

B_Σ negative ~ -10 TeV will suppress the decay rate, while
B_Σ positive may enhance the rate by one order of magnitude.

Running down from GUT

When one renormalizes the D=6, 5, 4 operators from the GUT to SUSY scale, they mix among themselves due to gaugino soft masses. We computed these effects using soft RG techniques [Kazakov '97]. Starting from the supersymmetric anomalous dimensions:

$$\frac{\lambda_6(S)}{\lambda_6(G)} = \prod_{\text{gauge groups}} \left(\frac{\alpha_{(i)}(S)}{\alpha_{(i)}(G)} \right)^{-\frac{\gamma_{6(i)}}{b_{(i)}}} \simeq 3$$

[Ibanez, Munoz '84]

we promote α to superfields, $(1 + m_{\tilde{g}}\theta^2 + m_{\tilde{g}}\bar{\theta}^2 + m_{\tilde{g}}^2\theta^2\bar{\theta}^2)\alpha$, and get:

$$4\pi \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} \lambda_6 \\ \lambda_6\xi \\ \lambda_6\xi^\dagger \\ \lambda_6\omega \end{pmatrix} = \sum_{\text{gauge groups}} \gamma_6 \alpha \begin{pmatrix} 1 & 0 & 0 & 0 \\ m_{\tilde{g}} & 1 & 0 & 0 \\ m_{\tilde{g}}^* & 0 & 1 & 0 \\ 2|m_{\tilde{g}}|^2 & m_{\tilde{g}}^* & m_{\tilde{g}} & 1 \end{pmatrix} \begin{pmatrix} \lambda_6 \\ \lambda_6\xi \\ \lambda_6\xi^\dagger \\ \lambda_6\omega \end{pmatrix},$$

Since $m_{\tilde{g}} \ll \xi$, $\omega \Rightarrow$ running is small in this scenario.

Conclusions, SUSY-GUT interplay

In SUSY GUT, there are soft SUSY-breaking terms in heavy sector:

- New operators of D=4,5 arise in proton decay.

  When dressed they contribute as standard D=6 ones.
- Dressing loop is enough to suppress them for standard soft terms.
- However, soft terms in the *heavy higgs sector* may be large, and they enter only in proton decay.
- They may definitely suppress also the gauge mediated decay, or even enhance it, bringing it into the region of future sensitivity!

Experimentally: probing high lifetimes in different channels useful!
Theoretically: we need *complete* theories of GUT+SUSY mediation!

Thanks!

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SUSY superfield decoupling

Chiral fields can be split: $\{\Phi_I\} \to \{\Phi_H, \Phi_A, \Phi_i\}$:

- Some heavy fields $\Phi_H = \langle \Phi_H \rangle$, in "Superunitary" gauge. [Fayet '76]
- Goldstones Φ_A are eaten by V_A;
- $\langle \Phi_H \rangle$ give mass to gauge bosons:

$$M^2_{AB} = 2g^2 \langle \Phi_H \rangle^\dagger T_A T_B \langle \Phi_H \rangle \, X_H \sim M^2_G \,,$$

- while light fields Φ_i remain in the current $J_A = g\, \Phi_i^\dagger T_A \Phi_i \, X_i$.

Decoupling theorem works easy in superfield formalism:

An effective, four-fields, D-term is at least D=6:

$$\frac{1}{M_G^2} \int (\Phi_i \Phi_i^\dagger \Phi_j \Phi_j^\dagger) \, \mathrm{d}^4\theta \,.$$

and D=6 does not contain $\phi\phi^*\phi\phi^*$, it only contains $\phi\Box\phi^*\phi\phi^*$ etc. . .

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Loop integral

One fermion and two scalars in the loop:

$$L(m_1, m_2, m_3) = m_3 \frac{m_1^2 m_2^2 \log \frac{m_1^2}{m_2^2} + m_2^2 m_3^2 \log \frac{m_2^2}{m_3^2} + m_1^2 m_3^2 \log \frac{m_3^2}{m_1^2}}{(m_1^2 - m_2^2)(m_1^2 - m_3^2)(m_2^2 - m_3^2)}$$

$$= \frac{1}{m_3} \frac{\frac{m^2}{m_3^2} - 1 - \log \frac{m^2}{m_3^2}}{\left(\frac{m^2}{m_3^2} - 1\right)^2} \qquad \text{for } m_1 = m_2 = m$$

with $m_{1,2}$ squark masses and m_3 the gaugino mass.