Where could SUSY be hiding?

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PLHC 2012 Vancouver
The problems with SUSY: direct bounds

ATLAS SUSY bounds from 2011 data
Most involve missing ET, stable charged particle, or LFV
The problems with SUSY: direct bounds

- Bounds assume large MET
- Bounds assume almost degenerate squarks/gluino

Ways out

1. No MET due to RPV - MFV SUSY
2. Spectrum not that degenerate - "Natural SUSY" can be achieved via compositeness
• Usual MSSM assumptions:

1. R-parity conservation to eliminate large B,L violating superpotential terms

\[ W_{RPV} = \lambda L \bar{L} \bar{e} + \lambda' Q L \bar{d} + \lambda'' \bar{u} \bar{d} \bar{d} + \mu' LH_u \]

2. Flavor universality: at some scale all soft terms flavor universal.

• This is a special case of MFV: only source of flavor violation are Yukawa couplings

(Buras et al. 2001, D’Ambrosio et al. 2002)

• Very conservative assumption, makes all FCNC’s sufficiently small
• R-parity clearly NOT necessary in MSSM

• Can add very small RPV couplings and all experimental bounds satisfied, very different pheno

• Not very appealing: why would those very small numbers show up? Not natural...

• Also, many possibilities, not clear how to organize them...

• RPV usually not taken very seriously...
Our proposal: the MFV assumption is sufficient to solve BOTH flavor AND B,L problems

Will NOT impose R-parity

Instead IMPOSE MFV - only source of flavor violation are Yukawa couplings

FCNC obviously OK

Claim B,L violation OK too

But LSP will decay, different LHC phenomenology

Gives predictions for RPV operators
MFV SUSY (Grossman, Heidenreich, C.C.)

• Will see R-parity (and thus B,L) emerges as an ACCIDENTAL APPROXIMATE low-energy symmetry

• More similar to SM story

• Idea previously put forward by Nikolidakis, Smith 2007

• When you apply MFV to SUSY need to make sure that you assign spurions to representations of SUSY

• Since Yukawas in superpotential, most reasonable assumption that spurions chiral superfields

• Can NOT use $Y^+$ in superpotential: very restrictive and predictive scenario
**MFV SUSY**

- Impose SU(3)$^5$ global symmetry (not U(1)’s)

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- Assume only spurions breaking this are Y’s
- Assume Y’s chiral superfields
- First assume no neutrino masses
The holomorphic invariants of SU(3)$^5$

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<th>(QQQ)</th>
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No invariant breaking lepton number!

At renormalizable level single chiral invariant!
Issue of lepton number: \( \mathbb{Z}_3^L \in SU(3)_L \times SU(3)_e \)

\[
L \rightarrow \omega L \quad , \quad \bar{e} \rightarrow \omega^{-1}\bar{e} \quad , \quad Y_e \rightarrow Y_e
\]

None of the spurions charged under this \( \mathbb{Z}_3 \)

This must be exact, lepton number can only be broken mod 3

Lowest Kähler term dim 8, very highly suppressed

In absence of neutrino mass lepton number almost exact

Proton will be stable in this limit
The Baryon number violating $W$

- Single superpotential term at renormalizable level

$$W_{BNV} = \frac{1}{2} w''(Y_u \bar{u})(Y_d \bar{d})(Y_d \bar{d})$$

- Could have Kähler and soft breaking corrections of form

$$K = Q^\dagger \left[ 1 + f_Q(Y_u Y_u^\dagger, Y_d Y_d^\dagger)^T + h.c. \right] Q + \bar{u}^\dagger \left[ 1 + Y_u^\dagger f_u(Y_u Y_u^\dagger, Y_d Y_d^\dagger)Y_u + h.c. \right] \bar{u}$$

$$+ \bar{d}^\dagger \left[ 1 + Y_d^\dagger f_u(Y_u Y_u^\dagger, Y_d Y_d^\dagger)Y_d + h.c. \right] \bar{d}$$

$$+ L^\dagger \left[ 1 + f_L(Y_e Y_e^\dagger)^T + h.c. \right] L + \bar{e}^\dagger \left[ 1 + f_e(Y_e Y_e^\dagger) + h.c. \right] \bar{e},$$

- Of course not B,L violating. Small flavor violating terms suppressed by MFV (GIM mechanism)
The Baryon number violating $W$

- The only allowed term:

$$W_{\text{BNV}} = \frac{1}{2} \lambda''_{ijk} \epsilon^{abc} \bar{u}_i d_j \bar{d}_k$$

- MFV predicts the size of these couplings:

$$\lambda''_{ijk} = w'' y_i^{(u)} y_j^{(d)} y_k^{(d)} \epsilon_{jkl} V_{il}^*$$

- Suppressed by Yukawa couplings and CKM angles

$$\lambda''_{u_{sb}} \sim t_\beta^2 \frac{m_b m_s m_u}{m_t^3} , \quad \lambda''_{u_{bd}} \sim t_\beta^2 \frac{m_b m_d m_u}{m_t^3} , \quad \lambda''_{u_{ds}} \sim \lambda^3 t_\beta^2 \frac{m_d m_s m_u}{2 m_t^3} ,$$

$$\lambda''_{c_{sb}} \sim \lambda t_\beta \frac{m_b m_c m_s}{m_t^3} , \quad \lambda''_{c_{bd}} \sim t_\beta^2 \frac{m_b m_c m_d}{m_t^3} , \quad \lambda''_{c_{ds}} \sim \lambda^2 t_\beta^2 \frac{m_c m_d m_s}{m_t^3} ,$$

$$\lambda''_{t_{sb}} \sim \lambda^2 t_\beta^2 \frac{m_b m_s}{m_t^2} , \quad \lambda''_{t_{bd}} \sim t_\beta^2 \frac{m_b m_d}{m_t^2} , \quad \lambda''_{t_{ds}} \sim t_\beta \frac{m_d m_s}{m_t^2} .$$
The Baryon number violating $W$

- The numerical values (for $\tan \beta = 45 \sim \text{max values}$):

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<th>$b d$</th>
<th>$d s$</th>
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<td>$2 \times 10^{-4}$</td>
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- Due to Yukawa suppression want as many 3rd generation quarks as possible

- But for B violating processes need light quarks for external states - will be strongly suppressed

- EXPLAINS small numbers for RPV couplings in terms of Yukawa, CKM!
Constraints from B violating processes

• Proton in this limit stable (see later when ν masses added)

• n-nbar oscillation:

\[ \tau_{n-\bar{n}} \geq 2.44 \times 10^8 \text{ s} \]

• dinucleon decay \( pp \rightarrow K^+K^+ \)

\[ \tau_{pp \rightarrow K^+K^+} \geq 1.7 \times 10^{32} \text{ yrs} \]

• Both from SuperK \( ^{16}\text{O} \) decay to various final states. Other dinucleon channels less constrained
n-nbar oscillation

• The leading diagram

\[
\mathcal{M}_{n-\bar{n}} \sim \tilde{\Lambda} t_\beta^6 \lambda^8 \frac{m_u m_d m_b^2}{m_t^8} \left( \frac{\tilde{\Lambda}}{m_\tilde{q}} \right)^4 g_s^2 \left( \frac{\tilde{\Lambda}}{m_\tilde{g}} \right) + \ldots 
\]
n-nbar oscillation

• Numerical value:

\[ t_{osc} \sim (9 \times 10^9 \text{ s}) \left( \frac{250 \text{ MeV}}{\Lambda} \right)^6 \left( \frac{m_{\tilde{q}}}{100 \text{ GeV}} \right)^4 \left( \frac{m_{\tilde{g}}}{100 \text{ GeV}} \right) \left( \frac{45}{\tan \beta} \right)^6 \]

• For most extreme values of parameters still an order of magnitude above the bound

• Comment: to estimate the magnitude of off-diagonal squark mass insertions (for LH squarks):

\[ V_{ij}^{(\text{neutral})} \equiv \frac{\delta m_{ij}^2}{m_{\text{soft}}^2} \sim \sum_k V_{ik} \left( y_k^{(u)} \right)^2 V_{kj} \]

\[ V_{ds}^{(\text{neutral})} \sim \lambda^5 \quad , \quad V_{db}^{(\text{neutral})} \sim \lambda^3 \quad , \quad V_{sb}^{(\text{neutral})} \sim \lambda^2 \quad , \quad V_{uc}^{(\text{neutral})} \sim y_b^2 \lambda^5 / 2 \quad , \quad V_{ut}^{(\text{neutral})} \sim y_b^2 \lambda^3 / 2 \quad , \quad V_{ct}^{(\text{neutral})} \sim y_b^2 \lambda^2 \]
**Dinucleon decay**

- **Leading diagrams:**

  \[
  p \begin{cases}
  u \rightarrow u \bar{s} \\
  d \rightarrow \tilde{t} \tilde{u}
  \end{cases}
\]

  \[
  p \begin{cases}
  u \rightarrow \tilde{u} \tilde{t}
  \end{cases}
\]

- **Estimate for decay width (following Goity and Sher):**

  \[
  \Gamma \sim \rho_N \frac{128\pi \alpha_s^2 \tilde{\Lambda}^{10}}{m_N^2 m_g^2 m_q^8} \left( \frac{\lambda^3 m_d m_s m_b^2}{2m_t^4 \tan^4 \beta} \right)^4
  \]
**Dinucleon decay**

- **Lifetime:**

  \[
  \tau_{NN \rightarrow KK} \sim (1.9 \times 10^{32} \text{ yrs}) \left( \frac{150 \text{ MeV}}{\tilde{\Lambda}} \right)^{10} \left( \frac{m_{\tilde{q},\tilde{g}}}{100 \text{ GeV}} \right)^{10} \left( \frac{17}{\tan \beta} \right)^{16}
  \]

- **Applying exp. bound** \( \tau \geq 1.7 \times 10^{32} \text{ yrs} \) yields bound

\[
\tan \beta \lesssim 17 \left( \frac{150 \text{ MeV}}{\tilde{\Lambda}} \right)^{5/8} \left( \frac{m_{\tilde{q},\tilde{g}}}{100 \text{ GeV}} \right)^{5/8}
\]

![Graph showing bounds on \( \tan \beta \) and \( m_{\tilde{q},\tilde{g}} \)]
Sources for non-holomorphic terms

• With SUSY breaking spurion X: additional superpotential from Kähler term:

\[ K = \frac{1}{M^2} X^\dagger (Y_u u) (Y_d^\dagger d d) \]

• Will be suppressed by \( F/M^2 \sim \frac{m_{\text{soft}}}{M} \)

• Only dangerous terms quadratic superpotential terms

\[ \frac{X^\dagger}{M} \tilde{\mu}_{ij} \Phi^i \Phi^j. \]

• gives a non-holomorphic supersymmetric mass term

\( \sim m_{\text{soft}} \tilde{\mu} \), in the absence of neutrino masses no relevant term (except \( \mu \))
LHC phenomenology

• Depends on who is LSP

• No reason for LSP to be neutral since it decays

• Could be
  • squark: stop or sbottom
  • neutralino/chargino
  • slepton

• Up-type squark mass matrix

\[
M^2_u = \begin{pmatrix}
  m^2_u + a_q Y_u Y_u^\dagger + b_q Y_d Y_d^\dagger + D_{uL} & A_u Y_u \\
  A_u^* Y_u^\dagger & m^2_u + a_u Y_u^\dagger Y_u + D_{uR}
\end{pmatrix}
\]

• Most plausible: stop lightest squark (or perhaps sbottom), others nearly degenerate
• Distribution of LSP: $\tan \beta=10$, $m_{\text{soft}}=500$ GeV, $m_{\text{stop}}<500$ GeV

• In squark sector most likely sbottom, or stop about 20%
LHC phenomenology

• Distribution of LSP: \( \tan \beta = 10 \), \( m_{\text{soft}} = 1000 \) GeV, \( m_{\text{stop}} < 500 \) GeV

• In squark sector most likely stop, the sbottom
LHC phenomenology

• Most interesting (and well motivated) scenario: LSP is stop.

• Stop can decay directly via RPV vertex:

\[
\tilde{t} \rightarrow \bar{s} \rightarrow \bar{b}
\]

• Lifetime:

\[
\tau_{\tilde{t}} \sim (2 \text{ \mu m}) \left( \frac{10}{\tan \beta} \right)^4 \left( \frac{300 \text{ GeV}}{m_{\tilde{t}}} \right) \left( \frac{1}{2 \sin^2 \theta_{\tilde{t}}} \right)
\]

• Branching: 90% b+s, 8% b+d, 2% d+s fixed by flavor parameters
LHC phenomenology

• Stop decay length:

\[
\tau_\tilde{t} \sim (2 \ \mu m) \left( \frac{10}{\tan \beta} \right)^4 \left( \frac{300 \ \text{GeV}}{m_\tilde{t}} \right) \left( \frac{1}{2 \sin^2 \theta_\tilde{t}} \right)
\]

• No displaced vertices in most of parameter space
• Sbottom LSP: first have to get a RH sbottom, additional Yukawa suppression in rate

\[
\tilde{b}_L \quad \tilde{b}_R
\]

• Get tops in final state and bit bigger region for displaced vertex
LHC phenomenology

- If neutralino or chargino LSP: has to decay via off-shell stop, 3-body decay increases lifetime

\[ \tau_{\tilde{N}} \sim (12 \ \mu m) \left( \frac{20}{\tan \beta} \right)^4 \left( \frac{300 \ \text{GeV}}{m_{\tilde{N}}} \right) \]

- Get tops in final state for neutralino and yet bigger region for displaced vertex (gluino would be similar)
LHC phenomenology

The neutralino LSP decay length

![Graph showing decay length as a function of tan β and m_N](image)
If the gluino is in the TeV energy range the model could be completely natural. While these should emphasize that in these models the gluino does not play an essential role. Thus even riparity violating decay of the gluino in the presence of a relevant searches are the ones carried out by CMS and also by CDF. Here the set bounds on the coupling SUSY. The more restrictive searches look for leptons among the final state particles, top and bottom quarks, and either a lepton or missing energy, as shown in Fig. m.j. Thus the signal of SUSY in the case of a stau LSP would be events with displaced vertices, in almost all of the relevant parameter space, lifetime of order LSP. For a neutralino LSP, displaced vertices can arise in a substantial region of parameter space, whereas for the stau, they are expected nearly everywhere. Figure m.v. The decay length $d$ of the lightest neutralino decays of the lightest neutralino involving top and bottom quarks, a light jet, and either a lepton or missing energy, as shown in Fig. m.m. Thus the signal of SUSY in the case of a stau LSP would be events such long lifetimes will give displaced vertices in almost all of the relevant parameter space, with lifetime of order $\tau_\tilde{\tau}$.

One needs an extension of the Higgs sector for example to NMSSMt type model to raise the Higgs mass in this case the Higgs mass in the simplest MSSM type extension will usually be too light. However, this does not necessarily alter the MFV structure of the theory. For example, while the decays of the lightest neutralino have been proposed in [lp–mj] for example the model of [mj] would rely on outoffequilibrium opens new possibilities for baryogenesis. Several scenarios that make use of this coupling have matter/antimatter asymmetry directly, and the leading explanation is baryogenesis via lepton number violation. LHC phenomenology.

The Higgs mass is too high in both of these theories to account for the observed matter asymmetry. The NMSSM has restricted couplings due to the a weakly broken discrete symmetry, the alteration of the MFV structure of the theory. For example, while the $\beta\alpha$ parameter is a good dark matter candidate in these models. While we are in MFV SUSY we are obviously forgoing this possibility. However, this does not necessarily mean that there cannot be a good dark matter candidate in these models.

One of the outstanding problems of the SM and the MSSM is the issue of baryogenesis. Throughout this paper we have been assuming a squark mass scale of order a few hundred GeV. This is necessary to make SUSY a natural solution of the hierarchy problem. However, this channel. The current bounds on the mass of the colored scalar using kiji LHC data for example to NMSSM type model to raise the Higgs mass over the jjm GeV LEP bound. Such an extension should not significantly alter the MFV structure of the theory. For example, while the $\beta\alpha$ parameter is a good dark matter candidate in these models. While we are in MFV SUSY we are obviously forgoing this possibility. However, this does not necessarily mean that there cannot be a good dark matter candidate in these models.

LHC phenomenology

If LSP slepton (stau), need to decay via off-shell neutralino/chargino AND stop

\[
\tilde{\ell} \to \tilde{\tau}^- t \to \ell \tilde{\tau}^- t \to \ell N \bar{s} \tilde{b}
\]

\[
\tilde{\ell} \to \tilde{\tau}^- t \to \ell N \bar{s} \tilde{b}
\]

\[
\tilde{\ell} \to \tilde{\tau}^- t \to \ell N \bar{s} \tilde{b}
\]

\[
\tau_\tilde{\tau} \sim (44 \ \mu m) \left( \frac{45}{\tan \beta} \right)^4 \left( \frac{500 \ \text{GeV}}{m_\tilde{\tau}} \right)
\]

4-body decay, almost certainly displaced vertex, some have tops some missing energy. This should be easier.
• **Stau decay length:**

![Graph showing the decay length of stau in units of μm as a function of tan β and m_τ̃.](image)

For a neutralino LSP, displaced vertices can arise in a substantial region of parameter space, whereas for the stau, they are expected nearly everywhere. The decay involving top and bottom quarks, a light jet, and either a lepton or missing energy, as shown in the figure, since it is a four-body decay, the NDA estimate for the width of the stau LSP is

$$\Gamma_{\tilde{\tau}} \sim m_{\tilde{\tau}} \frac{\pi}{5} |\lambda|^2 |\lambda_{tsb}|^2,$$

with lifetime of order

$$\tau_{\tilde{\tau}} \sim \frac{d_{\tilde{\tau}}}{m_{\tilde{\tau}} \tan \beta} \frac{\pi}{4} \frac{q_{ll}}{\text{GeV}}.$$

Such long lifetimes will give displaced vertices in almost all of the relevant parameter space, as shown in the figure. Thus the signal of SUSY in the case of a stau LSP would be events with displaced vertices, top and bottom quarks, and either a lepton or missing energy.

Current searches for parity-violating supersymmetry are not very restrictive for MFV SUSY. The more restrictive searches look for leptons among the final states and set bounds on the coupling $\lambda\tilde{\lambda}$. This is exactly the one vanishing in MFV SUSY. The more relevant searches are the ones carried out by CMS and also by CDF here, the parity-violating decay of the gluino in the presence of a $\bar{u}\bar{d}\bar{d}$ coupling is considered by searching for a resonance in $\text{oijet}$ final states, after appropriate kinematic cuts are introduced to separate potential SUSY events from QCD background. The most stringent CMS search using $0.1\text{pb}^{-1}$ of data yields a bound on the gluino mass $m_{\tilde{g}} > 3.5 \text{GeV}$. However, we should emphasize that in these models the gluino does not play an essential role. Thus even if the gluino is in the TeV energy range, the model could be completely natural.
Existing searches

- For stop LSP: dijet resonance search

\[ \tilde{t} \rightarrow \tilde{s} \rightarrow \tilde{b}d \]

- However stop production cross section quite low, \( m_{\text{stop}} = 200 \text{ GeV} \) it is about 200 fb at the Tevatron and 10 pb at the 7 TeV LHC.

- Dijet sensitivities about 3 orders of magnitude lower. Perhaps with b-tagging?
Existing searches

• The usual search for RPV does not apply here since the $QL\bar{d}$ coupling vanishes here.

• Relevant search: CMS/CDF search for 3-body decay of gluino via $\bar{u}\bar{d}\bar{d}$ vertex. Current bound from 2010 data $m_{\text{gluino}} > 280$ GeV. However for this gluino not very crucial, would be nice to have a search not relying on that.

• Atlas search for massive colored scalar in 4 jet events. Current bound from 2010 data 150-180 GeV on scalar octet. But scalar triplet smaller cross section...
Existing searches

- CMS: paired dijet resonance search (their motivation was colorons...)

![Diagram of CMS Detector and Trigger Description]

![Graph of Existing Searches]

![Diagrams of Pair-Produced Dijet Resonances]
Existing searches

- CMS: paired dijet resonance search (their motivation was colorons...)

Stop cross section larger than this bound, but acceptances usually very small, need a real simulation.

- Submitted REecast request (Berger, C.C., Grossman)
Same sign tops

• Mesino oscillation

\[ x = \frac{\Delta M}{\Gamma} \]

• For sbottom find \( x \geq 1 \), for stop \( x << 1 \).

• If sbottom LSP expect same sign tops

(Berger, C.C., Heidenreich, Grossman)
Same sign tops

(Berger, C.C., Heidenreich, Grossman)

- The distribution of the oscillation times

\[ \tan \beta = 10 \]

\[ \Delta m/\Gamma \]

- \[ L H \text{ sbottom} \]
- \[ R H \text{ sbottom} \]

\[ m_{\text{soft}} = 500 \text{ GeV} \]

\[ \tan \beta = 3 \]

\[ \Delta m/\Gamma \]

- \[ L H \text{ sbottom} \]
- \[ R H \text{ sbottom} \]
Same sign tops

(Berger, C.C., Heidenreich, Grossman)

• Get same sign leptons, MET + b jets

• Bounds on sbottom mass

![Diagram of SUSY processes](image)
Use jet substructure?

• Perhaps can fish out stop decays using jet substructure

(Berger, C.C., S.Lee, Grossman)

• Very preliminary results (only ttbar bckg yet), 14TeV, \( H_T > 1500 \) GeV, \( p_T > m \), two jets with substructure \( R=1 \), mass drop and two \( b \)-tags. Blue: ttbar bckgd, green: stop-antistop at 300 GeV.

\[
\tilde{t} \rightarrow \bar{b} \tilde{s}
\]

\[
\tilde{b} \rightarrow \bar{t} \tilde{s}
\]
• Ordinary LSP decays quickly in detector, not WIMP

• Gravitino would be long enough lived if light

\[ \tau_G \gtrsim (4 \times 10^{39} \text{ yr}) \left( \frac{1 \text{ GeV}}{m_{3/2}} \right)^3 \left( \frac{300 \text{ GeV}}{m_\tilde{q}} \right)^4 \left( \frac{\tan \beta}{10} \right)^8 \]

\[ \tau_{\tilde{G}} \sim (2 \times 10^{22} \text{ yrs}) \left( \frac{m_\tilde{q}}{300 \text{ GeV}} \right)^4 \left( \frac{10}{\tan \beta} \right)^4 \left( \frac{100 \text{ GeV}}{m_{3/2}} \right)^3 \]

• Depends on thermal history - needs more work

Dark matter?
Natural SUSY

• Other possible way of accommodating SUSY with MET searches

• First two generation squarks and gluino quite heavy

• LH stop, sbottom, RH stop light. $\sigma_{\text{SUSY}}$ small.

• Also solves flavor issue

• Originally suggested by Cohen, Kaplan, Nelson in ’96 as ``more minimal SSM”

• Only particles needed to solve hierarchy problem are right
The bounds on natural SUSY: naturalness

(Papucci, Ruderman, Weiler ’11)

• Fine tuning:
\[ \Delta \equiv \frac{2\delta m^2_H}{m^2_h}. \]

• Want this to be <10-20 %

• Higgsinos light, because
\[ -\frac{m_Z^2}{2} = |\mu|^2 + m^2_{H_u} \]

• So bound on \( \mu \):
\[ \mu \lesssim 200 \text{ GeV} \left( \frac{m_h}{120 \text{ GeV}} \right) \left( \frac{\Delta^{-1}}{20\%} \right)^{-1/2} \]

• At one loop largest contributions to \( m^2_{H_u} \) from stops:
\[ \delta m^2_{H_u}|_{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left( m^2_{Q_3} + m^2_{u_3} + |A_t|^2 \right) \log \left( \frac{\Lambda}{\text{TeV}} \right) \]

• Bound:
\[ \sqrt{m^2_{t_1} + m^2_{t_2}} \lesssim 600 \text{ GeV} \frac{\sin \beta}{(1 + x_t^2)^{1/2}} \left( \frac{\log (\Lambda/\text{TeV})}{3} \right)^{-1/2} \left( \frac{m_h}{120 \text{ GeV}} \right) \left( \frac{\Delta^{-1}}{20\%} \right)^{-1/2} \]

\[ x_t = A_t/\sqrt{m^2_{t_1} + m^2_{t_2}}. \]
The bounds on natural SUSY: naturalness
(Papucci, Ruderman, Weiler ’11)

• **Gluino** contributes at 2 loops:

\[ \delta m_{H_u}^{2} |_{\text{gluino}} = -\frac{2}{\pi^2} y_t^2 \left( \frac{\alpha_s}{\pi} \right) |M_3|^2 \log^2 \left( \frac{\Lambda}{\text{TeV}} \right) \]

• Can be somewhat heavier, different log dependence

\[ M_3 \lesssim 900 \text{ GeV} \sin \beta \left( \frac{\log \left( \frac{\Lambda}{\text{TeV}} \right)}{3} \right)^{-1} \left( \frac{m_h}{120 \text{ GeV}} \right) \left( \frac{\Delta^{-1}}{20\%} \right)^{-1/2} \]

• Electroweak gauginos can be even more heavy

\[ (M_1, M_2) \lesssim (3 \text{ TeV}, 900 \text{ GeV}) \left( \frac{\log \left( \frac{\Lambda}{\text{TeV}} \right)}{3} \right)^{-1/2} \left( \frac{m_h}{120 \text{ GeV}} \right) \left( \frac{\Delta^{-1}}{20\%} \right)^{-1/2} \]
The bounds on natural SUSY: naturalness

(Papucci, Ruderman, Weiler ’11)

Below TeV scale

Above TeV scale

Gluino and Winos not as clear-cut: gluino could be heavier, while wino definitely below TeV...
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler ’11)

• **Simplified model:** only left handed stop/sbottom, right handed stop decaying to higgsinos:

![Diagram](image)

• **Bounds from ~ 1 fb⁻¹ data:**

![Graphs showing LHC limits on natural SUSY](image)
• Simplified model: only left handed stop/sbottom, right handed stop decaying to higgsinos:

- Estimate for bounds from 10 fb\(^{-1}\):
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler ’11)

• Simplified model: only left handed stop/sbottom, right handed stop decaying to binos or gravitinos:

• Bounds from ~ 1 fb⁻¹ data, no bound on RH stop.
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler ’11)

• For completeness gluino bounds:

• Bounds from ~ 1 fb⁻¹ data:
The other problem with SUSY: Little hierarchy

- Higgs mass: fixed by quartic coupling

\[ V(H) = \lambda (|H|^2 - \frac{v^2}{2})^2 \]

- SUSY: quartic coupling = gauge coupling (which sets W,Z mass)

- Leading result: \( m_h \leq M_Z \)

- But we know from LEP \( m_h \geq 114 \text{ GeV} \)

- LHC: \( m_h \sim 125 \text{ GeV} \)
• Very hard to overcome this in SUSY

• Need to assume that loop correction to quartic is large:

\[
m_{Higgs}^2 = M_Z^2 + \frac{3m_t^2 \lambda_t^2}{4\pi^2} \log \frac{m_{\tilde{t}}}{m_t}
\]

• Need large stop-top splitting

• But large loops and splittings are exactly what we are trying to avoid in SUSY

• Back to some fine tuning

\[
M_Z^2 \sim -2m_{H_u}^2
\]

vs.

\[
m_{H_u}^2 = m_0^2 - \frac{3\lambda_t^2 m_{\tilde{t}}^2}{4\pi^2} \log \frac{\Lambda_{UV}^2}{m_{\tilde{t}}^2}
\]

• Implies <1% tuning generically
**MSSM naturalness for 125 GeV Higgs**

(Hall, Pinner, Ruderman, ’11)

- In MSSM very hard to get 125 GeV with light stop:

  ![MSSM Higgs Mass](image-url)

- Fine tuning:

  ![Higgs Mass vs. Fine Tuning](image-url)
Light stops from compositeness (and a 125 GeV Higgs)

• Idea: some fields composite, others not

• Additional strong confining interaction producing massless composites - can be described via “Seiberg duality”

• Have a confining gauge group (in this case SU(4)) that produces massless composite mesons, gauge fields and quarks

• Identify some of these composites with the MSSM Higgs, left handed top/stop, sbottom, right handed stop, EW gauge fields/gauginos: the fields needed for natural SUSY

• Important ingredient: Higgs sector will NATURALLY contain a singlet and NMSSM-type superpotential: needed to lift Higgs
The Minimal Composite Supersymmetric SM (MCSSM) (CC, Shirman, Terning ’11 CC, Randall, Terning ’12)

- Electric theory SU(4) with 6 flavors

<table>
<thead>
<tr>
<th></th>
<th>SU(4)</th>
<th>SU(6)₁</th>
<th>SU(6)₂</th>
<th>U(1)ᵥ</th>
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<td>□</td>
<td>-1</td>
<td>1/3</td>
</tr>
</tbody>
</table>

\[ W_{\text{tree}} = \mu \mathcal{F} (Q₄ \bar{Q}₄ + Q₅ \bar{Q}₅) + \mu_f Q₆ \bar{Q}₆ \]

- Becomes strongly coupled at \( \sim 10 \) TeV, produces massless composites

<table>
<thead>
<tr>
<th></th>
<th>SU(2)ₘₐₙ</th>
<th>SU(6)₁</th>
<th>SU(6)₂</th>
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<th>U(1)ᵣ</th>
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<td>3/3</td>
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</tbody>
</table>

\[ W_{\text{dyn}} = y \bar{q} M q. \]
Where is the standard model in the MCSSM?

(CC, Shirman, Terning ’11
CC, Randall, Terning ’12)

- Two SU(2) groups, one of them "magnetic" composite SU(2)

- Other elementary embedded into flavor symmetry

\[ SU(6)_1 \supset SU(3)_c \times SU(2)_{el} \times U(1)_Y \]
\[ SU(6)_2 \supset SU(3)_X \times SU(2)_{el} \times U(1)_Y \]

- Composites:

\[ q = Q_3, H, H_d \]
\[ \bar{q} = X, \bar{H}, H_u \]

\[ M = \begin{pmatrix}
V & U & \bar{t} \\
E & G + P & \phi_u \\
R & \phi_d & S
\end{pmatrix} \]

- Relevant superpotential:

\[ W \supset y_P(\mathcal{H}\bar{\mathcal{H}} - \mathcal{F}^2) + y_S(H_uH_d - f^2) + yQ_3H_u\bar{t} + yH_u\mathcal{H}\phi_u + yH_d\bar{\mathcal{H}}\phi_d \]
A model with light stops and 125 GeV higgs

(CC, Randall, Terning '12, CC, Shirman, Terning '11)

•The relevant part of the Higgs potential:

\[ V = y^2 |H_u H_d| - f^2 |H_u|^2 + y^2 |S|^2 (|H_u|^2 + |H_d|^2) + m_S^2 |S|^2 + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 \]

\[ + (A S H_u H_d + T S + h.c.) + \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2 \]
A model with light stops and 125 GeV higgs

(CC, Shirman, Terning '11
CC, Randall, Terning '12)

• The relevant part of the Higgs potential:

\[ V = y^2 |H_u H_d| - f^2 |H_u|^2 + y^2 |S|^2 (|H_u|^2 + |H_d|^2) + m_S^2 |S|^2 + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 \]

\[ + (A S H_u H_d + T S + h.c.) + \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2 \] (1)

• usual SUSY quartic
A model with light stops and 125 GeV higgs

• The relevant part of the Higgs potential:

\[
V = y^2 |H_u H_d - f^2|^2 + y^2 |S|^2 (|H_u|^2 + |H_d|^2) + m_S^2 |S|^2 + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 \\
+ (A S H_u H_d + TS + h.c.) + \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2
\]

• Additional NMSSM-like quartic due to confining dynamics - does not have to be small, can be > 1. \(\tan \beta\) does NOT have to be large, in fact can be < 1

• \(S\) singlet a composite, other parameters soft breaking terms that can be estimated from strong dynamics in SUSY

• \(f\) will drive EWSB (different that MSSM, get EWSB w/o SUSY breaking). Good: higgs mass not related to Z mass, bad: why \(f \sim v\)?
**A model with light stops and 125 GeV higgs**

(CC, Shirman, Terning '11
CC, Randall, Terning '12)

- **The EWSB vacuum:**
  \[
  \langle H_u^0 \rangle = \frac{v}{\sqrt{2}} \sin \beta, \quad \langle H_d^0 \rangle = \frac{v}{\sqrt{2}} \cos \beta
  \]

  \[
  \langle S \rangle = -\frac{\sqrt{2} (A v^2 \sin \beta \cos \beta + 2T)}{2M_S^2 + y^2 v^2}
  \]

  will generate effective \(\mu=y\) \(\langle S \rangle\)

- **At minimum**
  \[
  \frac{y^2 v^2}{2} = \frac{2(y^2 f^2 - AS)}{\sin 2\beta} - 2y^2 S^2 - m_{H_u}^2 - m_{H_d}^2
  \]

- **Fine tuning about** \(\frac{y^2 v^2}{2m_{H_u}^2}\) **better than in MSSM, and stop can be light...**

- **Bound on gluino mass:** don’t want to lift stop too much
  \[
  \Delta m_{\tilde{g}} \sim \frac{32}{3} \frac{\alpha_s}{4\pi} |M_3|^2 \log \left( \frac{\Lambda}{\text{TeV}} \right)
  \]

  will keep gluino below 1.5 TeV to have

  400 GeV stop natural
The SUSY breaking hierarchy:

(CC, Randall, Terning ’12)

• If strong dynamics close to conformal (depends on details of the SU(4) theory, in this case means $F \geq 6$)

• Assuming that soft breaking generated above confinement scale $\Lambda$

• Elementary fields (first two generation squarks, sleptons, gluino get mass $m_{el} \sim M_3 \sim \text{few} \cdot \text{TeV}$

• Composites get suppressed soft breaking masses $m_{comp} \sim \frac{m_{el}^2}{\Lambda} \sim M_1 \sim M_2 \sim A \sim \text{few} \cdot 100 \text{ GeV}$

• For $\Lambda \sim 5-10 \text{ TeV}$ composites in few 100 GeV range
The input parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>spectrum 1</th>
<th>spectrum 2</th>
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<th>spectrum 4</th>
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<td>$T$</td>
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<td>$f$</td>
<td>100 GeV</td>
<td>100 GeV</td>
<td>293 GeV</td>
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</table>

• Other parameters determined from minimizing Higgs potl

• Augmented NMSSMtools to implement different Higgs potential, calculate spectra, decay rates. Looked at four characteristic examples with very light stops (clearly can make them somewhat heavier if needed)
1. Stealth stop

- Stop almost degenerate with top
- First neutralino close by
- Heavier stop, sbottom ~ 500 GeV
- Other fields over 1 TeV

<table>
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<tr>
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<th>$H_1$</th>
<th>$\tilde{t}_1$</th>
<th>$N_1$</th>
<th>$H^\pm$</th>
<th>$H_2$</th>
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<th>$C_1$</th>
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<td>501</td>
<td>429</td>
<td>501</td>
<td>876</td>
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</tbody>
</table>
**Four different sample spectra** (CC, Randall, Terning ’12)

1. **Stealth stop**

- \( \tilde{t}_1 \rightarrow t + LSP \) 100%
- \( C_1 \rightarrow \tilde{t}_1 + b^\dagger \) 84%
- \( C_1 \rightarrow N_1 + W^\pm \) 16%
- \( \tilde{b}_1 \rightarrow \tilde{t}_1 + W^- \) 97%
- \( \tilde{b}_1 \rightarrow \tilde{t}_1 + H^- \) 3%
- \( \tilde{t}_2 \rightarrow \tilde{t}_1 + Z \) 51%
- \( t_2 \rightarrow t + N_1 \) 27%
- \( \tilde{t}_2 \rightarrow b + C_1^+ \) 11%
- \( \tilde{t}_2 \rightarrow \tilde{t}_1 + H_1 \) 10%

- Stop decays to top + gravitino - not much missing ET. \( \sigma \approx 15 \text{ pb}, 10\% \text{ of } tt\text{bar} 
- Need precise \( \sigma_{\text{top}} \)
- Next stop, sbottom \( \approx 10 \text{ fb} \)
- Sbottom: \( ttWW \)
- Stop2: \( ttZZ, ttbbW^*W^* \)
- Could have displaced top vertex
Four different sample spectra

(CC, Randall, Terning '12)

2. Stop NLSP with heavier N₁

<table>
<thead>
<tr>
<th>GeV</th>
<th>H₁</th>
<th>C₁</th>
<th>N₁</th>
<th>N₂</th>
<th>N₃</th>
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</tbody>
</table>

- Stop somewhat heavier, still close to t
- First neutralino heavier (should be 429 GeV)
- Heavier stop, sbottom ~ 500 GeV
Four different sample spectra

(CC, Randall, Terning ’12)

2. Stop NLSP with heavier $N_1$

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<tr>
<th>Particle</th>
<th>Decay</th>
<th>Percentage</th>
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<td>$t + \tilde{t}^*$</td>
<td>50%</td>
</tr>
<tr>
<td>$N_1$</td>
<td>$t + \tilde{t}$</td>
<td>50%</td>
</tr>
<tr>
<td>$\tilde{b}_1$</td>
<td>$\tilde{t}_1 + W^-$</td>
<td>100%</td>
</tr>
<tr>
<td>$\tilde{t}_2$</td>
<td>$\tilde{t}_1 + Z$</td>
<td>78%</td>
</tr>
<tr>
<td>$\tilde{t}_2$</td>
<td>$\tilde{b}_1 + W^+$</td>
<td>14%</td>
</tr>
<tr>
<td>$\tilde{t}_2$</td>
<td>$\tilde{t}_1 + H_1$</td>
<td>8%</td>
</tr>
</tbody>
</table>

- Stop decays to top + gravitino - not much missing ET. $\sigma \approx 8$ pb, 5% of ttbar
- Need even more precise $\sigma_{\text{top}}$
- $N_1 \rightarrow t + \text{stop}$, tttt final states, still small missing E.
- Sbottom: ttWW
- Stop2: ttZZ, ttWWWWW
Four different sample spectra

3. Minimal gauge mediation

**Table 6: Branching fractions for benchmark spectra 3 and 4.**

<table>
<thead>
<tr>
<th></th>
<th>( N_1 )</th>
<th>88 GeV</th>
<th>( C_2 )</th>
<th>415 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_1 )</td>
<td>128 GeV</td>
<td>( N_4 )</td>
<td>434 GeV</td>
<td></td>
</tr>
<tr>
<td>( \tilde{t}_1 )</td>
<td>191 GeV</td>
<td>( H_2 )</td>
<td>473 GeV</td>
<td></td>
</tr>
<tr>
<td>( N_2 )</td>
<td>192 GeV</td>
<td>( \tilde{t}_2 )</td>
<td>517 GeV</td>
<td></td>
</tr>
<tr>
<td>( N_3 )</td>
<td>291 GeV</td>
<td>( N_5 )</td>
<td>613 GeV</td>
<td></td>
</tr>
<tr>
<td>( C_1 )</td>
<td>327 GeV</td>
<td>( H^\pm )</td>
<td>650 GeV</td>
<td></td>
</tr>
<tr>
<td>( \tilde{b}_1 )</td>
<td>350 GeV</td>
<td>( H_3 )</td>
<td>657 GeV</td>
<td></td>
</tr>
<tr>
<td>( A_1 )</td>
<td>412 GeV</td>
<td>( A_2 )</td>
<td>702 GeV</td>
<td></td>
</tr>
</tbody>
</table>

- Neutralino LSP or NLSP, missing energy, but reduced \( \sigma \)
- Stop still pretty light close to top
### Four different sample spectra

(CC, Randall, Terning '12)

#### 3. Minimal gauge mediation

![Diagram of particle masses and possible decay modes.]

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{t}_1 \rightarrow N_1^+ + b + W^+$</td>
<td>100%</td>
</tr>
<tr>
<td>$\tilde{b}_1 \rightarrow N_3 + b$</td>
<td>80%</td>
</tr>
<tr>
<td>$\tilde{b}_1 \rightarrow \tilde{t}_1 + W^-$</td>
<td>95%</td>
</tr>
<tr>
<td>$\tilde{b}_1 \rightarrow N_3 + b$</td>
<td>4%</td>
</tr>
<tr>
<td>$\tilde{b}_1 \rightarrow N_1 + b$</td>
<td>1%</td>
</tr>
<tr>
<td>$\tilde{t}_2 \rightarrow \tilde{t}_1 + Z$</td>
<td>42%</td>
</tr>
<tr>
<td>$\tilde{t}_2 \rightarrow \tilde{b}_1 + W^+$</td>
<td>31%</td>
</tr>
<tr>
<td>$\tilde{t}_2 \rightarrow N_2 + t$</td>
<td>10%</td>
</tr>
<tr>
<td>$\tilde{t}_2 \rightarrow C_2^+ + b$</td>
<td>8%</td>
</tr>
<tr>
<td>$\tilde{t}_2 \rightarrow N_1 + t$</td>
<td>4%</td>
</tr>
<tr>
<td>$\tilde{t}_2 \rightarrow C_1^+ + b$</td>
<td>3%</td>
</tr>
<tr>
<td>$\tilde{t}_2 \rightarrow N_3 + t$</td>
<td>2%</td>
</tr>
</tbody>
</table>

- If gauge mediation gravitino LSP
- $N_1 \rightarrow \gamma + \text{gravitino}, \text{missing ET}$
- stop $\rightarrow t^* + N_1$
- stop2 $\rightarrow$ stop1 $Z, s\text{bottom} W, N, t, C, b$
- j+MET, j+t+MET, j+W/Z+MET or photons, also longer cascades
Four different sample spectra

4. High duality scale

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$</td>
<td>126</td>
</tr>
<tr>
<td>$A_1$</td>
<td>190</td>
</tr>
<tr>
<td>$N_1$</td>
<td>217</td>
</tr>
<tr>
<td>$\tilde{t}_1$</td>
<td>284</td>
</tr>
<tr>
<td>$H_2$</td>
<td>339</td>
</tr>
<tr>
<td>$H^\pm$</td>
<td>341</td>
</tr>
<tr>
<td>$C_1$</td>
<td>341</td>
</tr>
</tbody>
</table>

- Neutralino LSP or NLSP
- $N_1$ over 200 GeV, stop around 300

(CC, Randall, Terning ’12)
Four different sample spectra

(CC, Randall, Terning ’12)

4. High duality scale

- \( \tilde{t}_1 \rightarrow N_1 + c \)  99%
- \( \tilde{t}_1 \rightarrow N_1 + u \)  1%
- \( \tilde{b}_1 \rightarrow \tilde{t}_1 + W^- \)  100%
- \( \tilde{t}_2 \rightarrow \tilde{t}_1 + Z \)  28%
- \( \tilde{t}_2 \rightarrow C_1^+ + b \)  24%
- \( \tilde{t}_2 \rightarrow \tilde{b}_1 + W^+ \)  20%
- \( \tilde{t}_2 \rightarrow N_2 + t \)  15%
- \( \tilde{t}_2 \rightarrow N_2 + t \)  14%

• stop\( \rightarrow \) N\(_1\) + c
• stop\(_2\) \( \rightarrow \) stop\(_1\) + Z, C + b, sbottom + W, N + t
• sbottom\( \rightarrow \) stop\(_1\) + W
• Final states: j + MET, j + t + MET, j + W / Z + MET
• Traditional SUSY at reduced rates
Higgs branchings

<table>
<thead>
<tr>
<th>SM fields</th>
<th>spectrum 1</th>
<th>spectrum 2</th>
<th>spectrum 3</th>
<th>spectrum 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>1.02</td>
<td>1.02</td>
<td>0.95</td>
<td>0.85</td>
</tr>
<tr>
<td>gluons</td>
<td>0.65</td>
<td>0.83</td>
<td>0.82</td>
<td>0.73</td>
</tr>
<tr>
<td>$WW, ZZ$</td>
<td>0.89</td>
<td>0.96</td>
<td>0.89</td>
<td>0.74</td>
</tr>
<tr>
<td>$u\bar{u}$</td>
<td>0.72</td>
<td>1.0</td>
<td>0.89</td>
<td>0.72</td>
</tr>
<tr>
<td>$d\bar{d}$</td>
<td>1.01</td>
<td>0.91</td>
<td>0.89</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Not so different from SM: plausible that LHC Higgs results can be reproduced
Summary

• No hint for SUSY from LHC yet

• No MET events

• Higgs at 125 GeV problematic for MSSM

• Ways out:

  1. **RPV**: no MET. Simple model giving realistic patterns and new LHC pheno: MFV SUSY

  2. **Natural SUSY**: small MET, either small $\sigma$ or top background. Model realizing: MCSSM - composite Higgs, 3rd generation squarks, higgsinos, neutralinos/charginos. Composite fields lighter, and NMSSM potential allows 125 GeV Higgs.
Summary

• While it is disappointing that we have not seen SUSY yet...

• ...for now there is still ample of places where SUSY could be hiding
Backup slides
Incorporating neutrino masses

- Once added can have L violation & proton decay

- Assume mass from heavy RH neutrinos & see-saw

  \[ W_{\text{lept}} = Y_e L H_d \bar{e} + Y_N L H_u \bar{N} + \frac{1}{2} M_N \bar{N} \bar{N} \]

- Symmetry in lepton sector \( \text{SU}(3)_L \times \text{SU}(3)_e \times \text{SU}(3)_N \)

- Now we have three spurions \( Y_{e,\nu} \) and \( M \)

- \( M \) is a symmetric, different patterns allowed
Incorporating neutrino masses

• The table of symmetries:

<table>
<thead>
<tr>
<th></th>
<th>SU(3)$_L$</th>
<th>SU(3)$_e$</th>
<th>SU(3)$_N$</th>
<th>U(1)$_{B-L}$</th>
<th>U(1)$_H$</th>
<th>U(1)$_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>[2]</td>
<td>1</td>
<td>1</td>
<td>−1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\bar{e}$</td>
<td>1</td>
<td>[2]</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\bar{N}$</td>
<td>1</td>
<td>1</td>
<td>[2]</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$Y_e$</td>
<td>[2]</td>
<td>[2]</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$M_N$</td>
<td>1</td>
<td>1</td>
<td>[2]</td>
<td>−2</td>
<td>0</td>
<td>−2</td>
</tr>
</tbody>
</table>
Incorporating neutrino masses

• Table of holomorphic invariants:

<table>
<thead>
<tr>
<th>Expression</th>
<th>SU(2)_L</th>
<th>U(1)_Y</th>
<th>U(1)_L</th>
<th>( \mathbb{Z}_2^R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>((LL) \left( \tilde{Y}_N M_N \tilde{Y}_N \right) (LL) )</td>
<td>1</td>
<td>-2</td>
<td>4</td>
<td>+</td>
</tr>
<tr>
<td>((LL) \left( \tilde{Y}_N M_N \tilde{Y}_N \right) (Y_e \bar{e}) )</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>((LL) \tilde{Y}_N M_N \bar{N} )</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>(L \left( Y_N \bar{M}_N Y_N \right) (Y_e \bar{e}) (Y_N \bar{N}) )</td>
<td>□</td>
<td>1/2</td>
<td>-1</td>
<td>-</td>
</tr>
<tr>
<td>( L Y_N \bar{N} )</td>
<td>□</td>
<td>-1/2</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>( \bar{e} Y_e \tilde{Y}_N M_N \bar{N} )</td>
<td>1</td>
<td>1</td>
<td>-2</td>
<td>+</td>
</tr>
<tr>
<td>((Y_e \bar{e}) \left( \tilde{Y}_N M_N \tilde{Y}_N \right) (Y_e \bar{e}))</td>
<td>1</td>
<td>2</td>
<td>-2</td>
<td>+</td>
</tr>
<tr>
<td>( L \left( Y_N \bar{M}_N Y_N \right) )</td>
<td>□□</td>
<td>-1</td>
<td>2</td>
<td>+</td>
</tr>
</tbody>
</table>

\[ \tilde{Y} = \text{cof } Y = Y^{-1} \det Y \]
Incorporating neutrino masses

• Allowed renormalizable superpotential term

\[ W_{\text{LNV}} = \frac{1}{2\Lambda_R} w' (LL) \left( \tilde{Y}_N M_N \tilde{Y}_N \right) (Y_e \bar{e}) \]

• Dimensionless expansion parameter

\[ \mu_N \equiv \frac{1}{\Lambda_R} M_N \]

• \( \Lambda_R \) some heavy scale, usually take \( M_{\text{GUT}} \)

• Since \( L \sim H_d \) we can now also add quadratic \( L \) violating terms, these will be more important! Both superpotential and Kahler
Incorporating neutrino masses

• Leading bilinear terms:

\[ W_{\text{LNV}}^{(\text{non-hol})} = m_{\text{soft}}[\mathcal{V}^\dagger]^a L_a H_u \quad K_{\text{LNV}} = [\mathcal{V}^\dagger]^a L_a H_d^\dagger + h.c. \]

• Possible contributions:

\[ \mathcal{V}_a^{(1)} = \frac{1}{\Lambda_R} \varepsilon_{abc} \left[ \tilde{Y}_N^\dagger \right]^b_i \left[ M_N^\dagger \right]^{ij} \left[ Y_N \right]^c_j, \quad \mathcal{V}_a^{(2)} = \frac{1}{\Lambda_R} \varepsilon_{abc} \left[ Y_e Y_e^\dagger \right]^b_d \left[ Y_N M_N^\dagger Y_N \right]^{cd} \]

• Similar soft breaking masses:

\[ \mathcal{L}_{\text{mix}} = m_{\text{soft}}^2 [\mathcal{V}^\dagger]^a \tilde{L}_a H_d^\dagger + h.c. \]

• After EWSB will give small sneutrino VEV and neutrino gaugino mixing

\[ \langle L_a \rangle \sim -\nu_u \mathcal{V}_a \quad \mathcal{L} \supset -\nu_u \lambda (\mathcal{V}^\dagger L) + c.c. \]
Proton decay constraints

• Assume structure of neutrino masses (Casas & Ibarra)

\[ Y_N^T = \frac{1}{v_u} \text{diag} \left( \sqrt{M_{R1}}, \sqrt{M_{R2}}, \sqrt{M_{R3}} \right) R \text{diag} \left( \sqrt{m_{\nu1}}, \sqrt{m_{\nu2}}, \sqrt{m_{\nu3}} \right) U^\dagger \]

• R is RH neutrino mixing matrix (unknown), U LH mixing matrix - O(1) angles, \( M_R \): RH neutrino masses, \( m_\nu \): LH light neutrino masses.

• Assume all the Y’s roughly same order, also \( m_\nu \)’s roughly equal (worst case scenario, could even have one \( m_\nu = 0 \) ...

\[ Y_N \sim \frac{\sqrt{M_R} m_\nu}{v_u} \]
Proton decay constraints

• The L violating spurions are then

• Superpotential term:
  \[ \lambda_{ijk} \sim \frac{M_R^3 m_\nu^2}{\Lambda_R v_u^4} y_k^{(e)} \]

• Kähler/soft terms:
  \[ \mathcal{V}^{(1)}_i \sim \frac{M_R^2 m_\nu^3}{\Lambda_R v_u^3}, \quad \mathcal{V}_{e,\mu}^{(2)} \sim \frac{M_R^2 m_\nu}{\Lambda_R v_u^2} y_\tau^2, \quad \mathcal{V}_\tau^{(2)} \sim \frac{M_R^2 m_\nu}{\Lambda_R v_u^2} y_\mu^2 \]

• The latter actually dominate:
  \[ \lambda_{ijk} \sim y_k^{(e)} Y_N \mathcal{V}^{(1)} \]

• Will neglect superpotential terms
Proton decay constraints

• The leading diagrams:

\[
\begin{align*}
\text{n} & \rightarrow l^- K^+ \\
\text{p} & \rightarrow \nu K^+
\end{align*}
\]

• Strongest bound from matrix element

\[
\mathcal{M}_{p \rightarrow K^+ \bar{\nu}} \sim \frac{\lambda^3 m_d}{2 m_t m_{\tilde{N}}} \left( \frac{\tilde{\Lambda}}{m_{\tilde{q}}} \right)^2 \mathcal{V} \tan^4 \beta
\]
Proton decay constraints

- The experimental bounds:

\[
\begin{align*}
\tau_{p \to e^+ K^0} &\geq 1.0 \times 10^{33} \text{ yrs} , \\
\tau_{p \to \mu^+ K^0} &\geq 1.3 \times 10^{33} \text{ yrs} , \\
\tau_{p \to \nu K^+} &\geq 2.3 \times 10^{33} \text{ yrs} , \\
\tau_{n \to e^- K^+} &\geq 3.2 \times 10^{31} \text{ yrs} , \\
\tau_{n \to \mu^- K^+} &\geq 5.7 \times 10^{31} \text{ yrs} , \\
\tau_{n \to \nu K^0} &\geq 1.3 \times 10^{32} \text{ yrs} ,
\end{align*}
\]

- Bound on quadratic spurion:

\[
V \tan^4 \beta \lesssim (3 \times 10^{-14}) \left( \frac{m_{q}}{100 \text{ GeV}} \right)^2 \left( \frac{m_{\tilde{N}}}{100 \text{ GeV}} \right)
\]

- Translated into bound on \( M_R \):

\[
M_R \lesssim (3 \times 10^7 \text{ GeV}) \left( \frac{10}{\tan \beta} \right)^3 \left( \frac{m_{q,\tilde{N}}}{100 \text{ GeV}} \right)^{3/2} \left( \frac{\Lambda_R}{10^{16} \text{ GeV}} \right)^{1/2}
\]
Proton decay constraints

• The bound on $M_R$ in units of $10^6$ GeV:

$\Lambda_R = 10^{16}$ GeV and $m_\nu = 0.1$ eV fixed
Proton decay constraints

• If gravitino very light proton can decay w/o L violation:

\[
\begin{pmatrix}
  u & u & u \\
  d & \bar{s} & \\
  u & \tilde{u} & \\
  p & \tilde{t} & \tilde{G}
\end{pmatrix}
\]

\[\Gamma \sim \frac{m_p}{8\pi} \left( \frac{\Lambda}{m_\tilde{q}} \right)^4 \left( \frac{\Lambda^2}{\sqrt{3}m_{3/2}M_{pl}} \right)^2 \frac{\lambda^6 m_d^2 m_s^2 m_b^4}{4m_t^8} \tan^8 \beta\]

• Width:
Proton decay constraints

- Will constrain gravitino mass:

\[ m_{3/2} \gtrsim (300 \text{ KeV}) \left( \frac{300 \text{ MeV}}{m_{\tilde{q}}} \right)^2 \left( \frac{\tan \beta}{10} \right)^4 \]

- Gravitino mass bound in units of keV
**Higher dimensional operators**

- For baryon number violation:
  \[ K_{BNV}^{(5)} = \frac{1}{\Lambda} (Y_u Y_u^\dagger + Y_d Y_d^\dagger) Q Q Y_d^\dagger d^\dagger \]

- Subleading as long as \( \Lambda > 10^{12} \text{ GeV} \)

- For lepton number violation: subleading to \( \mathcal{N}^{(2)} \)

- B and L violating Kähler terms: first show up at dimension 6, the dangerous R-parity even
  \[ Q^3 L, \quad \bar{u} \bar{u} \bar{d} \bar{d} \bar{e}, \quad \text{and} \quad \bar{u} \bar{d} \bar{d} \bar{N} \]

are absent