Where could SUSY be hiding?

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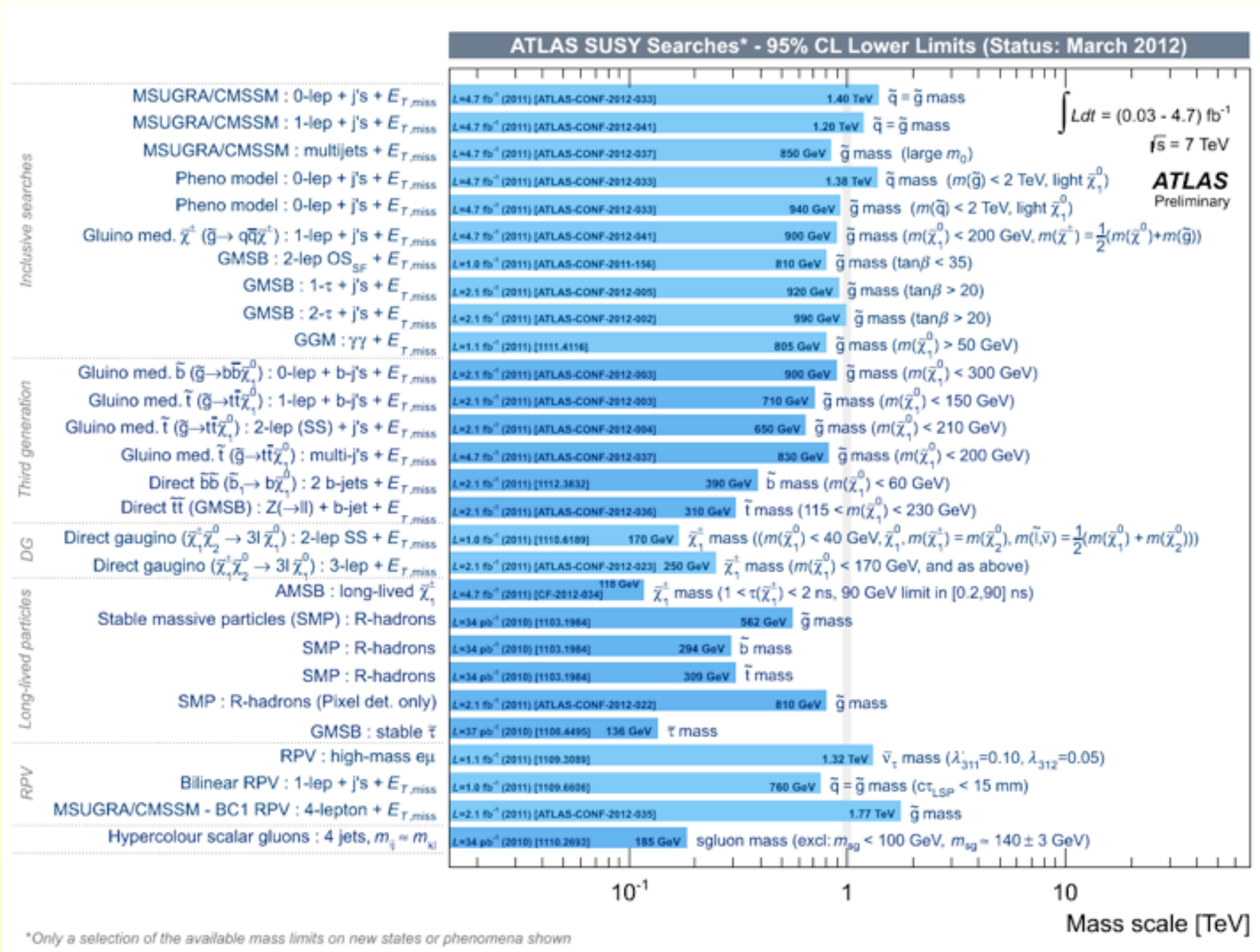
PHENO 2012 Pittsburgh

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

MFV SUSY

(Grossman, Heidenreich, C.C.'11)

•Usual MSSM assumptions:

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

$$W_{RPV} = \lambda L L \bar{e} + \lambda' Q L \bar{d} + \lambda'' \bar{u}\bar{d}\bar{d} + \mu' L H_u$$

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

•This is a special case of MFV: only source of flavor viola
Yukawa couplings (Buras et al. 2001, D'Ambrosio et al. 2002)

•Very conservative assumption, makes all FCNC's sufficiently small

MFV SUSY

- 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...

MFV SUSY

(Grossman, Heidenreich, C.C.)

- Our proposal: the MFV assumption is sufficient to 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)

	$SU(3)_Q$	$SU(3)_u$	$SU(3)_d$	$SU(3)_L$	$SU(3)_e$	$U(1)_{B-L}$	$U(1)_H$
Q	$\overline{\Box}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$1/3$	0
$\bar{u}$	$\mathbf{1}$	$\Box$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	0
$\bar{d}$	$\mathbf{1}$	$\mathbf{1}$	$\Box$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	0
L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\Box}$	$\mathbf{1}$	-1	0
$\bar{e}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\Box$	1	0
H_u	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	1
H_d	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
Y_u	$\Box$	$\overline{\Box}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
Y_d	$\Box$	$\mathbf{1}$	$\overline{\Box}$	$\mathbf{1}$	$\mathbf{1}$	0	1
Y_e	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\Box$	$\overline{\Box}$	0	1

- Assume only spurions breaking this are Y's

- Assume Y's chiral superfields

- First assume no neutrino masses

MFV SUSY

- The holomorphic invariants of SU(3)^5

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$	$\mathbb{Z}_2^R$
(QQQ)	$\mathbf{1}$	$\square\square\square$	$1/2$	1	0	$-$
$(QQ)Q$	$\mathbf{8}$	$\square$	$1/2$	1	0	$-$
$(Y_u\bar{u})(Y_u\bar{u})(Y_d\bar{d})$	$\mathbf{8}\oplus\mathbf{1}$	$\mathbf{1}$	-1	-1	0	$-$
$(Y_u\bar{u})(Y_d\bar{d})(Y_d\bar{d})$	$\mathbf{8}\oplus\mathbf{1}$	$\mathbf{1}$	0	-1	0	$-$
$\det\bar{u}$	$\mathbf{1}$	$\mathbf{1}$	-2	-1	0	$-$
$\det\bar{d}$	$\mathbf{1}$	$\mathbf{1}$	1	-1	0	$-$
$QY_u\bar{u}$	$\mathbf{8}\oplus\mathbf{1}$	$\square$	$-1/2$	0	0	$+$
$QY_d\bar{d}$	$\mathbf{8}\oplus\mathbf{1}$	$\square$	$1/2$	0	0	$+$
$LY_e\bar{e}$	$\mathbf{1}$	$\square$	$1/2$	0	0	$+$
H_u	$\mathbf{1}$	$\square$	$1/2$	0	0	$+$
H_d	$\mathbf{1}$	$\square$	$-1/2$	0	0	$+$

- No invariant breaking lepton number!

- At renormalizable level single chiral invariant!

MFV SUSY

- Issue of lepton number: $\mathbb{Z}_3^L \in \mathrm{SU}(3)_L \times \mathrm{SU}(3)_e$

$$L \to \omega L \ , \quad \bar{e} \to \omega^{-1} \bar{e} \ , \quad Y_e \to Y_e$$

- None of the spurions charged under this 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

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

- Could have Kähler and soft breaking corrections of form

$$\begin{aligned} K \;=\;& Q^\dagger \left[1 + f_Q(Y_u Y_u^\dagger, Y_d Y_d^\dagger)^T + h.c.\right] Q + \bar{u}^\dagger \left[1 + Y_u^\dagger\, f_u(Y_u Y_u^\dagger, Y_d Y_d^\dagger) Y_u + h.c.\right] \bar{u} \\ & + \bar{d}^\dagger \left[1 + Y_d^\dagger\, f_u(Y_u Y_u^\dagger, Y_d Y_d^\dagger) Y_d + h.c.\right] \bar{d} \\ & + L^\dagger \left[1 + f_L(Y_e Y_e^\dagger)^T + h.c.\right] L + \bar{e}^\dagger \left[1 + f_e(Y_e^\dagger Y_e) + h.c.\right] \bar{e}\,, \end{aligned}$$

- Of course not B,L violating. Small flavor violating terms suppressed by MFV (GIM mechanism)

The Baryon number violating W

- The only allowed term:

$$W_{\rm BNV} = \frac{1}{2}\lambda''_{ijk}\epsilon^{abc}\bar{u}^i_a\bar{d}^j_b\bar{d}^k_c$$

- MFV predicts the size of these couplings:

$$\lambda''_{ijk} = w'' y^{(u)}_i y^{(d)}_j y^{(d)}_k \epsilon_{jkl} V^\star_{il}$$

- Suppressed by Yukawa couplings and CKM angles

$$\lambda''_{usb} \sim t_\beta^2 \frac{m_b m_s m_u}{m_t^3}\,, \qquad \lambda''_{ubd} \sim \lambda t_\beta^2 \frac{m_b m_d m_u}{m_t^3}\,, \qquad \lambda''_{uds} \sim \lambda^3 t_\beta^2 \frac{m_d m_s m_u}{2\, m_t^3}\,,$$

$$\lambda''_{csb} \sim \lambda t_\beta^2 \frac{m_b m_c m_s}{m_t^3}\,, \qquad \lambda''_{cbd} \sim t_\beta^2 \frac{m_b m_c m_d}{m_t^3}\,, \qquad \lambda''_{cds} \sim \lambda^2 t_\beta^2 \frac{m_c m_d m_s}{m_t^3}\,,$$

$$\lambda''_{tsb} \sim \lambda^3 t_\beta^2 \frac{m_b m_s}{m_t^2}\,, \qquad \lambda''_{tbd} \sim \lambda^2 t_\beta^2 \frac{m_b m_d}{m_t^2}\,, \qquad \lambda''_{tds} \sim t_\beta^2 \frac{m_d m_s}{m_t^2}\,.$$

The Baryon number violating W

•The numerical values (for tan β=45 ~ max values):

	$s\,b$	$b\,d$	$d\,s$
u	5×10^{-7}	6×10^{-9}	3×10^{-12}
c	4×10^{-5}	1.2×10^{-5}	1.2×10^{-8}
t	2×10^{-4}	6×10^{-5}	4×10^{-5}

•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:

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

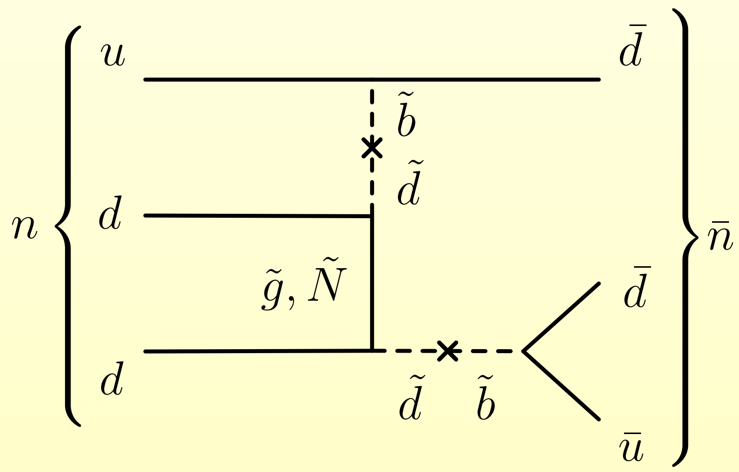
- dinucleon decay $pp \to K^+K^+$

$$\tau_{pp\to K^+K^+} \geq 1.7 \times 10^{32} \text{ yrs}$$

- Both from SuperK ^{16}O decay to various final states. Other dinucleon channels less constrained

n-nbar oscillation

- The leading diagram



- Estimate for matrix element:

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

n-nbar oscillation

- Numerical value:

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

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

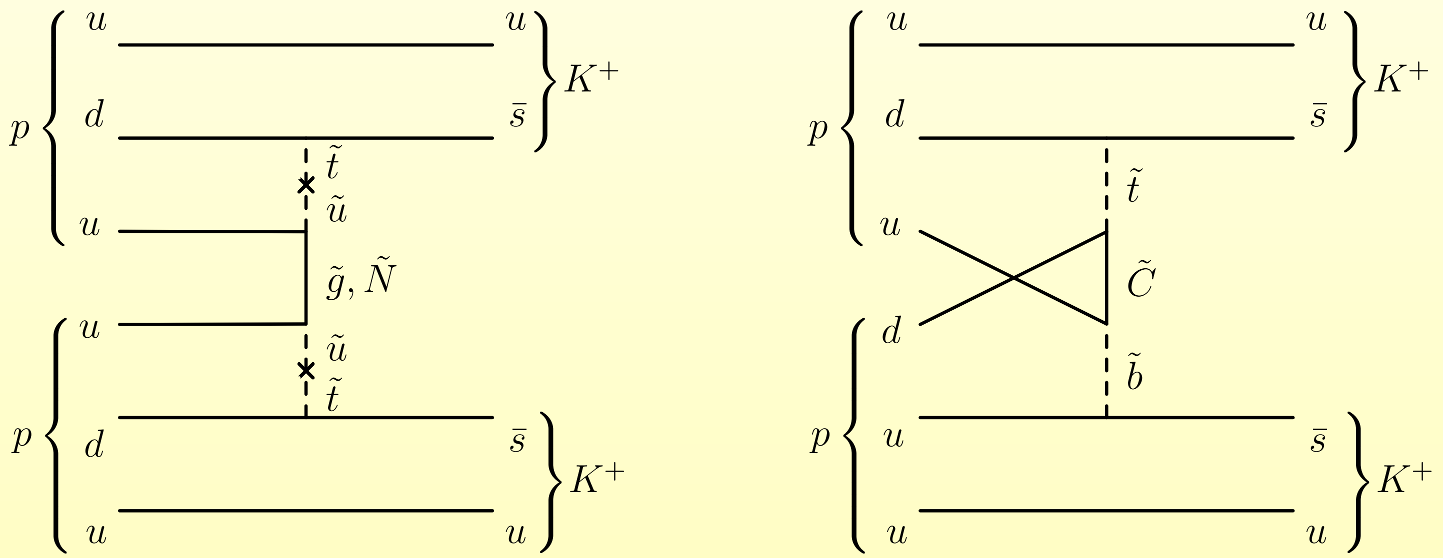
- Comment: to estimate the magnitude of off-diagonal squark mass insertions (for LH squarks):

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

$$V_{ds}^{\rm (neutral)} \sim \lambda^5 \quad , \quad V_{db}^{\rm (neutral)} \sim \lambda^3 \ , \quad V_{sb}^{\rm (neutral)} \sim \lambda^2 \, ,$$
$$V_{uc}^{\rm (neutral)} \sim y_b^2 \, \lambda^5/2 \quad , \quad V_{ut}^{\rm (neutral)} \sim y_b^2 \, \lambda^3/2 \ , \quad V_{ct}^{\rm (neutral)} \sim y_b^2 \, \lambda^2$$

Dinucleon decay

- Leading diagrams:



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

$$\Gamma \sim \rho_N \frac{128\pi\alpha_s^2\tilde{\Lambda}^{10}}{m_N^2 m_{\tilde{g}}^2 m_{\tilde{q}}^8} \left(\frac{\lambda^3 m_d m_s m_b^2}{2m_t^4} \tan^4\beta \right)^4$$

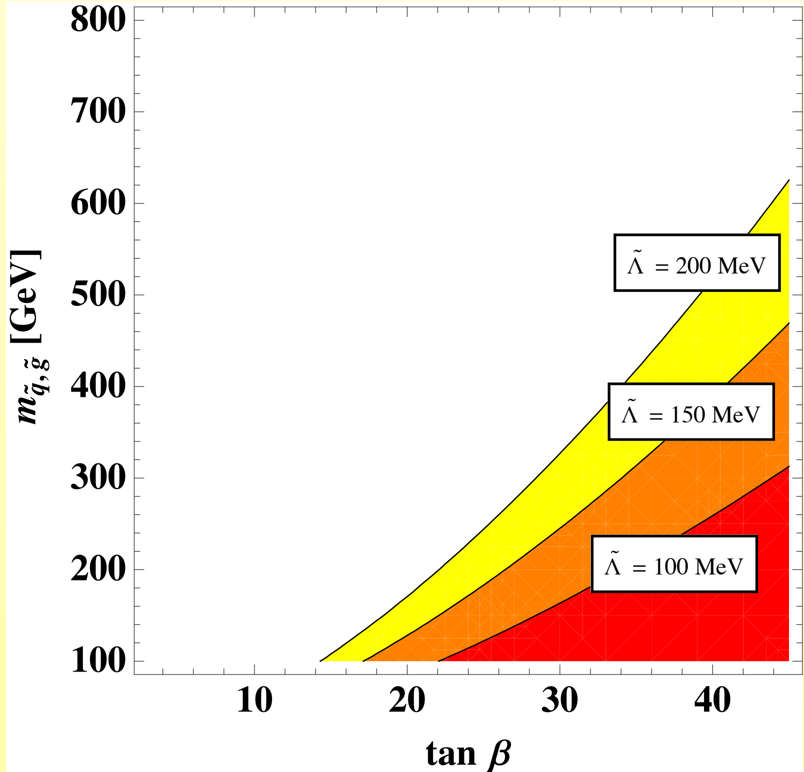
Dinucleon decay

- Lifetime:

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

- Applying exp. bound $\tau \geq 1.7\ 10^{32}$ yrs yields bound

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



Sources for non-holomorphic terms

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

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

- Will be suppressed by $F/M^2 \sim \frac{m_{soft}}{M}$

- Only dangerous terms quadratic superpotential terms

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

- gives a non-holomorphic supersymmetric mass term ~ $m_{soft}\tilde{\mu}$, in the absence of neutrino masses no relevant term (except μ)

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

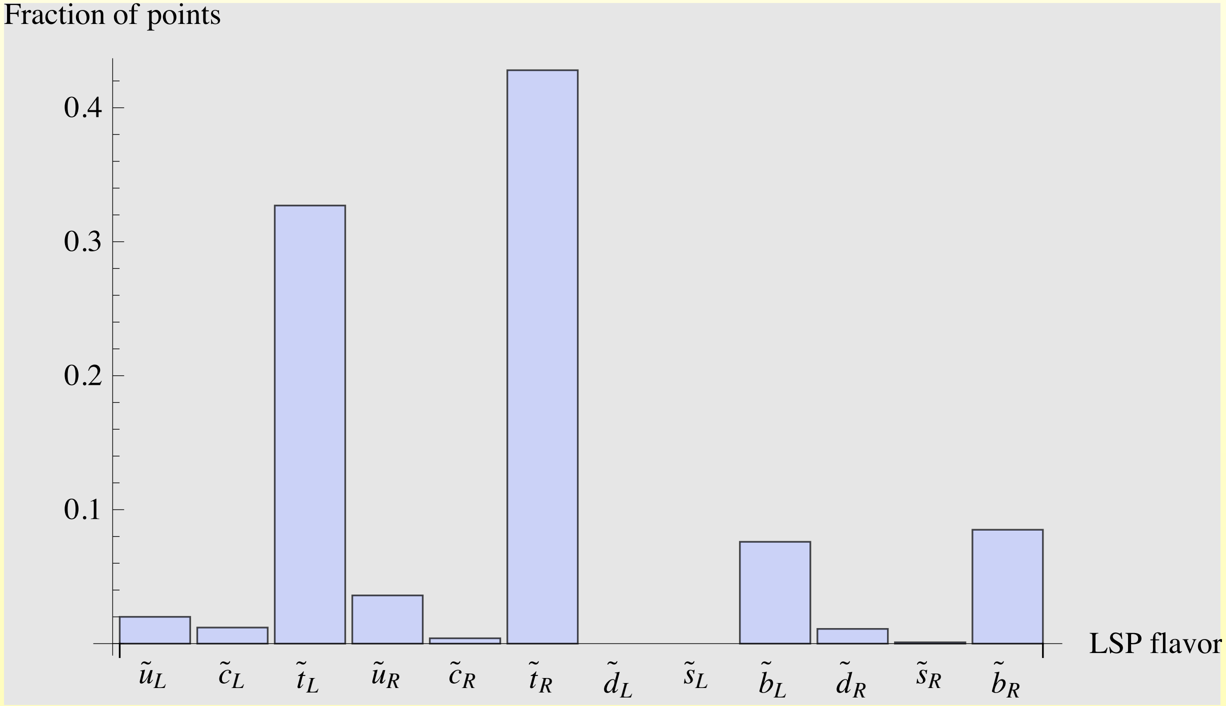
$$M^2_{\tilde{U}} = m^2_{\rm soft} \begin{pmatrix} 1 + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger & \delta\, Y_u \\ \delta^\star\, Y_u^\dagger & 1 + \gamma Y_u^\dagger Y_u \end{pmatrix} + \ldots$$

- Most plausible: stop lightest squark (or perhaps sbottom), others nearly degenerate

LHC phenomenology

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

- Distribution of LSP

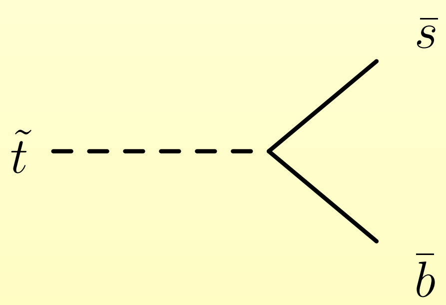


- In squark sector most likely stop, or sometimes sbottom

LHC phenomenology

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

•Stop can decay directly via RPV vertex:



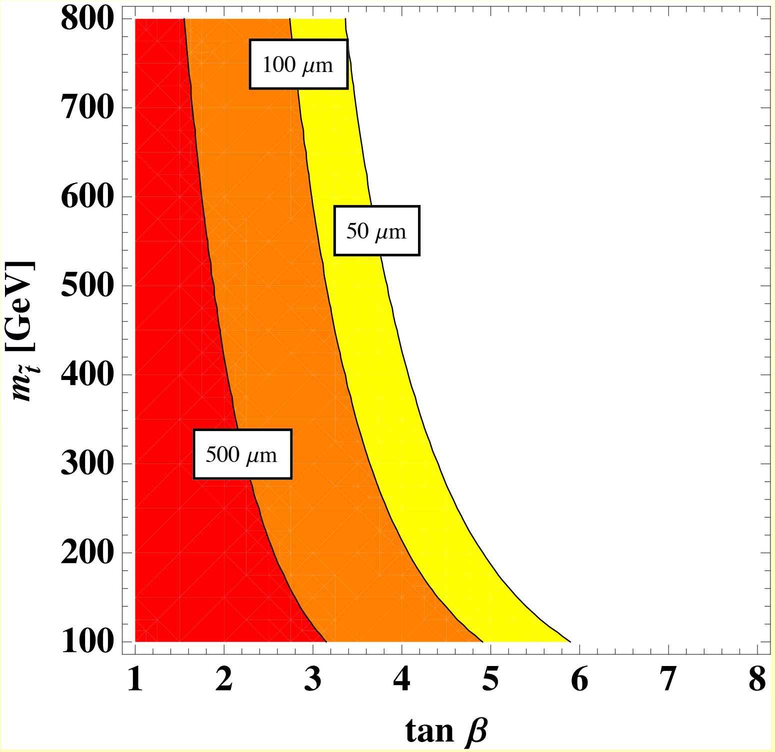
•Lifetime:

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

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

LHC phenomenology

- Stop decay length:

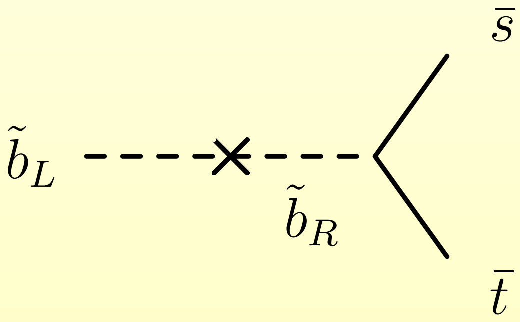


- No displaced vertices in most of parameter space

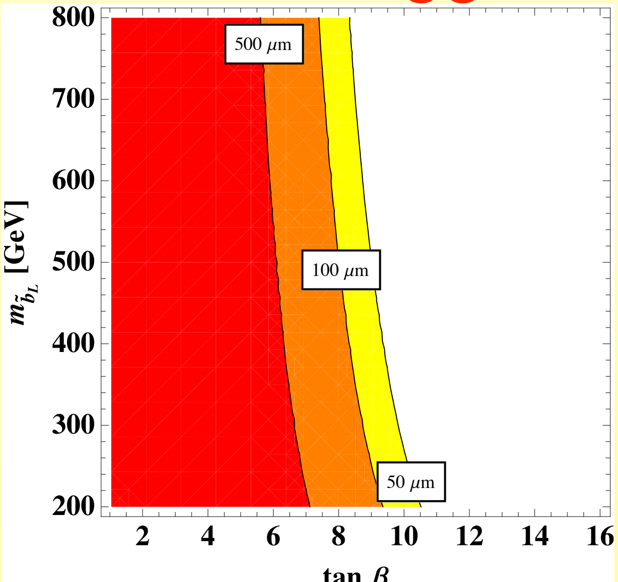
$$\tau_{\tilde{t}} \sim (2\ \mu\mathrm{m}) \left(\frac{10}{\tan\beta}\right)^4 \left(\frac{300\ \mathrm{GeV}}{m_{\tilde{t}}}\right) \left(\frac{1}{2\sin^2\theta_{\tilde{t}}}\right)$$

LHC phenomenology

- Sbottom LSP: first have to get a RH sbottom, additional Yukawa suppression in rate

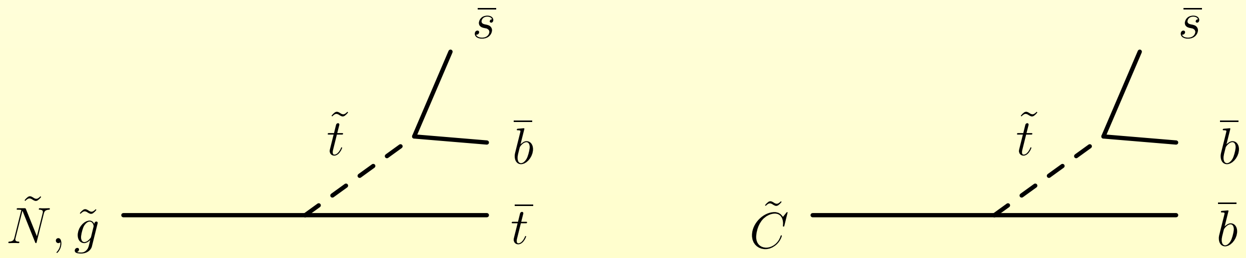


- Get tops in final state and bit bigger region for displaced vertex



LHC phenomenology

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

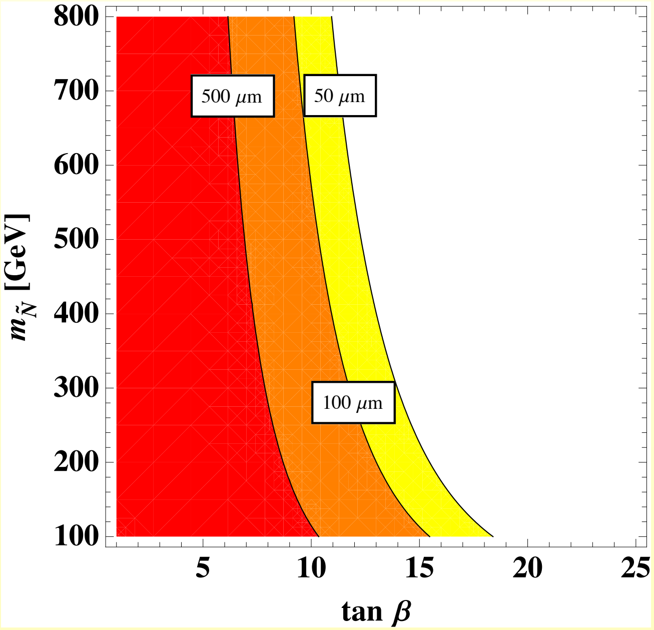


- Get tops in final state for neutralino and yet bigger region for displaced vertex (gluino would be similar)

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

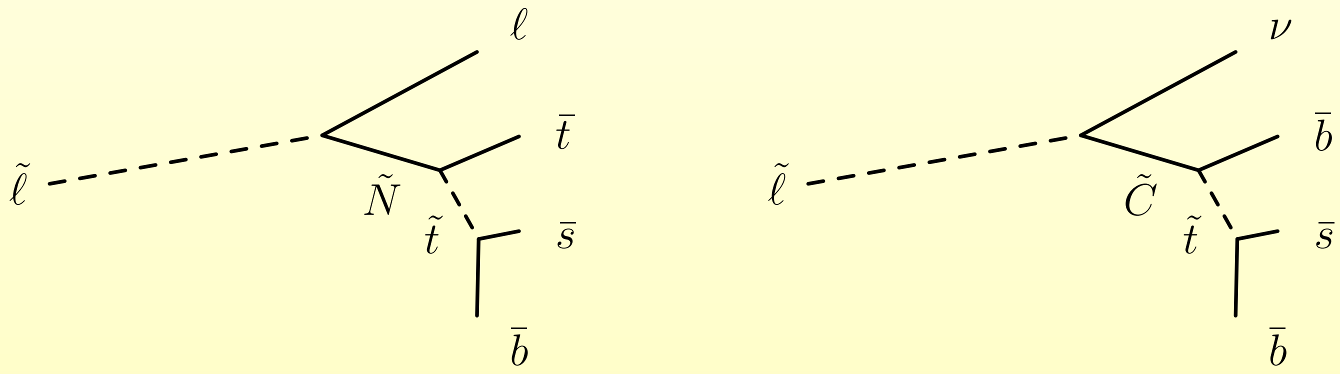
LHC phenomenology

- The neutralino LSP decay length



LHC phenomenology

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

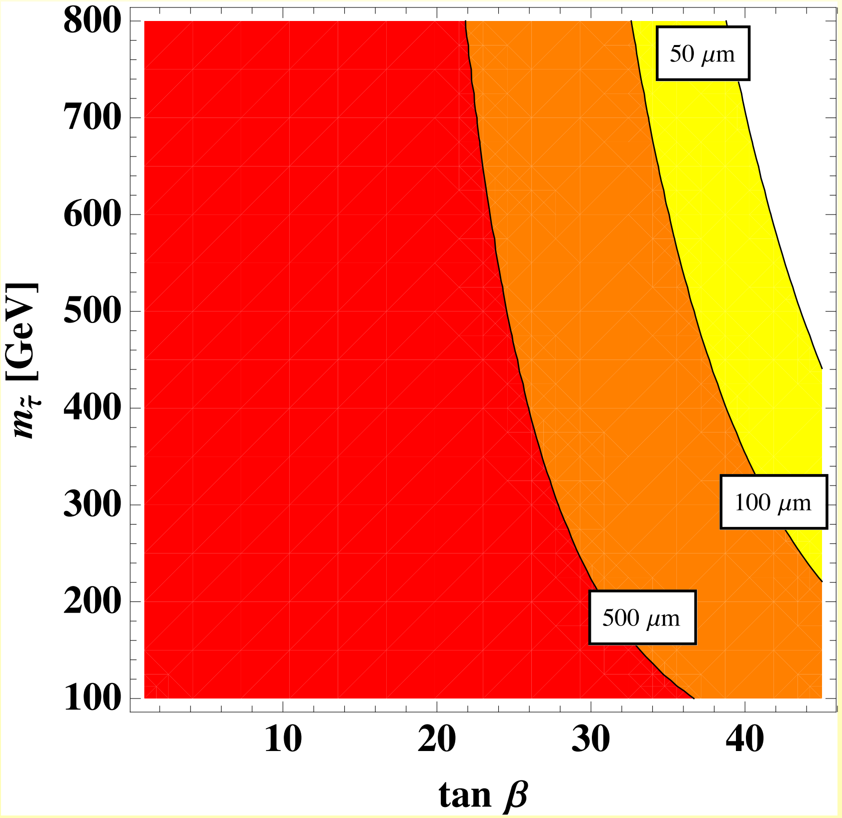


- 4-body decay, almost certainly displaced vertex, some have tops some missing energy. This should be easier.

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

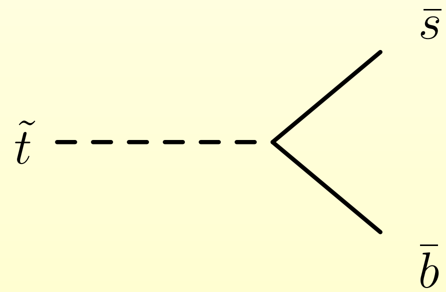
LHC phenomenology

- Stau decay length:



Existing searches

•For stop LSP: dijet resonance search



•However stop production cross section quite low, m_{stop}= 200 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

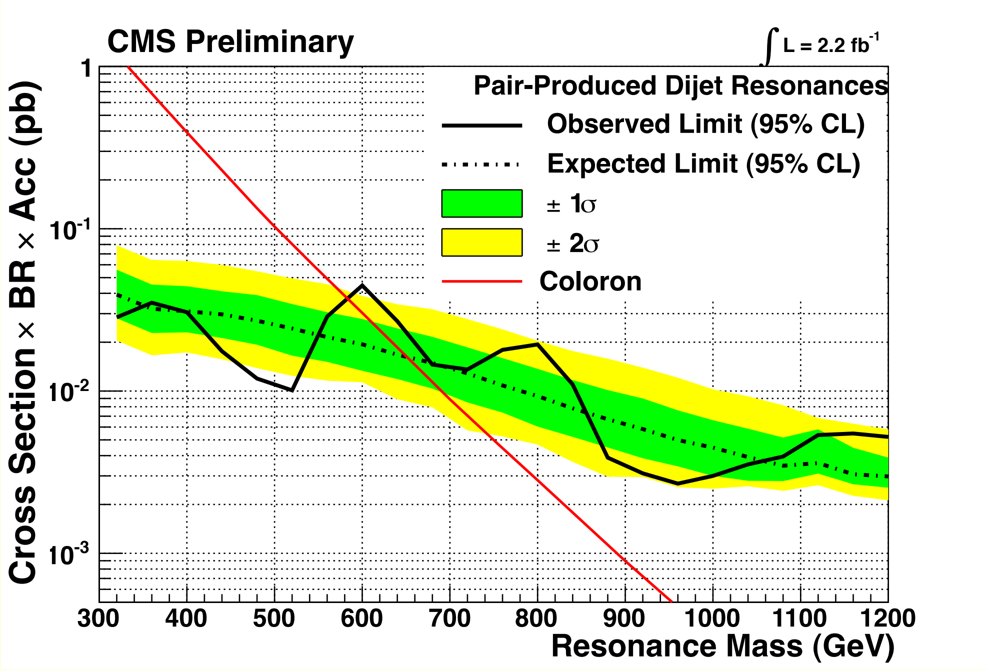
- The usual search for RPV does not apply here since the $QL\bar{d}$ coupling vanishes here.

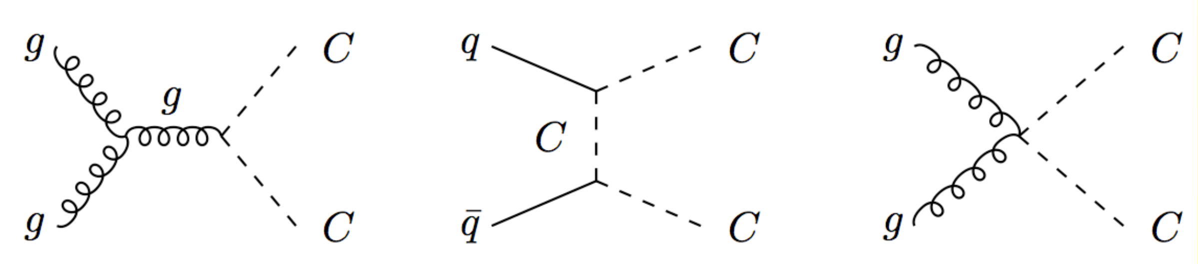
- Relevant search: CMS/CDF search for 3-body decay of gluino via $\bar{u}\bar{d}\bar{d}$ vertex. Current bound from 2010 data m_{gluino}>280 GeV. However for this gluino not very crucial, would be nice to have a search not relying on that.

- 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

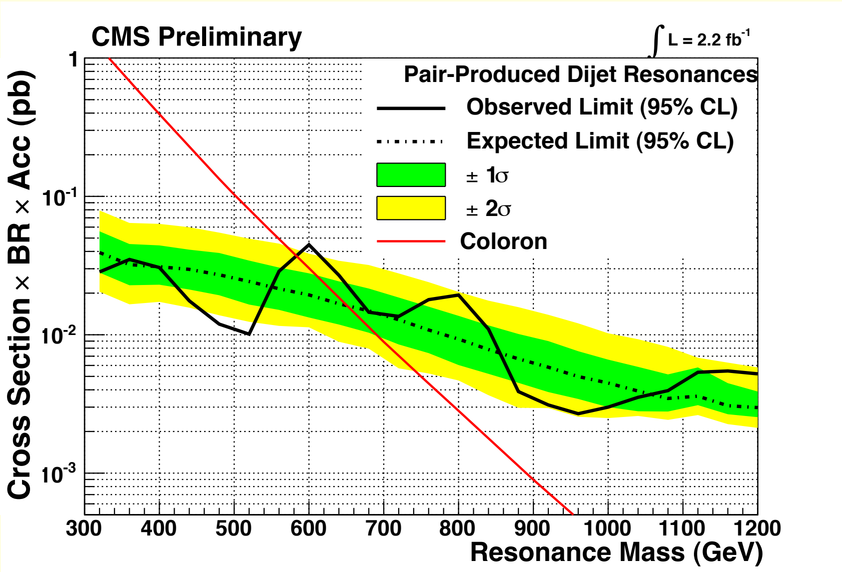
- CMS: paired dijet resonance search (their motivation was colorons...)

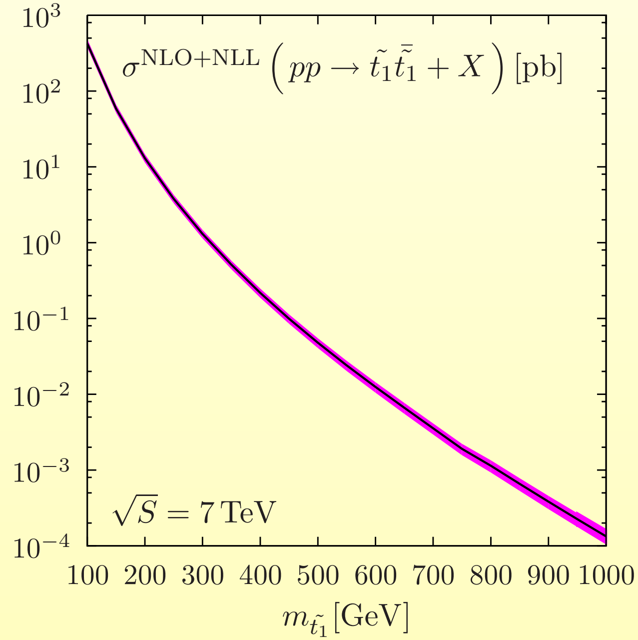




Existing searches

- 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.

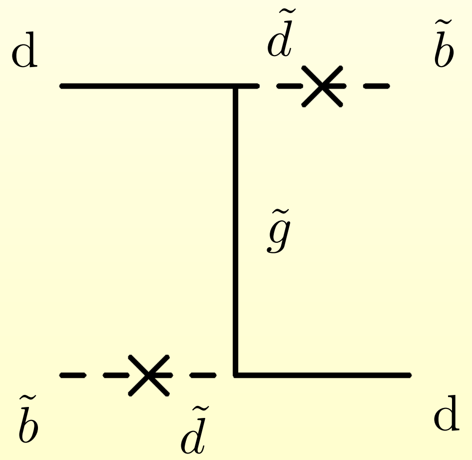
- Submitted RECAST request (Berger, C.C., Grossman)

Same sign tops?

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

- Mesino oscillation

$$x = \frac{\Delta M}{\Gamma}$$



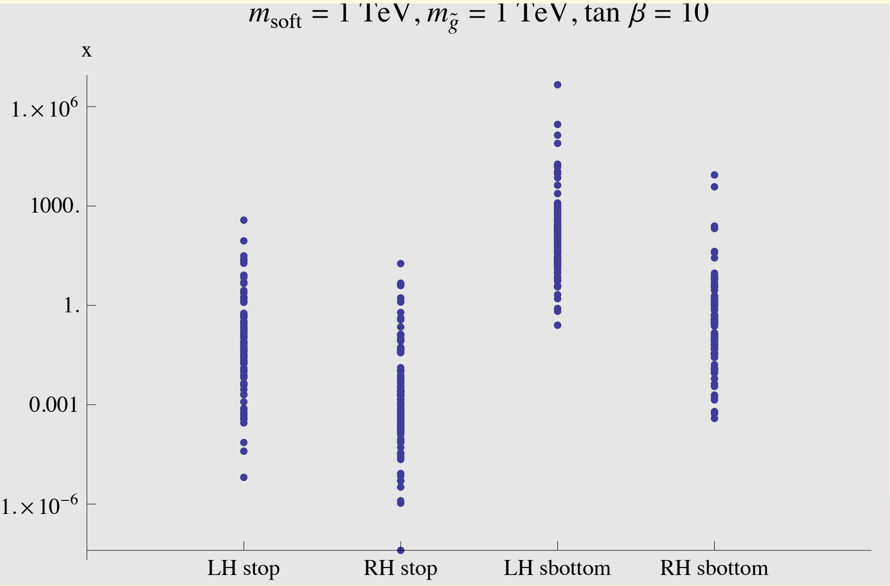
- For sbottom find x≥1, for stop x<<1.

- If sbottom LSP expect same sign tops

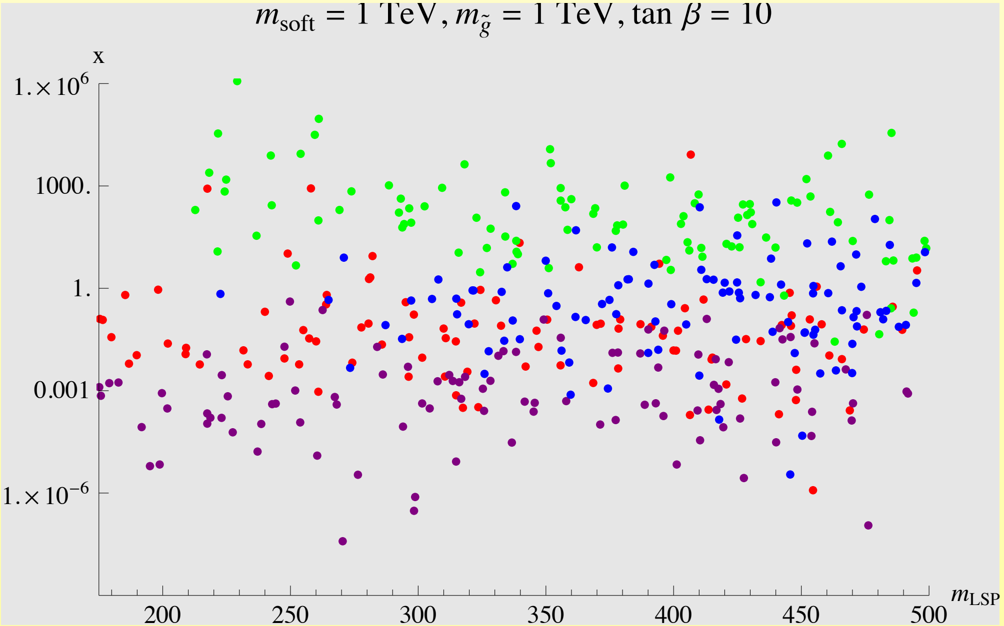
Same sign tops?

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

- The distribution of the oscillation times



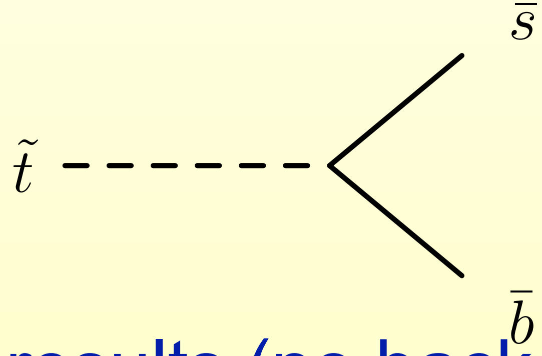
Red = LH stop
Purple = RH stop
Green = LH sbottom
Blue = RH sbottom



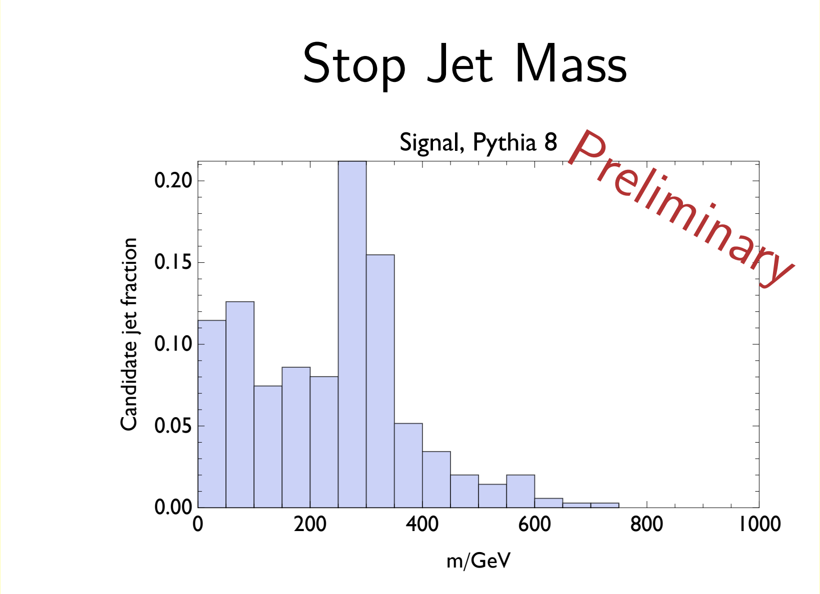
Use jet substructure?

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

- Perhaps can fish out stop decays using jet substructure



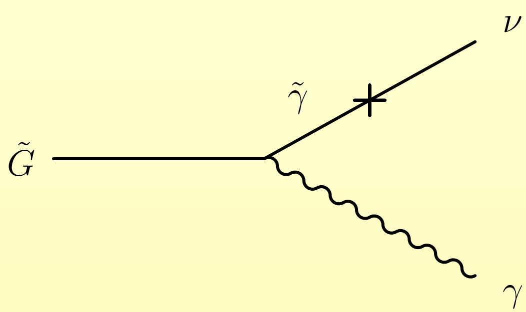
- Very preliminary results (no background yet), p_T>100 GeV at the 14 TeV LHC, planar flow>0.01.

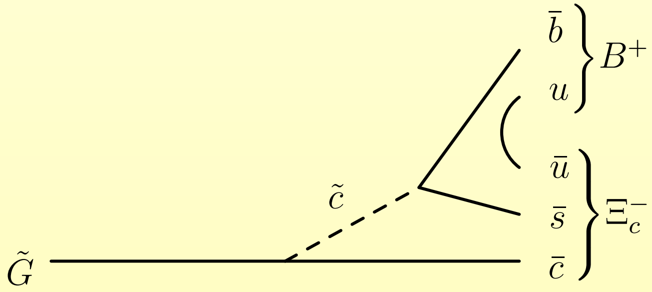


Dark matter?

- Ordinary LSP decays quickly in detector, not WIMP

- Gravitino would be long enough lived if light





$$\tau_{\tilde{G}} \gtrsim (4 \times 10^{39}\ \mathrm{yr}) \left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right)^3 \left(\frac{300\ \mathrm{GeV}}{m_{\tilde{q}}}\right)^4 \left(\frac{\tan\beta}{10}\right)^8$$

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

- Depends on thermal history - needs more work

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. σ_{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: $$\Delta \equiv \frac{2\delta m_H^2}{m_h^2}.$$
- Want this to be <10-20 %
- Higgsinos light, because $$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$
- So bound on μ: $$\mu \lesssim 200\,\mathrm{GeV}\left(\frac{m_h}{120\,\mathrm{GeV}}\right)\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$
- At one loop largest contributions to $m_{H_u}^2$ from stops:

$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

- Bound: $$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim 600\,\mathrm{GeV}\frac{\sin\beta}{(1+x_t^2)^{1/2}}\left(\frac{\log(\Lambda/\mathrm{TeV})}{3}\right)^{-1/2}\left(\frac{m_h}{120\,\mathrm{GeV}}\right)\left(\frac{\Delta^{-1}}{20\%}\right)$$

$x_t = A_t/\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}.$

The bounds on natural SUSY: naturalness

(Papucci, Ruderman, Weiler '11)

- Gluino contributes at 2 loops:

$$\delta m^2_{H_u}|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

- Can be somewhat heavier, different log dependence

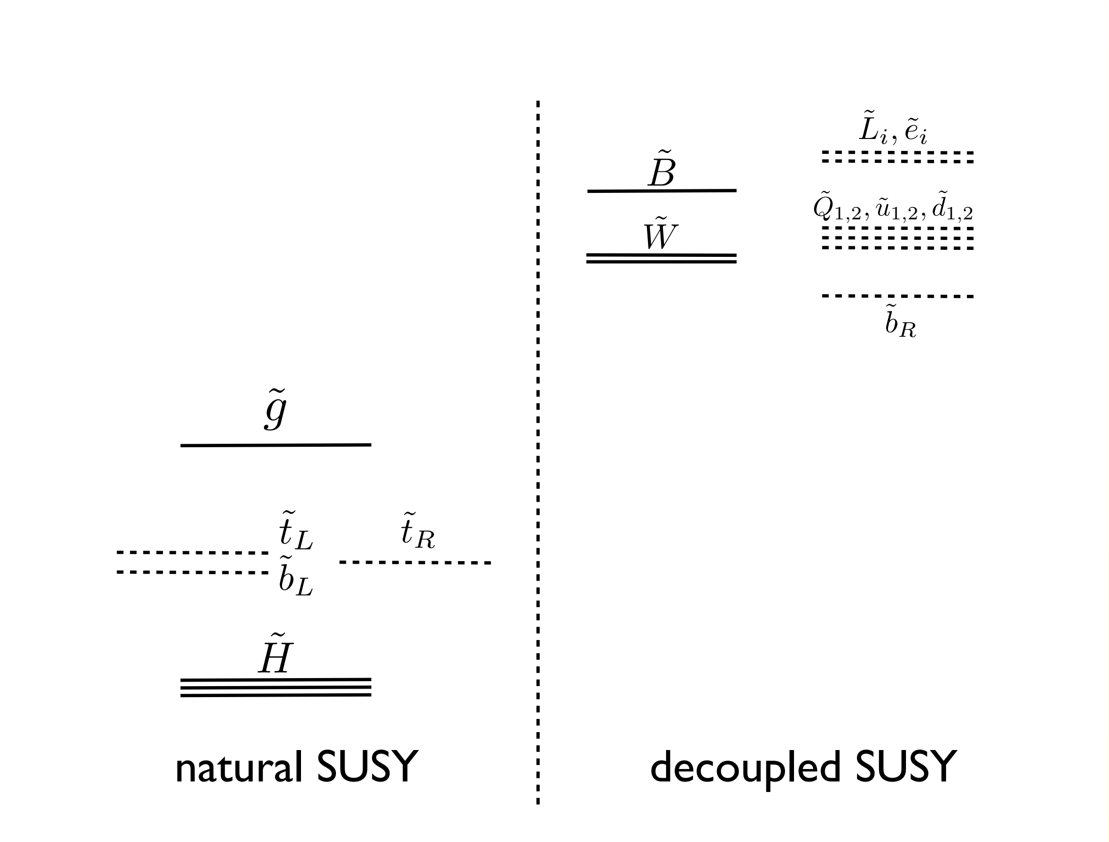
$$M_3 \lesssim 900\,\mathrm{GeV}\sin\beta \left(\frac{\log\left(\Lambda/\,\mathrm{TeV}\right)}{3}\right)^{-1} \left(\frac{m_h}{120\,\mathrm{GeV}}\right) \left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

- Electroweak gauginos can be even more heavy

$$(M_1, M_2) \lesssim (3\,\mathrm{TeV}, 900\,\mathrm{GeV}) \left(\frac{\log\left(\Lambda/\,\mathrm{TeV}\right)}{3}\right)^{-1/2} \left(\frac{m_h}{120\,\mathrm{GeV}}\right) \left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

The bounds on natural SUSY: naturalness

(Papucci, Ruderman, Weiler '11)



Below TeV scale

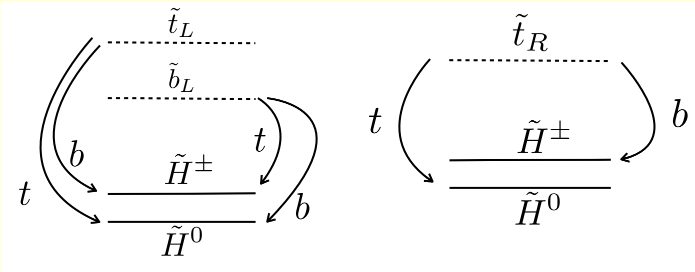
Above TeV scale

Gluino and Winos not as clear-cut: gluino could be heavier, while wino definitely below TeV...

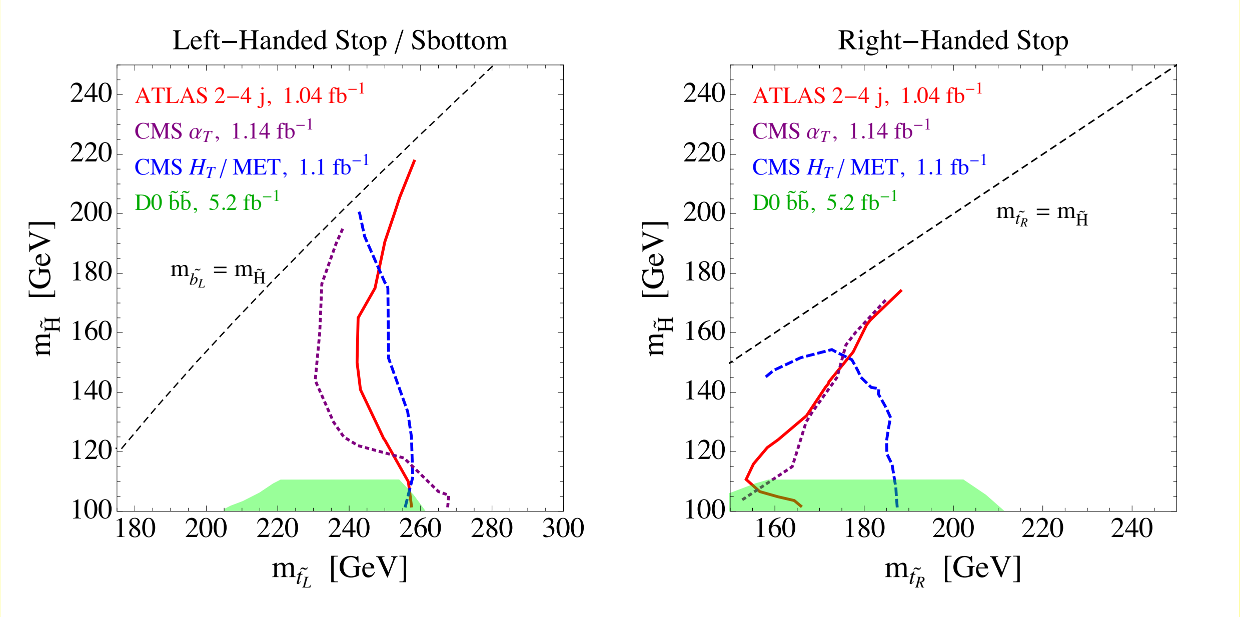
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler '11)

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



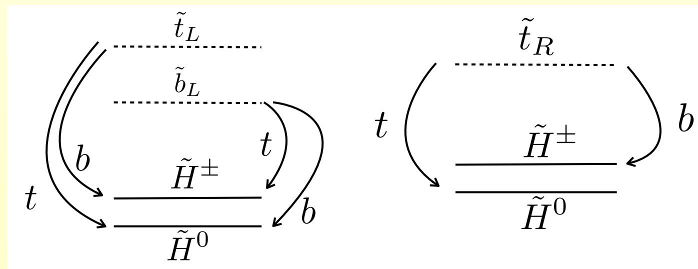
- Bounds from ~ 1 fb^{-1} data:



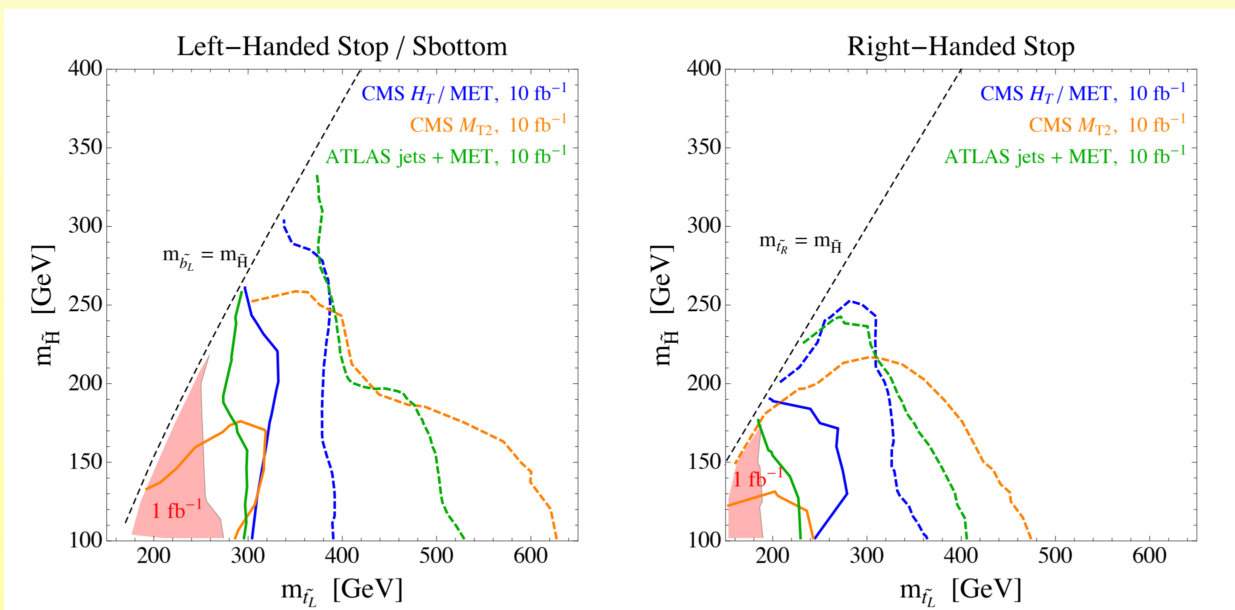
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler '11)

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



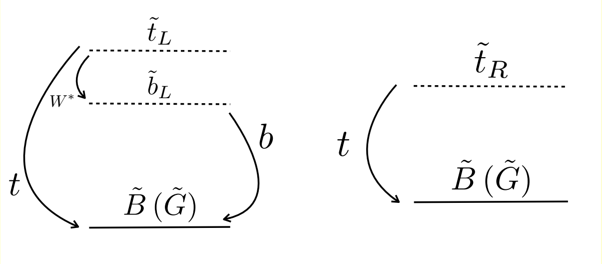
- Estimate for bounds from 10 fb^{-1} :



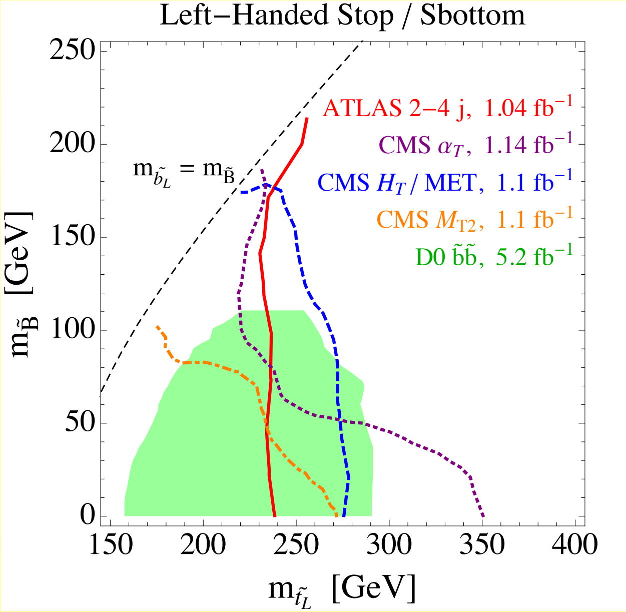
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler '11)

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



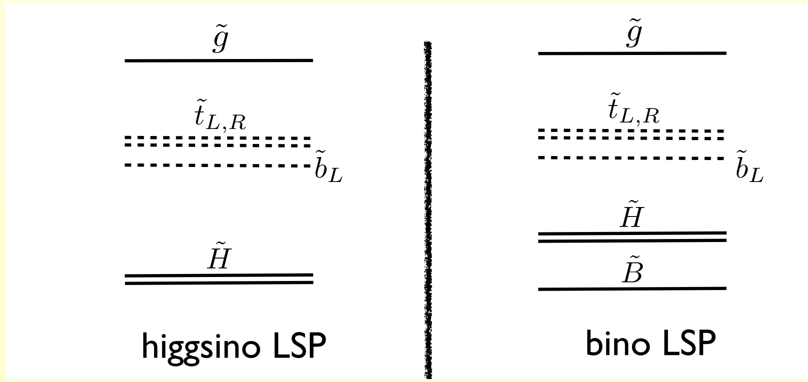
•Bounds from ~ 1 fb^{-1} data, no bound on RH stop.



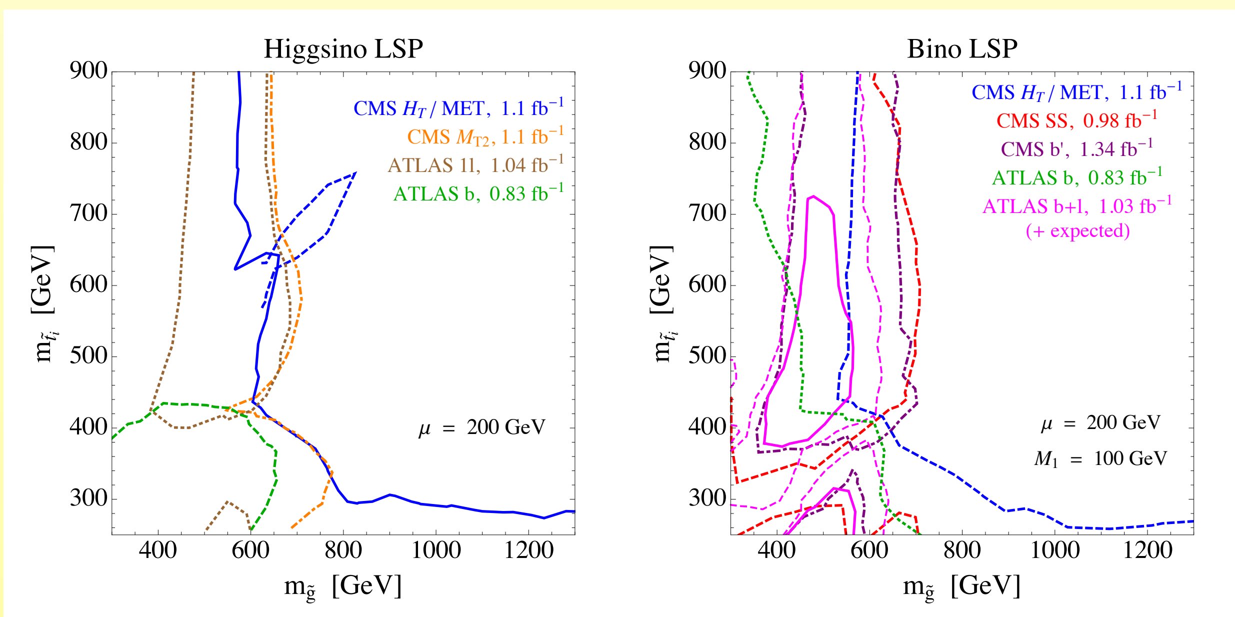
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler '11)

- For completeness gluino bounds:



- Bounds from ~ 1 fb^{-1} data:

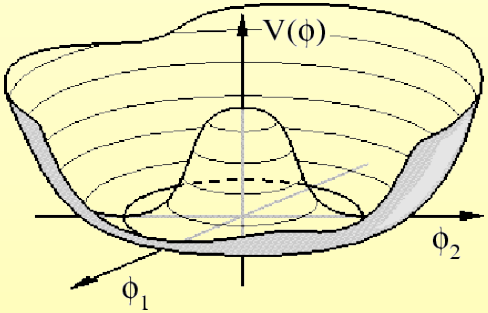


The other problem with SUSY: Little hierarchy

- 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 $m_h \geq 114\,\mathrm{GeV}$

- LHC: $m_h \sim 125\mathrm{GeV}$

•Very hard to overcome this in SUSY

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

$$m^2_{Higgs} = M_Z^2 + \frac{3m_t^2\lambda_t^2}{4\pi^2}\log\frac{m_{\tilde{t}}}{m_t}$$

•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

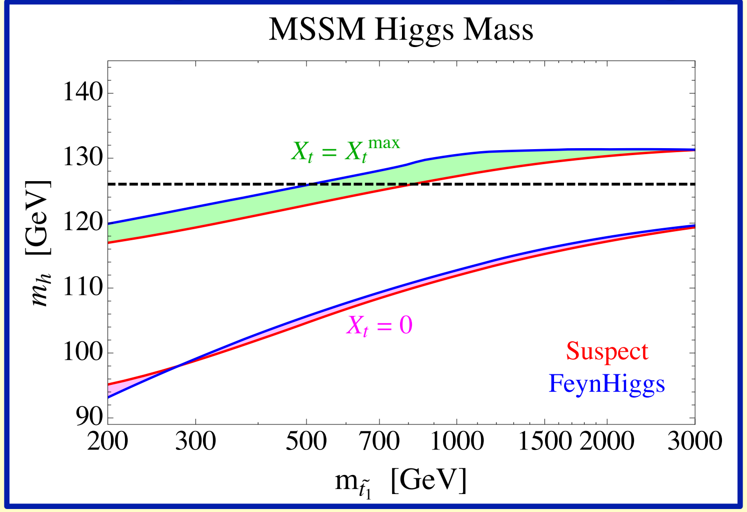
$$M_Z^2 \sim -2m^2_{H_u}$$ vs. $$m^2_{H_u} = m_0^2 - \frac{3\lambda_t^2 m_{\tilde{t}}^2}{4\pi^2}\log\frac{\Lambda^2_{UV}}{m^2_{\tilde{t}}}$$

•Implies <1% tuning generically

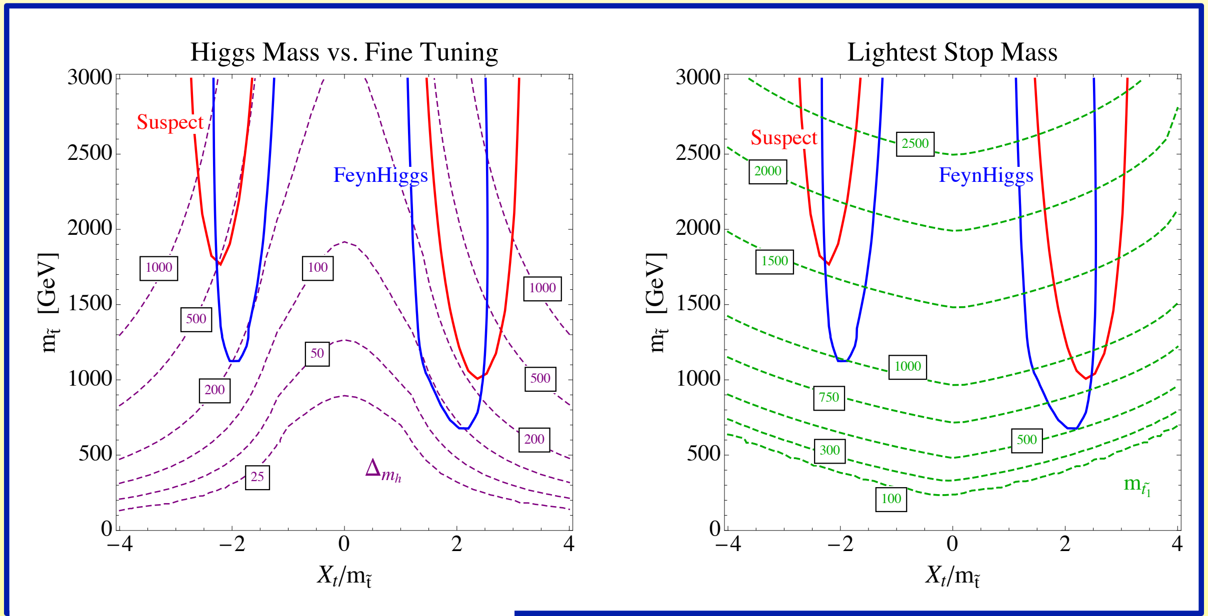
MSSM naturalness for 125 GeV Higgs

(Hall, Pinner, Ruderman, ’11)

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



- Fine tuning:



Light stops from compositeness (and a 125 GeV Higgs)

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

- 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

	$SU(4)$	$SU(6)_1$	$SU(6)_2$	$U(1)_V$	$U(1)_R$
$\mathcal{Q}$	$\square$	$\overline{\square}$	$\mathbf{1}$	1	$\frac{1}{3}$
$\bar{\mathcal{Q}}$	$\overline{\square}$	$\mathbf{1}$	$\overline{\square}$	-1	$\frac{1}{3}$

$$W_{tree} = \mu_{\mathcal{F}}(\mathcal{Q}_4\bar{\mathcal{Q}}_4 + \mathcal{Q}_5\bar{\mathcal{Q}}_5) + \mu_f \mathcal{Q}_6\bar{\mathcal{Q}}_6$$

- Becomes strongly coupled at ~ 10 TeV, produces massless composites

	$SU(2)_{\rm mag}$	$SU(6)_1$	$SU(6)_2$	$U(1)_V$	$U(1)_R$
q	$\square$	$\square$	$\mathbf{1}$	2	$\frac{2}{3}$
$\bar{q}$	$\overline{\square}$	$\mathbf{1}$	$\square$	-2	$\frac{2}{3}$
M	$\mathbf{1}$	$\overline{\square}$	$\overline{\square}$	0	$\frac{2}{3}$

$$W_{dyn} = y\,\bar{q}Mq\ .$$

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

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

- Composites:

$$q = Q_3, \mathcal{H}, H_d \qquad \bar{q} = X, \bar{\mathcal{H}}, H_u$$

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

- Relevant superpotential:

$$W \supset yP(\mathcal{H}\bar{\mathcal{H}} - \mathcal{F}^2) + yS(H_u H_d - f^2) + yQ_3 H_u \bar{t} + yH_u \mathcal{H}\phi_u + yH_d \bar{\mathcal{H}}\phi_d$$

A model with light stops and 125 GeV higgs

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

- The relevant part of the Higgs potential:

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

(

A model with light stops and 125 GeV higgs

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

- The relevant part of the Higgs potential:

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

- usual SUSY quartic

A model with light stops and 125 GeV higgs

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

•The relevant part of the Higgs potential:

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

• additional NMSSM-like quartic due to confining dynamics - does not have to be small, can be > 1. tan β 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~v?

A model with light stops and 125 GeV higgs

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

- The EWSB vacuum: $\langle H_u^0 \rangle = \frac{v}{\sqrt{2}} \sin\beta \,, \qquad \langle H_d^0 \rangle = \frac{v}{\sqrt{2}} \cos\beta$

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

will generate effective μ=y <S>

- 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

$$\Delta m_{\tilde{t}} \sim \frac{32}{3} \frac{\alpha_s}{4\pi} |M_3|^2 \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

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≥6)

- Assuming that soft breaking generated above confinement scale Λ

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

- Composites get **suppressed** soft breaking masses

$$m_{comp} \sim \frac{m_{el}^2}{\Lambda} \sim M_1 \sim M_2 \sim A \sim \mathrm{few} \cdot 100 \ \mathrm{GeV}$$

- For Λ~5-10 TeV composites in few 100 GeV range

The input parameters

parameter	spectrum 1	spectrum 2	spectrum 3	spectrum 4
$\tan\beta$	0.85	1.3	1.0	0.97
A	300 GeV	540 GeV	350 GeV	400 GeV
T	4×10^7 GeV^3	1.4×10^7 GeV^3	3.35×10^7 GeV^3	6×10^6 GeV^3
$m_{Q_{33}}$	500 GeV	500 GeV	350 GeV	400 GeV
$m_{U_{33}}$	250 GeV	350 GeV	350 GeV	400 GeV
M_1	600 GeV	700 GeV	85 GeV	600 GeV
M_2	800 GeV	800 GeV	282 GeV	1200 GeV
m_S	400 GeV	350 GeV	350 GeV	100 GeV
M_{Sf}	0 GeV	-350 GeV	0 GeV	0 GeV
f	100 GeV	100 GeV	293 GeV	100 GeV

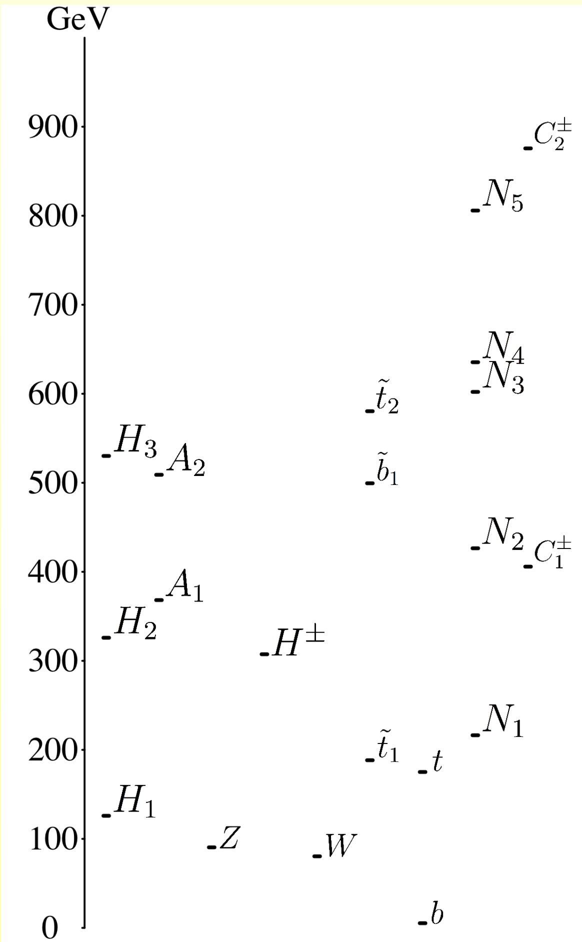
- Other parameters determined from minimizing Higgs potl

- 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)

Four different sample spectra

(CC, Randall, Terning '12)

1. Stealth stop



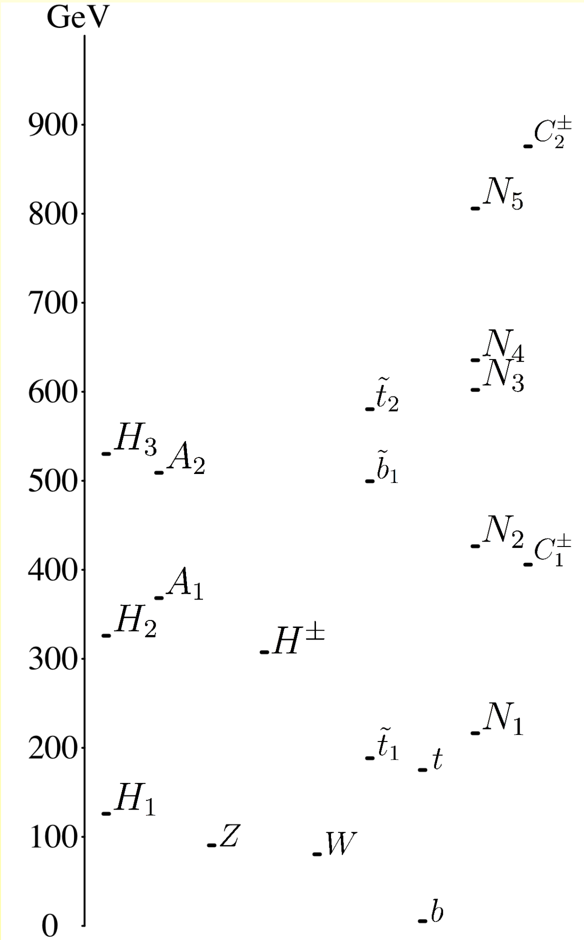
H_1	125 GeV	$\tilde{b}_1$	499 GeV
$\tilde{t}_1$	188 GeV	A_2	509 GeV
N_1	216 GeV	H_3	530 GeV
$H^\pm$	307 GeV	$\tilde{t}_2$	580 GeV
H_2	326 GeV	N_3	602 GeV
A_1	368 GeV	N_4	635 GeV
C_1	406 GeV	N_5	805 GeV
N_2	426 GeV	C_2	876 GeV

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

Four different sample spectra

(CC, Randall, Terning '12)

1. Stealth stop



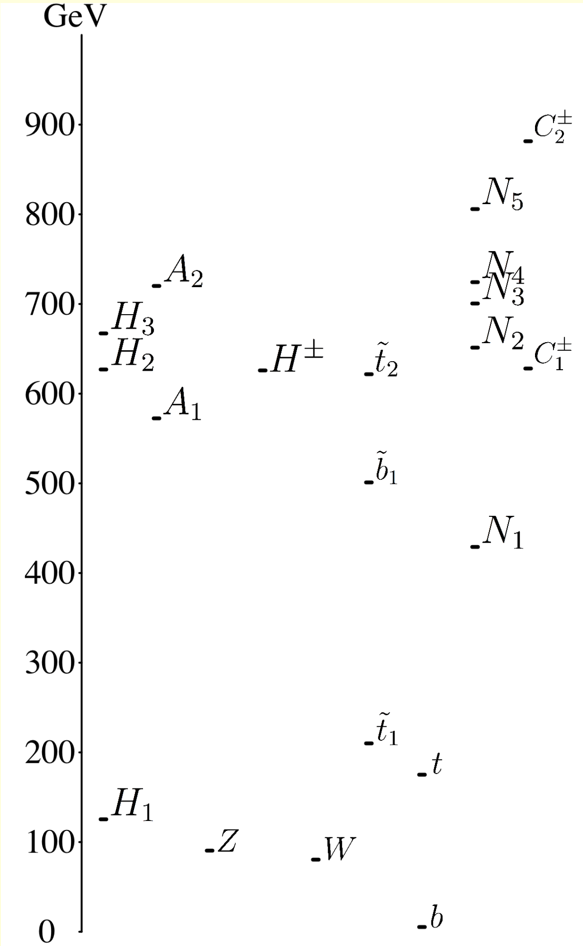
$\tilde{t}_1$	$\rightarrow t + LSP$	100%
C_1	$\rightarrow \tilde{t}_1 + b^\dagger$	84%
C_1	$\rightarrow N_1 + W^\pm$	16%
$\tilde{b}_1$	$\rightarrow \tilde{t}_1 + W^-$	97%
$\tilde{b}_1$	$\rightarrow \tilde{t}_1 + H^-$	3%
$\tilde{t}_2$	$\rightarrow \tilde{t}_1 + Z$	51%
$\tilde{t}_2$	$\rightarrow t + N_1$	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 muc missing ET. σ~15 pb, 10% of ttbar
- Need precise σ_{top}
- Next stop, sbottom ~10 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 N_1



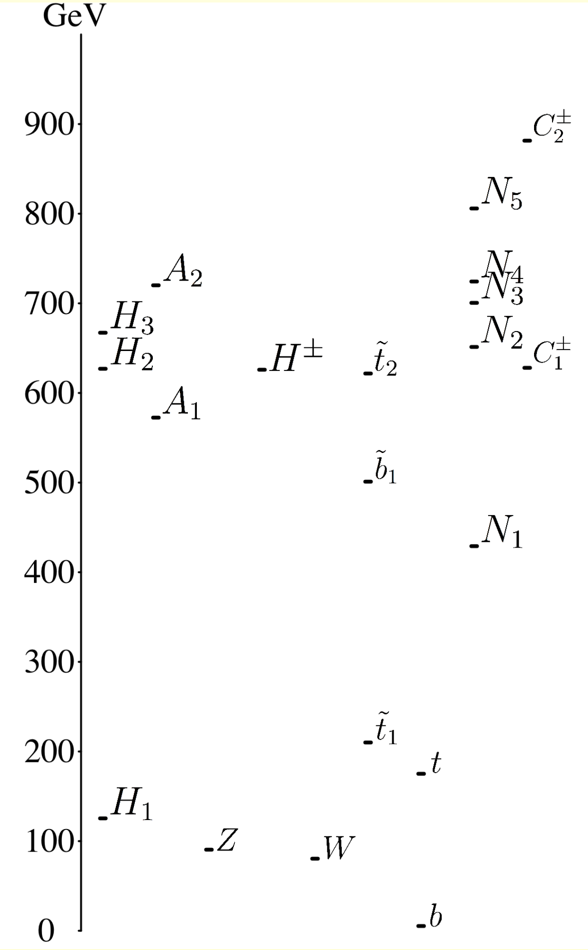
H_1	125 GeV	C_1	628 GeV
$\tilde{t}_1$	210 GeV	N_2	651 GeV
N_1	429 GeV	H_3	667 GeV
$\tilde{b}_1$	501 GeV	N_3	700 GeV
A_1	572 GeV	A_2	720 GeV
$\tilde{t}_2$	621 GeV	N_4	724 GeV
$H^\pm$	626 GeV	N_5	806 GeV
H_2	627 GeV	C_2	881 GeV

- 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



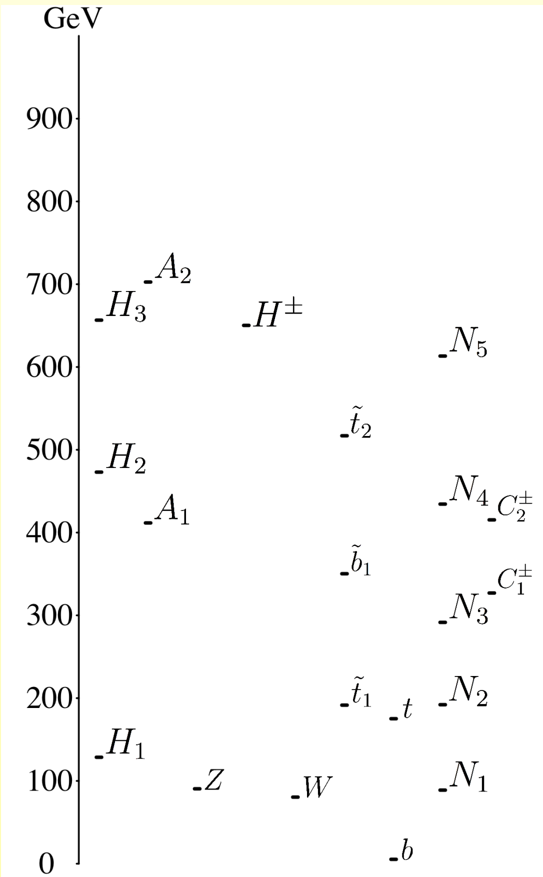
$\tilde{t}_1$	$\to t + LSP$	100%
N_1	$\to t + \tilde{t}^*$	50%
N_1	$\to \bar{t} + \tilde{t}$	50%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	100%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	78%
$\tilde{t}_2$	$\to \tilde{b}_1 + W^+$	14%
$\tilde{t}_2$	$\to \tilde{t}_1 + H_1$	8%

- Stop decays to top + gravitino - not much missing ET. σ~8 pb, 5% of ttbar
- Need even more precise σ_{top}
- $N_1 \to$ t+stop, tttt final states, still small missing E.
- Sbottom: ttWW
- Stop2: ttZZ, ttWWWW

Four different sample spectra

(CC, Randall, Terning '12)

3. Minimal gauge mediation



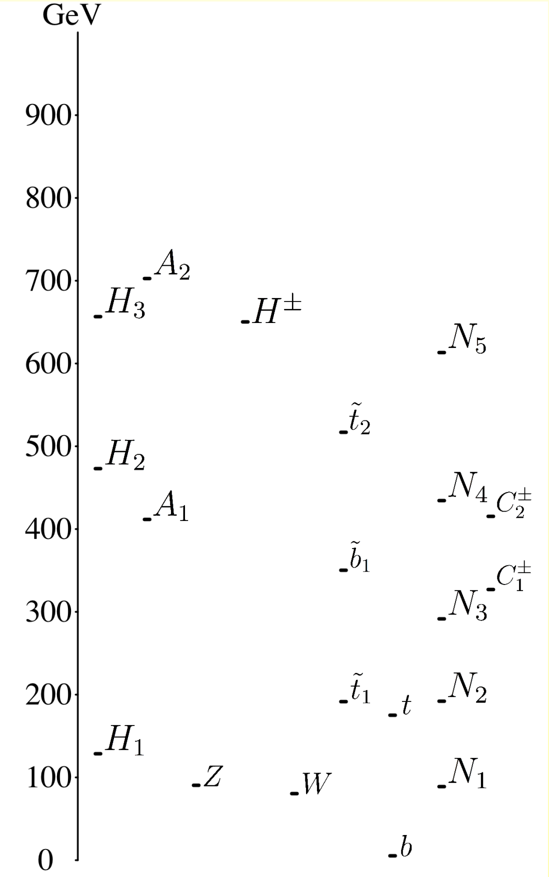
N_1	88 GeV	C_2	415 GeV
H_1	128 GeV	N_4	434 GeV
$\tilde{t}_1$	191 GeV	H_2	473 GeV
N_2	192 GeV	$\tilde{t}_2$	517 GeV
N_3	291 GeV	N_5	613 GeV
C_1	327 GeV	$H^\pm$	650 GeV
$\tilde{b}_1$	350 GeV	H_3	657 GeV
A_1	412 GeV	A_2	702 GeV

- Neutralino LSP or NLSP, missing energy, but reduced σ
- Stop still pretty light close to top

Four different sample spectra

(CC, Randall, Terning '12)

3. Minimal gauge mediation



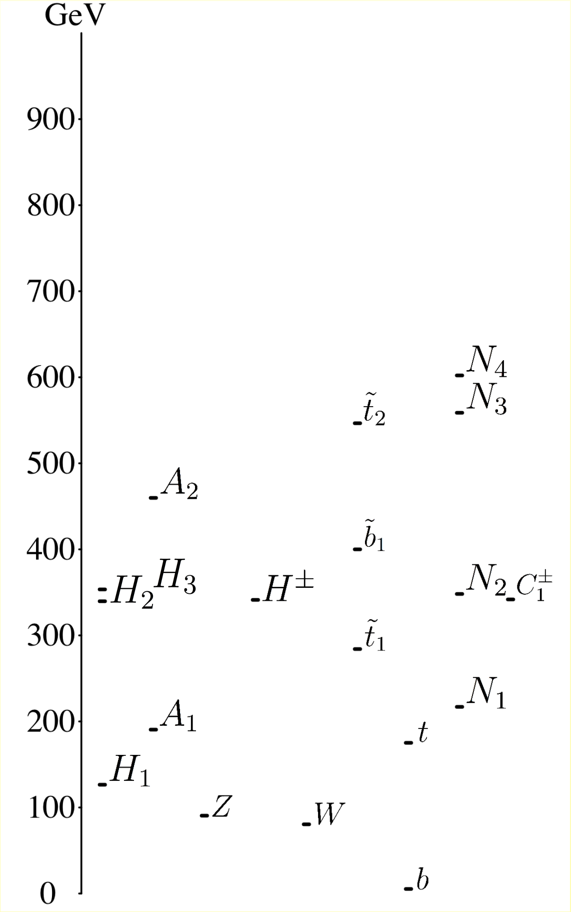
$\tilde{t}_1$	$\to N_1^+ + b + W^+$	100%
$\tilde{b}_1$	$\to N_3 + b$	80%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	95%
$\tilde{b}_1$	$\to N_3 + b$	4%
$\tilde{b}_1$	$\to N_1 + b$	1%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	42%
$\tilde{t}_2$	$\to \tilde{b}_1 + W^+$	31%
$\tilde{t}_2$	$\to N_2 + t$	10%
$\tilde{t}_2$	$\to C_2^+ + b$	8%
$\tilde{t}_2$	$\to N_1 + t$	4%
$\tilde{t}_2$	$\to C_1^+ + b$	3%
$\tilde{t}_2$	$\to N_3 + t$	2%

- If gauge mediation gravitino LSP
- $N_1 \to \gamma$+gravitino, missing ET
- stop$\to t^* + N_1$
- stop2→stop1 Z,sbottom W,N t, C b,
- j+MET, j+t+MET, j+W/Z+MET or photons, also longer cascades

Four different sample spectra

(CC, Randall, Terning '12)

4. High duality scale



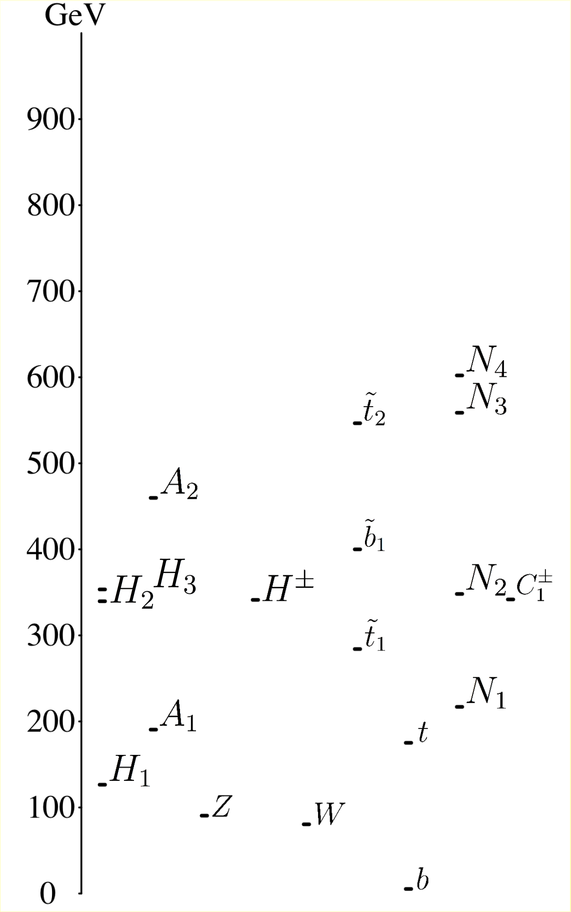
H_1	126 GeV	N_2	348 GeV
A_1	190 GeV	H_3	353 GeV
N_1	217 GeV	$\tilde{b}_1$	400 GeV
$\tilde{t}_1$	284 GeV	A_2	460 GeV
H_2	339 GeV	$\tilde{t}_2$	546 GeV
$H^\pm$	341 GeV	N_3	559 GeV
C_1	341 GeV	N_4	602 GeV

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

Four different sample spectra

(CC, Randall, Terning '12)

4. High duality scale



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

- stop→N_1+c
- stop2→stop1+Z, C+b, sbottom+W,N+t
- sbottom→stop1+W
- Final states: j+MET, j+t+MET, j+W/Z +MET
- Traditional SUSY at reduced rates

Higgs branchings

SM fields	spectrum 1	spectrum 2	spectrum 3	spectrum 4
$\gamma\gamma$	1.02	1.02	0.95	0.85
gluons	0.65	0.83	0.82	0.73
WW, ZZ	0.89	0.96	0.89	0.74
$u\bar{u}$	0.72	1.0	0.89	0.72
$d\bar{d}$	1.01	0.91	0.89	0.77

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 σ 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 $SU(3)_L$ x $SU(3)_e$ x $SU(3)_N$

- Now we have three spurions $Y_{e,v}$ and M

- M is a symmetric, different patterns allowed

Incorporating neutrino masses

- The table of symmetries:

	$\mathrm{SU}(3)_L$	$\mathrm{SU}(3)_e$	$\mathrm{SU}(3)_N$	$\mathrm{U}(1)_{B-L}$	$\mathrm{U}(1)_H$	$\mathrm{U}(1)_N$
L	$\bar{\square}$	$\mathbf{1}$	$\mathbf{1}$	-1	0	0
$\bar{e}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	1	0	0
$\bar{N}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	1	0	1
Y_e	$\square$	$\bar{\square}$	$\mathbf{1}$	0	1	0
Y_N	$\square$	$\mathbf{1}$	$\bar{\square}$	0	-1	-1
M_N	$\mathbf{1}$	$\mathbf{1}$	$\overline{\square\square}$	-2	0	-2

Incorporating neutrino masses

- Table of holomorphic invariants:

	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_L$	$\mathbb{Z}_2^R$
$(LL)\left(\tilde{Y}_N M_N \tilde{Y}_N\right)(LL)$	$\mathbf{1}$	-2	4	$+$
$(LL)\left(\tilde{Y}_N M_N \tilde{Y}_N\right)(Y_e\bar{e})$	$\mathbf{1}$	0	1	$-$
$(LL)\,\tilde{Y}_N M_N \bar{N}$	$\mathbf{1}$	-1	1	$-$
$L\left(Y_N \tilde{M}_N Y_N\right)(Y_e\bar{e})\left(Y_N\bar{N}\right)$	$\square$	$1/2$	-1	$-$
$LY_N\bar{N}$	$\square$	$-1/2$	0	$+$
$\bar{e}Y_e\tilde{Y}_N M_N \bar{N}$	$\mathbf{1}$	1	-2	$+$
$(Y_e\bar{e})\left(\tilde{Y}_N M_N \tilde{Y}_N\right)(Y_e\bar{e})$	$\mathbf{1}$	2	-2	$+$
$L\left(Y_N \tilde{M}_N Y_N\right)L$	$\square\square$	-1	2	$+$
$M_N\bar{N}\bar{N}$	$\mathbf{1}$	0	-2	$+$

$$\tilde{Y} = \mathrm{cof}\ Y = Y^{-1}\det Y$$

Incorporating neutrino masses

- Allowed renormalizable superpotential term

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

- Dimensionless expansion parameter

$$\mu_N \equiv \frac{1}{\Lambda_R} M_N$$

- Λ_R some heavy scale, usually take M_{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:

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

- Possible contributions:

$$\mathcal{V}_a^{(1)} = \frac{1}{\Lambda_R} \varepsilon_{abc} \left[\tilde{Y}_N^\dagger\right]_i^b [M_N^\dagger]^{ij} [Y_N]_j^c \quad , \quad \mathcal{V}_a^{(2)} = \frac{1}{\Lambda_R} \varepsilon_{abc} \left[Y_e Y_e^\dagger\right]_d^b \left[Y_N M_N^\dagger Y_N\right]^{cd}$$

- Similar soft breaking masses:

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

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

$$\langle L_a \rangle \sim -v_u \mathcal{V}_a \qquad \mathcal{L} \supset -v_u \lambda (\mathcal{V}^\dagger L) + c.c.$$

Proton decay constraints

- Assume structure of neutrino masses (Casas & Ibarra)

$$Y_N^T = \frac{1}{v_u}\,\mathrm{diag}\left(\sqrt{M_{R1}}, \sqrt{M_{R2}}, \sqrt{M_{R3}}\right)\; R\,\mathrm{diag}\left(\sqrt{m_{\nu 1}}, \sqrt{m_{\nu 2}}, \sqrt{m_{\nu 3}}\right)\, U^\dagger$$

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

- Assume all the Y's roughly same order, also m_ν's roughly equal (worst case scenario, could even have one m_ν=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:

$$\mathcal{V}_i^{(1)} \sim \frac{M_R^{\frac{5}{2}} m_\nu^{\frac{3}{2}}}{\Lambda_R\, v_u^3} \;, \quad \mathcal{V}_{e,\mu}^{(2)} \sim \frac{M_R^2\, m_\nu}{\Lambda_R\, v_u^2}\, y_\tau^2 \;, \quad \mathcal{V}_\tau^{(2)} \sim \frac{M_R^2\, m_\nu}{\Lambda_R\, v_u^2}\, y_\mu^2$$

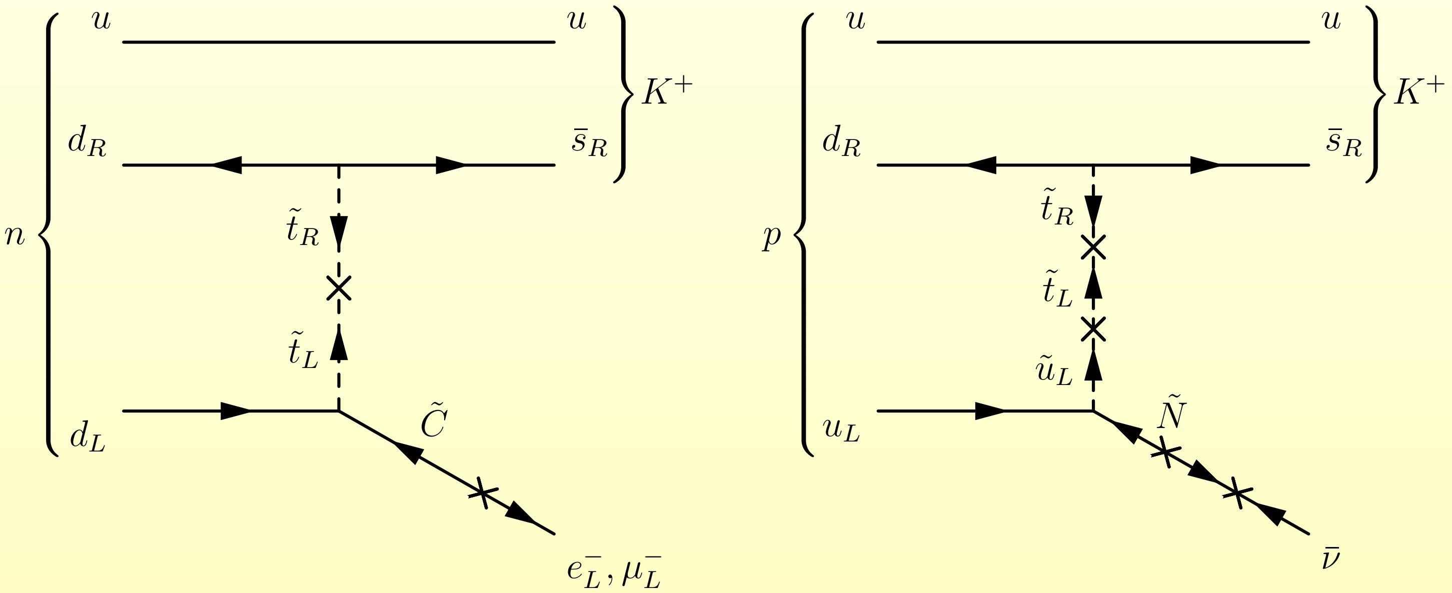
- The latter actually dominate:

$$\lambda_{ijk} \sim y_k^{(e)} Y_N\, \mathcal{V}^{(1)}$$

- Will neglect superpotential terms

Proton decay constraints

- The leading diagrams:



$n \rightarrow l^- K^+$ $\qquad$ $p \rightarrow \nu K^+$

- Strongest bound from matrix element

$$\mathcal{M}_{p\rightarrow K^+\bar{\nu}} \sim \frac{\lambda^3\, m_d\, m_s\, m_b^2}{2\, m_t^3\, m_{\tilde{N}}} \left(\frac{\tilde{\Lambda}}{m_{\tilde{q}}}\right)^2 \mathcal{V} \tan^4 \beta$$

Proton decay constraints

- The experimental bounds:

$$\tau_{p\to e^+ K^0} \geq 1.0\times 10^{33}\ \text{yrs} \quad , \quad \tau_{n\to e^- K^+} \geq 3.2\times 10^{31}\ \text{yrs}\ ,$$
$$\tau_{p\to \mu^+ K^0} \geq 1.3\times 10^{33}\ \text{yrs} \quad , \quad \tau_{n\to \mu^- K^+} \geq 5.7\times 10^{31}\ \text{yrs}\ ,$$
$$\tau_{p\to \nu K^+} \geq 2.3\times 10^{33}\ \text{yrs} \quad , \quad \tau_{n\to \nu K^0} \geq 1.3\times 10^{32}\ \text{yrs}\ ,$$

- Bound on quadratic spurion:

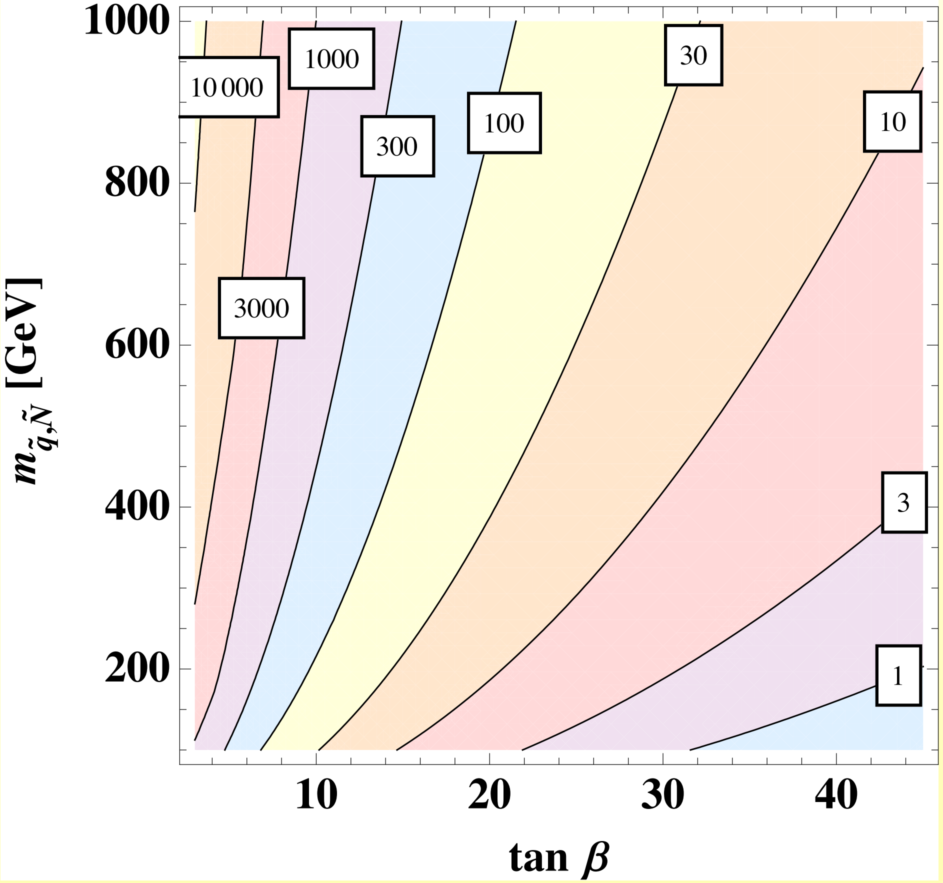
$$\mathcal{V}\,\tan^4\beta \lesssim (3\times 10^{-14})\left(\frac{m_{\tilde{q}}}{100\ \text{GeV}}\right)^2\left(\frac{m_{\tilde{N}}}{100\ \text{GeV}}\right)$$

- Translated into bound on M_R:

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

Proton decay constraints

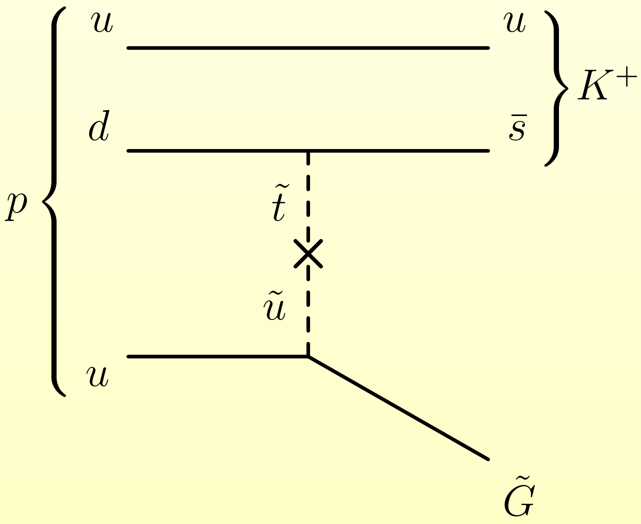
- The bound on M_R in units of 10^6 GeV:



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

Proton decay constraints

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



- Width:

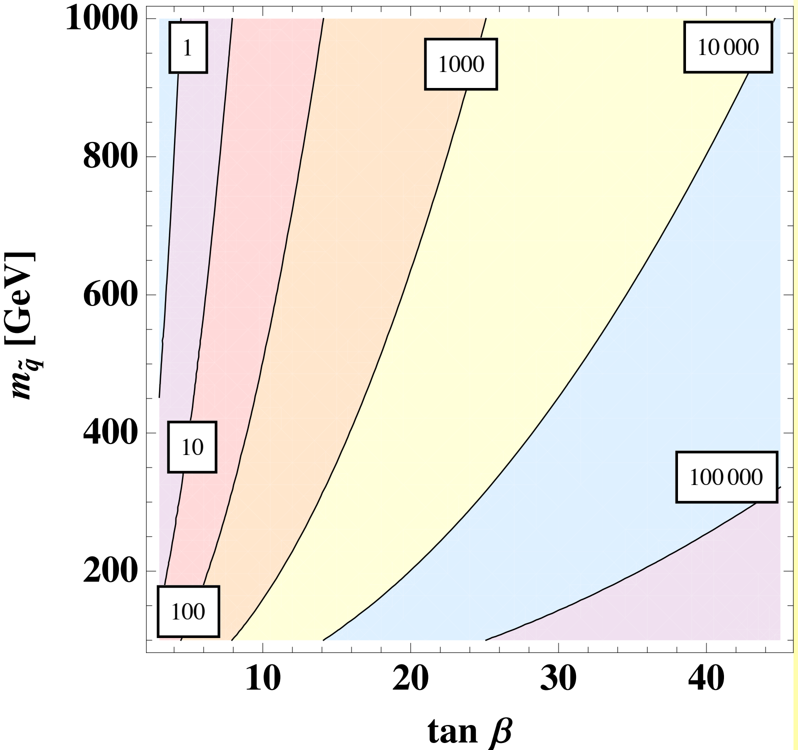
$$\Gamma \sim \frac{m_p}{8\pi}\left(\frac{\tilde{\Lambda}}{m_{\tilde{q}}}\right)^4 \left(\frac{\Lambda^2}{\sqrt{3}m_{3/2}M_{\rm pl}}\right)^2 \frac{\lambda^6 m_d^2 m_s^2 m_b^4}{4m_t^8}\tan^8\beta$$

Proton decay constraints

- Will constrain gravitino mass:

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

- Gravitino mass bound in units of keV



Higher dimensional operators

- For baryon number violation:

$$K^{(5)}_{BNV} = \frac{1}{\Lambda}(Y_u Y_u^\dagger + Y_d Y_d^\dagger) Q Q Y_d^\dagger \bar{d}^\dagger$$

- Subleading as long as $\Lambda > 10^{12}$ GeV

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

- B and L violating Kähler terms: first show up at dimension 6, the dangerous R-parity even

$$Q^3 L,\ \bar{u}\bar{u}\bar{d}\bar{e},\ \text{and}\ \bar{u}\bar{d}\bar{d}\bar{N}$$

are absent