MFV SUSY: A Natural Alternative to R-parity

Ben Heidenreich

with Csaba Csáki and Yuval Grossman

Cornell University, LEPP

Hidden SUSY Workshop, Weds., Nov. 9th, 2011

arXiv:1111.1239

The many problems of the MSSM

How to make the MSSM phenomenologically acceptable?

- Proton decay? $\longrightarrow$ R-parity

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

- FCNCs? $\longrightarrow$ flavor universality
- LHC results? $\longrightarrow$ heavy squarks. . . ?

Heavy stop leads to fine tuning of Higgs mass

JR: The MSSM is on the edge of being fine-tuned

A different approach

Minimal flavor violation (MFV) can solve all these problems

- FCNCs $\checkmark$
- Proton decay? $\checkmark$ (Even without R-parity)*
- LHC results? Violate R-parity!
  - LSP decays promptly
  - No missing energy / displaced vertices
  - Squarks can be light

Replace several assumptions with a single one: “MFV SUSY”

*Nikolodakis & Smith, ’07

Minimal Flavor Violation

Impose a spurious $\mathrm{SU}(3)^5$ symmetry.

	$\mathrm{SU}(3)_Q$	$\mathrm{SU}(3)_u$	$\mathrm{SU}(3)_d$	$\mathrm{SU}(3)_L$	$\mathrm{SU}(3)_e$
Q	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\bar{u}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\bar{d}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$
L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$
$\bar{e}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$
H_u	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
H_d	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
Y_u	$\square$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
Y_d	$\square$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$
Y_e	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\overline{\square}$

$$W_{\mathrm{MSSM}} = \mu H_u H_d + Y_u Q \bar{u} H_u + Y_d Q \bar{d} H_d + Y_e L \bar{e} H_d$$

Minimal Flavor Violation, cont.

- Assume Yukawas are the only spurions breaking $\mathrm{SU}(3)^5$.
- Agnostic about high-scale physics
- RGE stable
- FCNCs suppressed by the GIM mechanism, as in SM
- Don't impose $U(1)^5$ flavor symmetry
    - Not needed to suppress FCNCs
    - Contains R-parity

MFV SUSY Superpotential

- Spurions are holomorphic: $Y^\dagger$ cannot appear in W
- Superpotential built from holomorphic flavor singlets:

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$U(1)_L$	$\mathbb{Z}_2^R$
(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 lepton number violation!

Proton Stability

- Proton decay requires LNV (if no light unflavored fermions)
- Lepton number preserved by W
- $\mathbb{Z}_3^{(L)} = \mathrm{U}(1)_L \cap [\mathrm{SU}(3)_L \times \mathrm{SU}(3)_e]$ an exact symmetry
- $|\Delta L| = 3$ operators first at dim. eight in Kähler potential
  - Cutoff suppression more than sufficient
  - Proton very long lived
- Story will change for $m_\nu \neq 0$

Baryon number violation

A single RPV coupling allowed:

$$W_{\mathrm{BNV}} = \frac{1}{2} w'' \varepsilon_{ijk}\, \varepsilon^{abc} (Y_u \bar{u})^i_a (Y_d \bar{d})^j_b (Y_d \bar{d})^k_c$$

where w'' an $\mathcal{O}(1)$ parameter.

$$\lambda''_{ijk} = w'' \varepsilon_{lmn} \, [Y_u]^l_i \, [Y_d]^m_j \, [Y_d]^n_k = w'' y^{(u)}_i y^{(d)}_j y^{(d)}_k \epsilon_{jkl} V^\star_{il}$$

$$Y_u = \frac{1}{v_u} V^\dagger_{CKM} \, \mathrm{diag}(m_u, m_c, m_t) \quad , \quad Y_d = \frac{1}{v_d} \mathrm{diag}(m_d, m_s, m_b) \quad , \quad Y_e = \frac{1}{v_d} \mathrm{diag}(m_e, m_\mu, m_\tau)$$

The λ''_{ijk} coupling

$$\lambda''_{usb} \sim t_\beta^2 \frac{m_b m_s m_u}{m_t^3}\,, \quad \lambda''_{ubd} \sim \lambda t_\beta^2 \frac{m_b m_d m_u}{m_t^3}\,, \quad \lambda''_{uds} \sim \lambda^3 t_\beta^2 \frac{m_d m_s m_u}{2\,m_t^3}\,,$$
$$\lambda''_{csb} \sim \lambda t_\beta^2 \frac{m_b m_c m_s}{m_t^3}\,, \quad \lambda''_{cbd} \sim t_\beta^2 \frac{m_b m_c m_d}{m_t^3}\,, \quad \lambda''_{cds} \sim \lambda^2 t_\beta^2 \frac{m_c m_d m_s}{m_t^3}\,,$$
$$\lambda''_{tsb} \sim \lambda^3 t_\beta^2 \frac{m_b m_s}{m_t^2}\,, \quad \lambda''_{tbd} \sim \lambda^2 t_\beta^2 \frac{m_b m_d}{m_t^2}\,, \quad \lambda''_{tds} \sim t_\beta^2 \frac{m_d m_s}{m_t^2}\,.$$

where $m_t \sim v \sim \sqrt{v_u^2 + v_d^2}, \quad \langle H_{u,d} \rangle = v_{u,d}, \quad w'' \sim 1$

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3/2 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \quad , \quad \lambda \sim \frac{1}{5}$$

Numerical estimate

$\lambda''_{ijk} \sim$

	$s\,b$	$b\,d$	$d\,s$
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}

for $\tan\beta = 45$, using

$$m_u \sim 3 \text{ MeV} \quad , \quad m_c \sim 1.3 \text{ GeV} \quad , \quad m_t \sim 173 \text{ GeV} \sim v \quad ,$$
$$m_d \sim 6 \text{ MeV} \quad , \quad m_s \sim 100 \text{ MeV} \quad , \quad m_b \sim 4 \text{ GeV} \; .$$

Flavor changing

- BNV constrained by $|\Delta B| = 2$ processes
- λ''_{tsb} the biggest, $\mathcal{O}(10^{-4})$, all 2[nd]/3[rd] gen. (s)quarks
- Not the whole story: flavor-changing suppressed

Soft masses:

$$\mathcal{L}_{\text{soft}} \supset m^2_{\text{soft}}\, \tilde{Q}^\star \left[1 + \alpha (Y_u Y_u^\dagger)^T + \beta (Y_d Y_d^\dagger)^T + \ldots\right] \tilde{Q} + \ldots$$

Mass mixing:

$$V_{ij}^{(\text{neutral})} \equiv \frac{\delta m^2_{ij}}{m^2_{\text{soft}}} \sim \sum_k V^\dagger_{ik} \left[y_k^{(u)}\right]^2 V_{kj} \qquad \text{(down-type)}$$

Flavor changing, cont.

Estimate:

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

Also suppressed:

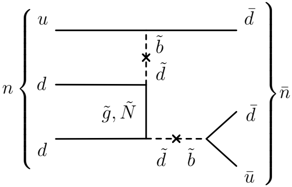
- Charged flavor changing $\longrightarrow$ CKM suppression
- Left-right mixing $\longrightarrow$ Yukawa suppression

Constraints on baryon number violation

- Baryon number violation suppressed by
  - $\mathcal{O}(10^{-4})$ vertex factor
  - Yukawa and CKM suppression for flavor changing
- Proton stable because LNV very small
- Limits on $|\Delta B| = 2$ processes:

$$\left.\begin{aligned} \tau_{n-\bar{n}} &\geq 2.44 \times 10^{8}\ \mathrm{s} \\ \tau_{pp\to K^+K^+} &\geq 1.7 \times 10^{32}\ \mathrm{yrs} \end{aligned}\right\} \text{Super-K data}$$

$n - \bar{n}$ oscillations

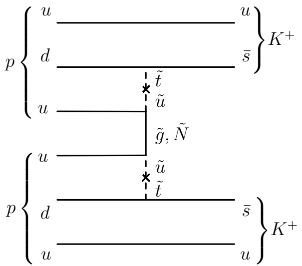


$$\mathcal{M}_{n-\bar{n}} \sim \tilde{\Lambda}\, t_\beta^6\, \lambda^8\, \frac{m_u^2 m_d^2 m_b^4}{m_t^8} \left(\frac{\tilde{\Lambda}}{m_{\tilde{q}}}\right)^4 \left[g_s^2 \left(\frac{\tilde{\Lambda}}{m_{\tilde{g}}}\right) + \ldots\right]$$

$$t_{\rm osc} \sim \mathcal{M}^{-1} \sim (9 \times 10^9\ \mathrm{s}) \left(\frac{250\ \mathrm{MeV}}{\tilde{\Lambda}}\right)^6 \left(\frac{m_{\tilde{q},\tilde{g}}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{45}{\tan\beta}\right)^6$$

No constraint!

Dinucleon decay



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

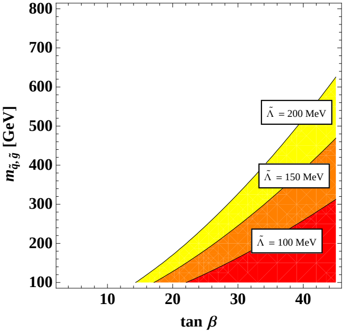
cf. Goity and Sher

Best guess: $\tilde{\Lambda} \sim 150$ GeV

A nontrivial constraint

Using $\rho_N \sim 0.25\ \mathrm{fm}^{-3}$ and $\alpha_s \sim 0.12$, get

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



The story so far. . .

- Moderate constraint from dinucleon decay
- $n - \bar{n}$ oscillations slow enough
- Proton effectively stable
- What about neutrino masses?

Dirac masses don't change anything:

$$W_{\text{lept}} = Y_e L \bar{e} H_d + Y_N L \bar{N} H_u$$

Y_N leaves $\mathbb{Z}_3^L$ unbroken

The seesaw mechanism

- $W_{\text{lept}} = Y_e L \bar{e} H_d + Y_N L \bar{N} H_u + \frac{1}{2} M_N \bar{N} \bar{N}$
- Spurious flavor symmetry now $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_e \times \mathrm{SU}(3)_N$

	$\mathrm{SU}(3)_L$	$\mathrm{SU}(3)_e$	$\mathrm{SU}(3)_N$
L	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$
$\bar{e}$	$\mathbf{1}$	$\square$	$\mathbf{1}$
$\bar{N}$	$\mathbf{1}$	$\mathbf{1}$	$\square$
Y_e	$\square$	$\overline{\square}$	$\mathbf{1}$
Y_N	$\square$	$\mathbf{1}$	$\overline{\square}$
M_N	$\mathbf{1}$	$\mathbf{1}$	$\overline{\square\square}$

- Now M_N breaks $\mathbb{Z}_3^L$, $|\Delta L| = 1$ possible
- Use dimensionless spurion $\frac{1}{\Lambda_R} M_N$, $\Lambda_R \gtrsim M_N$ heavy scale

Lepton number violation

Renormalizable LNV terms:

- $W_{\text{LNV}} = \frac{1}{2\Lambda_R} w' \, (LL) \left(\tilde{Y}_N M_N \tilde{Y}_N\right) (Y_e \bar{e}) \qquad (\tilde{Y}_N = \text{cof}\, Y_N = (\det Y_N)\, Y_N^{-1})$
- Kähler correction: $K_{\text{LNV}} = \mathcal{V} L^\dagger H_d + c.c.$

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

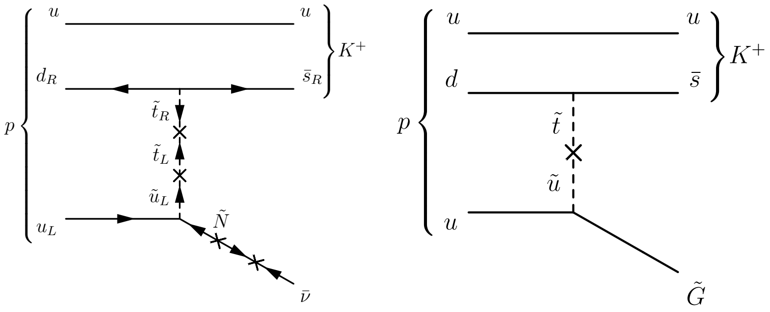
- $\mathcal{L}_{\text{soft}}^{\text{LNV}} = m_{\text{soft}}^2 \mathcal{V} \tilde{L}^\star \tilde{H}_d + c.c. + \text{A term}$
- After EWSB
  - Sneutrino VEV: $\langle \tilde{L}_a \rangle \sim -v_d \mathcal{V}_a$
  - Gaugino/lepton mixing: $\mathcal{L}_{\text{mix}} \sim -v_d \lambda (\mathcal{V}^\dagger L)$

Lepton number violation, cont.

- Casas & Ibarra: $Y_N^T = \frac{1}{v_u}\,\mathrm{diag}\left(\sqrt{M_{Ri}}\right)\,R\,\mathrm{diag}\left(\sqrt{m_{\nu i}}\right)\,U_{\mathrm{PMNS}}^\dagger$
  - U_{PMNS} non-hierarchical
  - R and M_{Ri} not constrained by expt
  - Neutrino mass scale unknown
- For simplicity, take $M_{Ri} \sim M_R$, $R \sim \mathcal{O}(1)$, $m_{\nu i} \sim m_\nu \sim 0.1\ \mathrm{eV}$
  $\rightarrow Y_N \sim \frac{\sqrt{m_\nu M_R}}{v_u}$
- $\mathcal{V}_i^{(1)} \sim \frac{M_R^{\frac{5}{2}}\, m_\nu^{\frac{3}{2}}}{\Lambda_R\, v_u^3}$, $\mathcal{V}_{e,\mu}^{(2)} \sim \frac{M_R^2\, m_\nu}{\Lambda_R\, v_u^2}\, y_\tau^2$, $\mathcal{V}_\tau^{(2)} \sim \frac{M_R^2\, m_\nu}{\Lambda_R\, v_u^2}\, y_\mu^2$
  $(\mathcal{V} = \mathcal{V}^{(1)} + \mathcal{V}^{(2)})$
- $\lambda_{ijk} \sim y_k^{(e)}\, Y_N\, \mathcal{V}^{(1)}$ $\longrightarrow$ subdominant

Proton decay

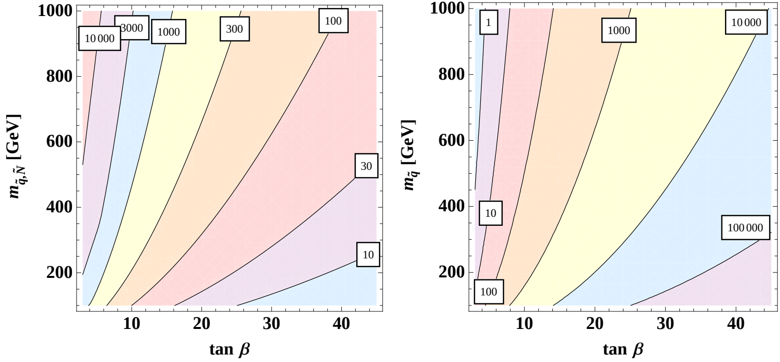
- $p \to K^+ \bar{\nu}$ $\qquad$ $p \to K^+ \tilde{G} \quad (m_{\tilde{G}} \lesssim 450 \text{ MeV})$



- $\tau_{p \to K^+ \nu} \gtrsim 2.3 \times 10^{33}$ yrs $\qquad$ (Super K)
- Matrix element $\tilde{\Lambda}^2 \sim (250 \text{ MeV})^2$ $\qquad$ (Lattice QCD)

Constraints from proton decay

- Bound on LNV: $\mathcal{V} \tan^3\beta \lesssim (3\times 10^{-14}) \left(\frac{m_{\tilde{q}}}{100\ \text{GeV}}\right)^2 \left(\frac{m_{\tilde{N}}}{100\ \text{GeV}}\right)$
- Upper bound on M_R in 10^6 GeV: Lower bound on $m_{3/2}$ in KeV:

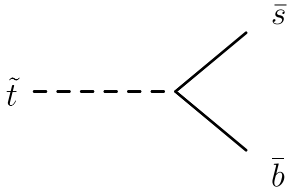


(For $\Lambda_R = 10^{16}$ GeV)

The LSP

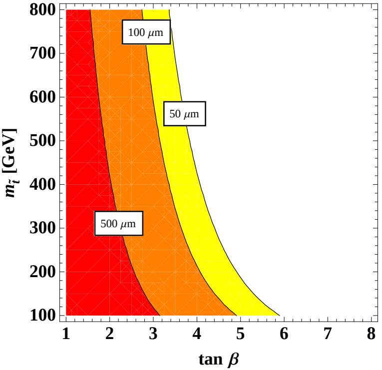
- LHC pheno will depend on LSP
- LSP not stable: can be charged, colored!
- Up-type squarks: $M^2_{\tilde{U}} = m^2_{\text{soft}} \begin{pmatrix} 1 + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger & \delta\, Y_u \\ \delta^\star\, Y_u^\dagger & 1 + \gamma Y_u^\dagger Y_u \end{pmatrix} + \ldots$
- Down-type: $M^2_{\tilde{D}} = m^2_{\text{soft}} \begin{pmatrix} 1 + \alpha' Y_u Y_u^\dagger + \beta' Y_d Y_d^\dagger & \delta'\, Y_d \\ \delta'^\star\, Y_d^\dagger & 1 + \gamma' Y_d^\dagger Y_d \end{pmatrix} + \ldots$
- One stop naturally light; $\tilde{b}_L$ also possible LSP
- stau LSP $\longrightarrow$ nearly degenerate spectrum
- Neutralino, chargino, gluino also possible LSPs

Stop LSP



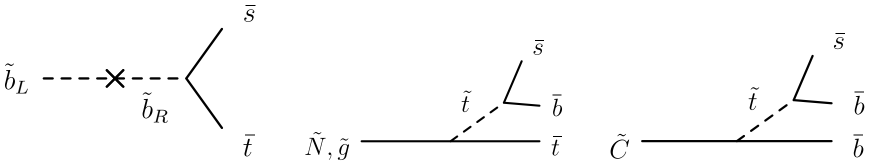
$$c\tau_{\tilde{t}} \sim (2\ \mu\text{m}) \left(\frac{10}{\tan\beta}\right)^4 \left(\frac{300\ \text{GeV}}{m_{\tilde{t}}}\right) \left(\frac{1}{2\sin^2\theta_{\tilde{t}}}\right)$$

$$90\%\ b+s,\ 8\%\ b+d,\ 2\%\ d+s$$



- Generically prompt (no $\not{E}_T$, no displaced vertices)
- No tops / leptons in final state. . . more b-jets, resonance?

Other LSPs



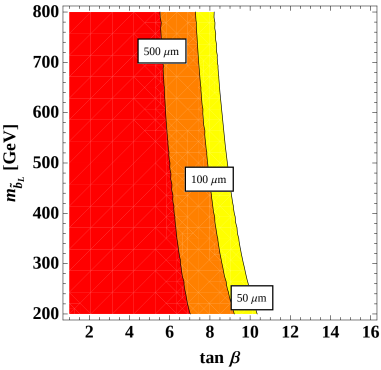
- Sbottom decay y_b suppressed
- Neutralino/chargino: 3-body decay, $\sim \frac{1}{16\pi^2}$ suppressed

$$\tau_{\tilde{b}_L} \sim (41\ \mu\text{m}) \left(\frac{10}{\tan\beta}\right)^6 \left(\frac{300\ \text{GeV}}{m_{\tilde{b}_L}}\right) \quad , \quad \tau_{\tilde{N}} \sim (12\ \mu\text{m}) \left(\frac{20}{\tan\beta}\right)^4 \left(\frac{300\ \text{GeV}}{m_{\tilde{N}}}\right)$$

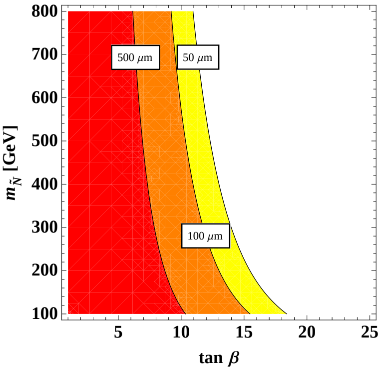
- $\tilde{b}_L$, $\tilde{N}$: final-state tops, $\tilde{C}$: many b-jets

Lifetimes

$\tilde{b}_L$ LSP:

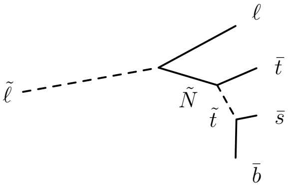


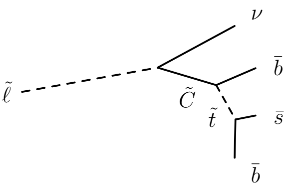
$\tilde{N}, \tilde{C}$ LSP:



Displaced vertices can be avoided!

Stau LSP





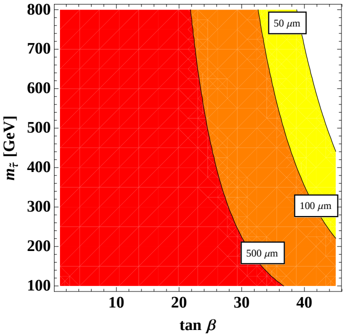
Four-body decay $\to \left(\frac{1}{16\pi^2}\right)^2$

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

Displaced vertices!

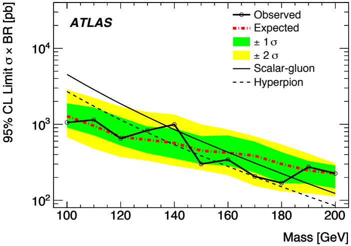
Missing $\not{E}_T$! (neutrinos)

final state leptons/tops



RPV searches

- Many searches look for $\lambda' L Q \bar{d} \longrightarrow$ irrelevant!
- Searches for $\lambda'' \bar{u}\bar{d}\bar{d}$:
  - CMS/CDF: look for 3-jet resonance $\longrightarrow m_{\tilde{g}} \gtrsim 280$ GeV*
  - ATLAS: look for colored-scalar in 4-jet events:

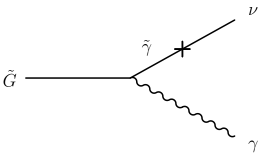


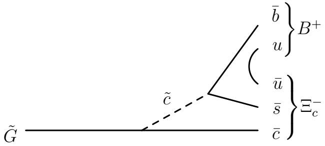
(arXiv:1110.2693)

*Analysis assumes gluino LSP

Dark matter?

- SM LSP short-lived... not dark matter
- Gravitino could be true LSP





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

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

- Generically long-lived $\longrightarrow$ DM candidate
- Relic abundance depends on thermal history

Conclusions

A different approach to low-scale SUSY

- MFV instead of R-parity
- Many fewer parameters than generic RPV $\longrightarrow$ predictive
- LNV strongly suppressed; proton stable
- Weak bound on $\tan\beta$ from dinucleon decay
- Stop LSP decays promptly, no $\not{E}_T$, no displaced vertices
  $\longrightarrow$ hard to detect
- Other LSPs have interesting phenomenology

Future Directions

- Detailed collider studies for different LSPs
- LHC searches
- Better understanding of dinucleon decay matrix elements
- Baryogenesis from BNV coupling?
- Gravitino dark matter?
- Model building: UV completions of MFV SUSY