Natural Models of R-parity violation

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Based on work with

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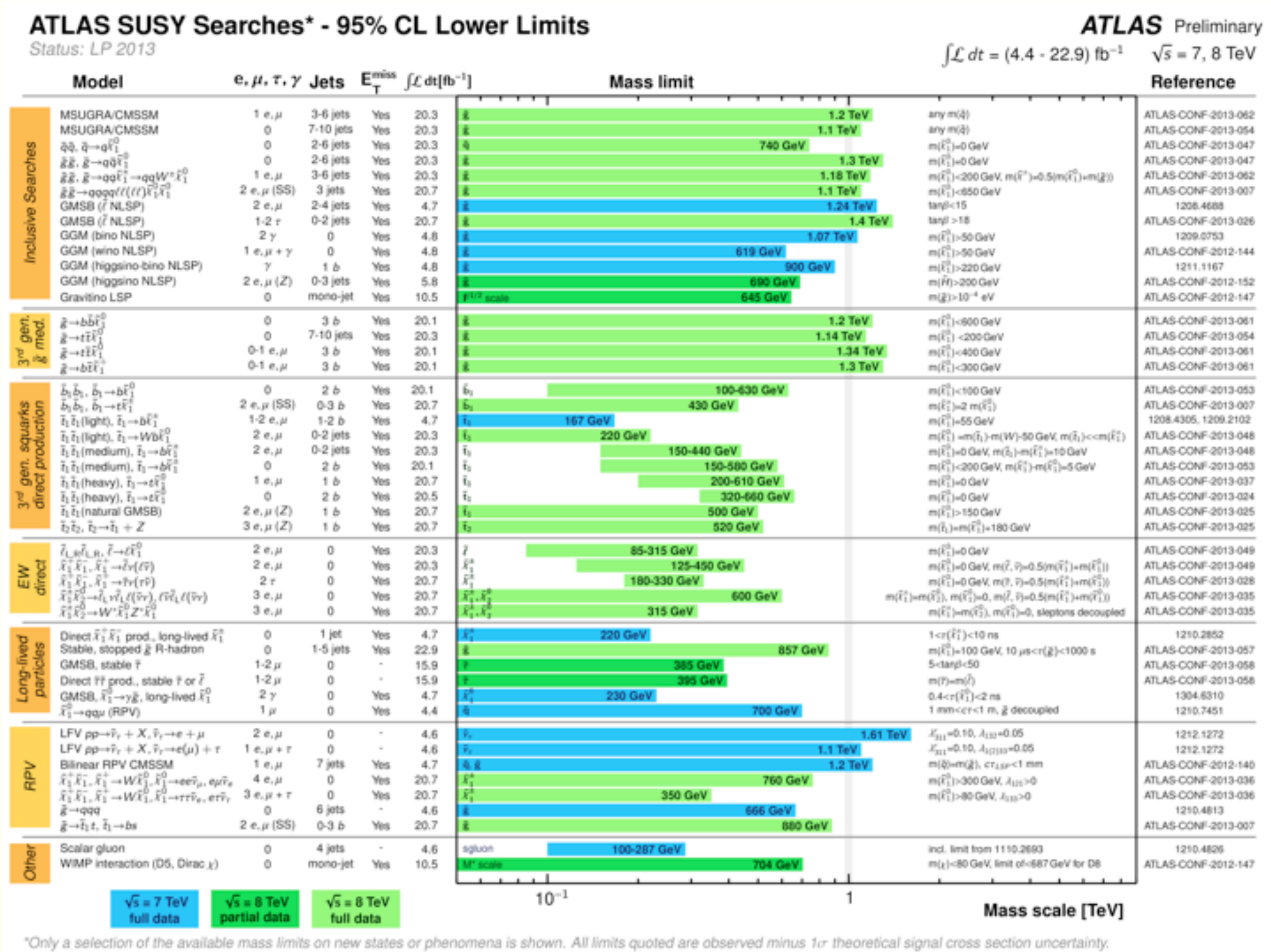
to appear soon

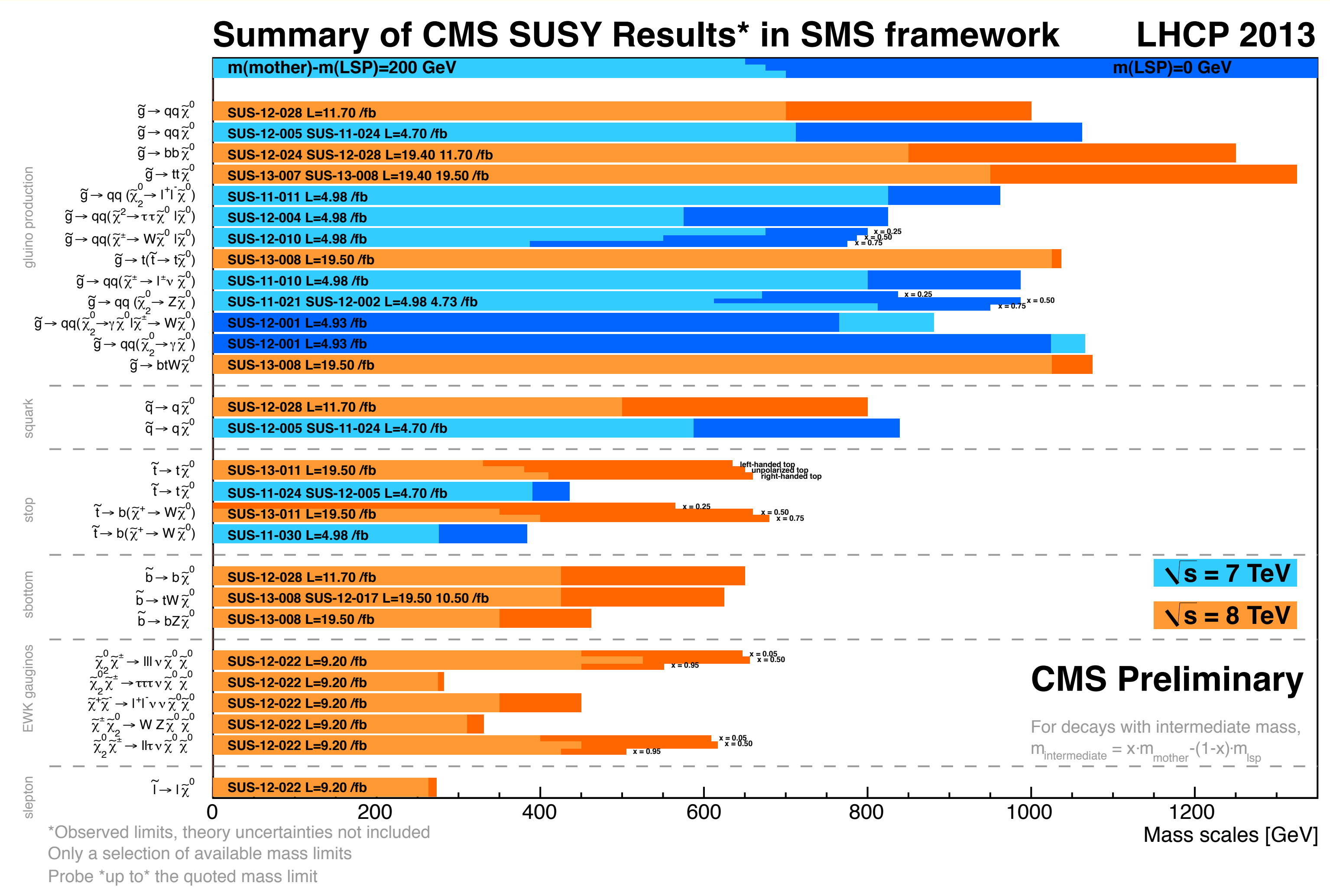
No sign of superpartners as of today from LHC



ATLAS SUSY bounds from May 2013

Most involve missing ET, stable charged particle, or LFV

No sign of superpartners as of today from LHC



CMS SUSY bounds from May 2013 LHCP Conference

Most involve missing ET, stable charged particle, or LFV

- Bounds usually assume large MET, and/or leptons
- Bounds often assume almost degenerate squarks/gluino

Ways out

1. No MET due to RPV - focus of this talk

2. Spectrum not that degenerate - ``Natural SUSY" can be achieved via compositeness

3. Spectrum more degenerate/decays stealthy

4. Production more suppressed than in MSSM, eg. R-symmetric SUSY with Dirac gaugino masses

RPV in 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...

RPV in SUSY

•Show two scenarios where RPV automatically suppressed

1. RPV related to Yukawa couplings. Use existing small couplings. Very simple and predictive frameworks possible.

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

2. RPV broken in hidden sector only. RPV operators automatically suppressed by F/M^2 . Operators can come from Kähler potential - not even catalogued till now!

(C.C., Kuflik, Volansky '13)

RPV from Flavor: MFV SUSY

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

•Usual MSSM assumptions:

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

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

•Original observation:

``Matter parity"

$$(Q, \bar{u}, \bar{d}, L, \bar{e}) \to -(Q, \bar{u}, \bar{d}, L, \bar{e})$$

is a symmetry of wanted terms, but not of RPV terms

Usually impose this.

RPV from Flavor: MFV SUSY

•Our simple observation:

RPV terms are also not invariant under SU(3)^5 flavor symmetries

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

•If not too many sources of flavor violation survive at low-energies: could expect that RPV related to Yukawas

•Simplest (though not unique) assumption: only source for flavor breaking are Yukawas (MFV assumption)

•Of course in any theory of flavor this idea can be pushed through even if not MFV, results very similar

MFV SUSY

- Our proposal: the MFV assumption is sufficient to to solve BOTH flavor AND B,L problems of SUSY

- 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

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

•More similar to SM story where B,L accidental symmetry

•RPV operators related to Yukawa couplings

•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)

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

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

$$(Y_u\bar{u})(Y_d\bar{d})(Y_d\bar{d})$$

MFV SUSY

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

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

- 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:

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

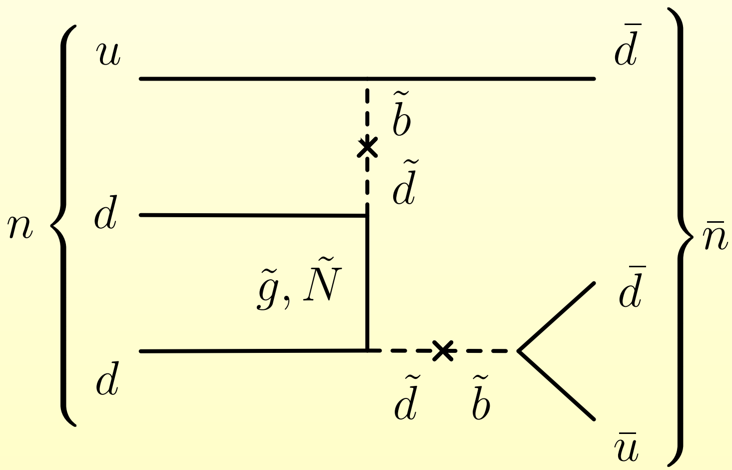
- dinucleon decay $pp \to K^+K^+$

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

- 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:

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

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

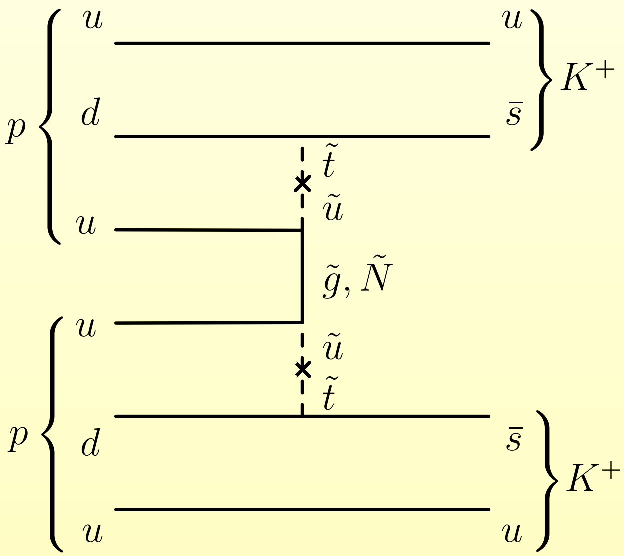
- Comment: to estimate the magnitude of off-diagonal squark mass insertions (for LH squarks):

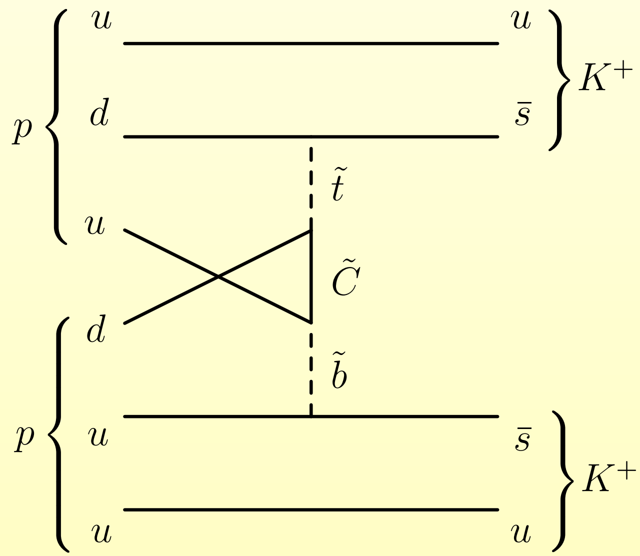
$$V_{ij}^{\rm (neutral)} \equiv \frac{\delta m_{ij}^2}{m_{\rm soft}^2} \sim \sum_k V_{ik}^\dagger \left[y_k^{(u)}\right]^2 V_{kj}$$

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

Dinucleon decay

- Leading diagrams:





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

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

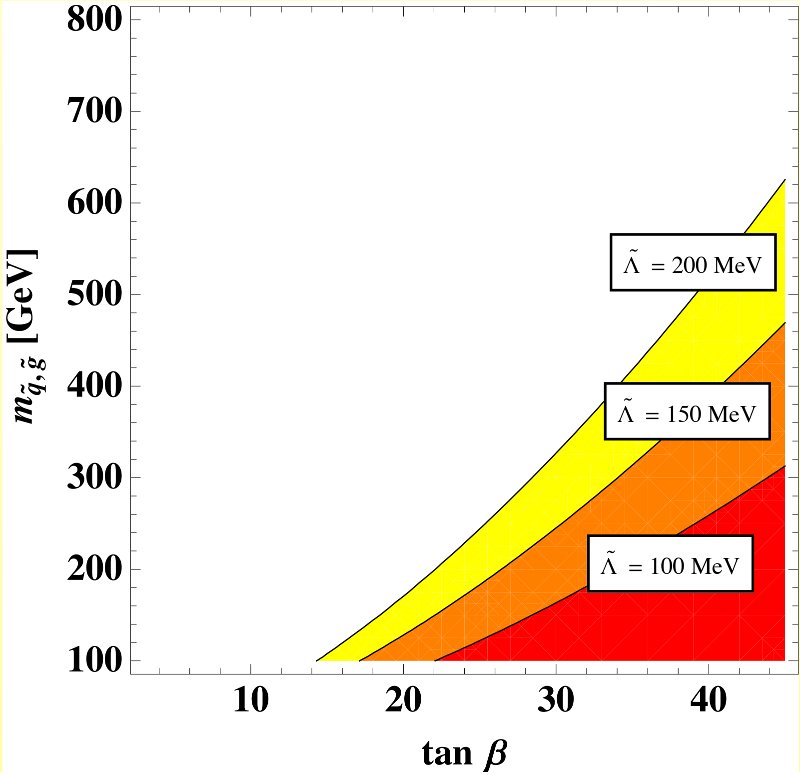
Dinucleon decay

- 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

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



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

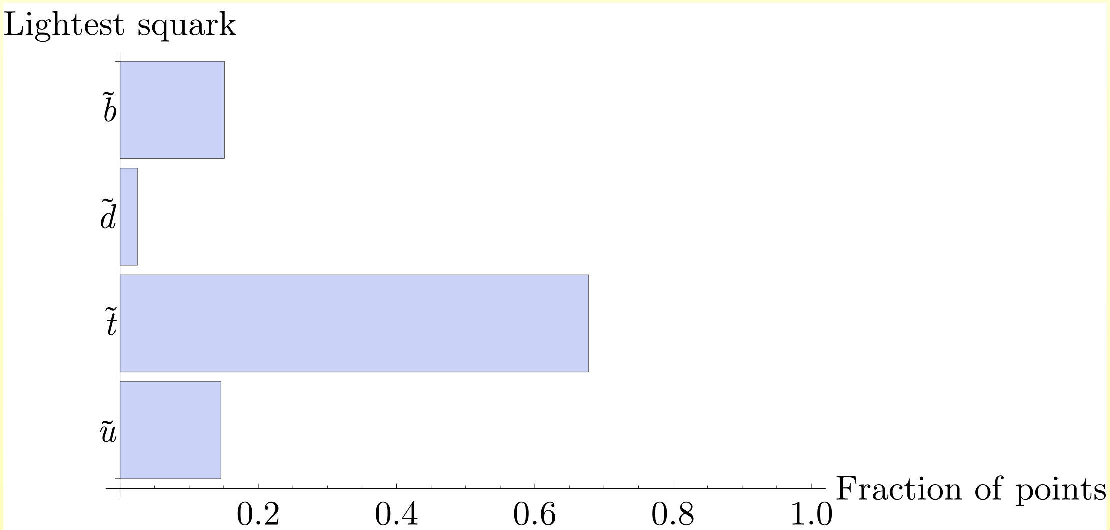
$$M^2_{\tilde{u}} = \begin{pmatrix} m^2_{\tilde{q}}\mathbb{1} + a_q Y_u Y_u^\dagger + b_q Y_d Y_d^\dagger + D_{u_L} & A_u Y_u \\ A_u^* Y_u^\dagger & m^2_{\tilde{u}}\mathbb{1} + a_u Y_u^\dagger Y_u + D_{u_R} \end{pmatrix}$$

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

LHC phenomenology

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

- Distribution of LSP: tan β=10, m_{soft}=1TeV, m_{stop}<500 GeV

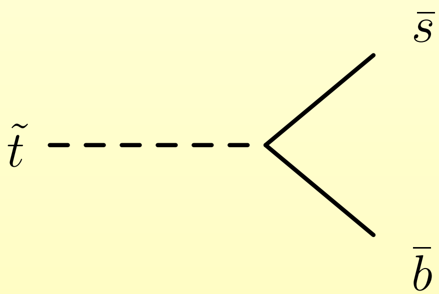


- In squark sector most likely stop, or sbottom about 20%

LHC phenomenology

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

•Stop can decay directly via RPV vertex:



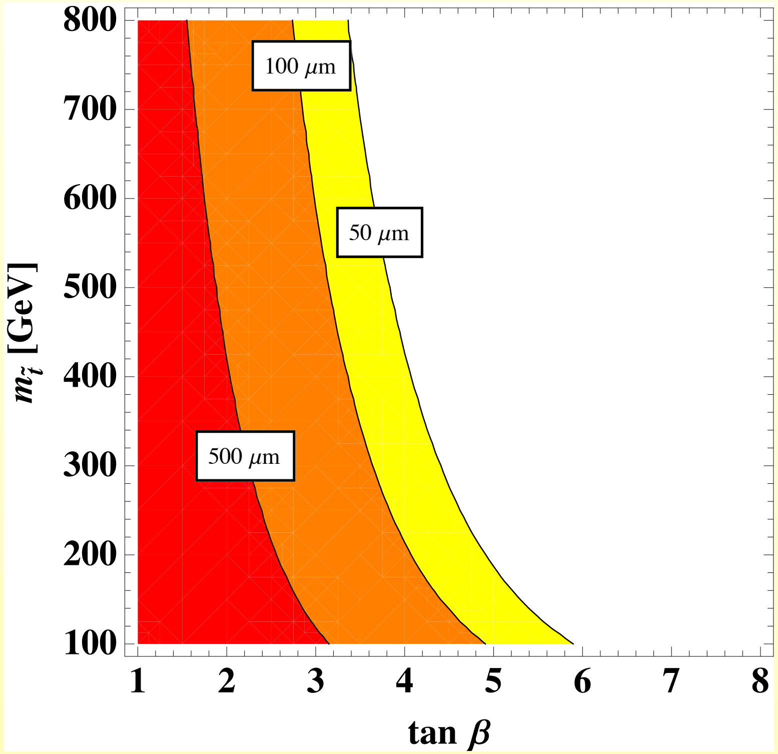
•Lifetime:

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

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

LHC phenomenology

- Stop decay length:

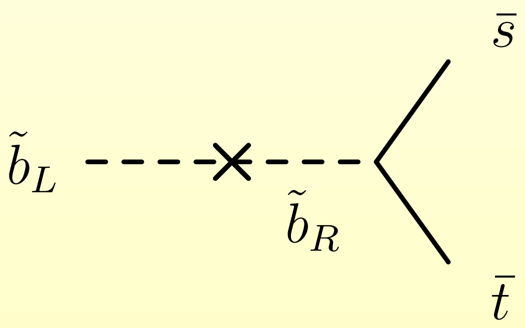


- No displaced vertices in most of parameter space

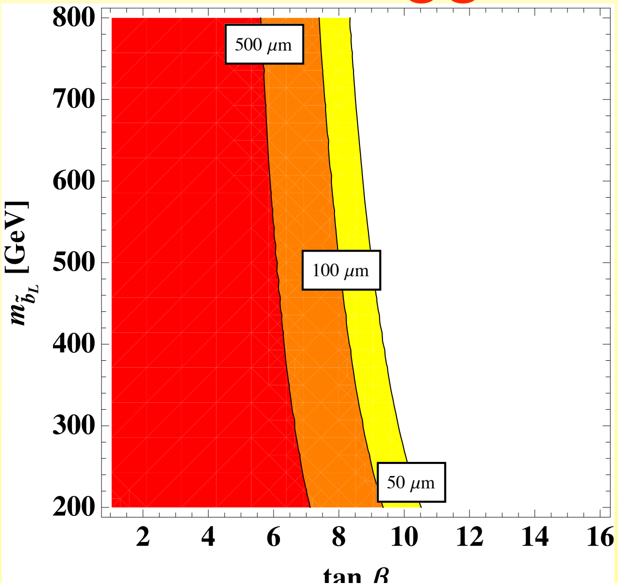
$$\tau_{\tilde{t}} \sim (2\ \mu\mathrm{m}) \left(\frac{10}{\tan\beta}\right)^4 \left(\frac{300\ \mathrm{GeV}}{m_{\tilde{t}}}\right) \left(\frac{1}{2\sin^2\theta_{\tilde{t}}}\right)$$

LHC phenomenology

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

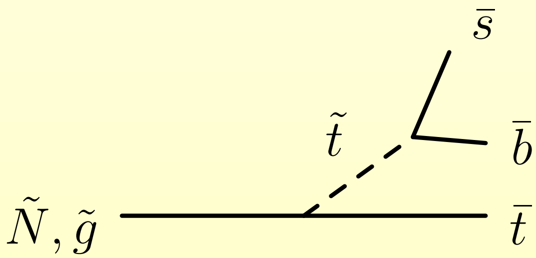


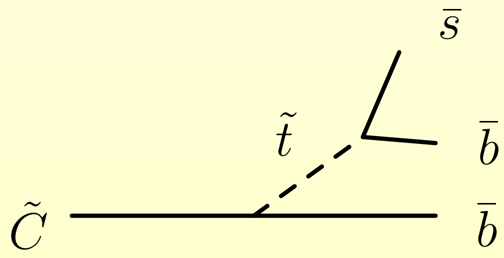
- Get tops in final state and bit bigger region for displaced vertex



LHC phenomenology

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



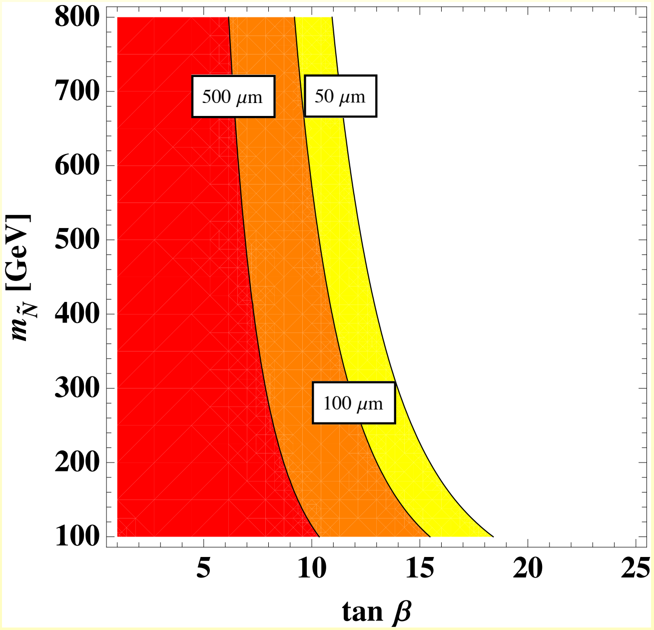


- Get tops in final state for neutralino and yet bigger region for displaced vertex (gluino would be similar)

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

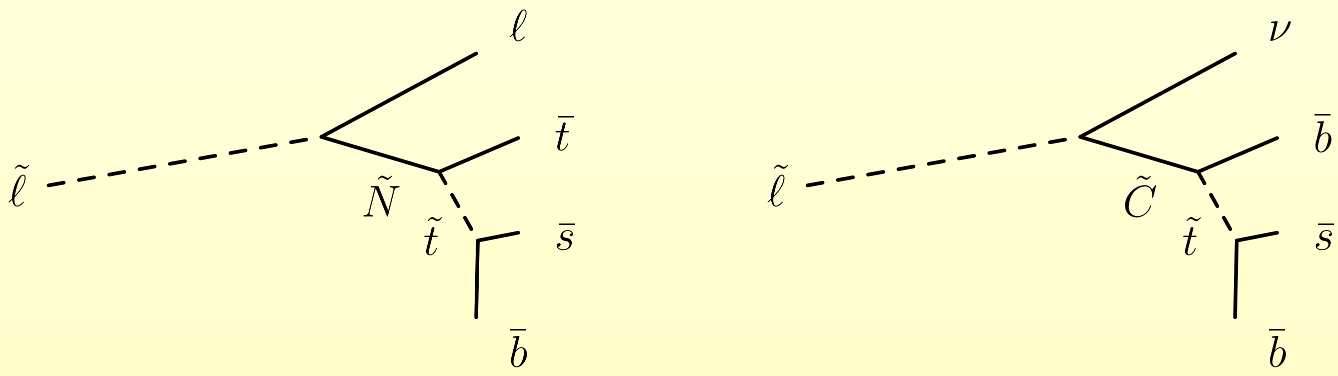
LHC phenomenology

- The neutralino LSP decay length



LHC phenomenology

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

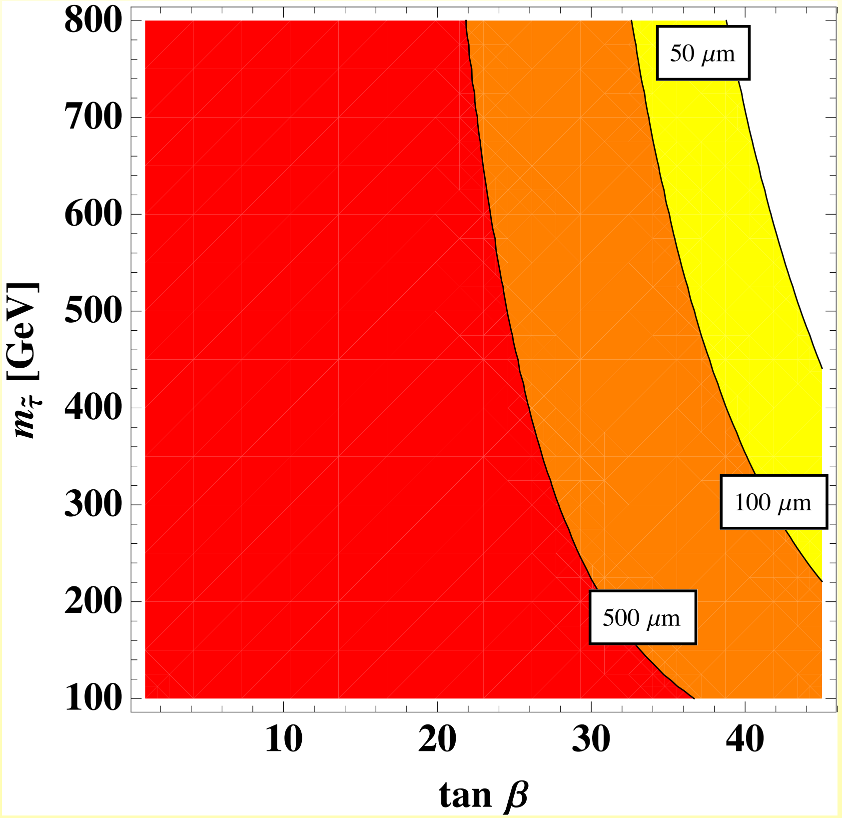


- 4-body decay, almost certainly displaced vertex, some have tops some missing energy. This should be easier.

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

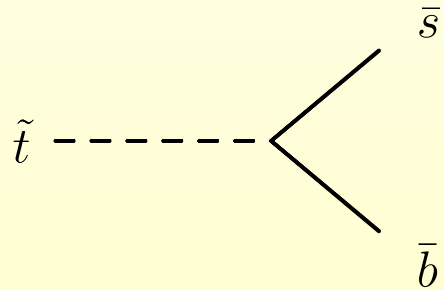
LHC phenomenology

- Stau decay length:



Existing searches

•For stop LSP: dijet resonance search

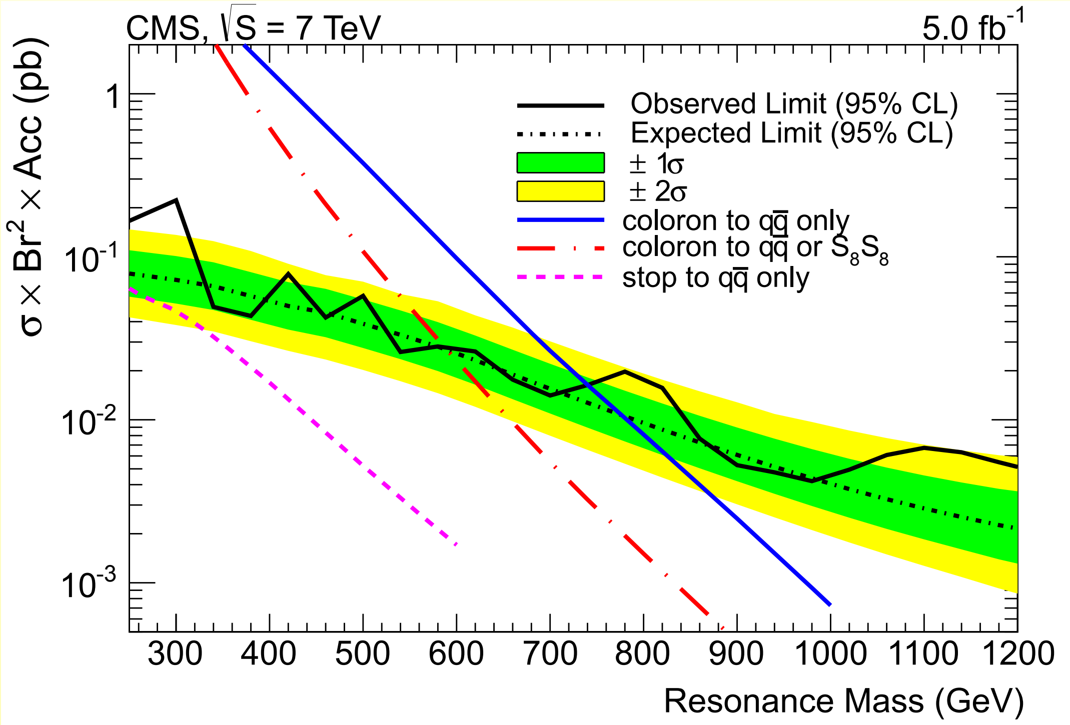


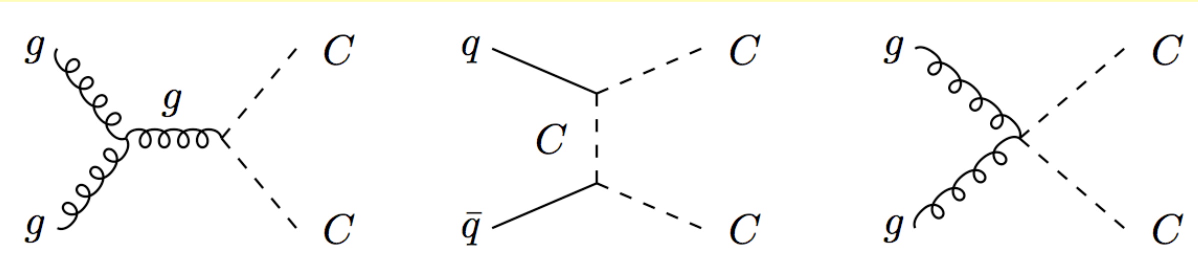
•However stop production cross section quite low, m_{stop}= 200 GeV it is about 200 fb at the Tevatron and 10 pb at the 7 TeV LHC.

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

Existing searches

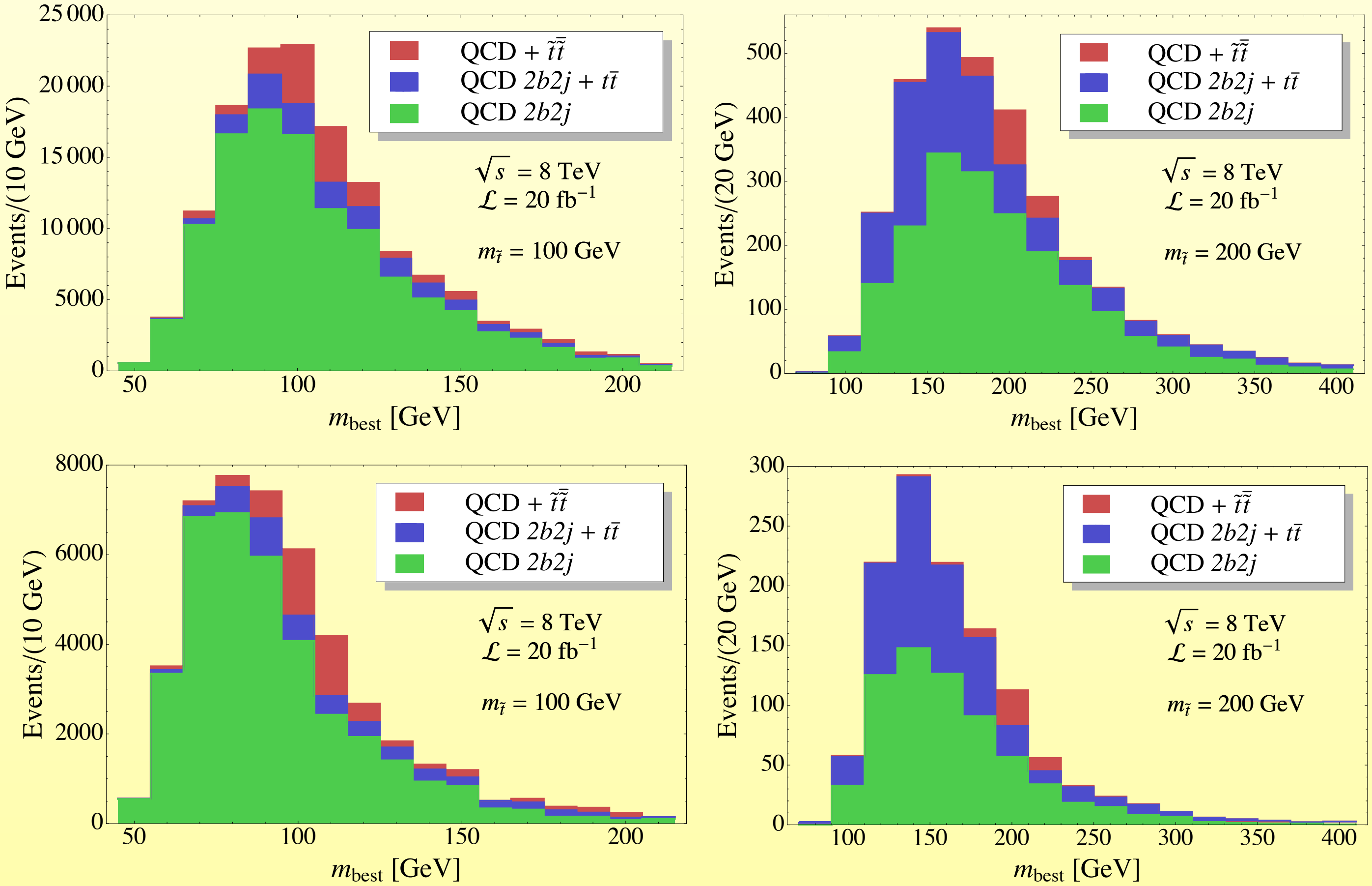
•CMS: paired dijet resonance search (their motivation was colorons...)





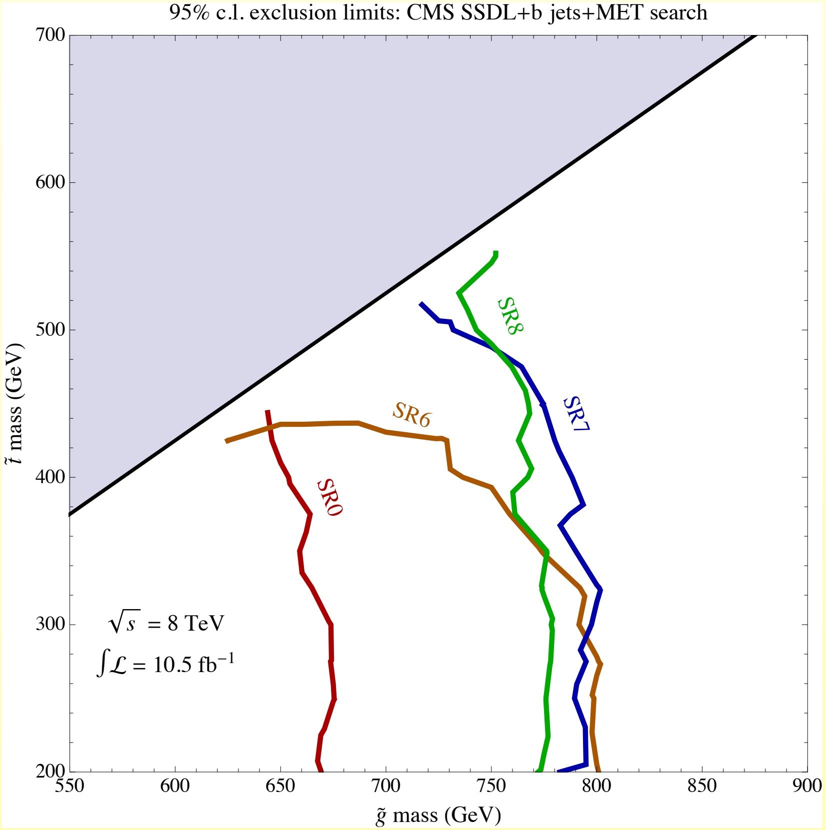
Refined paired dijet for low mass region?

- A recent analysis based on dijet+b-tagging: (Franceschini+Torre ’12)



Existing searches

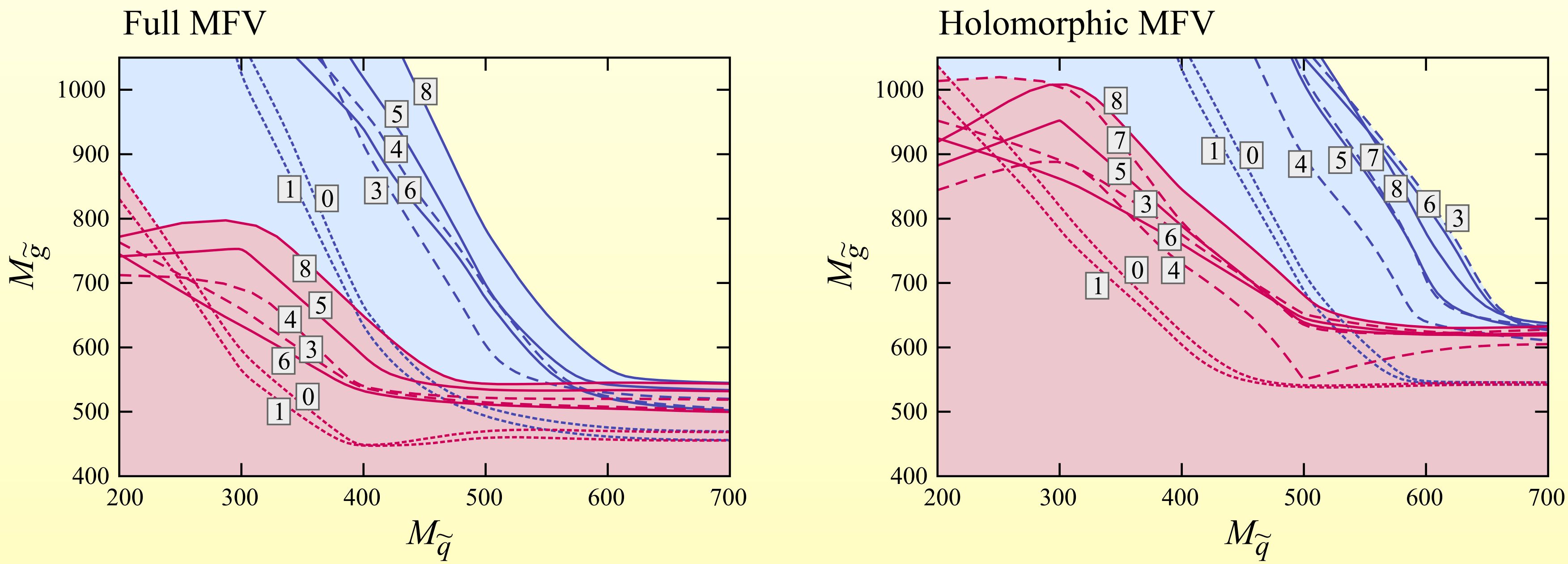
- Same sign dilepton via gluino production (Berger, Perelstein, Saelim, Tanedo)



- m_{gluino}> 800 GeV, squarks could still be ~ 300 GeV

Same-sign dilepton

- A very recent detailed analysis (Durieux+Smith)



- Here $M_{\tilde{q}}$ are first two generation squark masses.

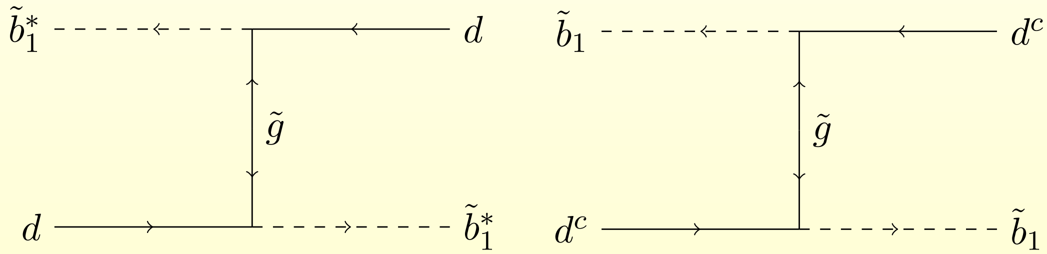
- Case of light stop: $M_{\tilde{q}} \to \infty$

- Bound in this case: $M_{\tilde{g}} \geq 630\ \mathrm{GeV}$

Same sign tops

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

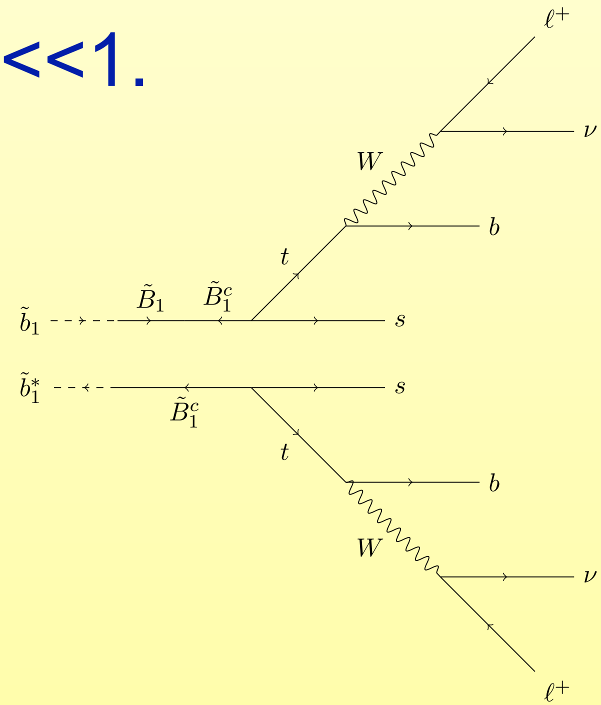
- Mesino oscillation



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

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

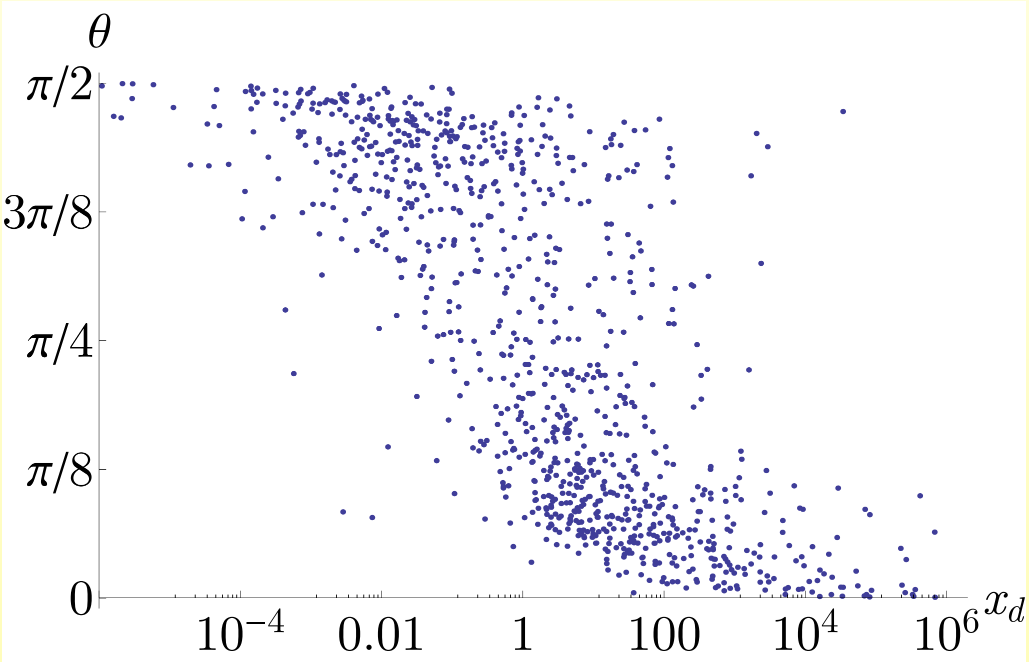
- If sbottom LSP expect same sign tops



Same sign tops

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

- The distribution of the sbottom mesino oscillation times



m_{soft}=500 GeV

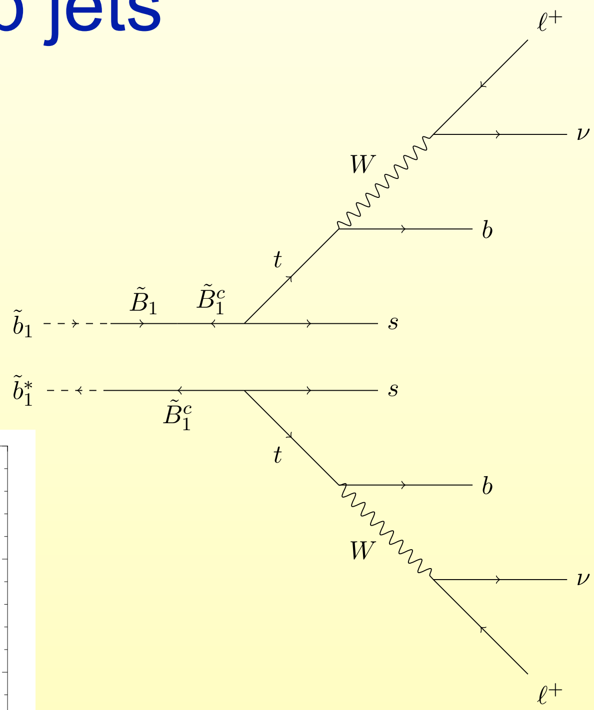
- Large fraction has x>1, especially for LH sbottom LSP's

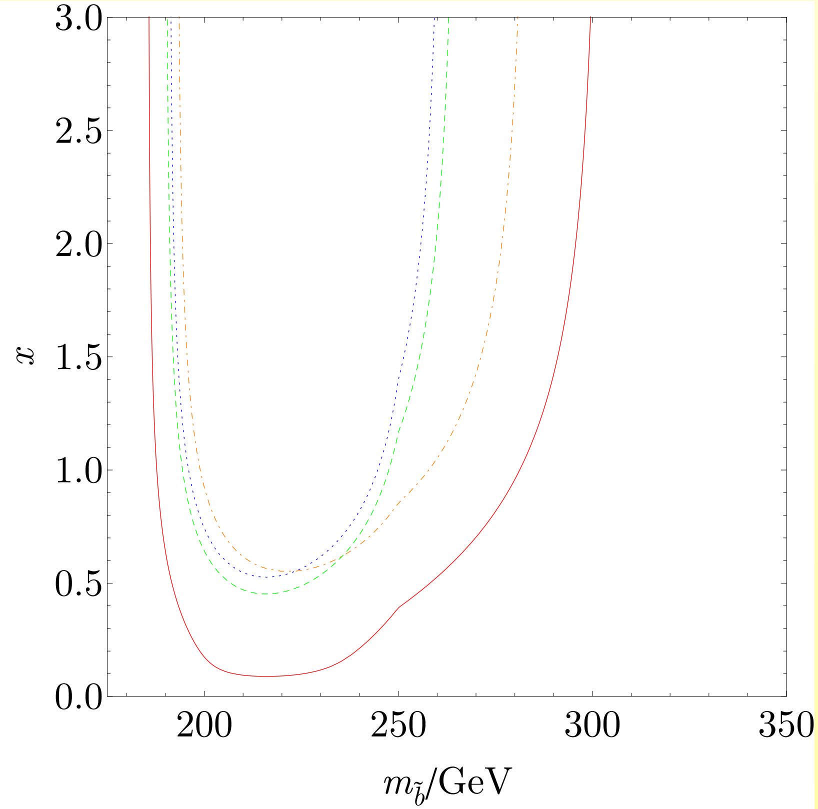
Same sign tops

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

- Get same sign leptons, MET + b jets

- Bounds on sbottom mass by translating CMS bounds same sign dileptons + b jets + MET

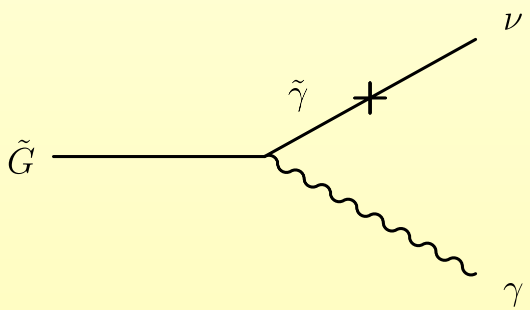


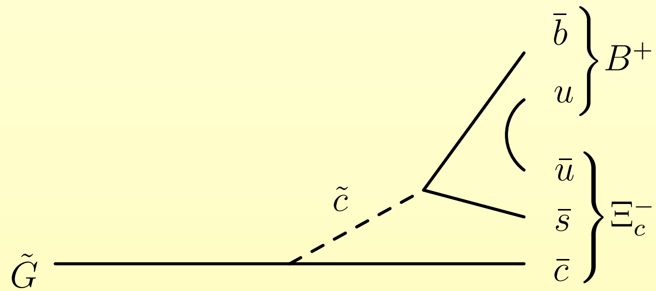


Dark matter?

- 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

UV completion

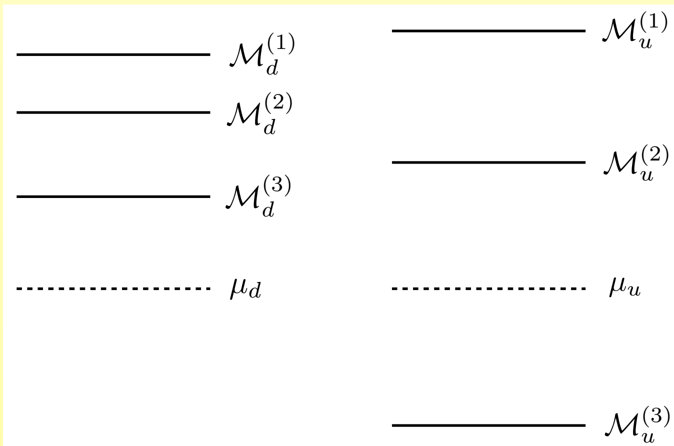
(C.C., Heidenreich '13, see also Krnjaic & Stolarsky; Franceschini & Mohapatra)

- To find UV completion need to give a theory of flavor

- Mixing via heavy RH fermions

$$W = \lambda_u q \bar{U} H_u + \lambda_d q \bar{D} H_d + \frac{1}{2}\lambda_{\rm bnv} \bar{U}\bar{D}\bar{D} + U \mathcal{M}_u \bar{U} + D \mathcal{M}_d \bar{D} + U \mu_u \bar{u} + D \mu_d \bar{d}\,,$$

- Effective Yukawa $Y_x = \lambda_x \Upsilon_x \left(\mathbf{1} + \Upsilon_x^\dagger \Upsilon_x\right)^{-1/2}\,, \quad \Upsilon_x \equiv -\mathcal{M}_x^{-1}\mu_x\,,$



UV completion (C.C., Heidenreich)

- A complete model based on gauged SU(3) flavor plus discrete R-symmetry

	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$U(1)_Y$	$\mathrm{SU}(3)_F$	$\mathbb{Z}_{11}[\omega_{11}^{-2}]$
q	$\square$	$\square$	$1/6$	$\square$	ω_{11}^3
$\bar{u}$	$\bar{\square}$	$\mathbf{1}$	$-2/3$	$\square$	ω_{11}^4
$\bar{d}$	$\bar{\square}$	$\mathbf{1}$	$1/3$	$\square$	ω_{11}^5
ℓ	$\mathbf{1}$	$\square$	$-1/2$	$\square$	ω_{11}^4
$\bar{e}$	$\mathbf{1}$	$\mathbf{1}$	1	$\square$	1
$\bar{U}$	$\bar{\square}$	$\mathbf{1}$	$-2/3$	$\bar{\square}$	ω_{11}^3
$\bar{D}$	$\bar{\square}$	$\mathbf{1}$	$1/3$	$\bar{\square}$	ω_{11}^3
$\bar{E}$	$\mathbf{1}$	$\mathbf{1}$	1	$\bar{\square}$	ω_{11}^2
U	$\square$	$\mathbf{1}$	$2/3$	$\bar{\square}$	ω_{11}
D	$\square$	$\mathbf{1}$	$-1/3$	$\bar{\square}$	ω_{11}^5
E	$\mathbf{1}$	$\mathbf{1}$	-1	$\bar{\square}$	ω_{11}^4
$\bar{N}$	$\mathbf{1}$	$\mathbf{1}$	0	$\bar{\square}$	ω_{11}^2
H_u	$\mathbf{1}$	$\square$	$1/2$	1	ω_{11}^3
H_d	$\mathbf{1}$	$\square$	$-1/2$	1	ω_{11}^3
S	$\mathbf{1}$	$\mathbf{1}$	0	1	ω_{11}^3

	$\mathrm{SU}(3)_F$	$\mathbb{Z}_{11}[\omega_{11}^{-2}]$
$\Phi_{u,n}$	$\square\square$	ω_{11}^5
Φ_d	$\square\square$	ω_{11}
Φ_e	$\square\square$	ω_{11}^3
$\bar{\Phi}_{u,n}$	$\overline{\square\square}$	ω_{11}^4
$\bar{\Phi}_d$	$\overline{\square\square}$	ω_{11}^8
$\bar{\Phi}_e$	$\overline{\square\square}$	ω_{11}^6
ϕ_u	1	ω_{11}^4
ϕ_d	1	ω_{11}^{-1}
ϕ_e	1	ω_{11}^5

$$
\begin{aligned}
W \;=\; & \lambda_u q\bar{U}H_u + \lambda_d q\bar{D}H_d + \lambda_n \ell\bar{N}H_u + \lambda_e \ell\bar{E}H_d + \lambda_b \bar{U}\bar{D}\bar{D} + \lambda_h S H_u H_d + \lambda_s S^3 \\
& + \Phi_u U\bar{U} + \Phi_d D\bar{D} + \Phi_e E\bar{E} + \Phi_n \bar{N}^2 + \phi_u U\bar{u} + \phi_d D\bar{d} + \phi_e E\bar{e}
\end{aligned}
$$

The mass scales (C.C., Heidenreich)

$\Lambda \sim 10^{19}$ GeV

$\langle \Phi \rangle \sim M_{FBG} \sim 10^6$ TeV

$\mu_d \sim 100$ TeV

$\mu_u \sim 1 - 10$ TeV $\sim m_{U,\bar{U}}$

$m_{soft} \sim 300$ GeV

UV completion (C.C., Heidenreich)

• With these scales the dangerous higher dimensional operators sufficiently small

•Dim 5: $$W^{(5)}_{\rm LNV} = \frac{1}{\Lambda}\bar{\Phi}_d \bar{N} D \bar{d} + \frac{1}{\Lambda}\phi_d \bar{N} D \bar{D} + \frac{1}{\Lambda}\phi_d \bar{U} D \bar{E} + \frac{1}{\Lambda} S \bar{N} U \bar{U} + \frac{1}{\Lambda} S \bar{N}^3$$

•Dim 6: $$W^{(6)}_{\rm LNV} = \frac{1}{\Lambda^2}\bar{N}\bar{\Phi}_e \bar{\Phi}_u^3 + \frac{1}{\Lambda^2}\bar{N}\bar{\Phi}_u \Phi_d^3 + \dots$$

•May help EWSB via S-tadpole of the right size (~300 GeV):

$$W^{(5)}_{\rm EW} = \frac{1}{\Lambda} S \phi_d \Phi_d \bar{\Phi}_e + \frac{1}{\Lambda} S \phi_d \Phi_e \bar{\Phi}_u$$

Dynamical RPV (C.C., Kuflik, Volansky, to appear)

•Idea: RP conserved in visible sector

•Only broken in hidden sector where SUSY is broken. Same dynamics could be responsible for SUSY breaking and RPV!

•RPV operators may naturally appear in Kähler potential and may or may not be present in superpotential

•Often $W_{RPV} = \lambda L L \bar{e} + \lambda' Q L \bar{d} + \lambda'' \bar{u} \bar{d} \bar{d} + \mu' L H_u$
NOT leading source for RPV!

Dynamical RPV (C.C., Kuflik, Volansky, to appear)

•Assumptions:

1. Dynamical RPV: RPV is broken dynamically in hidden sector

2. RPV is related to SUSY breaking: novel non-holomorphic operators may show up in the Kähler pot:

$$\mathcal{O}_{\rm nhRPV} = \eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}_k^\dagger + \eta'_{ijk}Q_i\bar{u}_jL_k^\dagger + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}_k^\dagger$$

with $$K_{\rm dRPV} = \frac{1}{X^\dagger}\mathcal{O}_{\rm nhRPV}$$

where X is SUSY and RP breaking spurion

$$X = M + \theta^2 F_X$$

Dynamical RPV

(C.C., Kuflik, Volansky, to appear)

•Assumptions:

1. Dynamical RPV
2. RPV is related to SUSY breaking

3. Dynamical solution to SM flavor hierarchy. Use flavor mediation to generate additional hierarchies in the RPV terms.

A Frogatt-Nielsen type gauged U(1) could be responsible for most of gauge mediation (=flavor mediation), which will generate the hierarchies in the RPV terms.

Holomorphic or non-holomorphic?

- Which operator will dominate?

$$\mathcal{O}_{\rm hRPV} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k + \frac{1}{2}\lambda''_{ijk}\bar{u}_i\bar{d}_j\bar{d}_k$$

$$\mathcal{O}_{\rm nhRPV} = \eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}^\dagger_k + \eta'_{ijk}Q_i\bar{u}_jL^\dagger_k + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}^\dagger_k$$

- Depends on dynamics, often non-holo will!

- E.g. assume B-L conserved in visible sector, broken by spurion X $X = M + \theta^2 F_X$

- If X has B-L charge -1:

$$K_{\rm dRPV} = \frac{1}{X^\dagger}\mathcal{O}_{\rm nhRPV} + \frac{X^\dagger}{M^2_{\rm Pl}}O_{\rm hRPV} + h.c.$$

$$W_{\rm dRPV} = \frac{X}{M^2_{\rm Pl}}\kappa_{ijk}H_dQ_iQ_jQ_k\,.$$

Holomorphic or non-holomorphic?

- In this case non-holomorphic dominates

- For B-L charge +1: $\frac{1}{X^\dagger} O_{hRPV}$ vs. $\frac{1}{X} O_{nhRPV}$

- Naively same order, but for non-holo need F-term from $d^+ \propto m_d$. Likely more suppressed...

- Fractional charge: assuming no fractional powers of fields, only $B\text{-}L_X = 1/n$ can generate RPV terms.

- For n even: $(X/X^\dagger)^n O_{hRPV}/M_{Pl}$ vs. $(X^\dagger/X)^n O_{nhRPV}/M_{Pl}$ equally suppressed

- For n odd: depending on sign of n holo or non-holo will dominate

Flavor structure

- Expectation in a F-N-type model:

$$\eta''_{ijk} \sim \epsilon^{|q_{Q_i}+q_{Q_j}-q_{d_k}|}$$

- q's are F-N charges of the various SM fields

- $\epsilon \sim 0.2$ small flavor parameter

- Will give additional suppression in addition to

$$\epsilon_X \equiv \frac{F_X}{M^2} \sim 10^{-3} - 10^{-5}$$

Low-energy constraints

- Assume non-holomorphic operators dominate

$$K_{\mathrm{dRPV}} = \frac{1}{X^\dagger}\mathcal{O}_{\mathrm{nhRPV}}$$

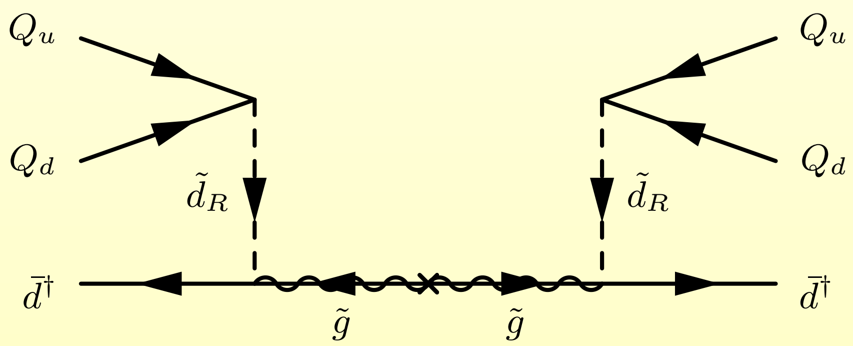
- Will get terms of the form

$$\int d^2\theta \frac{F_X}{M^2}\left(\eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}_k^\dagger + \eta'_{ijk}Q_i\bar{u}_jL_k^\dagger + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}_k^\dagger\right)$$

- Strange SUSY structure (e.g. scalar must come from the operators with dagger...)

Low-energy constraints: ΔB=2

- n-nbar oscillation and dinucleon decay



- Dim 9 operator generated $$\frac{1}{\Lambda_{ijk}^5}(Q_i Q_i Q_j Q_j \bar{d}_k^\dagger \bar{d}_k^\dagger)$$

- Suppression scale: $$\frac{1}{\Lambda_{ijk}^5} = 4\pi\alpha_s \frac{\eta''_{iik}\eta''_{jjk}}{m_{\tilde{g}} m^4_{\tilde{d}._{R,k}}} \epsilon_X^2$$

Low-energy constraints: ΔB=2

- n-nbar oscillation bound:

$$\tau_{n-\bar{n}} \simeq \frac{\Lambda_{111}^5}{2\pi\tilde{\Lambda}_{QCD}^6}$$

$$\tau_{n-\bar{n}} \simeq 3\times 10^8 \text{ s} \left(\frac{m_{\tilde{d}_{R1}}}{\text{TeV}}\right)^4 \left(\frac{m_{\tilde{g}}}{\text{TeV}}\right) \left(\frac{2\cdot 10^{-4}}{\eta''_{111}}\right)^2 \left(\frac{10^{-3}}{\epsilon_X}\right)^2$$

- Dinucleon decay (τ>10^{32} yr):

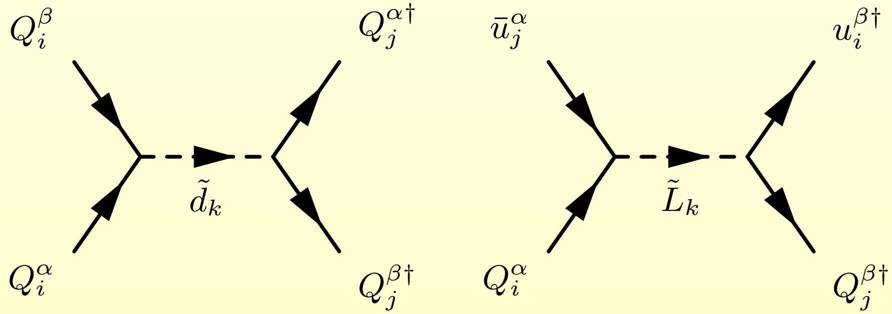
$$pp \to \pi^+\pi^+(K^+K^+)$$

$$\Gamma \simeq \frac{8}{\pi}\frac{\rho_N}{m_N^2}\frac{\tilde{\Lambda}_{QCD}^{10}}{\Lambda_{11k}^{10}}$$

$$\tau_{pp} \simeq 2\times 10^{34} \text{ yr} \left(\frac{m_{\tilde{d}_{R,k}}^8 m_{\tilde{g}}^2}{\text{TeV}^{10}}\right) \left(\frac{2\cdot 10^{-4}}{\eta''_{11k}}\right)^4 \left(\frac{10^{-3}}{\epsilon_X}\right)^4$$

Low-energy constraints: ΔF=2

- FCNC's generated at tree-level:



- Operators generated:

$$\begin{aligned}\mathcal{Q}_1^{q_i q_j} &\equiv -\tfrac{1}{2}(Q_i^\alpha Q_i^\beta)(Q_j^{\alpha\dagger} Q_j^{\beta\dagger})\\ \mathcal{Q}_4^{q_i q_j} &\equiv \bar{u}_j^\alpha Q_i^\alpha Q_j^{\beta\dagger} \bar{u}_i^{\beta\dagger}\end{aligned}$$

- Suppression scales:

$$\frac{1}{\Lambda_{1,ij}^2} = \frac{\eta''_{iik}\eta''^{*}_{jjk}}{m^2_{\tilde{d}_{R,k}}}\epsilon_X^2, \qquad \frac{1}{\Lambda_{4,ij}^2} = \frac{|\eta'_{ijk}|^2}{m^2_{\tilde{\nu}_{L,k}}}\epsilon_X^2$$

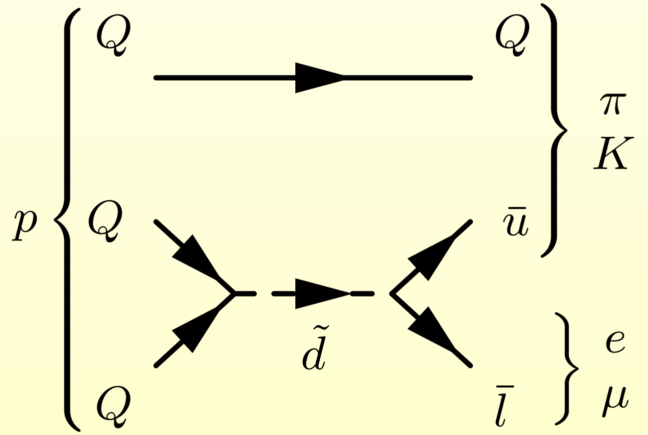
Low-energy constraints: ΔF=2

- Bounds from neutral meson mixings:

$$
\begin{aligned}
\Delta m_K &: \ |\eta''_{11k}\eta''^*_{22k}\epsilon_X^2| \lesssim 10^{-10}, \\
\Delta m_D &: \ |\eta''_{11k}\eta''^*_{22k}\epsilon_X^2| \lesssim 10^{-8}, \qquad |\eta'_{12k}\epsilon_X|^2 \lesssim 10^{-9} \\
\Delta m_{B_d} &: \ |\eta''_{11k}\eta''^*_{33k}\epsilon_X^2| \lesssim 10^{-7}, \\
\Delta m_{B_s} &: \ |\eta''_{23k}\eta''^*_{33k}\epsilon_X^2| \lesssim 10^{-7}.
\end{aligned}
$$

Proton decay to leptons

- If both B and L violated:

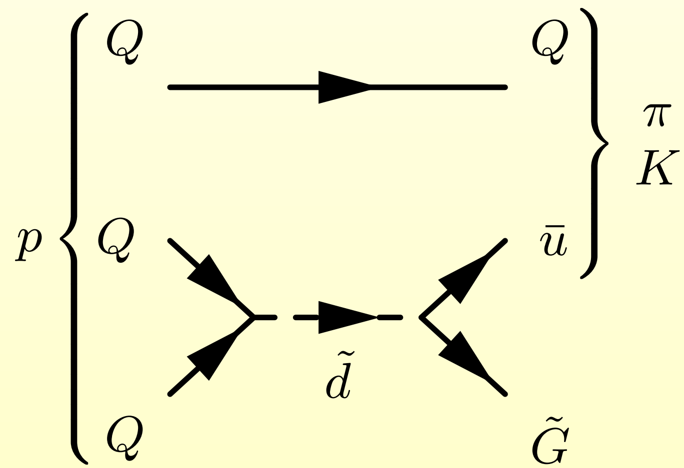


- Lifetime:

$$\tau \simeq 5 \cdot 10^{33} \mathrm{yr} \left(\frac{m_{\tilde{d}_{R\,k}}}{\mathrm{TeV}} \right)^4 \left(\frac{6 \cdot 10^{-19}}{|\eta_{m\ell k} \eta''_{11k}|} \right)^2 \left(\frac{10^{-3}}{\epsilon_X} \right)^4$$

Proton decay to light gravitino

- Don't need L violation



- Lifetime:

$$\tau \sim 5 \cdot 10^{32}\mathrm{yr} \left(\frac{m_{\tilde{d}_i}}{\mathrm{TeV}}\right)^4 \left(\frac{M}{10^5\mathrm{TeV}}\right)^4 \left(\frac{10^{-8}}{|\eta''_{11i}|}\right)^2 \left(\frac{F}{F_X}\right)^2$$

- If F_X the only source of SUSY breaking F drops out from expression, depends only on M and couplings. Can be reduced by F_X<F.

LHC phenomenology

- Again depends crucially on who the LSP is

- E.g. third generation squarks

1. sbottom LSP

Can decay $\tilde{b} \to \bar{t} + \bar{b}$ unusual mode, not there in usual RPV.

$$\tau_{\tilde{b}}^{-1} = \frac{|\eta''_{333}|^2}{8\pi} \epsilon_X^2 m_{\tilde{b}}$$

- These sbottom decays expected to be prompt

LHC phenomenology

2. stop LSP

- More subtle: decay amplitude chirally suppressed

$$\frac{i}{M}(\tilde{Q}_i Q_j + \tilde{Q}_j Q_i)\sigma^\mu \partial_\mu \bar{d}^{\dagger k} \subset \int d^4\theta \frac{1}{X^\dagger} Q_i Q_j \bar{d}^{*k}$$

- Resulting decay: $\tilde{t} \to \bar{b}\bar{b}$ again special to dRPV

- Might be displaced $\Gamma_{\tilde{t}\to\bar{b}\bar{b}} = \frac{|\eta''_{333}|^2}{\pi}\left(\frac{m_b}{M}\right)^2 m_{\tilde{t}_L}$

$$c\tau_{\tilde{t}} \simeq 1 \text{ mm} \left(\frac{300 \text{ GeV}}{m_{\tilde{t}}}\right)\left(\frac{M}{10^8 \text{GeV}}\right)^2 \left(\frac{1}{|\eta''_{333}|}\right)^2$$

Summary

- No hint for SUSY from LHC yet, no MET events, Higgs at 125 GeV problematic for MSSM

- RPV provides a potential way out

- Why is RPV so small?

1. RPV related to Yukawa couplings. If RPV generated by same mechanism as flavor in visible sector, expect relations

$$\lambda'' \propto Y_u Y_d Y_d$$

2. RPV from the hidden sector. Expect couplings suppressed

$$\frac{F}{M^2}\epsilon^{q_i+q_j+q_k}$$

Summary

- Both possibilities can satisfy low-energy constraints

- Both give distinct LHC phenomenology

- MFV: $\tilde{t} \to \bar{b} + \bar{s}$ usually prompt, hard to disentangle from background

- dRPV: different operators in Lagrangian

$$\int d^2\theta \frac{F_X}{M^2}\left(\eta_{ijk}\bar{u}_i\bar{e}_j\bar{d}_k^\dagger + \eta'_{ijk}Q_i\bar{u}_jL_k^\dagger + \frac{1}{2}\eta''_{ijk}Q_iQ_j\bar{d}_k^\dagger\right)$$

Prompt $\tilde{b} \to \bar{t} + \bar{b}$ or chirally suppressed $\tilde{t} \to \bar{b}\bar{b}$

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 $Y_{e,\nu}$ 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:

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

- Possible contributions:

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

- Similar soft breaking masses:

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

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

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

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:

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

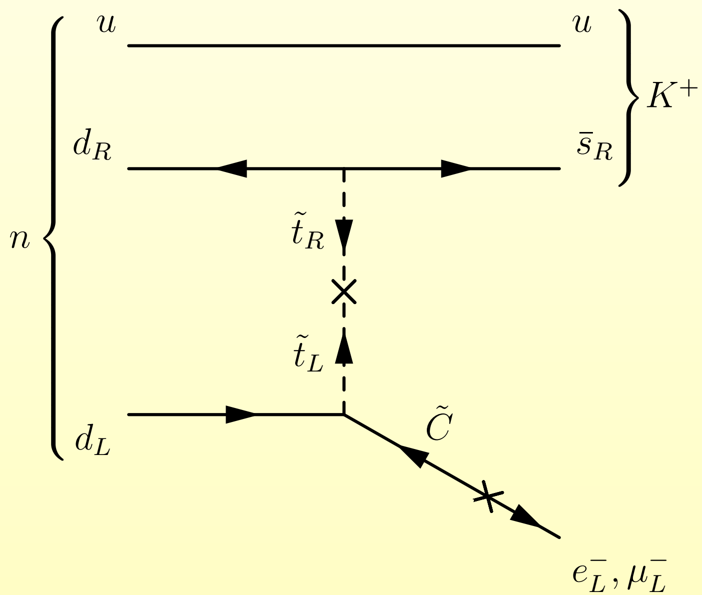
- The latter actually dominate:

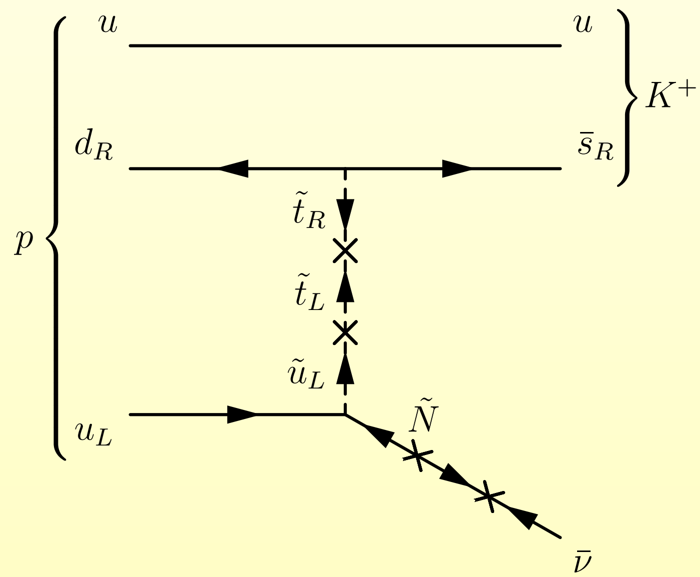
$$\lambda_{ijk} \sim y_k^{(e)} Y_N\, \mathcal{V}^{(1)}$$

- Will neglect superpotential terms

Proton decay constraints

- The leading diagrams:





n→l⁻ K⁺ p→ν K⁺

- Strongest bound from matrix element

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

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:

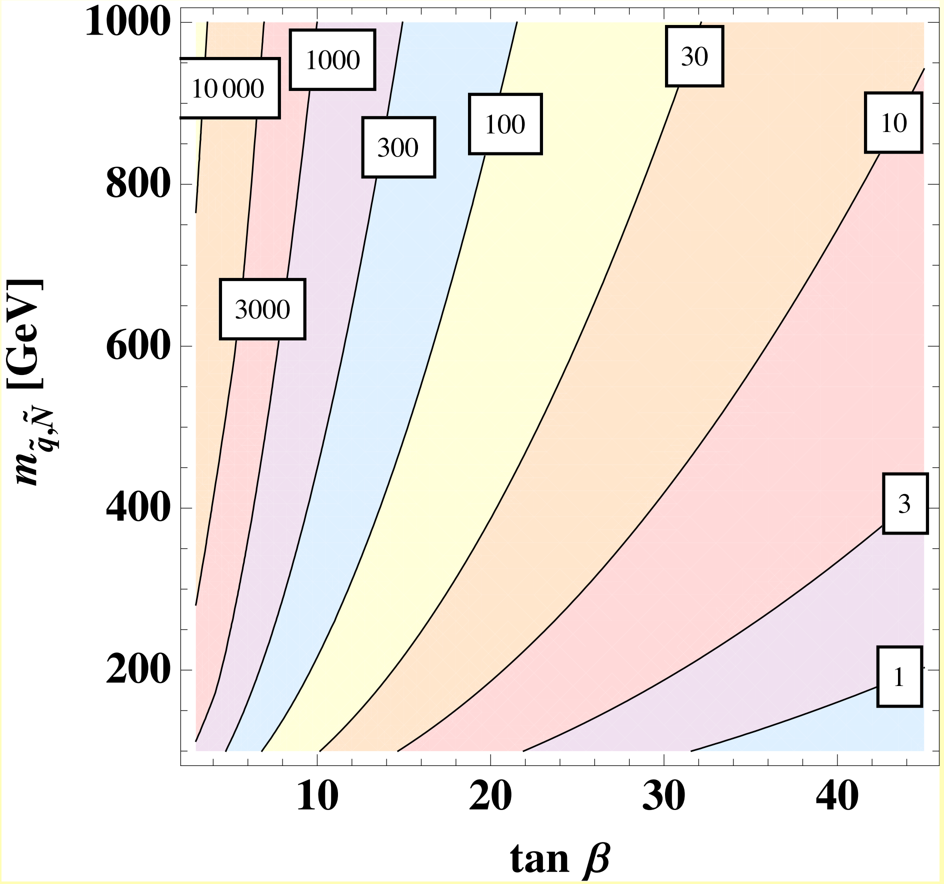
$$\mathcal{V}\tan^4\beta \lesssim (3\times 10^{-14})\left(\frac{m_{\tilde q}}{100\ \text{GeV}}\right)^2\left(\frac{m_{\tilde N}}{100\ \text{GeV}}\right)$$

- 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

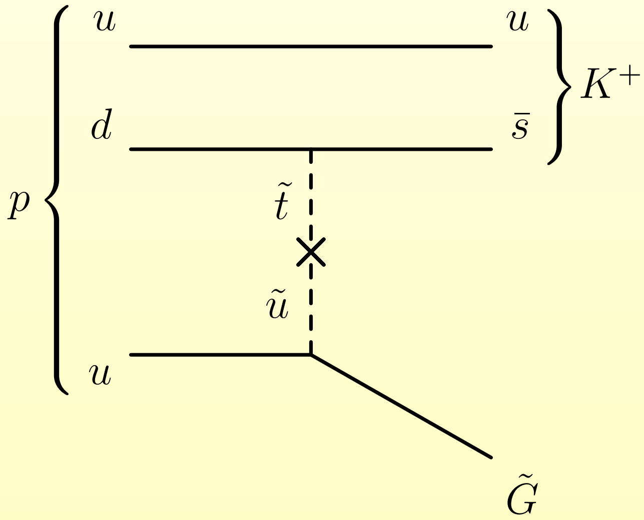
- The bound on M_R in units of 10^6 GeV:



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

Proton decay constraints

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



- Width:

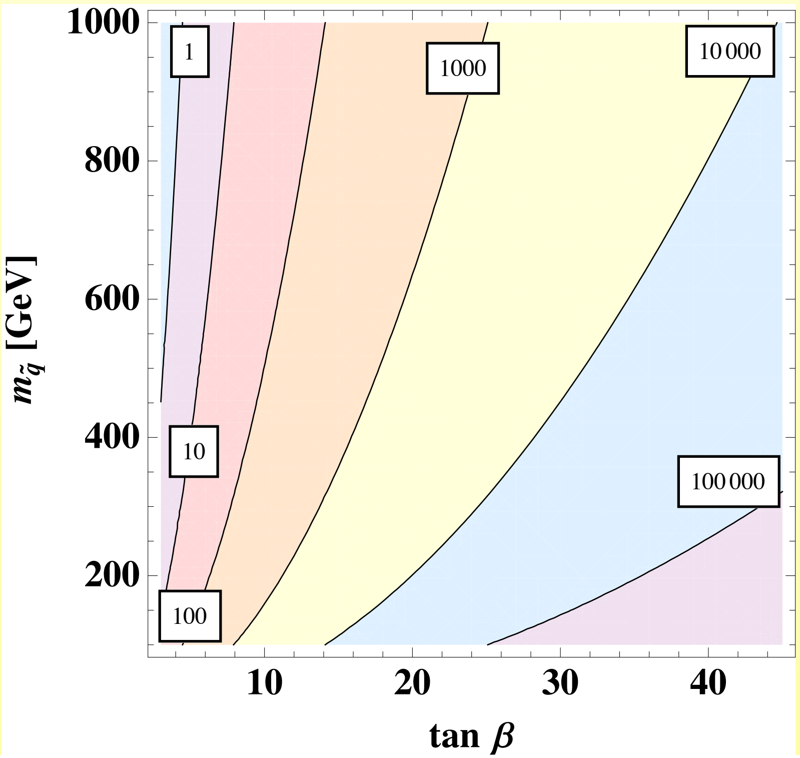
$$\Gamma \sim \frac{m_p}{8\pi}\left(\frac{\tilde{\Lambda}}{m_{\tilde{q}}}\right)^4 \left(\frac{\Lambda^2}{\sqrt{3}m_{3/2}M_{\rm pl}}\right)^2 \frac{\lambda^6 m_d^2 m_s^2 m_b^4}{4m_t^8}\tan^8\beta$$

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 \infty



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)

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