Simultaneous B and L Violation in the MSSM

Bob Zheng

Based on work in preparation arXiv:1405.????
with Cyrus Faroughy (JHU) and Siddharth Prabhu (Yale)

Michigan Center for Theoretical Physics

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Outline

1. "Large" LLE^c, $U^cD^cD^c$ couplings w/o fast proton decay
   Requires antisymmetric flavor structure for LLE^c

2. Collider phenomenology of $LLE^c + U^cD^cD^c$

Overview of RPV SUSY

$$W_{RPV} = \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k + \lambda'_{ijk} Q_i L_j D^c_k + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \kappa_i L_i H_u$$

- In RPV MSSM, collider + DM phenomenology qualitatively different

  c.f. talks by P Saraswat, AK Lehan, K Pedro

  Review by Barbier, Dudas et. al hep-ph/0406039

- $\lambda'' U^c D^c D^c$ violates B, all other couplings violate L.

- Canonical approach: assume only B or L violation to avoid fast proton decay

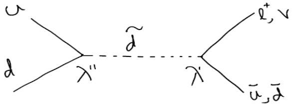
2-Body Proton Decay Constraints

$$W_{RPV} = \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c + \lambda'_{ijk} Q_i L_j D_k^c + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \kappa_i L_i H_u$$

Strongest constraints: $\tau(N \to M\ell^+) \gtrsim 10^{34}$ yrs **Super-K,1203.4030**

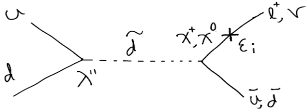
- $\left|\lambda''_{1\,1(2)\,j}\lambda'_{1\,j\,k}\right| \lesssim 10^{-24}\left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^2$

  Hinchliffe and Kaeding, Phys Rev. D47 (1993) 279



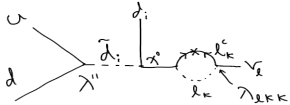
- $\left|\lambda''_{1\,1(2)\,j}\left(\frac{\kappa_i}{\mu}\right)\right| \lesssim 10^{-21}\left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^2$

  Bhattacharya and Pal, hep-ph/9809493



- $\left|\lambda''_{1\,1(2)\,j}\,\lambda_{k\,l\,l}\right| \lesssim 10^{-24}\left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^2$

  Bhattacharya and Pal, hep-ph/9809493



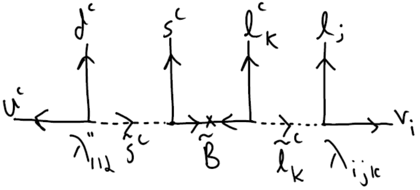
For λ'' couplings to heavy flavors, bounds weaken by $10^6 - 10^{12}$

Smirnov and Vissani, hep-ph/9601387

4-Body Proton Constraints

$|\lambda_{ijk}\,\lambda''_{112}|$, $i \neq j \neq k$ does not induce 2-body proton decay.

Induce 4-body $p \to K^+ \nu \ell^+ \ell^-$ via 6-fermion operators:



$\Gamma(p \to K^+ \ell^+ \ell^- \nu)$ computed with chiral lagrangian techniques.

Claudson, Wise, Hall Nucl.Phys. B195 (1982); JLQCD Collab. hep-lat/9911026

Imposing $p \to e^+, \mu^+ + \text{anything} \lesssim 10^{32}$ yrs results in:

$$\left|\lambda''_{112}\lambda_{ijk}\right| \lesssim 1 \times 10^{-10} \left(\frac{\tilde{m}}{1\,\text{TeV}}\right)^5, \quad i \neq j \neq k$$

3-body decay $p \to \nu\nu\ell^+$ subdominant contributions (see backup)

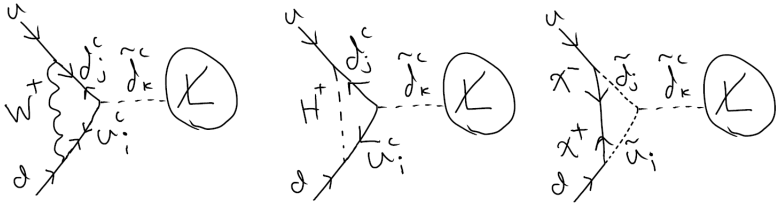
Weaker Constraints on λ'' Couplings to Heavy Flavors

$|\lambda''_{112}\lambda_{ijk}| \lesssim 10^{-10}\left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^5$; all other $|\lambda''_{lmn}\lambda_{ijk}|$ have weaker bounds.

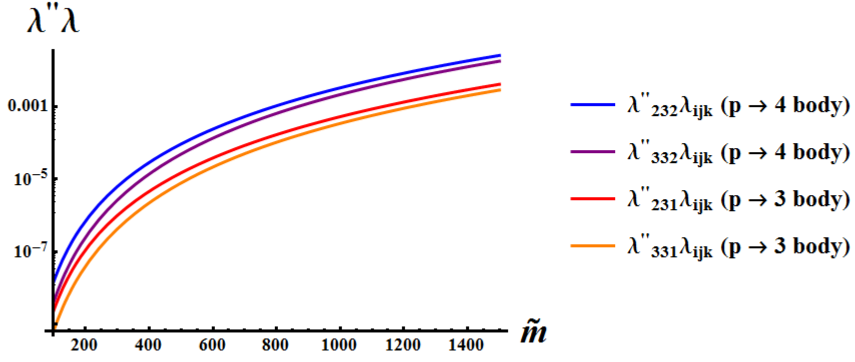
- $\lambda''_{lmn} = \lambda''_{113}, \lambda''_{123}, \lambda''_{212}, \lambda''_{312}$ induce proton decay at tree level. Bounds suppressed by flavor changing squark mass insertions.
- $\lambda''_{213}, \lambda''_{223}, \lambda''_{313}, \lambda''_{323}$ induce proton decay at loop level.

Smirnov and Vissani, hep-ph/9601387.

- Loop diagram suppressed by V_{CKM} and quark mass insertions.



Constraints on λ'' Couplings to Heavy Flavors: Results



λ''_{232}, λ''_{332} induce 4-body proton decay $p \to K^+\ell^+\ell^-\nu$

λ''_{231}, λ''_{331} induce 3-body proton decay $p \to \nu\nu\ell^+$

Enforcing Antisymmetry in LLE^c with a Flavor Symmetry

How can we enforce antisymmetry in λ_{ijk} in mass eigenstate basis?

	L	E^c	Y_E	Y_N
$SU(3)_L$	$\mathbf{3}$	$\mathbf{3}$	$\overline{\mathbf{6}}$	$\overline{\mathbf{6}}$
$U(1)$	1	-2	1	-2

Impose flavor symmetry, spontaneously broken by Y_E, Y_N

Similar to MFV RPV, Nikolidakis and Smith 0710.3129, Csaki et. al 1111.1239

Invariant superpotential terms:

$$W_L = H_d L\, Y_E\, E^c + \frac{1}{M_R} LH_u\, Y_N\, LH_u + \lambda \epsilon_{ijk} L_i L_j E^c_k + \ldots$$

Y_E is complex symmetric matrix, so $Y_E^{diag} = U^T Y_E U$

Can always diagonalize Y_E via $SU(3)$ trans. $L \to UL, E^c \to UE^c$

WLOG, λ_{ijk} is antisymmetric in basis where Y_E is diagonal

Spurion analysis bounds $M_R \lesssim$ PeV (see backup)

Collider Phenomenology of $LLE^c + U^c D^c D^c$

Standard $\not{B}(\not{L})$ RPV: Sparticles decay via gauge or $\not{B}(\not{L})$ coupling

$LLE^c + U^c D^c D^c$ can give qualitatively different physics:

1. $\Gamma(\tilde{X} \to \not{B}) \sim \Gamma(\tilde{X} \to \not{L}) \gtrsim \Gamma(\tilde{X} \to \mathrm{R-parity\ cons.})$
   $\tilde{X}$ has $\mathcal{O}(1)$ BR to both $\not{B}$ and $\not{L}$ final states.

2. $\Gamma(\tilde{X}_1 \to \not{B}) \gtrsim \Gamma(\tilde{X}_1 \to \not{L}), \Gamma(\tilde{X}_1 \to \mathrm{R-parity\ cons.})$
   $\Gamma(\tilde{X}_2 \to \not{L}) \gtrsim \Gamma(\tilde{X}_2 \to \not{B}), \Gamma(\tilde{X}_2 \to \mathrm{R-parity\ cons.})$
   $\tilde{X}_1$ decays via $\not{B}$, $\tilde{X}_2$ decays via $\not{L}$

Both scenarios require $\Gamma(\tilde{X} \to \not{L}\,\mathrm{or}\,\not{B}) \gtrsim \Gamma(\tilde{X} \to \mathrm{R-parity\ cons.})$

Case 1: $\tilde{X} \to \not{B}$, $\tilde{X} \to \not{L}$

Example: Electroweak gaugino (Wino/Bino) LSP $\tilde{\chi}$.

$$\not{B} : \tilde{\chi} \to qqq, \;\; \not{L} : \tilde{\chi} \to \ell\ell\ell$$

$$\text{If } \lambda'' \sim \lambda, \; \Gamma(\tilde{\chi} \to \not{B}) \sim \Gamma(\tilde{\chi} \to \not{L})$$

New final states from colored sparticle production

- $\tilde{g}\tilde{g} \to qq\tilde{\chi}qq\tilde{\chi} \to 7q\,3\ell$
- $\tilde{q}\tilde{q} \to q\tilde{\chi}q\tilde{\chi} \to 5q\,3\ell$
- $\tilde{q}\tilde{g} \to q\tilde{\chi}qq\tilde{\chi} \to 6q\,3\ell$

High jet *and* lepton multiplicity, soft MET spectrum

Still constrained by standard RPV searches

BR doesn't weaken bounds by much due to rapidly falling xsec

Case 2: $\tilde{X}_1 \to \not{B}$, $\tilde{X}_2 \to \not{L}$

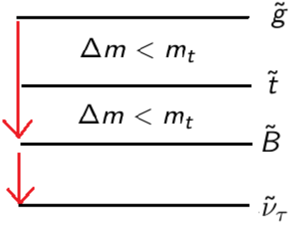
For non-LSP $\tilde{X}$, $\Gamma(\tilde{X} \to \not{L}, \not{B}) \gtrsim \Gamma(\tilde{X} \to \text{RPC})$ requires either:

- $\tilde{X} \to$ RPC kinematically forbidden/suppressed, or
- $\lambda'' \gtrsim g$

Will discuss 1st case; 2nd case possible if λ'' couples to c, b, t

Are there scenarios where bounds are weaker than standard RPV?

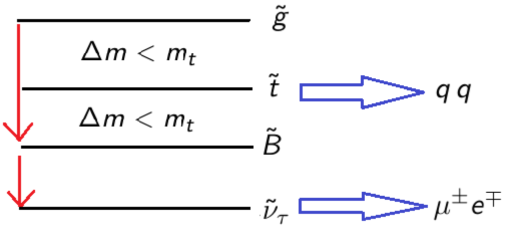
Example spectrum, motivated by natural SUSY:



- $\tilde{g} \to t\tilde{t}$ forbidden
- $\tilde{t} \to t\tilde{B}$ forbidden
- $\tilde{g} \to qq\tilde{B}$
- $\tilde{B} \to \nu_\tau \tilde{\nu}_\tau$

Case 2: $\tilde{X}_1 \to \not{B}$, $\tilde{X}_2 \to \not{L}$ Cont.

Turn on RPV Couplings:



If $10^{-2} \lesssim \frac{|\lambda''|}{|\lambda|} \lesssim 10^2$

Gluino pair production:

$\tilde{g}\tilde{g} \to 4q\ 2\nu_\tau\ 2\tilde{\nu}_\tau$
$\quad \to 4q\ 2\nu_\tau\ 2(\mu^\pm e^\mp)$

Stop pair production:

$\tilde{t}\tilde{t} \to 4q$

Associated production:

$\tilde{g}\tilde{t} \to 4q\ \nu_\tau\ \mu^\pm e^\mp$

If $\lambda \sim 10^{-7}$, $\tilde{\nu}_\tau \to \mu^\pm e^\pm$ has $c\tau \sim \mathcal{O}(100)$ cm, displaced decay

Final state $\mu^\pm e^\mp$ fail impact parameter cuts, weakens bounds from prompt searches involving leptons

Saraswat et. al, arXiv:1205.2671, Batell et. al 1309.2297

Case 2: $\tilde{X}_1 \to \not{B}$, $\tilde{X}_2 \to \not{L}$ Cont.

- $\tilde{t}\tilde{t} \to 4$ jets notoriously difficult channel, allows $\tilde{t} \lesssim 500$ GeV

  Brust, Katz, Lawrence, Sundrum arXiv:1110.6670

  For proposals on improving the situation, see e.g. **Brust et.al 1206.2353, Bai et. al 1309.6631**

- $\tilde{g}$ decays via $\not{L}$, decreased jet multiplicity weakens bounds from multijet channels discussed by Saraswat et.al 1403.7197

- $\tilde{g}$ decay produces displaced $e^{\pm}\mu^{\pm}$, avoid ATLAS constraints on displaced μ+jets
  See Lehan's talk, ATLAS-CONF-2013-092

- May still be hit by jets + MET due to MET from final state ν, muon veto

- Associated prod. $\tilde{g}\tilde{t} \to 4q\nu_\tau\tilde{\nu}_\tau$, displaced $\tilde{\nu}_\tau \to \mu^{\pm}e^{\mp}$ gives unique final state not present in standard RPV

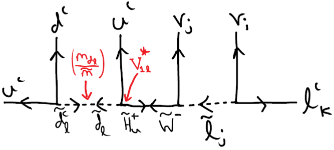
Thanks for listening!
Questions?

Backup Slides

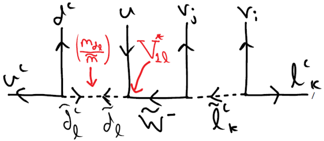
Subdominant 3-Body Proton Decay Constraints

$|\lambda_{ijk}\,\lambda''_{11\ell}|$, $i \neq j \neq k$ also induces $p \to \ell^+ \nu\nu$

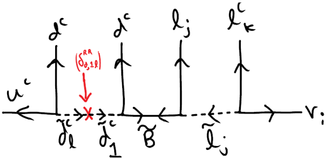
Effective operators suppressed by $d_\ell \to d$ flavor changing effects:



$$\frac{\Gamma(p \to \ell^+ \nu\nu)}{\Gamma(p \to K^+ \ell^+ \ell^- \nu)} \approx 10^3\, V^{*\,2}_{1\ell}\, g^4\, y_u^2 \left(\frac{m_{d_\ell}}{\tilde{m}}\right)^2 \ll 1$$



$$\frac{\Gamma(p \to \ell^+ \nu\nu)}{\Gamma(p \to K^+ \ell^+ \ell^- \nu)} \approx 10^3\, V^{*\,2}_{1\ell}\, g^4 \left(\frac{m_p m_{d_\ell}}{\tilde{m}^2}\right)^2 \ll 1$$



$$\frac{\Gamma(p \to \ell^+ \nu\nu)}{\Gamma(p \to K^+ \ell^+ \ell^- \nu)} \approx 10^3 \left(\delta^{RR}_{d,1\ell}\right)^2$$

Spurion Analysis of $SU(3)_L$: Bounds on RH Neutrino Mass

	L	E^c	Y_E	Y_N
$SU(3)_L$	$\mathbf{3}$	$\mathbf{3}$	$\bar{\mathbf{6}}$	$\bar{\mathbf{6}}$
$U(1)$	1	-2	1	-2

Y_E, Y_N break $SU(3)_L$, perform spurion analysis to catalogue generated operators

Dangerous operators, to lowest order in spurions:

$$W \supset \alpha_{ij} Q_i \left(Y_N^2 Y_E^3 L\right) D_j^c + \kappa \left(Y_N^2 Y_E^3 L\right) H_u + m_{soft}\, b_1 \left((Y_E^\dagger)^2 Y_E L\right) H_u$$

Fixing $m_\nu \sim 0.1$ eV, $|\lambda''_{112}\lambda'| \lesssim 10^{-24} \left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^2$ implies:

$$M_R \lesssim \left(\frac{\tilde{m}}{\mathrm{TeV}}\right) \sqrt{\frac{\cot^3\beta}{\sin\beta\, \lambda''_{112}\alpha_{ij}}} \times 100\,\mathrm{TeV}$$

Additional model building can give $\kappa \sim \langle S \rangle \sim \mu$, $b_1 \sim \frac{\langle S \rangle}{M} \ll 1$