The Fate of R-Parity

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07 Dec 2010

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References

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  Phys.Rev.Lett.102:181802,2009
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SUSY

- Gauge hierarchy, GUTs, REWSB
- SUSY breaking, flavor protlem
- Plus: <u>SUSY has robust predictions</u>

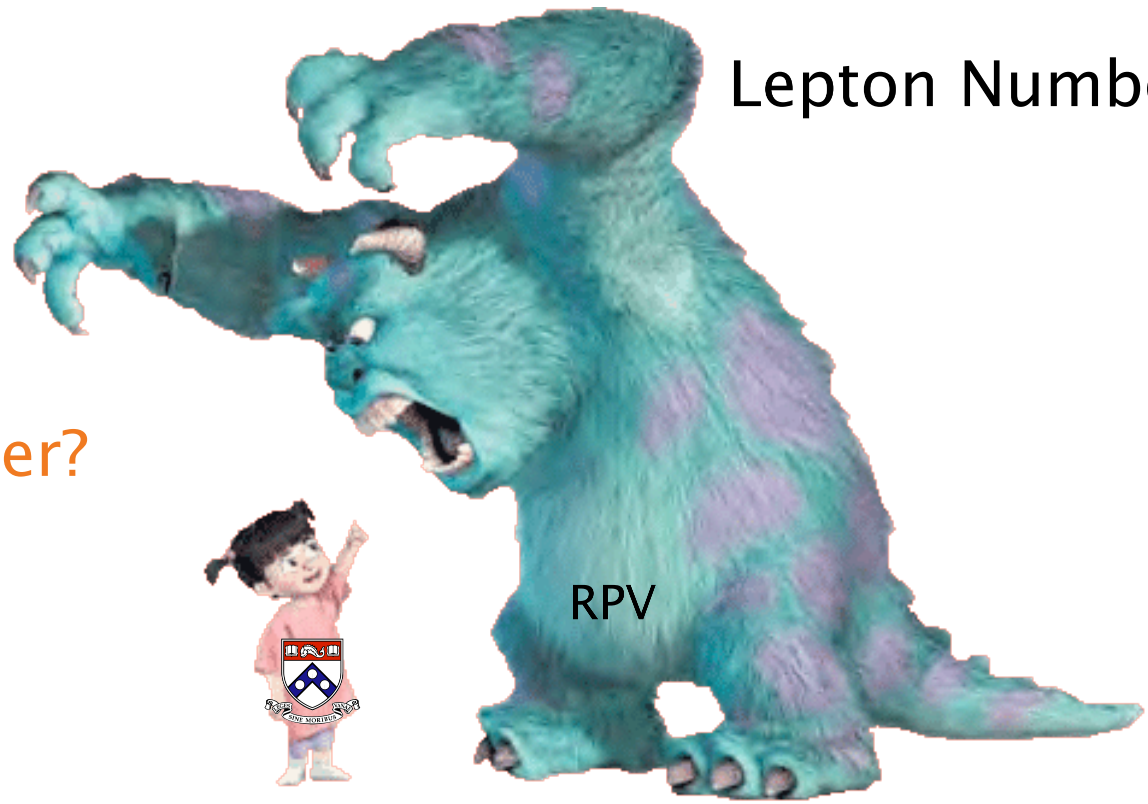
If R-parity is conserved!

- Missing energy at colliders
- WIMP dark matter

R-Parity Violation Can Be Scary!

Lepton Number Violation?

Dark Matter?



Proton Decay?!?

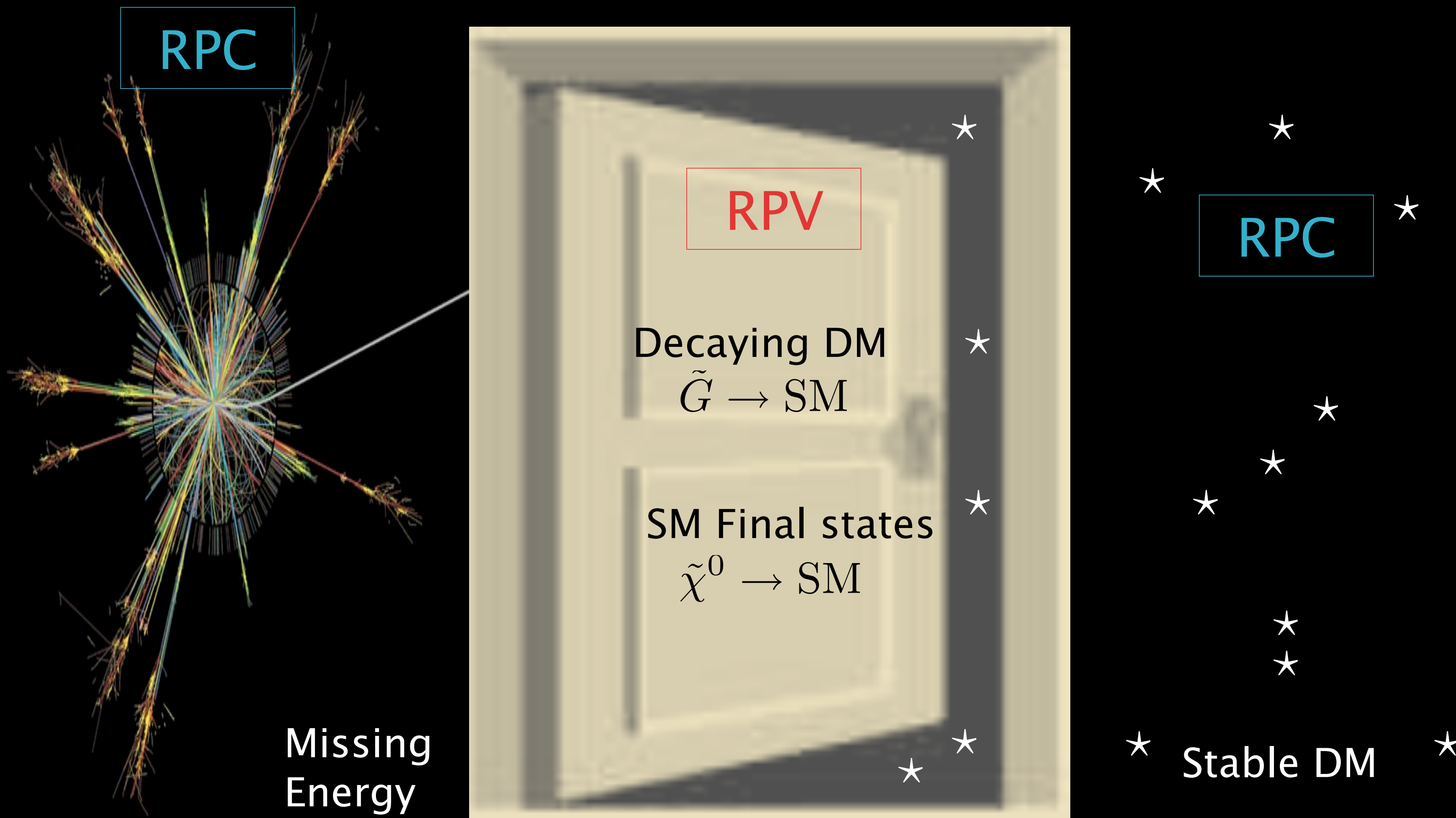
Doesn't have to be! (Spontaneous Breaking)

No Proton decay!

Dark Matter Candidate: gravitino LSP

LNV bounds can be satisfied

SUSY: Cosmo & Pheno hinges on R–parity.



MSSM and B – L violation

- No accidental *B–L* as in the SM

$$W = W_{\rm MSSM} + W_?$$

- With:

$$W_{\rm MSSM} = Y_U\, Q\, H_u\, u^c + Y_d\, Q\, H_d\, d^c + Y_E\, L\, H_d\, e^c + \mu\, H_u\, H_d$$

- L has the same quantum numbers as H_d

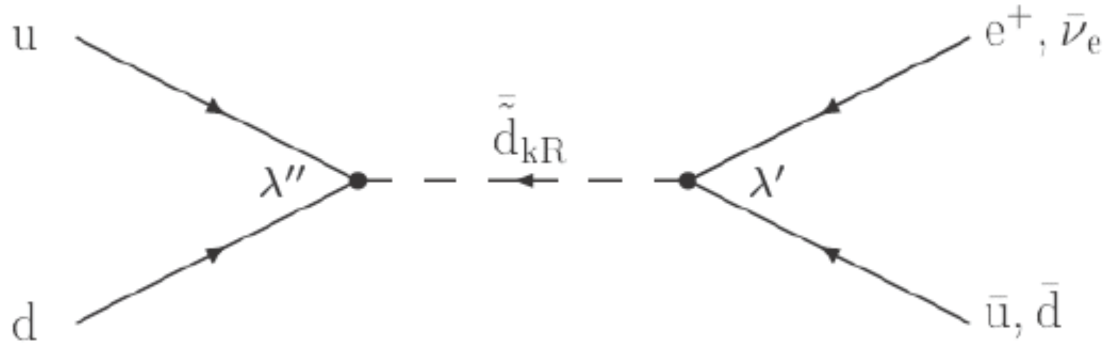
$$W_? : \quad W_{\Delta L=1} = \lambda'\, Q\, L\, d^c + \lambda\, L\, L\, e^c + \mu'\, H_u\, L$$

$$W_{\Delta B=1} = \lambda''\, u^c\, d^c\, d^c$$

MSSM Proton Decay

- Lepton and baryon number violation lead to proton decay:

$$\lambda''\, u^c\, d^c\, d^c \quad \& \quad \lambda'\, Q\, L\, d^c$$

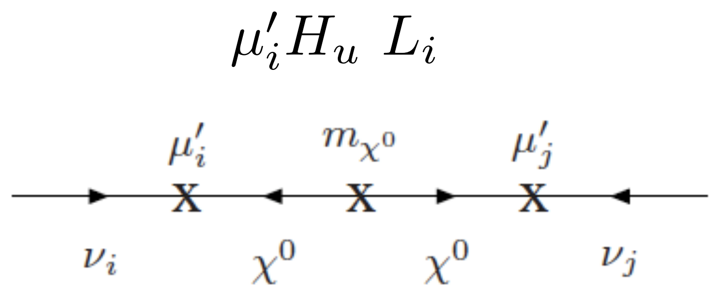


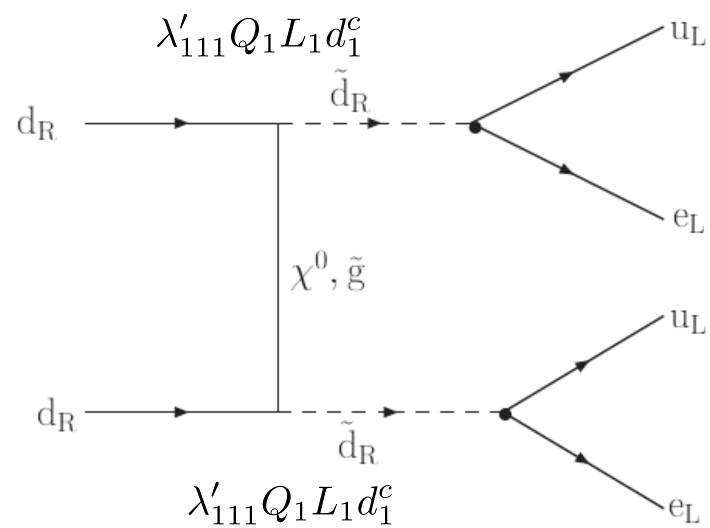
- Untenable with bounds: $\tau_p > 10^{32}$ years

$$|\lambda' \lambda''| < 10^{-26}$$

R-parity

- Good time to panic:
  - Impose R-parity: $R_P = (-1)^{3(B-L)+2S}$
- Forbids *all* non-SM terms, but
  - *Only Lepton or only Baryon number violation is ok*
- $W_{\Delta L=1}$: Majorana neutrino masses and $0\nu 2\beta$





R-parity: A Closer look

- As an "R"-symmetry

  R_p(Particle) = 1 R_p(Sparticle) = -1
- In Lagrangian: even number of sparticles:
  - Lightest Sparticle (LSP) is stable – Super Z_2
  - Dark Matter and missing energy.
- As Matter Parity
  - $(-1)^{2S}$: Spin – trivially satisfied
  - $(-1)^{3(B-L)}$: Subgroup of $U(1)_{B-L}$
    - Forbids $\Delta(B-L) = 1$
    - But allows seesaw: $\frac{(L\ H)^2}{M_{B-L}} \rightarrow \frac{v^2}{M_{B-L}} \nu\ \nu$

Approach

- *B−L* is the essential element
- *Ad. Hoc.* discrete symmetry is not very satisfying: yet powerful consequences
- Missing out on potentially interesting pheno

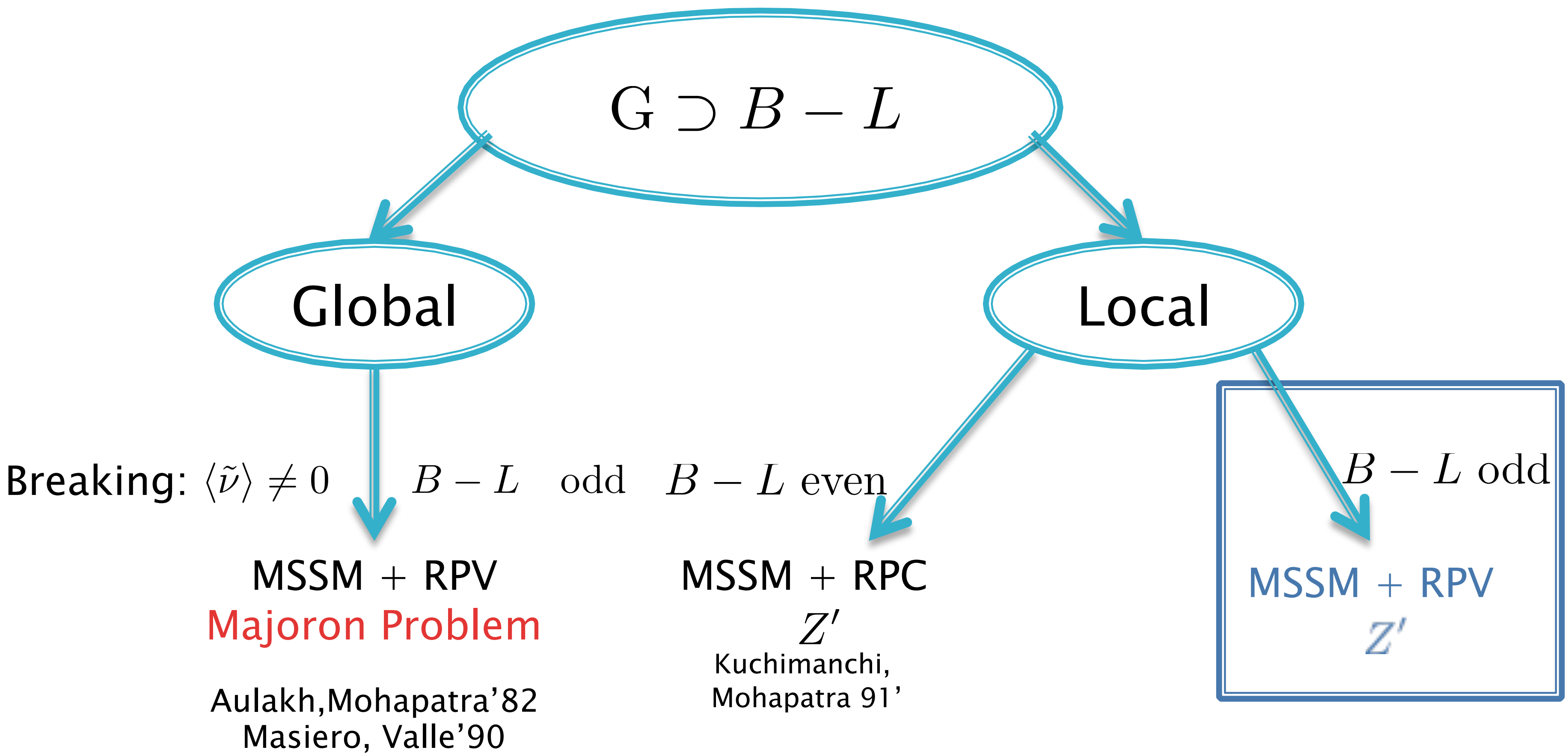
- Focus on theories motivated by *B−L*
  - Understand R-parity within their context
  - Realistic scenarios should be studied
  - Emphasis on low energy

Outline

1. History of *B–L* and R–parity
2. Minimal *B–L* Models: theory and colliders
3. Minimal Left–Right: theory and colliders
4. Radiative B–L Symmetry Breaking
5. Conclusions

Hayashi, Murayama '85; Mohapatra '86 & '86, Martin '92

B–L and R–parity



Minimal B-L Models: Theory

Local B-L: $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \sim (2, \tfrac{1}{3}, \tfrac{1}{3}) \qquad u^c \sim (1, -\tfrac{4}{3}, -\tfrac{1}{3}) \qquad d^c \sim (1, \tfrac{2}{3}, -\tfrac{1}{3})$$

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \sim (2, -1, -1) \qquad e^c \sim (1, 2, 1)$$

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \sim (2, 1, 0) \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \sim (2, -1, 0)$$

Higgs? Need to break:

$$SU(2)_L \times U(1)_Y \times U(1)_{B-L} \rightarrow SU(2)_L \times U(1)_Y$$

P. Fileviez Perez, S.S., **Phys.Lett.B673:251**, 2009
V. Barger, P. Fileviez Perez, S.S., **Phys.Rev.Lett.**102:181802,2009
Braun, He, Ovrut, Pantev '05, Ambroso, Ovrut '09

Anomaly Cancellation

- Look at linear $U(1)_{B-L}$ anomaly, (B–L & gravity)

$$\Sigma(B-L) = 3\left[\underbrace{3\times 2\times \tfrac{1}{3}}_{Q} + \underbrace{3(-\tfrac{1}{3})}_{u^c} + \underbrace{3(-\tfrac{1}{3})}_{d^c} + \underbrace{2(-1)}_{L} + \underbrace{1(1)}_{e^c}\right] = -3$$

- Add 3 B–L=1 fields, no SM charge:
  - Right-handed neutrinos: $3\ \nu^c \ \sim \ (1,1,0,1)$

$$W_{B-L} = W_{MSSM} + Y_\nu\, L\, H_u\, \nu^c$$

- Still, how do you break $U(1)_{B-L}$?

Look no further!
The answer is under our nose (nus)

$$\boxed{\langle\tilde{\nu}^c\rangle \neq 0 : \mathrm{SM}\times U(1)_{B-L} \longrightarrow \mathrm{SM}}$$

Symmetry Breaking

$$\langle \nu^c \rangle \equiv \frac{v_R}{\sqrt{2}}$$

$$\langle \nu \rangle \equiv \frac{v_L}{\sqrt{2}}$$

$$\langle H_u^0 \rangle \equiv \frac{v_u}{\sqrt{2}}$$

$$\langle H_d^0 \rangle \equiv \frac{v_u}{\sqrt{2}}$$

$$\langle V_F \rangle = \boxed{-\frac{1}{\sqrt{2}} Y_\nu \, \mu \, v_d \, v_L \, v_R}$$

$$\langle V_D \rangle = \boxed{\frac{1}{32} g_{BL}^2 (v_R^4} - 2 v_L^2 v_R^2 + v_L^4)$$

$$\langle V_{\rm soft} \rangle = \boxed{\frac{1}{2} v_L^2 m_{\tilde{L}}^2} + \boxed{\frac{1}{2} v_R^2 m_{\tilde{\nu}^c}^2} + \boxed{\frac{1}{\sqrt{2}} a_\nu v_u v_L v_R}$$

$v_R \gg v_u, v_d \gg v_L$ MSSM minimization conditions stay the same

$$v_R = \sqrt{\frac{-8 \, m_{\tilde{\nu}^c}^2}{g_{BL}^2}}$$

SM like VEV: $m_{\tilde{\nu}^c}^2 < 0$

$$v_L = \frac{Y_\nu \, \mu \, v_d - a_\nu v_u}{\sqrt{2} \left(m_{\tilde{L}}^2 - \frac{1}{8} g_{BL}^2 v_R^2 \right)}$$

Induced by linear term

Spontaneous RpV!

$$W \supset Y_\nu \, L \, H_u \, \nu^c \to Y_\nu \, \langle \tilde{\nu}^c \rangle \, L \, H_u$$

- Spontaneous R-parity violation! $(B-L)(\tilde{\nu}^c) = 1$
- Bilinear R-parity violation: $\mu' \equiv Y_\nu \, \langle \tilde{\nu}^c \rangle$
- Bilinears from "kinetic" terms too:

$$g_{B-L} v_R \nu^c \, \tilde{B}', \;\; g_2 v_L \nu \, \tilde{W}^0, \;\; g_2 v_L e^- \, \tilde{W}^+$$

- W is B-L invariant, also global $U(1)_B$ and $U(1)_L$

$$W = Q \; H_u \; u^c + Q \; H_d \; d^c + L \; H_d \; e^c + L \; H_u \; \nu^c$$

  - And B($\tilde{\nu}^c$) = 0 so $\lambda'' \, u^c \, d^c \, d^c \to 0$

- Trilinears small in SRPV: $W \supset \gamma \frac{\langle \tilde{\nu}^c \rangle \, u^c \, d^c \, d^c}{\Lambda}; \quad \lambda'' \equiv \gamma \frac{\langle \tilde{\nu}^c \rangle}{\Lambda}$

Neutrinos and Neutralinos

Neutrinos/neutralinos, charginos/charged leptons, Higgs/sleptons mix

$$(\nu,\ \nu^c,\ \tilde{\chi}^0) \longrightarrow \mathcal{M}_N = \begin{pmatrix} 0 & M_\nu^D & \Gamma \\ \left(M_\nu^D\right)^T & 0 & G \\ \Gamma^T & G^T & M_{\tilde{\chi}^0} \end{pmatrix}$$

M_ν^D: Dirac neutrino mass;

Γ and $G \sim Y\,v,\ g\,v$; RPV

$M_{\tilde{\chi}^0}$: MSSM neutralino mass matrix

$$y_\nu \to 0:\ m_\nu \sim \frac{\mu\, v_L^2}{2\, v_d\, v_u} < 10^{-9}\ \text{GeV}; \qquad \therefore v_L < 10^{-3}\ \text{GeV}$$

$$v_L \to 0:\ m_\nu \sim \frac{g^2 Y_\nu v_d^2 v_R^2}{\mu^2 M_\chi} < 10^{-9}\ \text{GeV}; \quad \therefore Y_\nu < 10^{-5}$$

Full Minimization

- Examine Minimization with 2 families:

$$v_{R_1}\ (D_{B-L} - (m^2_{\tilde{\nu}^c})_1) = 0$$
$$v_{R_2}\ (D_{B-L} - (m^2_{\tilde{\nu}^c})_2) = 0$$

- If $m^2_{\tilde{\nu}^c}$ is degenerate:
  - Can rotate VEV to one generation
  - If not, still only one generation gets a VEV

- Lepton number violation in one generation

V. Barger, P. Fileviez Perez, S.S. arXiv:1010.4023; Ghosh, Senjanovic, Zhang '10

Three Layers of Neutrinos

- Only one heavy Majorana right-handed neutrino

- Other two are Dirac-like or Majorana but equal/less massive then actives, *e.g.*

Normal Hierarchy:

Spectrum

- Z': $M_{Z'} = \frac{1}{2} g_{B-L} v_R; \quad \frac{M'_Z}{g_{B-L}} > 5 \text{ TeV} \rightarrow v_R > 10 \text{ TeV}$
- Scalars: Higgs and Sleptons mix, but not when $v_R \gg v_u, v_d \gg v_L$

$$\mathrm{Im}\,\tilde{\nu}^c \quad - \quad \text{Eaten by } Z'$$

$$m^2_{Re\tilde{\nu}^c} = \frac{1}{4} g^2_{BL} v^2_R = M^2_{Z'}$$

$$m^2_{\tilde{e}_R} = m^2_{\tilde{e}^c} + \frac{1}{8} g^2_{BL} v^2_R + \frac{1}{4} g^2_1 (v^2_u - v^2_d)$$

- Sfermions: new D-term contributions

$$\Delta m^2_\phi = \frac{1}{8} (B-L)(\phi)\, g^2_{BL}\, v^2_R$$

Quick Summary

- Minimal: Particle content = MSSM + r.h. neutrino – no new Higgs!
- Predictive: *B–L* scale = RPV scale = SUSY mass scale.
- No rapid proton decay.
- Neutrino masses.
- Low energy; connection to *B–L* through Z'.

P. Fileviez Perez, S.S., **Phys.Rev.** D80:015004,2009

Beyond *B–L*

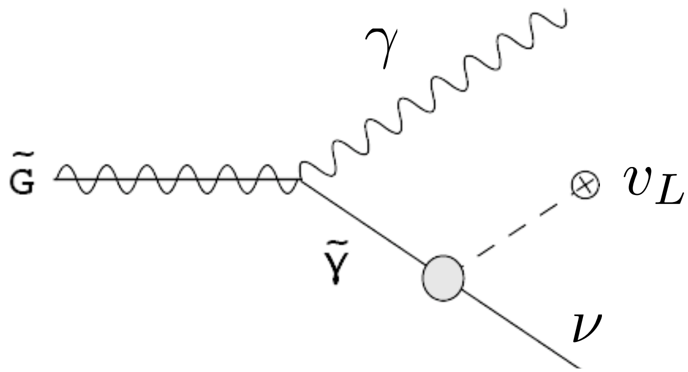
- Consider $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$
- Most general X (with 3 ν^c) is a linear combination of hypercharge and *B–L*

$$\mathrm{X = aY + b(B\text{-}L)}$$

- Charges $X_{\nu^c} = b,\ X_{H_u} = a,\ X_{H_d} = -a,\ X_L = -(a+b)$
- $\boxed{SO(10) \to SU(5) \times U(1)_X \text{ when } a = 1,\ b = -\frac{5}{4}}$

Dark Matter

LSP Gravitino decay: suppressed by Planck scale and neutrino masses



$$\mathcal{M} \sim \frac{v_L m_{3/2}}{M_P m_{\chi^0}}$$

$$\Gamma \sim \frac{m_{3/2}^3 v_L^2}{M_P^2 m_\chi^{02}}$$

$$\tau \sim 10^{26}\ \mathrm{sec} \times \left(\frac{m_\chi^0}{1000\ \mathrm{GeV}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right)^3 \left(\frac{10^{-4}\ \mathrm{GeV}}{v_L}\right)^2$$

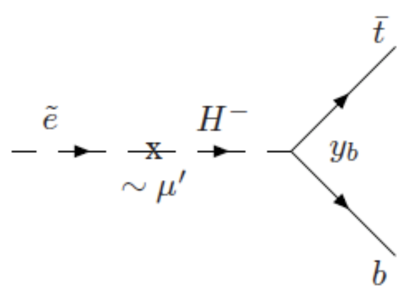
Minimal B-L Models: Colliders

Bilinear RPV

- Only Bilinear RPV, one source:

$$\mathcal{L} \supset \mu' \left(\nu \, \tilde{H}_u^0 - e \, \tilde{H}_u^+ \right) ; \quad \mu' \equiv y_\nu \langle \tilde{v}^c \rangle \sim 10^{-3} \text{ GeV}$$

  - Which mixes the leptons with the Higgsinos
- Leads to effective trilinear couplings:



Looks like: $W = \lambda' \; Q \; L \; d^c$

Effective size: $\lambda' \sim \frac{\mu'}{m_{\tilde{H}^-}} y_b \sim 10^{-6}$

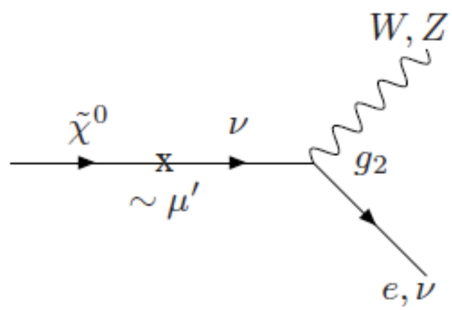
- No effects on production
- Induces LSP decays (NLSP with gravitino LSP), no missing E
- Displayed vertices are possible

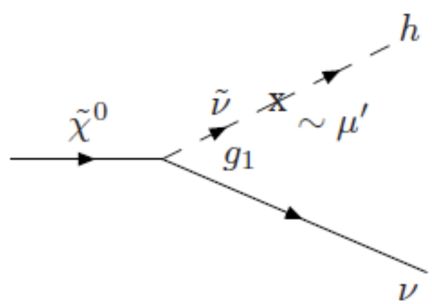
Campos et al. 0712.2156

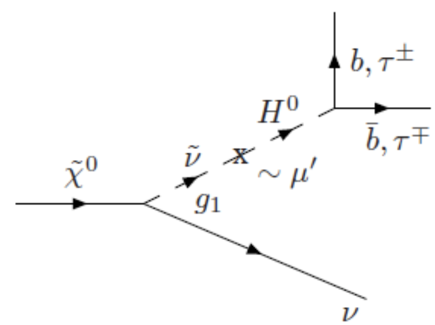
MSUGRA: RPC v. RPV

- Universal soft masses at the GUT scale
  - Typically leads to neutralino LSP – Mostly Bino
- Decay channels include

$$
\begin{aligned}
\tilde{\chi}^0 &\to W^{\pm} l^{\mp} \\
&\to Z\nu \\
&\to h\nu \\
&\to \nu\tau^{\pm}\tau^{\mp} \\
&\to \nu b\bar{b}
\end{aligned}
$$

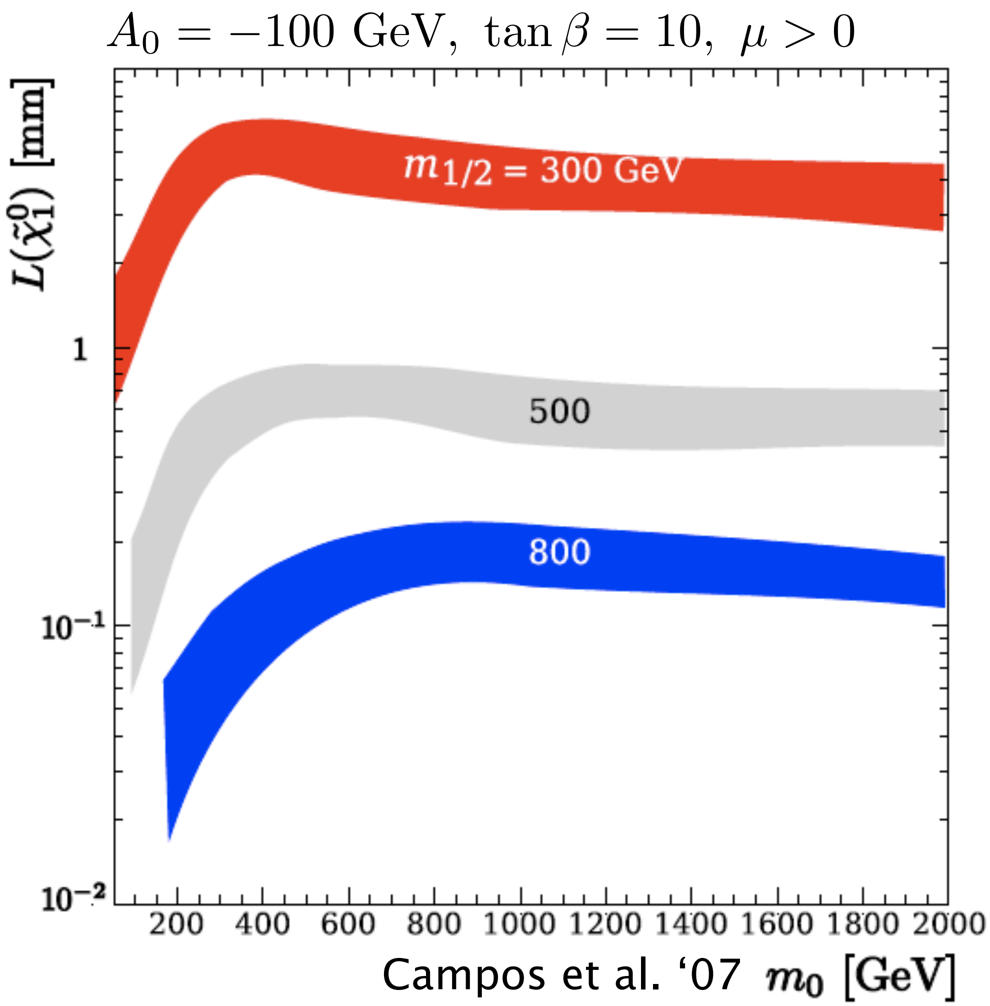






Further suppressed, because of off-shell H^0

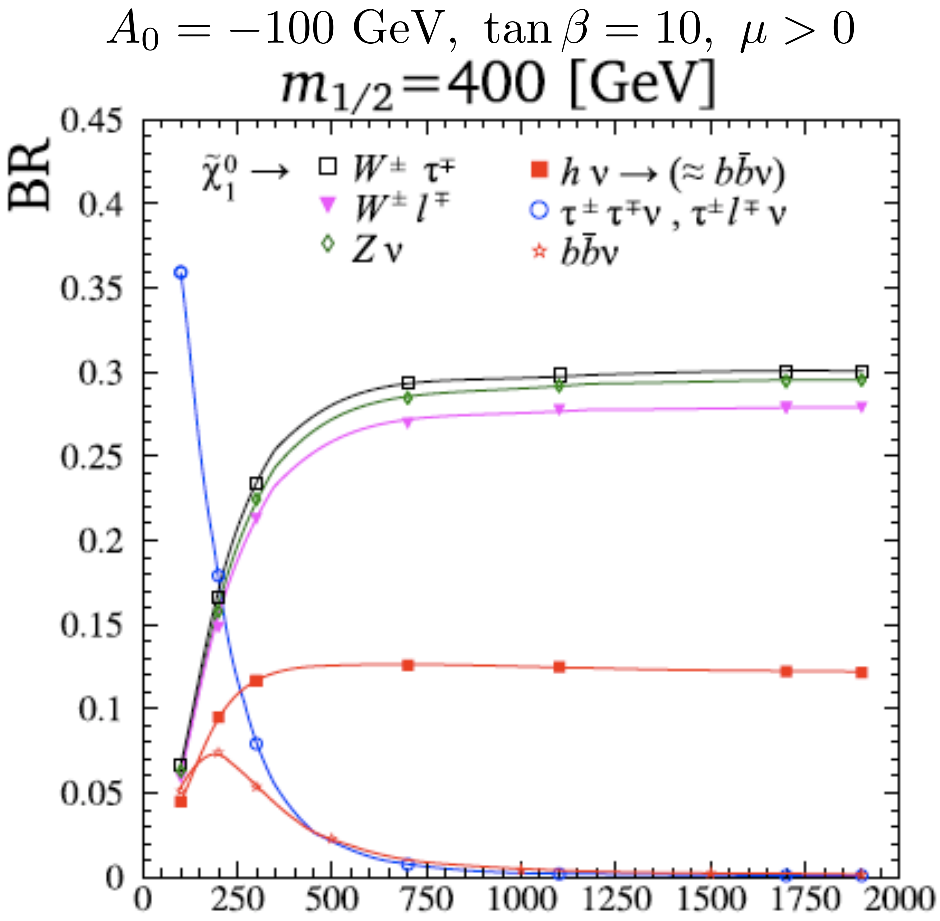
Decay Length for LSP



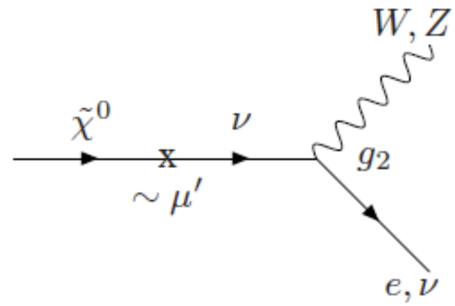
Campos et al. '07

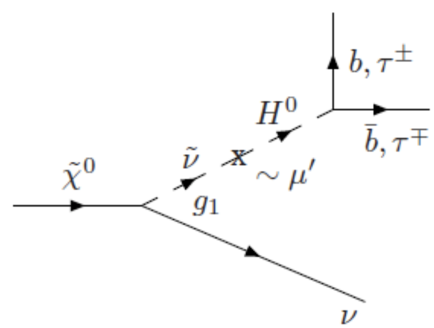
Displaced Vertices
(scanned values chosen to satisfy neutrino physics)

Branching Ratios



Campos et al. '07

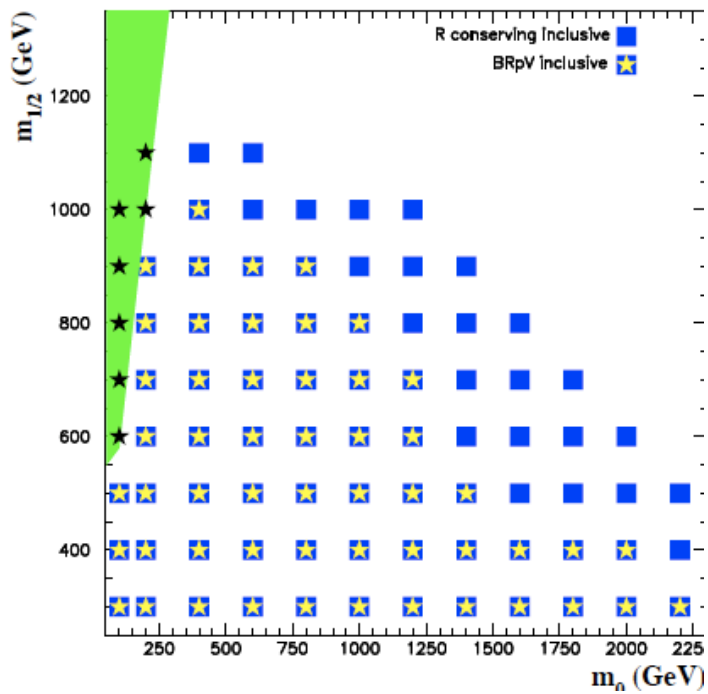




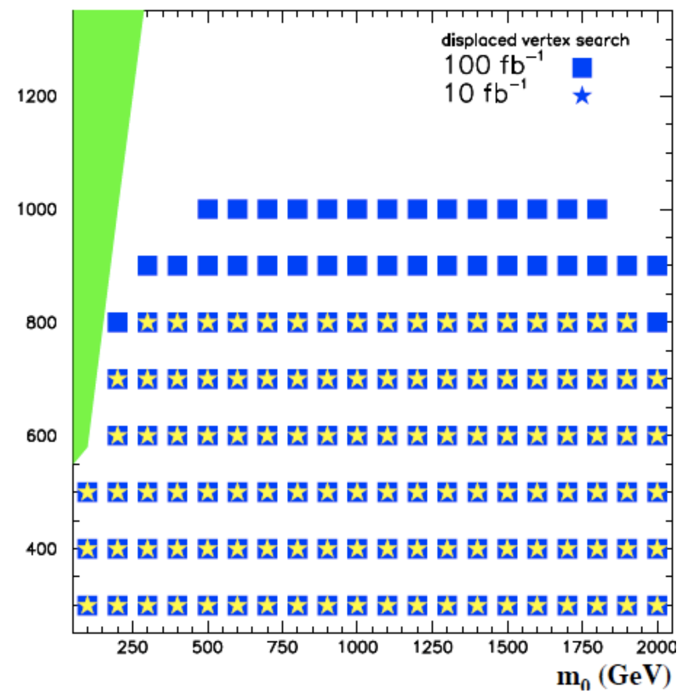
SUSY Reach:

$$A_0 = -100\ \mathrm{GeV},\ \tan\beta = 10,\ \mu > 0,\ 10\ \mathrm{fb}^{-1}$$

Inclusive jets, missing E



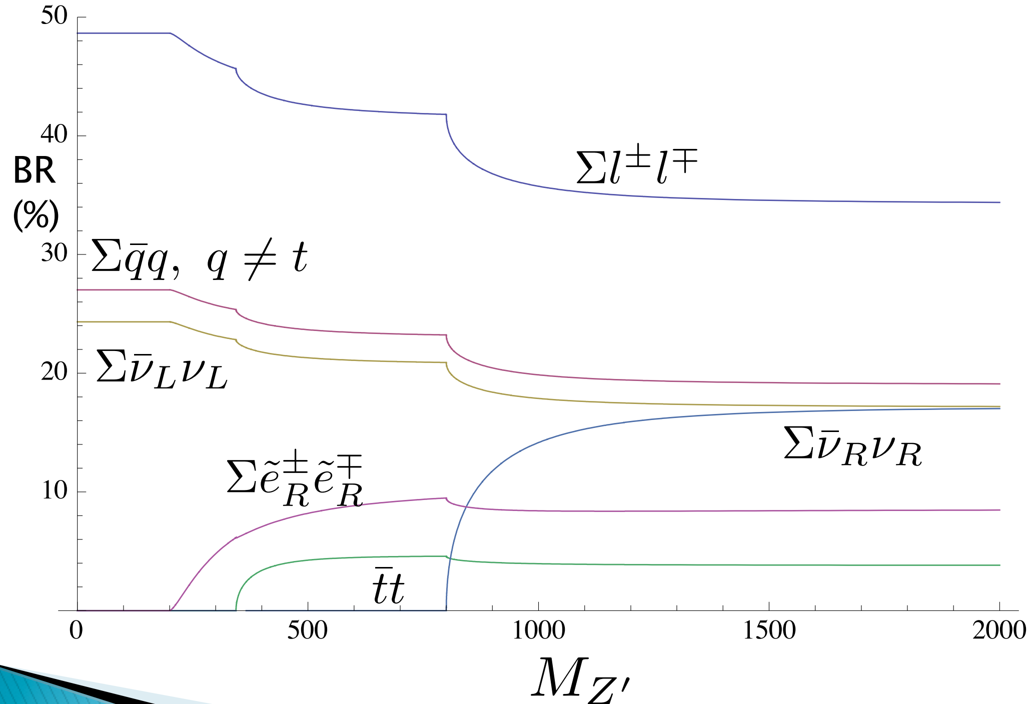
Displaced Vertices ≥ 5



Campos et al. '07

B–L Z'

- Vector coupling only
  - Coupling to leptons: g_{B-L}
  - Coupling to quarks: $\frac{1}{3}g_{B-L}$



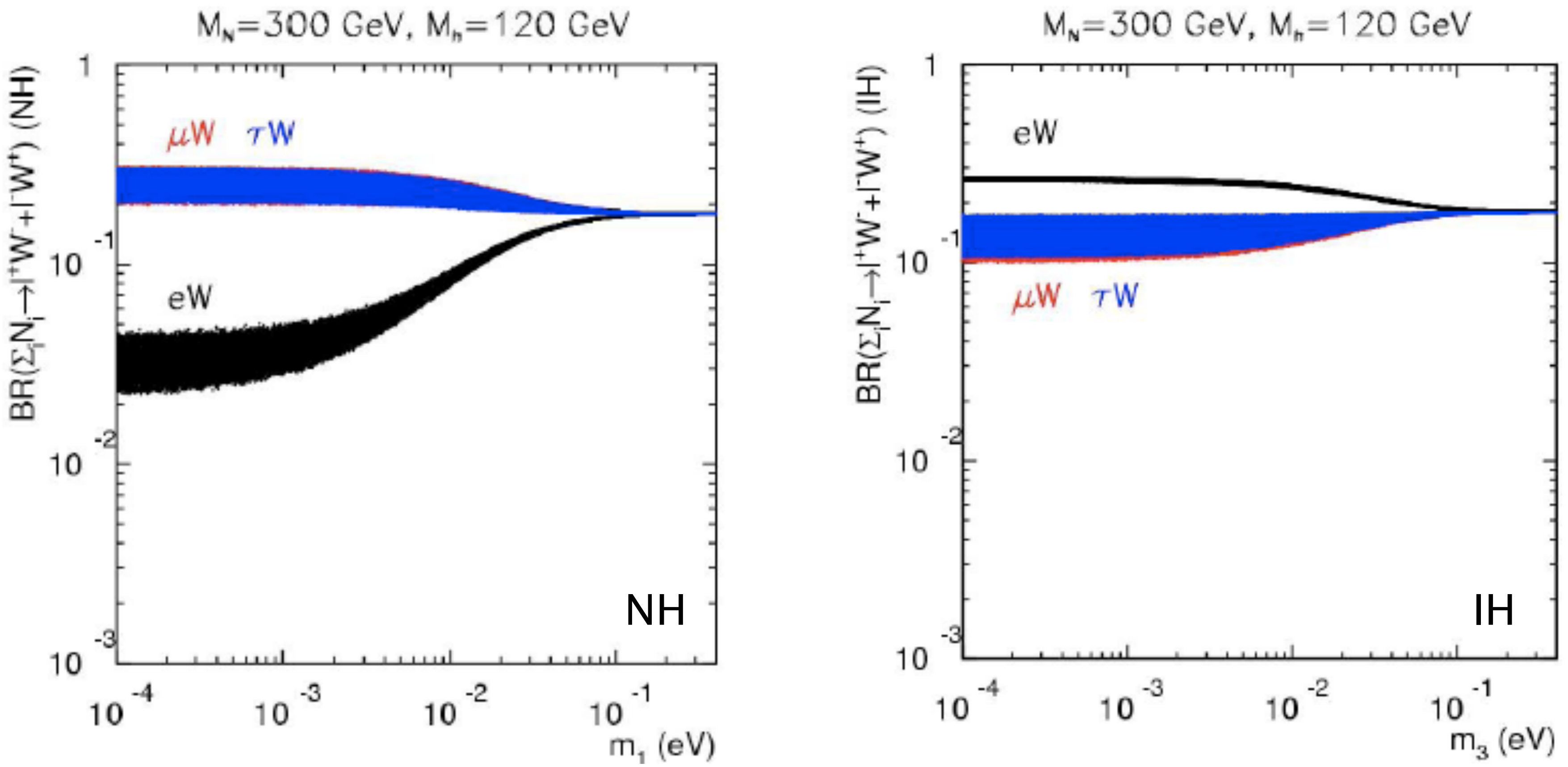
Degenerate right-handed neutrinos and right-handed selectrons.

$$\frac{\mathrm{BR}(e^{\pm}e^{\mp}+\mu^{\pm}\mu^{\mp})}{\mathrm{BR}(qq)} \sim \frac{6}{5}$$

Right-handed neutrinos are heavy Majorana particles lead to LNV: like sign dilpetons

Right-handed Neutrino Decays

$$Z' \to NN \to \mu^-\mu^-W^+W^+$$

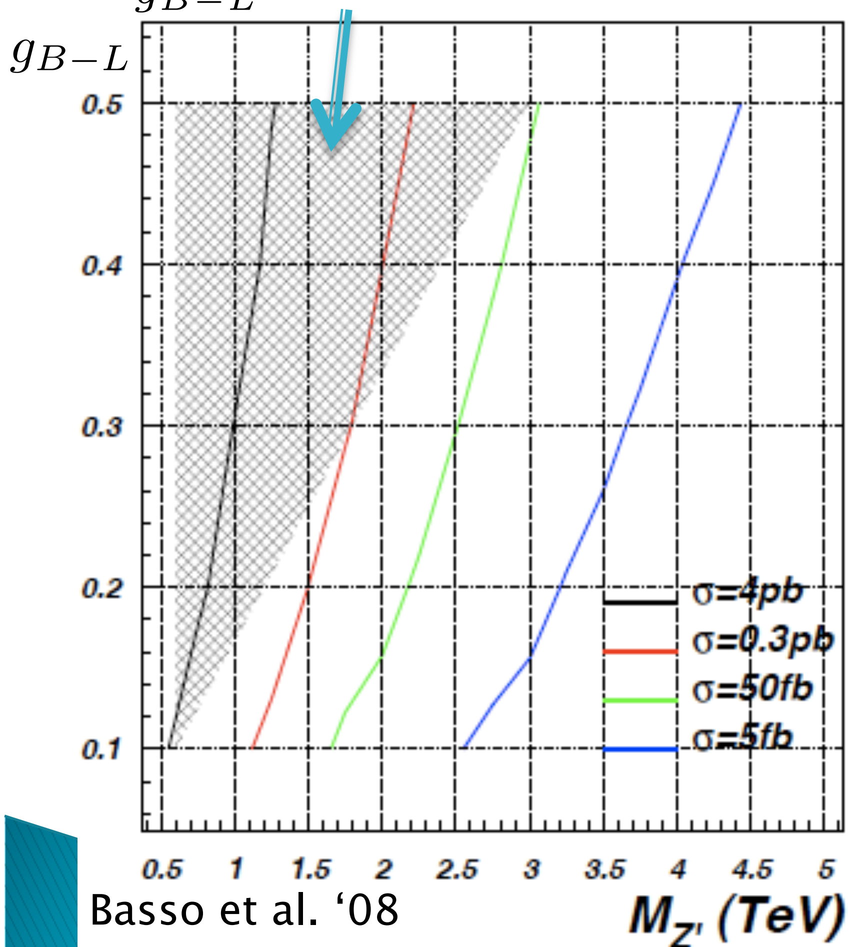


Fileviez Perez, Han, Li '09

Decays depend on neutrino parameters. Might connect to neutrino sector.

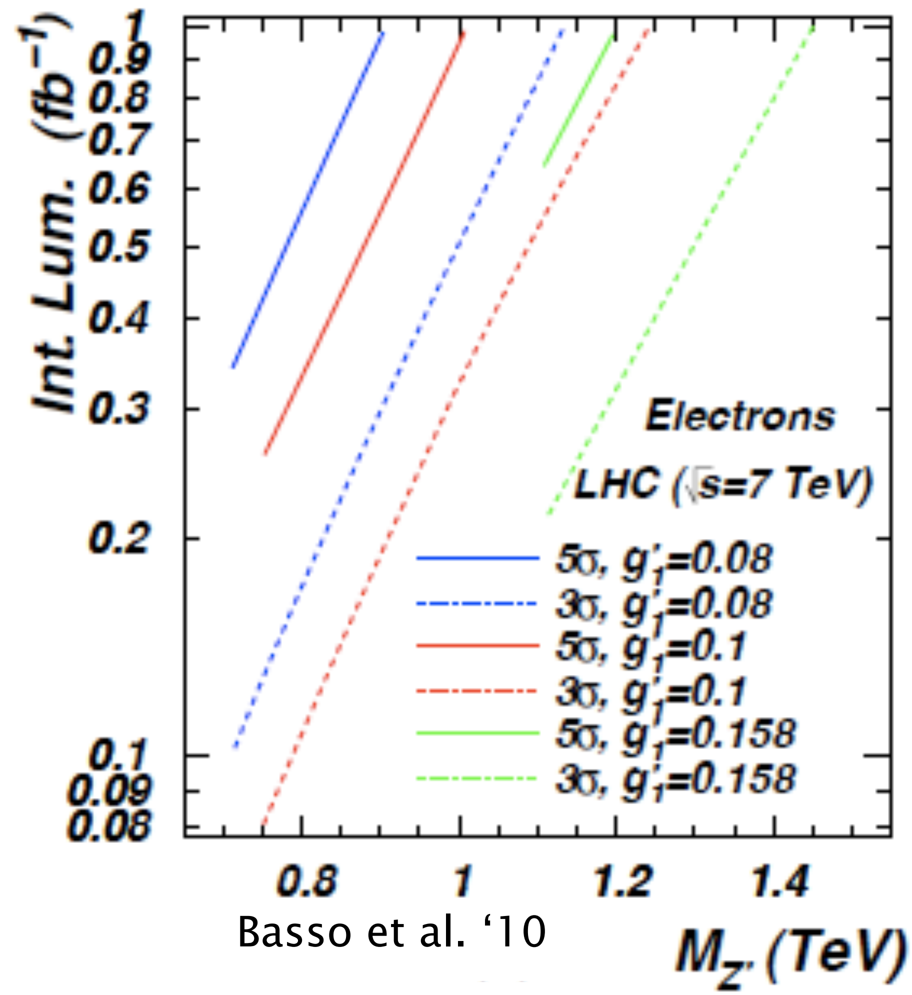
Z' at the LHC

$\frac{M_{Z'}}{g_{B-L}} < 6\ \mathrm{TeV}$ Cross Section



Basso et al. '08

Int. Lum needed
for 3 and 5σ ,electron channel



Basso et al. '10

Z' Decay and RPV

- LSP couples to Z' (sfermion)
  - LSP decays via RPV, $Z' \to \bar{f}\, f\, \bar{f}\, f$

$$Z' \to \tilde{\nu}\ \tilde{\nu}^*$$

$$\tilde{\nu}_i \to l_j^{\pm} l_k^{\mp};\ \text{possible final state: } \mu^+ e^- e^+ e^-$$ Lee '08

$$\tilde{\nu}_i \to jj$$

$$Z' \to \tilde{l}^+ \tilde{l}^-$$

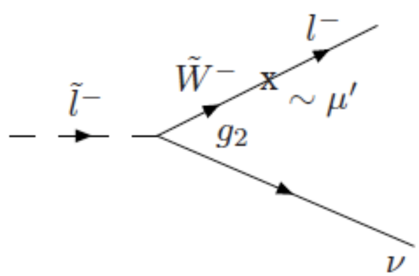
$$\tilde{l}_i^{\pm} \to \nu l_j^{\pm}$$

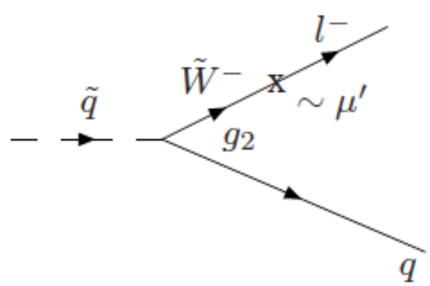
$$\tilde{l}_i^{\pm} \to jj$$

$$Z' \to \tilde{q}\tilde{q}^*$$

$$\tilde{q} \to q l^{\pm}$$

$$\tilde{q} \to q\nu$$





Displaced vertices probable

Minimal Left-Right: Theory

Pati, Salam'74; Mohapatra, Pati'75; Mohapatra, Senjanovic'75

R-parity and Left-Right Symmetry

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Why Left-Right
  - Vacuum prefers $v_R >> v_{EW}$; suppresses V+A.
  - Consistent with SO(10) unification.
  - Natural framework for Leptogenesis.
  - Electric Charge:

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2}$$

  - And of course neutrino masses.

Matter content

With $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ charge

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \sim (2, 1, 1, \frac{1}{3}) \qquad Q^c = \begin{pmatrix} u^c \\ d^c \end{pmatrix} \sim (1, 2, 1, -\frac{1}{3})$$

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \sim (2, 1, 1, -1) \qquad L^c = \begin{pmatrix} \boxed{\nu^c} \\ e^c \end{pmatrix} \sim (1, 2, 1, 1)$$

Required by gauge symmetry

Higgs? Need to break:

$$SU(2)_R \times U(1)_{B-L} \to U(1)_Y$$

Kuchimanchi, Mohapatra'95; Aulakh, Melfo, Senjanovic'98; Babu, Mohapatra'08

Higgs Sector For RpC

$$\hat{\Phi} = \begin{pmatrix} \hat{H}_D^0 & \hat{H}_U^+ \\ \hat{H}_D^- & \hat{H}_U^0 \end{pmatrix} \sim (2,2,0)$$

$$\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix} \sim (3,1,2) \qquad \Delta^c = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^{c+} & \Delta^{c++} \\ \Delta^{c0} & -\frac{1}{\sqrt{2}}\Delta^{c+} \end{pmatrix} \sim (3,1,-2)$$

$$\bar{\Delta} = \begin{pmatrix} \frac{1}{\sqrt{2}}\bar{\Delta}^- & \bar{\Delta}^0 \\ \Delta^{--} & -\frac{1}{\sqrt{2}}\Delta^- \end{pmatrix} \sim (3,1,-2) \qquad \bar{\Delta}^c = \begin{pmatrix} \frac{1}{\sqrt{2}}\bar{\Delta}^{c-} & \bar{\Delta}^{c0} \\ \Delta^{c--} & -\frac{1}{\sqrt{2}}\Delta^{c-} \end{pmatrix} \sim (3,1,2)$$

Plus $S \sim (1,1,0)$ or nonrenormalizable term

P. Filviez Perez, S.S., **Phys.Lett.B**673251, 2009

Higgs Sector For RpV

$$\hat{\Phi} = \begin{pmatrix} \hat{H}_D^0 & \hat{H}_U^+ \\ \hat{H}_D^- & \hat{H}_U^0 \end{pmatrix} \sim (2,2,0)$$

$$\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix} \sim (3,1,2) \qquad \Delta^c = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^{c+} & \Delta^{c++} \\ \Delta^{c0} & -\frac{1}{\sqrt{2}}\Delta^{c+} \end{pmatrix} \sim (3,1,-2)$$

$$\bar{\Delta} = \begin{pmatrix} \frac{1}{\sqrt{2}}\bar{\Delta}^- & \bar{\Delta}^0 \\ \bar{\Delta}^{--} & -\frac{1}{\sqrt{2}}\bar{\Delta}^- \end{pmatrix} \sim (3,1,-2) \qquad \bar{\Delta}^c = \begin{pmatrix} \frac{1}{\sqrt{2}}\bar{\Delta}^{c-} & \bar{\Delta}^{c0} \\ \bar{\Delta}^{c--} & -\frac{1}{\sqrt{2}}\bar{\Delta}^{c-} \end{pmatrix} \sim (3,1,2)$$

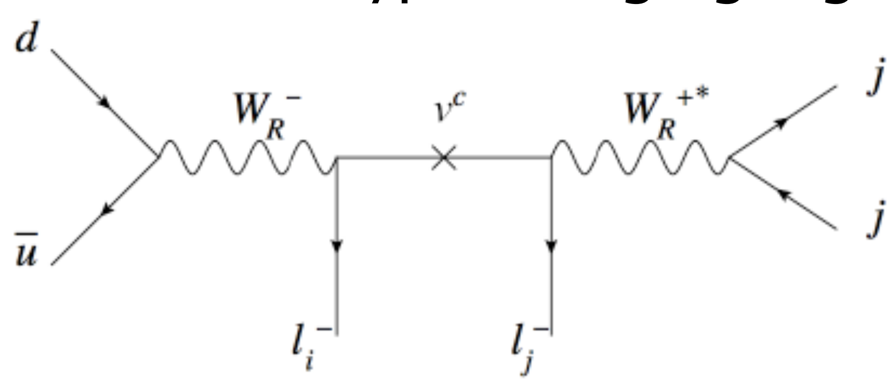
~~Plus $S \sim (1,1,0)$ or nonrenormalizable term~~

Again use $\langle \tilde{\nu}^c \rangle \neq 0$

The Simplest Supersymmetric Left-Right Model

Gauge Bosons

- $\tilde{L}^c = \begin{pmatrix} \tilde{e}^c \\ \tilde{\nu}^c \end{pmatrix}$ breaks the symmetry, $m^2_{\tilde{L}^c} < 0$
  - SM Z absorbs $\mathrm{Im}(H^0)$, $W^\pm_L$ absorbs $H^\pm$
  - LR Z' absorbs $\mathrm{Im}(H^0)$, $W^\pm_R$ absorbs $\tilde{e}^c$
- $W^\pm_R$ *couples only to right-handed states!*
- Z' to all matter: B-L and r-h gauge boson
  - Other combination: hypercharge gauge boson



Minimal Left-Right: Colliders

Chen, Ghosh, Mohapatra, Zhang '10

RPV and Left-Right

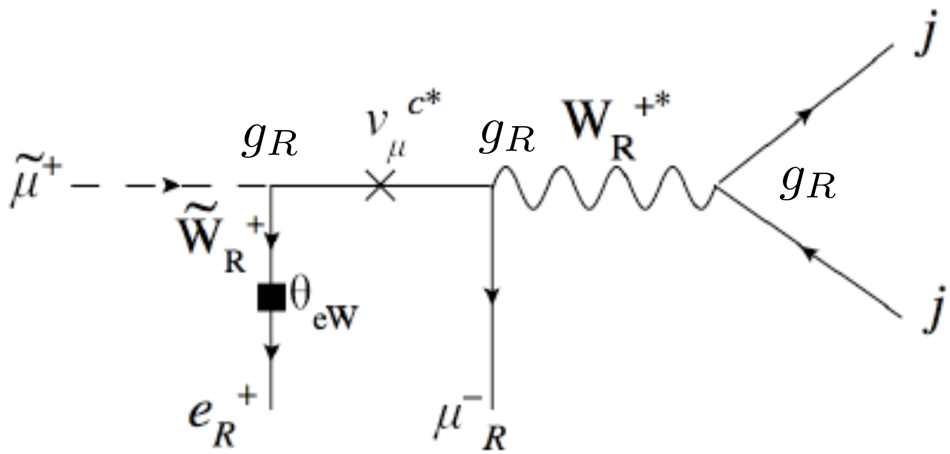
- Key Observation

$$\mathcal{L} \supset g_R \tilde{\nu}^{c*} e^c \; \tilde{W}_R^- \to g_R \langle \tilde{\nu}^c \rangle \, e^c \; \tilde{W}_R^-$$

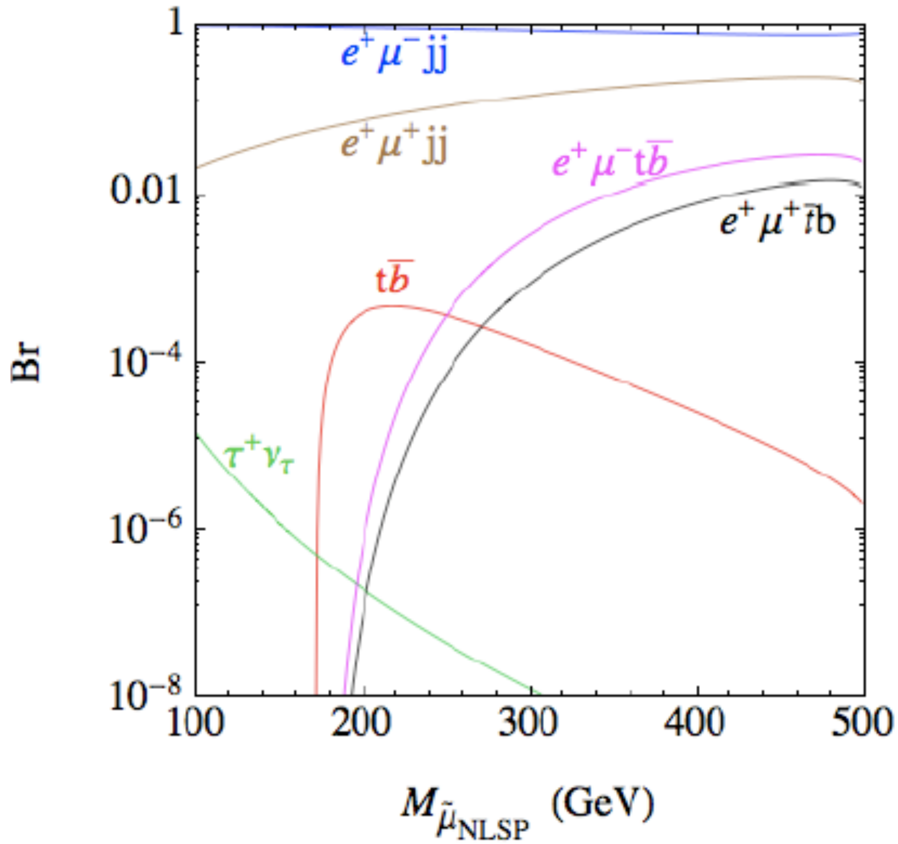
$$\sim 1 \text{ TeV } e^c \; \tilde{W}_R^- \equiv \theta_{eW} e^c \; \tilde{W}_R^-$$

Large RPV mixing!

- New decay for right-handed LSP slepton



Smuon Branching Ratio



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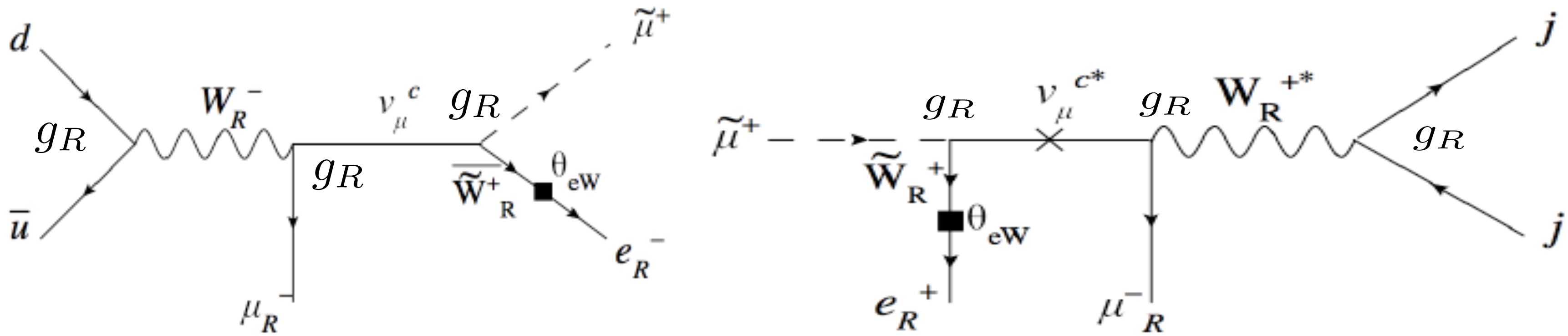
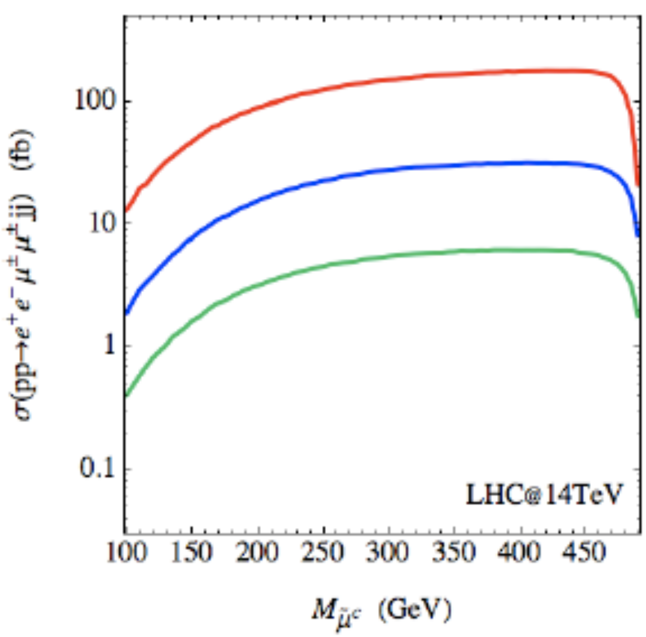
Assume very little left-right mixing in smuon sector.

Chen, Ghosh, Mohapatra, Zhang '10

Smuon Production Through W_R



$$pp \to \mu^\pm \mu^\pm e^+ e^- jj$$



Parameters:

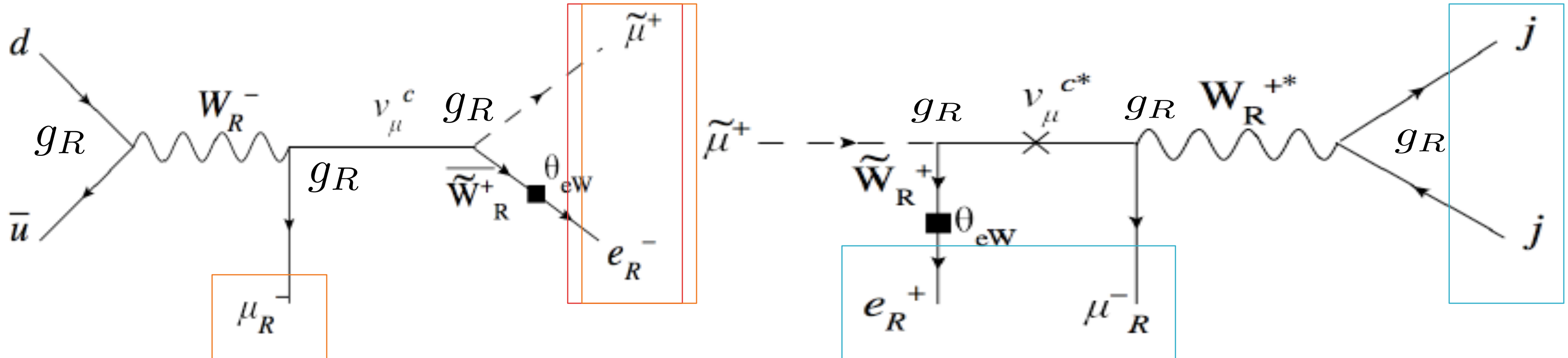
$$m_{\nu^c} = 500 \text{ GeV}$$
$$\theta_{eW} = 0.2$$
$$M_{W_R} = 1, 1.5, 2 \text{ TeV}$$

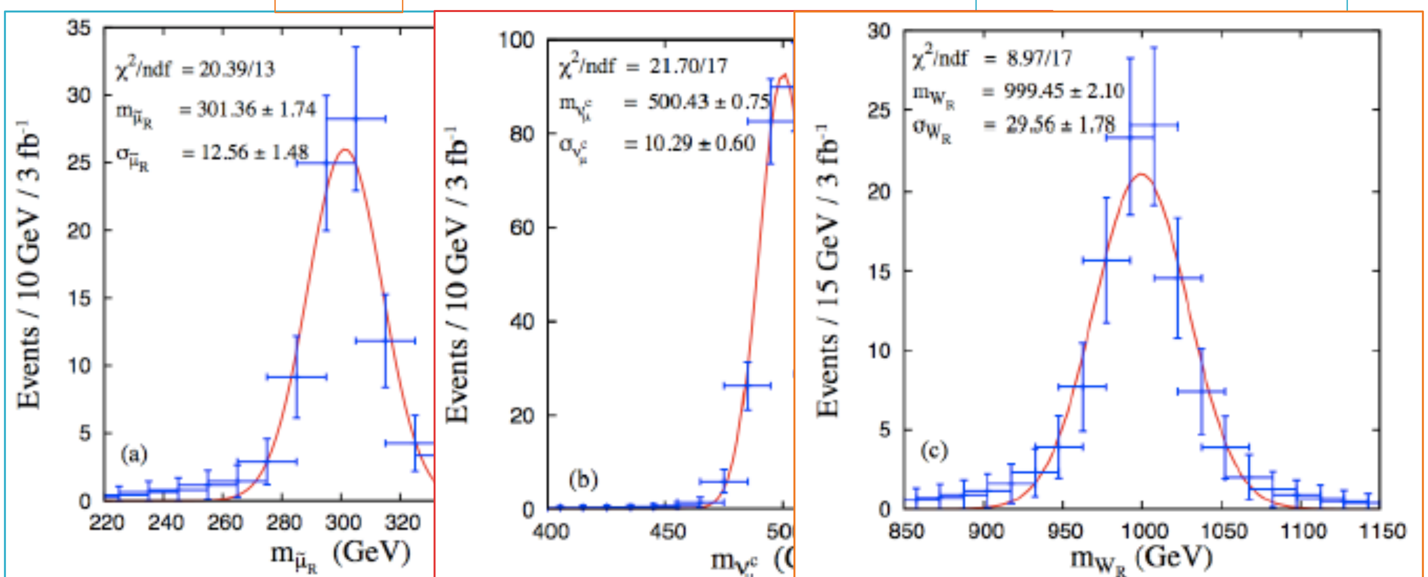
Cuts:

$$p_T(l_1) > 100 \text{ GeV}, \; p_T(l) > 15 \text{ GeV},$$
$$p_T(j) > 25 \text{ GeV}, \; \text{Missing E}_T < 30GeV$$

Chen, Ghosh, Mohapatra, Zhang '10

Reconstruction





Radiative B-L Breaking

Remaining Questions

- Why is right-handed sneutrino tachyonic?
  - Would like to mimic the success of REWSB in MSSM.
  - But RSB not possible in the minimal model (no large Yukawas).
    (Non-universal boundary conditions: Ambroso, Ovrut 0904.4509)
- What about even *B–L* Higgs (canonical Model)
  - Maybe RPC more important than minimalism.
- The answers are related!

Canonical U(1)$_{B-L}$

$$\mathrm{SM} \times U(1)_{B-L}$$

- Anomaly cancellation 3 ν^c; and add X and $\bar{X}$

$$B-L: X \sim -2; \quad \bar{X} \sim 2 \quad \nu^c \sim 1$$

$$\Delta W = Y_\nu\, L\, H_u\, \nu^c + f\, \nu^c\, \nu^c\, X + \mu_X\, X\, \bar{X}$$

- The "seesaw" Yukawa, f, can be large
  - Radiative symmetry breaking (RSB) possible, but…

$$m_X^2 \ < \ 0 \rightarrow \ \mathrm{RPC}$$

$$m_{\tilde{\nu}^c}^2 \ < \ 0 \rightarrow \ \mathrm{RPV}$$

What is the Fate of R-parity?

Minimization: RPC

$$\langle X \rangle \equiv x,\ \langle \bar{X} \rangle \equiv \bar{x}$$

- RPC: Similar to MSSM with $H_u \to X$ and $H_d \to \bar{X}$

$$\frac{1}{2} M_{Z'}^2 = -\left|\mu_X\right|^2 + \frac{m_X^2 \tan^2 z - m_{\bar{X}}^2}{1 - \tan^2 z}$$

$$M_{Z'} \equiv g_{BL}^2 \left(x^2 + \bar{x}^2\right) \qquad \tan\, z \equiv \tfrac{x}{\bar{x}}$$

- Nice marriage of:
  - R-parity Conservation
  - Type I seesaw

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & Y_\nu v_u \\ Y_\nu v_u & f \langle X \rangle \end{pmatrix} \to m_\nu \sim \frac{Y_\nu^2 v_u^2}{f \langle X \rangle}$$

Minimization: RPV

$$\langle V \rangle \supset -\frac{1}{\sqrt{2}} f \mu_X v_R^2 \bar{x} - \frac{1}{\sqrt{2}} a_X v_R^2 x - b_X x \bar{x}$$

- Linear terms if $v_R \neq 0$ then $x, \bar{x} \neq 0$

$$v_R \gg x, \bar{x}$$

$$v_R^2 \sim \frac{-m_{\tilde{\nu}^c}^2 (\mu_X^2 + m_{\bar{X}}^2)}{f^2 m_{\bar{X}}^2 + \frac{1}{8} g_{BL}^2 (\mu_X^2 + m_{\bar{X}}^2)} \quad \bar{x} \sim \frac{-m_{\tilde{\nu}^c}^2 f \mu_X}{\sqrt{2}(f^2 m_{\bar{X}}^2 + \frac{1}{8} g_{BL}^2 (\mu_X^2 + m_{\bar{X}}^2))}$$

- No μ problem and $\mu_X \to \infty$ decoupling, VEVs as in the minimal model:

$$v_R^2 \sim \frac{-8 m_{\tilde{\nu}^c}^2}{g_{BL}^2}$$

- Still have Type I seesaw

P. Fileviez Perez, S.S., arXiv: arXiv: 1005.4930

The Fate of *R*–parity

- RGEs, see which field becomes tachyonic:

$$X \quad \text{or} \quad \tilde{\nu}^c$$

- RGEs (one family approximation):

$$X_X \equiv m_X^2 + 2m_{\tilde{\nu}^c}^2 + 4a_X^2$$

$$16\pi^2 \frac{dm_{\tilde{\nu}^c}^2}{dt} = \boxed{8}\ f^2 X_X - \boxed{3}\ g_{BL}^2 M_{BL}^2$$

$$16\pi^2 \frac{dm_X^2}{dt} = \boxed{4}\ f^2 X_X - \boxed{12}\ g_{BL}^2 M_{BL}^2$$

Favors R–parity Violation!!!

$B\!-\!L$ and MSUGRA

- SUSY breaking scheme for numerical study: MSUGRA
- At the GUT scale:

$$m^2_{\tilde{\nu}^c} = m^2_X = \ldots = m^2_0$$
$$M_{BL} = \ldots = M_{1/2}$$

- Experimental constraints:

$$\frac{M_{Z'}}{g_{BL}} > 6 \text{ TeV} \;\rightarrow\; \text{Large } m^2_0$$

Hyperbolic Branch/Focus Point

HB/FP

- Distinguishing feature: heavier sfermions, lighter gauginos:

$$m_0^2 \gg M_{1/2}^2$$

  - Slower MSSM Higgs running, (decreased gluino mass)
  - Less fine-tuning, even for $m_0 \sim 10 \text{ TeV}$
  - Speeds up the running of the *B–L* fields
  - Allows the necessary hierarchy between electroweak and *B–L* Scales
  - Gauge part of RGE small:

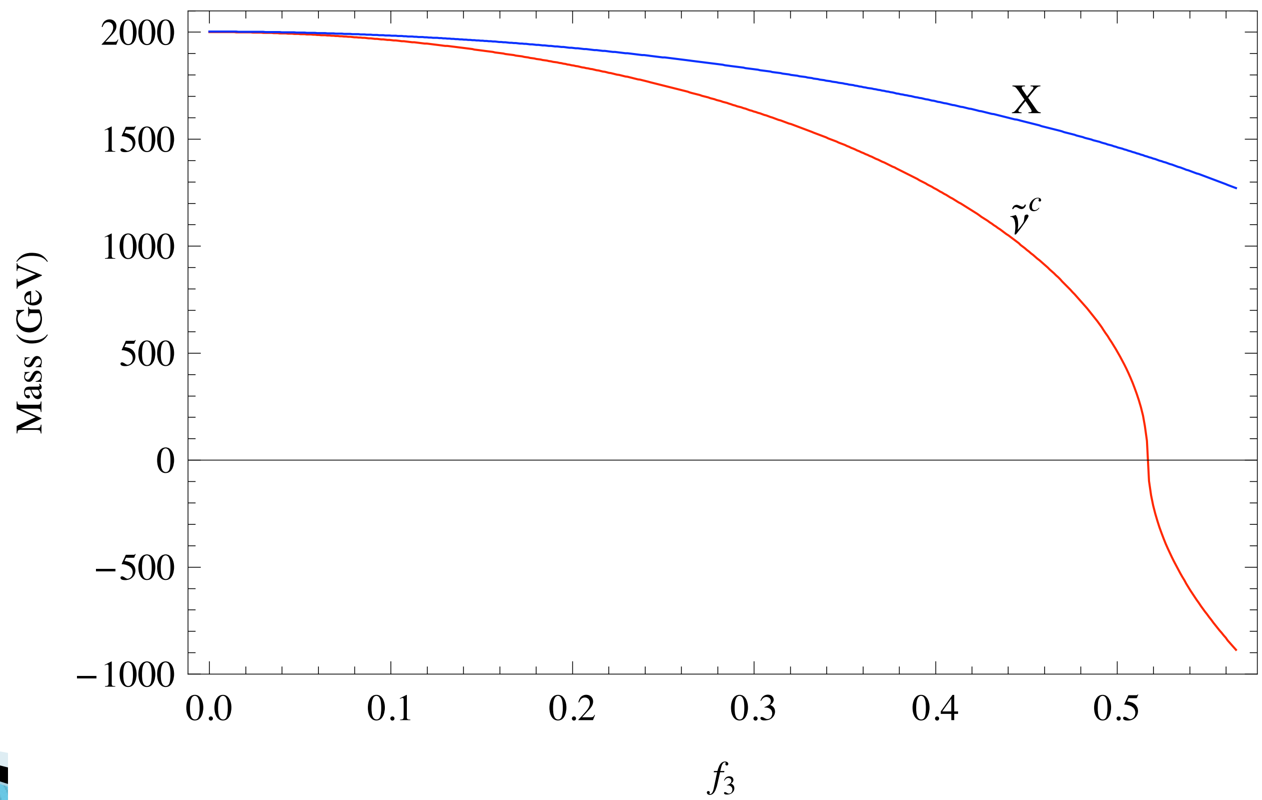
$$16\pi^2 \frac{dm_{\tilde{\nu}^c}^2}{dt} \sim 8 f^2 X_X$$

$$16\pi^2 \frac{dm_X^2}{dt} \sim 4 f^2 X_X$$

Check RSB: One Family

- Soft masses verses f_3:

$$m_0 = 2000\ \text{GeV};\ M_{1/2} = 200\ \text{GeV};\ A_0 = 0$$



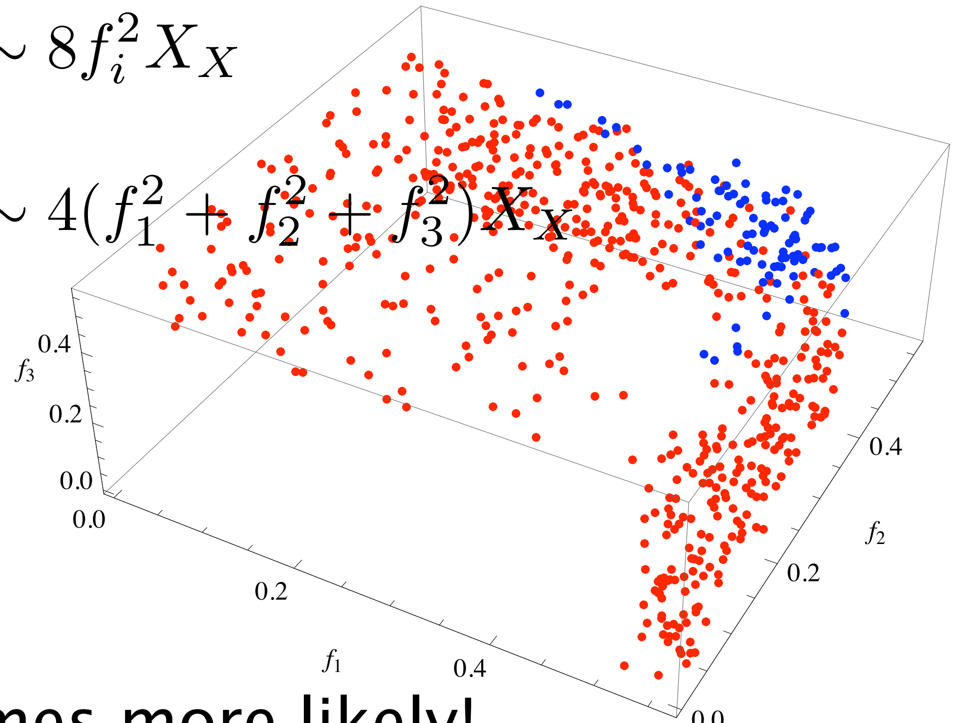
Three Families

- m_X^2 enhanced by $tr f$; RSB with RPC possible

$$16\pi^2 \frac{dm^2_{\tilde{\nu}^c_i}}{dt} \sim 8 f_i^2 X_X$$

$$16\pi^2 \frac{dm^2_X}{dt} \sim 4(f_1^2 + f_2^2 + f_3^2) X_X$$

$$\begin{aligned} m_0 &= 2000 \text{ GeV}, \\ M_{1/2} &= 200 \text{ GeV}, \\ A_0 &= 0 \end{aligned}$$



RPV 5 times more likely!

Even in the canonical model, RPV is probable!

Conclusions

- RPC is not a necessary in SUSY model building
  - Instead study models that explain its origin
- Two viable models with spontaneous RPV:
  - In the minimal *B–L*: R-parity spontaneously broken
  - Even with even charged Higgs, RSB prefers SRPV
- In both cases R-parity violation is viable:
  - No proton decay.
  - Scale of Sponaneous RPV and B-L breaking = SUSY scale.
  - Interesting for the LHC: Z', no M.E., displaced vertices.
  - Dark matter is still possible.

Global U(1)$_{B-L}$

- MSSM + global U(1)$_{B-L}$ (Aulakh and Mohapatra '82)

$$(B-L)(\tilde{\nu}) = -1 \qquad \langle \tilde{n} u \rangle \neq 0$$

- RPV: $Y_E \, \langle \tilde{\nu} \rangle \, \tilde{H}_d^- \, e^c$ and $g_2 \, \langle \tilde{\nu} \rangle \, \nu \, \tilde{W}^0$
  - Majoron (J): Goldstone boson of broken global U(1)$_{B-L}$

Ruled out by LEP invisible Z decay width

$$Z \rightarrow J\sigma$$

- **Hide Majoron: Singlet Majoron** (Masiero and Valle '90)
  - **Add N, S and 3 ν^c; complicated, motivation?**

$$\Delta W = Y_\nu \, L \, H_u \, \nu^c + Y \, \Phi \, \nu^c \, S$$

Local U(1)$_{B-L}$; Even Higgs

- First proposed in the context of Left-Right Models
  (Mohapatra '86)
- Simplified idea: add 3 ν^c, X and $\bar{X}$

$$\Delta W = Y_\nu \, L \, H_u \, \nu^c + f \, \nu^c \, \nu^c \, X + \mu_X \, X \, \bar{X}$$

$$(B-L)(X) = -2 \qquad \langle X \rangle \neq 0$$

- Nice marriage of:
  - R-parity Conservation
  - Type I seesaw

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & Y_\nu v_u \\ Y_\nu v_u & f \, \langle X \rangle \end{pmatrix} \rightarrow m_\nu \sim \frac{Y_\nu^2 v_u^2}{f \langle X \rangle}$$