Baryonic R-parity violation and Grand Unification

SUSY 2013, ICTP Trieste

Luca Di Luzio

Institut für Theoretische Teilchenphysik

Karlsruhe Institute of Technology

Based on arXiv:1305.7034 in collaboration with:

Marco Nardecchia (CP3-Origins, Odense) and Andrea Romanino (SISSA, Trieste)

Outline

- R-parity violating SUSY @ LHC
- GUT and (baryonic) RPV: the problem
- A simple SO(10) model

MSSM & R-parity

- Most generic superpotential

$$W_{RPC} = \mu\, h_u h_d + y^e_{ij}\, e^c_i l_j h_d + y^d_{ij}\, q_i d^c_j h_d + y^u_{ij}\, q_j u^c_j h_u$$

MSSM & R-parity

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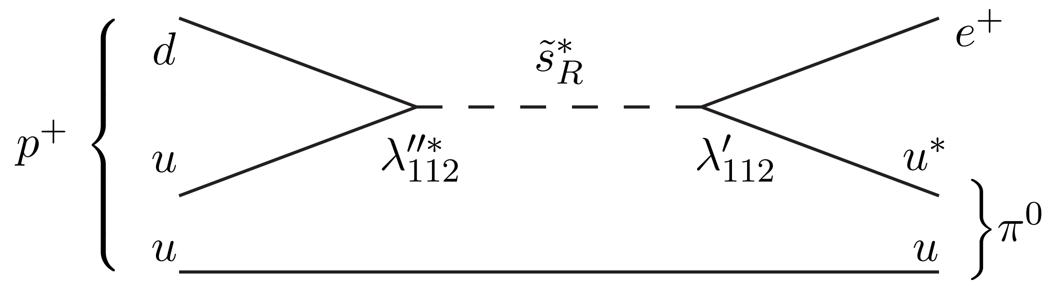
$$W_{RPV} = \mu_i\, h_u l_i + \lambda_{ijk}\, e^c_i l_j l_k + \lambda'_{ijk}\, q_i d^c_j l_k + \lambda''_{ijk}\, u^c_i d^c_j d^c_k$$

- W_{RPV} violates simultaneously L and B number



$$|\lambda' \cdot \lambda''^*| < 10^{-25} \div 10^{-9} \left(\frac{\tilde{m}}{1\ \text{TeV}}\right)^2$$

[Smirnov, Vissani (1996)]

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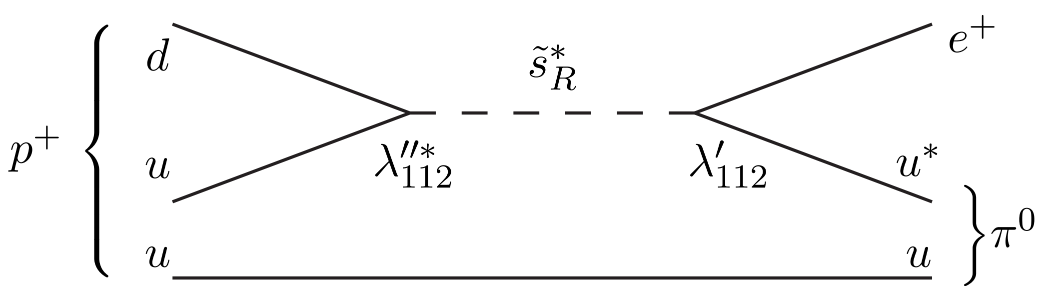

$$|\lambda' \cdot \lambda''^*| < 10^{-25} \div 10^{-9} \left(\frac{\tilde{m}}{1\ \mathrm{TeV}}\right)^2$$

[Smirnov, Vissani (1996)]

- Possible solution: $M_P = (-)^{3(B-L)}$ or (equivalently) $R_P = M_P(-)^{2S}$
  - B and L accidental global symmetries as in SM
  - LSP is stable (DM candidate)
  - LSP escapes the detector (missing energy)

However ...

- R-parity is not necessary
  - Small RPV couplings are "technically natural" (holomorphicity of W)
- R-parity is not sufficient for matter stability

$$W_5 \ni \frac{q\,q\,q\,l}{\Lambda} + \frac{u^c u^c d^c e^c}{\Lambda}$$

- R-parity violation might be welcome
  - Neutrino masses within the MSSM field content
  - DM can still be an unstable gravitino
  - Avoids missing energy signatures: LHC bounds can be relaxed

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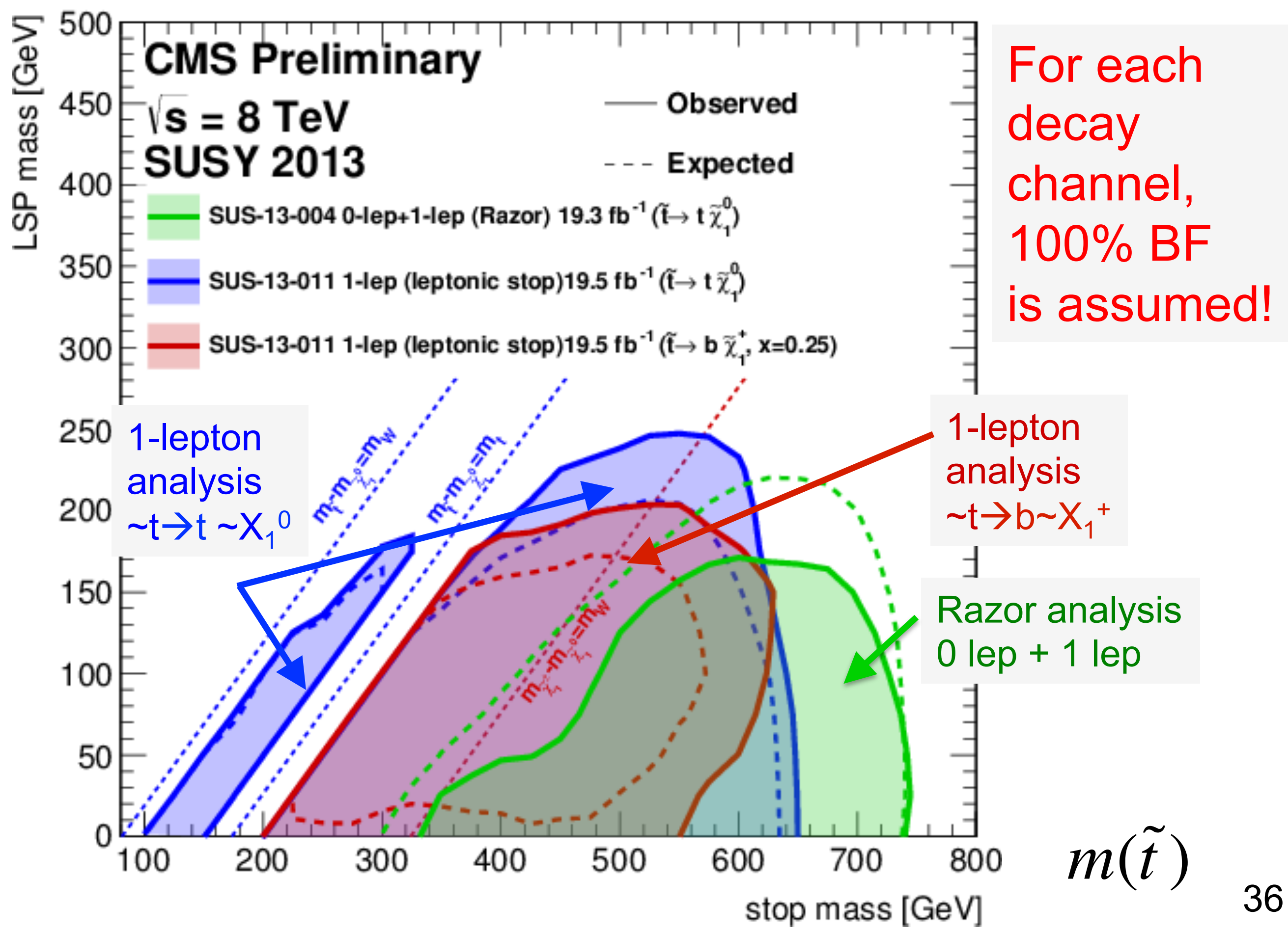
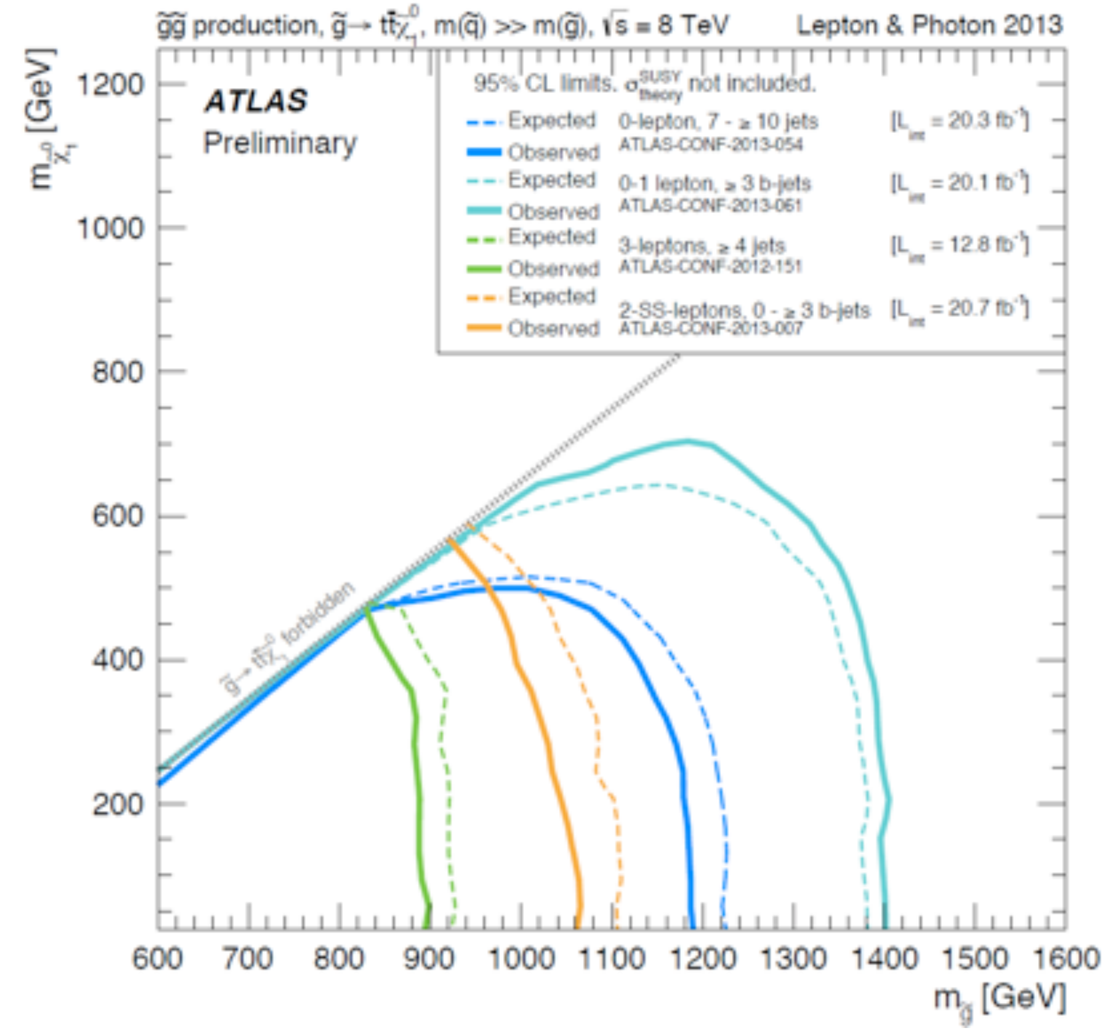
[...] [Brust, Katz, Lawrence, Sundrum (2012)] [Csaki, Grossman, Heidenreich (2012)] [Graham, Kaplan, Rajendran, Saraswat (2012)] [Allanach, Gripaios (2012)] [Dreiner, Staub, Vicente, Porod (2012)] [Brust, Katz, Sundrum (2012)] [Ruderman, Slayter, Weiner (2012)] [Evans, Kats (2012)] [Asano, Rolbiecki, Sakurai (2013)] [Han, Katz, Son, Tweedie (2013)] [Franceschini, Torre (2013)] [Krnjaic, Stolarski (2013)] [Bhattacherjee, Evans, Ibe, Matsumoto, Yanagida (2013)] [Franceschini, Mohapatra (2013)] [Csaki, Heidenreich (2013)] [Berger, Perelstein, Saelim, Tanedo (2013)] [Florez, Restrepo, Velasquez, Zapata (2013)] [Krnjaic, Tsai (2013)] [Monteux (2013)] [Durieux, Smith (2013)] [...]

Natural SUSY exclusions



[See plenary talk by J. Richman and parallel talk by M. D'Alfonso]



[See parallel talk by M. Barisonzi]

$$m_{\tilde{t}} \gtrsim 700 \text{ GeV}$$

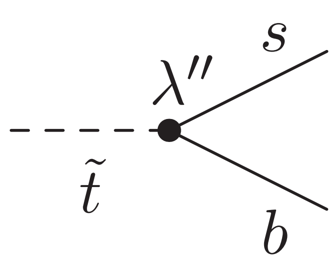
(barring light-stop window)

$$m_{\tilde{g}} \gtrsim 1.4 \text{ TeV}$$

R-parity violation @ LHC

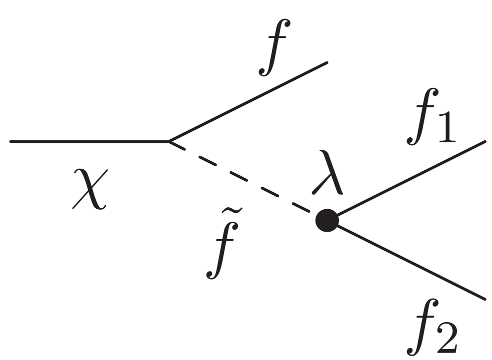
- R-parity violating decays end up into SM fermions

  - Stop decay



$$L = 100\ \mu\mathrm{m}\,(\beta\gamma)\left(\frac{500\ \mathrm{GeV}}{m_{\tilde{t}}}\right)\left(\frac{4\cdot 10^{-7}}{\lambda''}\right)^2$$

  - Neutralino decay



$$L = 100\ \mu\mathrm{m}\,(\beta\gamma)\left(\frac{m_{\tilde{f}}}{500\ \mathrm{GeV}}\right)^4\left(\frac{100\ \mathrm{GeV}}{m_{\chi}}\right)^5\left(\frac{2\cdot 10^{-3}}{\lambda}\right)^2$$

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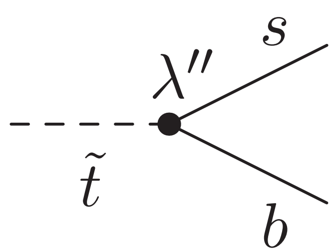

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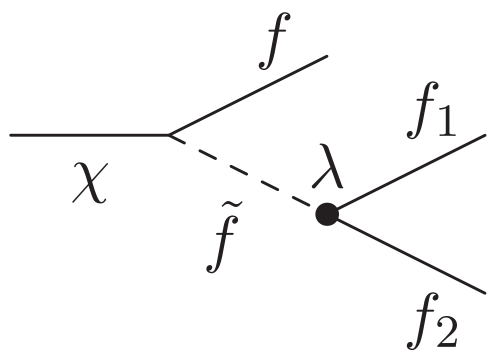

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- Prompt decays require RPV couplings of (at least) $\mathcal{O}(10^{-7})$

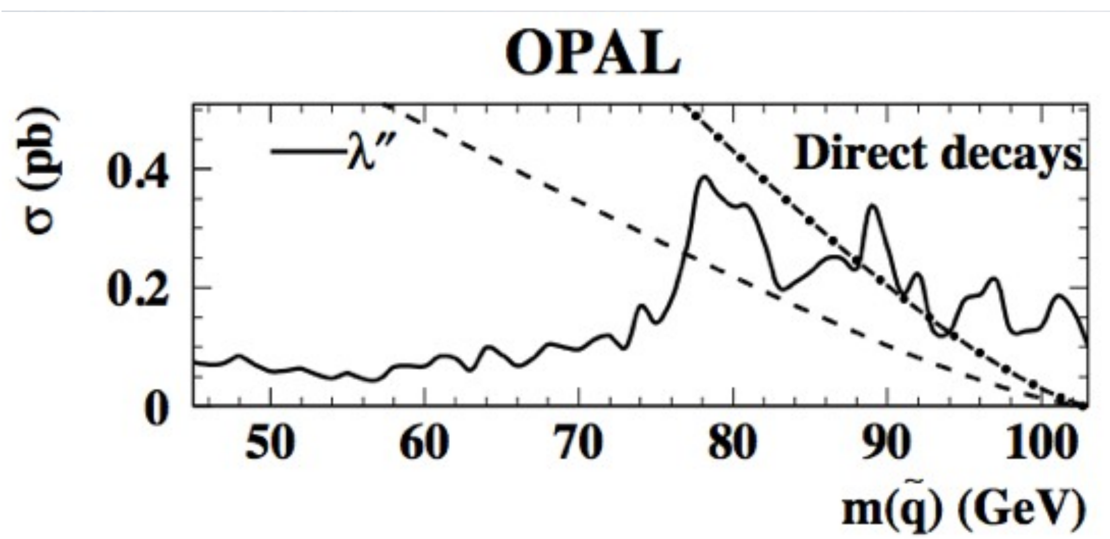
- Either baryonic or leptonic RPV because of p-decay

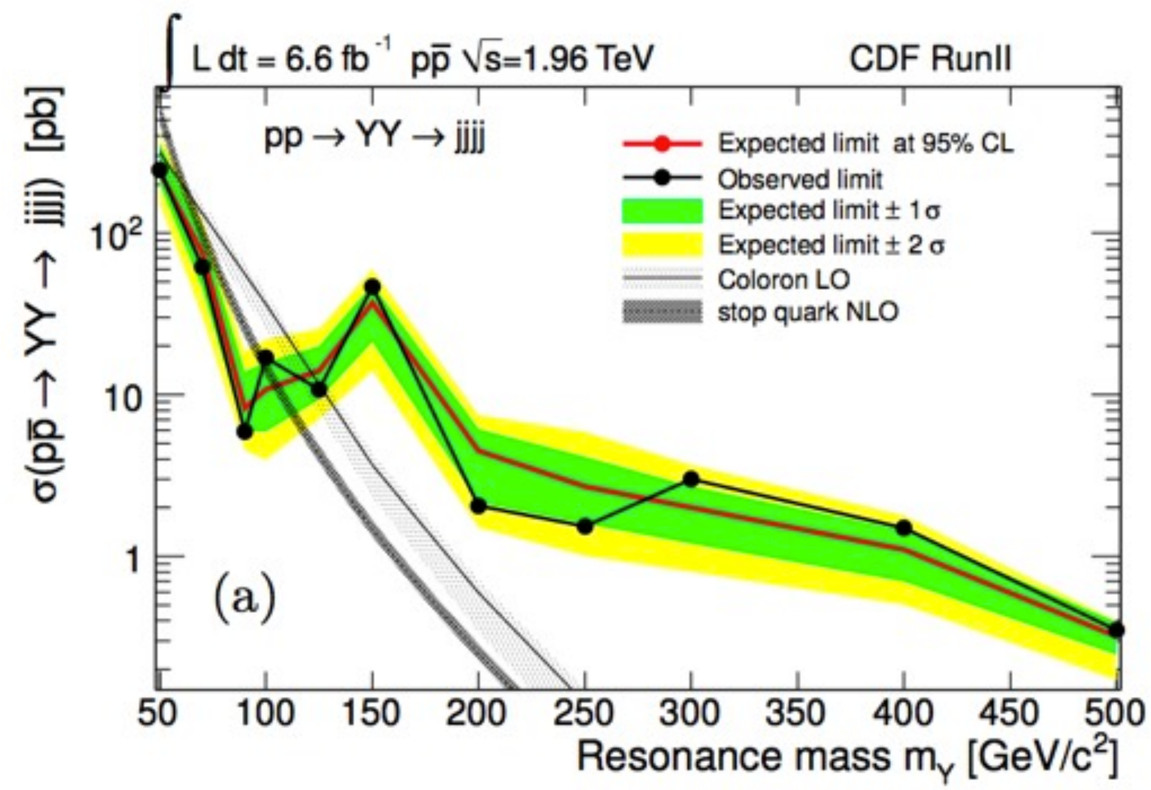
  - Leptonic: many leptons in the final state [See however parallel talk by P. Saraswat]

  - Baryonic: better to hide SUSY into QCD backgrounds

Baryonic RPV stops

- Current limits: LEP + Tevatron



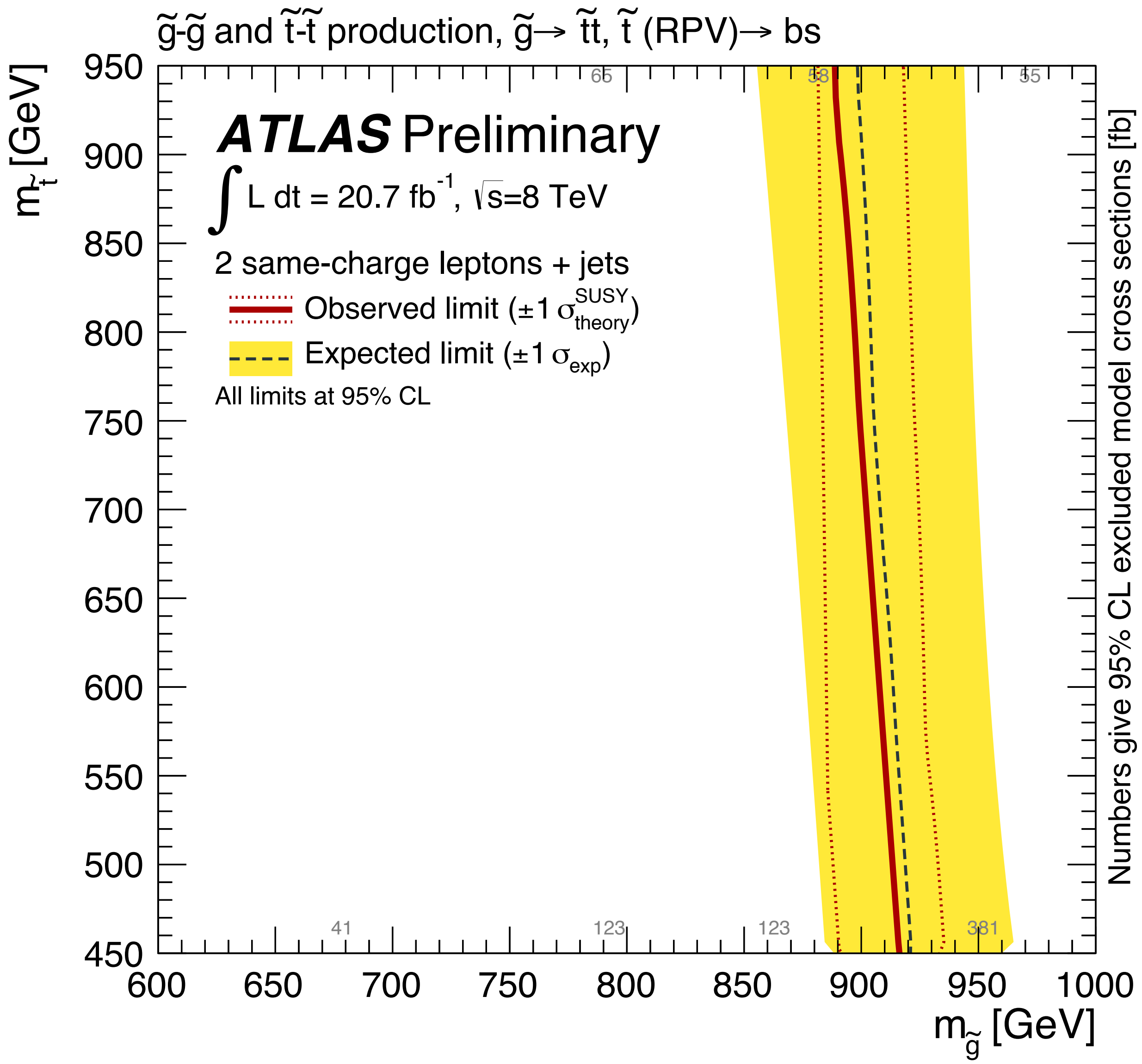


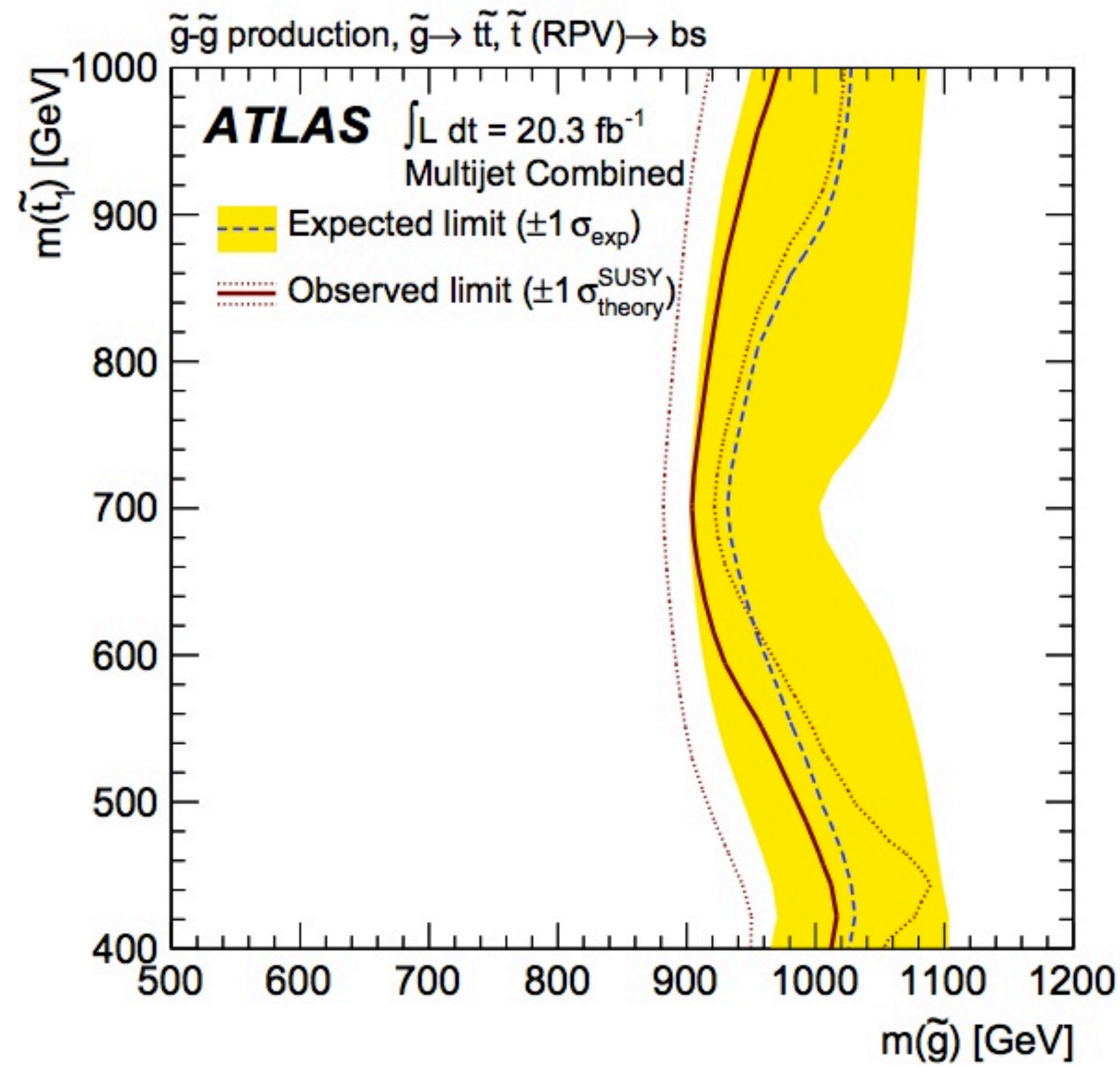
$$m_{\tilde{t}} \gtrsim 100 \text{ GeV}$$

- LHC not sensitive yet (however b-tagging techniques can improve on that)

[Franceschini, Torre (2012)]

Baryonic RPV gluinos





$$m_{\tilde{g}} \gtrsim 1 \text{ TeV}$$

Summary exclusions

- R-parity conserving

$$m_{\tilde{t}} \gtrsim 700 \text{ GeV} \qquad\qquad m_{\tilde{g}} \gtrsim 1.4 \text{ TeV}$$

- Baryonic R-parity violation

$$m_{\tilde{t}} \gtrsim 100 \text{ GeV} \qquad\qquad m_{\tilde{g}} \gtrsim 1 \text{ TeV}$$

- We improve on naturalness [See however parallel talk by M. Baryakhtar]

- But what about unification ???

RPV & GUT

- Natural expectation: RPV couplings either absent or simultaneously present

- $M_P = (-)^{3(B-L)}$ remnant of gauged B-L ? [Martin (1992)] [Mohapatra (1996)] [Aulakh, Bajc, Melfo, Rasin, Senjanovic (2000)] [...]

- Otherwise exact SU(5) invariance $\Longrightarrow$ $\lambda = \frac{1}{2}\lambda' = \lambda'' \equiv \Lambda$

$$\Lambda_{ijk}\,\overline{5}_i\overline{5}_j 10_k \supset \Lambda_{ijk}\,(e^c_i l_j l_k + 2\,q_i d^c_j l_k + u^c_i d^c_j d^c_k)$$

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- Matter stability requires (at least) $\Lambda_{ijk} < 10^{-10}\left(\frac{\tilde{m}}{1\ \mathrm{TeV}}\right)^2 \ll 10^{-7}$ [Smirnov, Vissani (1996)]
- LSP practically stable on the scale of the detector size
- Sizable RPV couplings apparently an issue for unification !

Baryonic RPV & GUT

- $W_{\rm ren} = W_{\rm MSSM} + \lambda''_{ijk} u^c_i d^c_j d^c_k$ [For soft baryonic RPV see parallel talk by Y. Tsai]

  - Minimal SU(5) + 2 x (5 + 5bar) + fine tuning [Smirnov, Vissani (1996)]
  - SU(5) + large representations [Tamvakis (1996)]
  - Flipped SU(5) [Giudice, Rattazzi (1997)]
  - SU(5) x SU(3) [Battacherjee, Evans, Matsumoto, Yanagida (2013)]

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- Rules of the game: [DL, Nardecchia, Romanino (2013)]

  - 4D fully unified gauge group: e.g. SU(5), SO(10), ...
  - Small representations: perturbativity up Planck scale
  - Renormalizable origin of the extra term
  - Absence of fine tuning

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Intuitive idea

- Let us consider SO(10) with the standard embedding of matter

$$16_a = q_a \oplus u^c_a \oplus d^c_a \oplus l_a \oplus e^c_a \oplus \nu^c_a \qquad (a = 1, 2, 3)$$

- To get $u^c d^c d^c$ we need a trilinear term in 16_a

$$\frac{16_H 16_a 16_b 16_c}{\Lambda} \xrightarrow{\langle 16_H \rangle = V_{16}} \frac{V_{16}}{\Lambda} 10_{16_a} \overline{5}_{16_b} \overline{5}_{16_c} \ni e^c l\, l,\; q\, d^c l,\; u^c d^c d^c$$

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- The unwanted operators feature SU(2)$_L$ doublets (q and l)

- An adjoint VEV in the T3R direction can project out the SU(2)$_L$ components

$$\langle 45_H \rangle = V_{45} T_{3R} \qquad\qquad (\langle 45_H \rangle 16_a)_{16} = V_{45}(-u^c_a + d^c_a - \nu^c_a + e^c_a)$$

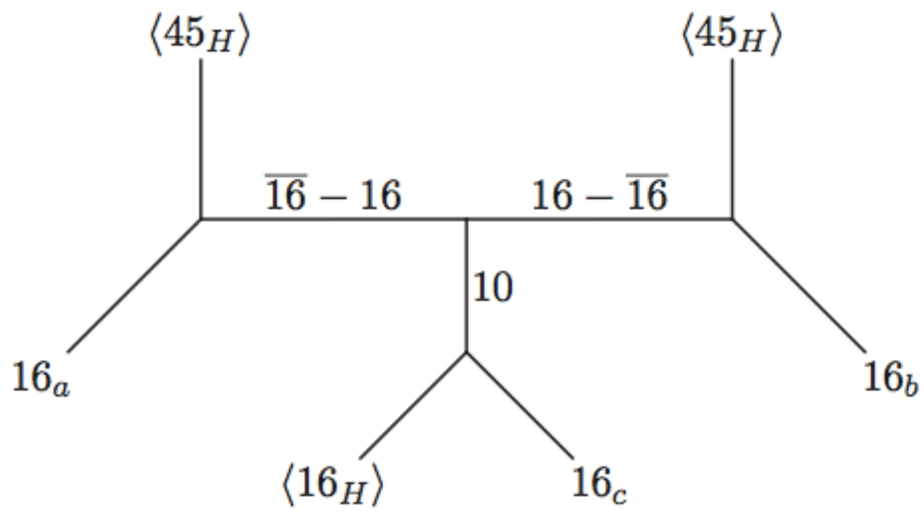
- Analogy with the Dimopoulos-Wilczek mechanism for 2-3 splitting in SO(10)

Intuitive idea

- Hence after SO(10) breaking

$$\frac{16_H (45_H 16_a)_{16} (45_H 16_b)_{16} 16_c}{\Lambda^3} \ni u^c_a d^c_b d^c_c$$

- NR operator points towards its UV completion (not unique)



$$W_{\rm RPV} = \lambda 16\, 16\, 10 + \alpha_a \overline{16}\, 45_H 16_a + \beta_a 16_H 16_a 10 + M_{16} \overline{16} 16 + \frac{M_{10}}{2} 10\, 10$$

- Integrating out the vector-like states in the decoupling limit $V_{45}, V_{16} \ll M_{16}, M_{45}$

$$\lambda''_{abc} = \frac{V_{45}^2\, V_{16}}{M_{16}^2\, M_{10}}\, \lambda\, \alpha_a \alpha_{[b} \beta_{c]}$$

In general ...

- Away from the dec. limit one has to inspect the mass matrices

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$$(\overline{d}^c_{\overline{16}} \;\; \overline{d}^c_{10}) \begin{pmatrix} V_{45}\,\alpha_a & M_{16} & 0 \\ V_{16}\,\beta_a & 0 & M_{10} \end{pmatrix} \begin{pmatrix} d^c_{16_a} \\ d^c_{16} \\ d^c_{10} \end{pmatrix}$$

$$(\overline{l}_{\overline{16}} \;\; \overline{l}_{10}) \begin{pmatrix} 0 & M_{16} & 0 \\ V_{16}\,\beta_a & 0 & M_{10} \end{pmatrix} \begin{pmatrix} l_{16_a} \\ l_{16} \\ l_{10} \end{pmatrix}$$

$$(\overline{u}^c_{\overline{16}}) \begin{pmatrix} -V_{45}\,\alpha_a & M_{16} \end{pmatrix} \begin{pmatrix} u^c_{16_a} \\ u^c_{16} \end{pmatrix}$$

$$(\overline{e}^c_{\overline{16}}) \begin{pmatrix} V_{45}\,\alpha_a & M_{16} \end{pmatrix} \begin{pmatrix} e^c_{16_a} \\ e^c_{16} \end{pmatrix}$$

$$(\overline{q}_{\overline{16}}) \begin{pmatrix} 0 & M_{16} \end{pmatrix} \begin{pmatrix} q_{16_a} \\ q_{16} \end{pmatrix}$$

$$16 \supset d^c_{\rm light} + u^c_{\rm light} + e^c_{\rm light}$$

$$10 \supset d^c_{\rm light} + \ell_{\rm light}$$

In general ...

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$$(\overline{u}^c_{\overline{16}}) \, (-V_{45}\, \alpha_a \;\; M_{16}) \begin{pmatrix} u^c_{16_a} \\ u^c_{16} \end{pmatrix}$$

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$$16 \supset d^c_{\rm light} + u^c_{\rm light} + e^c_{\rm light}$$

$$10 \supset d^c_{\rm light} + \ell_{\rm light}$$

$$16 \to a_i u^c_i$$

$$16 \to b_i d^c_i$$

$$10 \to c_i d^c_i$$

$$\lambda 16\, 16\, 10 \quad \Longrightarrow \quad \lambda''_{ijk} \propto a_i \left(b_j c_k - b_k c_j \right)$$

- Detailed flavour structure depends on the Yukawa sector

Pheno aspects: bounds

- Assume gravitino (LSP) heavier than the proton
- Upper bounds from ΔB = 2 & flavour ($m_{\rm soft} = \mathcal{O}(500\ {\rm GeV})$)

$$
\begin{aligned}
|\lambda''_{uds}| &< \mathcal{O}(10^{-5}) \quad [NN \to KK]\,, & |\lambda''_{cdb}\,\lambda''_{csb}| &< \mathcal{O}(10^{-3}) \quad [K-\overline{K}]\,,\\
|\lambda''_{udb}| &< \mathcal{O}(10^{-2}) \quad [n-\overline{n}]\,, & |\lambda''_{tdb}\,\lambda''_{tsb}| &< \mathcal{O}(10^{-3}) \quad [K-\overline{K}]\,,\\
|\lambda''_{tds}| &< \mathcal{O}(10^{-1}) \quad [n-\overline{n}]\,, & |\lambda''_{ids}\,\lambda''_{idb}| &< \mathcal{O}(10^{-1}) \quad [B^+ \to K^0\pi^+]\,,\\
|\lambda''_{tdb}| &< \mathcal{O}(10^{-1}) \quad [n-\overline{n}]\,, & |\lambda''_{ids}\,\lambda''_{isb}| &< \mathcal{O}(10^{-3}) \quad [B^- \to \phi\pi^-]\,,
\end{aligned}
$$

- Lower bounds from prompt decay (e.g. stop NLSP)

$$
L = 2\,{\rm mm}\,(\beta\gamma)\left(\frac{500\ {\rm GeV}}{m_{\tilde{q}^c}}\right)\left(\frac{0.9\cdot 10^{-7}}{\lambda''}\right)^2
$$

- $10^{-7} \lesssim \lambda'' \lesssim 10^{-5}$ does the job independently of the flavour structure

Pheno aspects: flavour

- GUT correlations

$$\lambda''_{ijk} \propto \alpha_i \beta_{[j} \gamma_{k]} \qquad \Longrightarrow \qquad \frac{\lambda''_{ids}}{\lambda''_{jds}} = \frac{\lambda''_{idb}}{\lambda''_{jdb}} = \frac{\lambda''_{isb}}{\lambda''_{jsb}} \qquad i, j = u, c, t$$

- relevant when many couplings are at play

- Hierarchical flavour pattern is predicted under assumptions

Yukawa $\Longleftarrow$ flavour breaking $\Longrightarrow$ RPV

- Natural to expect λ''_{tbs} as the dominant coupling

Conclusions

- The Naturalness status of the MSSM is under pressure
- R-parity violation (especially baryonic) can help
- Requires a quark-lepton asymmetry in apparent contrast with GUT
- Not necessarily ...
- Simple SO(10) models w/o fine-tuning can be conceived

Backup slides

Yukawa sector

- Add an extra 10_H

$$W_Y = y_{ab} 16_a\, 16_b\, 10_H + y_a 16_a 16\, 10_H + y\, 16\, 16\, 10_H$$

- Possibility to fit charged fermions

- Neutrino masses

  - cannot use R-parity violation because of p-decay

  - ΔL=2 effective operator: e.g. $16_a 16_b \overline{16}_H \overline{16}_H / \Lambda$

Yukawa sector

- Connect the flavour breaking in the Yukawa and RPV sectors

$$W_Y = y_{ab} 16_a\, 16_b\, 10_H + y_a 16_a 16\, 10_H + y\, 16\, 16\, 10_H$$

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- Horizontal SU(3)$_H$ symmetry (16_a ~ triplet)

- SU(3)$_H$ broken by two hierarchical spurions A >> B (A and B ~ anti-triplet)

$$\begin{aligned} \alpha_a &= r_\alpha A_a + s_\alpha B_a\,, \\ \beta_a &= r_\beta A_a + s_\beta B_a\,, \\ y_a &= r_z A_a + s_z B_a\,, \\ y_{ab} &= r_y A_a A_b + s_y B_a B_b + t_y \left(A_a B_b + B_a A_b\right)\,, \end{aligned} \quad \overset{\epsilon \ll 1}{\Longleftrightarrow} \quad \begin{aligned} (\alpha_a) &= \alpha(0,0,1) \\ (\beta_a) &= \beta(0,\epsilon,1) \\ y_{33} &\sim y_3 = \mathcal{O}(1) \\ y_{23} &= y_{32} \sim y_2 = \mathcal{O}(\epsilon) \\ y_{22} &= \mathcal{O}(\epsilon^2) \end{aligned}$$

- Predicts hierarchical pattern $\lambda''_{cbs} = -\epsilon \dfrac{y_{23}}{y_{33}} \lambda''_{tbs}$

- Qualitatively different from other frameworks like MFV-RPV [Nikolidakis, Smith (2008)]

[Csaki, Grossman, Heidenreich (2012)]

VEV alignment

$$W_{\text{vev-align.}} = m_1 45_H^2 + m_2 54_H^2 + \lambda_1 54_H 45_H^2 + \lambda_2 54_H^3$$

$$\langle 45_H \rangle = \text{diag}(V_R, V_R, V_{B-L}, V_{B-L}, V_{B-L}) \otimes i\sigma_2$$

$$\langle 54_H \rangle = \text{diag}(-\tfrac{3}{2}V_{54}, -\tfrac{3}{2}V_{54}, V_{54}, V_{54}, V_{54}) \otimes I$$

- SUSY vacuum implies $F_{45_H} = 0$, namely

$$(m_1 - \tfrac{3}{2}\lambda_1 V_{54})V_R = 0$$

$$(m_1 + \lambda_1 V_{54})V_{B-L} = 0$$

- A solution is provided by $m_1 = \frac{3}{2}\lambda_1 V_{54}$ and $V_{B-L} = 0$