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Update on R-Parity violation at the LHC

based on arXiv:$170(5+i).XXXXX$, $i = \{0, 1, 2\}$

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in collaboration with

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Reminder: R-Parity and R-Parity violation

$$R\text{-Parity: } R = (-1)^{3(B-L)+2s}$$

MSSM with R-Parity conservation (RPV):

$$\begin{aligned} W_{\text{MSSM}} &= \epsilon_{ab}\Big[(Y_u)_{ij}\,\hat{Q}_i^a\,\hat{H}_u^b\,\hat{\bar{U}}_j + (Y_d)_{ij}\,\hat{Q}_i^a\,\hat{H}_d^b\,\hat{\bar{D}}_j \\ &\quad + (Y_e)_{ij}\,\hat{L}^a\,\hat{H}_d^b\,\hat{\bar{E}}_j - \mu\hat{H}_d^a\,\hat{H}_u^b\Big] \end{aligned}$$

additional R-Parity-violating (RPV) terms:

$$\begin{aligned} W_{\text{RPV}} &= \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk}\,\hat{L}_i^a\,\hat{L}_j^b\,\hat{\bar{E}}_k + \lambda'_{ijk}\,\hat{L}_i^a\,\hat{Q}_j^b\,\hat{\bar{D}}_j - \kappa_i\,\hat{L}_i^a\,\hat{H}_u^a\right] \\ &\quad + \frac{1}{2}\epsilon_{xyz}\lambda''_{ijk}\,\hat{\bar{U}}_i^x\,\hat{\bar{D}}_j^y\,\hat{\bar{D}}_k^z \end{aligned}$$

$W_{\rm RPV} = \frac{1}{2}\lambda\, LL\bar{E} + \lambda'\, LQ\bar{D} + \frac{1}{2}\lambda''\, \bar{U}\bar{D}\bar{D}$

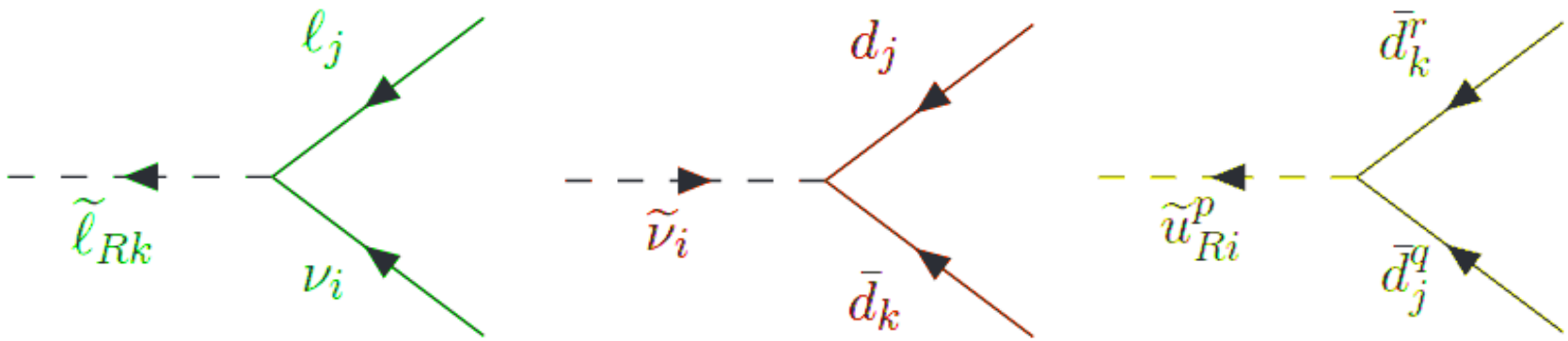
Consequences of R-Parity violation

New interactions with respect to RPC SUSY:

$$\mathcal{L}_{LL\bar{E}} = -\frac{1}{2}\lambda_{ijk}\Big(\tilde{\ell}^*_{Rk}\nu_i\ell_j + \tilde{\nu}_i\ell_j\bar{\ell}_k + \tilde{\ell}_{Lj}\bar{\ell}_k\nu_i - (j \leftrightarrow i)\Big) + \text{h.c.}$$

$$\mathcal{L}_{LQ\bar{D}} = -\lambda'_{ijk}\big(\tilde{d}^*_{Rk}\nu_i d_j + \tilde{\nu}_i d_j \bar{d}_k + \tilde{d}_{Lj}\bar{d}_k\nu_i - \tilde{d}^*_{Rk}\ell_i u_j - \tilde{u}_{Lj}\bar{d}_k\ell_i - \tilde{\ell}_{Li}u_j\bar{d}_k\big) + \text{h.c.}$$

$$\mathcal{L}_{\bar{U}\bar{D}\bar{D}} = -\frac{1}{2}\lambda'_{ijk}\epsilon_{pqr}\big(\tilde{u}^{p*}_{Ri}\bar{d}^q_j\bar{d}^r_k + \tilde{d}^{q*}_{Rj}\bar{u}^p_i\bar{d}^r_k + \tilde{d}^{r*}_{Rk}\bar{u}^p_i\bar{d}^q_j\big) + \text{h.c.}$$



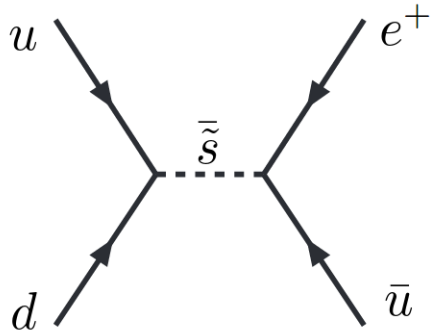
$W_{\text{RPV}} = \frac{1}{2}\lambda\, LL\bar{E} + \lambda'\, LQ\bar{D} + \frac{1}{2}\lambda''\, \bar{U}\bar{D}\bar{D}$

Consequences of R-Parity violation

sfermions couple to two fermions
violates baryon and lepton number

- Proton decay $\Rightarrow$ tight constraints on combinations of RPV operators

  e.g. $\lambda'_{11k} \cdot \lambda''_{11k} \lesssim 2 \cdot 10^{-27} \left(\frac{m_{\tilde{d}_k}}{100\ \text{GeV}} \right)^2$



Does R-Parity *have* to be imposed?

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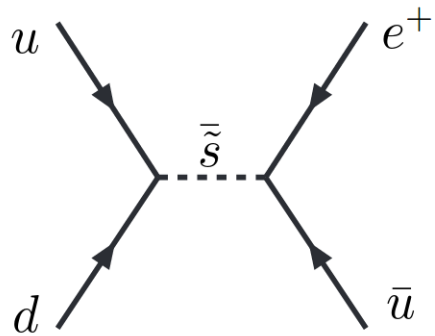


Does R-Parity *have* to be imposed?

No.

Other discrete symmetries as good as R-Parity: baryon triality, lepton parity [Dreiner,Luhn,Thormeier '05; Smirnov,Vissani '96]

$\Rightarrow$ If SUSY is taken seriously, then so should RPV-SUSY

$W_{\text{RPV}} = \frac{1}{2}\lambda\, LL\bar{E} + \lambda'\, LQ\bar{D} + \frac{1}{2}\lambda''\, \bar{U}\bar{D}\bar{D}$

LHC phenomenology

SUSY with conserved R-Parity

- pair-production of SUSY particles
- SUSY particles cascade-decay down to LSP, LSP escapes

$\Rightarrow$ High-energetic objects from decays, no resonances

$\Rightarrow$ Large amount of missing transverse momentum (MET)

SUSY with broken R-Parity

- resonant sfermion production possible
- LSP is unstable, many different decay possibilities depending on RPV operator
- (Possibly displaced vertices)

$\Rightarrow$ MET reduced or absent; resonances or double-resonances

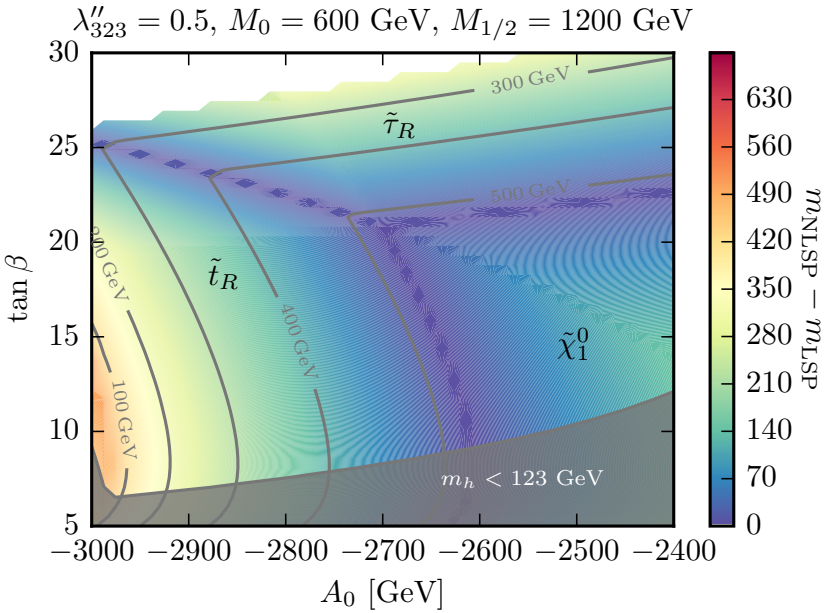
$\Rightarrow$ LHC pheno different for almost every coupling combination

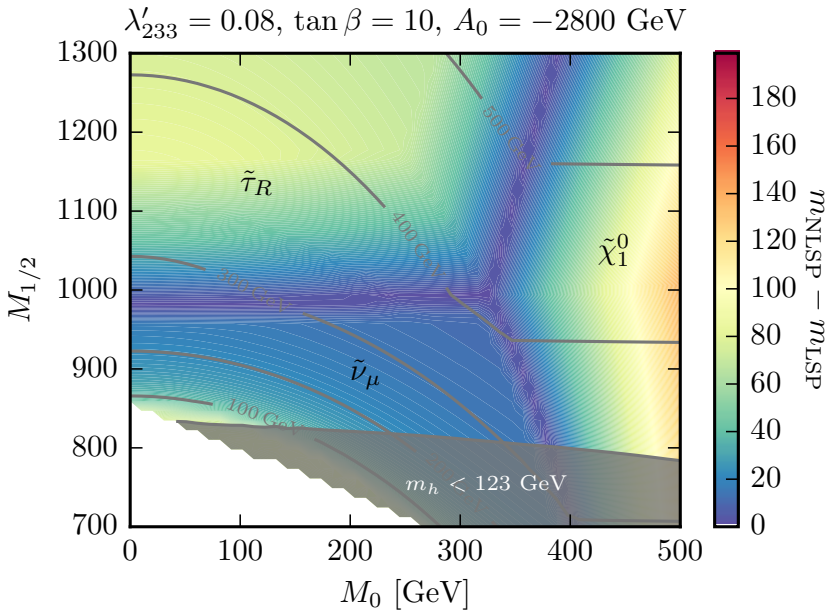
$W_{\text{RPV}} = \frac{1}{2}\lambda\, LL\bar{E} + \lambda'\, LQ\bar{D} + \frac{1}{2}\lambda''\, \bar{U}\bar{D}\bar{D}$

Other LSPs. What's the deal?

RPC-MSSM: forbid every param. space with non-neutralino LSP

RPV: Even with CMSSM boundaries, almost any LSP is possible





LHC pheno for instance: Produce $pp \to \tilde{t}\tilde{t}^*$

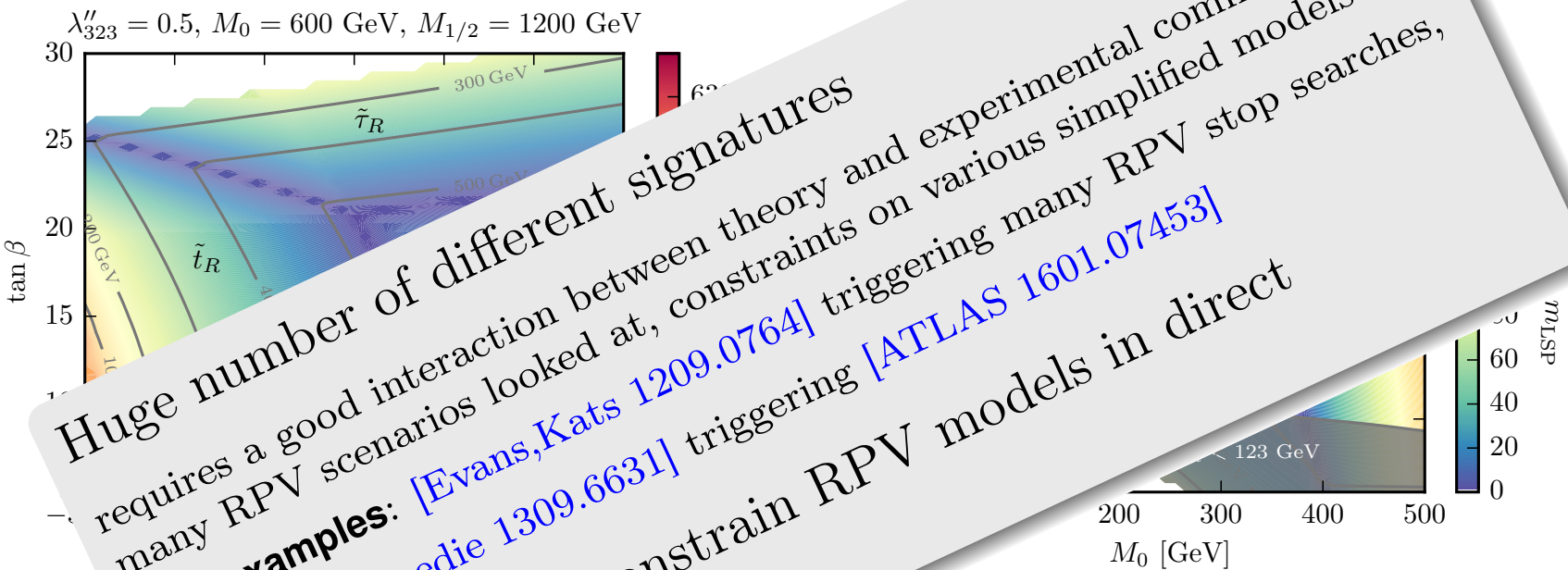
1. $\tilde{t}$ LSP: $\tilde{t}^* \to bs$; double-dijet resonance including b-jets
2. $\tilde{\chi}_1^0$ LSP: $\tilde{t}^* \to \bar{t}\tilde{\chi}_1^0 \to \bar{t}tbs$; many jets, possibly leptons & MET
3. $\tilde{\tau}$ LSP: $\tilde{t}^* \to \bar{t}\tilde{\chi}_1^0 \to \bar{t}\bar{\tau}\tilde{\tau}$; $\tilde{\tau} \to \nu bbs$; many jets, (τ) leptons, MET

$W_{\text{RPV}} = \frac{1}{2}\lambda\, LL\bar{E} + \lambda'\, LQ\bar{D} + \frac{1}{2}\lambda''\, \bar{U}\bar{D}\bar{D}$

Other LSPs. What's the deal?

RPC-MSSM: forbid every param. space with n… LSP

RPV: Even with CMSSM boundaries, alm… sible



Huge number of different signatures

requires a good interaction between theory and experimental community

many RPV scenarios looked at, constraints on various simplified models

Nice examples: [Evans,Kats 1209.0764] triggering many RPV stop searches, [Bai,Katz,Tweedie 1309.6631] triggering [ATLAS 1601.07453]

How well can we constrain RPV models in direct comparison to RPC?

LHC … $pp \to \tilde{t}\tilde{t}^*$

1. $\tilde{t}$ LS… …ujet resonance including b-jets
2. $\tilde{\chi}_1^0$ LS… $\to \bar{t}tbs$; many jets, possibly leptons & MET
3. $\tilde{\tau}$ LSP: … $t\tilde{\chi}_1^0 \to \bar{t}\bar{\tau}\tilde{\tau}$; $\tilde{\tau} \to \nu bbs$; many jets, (τ) leptons, MET

Setup

- consider small RPV couplings
  $\Rightarrow$ same spectrum as RPC but with prompt LSP decay
  $\Rightarrow$ directly compare RPC and RPV models
- take CMSSM boundary conditions, usual setup:
  $\tan\beta = 30,\ A_0 = -2M_0$
- use `CheckMATE` and all implemented searches [Drees et al. '13]

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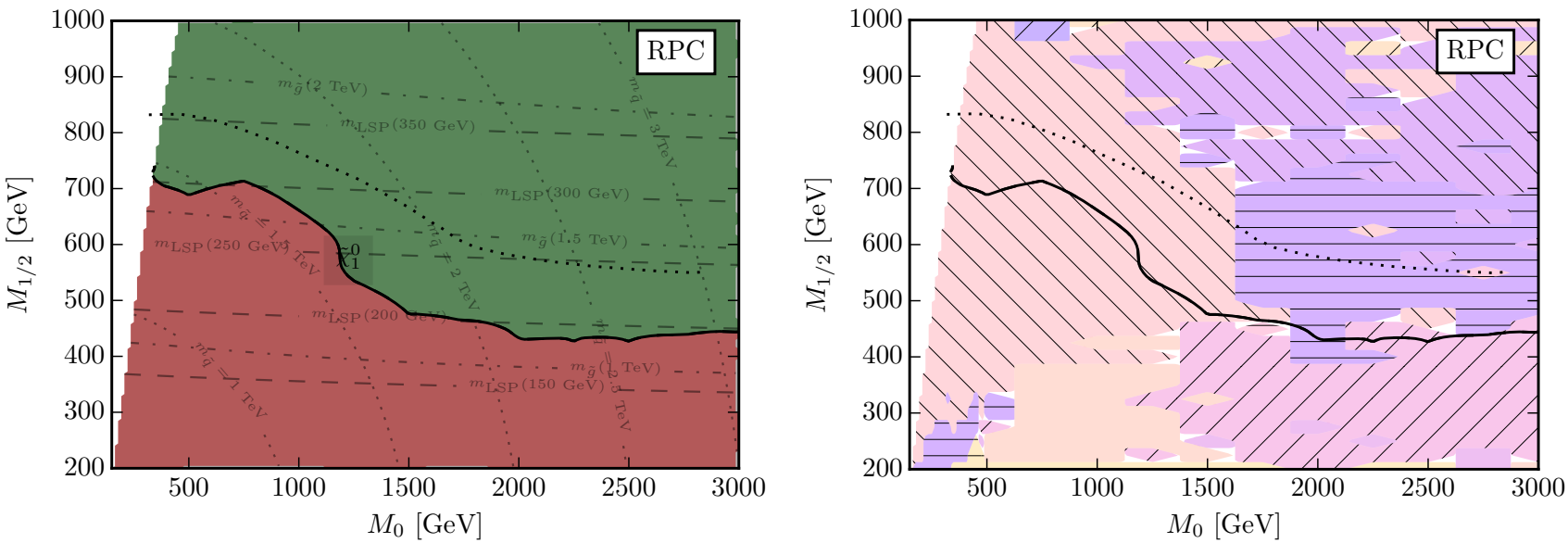
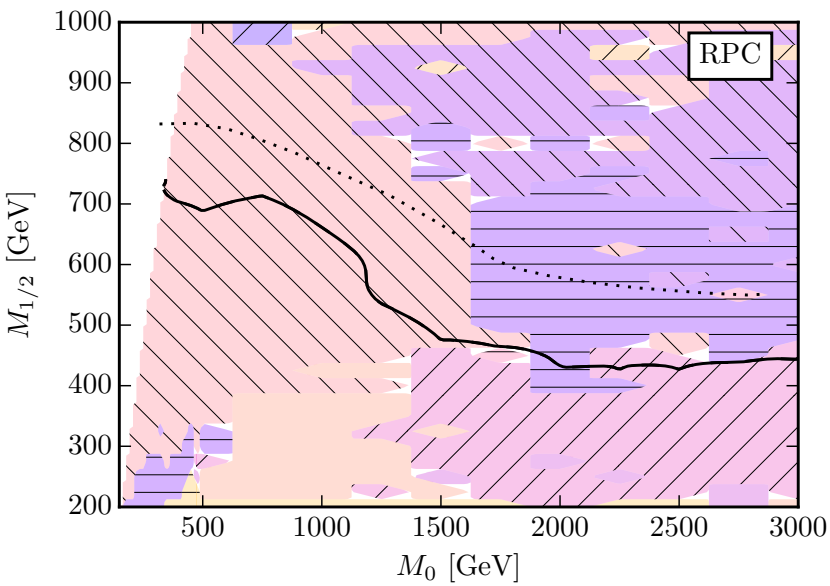
RPC-CMSSM:

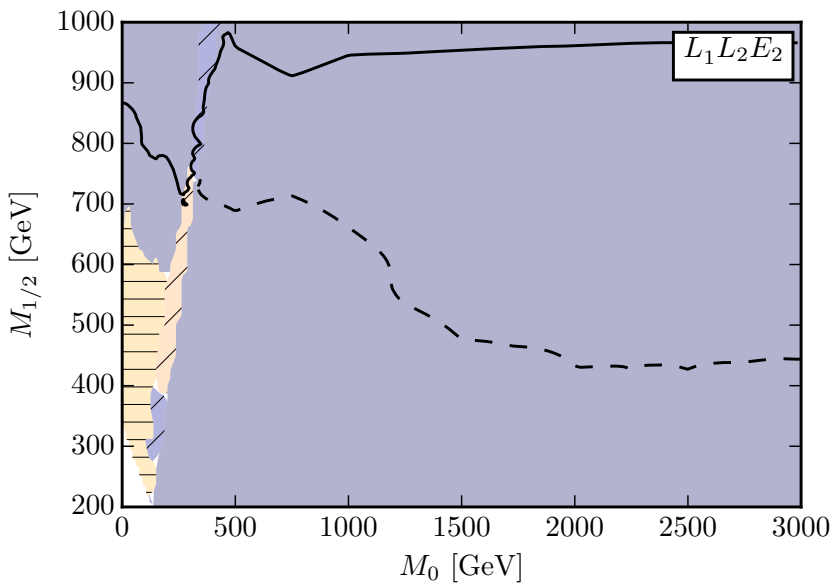


Recasting: RPV-CMSSM vs CMSSM

LLE-RPV vs RPC

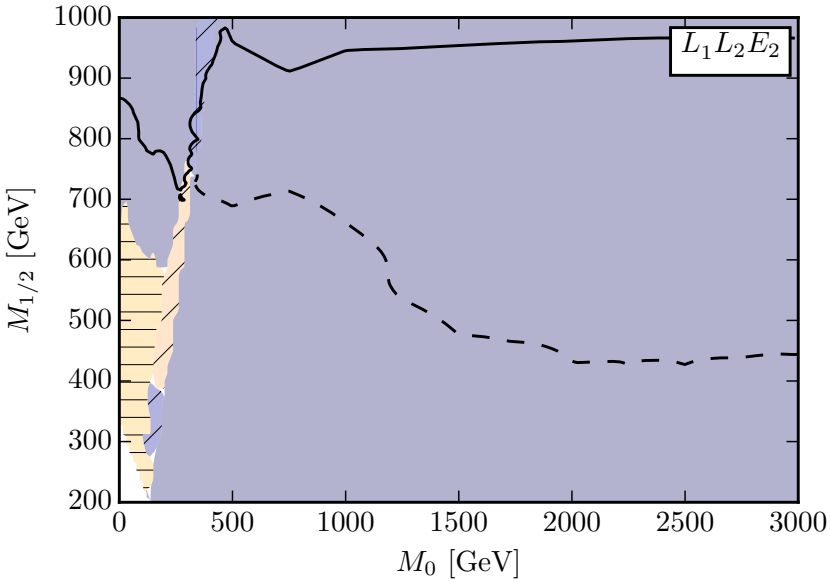
atlas_conf_2013_036 4ℓ + MET	**cms_1405_7570** various electroweakino searches	**atlas_1403_4853** 2ℓ + MET	**atlas_1501_07110** 1ℓ + Higgs + MET
atlas_1403_5294 2ℓ + MET	**atlas_1402_7029** 3ℓ + MET	**atlas_1407_0583** 1ℓ + $1b$ + MET	**cms_1504_03198** 1ℓ + $\geq 3j$ incl $\geq 1b$ + MET
atlas_1407_0600 $0-1\ell$ + $3b$ + MET	**atlas_conf_2013_061** $0-1\ell$ + $3b$ + MET	**atlas_conf_2013_024** 0ℓ+ $6j$ incl. $2b$ + MET	**atlas_1405_7875** 0ℓ + $2-6j$ + MET
atlas_1308_1841 0ℓ + $\geq 7j$ + MET	**atlas_conf_2013_062** $1-2\ell$ + $3-6j$ + MET	**atlas_1404_2500** 3ℓ or same-sign 2ℓ	**atlas_conf_2014_056** $t\bar{t}$ spin measurement
atlas_conf_2013_031 Higgs to WW spin measurement			

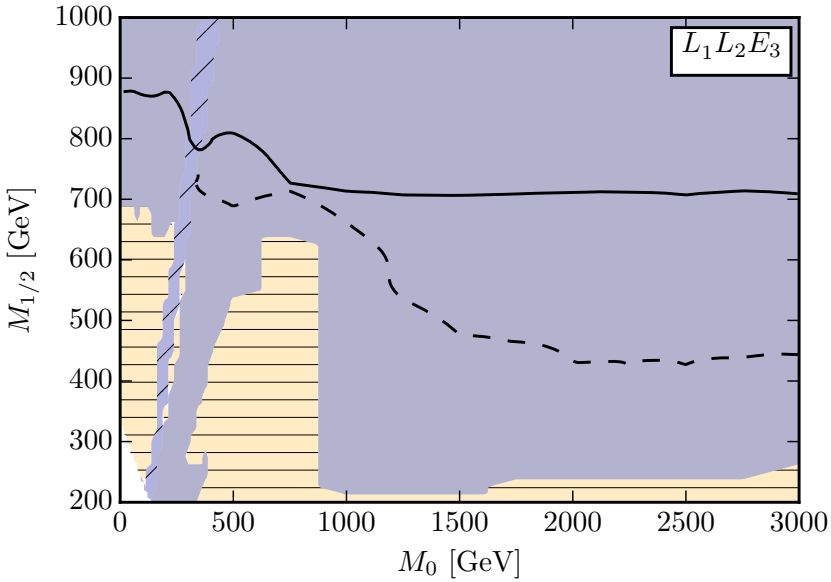




Recasting: RPV-CMSSM vs CMSSM

LLE-RPV vs RPC





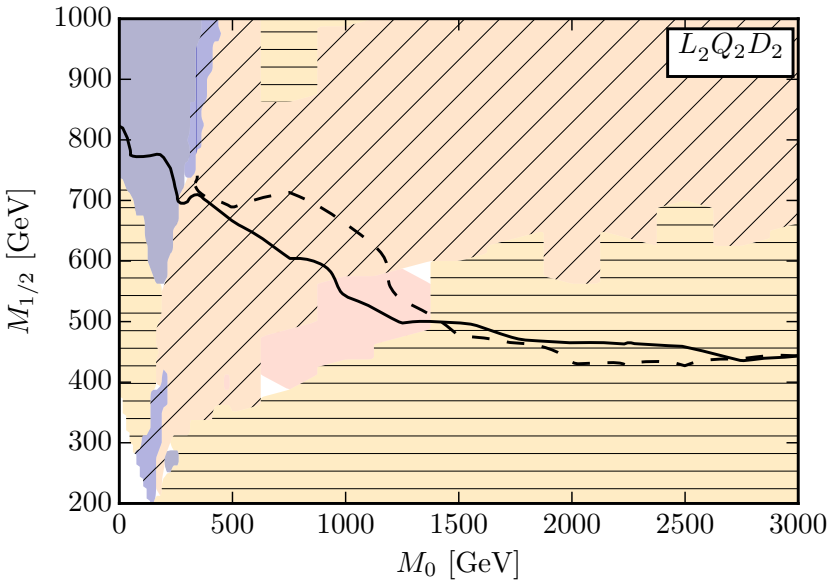
Electroweakino-pair-production dominates the discovery channels!

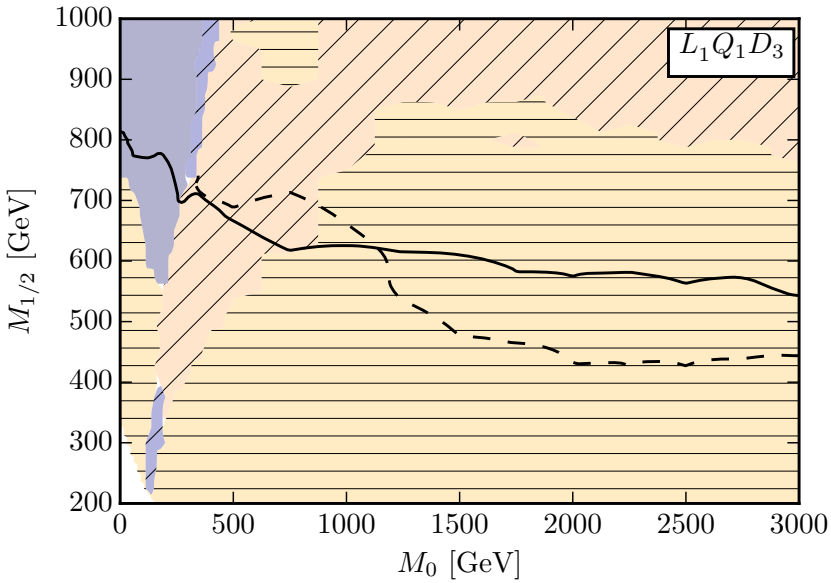
- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \to \ell\ell\nu$
- $\tilde{\tau}$ LSP: $\tilde{\chi}_1^0 \to \tau\tilde{\tau}$; $\tilde{\tau} \to e\nu/\tau\nu$ (via RGE-generated λ_{133})

- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \to \ell\tau\nu$
- $\tilde{\tau}$ LSP: $\tilde{\chi}_1^0 \to \tau\tilde{\tau}$; $\tilde{\tau} \to \ell\nu$

Recasting: RPV-CMSSM vs CMSSM

LQD-RPV vs RPC





- bounds comparable to RPC
- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \to \mu jj/\nu jj$
- $\tilde{\tau}$ LSP: $\tilde{\chi}_1^0 \to \tau\tilde{\tau}$; $\tilde{\tau} \to \mu\nu/\tau\nu$ (via RGE-generated λ_{233})

- more constrained than RPC for large M_0: b-tags
- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \to ebj/\nu bj$
- $\tilde{\tau}$ LSP: $\tilde{\chi}_1^0 \to \tau\tilde{\tau}$; $\tilde{\tau} \to \tau ebj/\tau\nu bj$

Recasting: RPV-CMSSM vs CMSSM

UDD-RPV vs RPC

atlas_conf_2013_036 4ℓ + MET	**cms_1405_7570** various electroweakino searches	**atlas_1403_4853** 2ℓ + MET	**atlas_1501_07110** 1ℓ + Higgs + MET
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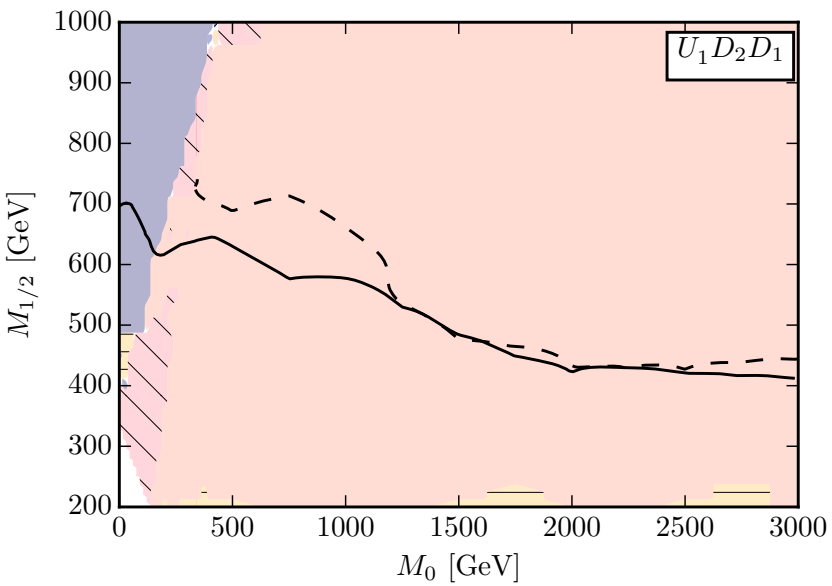
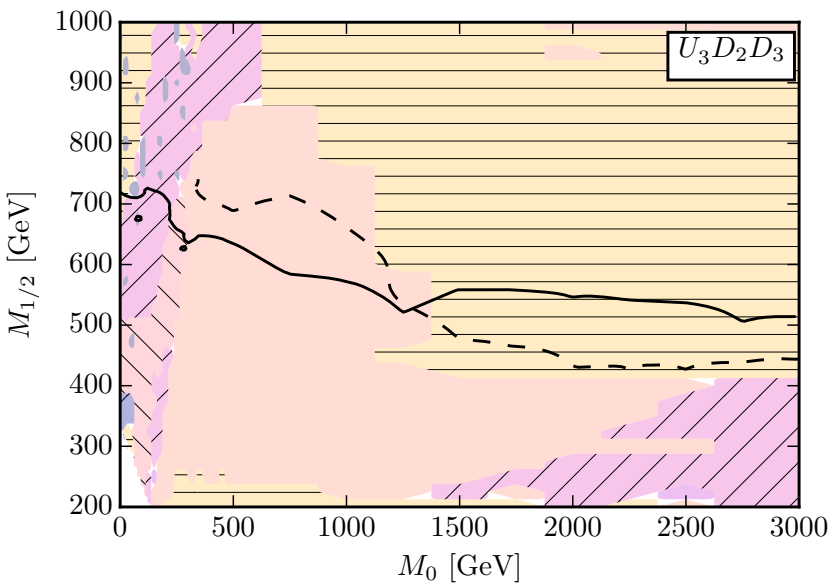




Conclusions

- Searches for RPV at the LHC need to consider much larger variety of final states than searches for RPC SUSY
- Good interaction between theory and experimental community: many different RPV-motivated scenarios considered
- RPV models are well-covered at the LHC
  Contrary to the common lore, bounds are comparable to RPC SUSY

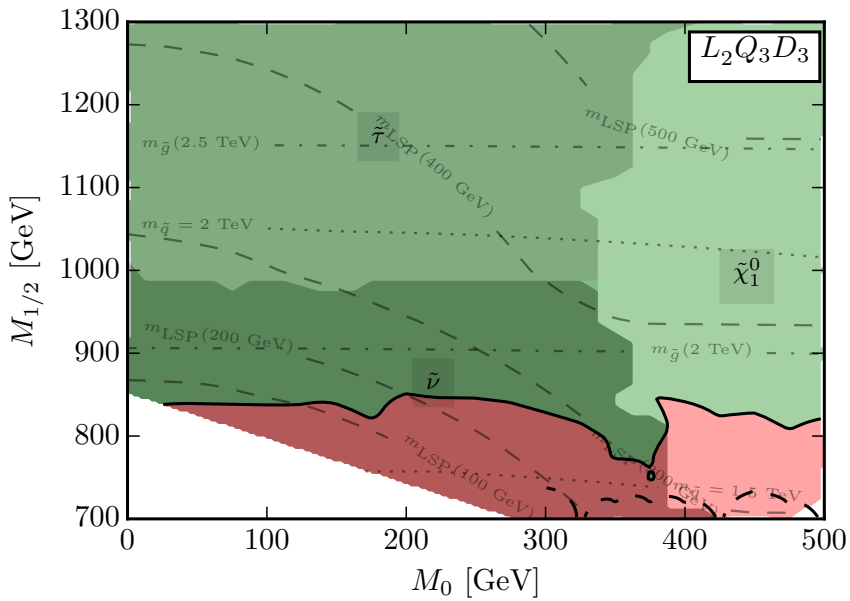
Thank you.

Criticism

- In gluino LSP scenarios with UDD: exp. analyses often consider all λ'' couplings on at the same time $\Rightarrow$ necessarily signal regions sensitive to tops dominate the exclusion bounds. It's not clear how the bounds change for, e.g., λ''_{121}.
- Little effort put into stau LSP scenarios

Large RPV couplings

For non-coloured and non-stau LSPs, the LHC phenomenology is usually similar compared to the neutralino LSP:



coloured prod.→ decay to neutralino → decay to on-shell LSP→...
coloured prod.→ decay to neutralino → decay via off-shell LSP→...