R-PARITY VIOLATION AT THE LHC

BASED ON ARXIV:1706.XXXXX

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in collaboration with

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Reminder: R-Parity and R-Parity violation

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

MSSM with R-Parity conservation (RPC):

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

additional R-Parity-violating (RPV) terms:

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

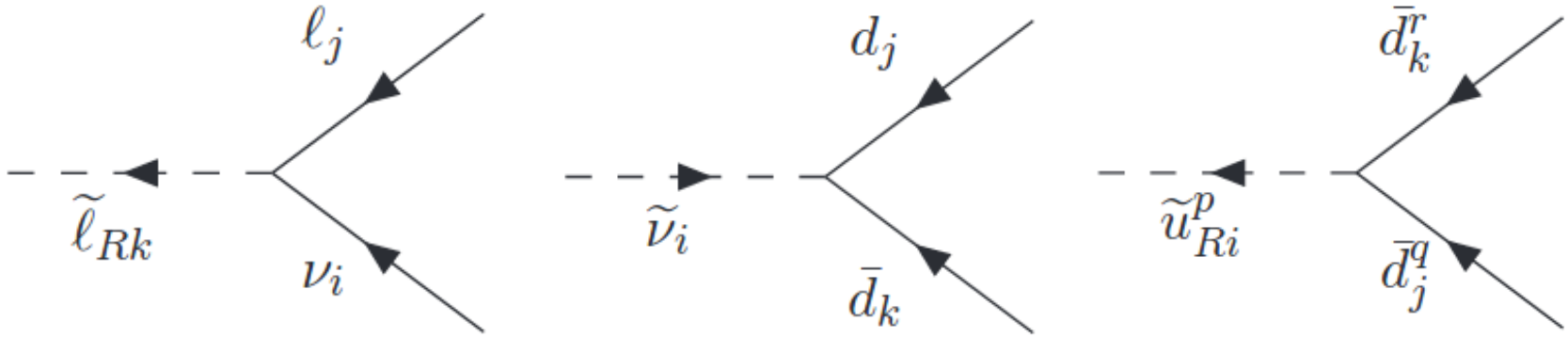
Consequences of R-Parity violation

New interactions with respect to RPC SUSY:

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

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

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



LHC phenomenology

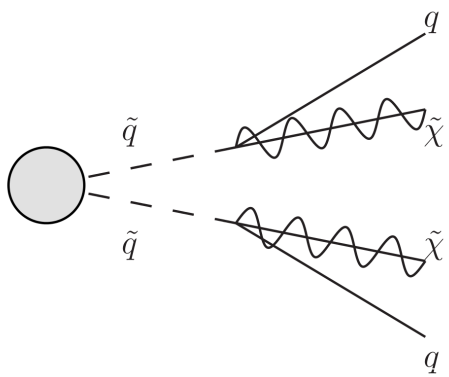
– SUSY with conserved R-Parity –

even number of SUSY particles per vertex

$\Rightarrow$ pair-production of SUSY particles

$\Rightarrow$ SUSY particles cascade-decay down to lightest supersymmetric particle (LSP)

$\Rightarrow$ LSP is stable and escapes



Search for

- High-energetic objects from decays, no resonances
- Large amount of missing transverse momentum (MET)

LHC phenomenology

– SUSY with broken R-Parity –

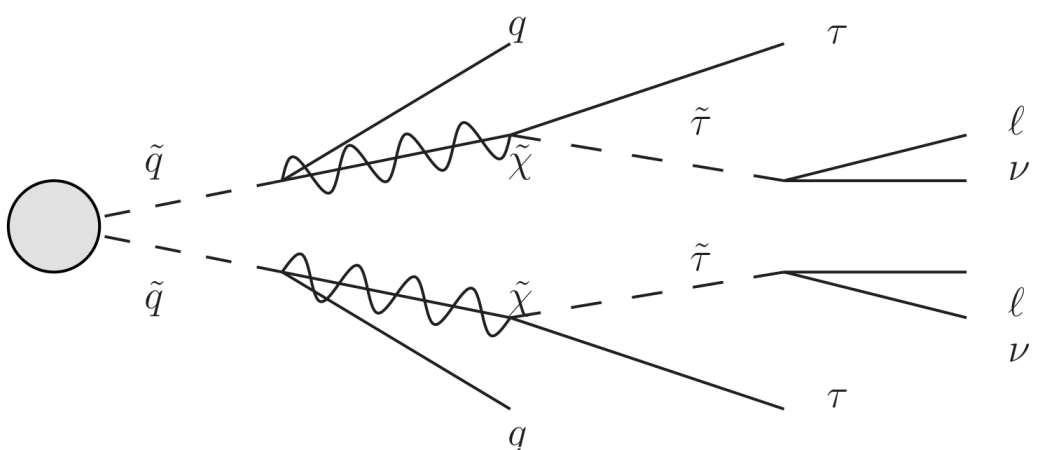
odd number of SUSY particles per vertex possible

- LSP can be any SUSY particle
- LSP decays

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

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

e.g.



"Turning on RPV helps weakening collider constraints"

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Is this statement still true?

- based on 'early' LHC where many searches were optimised for SUSY CMSSM scenarios
- true for certain simplified models [e.g. Buckley et al. '16]
- what's the situation now?
  ⇒ compile all relevant RPV signatures, their LHC coverage and the respective bounds (⟶ see upcoming paper)
  ⇒ compare coverage of CMSSM vs. RPV-CMSSM

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(RPV-)CMSSM

parameters at the unification scale ($M_{\rm GUT} \sim 10^{16}$ GeV):

$$m^2_{\text{soft, scalar}} = M_0^2\,, \qquad M_{\text{soft, gaugino}} = M_{1/2}\,,$$

$$T_{ij} = Y_{ij}\, A_0\,, \qquad \text{sign}(\mu)\,, \qquad \tan\beta = \frac{v_u}{v_d}$$

$$\Lambda_{\not{R}_p}$$

Recasting LHC results: 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 8 TeV searches [Drees et al. '13]
- Limitations: only leading order, no combination of signal regions

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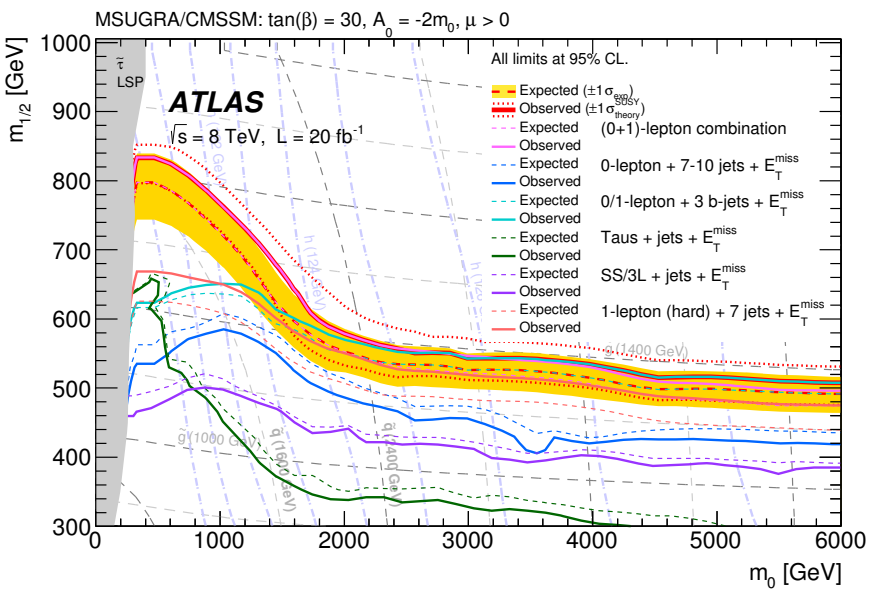
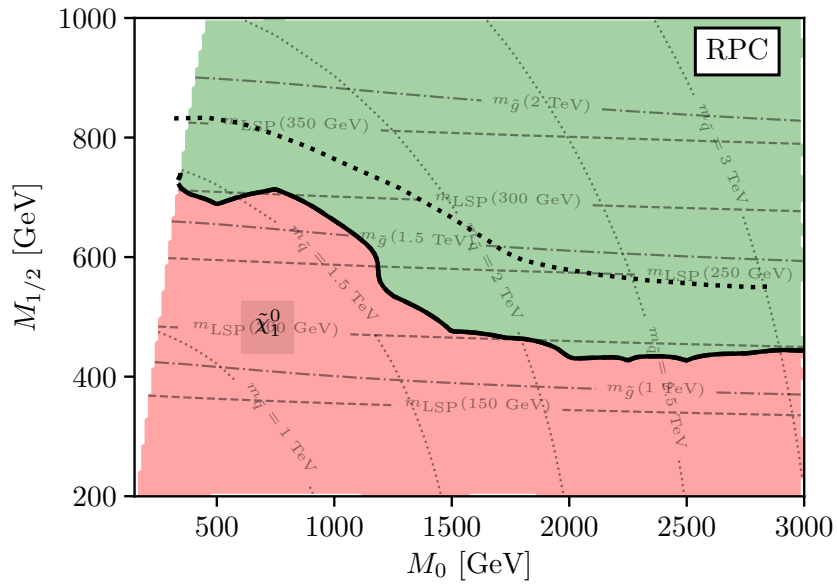
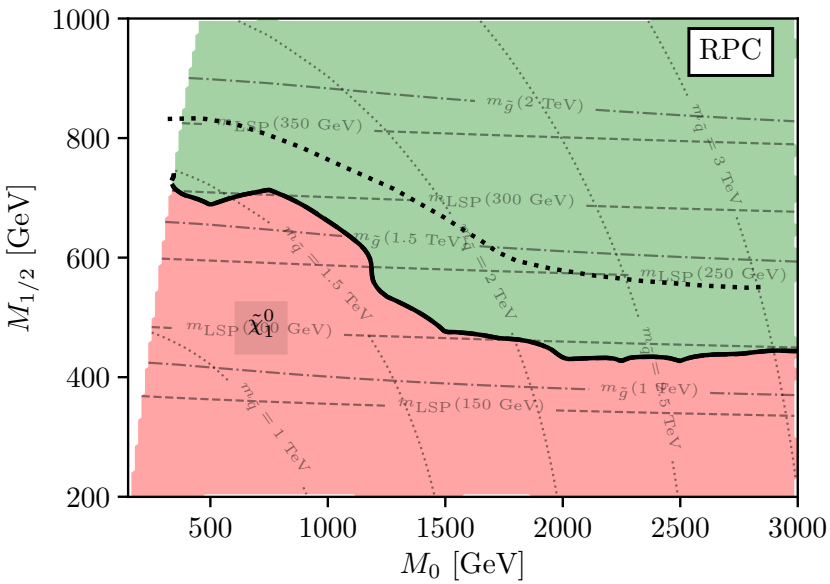
RPC-CMSSM:

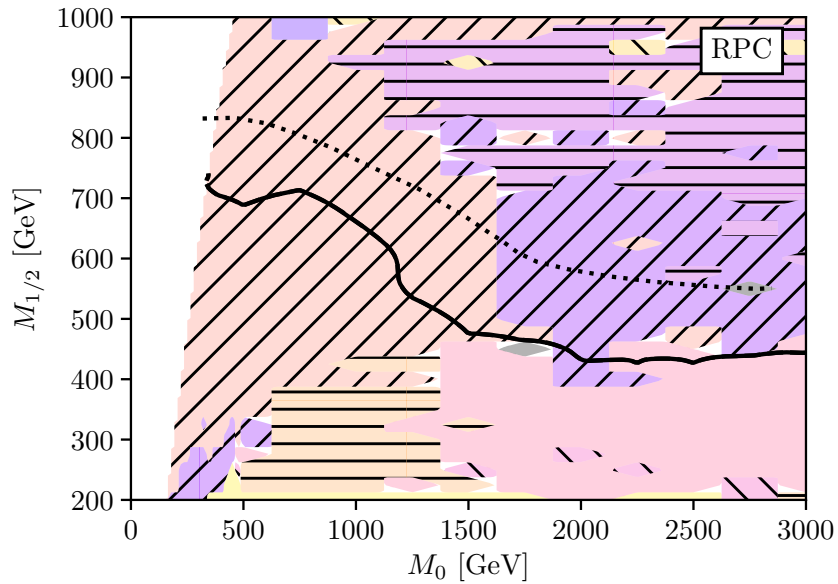




Recasting LHC results, RPC

atlas_conf_2013_036 4ℓ + MET	**cms_1405_7570** various electroweakino searches	**atlas_1403_4853** 2ℓ + MET	**atlas_1403_5294** 2ℓ + MET
atlas_1402_7029 3ℓ + MET	**atlas_1407_0583** $1\ell + 1b$ + MET	**cms_1504_03198** $1\ell + \geq 3j$ incl $\geq 1b$ + MET	**atlas_1407_0600** $0-1\ell + 3b$ + MET
atlas_conf_2013_061 $0-1\ell + 3b$ + MET	**atlas_1405_7875** $0\ell + 2-6j$ + MET	**atlas_1308_1841** $0\ell + \geq 7j$ + MET	**atlas_conf_2013_062** $1-2\ell + 3-6j$ + MET
atlas_1404_2500 3ℓ or same-sign 2ℓ			





Recasting LHC results, $LL\bar{E}$

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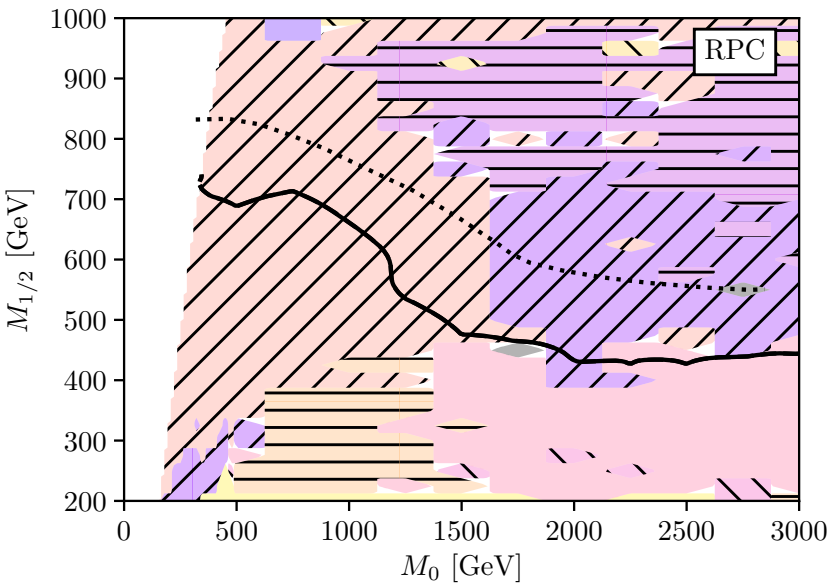
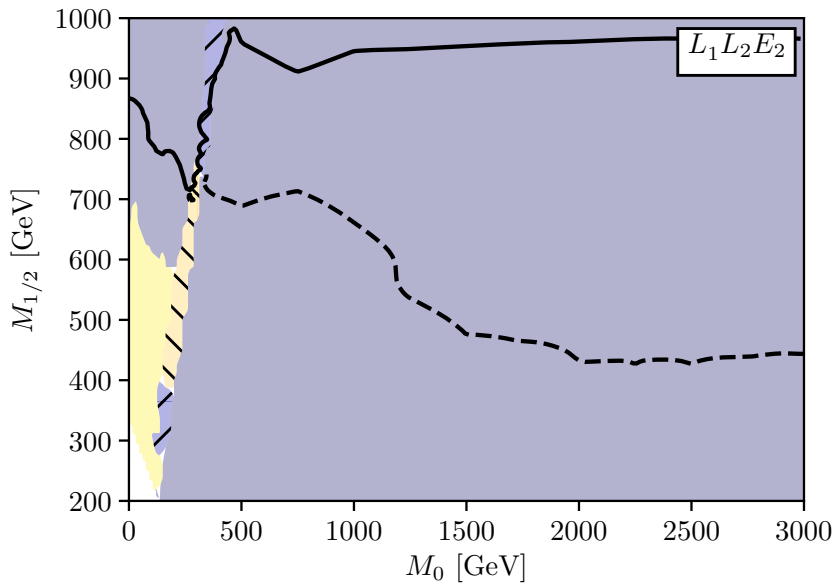
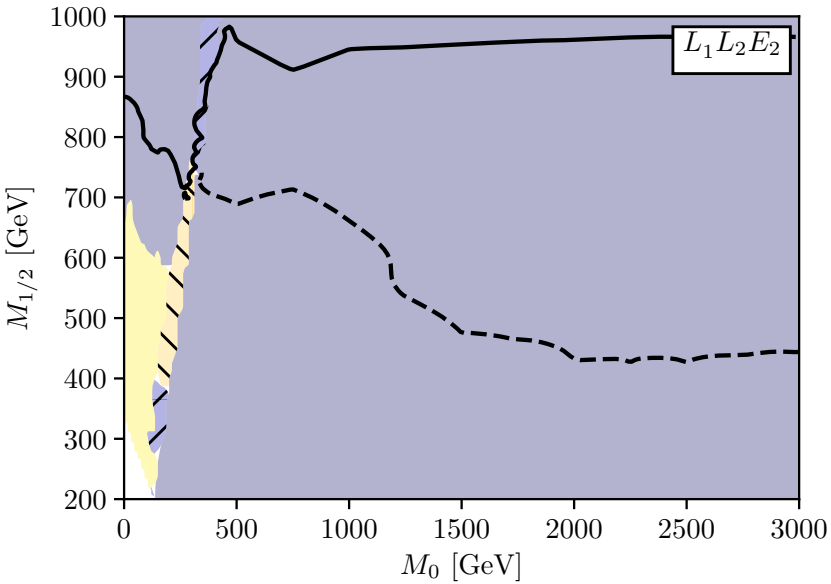
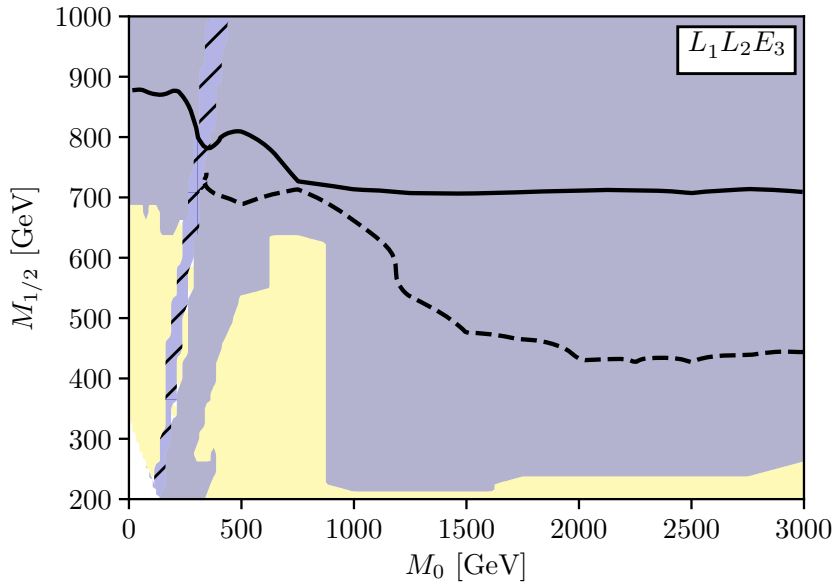
atlas_1402_7029 3ℓ + MET	**atlas_1407_0583** 1ℓ + $1b$ + MET	**cms_1504_03198** 1ℓ + $\geq 3j$ incl $\geq 1b$ + MET	**atlas_1407_0600** $0-1\ell$ + $3b$ + MET
atlas_conf_2013_061 $0-1\ell$ + $3b$ + MET	**atlas_1405_7875** 0ℓ + $2-6j$ + MET	**atlas_1308_1841** 0ℓ + $\geq 7j$ + MET	**atlas_conf_2013_062** $1-2\ell$ + $3-6j$ + MET
atlas_1404_2500 3ℓ or same-sign 2ℓ			





Recasting LHC results, $LL\bar{E}$





Electroweakino-pair-production dominates the discovery channels!

$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$$

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z/h, \qquad \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^\pm \qquad \text{or}$$
$$\tilde{\chi}_2^0 \to \tilde{\ell}_i \ell_i / \tilde{\nu}_j \nu_j, \qquad \tilde{\chi}_1^\pm \to \tilde{\ell}_i \nu_i / \tilde{\nu}_j \ell_j$$

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

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

Recasting LHC results, $LQ\bar{D}$

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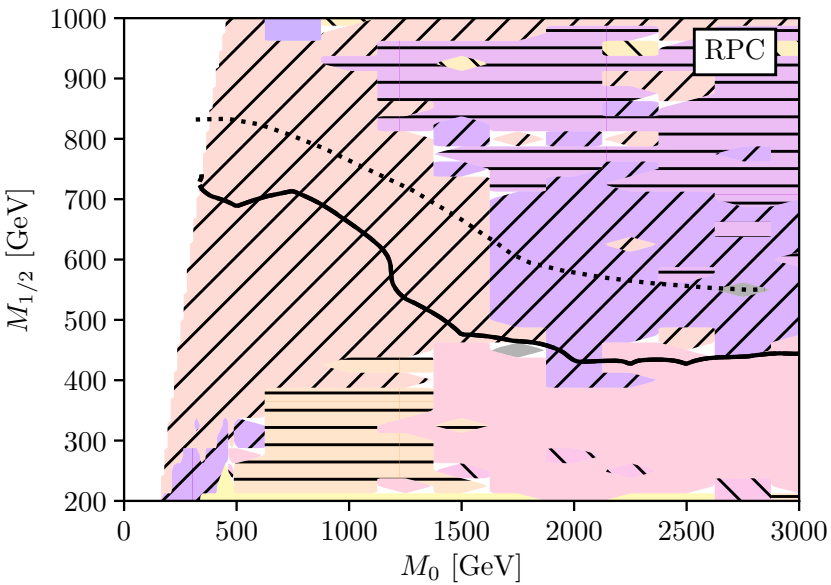
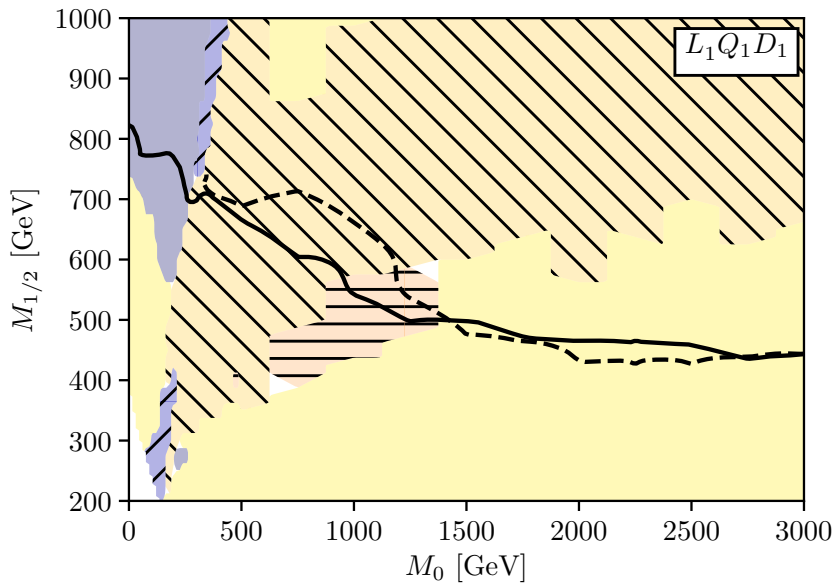
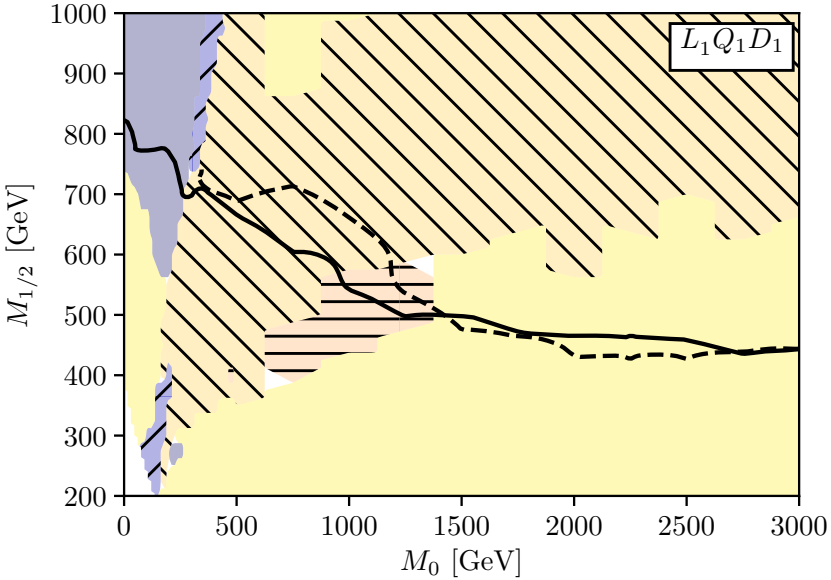
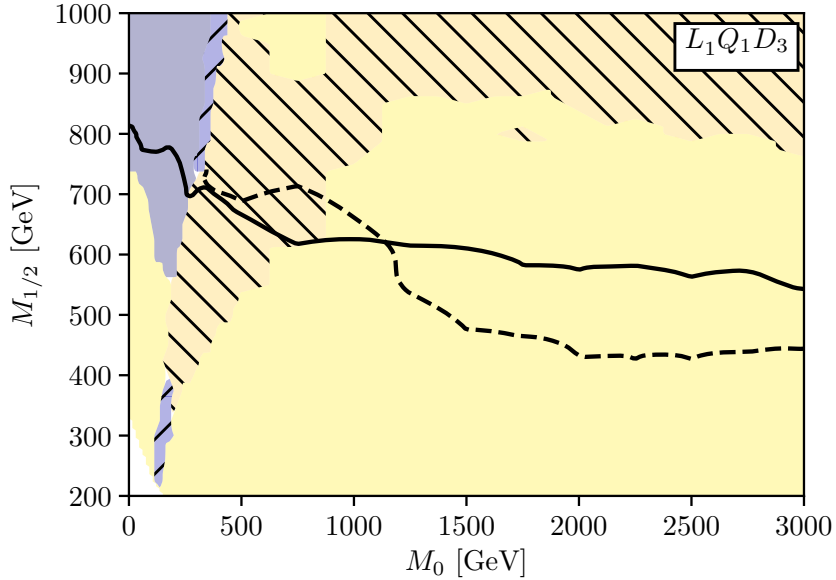




Recasting LHC results, $LQ\bar{D}$

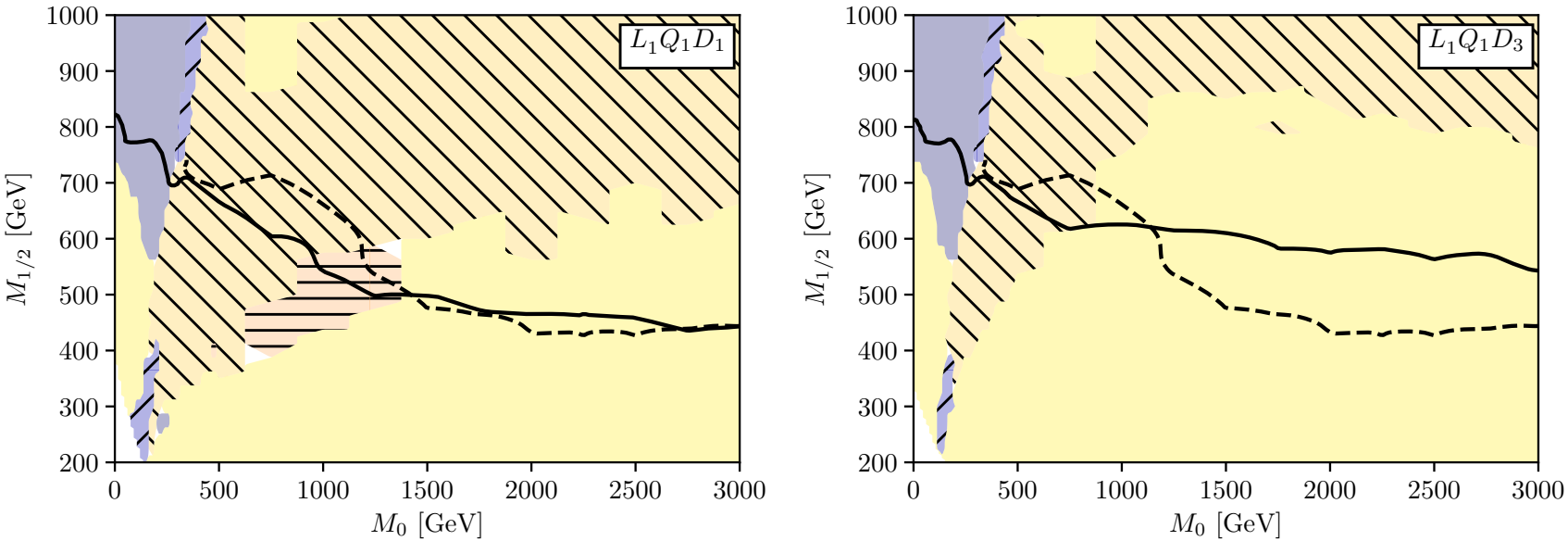




- bounds comparable to RPC
- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \to \mu jj/\nu jj$
- $\tilde{\tau}$ LSP: $\tilde{\chi}_1^0 \to \tau\tilde{\tau}$; $\tilde{\tau} \to \mu\nu/\tau\nu$ (via RGE-generated λ_{233})

- 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 LHC results, $LQ\bar{D}$



Sensitive analyses:

- ATLAS 1404.2500 (large M_0, gluino and stop pair-production):
  - 2 same-sign leptons and at least 3 jets or
  - 3 leptons and at least 4 jets
- ATLAS conf-2013-062 (low M_0, gluino associated production):
  - 1–2 leptons, 2–6 jets, $\not{E}_T$, considers b-tags
  - also tags soft leptons (motivated by compressed scenarios)

Recasting LHC results, $\bar{U}\bar{D}\bar{D}$

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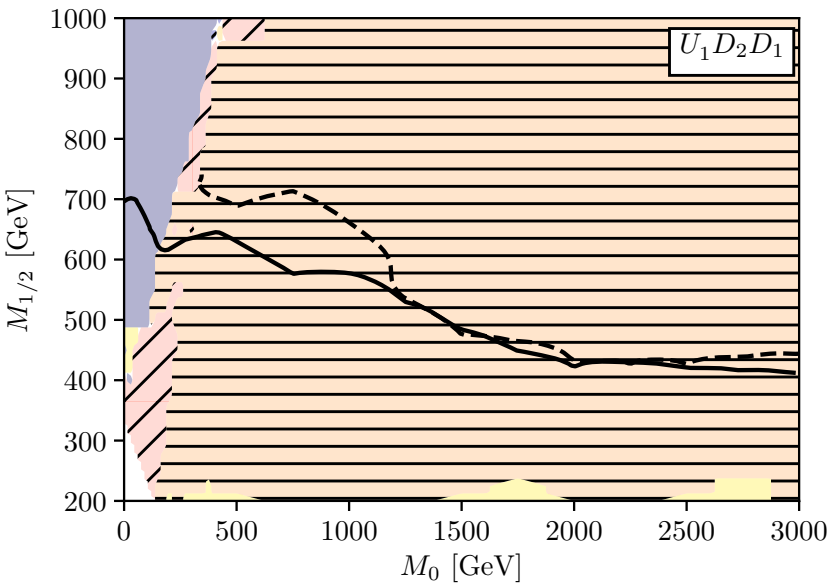

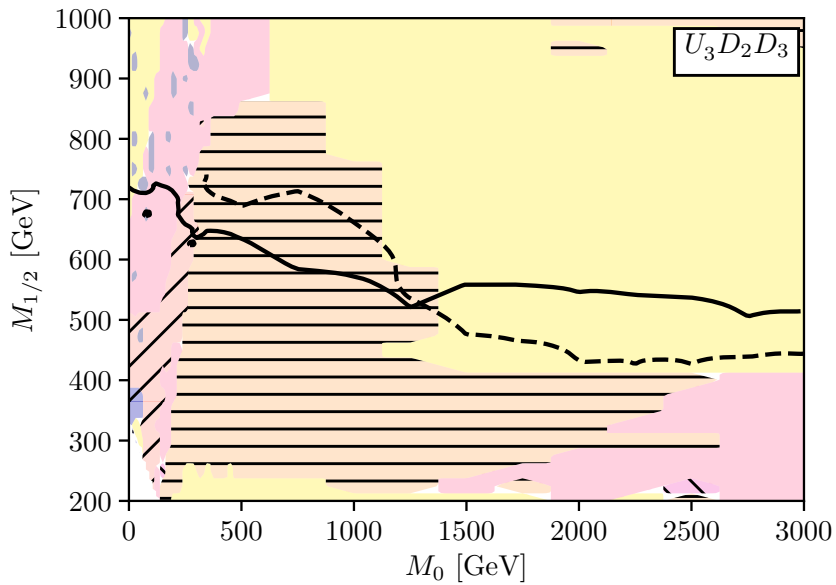

	$\tilde{\chi}_1^0$ LSP region					$\tilde{\tau}_1$ LSP region				
$\Lambda_{\not R_p}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{q}}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{q}}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\tau}_1}$
RPC	1140	620	1480	190	320	–	–	–	–	–
λ_{122}	2070	1320	1960	400	440	1580	1070	1430	290	230
λ_{123}	1680	980	1630	310	350	1790	1220	1620	340	260
λ_{131}	1850	1120	1700	350	380	1690	1150	1530	320	250
λ_{133}	1540	880	1440	280	300	1580	1070	1430	290	220
λ'_{111}	1180	650	1440	200	320	1580	1070	1430	290	220
λ'_{113}	1410	780	1440	240	320	1580	1070	1430	290	220
λ'_{131}	1160	640	1400	200	300	1580	1080	1430	290	200
λ'_{133}	1130	620	1400	190	300	1580	1070	1430	290	230
λ'_{311}	1110	620	1320	190	270	1370	940	1220	250	160
λ'_{313}	1130	620	1320	190	270	1370	940	1220	250	160
λ'_{323}	1130	610	1320	190	290	1370	940	1230	250	160
λ'_{331}	1150	620	1350	200	270	1370	940	1220	250	160
λ'_{333}	1170	660	1370	200	300	1670	1100	1490	320	230
λ''_{113}	1030	590	1350	170	270	1370	930	1240	250	180
λ''_{121}	1070	590	1350	180	270	1320	910	1180	240	160
λ''_{312}	1130	640	1350	190	270	1430	960	1290	260	180
λ''_{323}	1280	720	1350	220	270	1430	960	1300	260	190

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 but many signatures also covered by non-RPV analyses
- special case RPV-CMSSM:
  - squark masses mostly less constrained
  - other mass bounds comparable to or even stronger than RPC case

THANK YOU

Stau 4-body decay modes

$$\tilde{\tau}_1 \xrightarrow{\lambda_{ijk}} \begin{cases} \tau \ell_i \nu_j \ell_k \\ \tau \ell_j \nu_i \ell_k \\ \nu_\tau \nu_j \nu_j \ell_k \\ \nu_\tau \ell_i \ell_i \ell_k \\ \nu_\tau \nu_k \ell_i \nu_j \\ \nu_\tau \nu_k \nu_i \ell_j \end{cases} \qquad \tilde{\tau}_1 \xrightarrow{\lambda'_{ijk}} \begin{cases} \tau \ell_i u_j d_k \\ \tau \nu_i d_j d_k \\ \nu_\tau \nu_i u_j d_k \\ \nu_\tau \ell_i d_j d_k \\ \nu_\tau \ell_i d_j d_k \\ \nu_\tau \ell_i u_j u_k \\ \nu_\tau \nu_i u_j d_k \\ \nu_\tau \nu_i d_j u_k \end{cases} \qquad \tilde{\tau}_1 \xrightarrow{\lambda''_{ijk}} \begin{cases} \tau u_i d_j d_k \\ \nu_\tau u_j u_i d_k \\ \nu_\tau u_k u_i d_j \\ \nu_\tau d_i d_j d_k \end{cases}$$

LHC Signatures, $\tilde{\tau}_1$ LSP

Two separate cases:

1. $\Lambda_{\not R_p}$ couples directly to a (s)tau: two-body $\tilde{\tau}_1$ decay
   $\Rightarrow$ only small changes in phenomenology – e.g.

$$\tilde{\chi}_1^0\text{–LSP}: \quad \tilde{\chi}_1^0 \to \{\nu_\tau e^\pm e^\mp, \tau^\pm \nu_e e^\mp\}; \quad L_1 L_3 \bar{E}_1 \,,$$

$$\tilde{\tau}_1\text{–LSP}: \quad \tilde{\chi}_1^0 \to \tau^\pm \tilde{\tau}^\mp \to \tau^\pm \nu_e e^\mp; \quad L_1 L_3 \bar{E}_1 \,.$$

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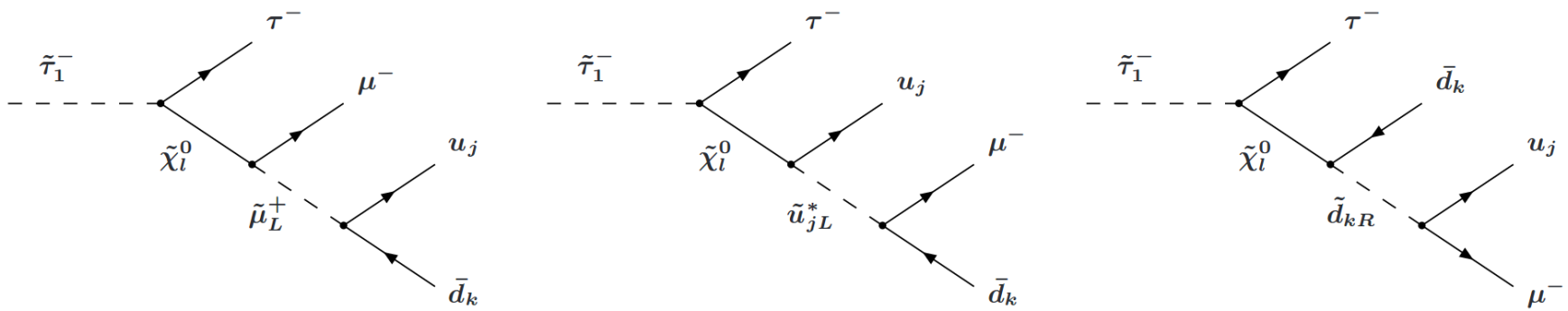
$$\tilde{\tau}_1\text{–LSP}: \quad \tilde{\chi}_1^0 \to \tau^\pm \tilde{\tau}^\mp \to \tau^\pm \nu_e e^\mp; \quad L_1 L_3 \bar{E}_1\,.$$

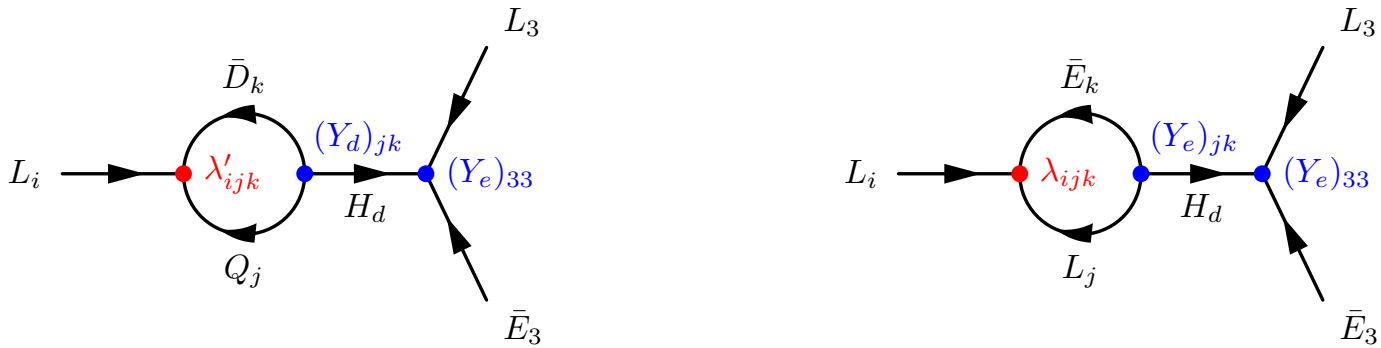
2. $\Lambda_{\not R_p}$ does not couple to a (s)tau: 4-body decay



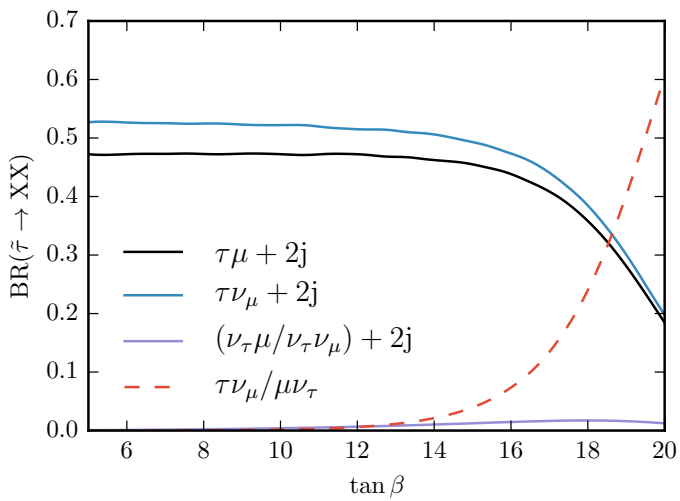
[Dreiner,Grab,Trenke '08]

LHC Signatures, $\tilde{\tau}_1$ LSP

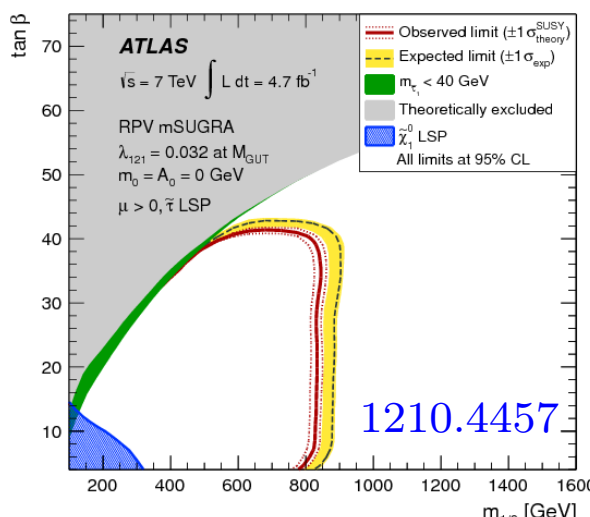
However, full model: RGE-generated operators:



$$16\pi^2 \frac{d}{dt}\lambda_{i33} = \lambda_{i33}\Big(-\frac{9}{5}g_1^2 - 3g_2^2 + 4(Y_e)_{33}^2\Big)$$
$$+3\lambda'_{ijk}(Y_e)_{33}(Y_d)_{jk} + \lambda_{ijk}(Y_e)_{33}(Y_e)_{jk}\,.$$



$\longleftrightarrow$

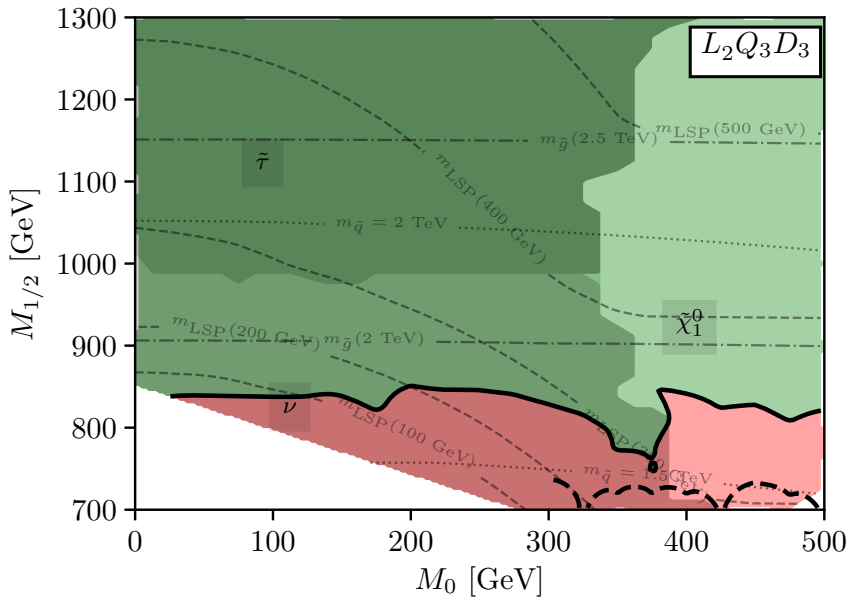


Criticism

- 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

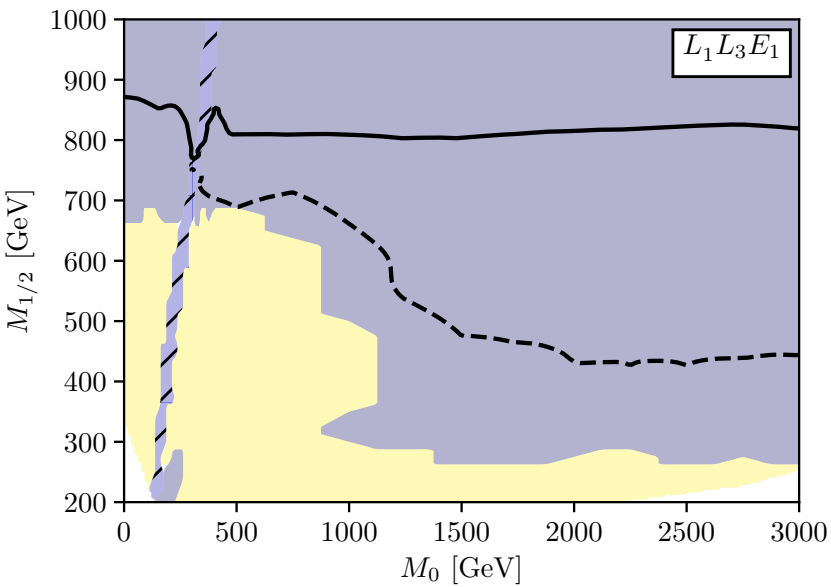
For non-coloured and non-stau LSPs, the LHC phenomenology is usually similar compared to the neutralino LSP:

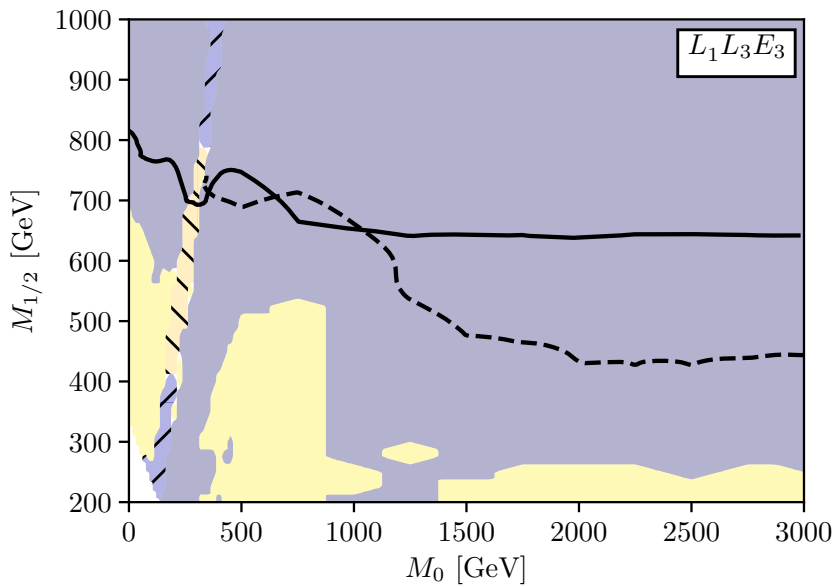


coloured prod.→ decay to neutralino → decay to on-shell LSP→...
coloured prod.→ decay to neutralino → decay via off-shell LSP→...

Recasting LHC results, $LL\bar{E}$

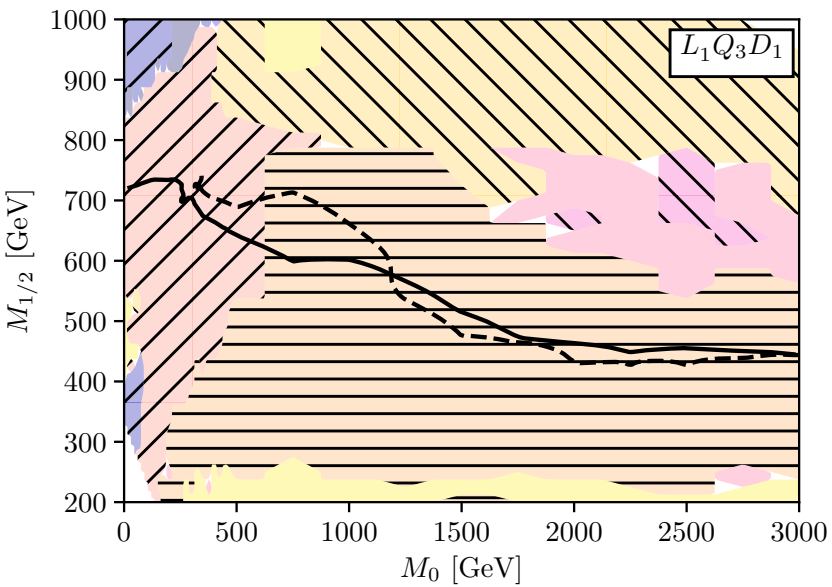
atlas_conf_2013_036 4ℓ + MET	**cms_1405_7570** various electroweakino searches	**atlas_1403_4853** 2ℓ + MET	**atlas_1403_5294** 2ℓ + MET
atlas_1402_7029 3ℓ + MET	**atlas_1407_0583** $1\ell + 1b$ + MET	**cms_1504_03198** $1\ell + \geq 3j$ incl $\geq 1b$ + MET	**atlas_1407_0600** $0-1\ell + 3b$ + MET
atlas_conf_2013_061 $0-1\ell + 3b$ + MET	**atlas_1405_7875** $0\ell + 2-6j$ + MET	**atlas_1308_1841** $0\ell + \geq 7j$ + MET	**atlas_conf_2013_062** $1-2\ell + 3-6j$ + MET
atlas_1404_2500 3ℓ or same-sign 2ℓ			

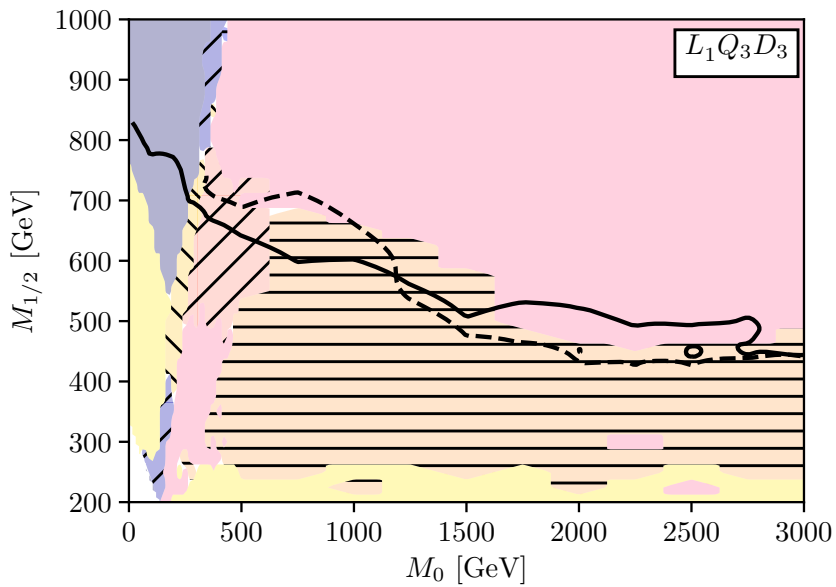




Recasting LHC results, $LQ\bar{D}$

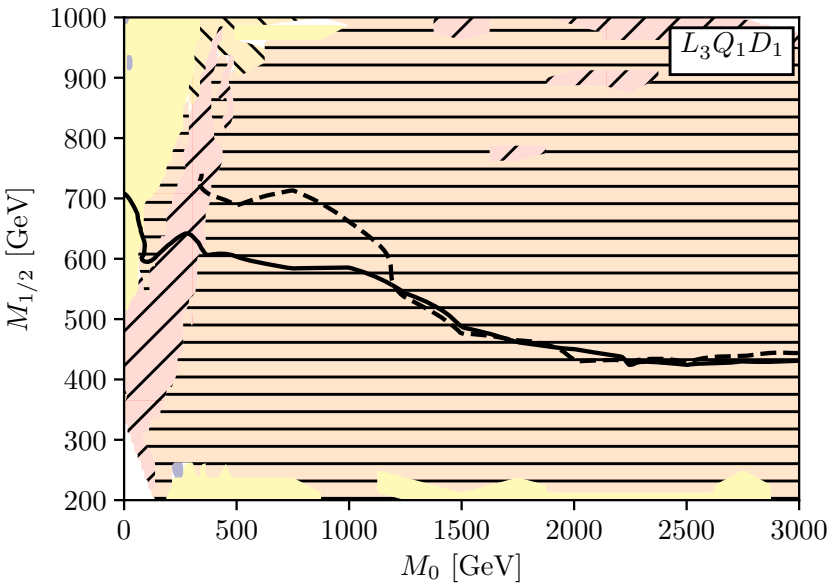
atlas_conf_2013_036 $4\ell + MET$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + MET$	**atlas_1403_5294** $2\ell + MET$
atlas_1402_7029 $3\ell + MET$	**atlas_1407_0583** $1\ell + 1b + MET$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + MET$	**atlas_1407_0600** $0 - 1\ell + 3b + MET$
atlas_conf_2013_061 $0 - 1\ell + 3b + MET$	**atlas_1405_7875** $0\ell + 2 - 6j + MET$	**atlas_1308_1841** $0\ell + \geq 7j + MET$	**atlas_conf_2013_062** $1 - 2\ell + 3 - 6j + MET$
atlas_1404_2500 3ℓ *or same-sign* 2ℓ			

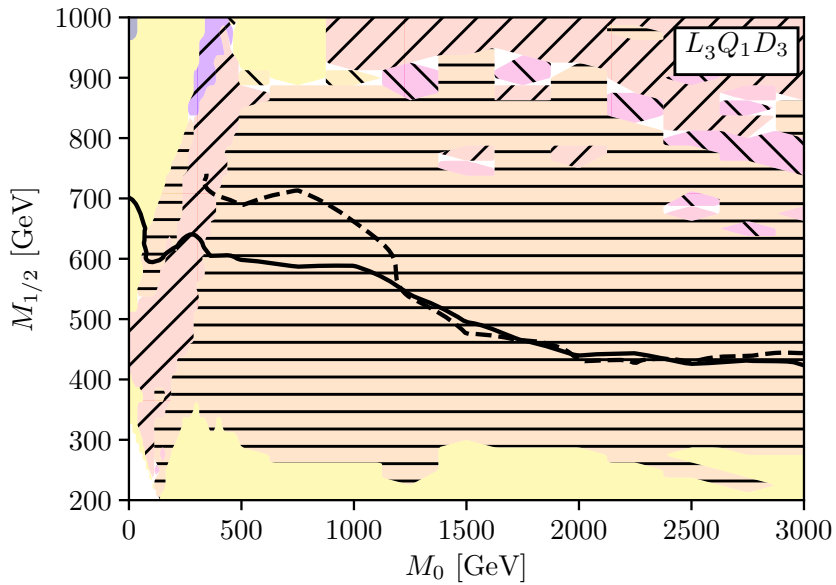




Recasting LHC results, $LQ\bar{D}$

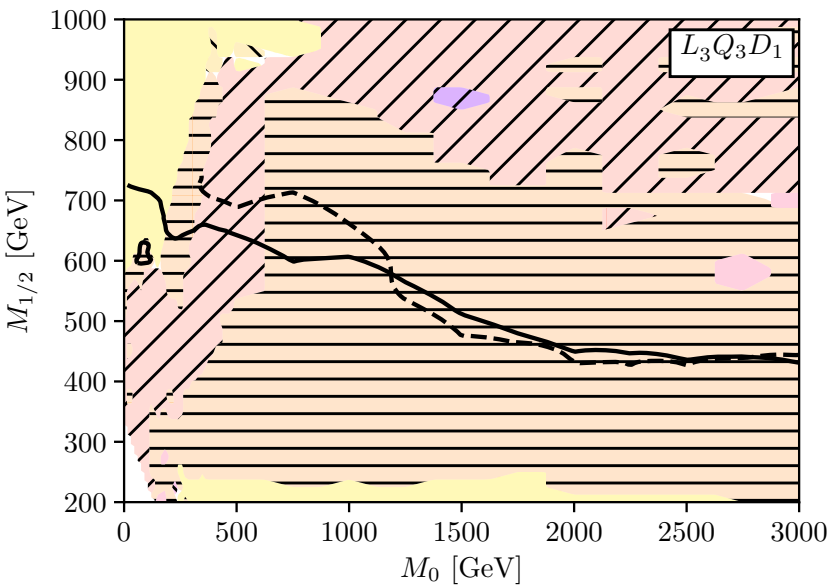
atlas_conf_2013_036 4ℓ + MET	**cms_1405_7570** various electroweakino searches	**atlas_1403_4853** 2ℓ + MET	**atlas_1403_5294** 2ℓ + MET
atlas_1402_7029 3ℓ + MET	**atlas_1407_0583** 1ℓ + $1b$ + MET	**cms_1504_03198** 1ℓ + $\geq 3j$ incl $\geq 1b$ + MET	**atlas_1407_0600** $0-1\ell$ + $3b$ + MET
atlas_conf_2013_061 $0-1\ell$ + $3b$ + MET	**atlas_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			

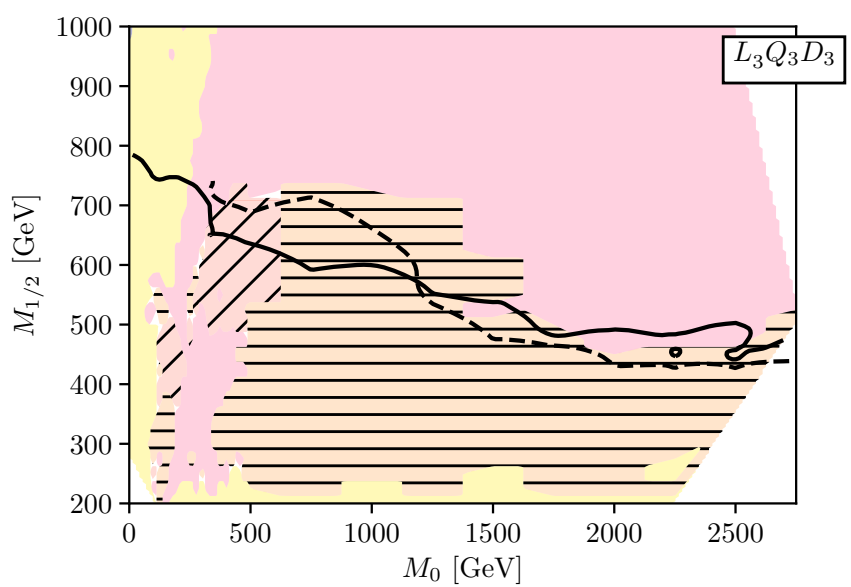




Recasting LHC results, $LQ\bar{D}$

atlas_conf_2013_036 4ℓ + MET	**cms_1405_7570** various electroweakino searches	**atlas_1403_4853** 2ℓ + MET	**atlas_1403_5294** 2ℓ + MET
atlas_1402_7029 3ℓ + MET	**atlas_1407_0583** $1\ell + 1b$ + MET	**cms_1504_03198** $1\ell + \geq 3j$ incl $\geq 1b$ + MET	**atlas_1407_0600** $0-1\ell + 3b$ + MET
atlas_conf_2013_061 $0-1\ell + 3b$ + MET	**atlas_1405_7875** $0\ell + 2-6j$ + MET	**atlas_1308_1841** $0\ell + \geq 7j$ + MET	**atlas_conf_2013_062** $1-2\ell + 3-6j$ + MET
atlas_1404_2500 3ℓ or same-sign 2ℓ			





Recasting LHC results, $\bar{U}\bar{D}\bar{D}$

atlas_conf_2013_036 4ℓ + MET	**cms_1405_7570** various electroweakino searches	**atlas_1403_4853** 2ℓ + MET	**atlas_1403_5294** 2ℓ + MET
atlas_1402_7029 3ℓ + MET	**atlas_1407_0583** $1\ell + 1b$ + MET	**cms_1504_03198** $1\ell + \geq 3j$ incl $\geq 1b$ + MET	**atlas_1407_0600** $0-1\ell + 3b$ + MET
atlas_conf_2013_061 $0-1\ell + 3b$ + MET	**atlas_1405_7875** $0\ell + 2-6j$ + MET	**atlas_1308_1841** $0\ell + \geq 7j$ + MET	**atlas_conf_2013_062** $1-2\ell + 3-6j$ + MET
atlas_1404_2500 3ℓ or same-sign 2ℓ