R-Parity Violation at the LHC

based on arXiv:1706.09418

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in collaboration with

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

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

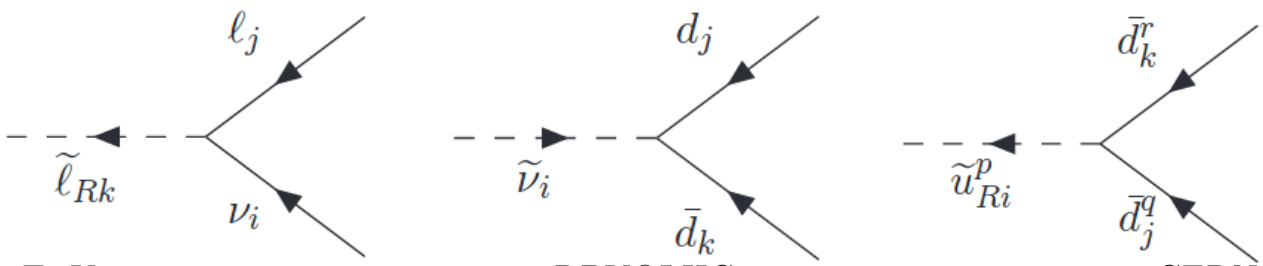
$$W_{\rm RPV} = \epsilon_{ab}\big[\frac{1}{2}\lambda_{ijk}\,\hat{L}_i^a\,\hat{L}_j^b\,\hat{\bar{E}}_k + \lambda'_{ijk}\,\hat{L}_i^a\,\hat{Q}_j^b\,\hat{\bar{D}}_j - \kappa_i\,\hat{L}_i^a\,\hat{H}_u^a\big] + \frac{1}{2}\epsilon_{xyz}\lambda''_{ijk}\,\hat{\bar{U}}_i^x\,\hat{\bar{D}}_j^y\,\hat{\bar{D}}_k^z$$

New interactions with respect to RPC SUSY:

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

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

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



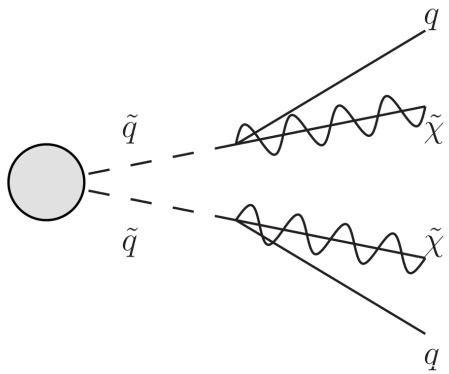
LHC phenomenology

– SUSY with conserved R-Parity –

$\Rightarrow$ 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

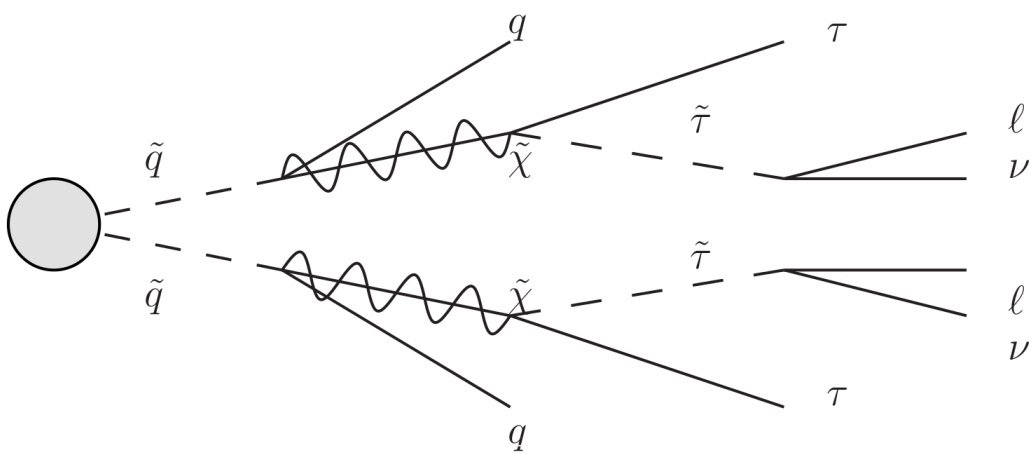
– SUSY with broken R-Parity –

- LSP decays
- LSP can be any SUSY particle

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

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

e.g.



Case: $LL\bar{E}$

- $\tilde{\chi}_1^0$ decays via off-shell sneutrino/slepton $\to \ell_i \nu_j \ell_k$
- Pair of neutralinos from coloured or electroweakino production
  $\Rightarrow$ 4 leptons+ $\not{E}_T$
- Easy signature, limits on simplified electroweakino models up to $\mathcal{O}(1\ \text{TeV})$

e.g.:
CMS 1606.08076: $0-4$ leptons
ATLAS-CONF-2016-075: 4^+ leptons

CMS 1709.05406: 3^+ leptons incl. 2 hadr. τ's

$\ell^\pm$ Signatures	RPV Operators
$e^+e^-e^+e^-$	$\lambda_{121,131}$
$\mu^+\mu^-\mu^+\mu^-$	$\lambda_{122,232}$
$\tau^+\tau^-\tau^+\tau^-$	$\lambda_{133,233}$
$e^+e^-e^\pm\mu^\mp$	λ_{121}
$e^+e^-e^\pm\tau^\mp$	λ_{131}
$\mu^+\mu^-\mu^\pm e^\mp$	λ_{122}
$\mu^+\mu^-\mu^\pm\tau^\mp$	λ_{232}
$\tau^+\tau^-\tau^\pm e^\mp$	λ_{133}
$\tau^+\tau^-\tau^\pm\mu^\mp$	λ_{233}
$e^+\mu^-e^\pm\mu^\mp$	$\lambda_{121,231,122,132}$
$e^+\tau^-e^\pm\tau^\mp$	$\lambda_{131,231,123,\ 133}$
$\mu^+\tau^-\mu^\pm\tau^\mp$	$\lambda_{132,232,123,233}$
$e^-\tau^+\mu^\pm\tau^\mp$	λ_{123}
$e^-\mu^+\tau^\pm\mu^\mp$	λ_{132}
$e^-\mu^+e^\pm\tau^\mp$	λ_{231}

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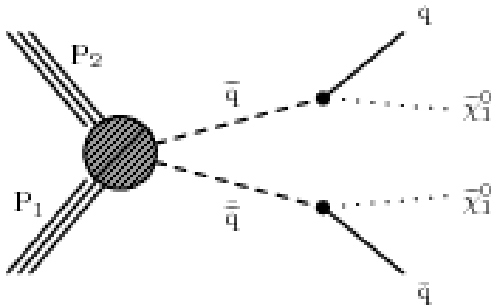
$e^-\tau^+\mu^\pm\tau^\mp$	λ_{123}
$e^-\mu^+\tau^\pm\mu^\mp$	λ_{132}
$e^-\mu^+e^\pm\tau^\mp$	λ_{231}

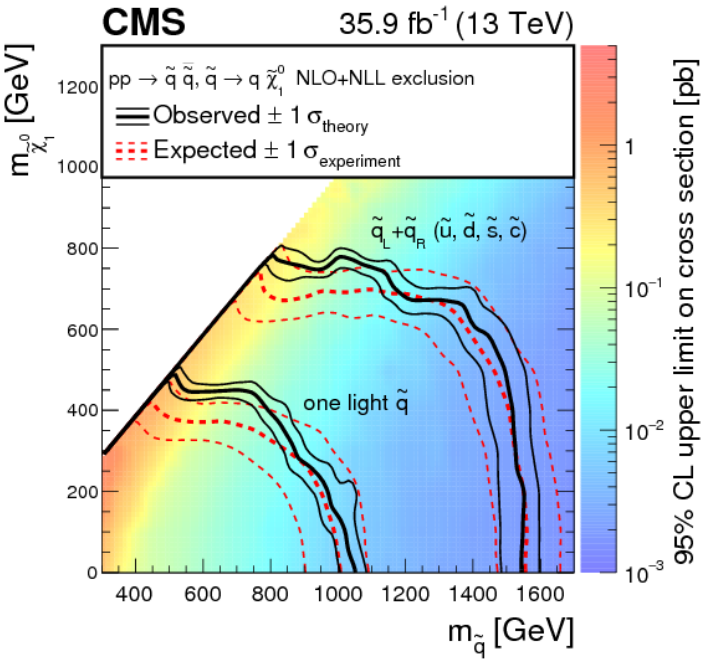
Case: $LL\bar{E}$

RPC:

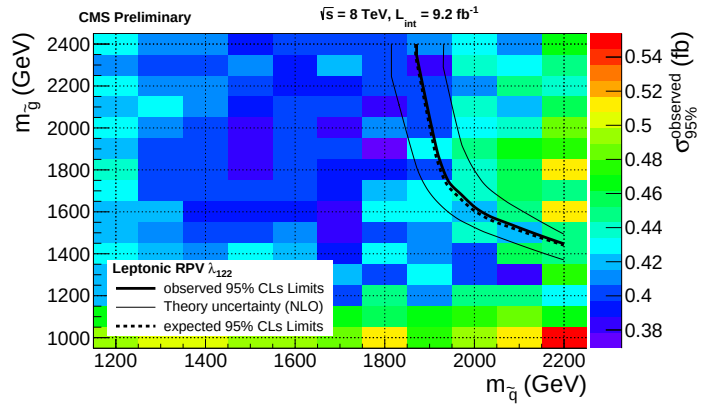
$m_{\tilde{q}} < 1.6\,\text{TeV}$ @ 13 TeV, $35.9\,\text{fb}^{-1}$

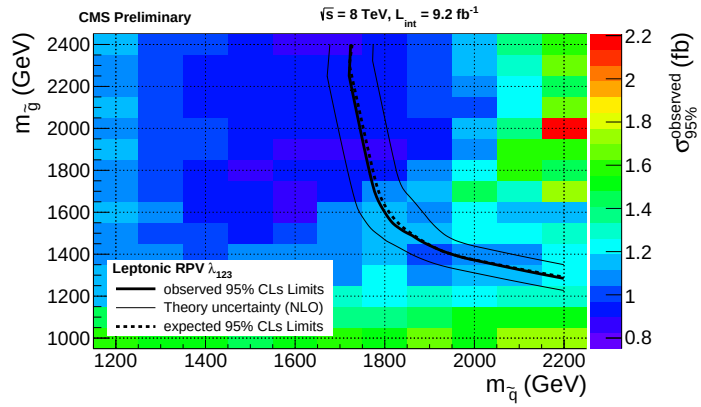
CMS, 1705.04650

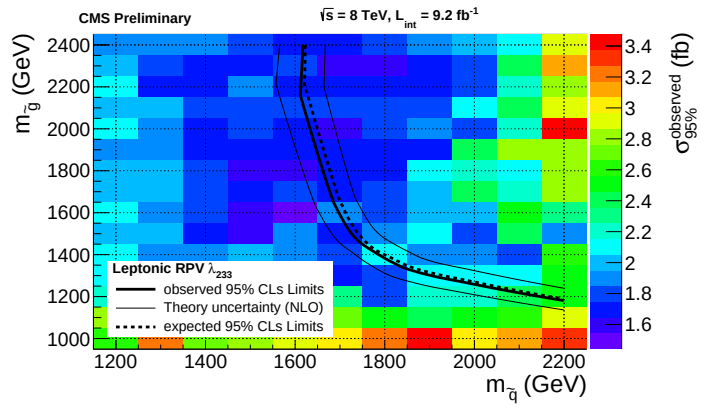




RPV: 8 TeV, $9.2\,\text{fb}^{-1}$







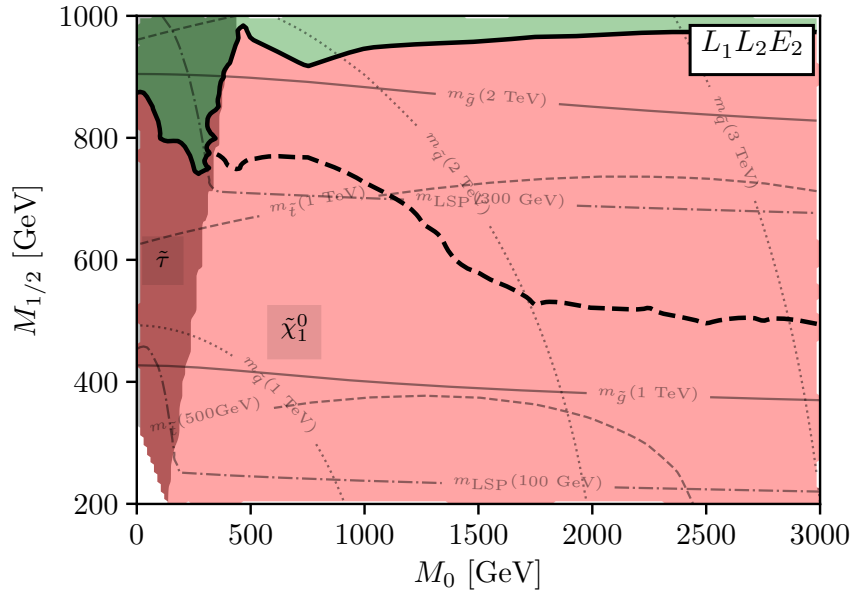
CMS-PAS-SUS-12-027, 3^{+}leptons

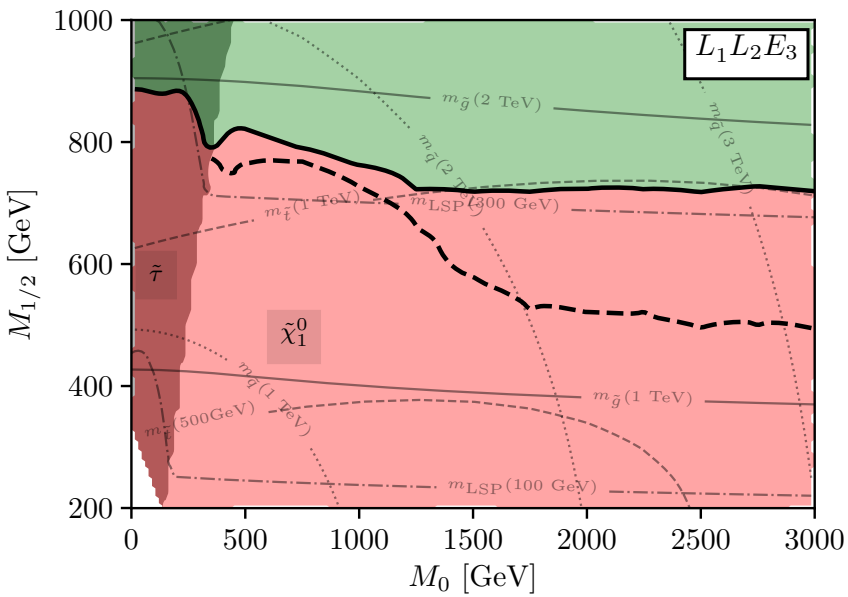
Case: $LL\bar{E}$

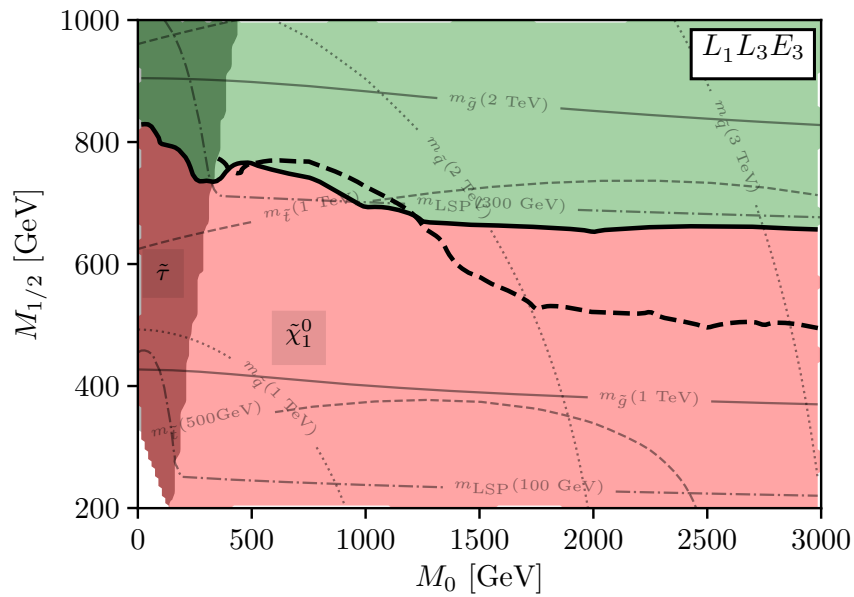
RPC-CMSSM vs RPV-CMSSM

use `CheckMATE` Drees, Dreiner, Tattersall, Schmeier, Kim '13 within CMSSM: unified mass parameters at unification scale ($M_{\rm GUT} \sim 10^{16}$ GeV):

$$(m^{\rm soft}_{\rm scalar})^2 = M_0^2\,, \quad T_{ij} = Y_{ij}\,A_0$$
$$M^{\rm soft}_{\rm gaugino} = M_{1/2}\,, \text{ setup :}$$
$$\tan\beta = 30\,, \mu > 0\,, A_0 = -2M_0$$







Case: $LL\bar{E}$

Projection – take with care

	current best limit	projected, HL-LHC	projected, HE-LHC, 3 ab^{-1}
	RPC		
$\tilde{t}$	1.1 TeV 1706.04402: 13 TeV, 35.9 fb^{-1}	2 TeV	3.3 TeV
$\tilde{q}$	1.6 TeV 1705.04650: 13 TeV, 35.9 fb^{-1}	2.8 TeV	4.9 TeV
$\tilde{g}$	2.1 TeV 1705.04650: 13 TeV, 35.9 fb^{-1}	3.2 TeV	5.1 TeV
	$LL\bar{E}$-RPV		
$\tilde{t}$	1 TeV CMS SUS-12-027: 8 TeV, 9.2 fb^{-1}	2.7 TeV	4.6 TeV
$\tilde{q}$	1.8 TeV CMS SUS-12-027: 8 TeV, 9.2 fb^{-1}	4.2 TeV	7.5 TeV
$\tilde{g}$	1.35 TeV 1405.5086: 8 TeV, 20.3 fb^{-1}	3.2 TeV	5.5 TeV

Projection: `Collider Reach` Salam, Weiler, http://collider-reach.web.cern.ch
Assumptions:

- signal and background driven by same partonic channel
- efficiencies, background rejection, etc. stays constant
- $\sigma_i \propto$ partonic luminosity at a given scale

Case: $LQ\bar{D}$

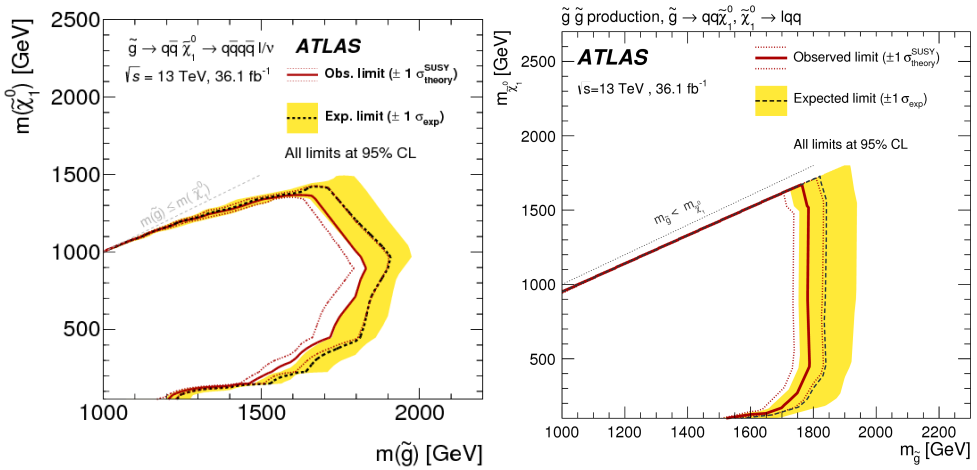
- $\tilde{\chi}_1^0$ decays via off-shell sneutrino/slepton/squark $\to \ell_i u_j d_k / \nu_i d_j d_k$
- Pair of neutralinos from coloured production $\Rightarrow$

  $0 - 2$ leptons, 4^+jets$(+ \not{E}_T)$
- Most promising strategy: at least one lepton, high jet multiplicity

e.g. ATLAS 1704.08493, 1706.03731: exclude up to $m_{\tilde{g}} \sim 1.8$ GeV

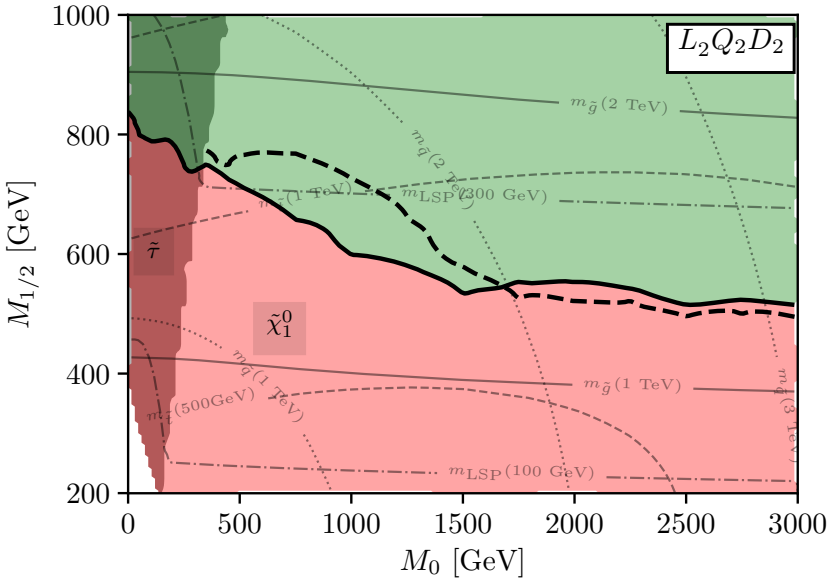
for $\lambda'_{ijk}, i \neq 3$

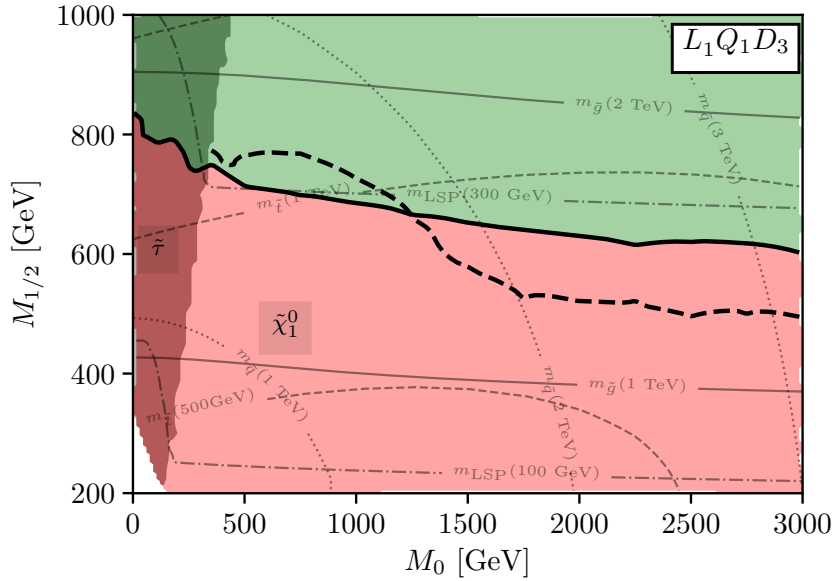
Signature	$LQ\bar{D}$ Operator
$[\ell_a^+ \ell_a^\pm,\ \ell_a^+ \not{E}_T]\ 4j$	λ'_{abc}
$[\ell_a^+ \ell_a^\pm,\ \ell_a^+ \not{E}_T]\ 2b2j$	λ'_{ab3}
$[\ell_a^+ \ell_a^\pm \bar{t}\ {}^{(-)}_{t},\ \ell_a^+ \bar{t} b\ \not{E}_T]\ 2j$	λ'_{a3c}
$[\ell_a^+ \ell_a^\pm \bar{t}\ {}^{(-)}_{t},\ \ell_a^+ \bar{t} b\ \not{E}_T]\ 2b$	λ'_{a33}
$[\tau^+ \tau^\pm,\ \tau^+ \not{E}_T]\ 4j$	λ'_{3bc}
$[\tau^+ \tau^\pm,\ \tau^+ \not{E}_T]\ 2b2j$	λ'_{3b3}
$[\tau^+ \tau^\pm \bar{t}\ {}^{(-)}_{t},\ \tau^+ \bar{t} b\ \not{E}_T]\ 2j$	λ'_{33c}
$[\tau^+ \tau^\pm \bar{t}\ {}^{(-)}_{t}, \tau^+ \bar{t} b\ \not{E}_T]\ 2b$	λ'_{333}
$\not{E}_T\ 4j$	$\lambda'_{abc}, \lambda'_{3bc}$
$\not{E}_T\ 2b2j$	$\lambda'_{ab3}, \lambda'_{3b3}, \lambda'_{a3c}, \lambda'_{33c}$
$\not{E}_T\ 4b$	$\lambda'_{a33}, \lambda'_{333}$



Case: $LQ\bar{D}$

RPC-CMSSM vs RPV-CMSSM





- low M_0: large MET signal gets lost $\rightarrow$ RPC more constrained
- large M_0: bounds comparable
- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \rightarrow \mu jj/\nu jj$
- $\tilde{\tau}$ LSP: $\tilde{\chi}_1^0 \rightarrow \tau\tilde{\tau}$; $\tilde{\tau} \rightarrow \mu\nu/\tau\nu$ (via RGE-generated λ_{233})

- more constrained than RPC for large M_0: b-tags
- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \rightarrow ebj/\nu bj$
- $\tilde{\tau}$ LSP: $\tilde{\chi}_1^0 \rightarrow \tau\tilde{\tau}$; $\tilde{\tau} \rightarrow \tau ebj/\tau\nu bj$
- Analysis: SS leptons + b-tags + MET ATLAS 1404.2500

Case: $LQ\bar{D}$

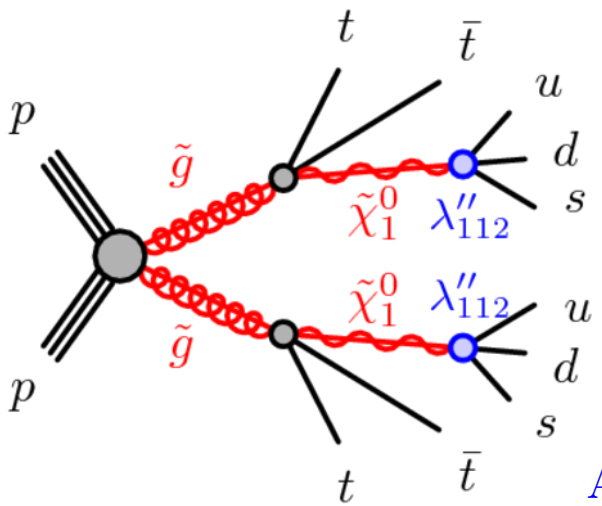
Projection – take with care

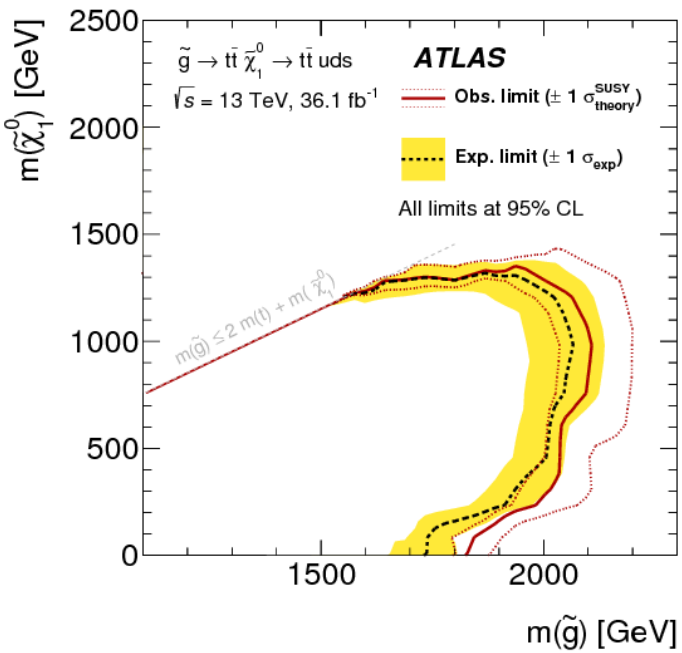
	current best limit	projected, HL-LHC	projected, HE-LHC, $3\,\text{ab}^{-1}$
	$LQ\bar{D}$, worst case: λ'_{3ij}		
$\tilde{t}$	580 GeV CMS 1408.0806, 8 TeV, $19.7\,\text{fb}^{-1}$	1.7 TeV	2.7 TeV
$\tilde{q}$	1.2 TeV ATLAS-CONF-2015-018, 8 TeV, $20.3\,\text{fb}^{-1}$	3.1 TeV	5.2 TeV
$\tilde{g}$	1.2 TeV ATLAS-CONF-2015-018, 8 TeV, $20.3\,\text{fb}^{-1}$	2.9 TeV	4.9 TeV
	$LQ\bar{D}$, best case: λ'_{ijk}, $i,j \neq 3$		
$\tilde{t}$	1 TeV CMS 1602.04334, 8 TeV, $19.7\,\text{fb}^{-1}$	2.5 TeV	4.3 TeV
$\tilde{q}$	1.4 TeV ATLAS-CONF-2015-018, 8 TeV, $20.3\,\text{fb}^{-1}$	3.4 TeV	5.9 TeV
$\tilde{g}$	1.8 TeV 1706.03731,1704.08493, 13 TeV, $36\,\text{fb}^{-1}$	2.8 TeV	4.9 TeV

Case: $\bar{U}\bar{D}\bar{D}$

- $\tilde{\chi}_1^0$ decays via off-shell squark $\to u_i\, d_j\, d_k$
- Pair of neutralinos from coloured production $\Rightarrow$ 6^+jets, possibly b's, t's
- (non-)appearance of 3rd generation $\{i, j, k\}$ requires different search strategies

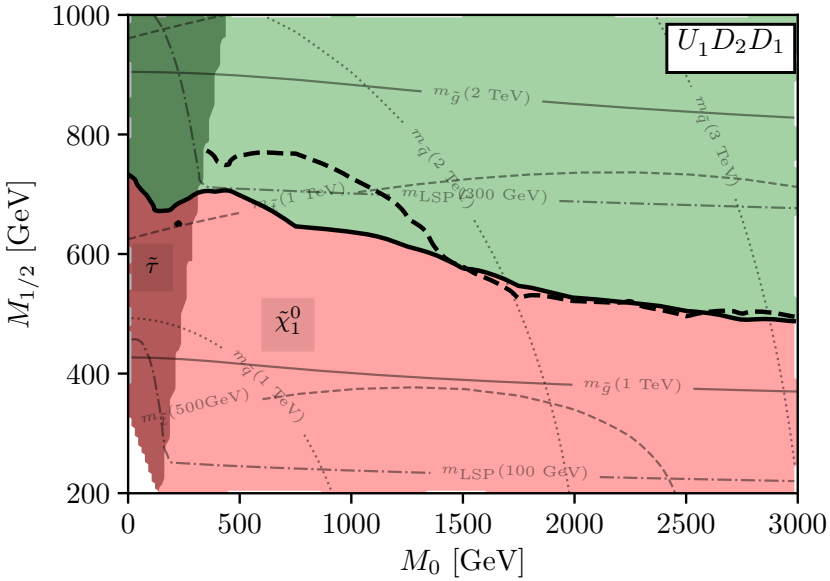
Signature	$\bar{U}\bar{D}\bar{D}$ Operator
$6j$	λ''_{abc}
$(2b)(4j)$	λ''_{ab3}
$(2t)(4j)$	λ''_{3bc}
$(2t)(2b)(2j)$	λ''_{3b3}

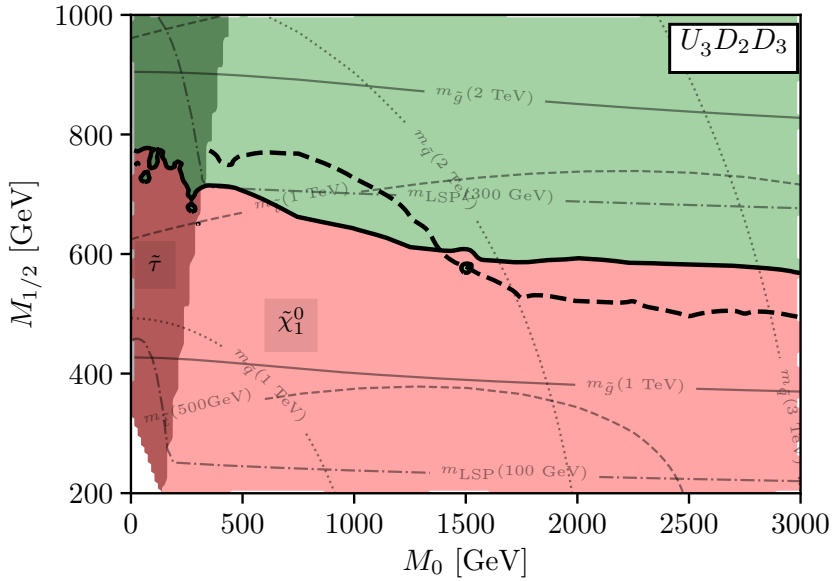




ATLAS 1704.08493

Case: $\bar{U}\bar{D}\bar{D}$ RPC-CMSSM vs RPV-CMSSM





low M_0: RPC MET searches more powerful

- large M_0: multijet analyses competitive with RPC searches!
- Analysis: 0 leptons, ≥ 7 jets

  ATLAS 1308.1841

- large M_0: more constrained than RPC
- $\tilde{\chi}_1^0 \to tbs \Rightarrow$ leptonic top decays, 2 b-jets, MET
- Analysis: SS leptons, b-tags and MET ATLAS 1404.2500

Case: $\bar{U}\bar{D}\bar{D}$ Projection – take with care

	current best limit	projected, HL-LHC	projected, HE-LHC, 3 ab^{-1}
	$\bar{U}\bar{D}\bar{D}$, λ''_{ijk}, $i,j,k \neq 3$		
$\tilde{t}$	–	–	–
$\tilde{q}$	[1.7 TeV CMS SUS-12-027: 8 TeV, 9.2 fb^{-1}]	[4 TeV]	[7.2 TeV] *
$\tilde{g}$	2.1 TeV ATLAS 1704.08493, 13 TeV, 36.1 fb^{-1}	3.2 TeV	5.1 TeV **
$\tilde{g}$	1 TeV ATLAS-CONF-2013-091, 8 TeV, 20.3 fb^{-1}	2.5 TeV	4.3 TeV †
	$\bar{U}\bar{D}\bar{D}$, best case: λ''_{3i3}		
$\tilde{t}$	1.3 TeV ATLAS 1704.08493, 13 TeV, 36.1 fb^{-1}	2.3 TeV	3.8 TeV
$\tilde{q}$	–	–	–
$\tilde{g}$	1.6 TeV ATLAS 1704.08493, 13 TeV, 36.1 fb^{-1}	2.6 TeV	4.4 TeV ‡

* assuming $\tilde{q} \to j\tilde{\chi}_2^0 \to j\ell\tilde{\ell} \to j\ell\ell\tilde{\chi}_1^0 \to j\ell\ell jjj$

** assuming $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0 \to t\bar{t}uds$

† assuming $\tilde{g} \to 3j$

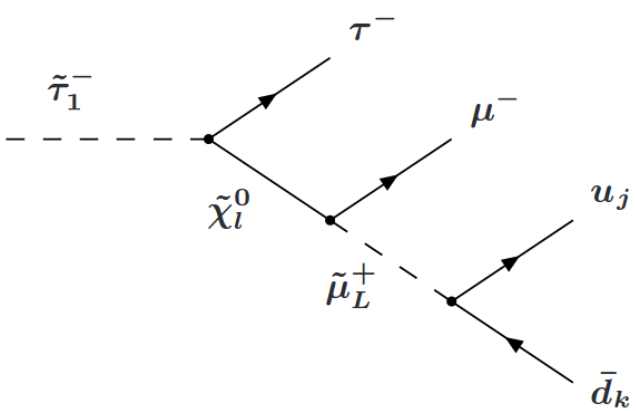
‡ assuming $\tilde{g} \to t\tilde{t} \to tbs$

Other scenarios in principle searched for, but no explicit bounds given.
E.g. ATLAS-CONF-2016-057: bounds on scenarios with all λ_{ijk} equal
$\to$ top final states dominate

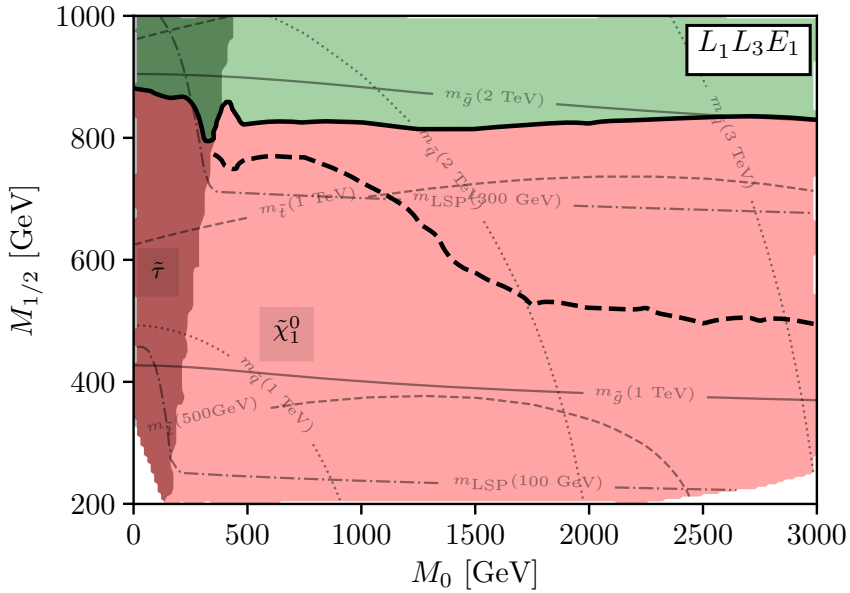
$\tilde{\tau}_1$ LSP – no direct searches!

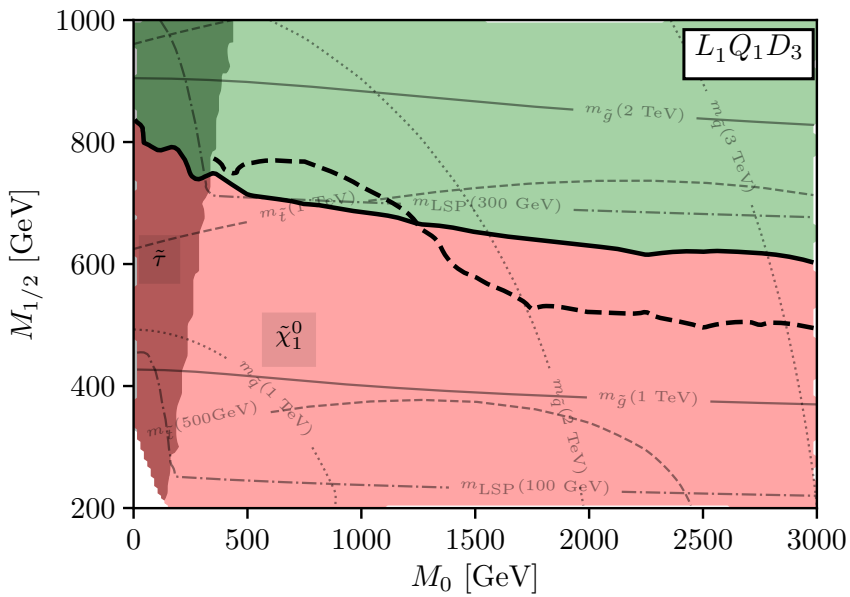
Two separate cases:

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. λ_{131}
   $\tilde{\chi}_1^0$–LSP : $\tilde{\chi}_1^0 \to \{\nu_\tau e^\pm e^\mp, \tau^\pm \nu_e e^\mp\}$
   $\tilde{\tau}_1$–LSP : $\tilde{\chi}_1^0 \to \tau^\pm \tilde{\tau}^\mp \to \tau^\pm \nu_e e^\mp$
2. $\Lambda_{\not R_p}$ does not couple to a (s)tau:
   4-body decay – e.g. λ'_{2jk}



Dreiner,Grab,Trenke '08

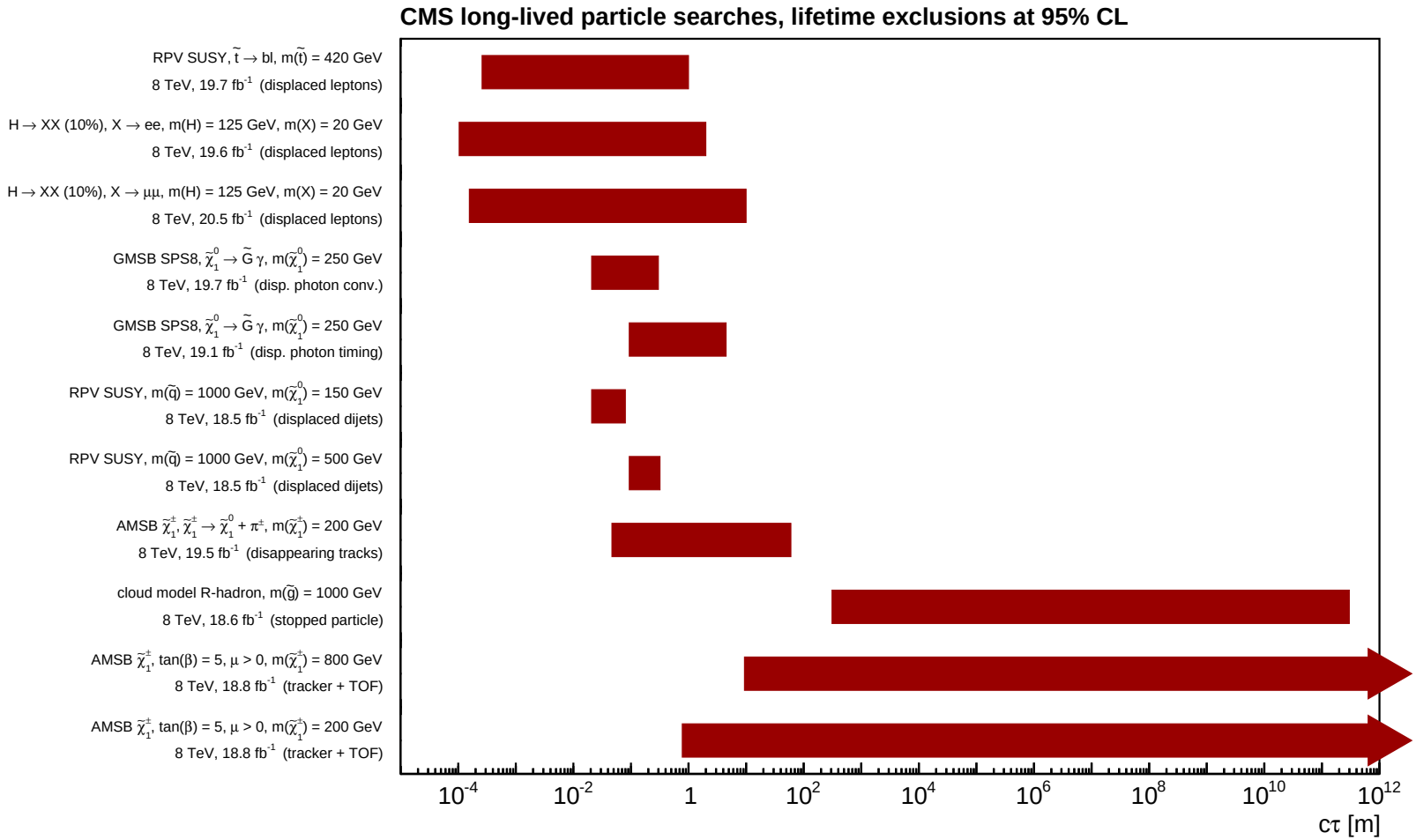




Displaced RPV signatures

- displaced leptons (also τ's), e.g. $\tilde{q}_i \to q_j \ell$, $\tilde{\ell}_i \to \nu_j \ell_k$, $\tilde{\chi}_1^0 \to \ell_i \ell_j \nu_k$, stau 4-body (!)
- dp. jets/tops, e.g. $\tilde{\nu} \to q_i \bar{q}_j$, $\tilde{\chi}_1^0 \to 3j$, tjj
- R-hadrons (e.g. long-lived gluinos)

see yesterday's talks by S. Pagan Griso, J. Alimena, C. Vazquez Sierra and D. Curtin



Conclusions

LHC searches for RPV:

- Despite its variety – good LHC coverage of RPV final states
- Prompt RPV does in general *not* loosen collider constraints w.r.t. RPC
- HL-LHC: entering the multi-TeV region

No direct searches performed for:

- stau LSPs (multi-tau final states)
- squark production for several $\bar{U}\bar{D}\bar{D}$ couplings

$\Rightarrow$ Recasting necessary for extracting the bounds

I have not/barely talked about:

- non-neutralino, non-stau LSPs
- single sparticle production
- displaced vertices; variety of signatures to be studied at HL-LHC

Thank You

	$\tilde{\chi}_1^0$ LSP region				$\tilde{\tau}_1$ LSP region				
$\Lambda_{\not R_p}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{q}}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{q}}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\tau}_1}$
RPC	1280	710	1560	220	–	–	–	–	–
λ_{122}	2070	1320	1960	400	1690	1140	1520	320	230
λ_{123}	1700	980	1630	310	1790	1220	1620	340	260
λ_{131}	1850	1120	1700	350	1740	1180	1580	330	260
λ_{133}	1590	920	1540	290	1690	1140	1520	320	230
λ'_{111}	1220	700	1520	210	1690	1140	1520	320	230
λ'_{113}	1480	850	1530	260	1690	1140	1520	320	230
λ'_{131}	1310	750	1450	230	1690	1150	1520	320	220
λ'_{133}	1310	750	1470	220	1690	1140	1520	320	230
λ'_{311}	1250	750	1400	210	1530	1040	1360	280	190
λ'_{313}	1290	730	1410	220	1530	1040	1360	280	190
λ'_{323}	1280	720	1400	220	1530	1040	1370	280	200
λ'_{331}	1330	750	1440	230	1580	1080	1420	290	210
λ'_{333}	1350	770	1420	240	1620	1060	1460	310	240
λ''_{113}	1250	720	1350	210	1420	970	1270	260	180
λ''_{121}	1260	730	1350	210	1480	1010	1330	270	200
λ''_{312}	1250	730	1350	210	1430	960	1290	260	180
λ''_{323}	1400	780	1350	250	1530	1040	1360	280	190

$LL\bar{E}$, BEST BOUNDS

Particle	Lower Bound [GeV]	$LL\bar{E}$ Coupling	Simplified Model	Comment	Reference
$\tilde{\chi}_1^0$	900 (740)	λ_{122} ($\lambda_{123,233}$)	$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 1\,\text{GeV}$	Wino production	CMS '16
$\tilde{\chi}_1^0$	900 (560) [260]	λ_{122} (λ_{123}) [λ_{233}]	$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 1\,\text{GeV}$	Higgsino production	CMS '16
$\tilde{\chi}_1^\pm$	up to 750 (470)	λ_{121} (λ_{133})	$\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$	$\tilde{W}^- \tilde{W}^+$ production	ATLAS '13
$\tilde{\chi}_1^\pm$	up to 1100	$\lambda_{121,122}$	$\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$	13 TeV update of ATLAS '13	ATLAS '16
$\tilde{\ell}_L^\pm$	500 (425)	$\lambda_{121,122}$ ($\lambda_{133,233}$)	$\tilde{\ell}^\pm \to \ell^\pm \tilde{\chi}_1^0$	$N_\ell \geq 4$, 8 TeV	ATLAS '14
$\tilde{\ell}_R^\pm$	425 (325)	$\lambda_{121,122}$ ($\lambda_{133,233}$)	$\tilde{\ell}^\pm \to \ell^\pm \tilde{\chi}_1^0$	$N_\ell \geq 4$, 8 TeV	ATLAS '14
$\tilde{\nu}_L$	450	$\lambda_{121,122}$	$\tilde{\nu} \to \nu \tilde{\chi}_1^0$	$N_\ell \geq 4$, 8 TeV	ATLAS '14
$\tilde{q}$	1850 (1750) [1600]	λ_{122} (λ_{123}) [λ_{233}]	$\tilde{q} \to q \tilde{\chi}_1^0$	$N_\ell \geq 3$, 8 TeV	CMS '12
$\tilde{t}_R$	950 (900) [900]	λ_{122} (λ_{123}) [λ_{233}]	$\tilde{t}_R \to t \tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} = 300\,\text{GeV}$ in CMS '12	CMS '12, '13, '16
$\tilde{g}$	1450 (1270) [1200] {1050}	$\lambda_{121,122}$ (λ_{123}) [λ_{233}] {λ_{133}}	$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	$N_\ell \geq 3$, 8 TeV	ATLAS '14,CMS '12

$LQ\bar{D}$, BEST BOUNDS

Particle	Lower Bound [GeV]	$LQ\bar{D}$ Coupling	Simplified Model	Comment	Reference
$\tilde{\chi}_1^0$	720 (620) [660] {500}	λ'_{131} (λ'_{131}) [λ'_{233}] {λ'_{233}}		$\tan\beta = 2$ (40) [2] {40}	CMS '16
$\tilde{\mu}$	440 (825) [1290]	λ'_{211} =0.003 (0.01) [0.04]	$\tilde{\mu} \to \mu\tilde{\chi}_1^0$	res. $\tilde{\mu}$ prod, $m_{\tilde{\chi}_1^0} = 200\,\text{GeV}$	CMS '13
$\tilde{q}$	1160 (1090) [1065]	$\lambda'_{abc,ab3}$ (λ'_{3bc}) [λ'_{3b3}]	$\tilde{q} \to q\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} = 0.5\, m_{\tilde{q}}$	ATLAS '15
	1315 (1360) [1225] {1215}	λ'_{abc} (λ'_{ab3}) [λ'_{3bc}] {λ'_{3b3}}		$m_{\tilde{\chi}_1^0} = 0.9\, m_{\tilde{q}}$	ATLAS '15
	1310 (1400) [2000]	$\lambda'_{23c,233}$		$m_{\tilde{g}} \lesssim 2000\,(1500)\,[1000]\,\text{GeV}$	CMS '12
$\tilde{g}$	1010 (970) [1070] {1050}	λ'_{abc} (λ'_{ab3}) [λ'_{3bc}] {λ'_{3b3}}	$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	$m_{\tilde{\chi}_1^0} = 0.1\, m_{\tilde{g}}$	ATLAS '15
	1135 (1085) [1220]	λ'_{abc} (λ'_{ab3}) [$\lambda'_{3bc,3b3}$]		$m_{\tilde{\chi}_1^0} = 0.5\, m_{\tilde{g}}$	ATLAS '15
	1285 (1260) [1200]	λ'_{abc} (λ'_{ab3}) [$\lambda'_{3bc,3b3}$]		$m_{\tilde{\chi}_1^0} = 0.9\, m_{\tilde{g}}$	ATLAS '15
	2000 (1500) [1000]	$\lambda'_{23c,233}$		$m_{\tilde{q}} \lesssim 1310\,(1400)\,[2000]\,\text{GeV}$	CMS '12
	1520 (1770) [1820]	λ'_{abc}		$m_{\tilde{\chi}_1^0} = 100\,(500)\,[890]\,\text{GeV}$	ATLAS '17
$\tilde{t}$	890 (1000)	λ'_{1bc} (λ'_{2bc})	$\tilde{t} \to b(\ell^+ 2j)_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_1^+} = 100\,\text{GeV}$	CMS '16
	580	λ'_{3bc}	$\tilde{t} \to b(\tau^+ 2j)_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_1^+} = 100\,\text{GeV}$	CMS '14
	710 (860)	λ'_{132} (λ'_{232})	$\tilde{t} \to 2b(\ell^+ j)_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_1^+} = m_{\tilde{t}} - (100\,\text{GeV})$	CMS '15

$\bar{U}\bar{D}\bar{D}$, BEST BOUNDS

Particle	Lower Bound [GeV]	$\bar{U}\bar{D}\bar{D}$ Coupling	Simpl. Model	Comment	Reference
$\tilde{q}$	1725 (1900) [2800]	λ''_{112}	$\tilde{q}_R \to j(\ell\ell\tilde{\chi}^0_1)_{\tilde{\chi}^0_2}$	$m_{\tilde{g}} \leq 2400\,(1500)\,[1200]\,\text{GeV}$	CMS '12
$\tilde{t}$	950 (980)	λ''_{3b3}	$\tilde{t} \to t\tilde{\chi}^0_{1,2}/b\tilde{\chi}^+_1$	$\tilde{\chi}^0_1 = \tilde{H}\ (\tilde{B})$, $m_{\tilde{\chi}^0_1} = 300\,\text{GeV}$	ATLAS '17
	1090 (1260)	λ''_{3b3}	$\tilde{t} \to t\tilde{\chi}^0_{1,2}/b\tilde{\chi}^+_1$	$\tilde{\chi}^0_1 = \tilde{H}\ (\tilde{B})$, $m_{\tilde{\chi}^0_1} = 800\,\text{GeV}$	ATLAS '17
$\tilde{g}$	1200 (1500) [2400]	λ''_{112}	$\tilde{g} \to jj(\ell\ell\tilde{\chi}^0_1)_{\tilde{\chi}^0_2}$	$m_{\tilde{q}} \leq 2800\,(1900)\,[1725]\,\text{GeV}$	CMS '12
	1850 (2100)	λ''_{112}	$\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$	$m_{\tilde{\chi}^0_1} = 100\,(800)\,\text{GeV}$	ATLAS '17
				$m_{\tilde{g}} > 2m_t + m_{\tilde{\chi}^0_1}$	ATLAS '17
	650 (950) [1020]	λ''_{212}	$\tilde{g} \to q\bar{q}\tilde{H}^0_1$	$m_{\tilde{q}} \leq 100\,(500)\,[900]\,\text{GeV}$ $m_{\tilde{H}^0_1} = \frac{3}{4}m_{\tilde{q}},\ m_{\tilde{c}} < m_{\tilde{g}}$	CMS '16
	675 (1020) [1075]	λ''_{212}	$\tilde{g} \to q\bar{q}\tilde{H}^0_1$	$m_{\tilde{q}} \leq 100\,(500)\,[900]\,\text{GeV}$ $m_{\tilde{H}^0_1} = \frac{3}{4}m_{\tilde{q}};\ m_{\tilde{b}} < m_{\tilde{g}}$	CMS '16
	650 (1020) [1100]	λ''_{213}	$\tilde{g} \to q\bar{q}\tilde{H}^0_1$	$m_{\tilde{q}} \leq 100\,(500)\,[900]\,\text{GeV}$ $m_{\tilde{H}^0_1} = \frac{3}{4}m_{\tilde{q}},\ m_{\tilde{b}} < m_{\tilde{g}}$	CMS '16
	650 (990) [1075]	λ''_{213}	$\tilde{g} \to q\bar{q}\tilde{H}^0_1$	$m_{\tilde{q}} \leq 100\,(500)\,[900]\,\text{GeV}$ $m_{\tilde{H}^0_1} = \frac{3}{4}m_{\tilde{q}};\ m_{\tilde{c}} < m_{\tilde{g}}$	CMS '16
	1040 (1555)	λ''_{ijk}	$\tilde{g} \to q\bar{q}\tilde{\chi}^0_1$	$m_{\tilde{\chi}^0_1} = 100\,(900)\,\text{GeV}$ all $\lambda''_{ijk} \neq 0$	ATLAS '16
	800 (1050)	λ''_{abc}	$\tilde{g} \to 5q$	$m_{\tilde{\chi}^0_1} = 50\,(600)\,\text{GeV}$	ATLAS '13

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
- Limitation: no combination of signal regions

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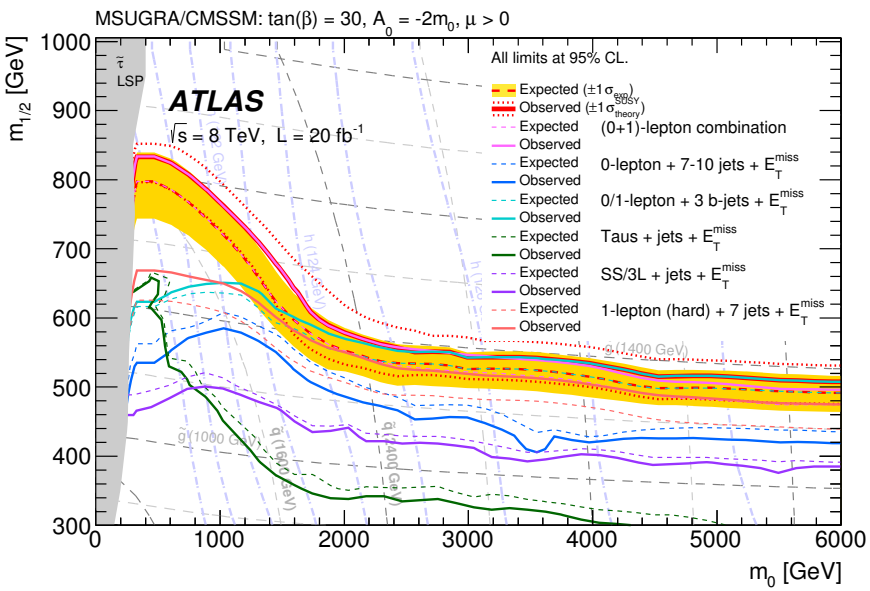
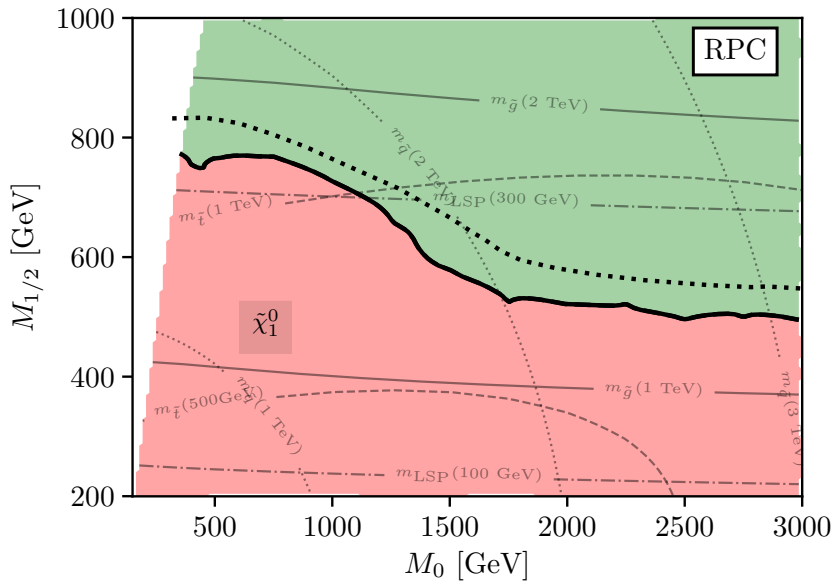
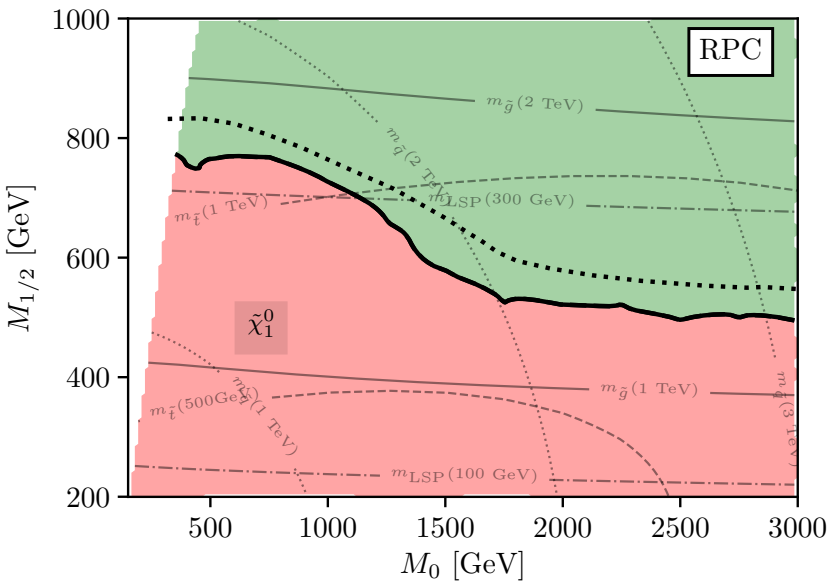
RPC-CMSSM:

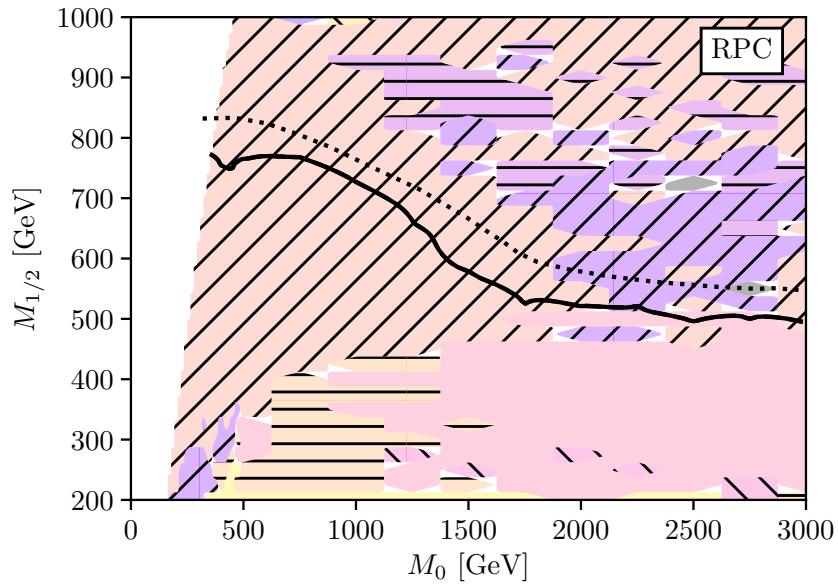




Recasting LHC results, RPC

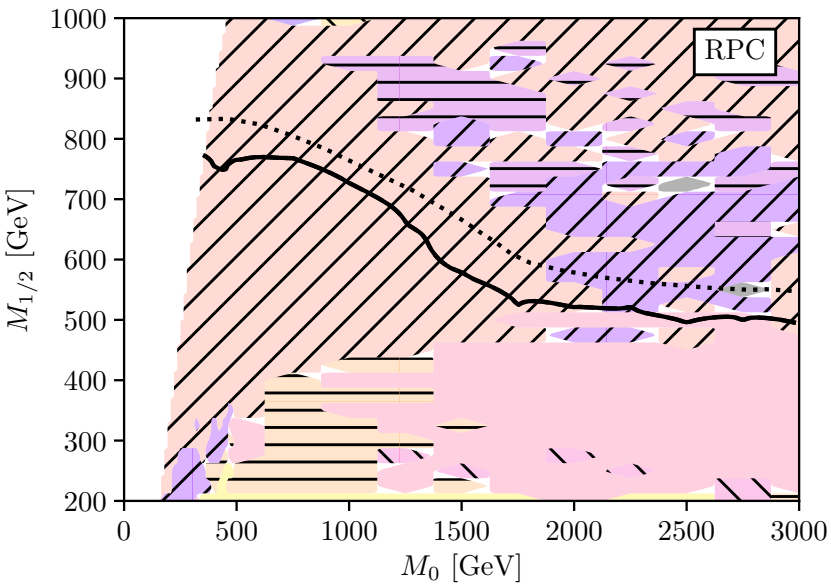
atlas_conf_2013_036 $4\ell + \not{E}_T$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + \geq 1b + \not{E}_T$	**atlas_1403_5294** $2\ell + \not{E}_T$
atlas_1402_7029 $3\ell + \not{E}_T$	**atlas_1407_0583** $1\ell + 1b + \not{E}_T$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + \not{E}_T$	**atlas_1407_0600** $0 - 1\ell + 3b + \not{E}_T$
atlas_conf_2013_061 $0 - 1\ell + 3b + \not{E}_T$	**atlas_1405_7875** $0\ell + 2 - 6j + \not{E}_T$	**atlas_1308_1841** $0\ell + \geq 7j + \not{E}_T$	**atlas_conf_2013_062** $1 - 2\ell + 3 - 6j + \not{E}_T$
atlas_1404_2500 3ℓ *or SS* $2\ell + 0$ *or* $\geq 0b + \not{E}_T$			

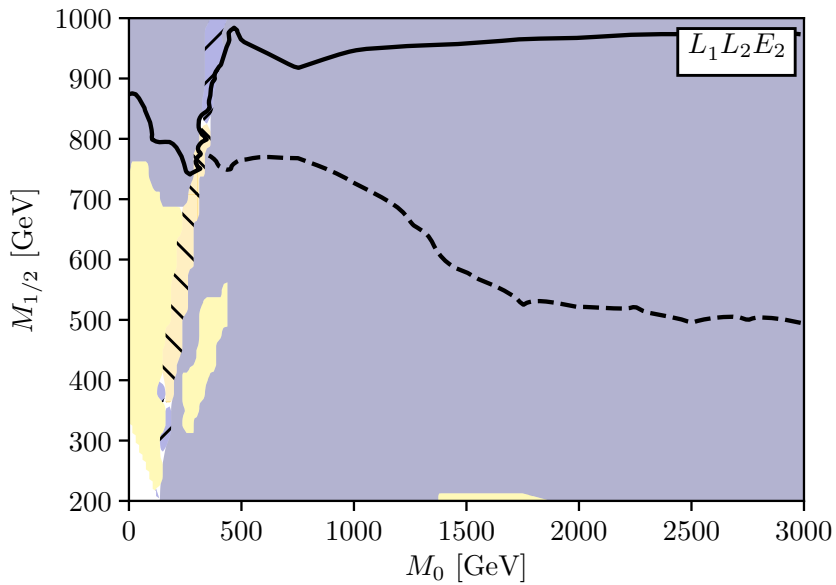




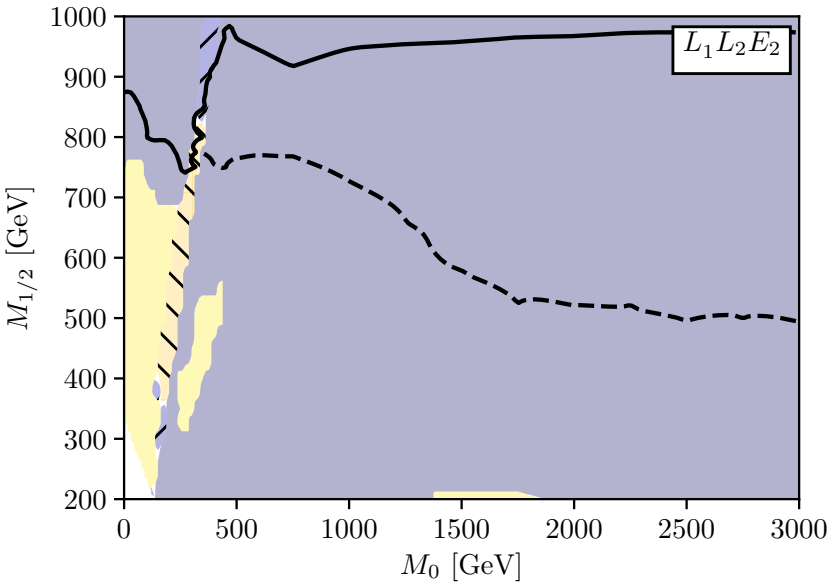
Recasting LHC results, $LL\bar{E}$

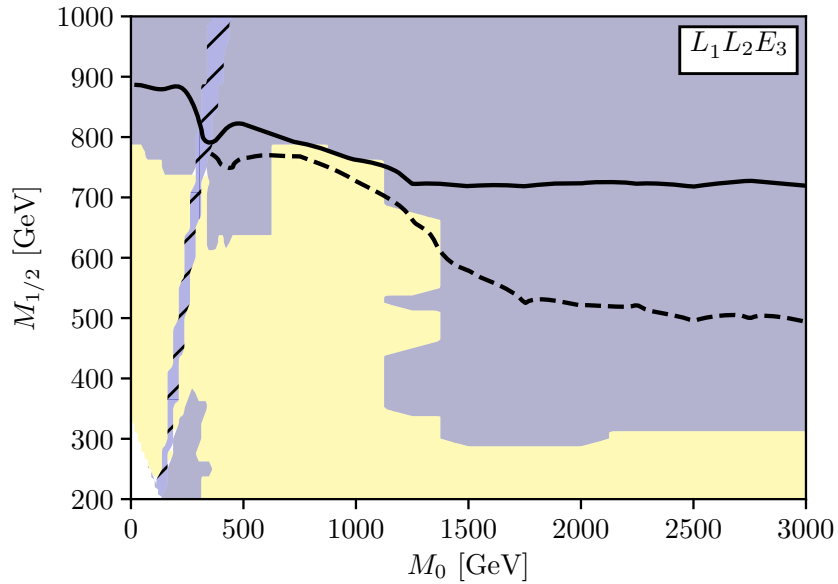
atlas_conf_2013_036 $4\ell + \not{E}_T$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + \geq 1b + \not{E}_T$	**atlas_1403_5294** $2\ell + \not{E}_T$
atlas_1402_7029 $3\ell + \not{E}_T$	**atlas_1407_0583** $1\ell + 1b + \not{E}_T$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + \not{E}_T$	**atlas_1407_0600** $0 - 1\ell + 3b + \not{E}_T$
atlas_conf_2013_061 $0 - 1\ell + 3b + \not{E}_T$	**atlas_1405_7875** $0\ell + 2 - 6j + \not{E}_T$	**atlas_1308_1841** $0\ell + \geq 7j + \not{E}_T$	**atlas_conf_2013_062** $1 - 2\ell + 3 - 6j + \not{E}_T$
atlas_1404_2500 3ℓ *or SS* 2ℓ + *0 or* $\geq 0b + \not{E}_T$			





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





Electroweakino-pair-production dominates the discovery channels!

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

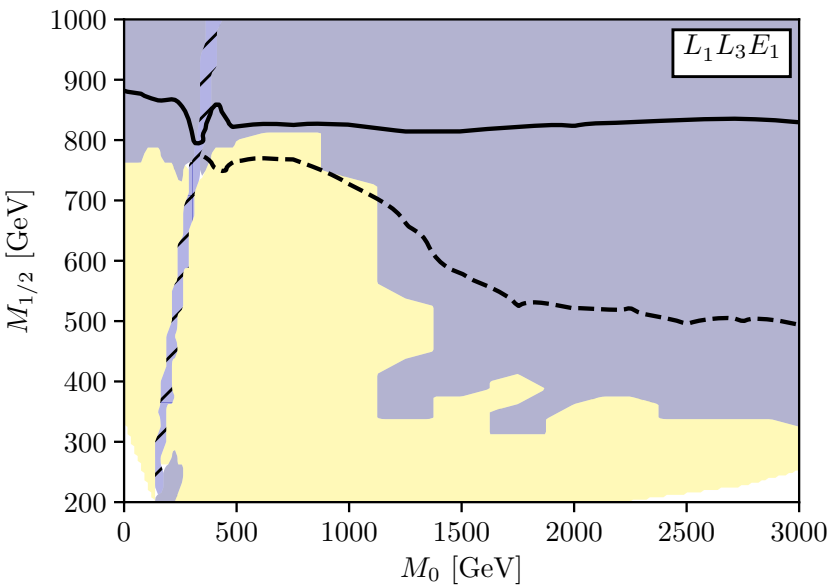
$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z/h, \qquad \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^\pm \qquad \text{or}$$
$$\tilde{\chi}_2^0 \to \tilde{\ell}_i \ell_i / \tilde{\nu}_j \nu_j, \quad \tilde{\chi}_1^\pm \to \tilde{\ell}_i \nu_i / \tilde{\nu}_j \ell_j$$

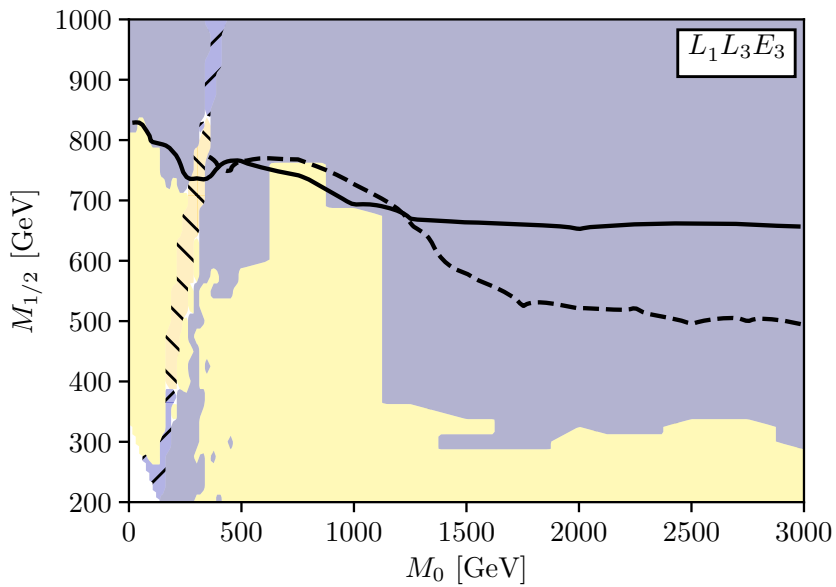
- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \to \ell\ell\nu$
- $\tilde{\tau}$ LSP: $\tilde{\tau} \to e\nu/\tau\nu$
  (via RGE-generated λ_{133})

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

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

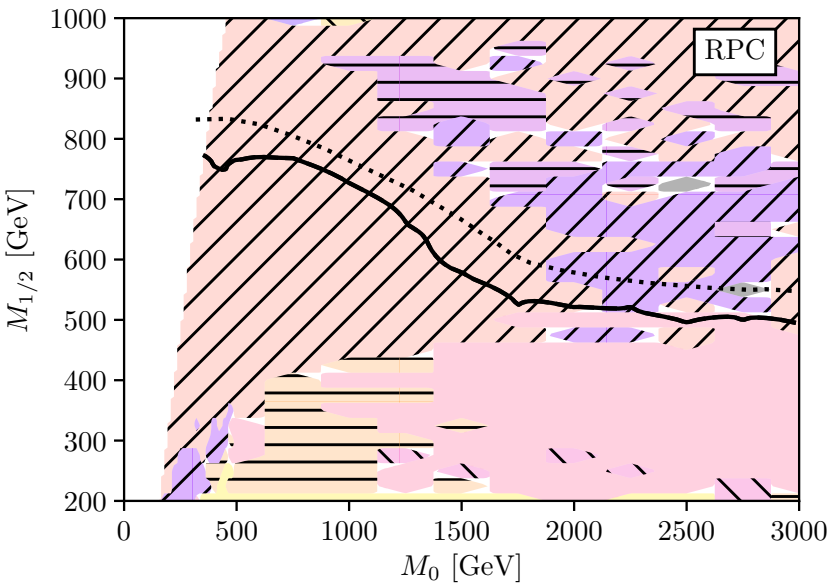
atlas_conf_2013_036 $4\ell + \not{E}_T$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + \geq 1b + \not{E}_T$	**atlas_1403_5294** $2\ell + \not{E}_T$
atlas_1402_7029 $3\ell + \not{E}_T$	**atlas_1407_0583** $1\ell + 1b + \not{E}_T$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + \not{E}_T$	**atlas_1407_0600** $0-1\ell + 3b + \not{E}_T$
atlas_conf_2013_061 $0-1\ell + 3b + \not{E}_T$	**atlas_1405_7875** $0\ell + 2-6j + \not{E}_T$	**atlas_1308_1841** $0\ell + \geq 7j + \not{E}_T$	**atlas_conf_2013_062** $1-2\ell + 3-6j + \not{E}_T$
atlas_1404_2500 3ℓ *or SS* $2\ell + 0$ *or* $\geq 0b + \not{E}_T$			

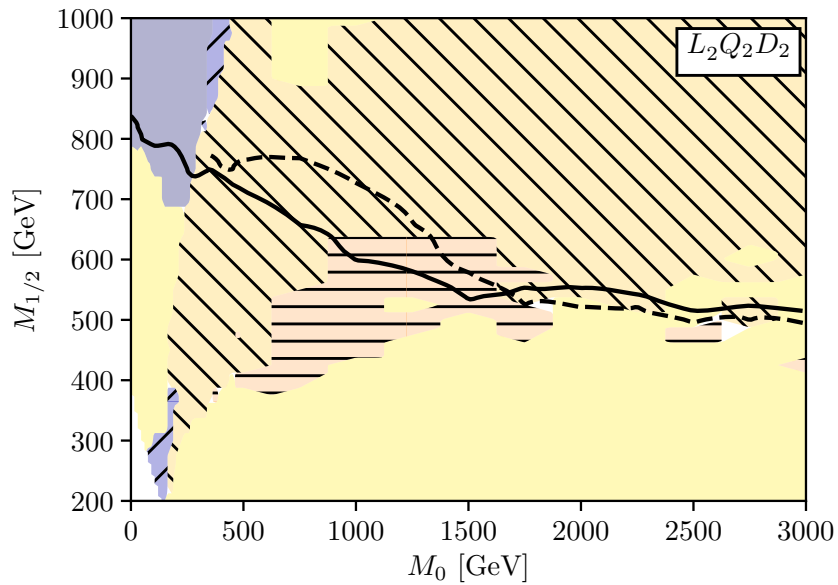




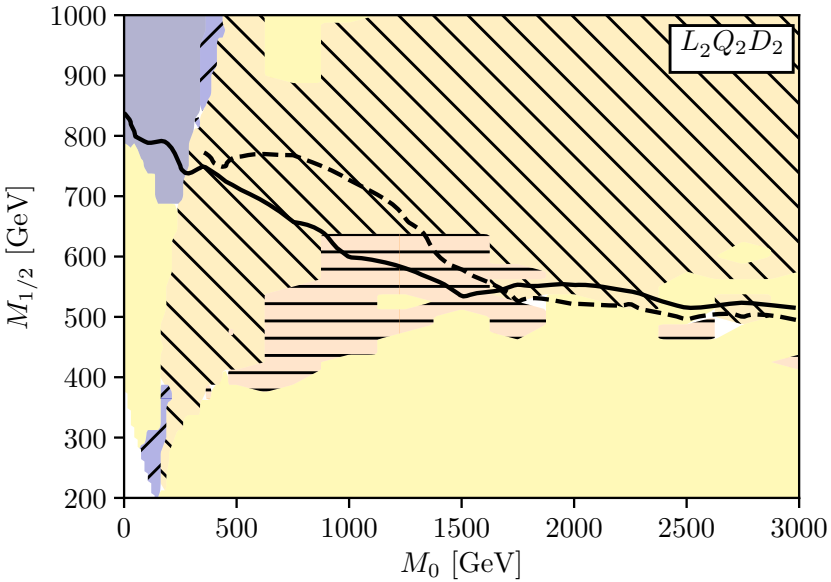
Recasting LHC results, $LQ\bar{D}$

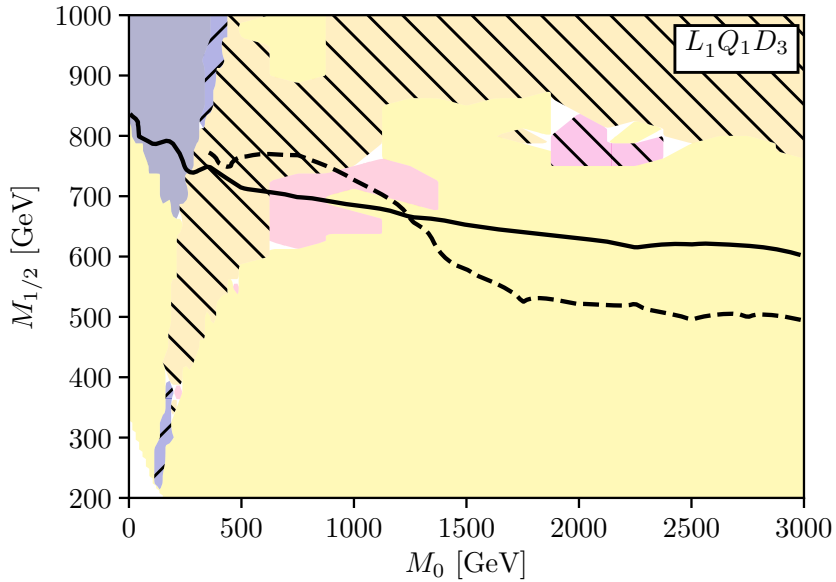
atlas_conf_2013_036 $4\ell + \not{E}_T$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + \geq 1b + \not{E}_T$	**atlas_1403_5294** $2\ell + \not{E}_T$
atlas_1402_7029 $3\ell + \not{E}_T$	**atlas_1407_0583** $1\ell + 1b + \not{E}_T$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + \not{E}_T$	**atlas_1407_0600** $0 - 1\ell + 3b + \not{E}_T$
atlas_conf_2013_061 $0 - 1\ell + 3b + \not{E}_T$	**atlas_1405_7875** $0\ell + 2 - 6j + \not{E}_T$	**atlas_1308_1841** $0\ell + \geq 7j + \not{E}_T$	**atlas_conf_2013_062** $1 - 2\ell + 3 - 6j + \not{E}_T$
atlas_1404_2500 3ℓ *or SS* 2ℓ + *0 or* $\geq 0b + \not{E}_T$			





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

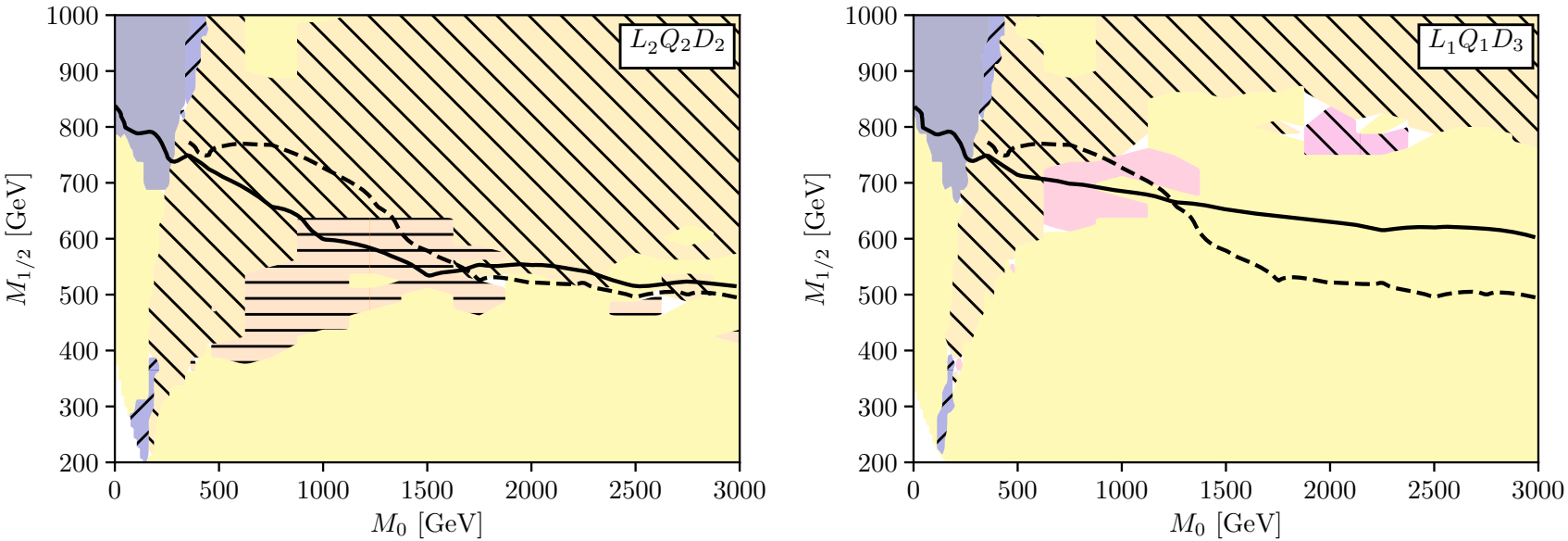




- bounds comparable to RPC
- $\tilde{\chi}_1^0$ LSP: $\tilde{\chi}_1^0 \to \mu jj/\nu jj$
- $\tilde{\tau}$ LSP: $\tilde{\chi}_1^0 \to \tau\tilde{\tau}$; $\tilde{\tau} \to \mu\nu/\tau\nu$ (via RGE-generated λ_{233})

- 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, $LQ\bar{D}$

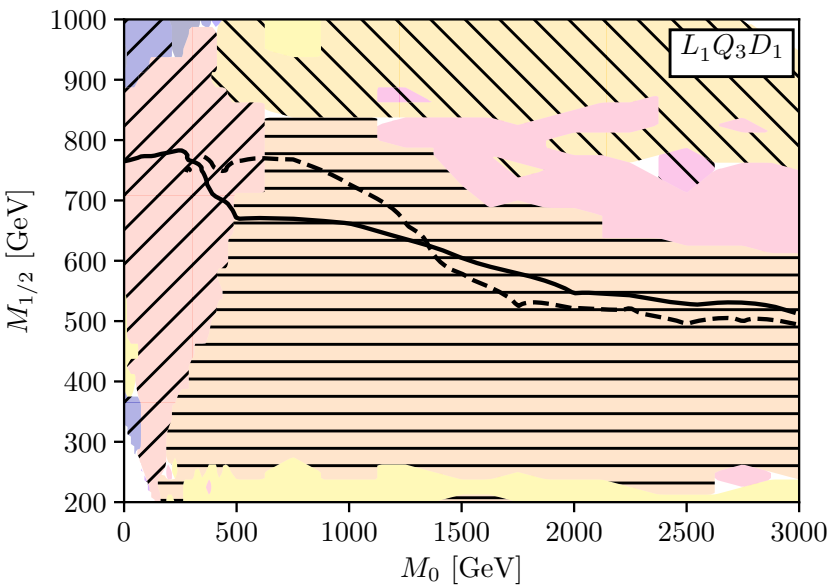


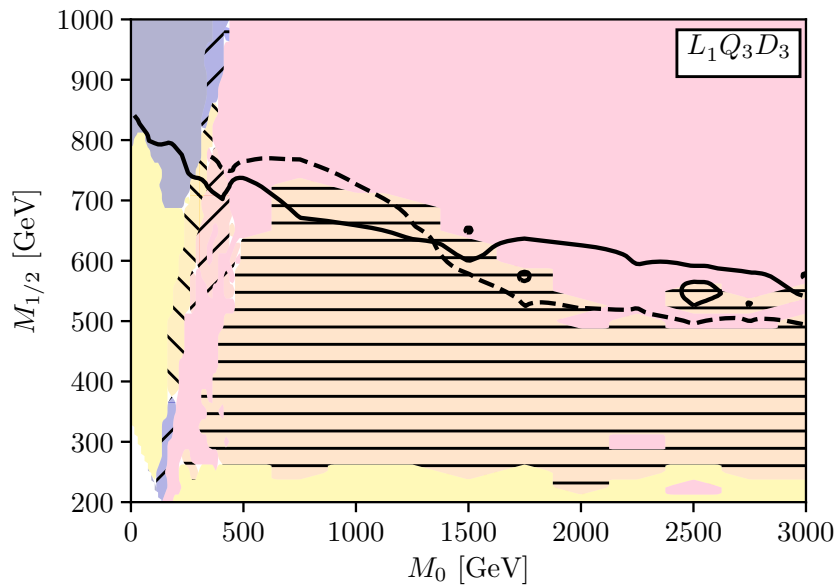
Sensitive analyses:

- 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, $LQ\bar{D}$

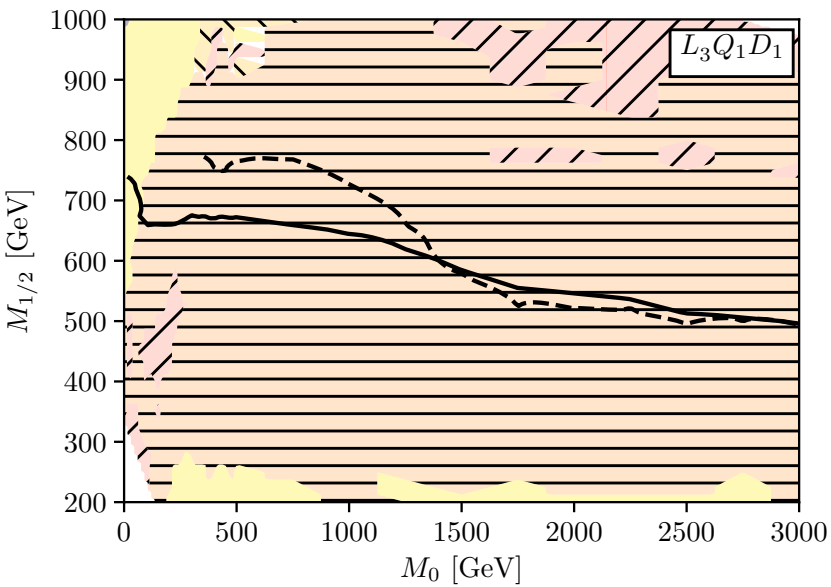
atlas_conf_2013_036 $4\ell + \not{E}_T$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + \geq 1b + \not{E}_T$	**atlas_1403_5294** $2\ell + \not{E}_T$
atlas_1402_7029 $3\ell + \not{E}_T$	**atlas_1407_0583** $1\ell + 1b + \not{E}_T$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + \not{E}_T$	**atlas_1407_0600** $0-1\ell + 3b + \not{E}_T$
atlas_conf_2013_061 $0-1\ell + 3b + \not{E}_T$	**atlas_1405_7875** $0\ell + 2-6j + \not{E}_T$	**atlas_1308_1841** $0\ell + \geq 7j + \not{E}_T$	**atlas_conf_2013_062** $1-2\ell + 3-6j + \not{E}_T$
atlas_1404_2500 3ℓ *or SS* $2\ell + 0$ *or* $\geq 0b + \not{E}_T$			

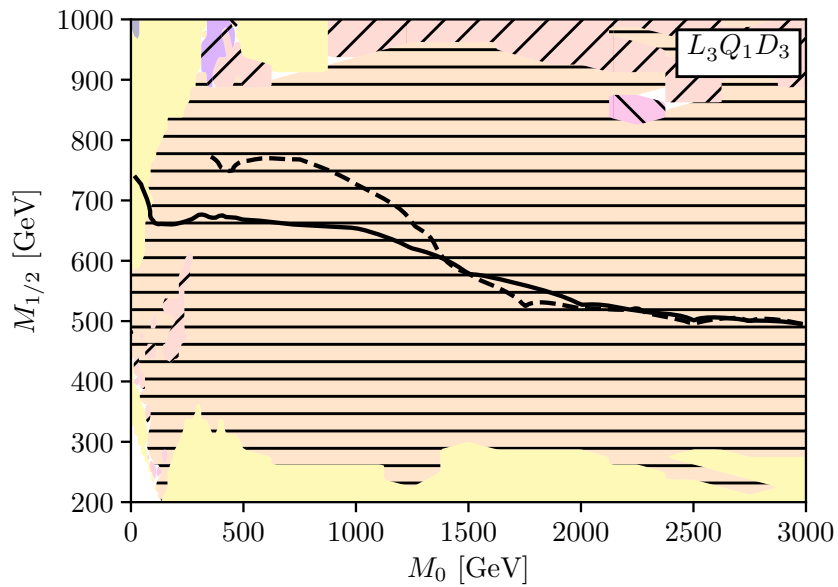




Recasting LHC results, $LQ\bar{D}$

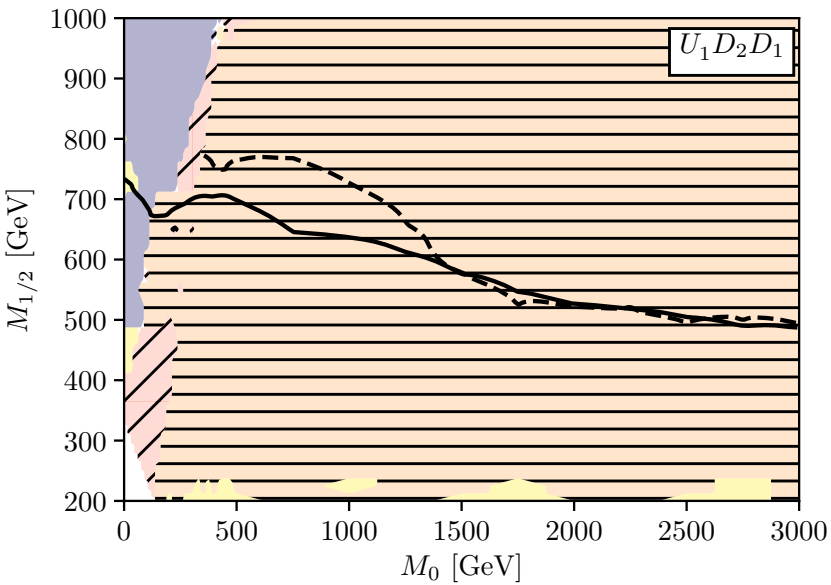
atlas_conf_2013_036 $4\ell + \not{E}_T$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + \geq 1b + \not{E}_T$	**atlas_1403_5294** $2\ell + \not{E}_T$
atlas_1402_7029 $3\ell + \not{E}_T$	**atlas_1407_0583** $1\ell + 1b + \not{E}_T$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + \not{E}_T$	**atlas_1407_0600** $0-1\ell + 3b + \not{E}_T$
atlas_conf_2013_061 $0-1\ell + 3b + \not{E}_T$	**atlas_1405_7875** $0\ell + 2-6j + \not{E}_T$	**atlas_1308_1841** $0\ell + \geq 7j + \not{E}_T$	**atlas_conf_2013_062** $1-2\ell + 3-6j + \not{E}_T$
atlas_1404_2500 3ℓ *or SS* $2\ell + 0$ *or* $\geq 0b + \not{E}_T$			

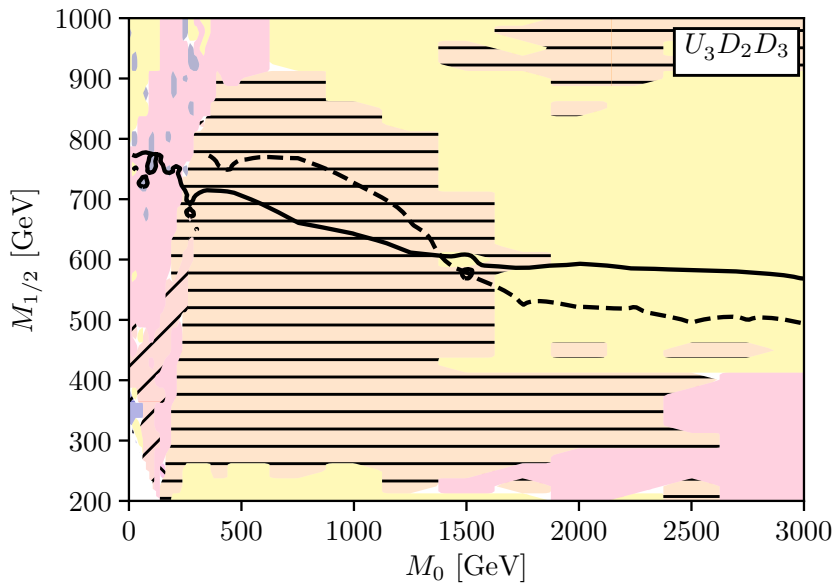




Recasting LHC results, $\bar{U}\bar{D}\bar{D}$

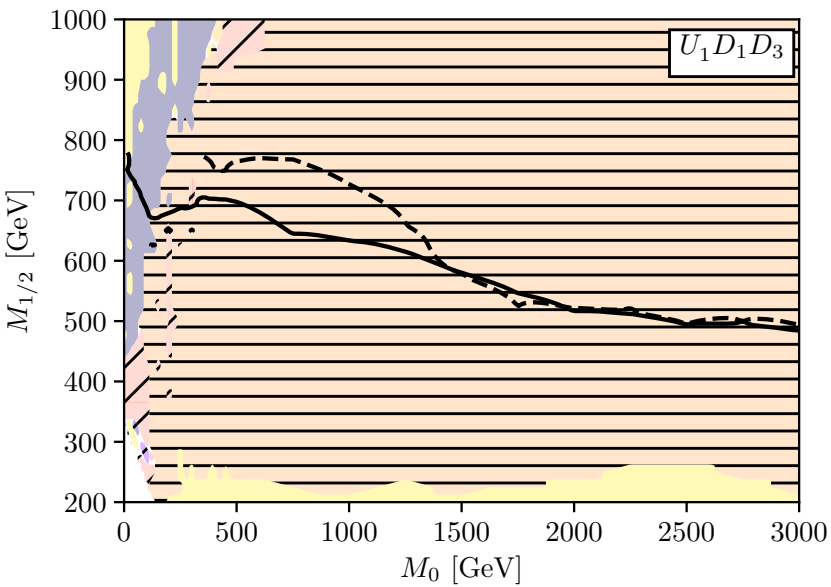
atlas_conf_2013_036 $4\ell + \not{E}_T$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + \geq 1b + \not{E}_T$	**atlas_1403_5294** $2\ell + \not{E}_T$
atlas_1402_7029 $3\ell + \not{E}_T$	**atlas_1407_0583** $1\ell + 1b + \not{E}_T$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + \not{E}_T$	**atlas_1407_0600** $0 - 1\ell + 3b + \not{E}_T$
atlas_conf_2013_061 $0 - 1\ell + 3b + \not{E}_T$	**atlas_1405_7875** $0\ell + 2 - 6j + \not{E}_T$	**atlas_1308_1841** $0\ell + \geq 7j + \not{E}_T$	**atlas_conf_2013_062** $1 - 2\ell + 3 - 6j + \not{E}_T$
atlas_1404_2500 3ℓ *or SS* 2ℓ + *0 or* $\geq 0b + \not{E}_T$			

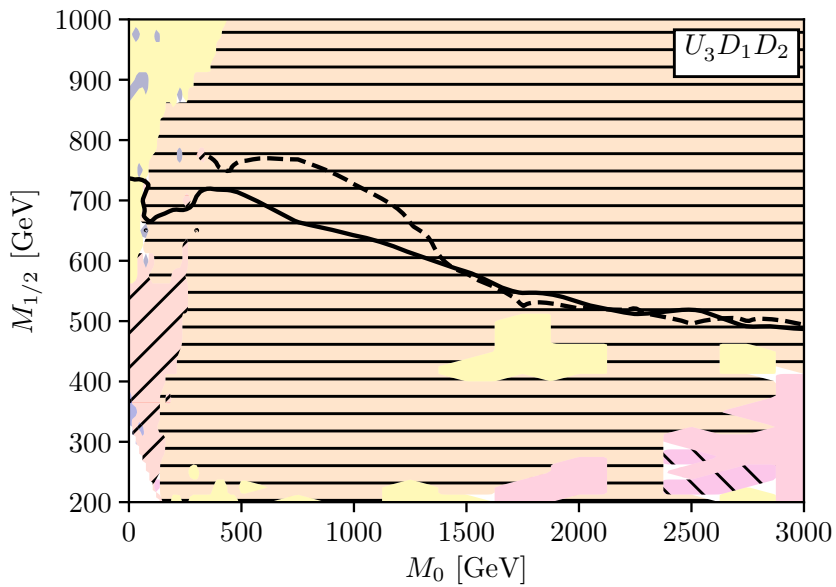




Recasting LHC results, $\bar{U}\bar{D}\bar{D}$

atlas_conf_2013_036 $4\ell + \not{E}_T$	**cms_1405_7570** *various electroweakino searches*	**atlas_1403_4853** $2\ell + \geq 1b + \not{E}_T$	**atlas_1403_5294** $2\ell + \not{E}_T$
atlas_1402_7029 $3\ell + \not{E}_T$	**atlas_1407_0583** $1\ell + 1b + \not{E}_T$	**cms_1504_03198** $1\ell + \geq 3j$ *incl* $\geq 1b + \not{E}_T$	**atlas_1407_0600** $0-1\ell + 3b + \not{E}_T$
atlas_conf_2013_061 $0-1\ell + 3b + \not{E}_T$	**atlas_1405_7875** $0\ell + 2-6j + \not{E}_T$	**atlas_1308_1841** $0\ell + \geq 7j + \not{E}_T$	**atlas_conf_2013_062** $1-2\ell + 3-6j + \not{E}_T$
atlas_1404_2500 3ℓ *or SS* $2\ell + 0$ *or* $\geq 0b + \not{E}_T$			





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.

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

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

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

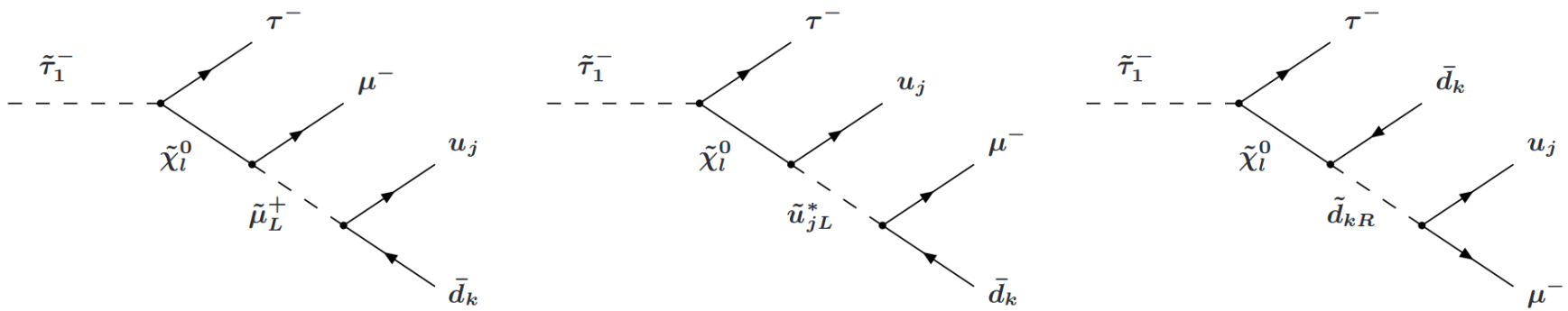
Two separate cases:

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.

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

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

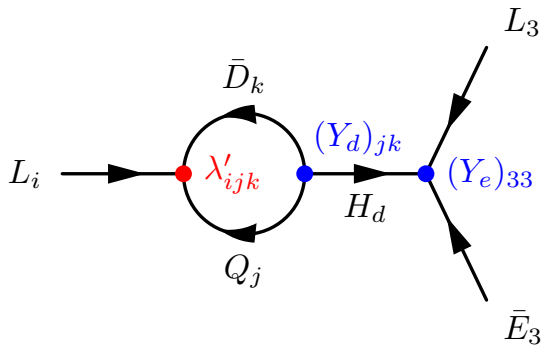
2. $\Lambda_{\not R_p}$ does not couple to a (s)tau: 4-body decay

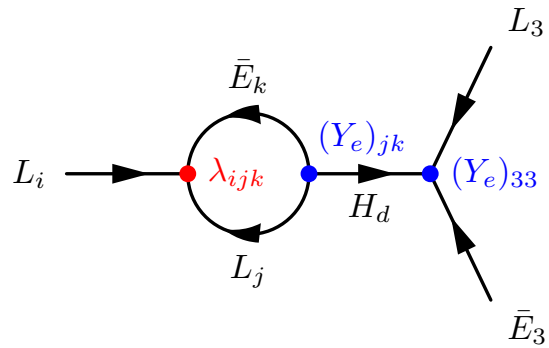


Dreiner,Grab,Trenke '08

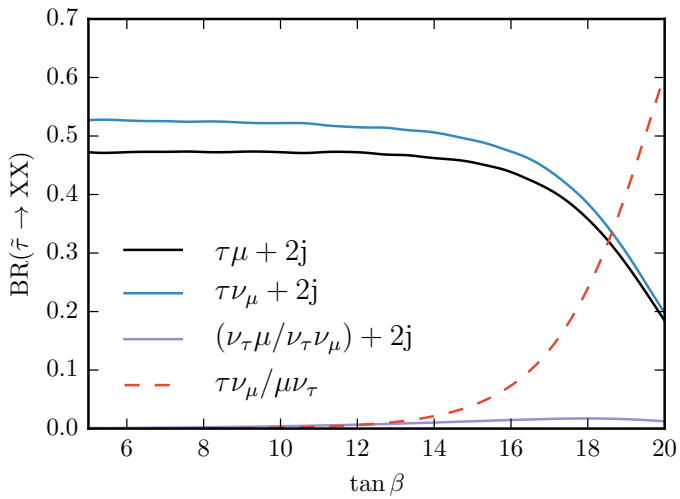
LHC Signatures, $\tilde{\tau}_1$ LSP

However, full model: RGE-generated operators:

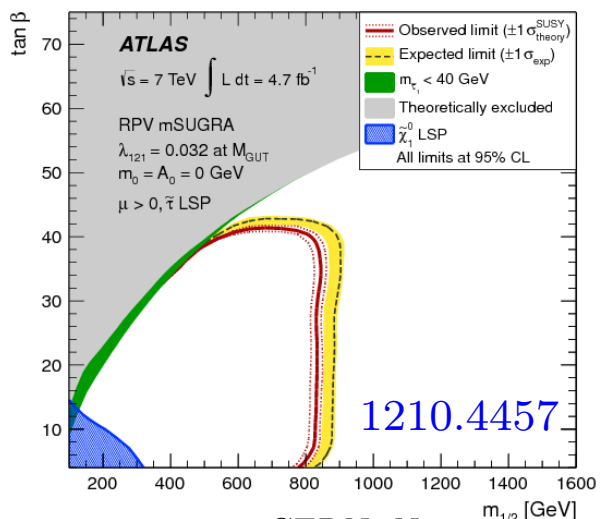




$$16\pi^2 \frac{d}{dt}\lambda_{i33} = \lambda_{i33}\Big(-\frac{9}{5}g_1^2 - 3g_2^2 + 4(Y_e)_{33}^2\Big)$$
$$+3\lambda'_{ijk}(Y_e)_{33}(Y_d)_{jk} + \lambda_{ijk}(Y_e)_{33}(Y_e)_{jk}\,.$$

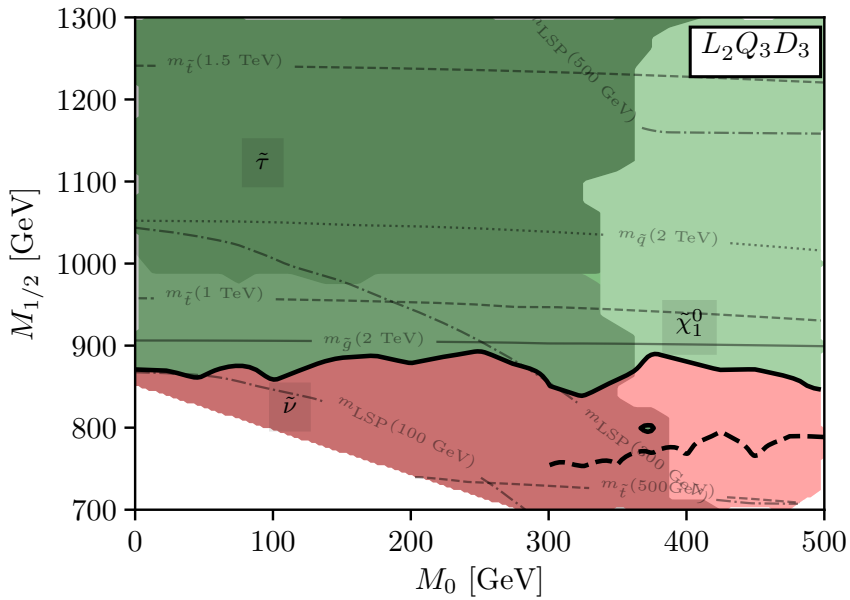


$\longleftrightarrow$



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→...