LHC phenomenology of supersymmetric models with a $U(1)_R$ baryon number

Kevin Earl

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Carleton University

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Outline

1. Motivation
2. $U(1)_R$ baryon number
3. Phenomenology
4. Conclusion

MSSM: superpotential

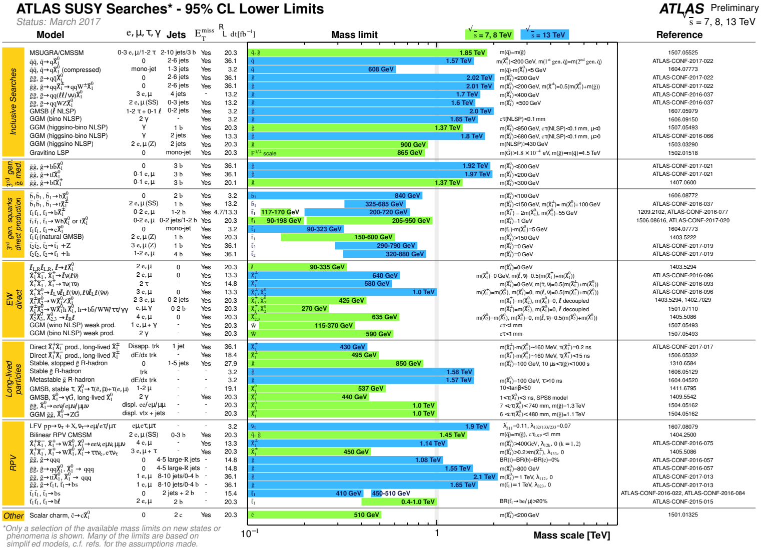
The most general superpotential:

$$W = y_u Q H_u U^c - y_d Q H_d D^c - y_e L H_d E^c + \mu H_u H_d \;\leftarrow \text{good}$$
$$+ \frac{1}{2}\lambda L L E^c + \lambda' L Q D^c + \frac{1}{2}\lambda'' U^c D^c D^c + \epsilon H_u L \;\leftarrow \text{bad}$$

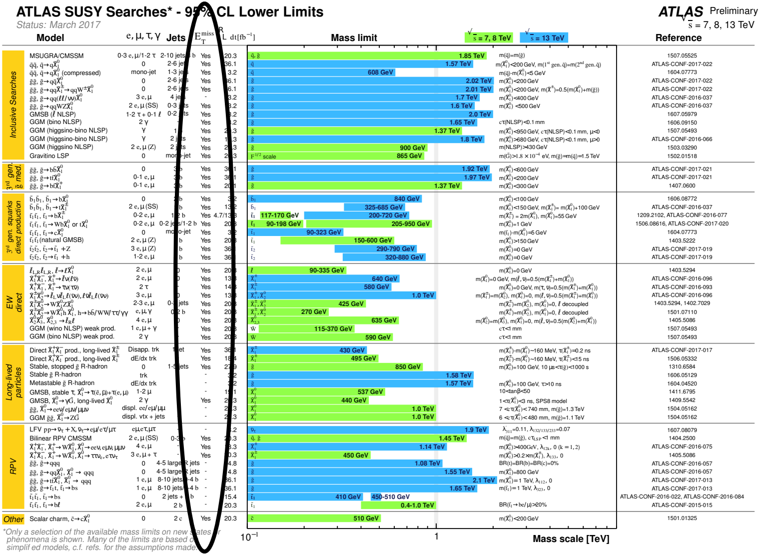
lepton number violating   baryon number violating

Invoke R-parity to forbid undesirable terms.

ATLAS susy searches



ATLAS susy searches involving MET



Thinking beyond the MSSM: *R*-symmetries

Instead of a discrete Z_2 symmetry, consider a global $U(1)_R$ symmetry.

$$\theta \to e^{i\alpha}\theta, \quad \theta^\dagger \to e^{-i\alpha}\theta^\dagger$$

Chiral superfield Φ with R-charge r_Φ transforms as $\Phi \to e^{ir_\Phi\alpha}\Phi$. Then

$$\phi \to e^{ir_\Phi\alpha}\phi, \quad \chi \to e^{i(r_\Phi-1)\alpha}\chi, \quad F \to e^{i(r_\Phi-2)\alpha}F$$

Vector superfields are real $V^\dagger = V$ and so have zero R-charge, $V \to V$.

gauginos have R-charge 1, $\lambda \to e^{i\alpha}\lambda$

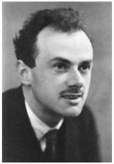
Minimal R-symmetric Supersymmeric Standard Model (MRSSM)
Kribs, Poppitz, Weiner '07

Different R-charge assignments are possible.
Frugiuele, Grégoire, Kumar, Pontón '12

Consequences of R-symmetries

Two consequences of R-symmetries:

- gauginos are now required to be Dirac fermions



  - Majorana gaugino mass terms are forbidden

- μ-term in the superpotential is forbidden by the R-symmetry

We must introduce additional fields.

$U(1)_R$ baryon number 1

Superfield	R-charge	Superfield	R-charge
Q	$4/3$		
U^c	$2/3$		
D^c	$2/3$		
L	1		
E^c	1		
H_u	0	R_d	2
H_d	0	R_u	2
B	0	S	0
W^i	0	T^i	0
G^a	0	O^a	0

$U(1)_R$ baryon number 2

This R-charge assignment is referred to as $U(1)_R$ baryon number because the R-charges of SM particles corresponds to their baryon number.

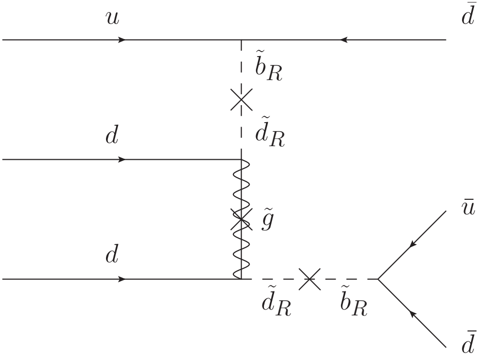
New superpotential:

$$W = y_u Q H_u U^c - y_d Q H_d D^c - y_e L H_d E^c + \mu_u H_u R_d + \mu_d R_u H_d$$
$$+\lambda_u^t H_u T R_d + \lambda_d^t R_u T H_d + \lambda_u^s S H_u R_d + \lambda_d^s S R_u H_d + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

↗ phenomenologically interesting and now baryon number conserving

Baryon number violating processes 1

Neutron-antineutron oscillation

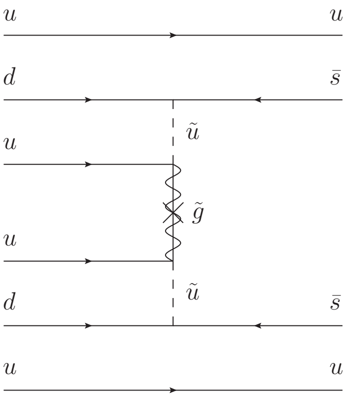


Unavoidably $U(1)_R$ breaking by anomaly mediation generates Majorana gaugino masses $\sim m_{3/2}/16\pi^2$.

$$\lambda''_{11i} \lesssim 2 \times 10^{-5} \left(\frac{1}{\delta^{RR}_{i1}}\right) \left(\frac{M_3^D}{1\text{TeV}}\right) \left(\frac{1\text{GeV}}{m_{3/2}}\right)^{1/2} \left(\frac{m_{\tilde{q}}}{1\text{TeV}}\right)^2 \left(\frac{250\text{MeV}}{\Lambda}\right)^3$$

Baryon number violating processes 2

Double nucleon decay: $pp \to K^+K^+$

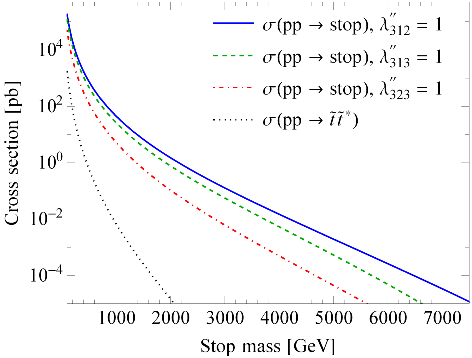


$$\lambda''_{112} \lesssim 2 \times 10^{-4} \left(\frac{M_3^D}{1\text{TeV}}\right) \left(\frac{1\text{GeV}}{m_{3/2}}\right)^{1/2} \left(\frac{m_{\tilde{q}}}{1\text{TeV}}\right)^2 \left(\frac{150\text{MeV}}{\tilde{\Lambda}}\right)^{5/2}$$

Stop phenomenology: stop LSP 1

Assume only λ''_{3ij} are non-zero. Then stops both resonantly produced, $pp \to \tilde{t}^*$, and pair produced $pp \to \tilde{t}\tilde{t}^*$.

13 TeV $\to$

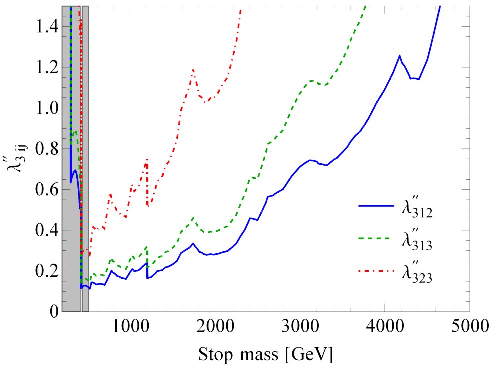


Stops can decay back to quarks, $\tilde{t}^* \to d_i d_j$.

Stop phenomenology: stop LSP 2

Signals:

- dijets: $pp \to \tilde{t}^* \to d_i d_j$
- paired dijets: $pp \to \tilde{t}^* \tilde{t} \to d_i d_j \bar{d}_i \bar{d}_j$



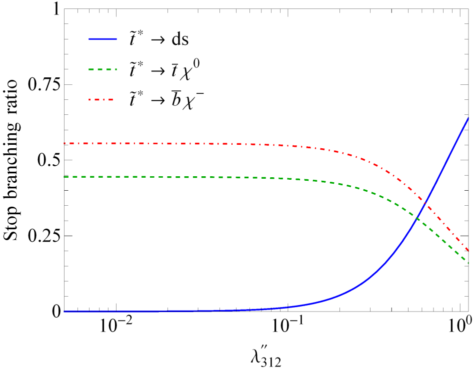
similar to Monteux '16

Stop phenomenology: neutralino LSP 1

Consider a Higgsino-up LSP. The stop can now decay three different ways:

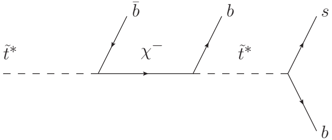
$$\tilde{t}^* \to d_i d_j, \quad \tilde{t}^* \to \bar{t}\chi^0, \quad \tilde{t}^* \to \bar{b}\chi^-.$$

600 GeV stop and 200 GeV neutralino →

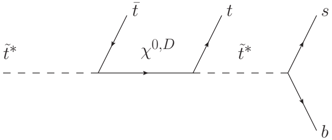


Stop phenomenology: neutralino LSP 2

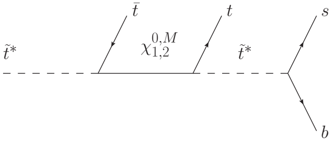
Stops decaying through charginos:

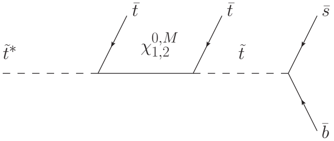


Stops decaying through Dirac neutralinos:



Stops decaying through Majorana neutralinos:

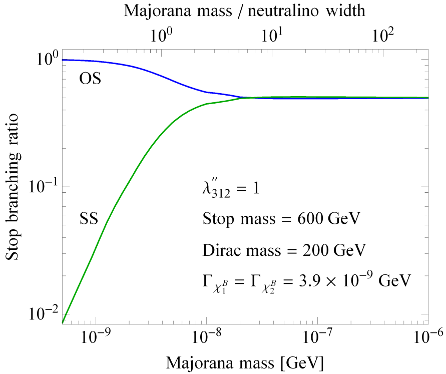




Stop phenomenology: neutralino LSP 3

Unavoidable $U(1)_R$ breaking generates Majorana gauginos masses. Dirac neutralinos split into two Majorana neutralinos.

How large does the breaking need to be so that same sign and opposite sign tops are produced equally from stop decays?



Stop phenomenology: neutralino LSP 4

Two production mechanisms:

- $pp \to \tilde{t}^*$
- $pp \to \tilde{t}^* \tilde{t}$

Three decay possibilities:

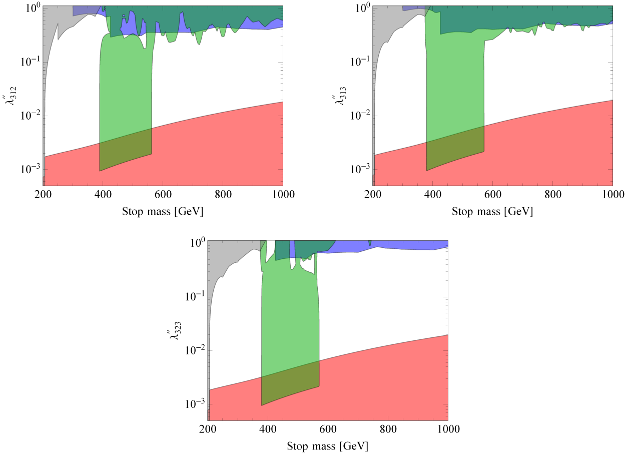
- $\tilde{t}^* \to d_i d_j$
- $\tilde{t}^* \to \bar{t}\chi^0$
- $\tilde{t}^* \to \bar{b}\chi^-$

Nine possible decay topologies. Can use LHC searches to constrain the parameter space.

Also possible to use displaced vertices from neutralino decays to constrain the parameter space.

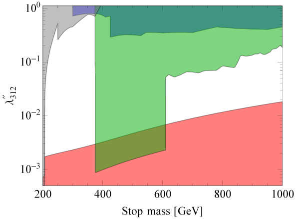
Stop phenomenology: neutralino LSP 5

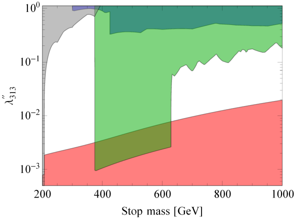
200 GeV Dirac neutralinos:

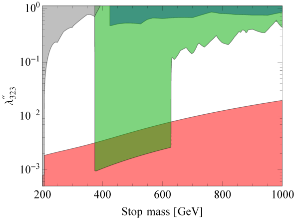


Stop phenomenology: neutralino LSP 6

200 GeV Majorana neutralinos:



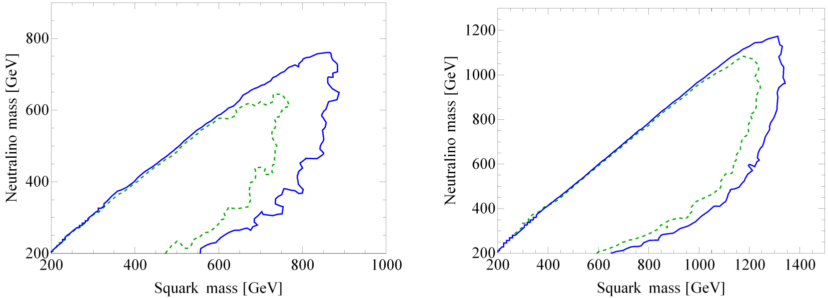




similar to Monteux '16

Squark phenomenology: neutralino LSP 1

Can also perform similar analysis for first two generations of squarks.



(a) λ''_{312} (b) λ''_{313} / λ''_{323}

Squark production cross section reduced due to Dirac gluinos.

Heikinheimo, Kellerstein, Sanz '11

Kribs, Martin '12

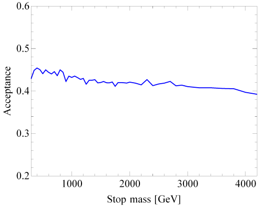
Conclusion

To summarize:

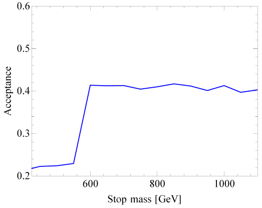
- lack of signals continues to push MSSM superparnter masses upwards
- this suggests thinking beyond the MSSM
- $U(1)_R$ baryon number is an example of an extended supersymmetry model
- baryon number violating constraints follow from $U(1)_R$ breaking
- parameter space with stops constrained by recent LHC searches
- similarly, squark parameter space also constrained

Back-up slides

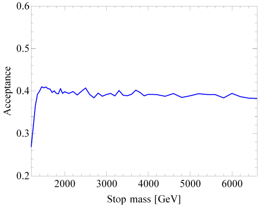
Dijet search efficiencies



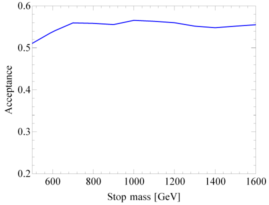
(a) ATLAS 1407.1376



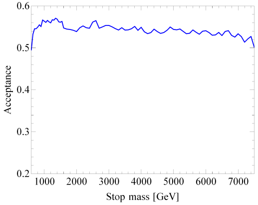
(b) ATLAS-CONF-2016-030



(c) ATLAS-CONF-2016-069



(d) CMS 1604.08907



(e) CMS-PAS-EXO-16-032

Stop decay topologies

With Dirac neutralinos:

(1) $pp \to \tilde{t}^* \to d_i d_j$

(2) $pp \to \tilde{t}^* \to \bar{t}\chi^0 \to \bar{t}td_i d_j$

(3) $pp \to \tilde{t}^* \to \bar{b}\chi^- \to \bar{b}bd_i d_j$

(4) $pp \to \tilde{t}^*\tilde{t} \to d_i d_j \bar{d}_i \bar{d}_j$

(5) $pp \to \tilde{t}^*\tilde{t} \to \bar{t}\chi^0 t\bar{\chi}^0 \to \bar{t}td_i d_j t\bar{t}\bar{d}_i\bar{d}_j$

(6) $pp \to \tilde{t}^*\tilde{t} \to \bar{b}\chi^- b\chi^+ \to \bar{b}bd_i d_j b\bar{b}\bar{d}_i\bar{d}_j$

(7) $pp \to \tilde{t}^*\tilde{t} \to d_i d_j t\bar{\chi}^0 \to d_i d_j t\bar{t}\bar{d}_i\bar{d}_j$

(8) $pp \to \tilde{t}^*\tilde{t} \to d_i d_j b\chi^+ \to d_i d_j b\bar{b}\bar{d}_i\bar{d}_j$

(9) $pp \to \tilde{t}^*\tilde{t} \to \bar{t}\chi^0 b\chi^+ \to \bar{t}td_i d_j b\bar{b}\bar{d}_i\bar{d}_j$

With Majorana neutralinos:

(2) $$pp \to \tilde{t}^* \to \bar{t}\chi^0 \to \begin{cases} \bar{t}td_i d_j \\ \bar{t}\bar{t}\bar{d}_i\bar{d}_j \end{cases}$$

(5) $$pp \to \tilde{t}^*\tilde{t} \to \bar{t}\chi^0 t\chi^0 \to \begin{cases} \bar{t}td_i d_j t\bar{t}\bar{d}_i\bar{d}_j \\ \bar{t}td_i d_j ttd_i d_j \\ \bar{t}\bar{t}\bar{d}_i\bar{d}_j t\bar{t}\bar{d}_i\bar{d}_j \\ \bar{t}\bar{t}\bar{d}_i\bar{d}_j ttd_i d_j \end{cases}$$

(7) $$pp \to \tilde{t}^*\tilde{t} \to d_i d_j t\chi^0 \to \begin{cases} d_i d_j t\bar{t}\bar{d}_i\bar{d}_j \\ d_i d_j ttd_i d_j \end{cases}$$

(9) $$pp \to \tilde{t}^*\tilde{t} \to \bar{t}\chi^0 b\chi^+ \to \begin{cases} \bar{t}td_i d_j b\bar{b}\bar{d}_i\bar{d}_j \\ \bar{t}\bar{t}\bar{d}_i\bar{d}_j b\bar{b}\bar{d}_i\bar{d}_j \end{cases}$$

LHC searches 1

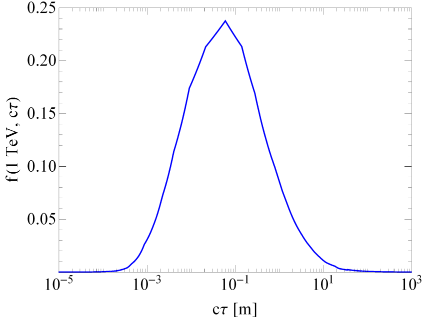
Collaboration	Search	Strategy
ATLAS	ATLAS-CONF-2016-037	2 (potentially negative) same sign leptons, total number of leptons, jets with $p_T > 25$, 40 or 50 GeV, b-jets, MET, $m_{\text{eff}} = \sum_{\substack{\text{jets}\\\text{leptons}}} p_T + \text{MET}$
ATLAS	ATLAS-CONF-2016-057	large ($R = 1.0$) jets J_i, $p_{T\,J_1} > 440$ GeV, $\lvert\Delta\eta_{J_1 J_2}\rvert < 1.4$, $M_J^\Sigma = \sum_{i=1}^{4} m_{J_i}$, small ($R = 0.4$) b-jets
ATLAS	ATLAS-CONF-2016-094	at least 1 lepton, jets with $p_T > 40$ or 60 GeV, b-jets with $p_T > 40$ or 60 GeV

LHC searches 2

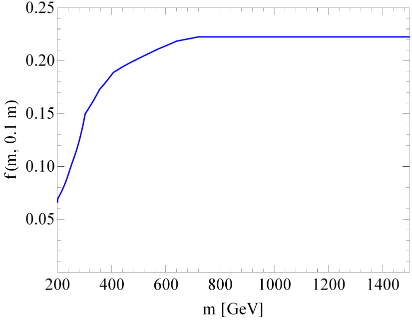
Collaboration	Search	Strategy
ATLAS	ATLAS-CONF-2016-013	exactly 1 lepton, jets, b-jets, mass-tagged jets = large ($R = 1.0$) jets with cuts, $m_{bb}^{\text{min}\,\Delta R}$ = invariant mass of closest b-jets, MET, MET + $M_T(\ell, \text{MET})$ where M_T = transverse mass
ATLAS	ATLAS-CONF-2016-032	2 same sign leptons, jets, b-jets, MET, $H_T = \sum_{\substack{\text{jets}\\ \text{leptons}}} p_T$
CMS	CMS-PAS-SUS-16-020	2 same sign leptons, jets, b-jets, $M_T^{\text{min}} = \min(M_T(\ell_1, \text{MET}), M_T(\ell_2, \text{MET}))$ where M_T = transverse mass, MET, $H_T = \sum_{\text{jets}} p_T$

Efficiency for reconstructing a single displaced vertex

Efficiency, f, as a function of neutralino mass, m, and decay length, $c\tau$.



(a) $m = 1$ TeV

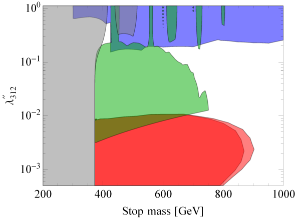


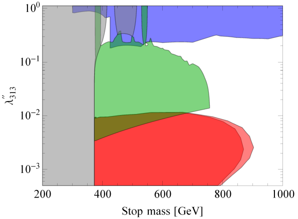
(b) $c\tau = 0.1$ m

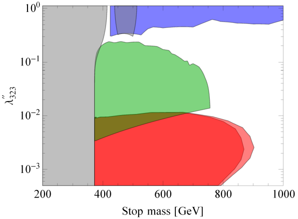
Based on CMS search 1411.6530.

Stop phenomenology: bino neutralino LSP 1

200 GeV Dirac neutralinos:

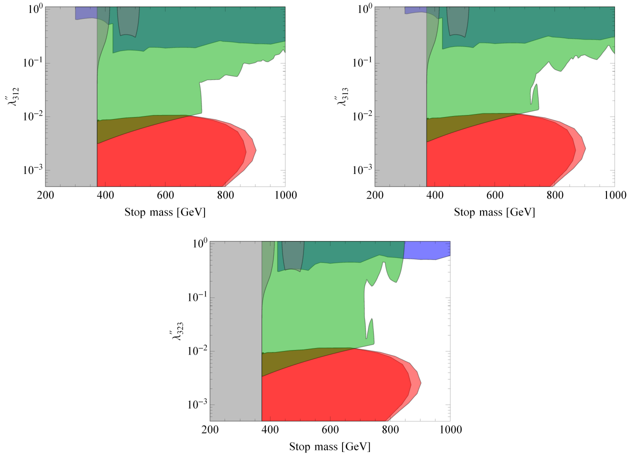






Stop phenomenology: bino neutralino LSP 2

200 GeV Majorana neutralinos:



similar to Monteux '16

Squark decay topologies

With Dirac neutralinos:

(1) $pp \to \tilde{q}^*\tilde{q} \to d_{i/j} t \bar{d}_{i/j} \bar{t}$

(2) $pp \to \tilde{q}^*\tilde{q} \to \bar{q}\chi^0 q\bar{\chi}^0 \to \bar{q} t d_i d_j q \bar{t} \bar{d}_i \bar{d}_j$

(3) $pp \to \tilde{q}^*\tilde{q} \to \bar{q}'\chi^+ q'\chi^- \to \bar{q}' \bar{b} \bar{d}_i \bar{d}_j q' b d_i d_j$

(4) $pp \to \tilde{q}^*\tilde{q} \to d_{i/j} t q \bar{\chi}^0 \to d_{i/j} t q \bar{t} \bar{d}_i \bar{d}_j$

(5) $pp \to \tilde{q}^*\tilde{q} \to d_{i/j} t q' \chi^- \to d_{i/j} t q' b d_i d_j$

(6) $pp \to \tilde{q}^*\tilde{q} \to \bar{q}\chi^0 q'\chi^- \to \bar{q} t d_i d_j q' b d_i d_j$

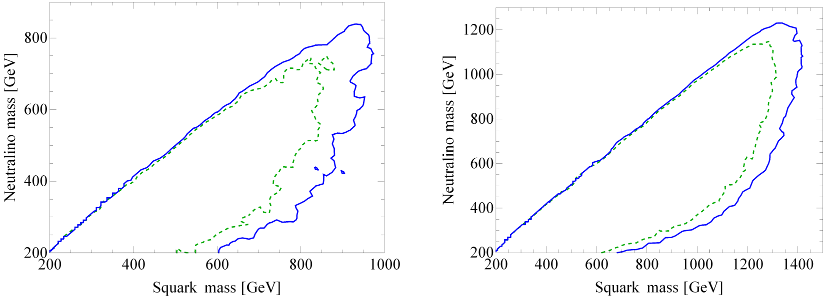
With Majorana neutralinos:

(2) $$pp \to \tilde{q}^*\tilde{q} \to \bar{q}\chi^0 q\chi^0 \to \begin{cases} \bar{q} t d_i d_j q \bar{t} \bar{d}_i \bar{d}_j \\ \bar{q} t d_i d_j q t d_i d_j \\ \bar{q} \bar{t} \bar{d}_i \bar{d}_j q \bar{t} \bar{d}_i \bar{d}_j \\ \bar{q} \bar{t} \bar{d}_i \bar{d}_j q t d_i d_j \end{cases}$$

(4) $$pp \to \tilde{q}^*\tilde{q} \to d_{i/j} t q \chi^0 \to \begin{cases} d_{i/j} t q \bar{t} \bar{d}_i \bar{d}_j \\ d_{i/j} t q t d_i d_j \end{cases}$$

(6) $$pp \to \tilde{q}^*\tilde{q} \to \bar{q}\chi^0 q'\chi^- \to \begin{cases} \bar{q} t d_i d_j q' b d_i d_j \\ \bar{q} \bar{t} \bar{d}_i \bar{d}_j q' b d_i d_j \end{cases}$$

Squark phenomenology: bino neutralino LSP 1



(a) λ''_{312} (b) λ''_{313} / λ''_{323}