

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

Kevin Earl

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Carleton University

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Pheno 2017

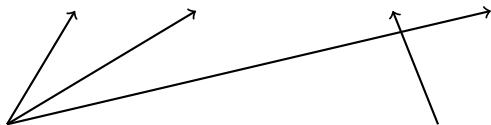
Outline

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

MSSM: superpotential

The most general superpotential:

$$\begin{aligned}
 W = & y_u QH_u U^c - y_d QH_d D^c - y_e LH_d E^c + \mu H_u H_d \leftarrow \text{good} \\
 & + \frac{1}{2}\lambda LLE^c + \lambda' LQD^c + \frac{1}{2}\lambda'' U^c D^c D^c + \epsilon H_u L \leftarrow \text{bad}
 \end{aligned}$$



lepton number violating

baryon number violating

Invoke R -parity to forbid undesirable terms.

ATLAS susy searches

ATLAS SUSY Searches* - 95% CL Lower Limits

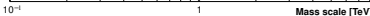
Status: March 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	e, μ, τ, γ	Jets	$E_{\text{miss}}^{\text{min}}$	$R_{\text{d}}^{\text{d}(\text{fb}^{-1})}$	Mass limit	$\tau = 7, 8 \text{ TeV}$	$\tau = 13 \text{ TeV}$	Reference
Inclusive Searches	MSUGRA/CMSSM	$0.3 \leq \mu \leq 2$	$2-10$	jets + b	Yes	20.3	4.1	1507.0525
	$4\bar{b}_1 \rightarrow 4\bar{b}_2$	0	2-6	jets	Yes	36.1	1.85 TeV	$m(\tilde{g}) = m(\tilde{u})$
	$4\bar{b}_1 \rightarrow 4\bar{b}_2$ (compressed)	mono-jet	1-3	jets	Yes	3.2	1.57 TeV	$m(\tilde{g}) = 200 \text{ GeV}, m(\tilde{u}) = \text{para.}, m(\tilde{t}^{\pm}) = 2m(\tilde{g})$
	$\tilde{g} \rightarrow q\bar{q}$	0	2-6	jets	Yes	36.1	608 GeV	$m(\tilde{g}) = 400 \text{ GeV}$
	$\tilde{g} \rightarrow q\bar{q} \rightarrow q\bar{q} W^{\pm} X^0$	0	2-6	jets	Yes	36.1	2.02 TeV	$m(\tilde{g}) = 200 \text{ GeV}$
	$\tilde{g} \rightarrow q\bar{q} W^{\pm} W^{\pm} X^0$	0	2-6	jets	Yes	36.1	2.01 TeV	$m(\tilde{g}) = 200 \text{ GeV}, m(\tilde{u}) = 0.5 m(\tilde{g}), m(\tilde{t}) = m(\tilde{g})$
	$\tilde{g} \rightarrow q\bar{q} W^{\pm} X^0$	$2 \leq \mu$ (SS)	0-3	jets	Yes	13.2	1.7 TeV	$m(\tilde{g}) = 400 \text{ GeV}$
	GMSB (f NLSIP)	$1-2 \tau, 0-1 f$	0-2	jets	Yes	3.2	1.8 TeV	$m(\tilde{g}) = 400 \text{ GeV}$
	OGM (bino NLSIP)	2γ	-	Yes	3.2	1.8 TeV	$c(NLSIP) = 0.1 \text{ mm}$	
	OGM (higgsino bino NLSIP)	γ	1 h	Yes	20.3	1.37 TeV	$m(\tilde{g}) = 200 \text{ GeV}, c(NLSIP) = 0.1 \text{ mm}, \mu = 0$	
OGM (higgsino bino NLSIP)	γ	2 jets	Yes	13.3	1.8 TeV	$m(\tilde{g}) = 200 \text{ GeV}, c(NLSIP) = 0.1 \text{ mm}, \mu = 0$		
OGM (higgsino NLSIP)	$2 \leq \mu$ (Z)	0-3	jets	Yes	20.3	900 GeV	$m(NLSIP) = 430 \text{ GeV}$	
Chargino LSP	0	mono-jet	Yes	20.3	777 scale	865 GeV	$m(\tilde{g}) = 1.8 \times 10^{-4} \times m(\tilde{g}) = m(\tilde{g}) = 1.5 \text{ TeV}$	
1st gen. s-quark direct production	$\tilde{g} \rightarrow b\bar{b}$	0	3 h	Yes	36.1	1.92 TeV	$m(\tilde{g}) = 400 \text{ GeV}$	
	$\tilde{g} \rightarrow t\bar{t}$	0-1 e, μ	3 h	Yes	36.1	1.97 TeV	$m(\tilde{g}) = 200 \text{ GeV}$	
	$\tilde{g} \rightarrow b\bar{b} X^0$	0-1 e, μ	3 h	Yes	20.1	1.37 TeV	$m(\tilde{g}) = 200 \text{ GeV}$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	0	2 h	Yes	3.2	840 GeV	$m(\tilde{g}) = 100 \text{ GeV}$	
2nd gen. s-quark direct production	$\tilde{g} \rightarrow b\bar{b}$	2 e, μ (SS)	1 h	Yes	13.2	117-170 GeV	325-485 GeV	$m(\tilde{g}) = 150 \text{ GeV}, m(\tilde{t}^{\pm}) = m(\tilde{b}^{\pm}) = 100 \text{ GeV}$
	$\tilde{g} \rightarrow t\bar{t}$	0-2 e, μ	1-2 h	Yes	4.7/13.3	200-720 GeV	$m(\tilde{g}) = 2m(\tilde{t}^{\pm}), m(\tilde{b}^{\pm}) = 20 \text{ GeV}$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	0-2 e, μ	0-2 jets + 2 h	Yes	20.3	96-198 GeV	205-950 GeV	$m(\tilde{g}) = 100 \text{ GeV}$
	$\tilde{g} \rightarrow t\bar{t} X^0$	0	mono-jet	Yes	3.2	90-223 GeV	205-950 GeV	$m(\tilde{g}) = 100 \text{ GeV}, m(\tilde{t}^{\pm}) = m(\tilde{b}^{\pm}) = 100 \text{ GeV}$
	$\tilde{g} \rightarrow t\bar{t} X^0$	2 e, μ (Z)	1 h	Yes	20.3	150-400 GeV	$m(\tilde{g}) = 300 \text{ GeV}$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	3 e, μ (Z)	1 h	Yes	36.1	290-750 GeV	$m(\tilde{g}) = 400 \text{ GeV}$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	1-2 e, μ	4 h	Yes	36.1	320-880 GeV	$m(\tilde{g}) = 400 \text{ GeV}$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	2 e, μ	0	Yes	20.3	90-335 GeV	$m(\tilde{g}) = 0 \text{ GeV}$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	2 e, μ	0	Yes	13.3	840 GeV	$m(\tilde{g}) = 0 \text{ GeV}, m(\tilde{u}, \tilde{d}) = 0.5 m(\tilde{g}), m(\tilde{t}^{\pm}) = m(\tilde{b}^{\pm})$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	2 e, μ	0	Yes	14.8	580 GeV	$m(\tilde{g}) = 0 \text{ GeV}, m(\tilde{u}, \tilde{d}) = 0.5 m(\tilde{g}), m(\tilde{t}^{\pm}) = m(\tilde{b}^{\pm})$	
EW direct	$\tilde{g} \rightarrow t\bar{t} X^0$	3 e, μ	0	Yes	13.3	1.9 TeV	$m(\tilde{g}) = m(\tilde{u}), m(\tilde{d}) = 0.5 m(\tilde{g}), m(\tilde{t}^{\pm}) = m(\tilde{b}^{\pm})$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	2-3 e, μ	0-2 jets	Yes	20.3	425 GeV	$m(\tilde{g}) = m(\tilde{u}), m(\tilde{d}) = 0.5 m(\tilde{g}), m(\tilde{t}^{\pm}) = m(\tilde{b}^{\pm})$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	4 e, μ	0-2 h	Yes	20.3	270 GeV	$m(\tilde{g}) = m(\tilde{u}), m(\tilde{d}) = 0.5 m(\tilde{g}), m(\tilde{t}^{\pm}) = m(\tilde{b}^{\pm})$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	4 e, μ	0	Yes	20.3	635 GeV	$m(\tilde{g}) = m(\tilde{u}), m(\tilde{d}) = 0.5 m(\tilde{g}), m(\tilde{t}^{\pm}) = m(\tilde{b}^{\pm})$	
	OGM (wino NLSIP) weak prod.	1 $e, \mu + \gamma$	-	Yes	20.3	115-370 GeV	$c(NLSIP) = 0.1 \text{ mm}$	
	OGM (bino NLSIP) weak prod.	2 γ	-	Yes	20.3	590 GeV	$c(NLSIP) = 0.1 \text{ mm}$	
	Direct $\tilde{X}_1^0 \tilde{X}_1^0$ prod. long-lived \tilde{X}_1^0	Disapp. jet	1 jet	Yes	36.1	430 GeV	$m(\tilde{g}) = 100 \text{ GeV}, c(NLSIP) = 0.2 \text{ ns}$	
	Direct $\tilde{X}_1^0 \tilde{X}_1^0$ prod. long-lived \tilde{X}_1^0	disapp. trk	0	Yes	18.4	495 GeV	$m(\tilde{g}) = 100 \text{ GeV}, c(NLSIP) = 0.5 \text{ ns}$	
	Stable, stopped β R-hadron	trk	-	-	27.9	850 GeV	$m(\tilde{g}) = 100 \text{ GeV}, 10 \text{ pb} \rightarrow \text{sig} < 100 \text{ pb}$	
	Stable β R-hadron	trk	-	-	3.2	1.58 TeV	1806.05129	
Metastable β R-hadron	disapp. trk	-	-	3.2	1.97 TeV	1604.04620		
Long-lived particles	GMSB, $\tilde{g} \rightarrow t\bar{t} X^0$	$2 \leq \mu, \beta = 10^{-10}, c(NLSIP) = 0$	4 e, μ	Yes	20.3	537 GeV	$m(\tilde{g}) = 100 \text{ GeV}, \tau = 10 \text{ ns}$	
	GMSB, $\tilde{g} \rightarrow t\bar{t} X^0$	2γ	Yes	20.3	440 GeV	$1 = c(NLSIP) = 0 \text{ ns}, \beta = 10^{-10}, c(NLSIP) = 0$		
	GMSB, $\tilde{g} \rightarrow t\bar{t} X^0$	disapp. $col \rightarrow \text{jet} + \mu$	0	Yes	20.3	1.9 TeV	$7 < c(NLSIP) < 1.740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$	
	GMSB, $\tilde{g} \rightarrow t\bar{t} X^0$	disapp. $vs \rightarrow \text{jet} + \mu$	0	Yes	20.3	1.9 TeV	$6 < c(NLSIP) < 4.480 \text{ mm}, m(\tilde{g}) = 1.1 \text{ TeV}$	
	GMSB, $\tilde{g} \rightarrow t\bar{t} X^0$	disapp. $vs \rightarrow \text{jet} + \mu$	0	Yes	20.3	1.9 TeV	$6 < c(NLSIP) < 4.480 \text{ mm}, m(\tilde{g}) = 1.1 \text{ TeV}$	
RPV	LFV $\tilde{g} \rightarrow \bar{b}_1 + X, X \rightarrow \nu \mu + \tau \nu$	$\nu \mu + \tau \nu$	-	-	3.2	1.9 TeV	$\lambda_{111} = 0.11, \lambda_{112} = 0.07$	
	Bilinear RPV CMSSM	$2 \leq \mu$ (SS)	0-3 b	Yes	20.3	1.45 TeV	$m(\tilde{g}) = m(\tilde{u}), c(NLSIP) = 0 \text{ mm}$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	4 e, μ	0	Yes	13.3	1.14 TeV	$m(\tilde{g}) = 400 \text{ GeV}, \lambda_{111} = 0, \beta = 1, 2$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	3 $e, \mu + \tau$	-	Yes	20.3	400 GeV	$m(\tilde{g}) = 2m(\tilde{t}^{\pm}), \lambda_{111} = 0$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	0	4-5 large-R jets	-	14.8	1.08 TeV	$BR(\tilde{g}) \rightarrow BR(\tilde{u}) \rightarrow BR(\tilde{d}) = 0\%$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	0	4-5 large-R jets	-	14.8	1.55 TeV	$m(\tilde{g}) = 800 \text{ GeV}$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	1 e, μ	8-10 jets/0-4 h	-	36.1	2.3 TeV	$m(\tilde{g}) = 1 \text{ TeV}, \lambda_{111} = 0$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	1 e, μ	8-10 jets/0-4 h	-	36.1	1.65 TeV	$m(\tilde{g}) = 1 \text{ TeV}, \lambda_{111} = 0$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	0	2 jets + 2 h	-	15.4	410 GeV	$BR(\tilde{g}) \rightarrow BR(\tilde{u}) \rightarrow 20\%$	
	$\tilde{g} \rightarrow t\bar{t} X^0$	2 e, μ	2 h	-	20.3	450-510 GeV	$BR(\tilde{g}) \rightarrow BR(\tilde{u}) \rightarrow 20\%$	
Other	Scalar charm, $\tilde{t} \rightarrow c\bar{c}$	0	2 c	Yes	20.3	510 GeV	$m(\tilde{g}) = 200 \text{ GeV}$	
	Scalar charm, $\tilde{t} \rightarrow c\bar{c}$	0	2 c	Yes	20.3	510 GeV	$m(\tilde{g}) = 200 \text{ GeV}$	

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



ATLAS susy searches involving MET

ATLAS SUSY Searches* - 95% CL Lower Limits

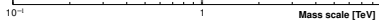
Status: March 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	c, μ, τ, γ	Jets	$E_{\text{miss}}^{\text{min}}$	L	d [fb $^{-1}$]	Mass limit	$\tau = 7, 8 \text{ TeV}$	$\tau = 13 \text{ TeV}$	Reference	
Inclusive Searches	MSUGRA/CMSSM	$0.3 < \mu, 1 \leq 2$	$2-10 \text{ jets}$	b	Yes	20.3	4.1	1.85 TeV	$m(\tilde{g})=m(\tilde{u})$	
	$4\tilde{g} \rightarrow 4\tilde{g}$	0	2-6 jets	b	Yes	38.1	1.57 TeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{u})=g, m(\tilde{t})=2m(\tilde{g})$	1507.0525	
	$4\tilde{g} \rightarrow 4\tilde{g}$ (compressed)	mono-jet	1-3 jets	b	Yes	3.2	608 GeV	$m(\tilde{g})=m(\tilde{u}) < 0 \text{ GeV}$	1604.0773	
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	2-6 jets	b	Yes	8.1	2.02 TeV	$m(\tilde{g})=200 \text{ GeV}$	ATLAS-COFP-2017-022	
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g} + \tilde{g}\tilde{g}W^{\pm}X^{\pm}$	0	2-6 jets	b	Yes	3.1	2.01 TeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{u})=0.5m(\tilde{g})+m(\tilde{g})$	ATLAS-COFP-2017-022	
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}H/\tilde{g}\tilde{g}A^{\pm}$	$2 < \mu$	2 jets	b	Yes	3.2	1.7 TeV	$m(\tilde{g})=400 \text{ GeV}$	ATLAS-COFP-2016-037	
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}WZ$	$2 < \mu$ (SS)	0-3 jets	b	Yes	2.2	1.8 TeV	$m(\tilde{g})=200 \text{ GeV}$	ATLAS-COFP-2016-037	
	GMSB (if NLSP)	$1.2 < \tau < 0.1 \text{ f}$	0-2 jets	b	Yes	2	2.0 TeV	$m(\tilde{g})=200 \text{ GeV}$	1607.05979	
	OGM (bino NLSP)	2 y	γ	Yes	2	2	1.83 TeV	$c(\text{NLSP}) \leq 0.1 \text{ mm}$	1606.09150	
	OGM (higgsino bino NLSP)	γ	1 jet	Yes	3	3	1.37 TeV	$m(\tilde{g})=200 \text{ GeV}, c(\text{NLSP}) \leq 0.1 \text{ mm}, \mu \leq 0$	1507.05495	
OGM (higgsino bino NLSP)	γ	2 jets	Yes	3	3	1.8 TeV	$m(\tilde{g})=400 \text{ GeV}, c(\text{NLSP}) \leq 0.1 \text{ mm}, \mu \leq 0$	ATLAS-COFP-2016-066		
OGM (higgsino NLSP)	$2 < \mu$ (Z)	2 jets	Yes	3	3	900 GeV	$m(\text{NLSP})=430 \text{ GeV}$	1503.03290		
Gravitino LSP	0	mono-jet	Yes	2	2	865 GeV	$m(\tilde{g})=1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})+m(\tilde{g})=1.5 \text{ TeV}$	1502.01516		
1st gen. s-quark & med. prod.	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{b}$	0-1 μ	2 jets	b	Yes	38.1	1.92 TeV	$m(\tilde{g})=600 \text{ GeV}$	ATLAS-COFP-2017-021	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	0-1 μ	2 jets	b	Yes	38.1	1.97 TeV	$m(\tilde{g})=600 \text{ GeV}$	ATLAS-COFP-2017-021	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{Z}$	0-1 μ	2 jets	b	Yes	38.1	1.37 TeV	$m(\tilde{g})=600 \text{ GeV}$	1407.0000	
	$\tilde{g}\tilde{g} \rightarrow c\tilde{c}\tilde{c}$	0	1 jet	b	Yes	2	840 GeV	$m(\tilde{g})=100 \text{ GeV}$	1606.08772	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{c}$	$2 < \mu$ (SS)	1 jet	b	Yes	13.2	F_1	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=m(\tilde{c})=100 \text{ GeV}$	ATLAS-COFP-2016-037	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{u}$	0-2 μ	1 jet	b	Yes	4.7119	F_2	$m(\tilde{g})=1.2m(\tilde{u}), m(\tilde{t})=0.25 \text{ GeV}$	1209.2102, ATLAS-COFP-2016-077	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{d}$ or $\tilde{u}\tilde{d}$	0-2 μ	0-2 jets	b	Yes	20.3	F_3	$m(\tilde{g})=1.2m(\tilde{u}), m(\tilde{t})=0.25 \text{ GeV}$	1506.08616, ATLAS-COFP-2017-020	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	0-2 μ	0-2 jets	b	Yes	20.3	F_4	$m(\tilde{g})=1.2m(\tilde{u}), m(\tilde{t})=0.25 \text{ GeV}$	1506.08616, ATLAS-COFP-2017-020	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{Z}$	$2 < \mu$ (Z)	0 jets	b	Yes	38.1	F_5	$m(\tilde{g})=150 \text{ GeV}$	1403.5322	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	$3 < \mu$ (Z)	0 jets	b	Yes	38.1	F_6	$m(\tilde{g})=290-790 \text{ GeV}$	ATLAS-COFP-2017-019	
EW direct	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	$2 < \mu$	0 jets	b	Yes	20.3	F_7	$m(\tilde{g})=60 \text{ GeV}$	ATLAS-COFP-2017-019	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{Z}$	$2 < \mu$	0 jets	b	Yes	20.3	F_8	$m(\tilde{g})=60 \text{ GeV}$	ATLAS-COFP-2017-019	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	$2 < \mu$	0 jets	b	Yes	13.2	F_9	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=100 \text{ GeV}$	1403.5394	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{Z}$	$2 < \mu$	0 jets	b	Yes	13.2	F_{10}	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=100 \text{ GeV}$	ATLAS-COFP-2016-036	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	$2 < \mu$	0 jets	b	Yes	13.2	F_{11}	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=100 \text{ GeV}$	ATLAS-COFP-2016-036	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{Z}$	$2 < \mu$	0 jets	b	Yes	13.2	F_{12}	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=100 \text{ GeV}$	ATLAS-COFP-2016-036	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	$2 < \mu$	0 jets	b	Yes	20.3	F_{13}	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=100 \text{ GeV}$	ATLAS-COFP-2016-036	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{Z}$	$2 < \mu$	0 jets	b	Yes	20.3	F_{14}	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=100 \text{ GeV}$	ATLAS-COFP-2016-036	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	$2 < \mu$	0 jets	b	Yes	20.3	F_{15}	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=100 \text{ GeV}$	ATLAS-COFP-2016-036	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{Z}$	$2 < \mu$	0 jets	b	Yes	20.3	F_{16}	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{t})=100 \text{ GeV}$	ATLAS-COFP-2016-036	
Long-lived particles	Direct $\tilde{X}_1^0 \tilde{X}_1^0$ prod. long-lived \tilde{X}_1^0	Disapp. trk	trk	Yes	38.1	F_{17}	430 GeV	$m(\tilde{X}_1^0)=160 \text{ MeV}, c(\tilde{X}_1^0)=0.2 \text{ ns}$	ATLAS-COFP-2017-017	
	Direct $\tilde{X}_1^0 \tilde{X}_1^0$ prod. long-lived \tilde{X}_1^0	disTrk	trk	Yes	38.1	F_{18}	495 GeV	$m(\tilde{X}_1^0)=160 \text{ MeV}, c(\tilde{X}_1^0)=15 \text{ ns}$	1506.05332	
	Stable, stopped \tilde{g} R-hadron	0-1 jets	trk	Yes	27.2	F_{19}	850 GeV	$m(\tilde{g})=100 \text{ GeV}, 10 \text{ ps} \leq c(\tilde{g}) \leq 100 \text{ ns}$	1310.0284	
	Stable \tilde{g} R-hadron	trk	trk	Yes	27.2	F_{20}	1.58 TeV	$m(\tilde{g})=100 \text{ GeV}, c(\tilde{g})=10 \text{ ns}$	1606.05129	
	Metastable \tilde{g} R-hadron	disTrk	trk	Yes	27.2	F_{21}	1.57 TeV	$m(\tilde{g})=100 \text{ GeV}, c(\tilde{g})=10 \text{ ns}$	1604.04620	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	$2 < \mu$	0 jets	b	Yes	38.1	F_{22}	537 GeV	$1.0 < \beta < 0.50$	1411.0790
	GMSB, $\tilde{X}_1^0 \rightarrow \tilde{g}\tilde{g}$, long-lived \tilde{X}_1^0	2 y	0 jets	b	Yes	3	F_{23}	$1 < \beta < 0.50$, no $\tilde{g}\tilde{g}$ model	1403.5542	
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{t}$	$2 < \mu$	0 jets	b	Yes	20.3	F_{24}	$7 < c(\tilde{X}_1^0) < 1.740 \text{ mm}, m(\tilde{g})=1.3 \text{ TeV}$	1504.05162	
	GMSB, $\tilde{X}_1^0 \rightarrow \tilde{g}\tilde{g}$, long-lived \tilde{X}_1^0	2 y	0 jets	b	Yes	20.3	F_{25}	$6 < c(\tilde{X}_1^0) < 1.480 \text{ mm}, m(\tilde{g})=1.1 \text{ TeV}$	1504.05162	
	RPV	LFV $\tilde{g}\tilde{g} \rightarrow \tilde{g} + X, X \rightarrow \tilde{g} + \nu\tau$	$\nu\tau$	trk	Yes	2	F_{26}	1.9 TeV	$\lambda_{111} = 0.11, \lambda_{111111} = 0.07$	1607.08079
Bilinear RPV CMSSM		$2 < \mu$ (SS)	0-3 jets	b	Yes	20.3	F_{27}	$m(\tilde{g})=m(\tilde{u}), c_{\tilde{g}\tilde{g}} = 0 \text{ mm}$	1404.2000	
$\tilde{X}_1^0 \tilde{X}_1^0 \rightarrow \tilde{g}\tilde{g}$		$4 < \mu$	0 jets	b	Yes	3	F_{28}	$m(\tilde{g})=400 \text{ GeV}, A_{0,1} = 0, \beta = 1, 2$	ATLAS-COFP-2016-075	
$\tilde{X}_1^0 \tilde{X}_1^0 \rightarrow \tilde{g}\tilde{g}$		$3 < \mu$	0 jets	b	Yes	3.3	F_{29}	$m(\tilde{g})=400 \text{ GeV}, A_{0,1} = 0, \beta = 1, 2$	1405.5086	
$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$		0-4.5 large β jets	4-8 jets	b	Yes	4.8	F_{30}	$\text{BR}(\tilde{g}) \rightarrow \text{BR}(\tilde{g}) = 0.5$	ATLAS-COFP-2016-057	
$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$		0-4.5 large β jets	4-8 jets	b	Yes	4.8	F_{31}	$m(\tilde{g})=800 \text{ GeV}$	ATLAS-COFP-2016-057	
$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$		$1 < \mu$	8-10 jets	b	Yes	1	F_{32}	$m(\tilde{g})=1 \text{ TeV}, A_{0,1} = 0$	ATLAS-COFP-2017-013	
$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$		$1 < \mu$	8-10 jets	b	Yes	1	F_{33}	$m(\tilde{g})=1 \text{ TeV}, A_{0,1} = 0$	ATLAS-COFP-2017-013	
$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$		$1 < \mu$	8-10 jets	b	Yes	15.4	F_{34}	$m(\tilde{g})=410 \text{ GeV}, 450-510 \text{ GeV}$	ATLAS-COFP-2016-022, ATLAS-COFP-2016-084	
$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$		$2 < \mu$	2 jets	b	Yes	20.3	F_{35}	$\text{BR}(\tilde{g}) \rightarrow \tilde{g}\tilde{g} \geq 20\%$	ATLAS-COFP-2015-015	
Other	Scalar charm, $\tilde{c} \rightarrow \tilde{c}^*$	0	2 jets	Yes	20.3	F_{36}	510 GeV	$m(\tilde{c})=200 \text{ GeV}$	1501.01325	

*Only a selection of the available mass limits on new particles/phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



Thinking beyond the MSSM: R -symmetries

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

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

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

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

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

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

Minimal R -symmetric Supersymmetric Standard Model (MRSSM)

Kribs, Poppitz, Weiner '07

Different R -charge assignments are possible.

Fruguele, 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:

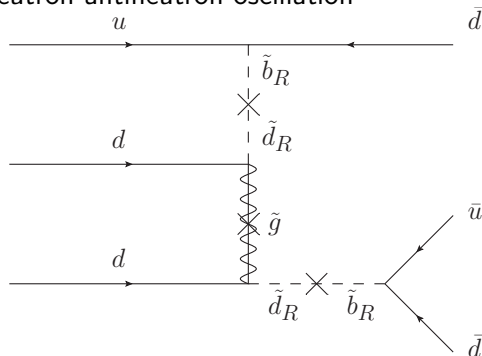
$$W = y_u QH_u U^c - y_d QH_d D^c - y_e LH_d E^c + \mu_u H_u R_d + \mu_d R_u H_d \\ + \lambda_u^t H_u T R_d + \lambda_d^t R_u T H_d + \lambda_u^s S H_u R_d + \lambda_d^s S R_u H_d + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c$$



phenomenologically interesting and
now baryon number conserving

Baryon number violating processes 1

Neutron-antineutron oscillation

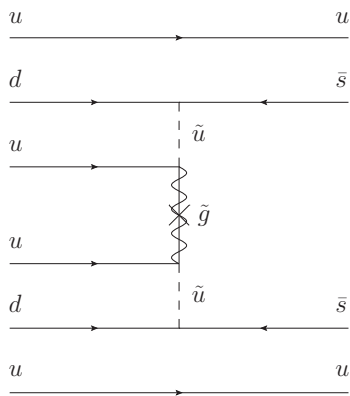


Unavoidably $U(1)_R$ breaking by anomaly mediation generates Majorana gaugino masses $\sim m_{3/2}/16\pi^2$.

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

Baryon number violating processes 2

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

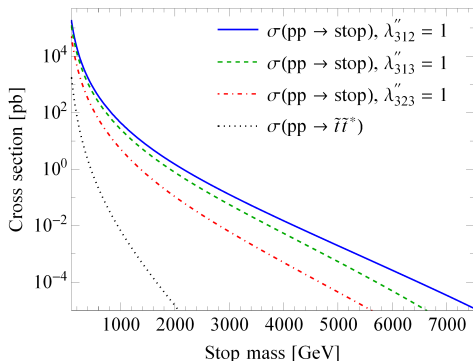


$$\lambda''_{112} \lesssim 2 \times 10^{-4} \left(\frac{M_3^D}{1\text{TeV}} \right) \left(\frac{1\text{GeV}}{m_{3/2}} \right)^{1/2} \left(\frac{m_{\tilde{q}}}{1\text{TeV}} \right)^2 \left(\frac{150\text{MeV}}{\tilde{\Lambda}} \right)^{5/2}$$

Stop phenomenology: stop LSP 1

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

13 TeV \rightarrow

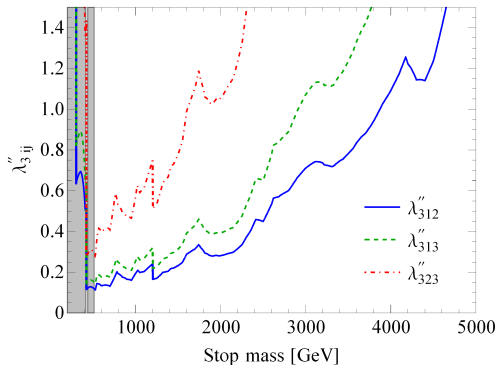


Stops can decay back to quarks, $\tilde{t}^* \rightarrow d_i d_j$.

Stop phenomenology: stop LSP 2

Signals:

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



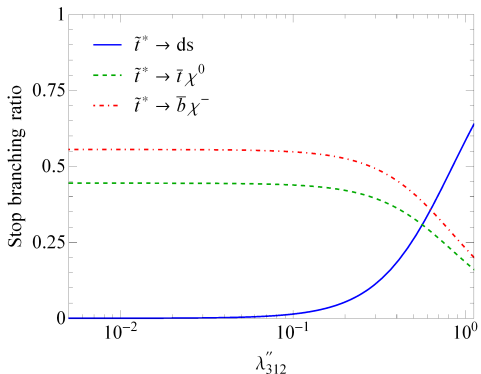
similar to Monteux '16

Stop phenomenology: neutralino LSP 1

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

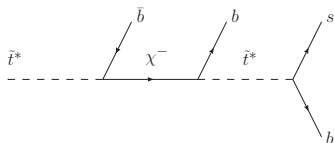
$$\tilde{t}^* \rightarrow d_i d_j, \quad \tilde{t}^* \rightarrow \bar{t} \chi^0, \quad \tilde{t}^* \rightarrow \bar{b} \chi^-.$$

600 GeV stop and
200 GeV neutralino \rightarrow

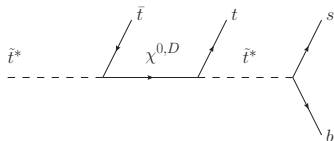


Stop phenomenology: neutralino LSP 2

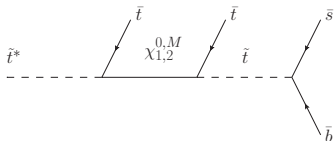
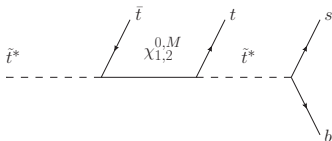
Stops decaying through charginos:



Stops decaying through Dirac neutralinos:



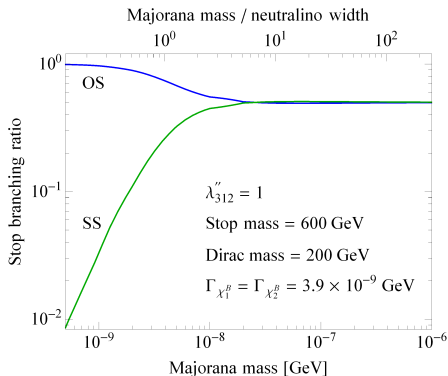
Stops decaying through Majorana neutralinos:



Stop phenomenology: neutralino LSP 3

Unavoidable $U(1)_R$ breaking generates Majorana gaugino 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:

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

Three decay possibilities:

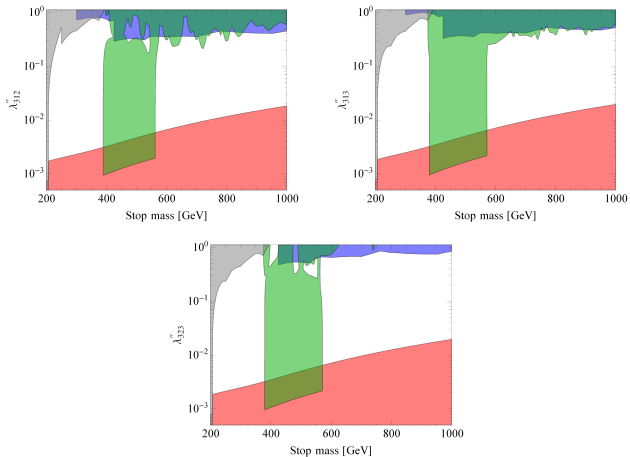
- $\tilde{t}^* \rightarrow d_i d_j$
- $\tilde{t}^* \rightarrow \bar{t} \chi^0$
- $\tilde{t}^* \rightarrow \bar{b} \chi^-$

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.

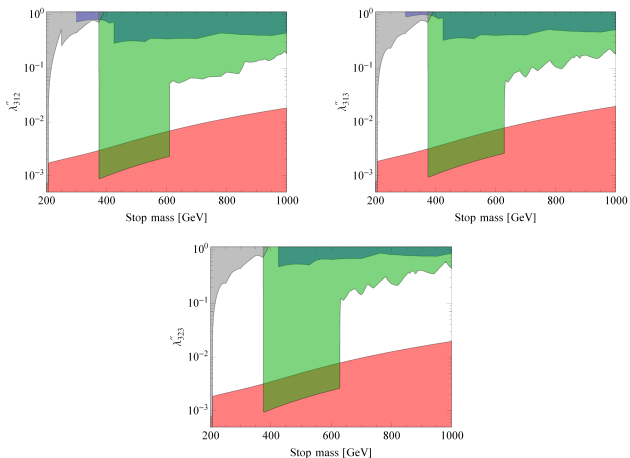
Stop phenomenology: neutralino LSP 5

200 GeV Dirac neutralinos:



Stop phenomenology: neutralino LSP 6

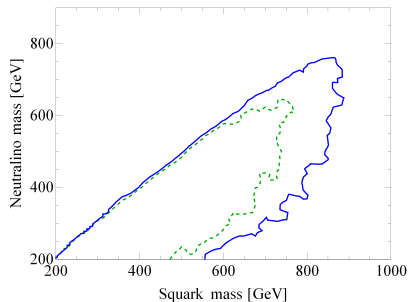
200 GeV Majorana neutralinos:



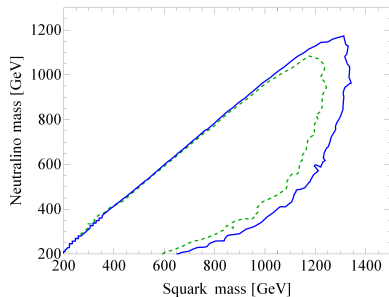
similar to Monteux '16

Squark phenomenology: neutralino LSP 1

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



(a) λ''_{312}



(b) $\lambda''_{313} / \lambda''_{323}$

Squark production cross section reduced due to Dirac gluinos.

Heikinheimo, Kellerstein, Sanz '11

Kribs, Martin '12

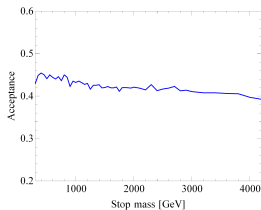
Conclusion

To summarize:

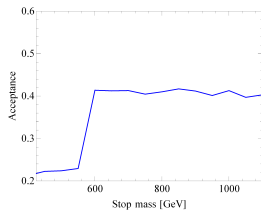
- lack of signals continues to push MSSM superpartner masses upwards
- this suggests thinking beyond the MSSM
- $U(1)_R$ baryon number is an example of an extended supersymmetry model
- baryon number violating constraints follow from $U(1)_R$ breaking
- parameter space with stops constrained by recent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

Back-up slides

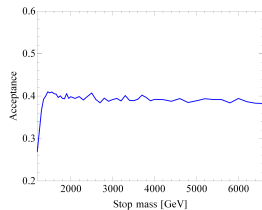
Dijet search efficiencies



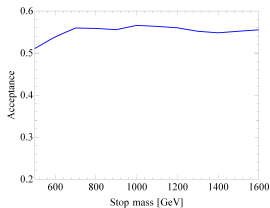
(a) ATLAS 1407.1376



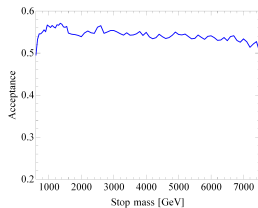
(b) ATLAS-CONF-2016-030



(c) ATLAS-CONF-2016-069



(d) CMS 1604.08907



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

Stop decay topologies

With Dirac neutralinos:

$$\begin{array}{lll}
 (1) & pp \rightarrow \tilde{t}^* \rightarrow d_i d_j & (2) \quad pp \rightarrow \tilde{t}^* \rightarrow \bar{t}\chi^0 \rightarrow \bar{t}t d_i d_j \\
 (3) & pp \rightarrow \tilde{t}^* \rightarrow \bar{b}\chi^- \rightarrow \bar{b}b d_i d_j \\
 (4) & pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow d_i d_j \bar{d}_i \bar{d}_j & (5) \quad pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow \bar{t}\chi^0 t\bar{\chi}^0 \rightarrow \bar{t}t d_i d_j \bar{t}\bar{t} \bar{d}_i \bar{d}_j \\
 (6) & & (6) \quad pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow \bar{b}\chi^- b\chi^+ \rightarrow \bar{b}b d_i d_j b\bar{b} \bar{d}_i \bar{d}_j \\
 (7) & pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow d_i d_j t\bar{\chi}^0 \rightarrow d_i d_j \bar{t}\bar{t} \bar{d}_i \bar{d}_j & (8) \quad pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow d_i d_j b\chi^+ \rightarrow d_i d_j b\bar{b} \bar{d}_i \bar{d}_j \\
 (9) & & (9) \quad pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow \bar{t}\chi^0 b\chi^+ \rightarrow \bar{t}t d_i d_j b\bar{b} \bar{d}_i \bar{d}_j
 \end{array}$$

With Majorana neutralinos:

$$\begin{array}{ll}
 (2) & pp \rightarrow \tilde{t}^* \rightarrow \bar{t}\chi^0 \rightarrow \begin{cases} \bar{t}t d_i d_j \\ \bar{t}\bar{t} \bar{d}_i \bar{d}_j \end{cases} \\
 (5) & pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow \bar{t}\chi^0 t\chi^0 \rightarrow \begin{cases} \bar{t}t d_i d_j \bar{t}\bar{t} \bar{d}_i \bar{d}_j \\ \bar{t}t d_i d_j t\bar{t} d_i d_j \\ \bar{t}\bar{t} \bar{d}_i \bar{d}_j \bar{t}\bar{t} \bar{d}_i \bar{d}_j \\ \bar{t}\bar{t} \bar{d}_i \bar{d}_j t\bar{t} d_i d_j \end{cases} \\
 (7) & pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow d_i d_j t\chi^0 \rightarrow \begin{cases} d_i d_j \bar{t}\bar{t} \bar{d}_i \bar{d}_j \\ d_i d_j t\bar{t} d_i d_j \end{cases} \\
 (9) & pp \rightarrow \tilde{t}^* \tilde{t} \rightarrow \bar{t}\chi^0 b\chi^+ \rightarrow \begin{cases} \bar{t}t d_i d_j b\bar{b} \bar{d}_i \bar{d}_j \\ \bar{t}\bar{t} \bar{d}_i \bar{d}_j b\bar{b} \bar{d}_i \bar{d}_j \end{cases}
 \end{array}$$

LHC searches 1

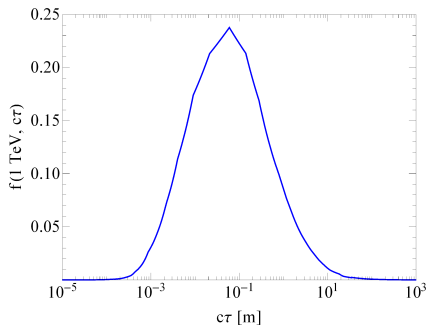
Collaboration	Search	Strategy
ATLAS	ATLAS-CONF-2016-037	2 (potentially negative) same sign leptons, total number of leptons, jets with $p_T > 25, 40$ or 50 GeV, b-jets, MET, $m_{\text{eff}} = \sum_{\text{jets, leptons}} p_T + \text{MET}$
ATLAS	ATLAS-CONF-2016-057	large ($R = 1.0$) jets J_i , $p_{T J_1} > 440$ GeV, $ \Delta\eta_{J_1 J_2} < 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

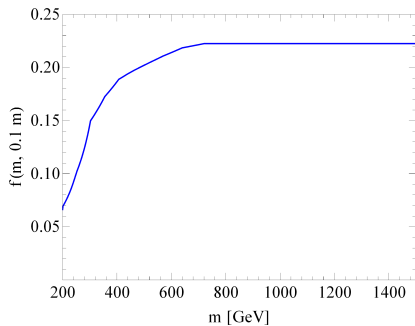
Collaboration	Search	Strategy
ATLAS	ATLAS-CONF-2016-013	<p>exactly 1 lepton, jets, b-jets, mass-tagged jets = large ($R = 1.0$) jets with cuts, $m_{bb}^{\min \Delta R}$ = invariant mass of closest b-jets, MET, MET + $M_T(\ell, \text{MET})$ where M_T = transverse mass</p>
ATLAS	ATLAS-CONF-2016-032	<p>2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

Efficiency for reconstructing a single displaced vertex

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



(a) $m = 1 \text{ TeV}$

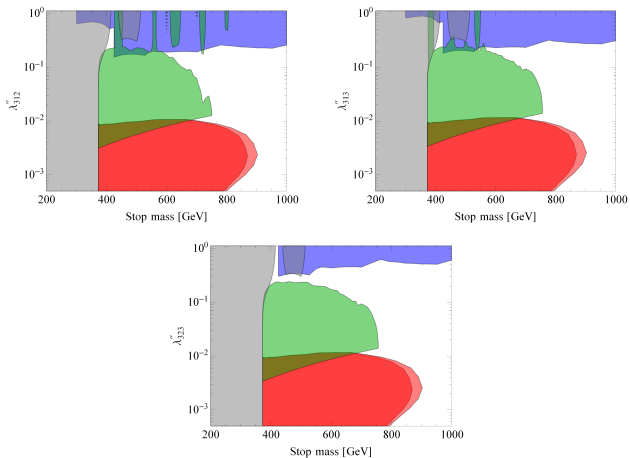


(b) $c\tau = 0.1 \text{ m}$

Based on CMS search 1411.6530.

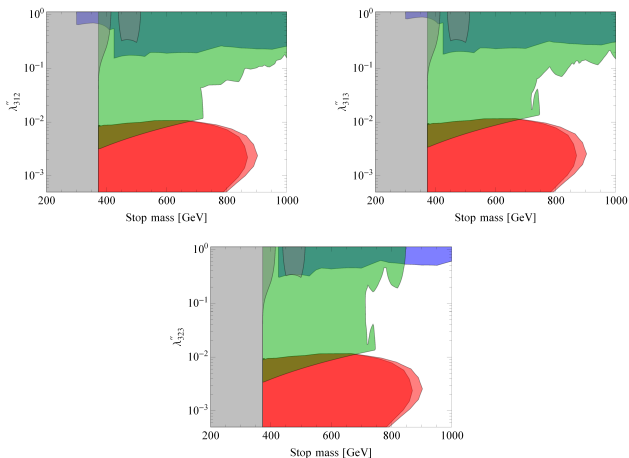
Stop phenomenology: bino neutralino LSP 1

200 GeV Dirac neutralinos:



Stop phenomenology: bino neutralino LSP 2

200 GeV Majorana neutralinos:



similar to Monteux '16

Squark decay topologies

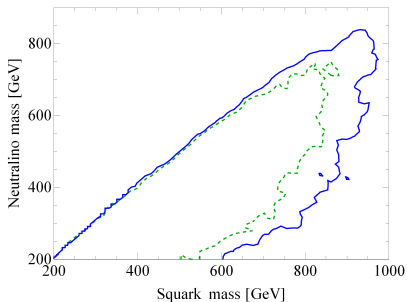
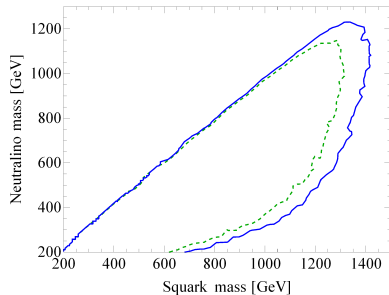
With Dirac neutralinos:

$$\begin{aligned}
 (1) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow d_{i/j} t \bar{d}_{i/j} \bar{t} \\
 (2) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow \bar{q} \chi^0 q \bar{\chi}^0 \rightarrow \bar{q} t d_i d_j q \bar{t} \bar{d}_i \bar{d}_j \\
 (3) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow \bar{q}' \chi^+ q' \chi^- \rightarrow \bar{q}' \bar{b} \bar{d}_i \bar{d}_j q' b d_i d_j \\
 (4) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow d_{i/j} t q \bar{\chi}^0 \rightarrow d_{i/j} t q \bar{t} \bar{d}_i \bar{d}_j \\
 (5) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow d_{i/j} t q' \chi^- \rightarrow d_{i/j} t q' b d_i d_j \\
 (6) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow \bar{q} \chi^0 q' \chi^- \rightarrow \bar{q} t d_i d_j q' b d_i d_j
 \end{aligned}$$

With Majorana neutralinos:

$$\begin{aligned}
 (2) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow \bar{q} \chi^0 q \chi^0 \rightarrow \begin{cases} \bar{q} t d_i d_j q \bar{t} \bar{d}_i \bar{d}_j \\ \bar{q} t d_i d_j q t d_i d_j \\ \bar{q} \bar{t} \bar{d}_i \bar{d}_j q \bar{t} \bar{d}_i \bar{d}_j \\ \bar{q} \bar{t} \bar{d}_i \bar{d}_j q t d_i d_j \end{cases} \\
 (4) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow d_{i/j} t q \chi^0 \rightarrow \begin{cases} d_{i/j} t q \bar{t} \bar{d}_i \bar{d}_j \\ d_{i/j} t q t d_i d_j \end{cases} \\
 (6) \quad & pp \rightarrow \tilde{q}^* \tilde{q} \rightarrow \bar{q} \chi^0 q' \chi^- \rightarrow \begin{cases} \bar{q} t d_i d_j q' b d_i d_j \\ \bar{q} \bar{t} \bar{d}_i \bar{d}_j q' b d_i d_j \end{cases}
 \end{aligned}$$

Squark phenomenology: bino neutralino LSP 1

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