



# The Effect of ATLAS Run-1 Supersymmetric Searches in the pMSSM

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# Introduction

## ATLAS has wide range of SUSY search results from Run-1

### ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

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

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	Reference		
Inclusive Searches	MSUGRA/CMSSM	0-3 $e, \mu$ / 1-2 $\tau$	2-10 jets/3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$	1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1405.7875	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$	100-440 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)<10 \text{ GeV}$	1507.05525	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\ell\ell / \ell\nu/\nu\nu/\tilde{\chi}_1^0$	2 $e, \mu$ (off- $Z$ )	2 jets	Yes	20.3	$\tilde{q}$	780 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1503.03290	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1405.7875	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow q\tilde{q}W^\pm\tilde{\chi}_1^0$	0-1 $e, \mu$	2-6 jets	Yes	20	$\tilde{g}$	1.26 TeV	$m(\tilde{\chi}_1^0)<300 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1507.05525	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\ell\ell / \ell\nu/\nu\nu/\tilde{\chi}_1^0$	2 $e, \mu$	0-3 jets	-	20	$\tilde{g}$	1.32 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1501.03555	
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau$ + 0-1 $\ell$	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	$\tan\beta > 20$	1407.0603	
	GGM (bino NLSP)	2 $\gamma$	-	Yes	20.3	$\tilde{g}$	1.29 TeV	$c\tau(\text{NLSP})<0.1 \text{ mm}$	1507.05493	
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)<900 \text{ GeV}, c\tau(\text{NLSP})<0.1 \text{ mm}, \mu<0$	1507.05493	
	GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes	20.3	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}_1^0)<850 \text{ GeV}, c\tau(\text{NLSP})<0.1 \text{ mm}, \mu>0$	1507.05493	
	GGM (higgsino NLSP)	2 $e, \mu$ ( $Z$ )	2 jets	Yes	20.3	$\tilde{g}$	850 GeV	$m(\text{NLSP})>430 \text{ GeV}$	1503.03290	
Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G})>1.8 \times 10^{-1} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$	1502.01518		
3 <sup>rd</sup> gen. g med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 $b$	Yes	20.1	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}_1^0)<400 \text{ GeV}$	1407.0600	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)<350 \text{ GeV}$	1308.1841	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tau\tilde{\tau}\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)<400 \text{ GeV}$	1407.0600	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)<300 \text{ GeV}$	1407.0600	
	3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)<90 \text{ GeV}$	1308.2631
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$		2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{b}_1$	275-440 GeV	$m(\tilde{\chi}_1^0)=2 m(\tilde{\chi}_1^0)$	1404.2500	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$		1-2 $e, \mu$	1-2 $b$	Yes	4.7/20.3	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)=2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=55 \text{ GeV}$	1209.2102, 1407.0583	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$		0-2 $e, \mu$	0-2 jets/1-2 $b$	Yes	20.3	$\tilde{t}_1$	90-191 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	1506.08616	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$		0	mono-jet/ $c$ -tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)<85 \text{ GeV}$	1407.0608	
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)		2 $e, \mu$ ( $Z$ )	1 $b$	Yes	20.3	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)>150 \text{ GeV}$	1403.5222	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$		3 $e, \mu$ ( $Z$ )	1 $b$	Yes	20.3	$\tilde{t}_2$	290-600 GeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}$	1403.5222	
EW direct		$\tilde{\ell}_L\tilde{\ell}_L, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1403.5294
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\ell\bar{\nu})$	2 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^\pm$	140-465 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tau\bar{\nu})$	2 $\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	100-350 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1407.0350	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}_L\nu\ell_L(\bar{\nu}\nu), \ell\bar{\nu}\ell_L(\bar{\nu}\nu)$	3 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^\pm$	700 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_2^0)=0, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm$	420 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_2^0)=0$ , sleptons decoupled	1403.5294, 1402.7029	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 $b$	Yes	20.3	$\tilde{\chi}_1^\pm$	250 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_2^0)=0$ , sleptons decoupled	1501.07110	
	$\tilde{\chi}_2^0\tilde{\chi}_2^0, \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R\ell$	4 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086	
	GGM (wino NLSP) weak prod.	1 $e, \mu$ + $\gamma$	-	Yes	20.3	$\tilde{W}$	124-361 GeV	$c\tau<1 \text{ mm}$	1507.05493	
	Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^0)-m(\tilde{\chi}_2^0)\sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm)=0.2 \text{ ns}$	1310.3675
		Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	482 GeV	$m(\tilde{\chi}_1^0)-m(\tilde{\chi}_2^0)\sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm)<15 \text{ ns}$	1506.05332
Stable, stopped $\tilde{g}$ R-hadron		0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s}<\tau(\tilde{g})<1000 \text{ s}$	1310.6584	
Stable $\tilde{g}$ R-hadron		trk	-	-	19.1	$\tilde{g}$	1.27 TeV	-	1411.6795	
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\nu}, \bar{\nu}) + \tau(e, \mu)$		1-2 $\mu$	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$10<\tan\beta<50$	1411.6795	
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$		2 $\gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$	435 GeV	$2<c\tau(\tilde{\chi}_1^0)<3 \text{ ns}$ , SPS8 model	1409.5542	
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\bar{e}\nu/\mu\bar{\mu}\nu$		displ. $e\bar{e}/\mu\bar{\mu}$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7<c\tau(\tilde{\chi}_1^0)<740 \text{ mm}, m(\tilde{g})=1.3 \text{ TeV}$	1504.05162	
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$		displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$6<c\tau(\tilde{\chi}_1^0)<480 \text{ mm}, m(\tilde{g})=1.1 \text{ TeV}$	1504.05162	
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu/\tau\tau$	$e\mu, \tau\tau, \mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	1.7 TeV	$A'_{111}=0.11, A'_{132/133/233}=0.07$	1503.04430	
	Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$	1.35 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{\text{LSP}}<1 \text{ mm}$	1404.2500	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow e\bar{e}\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 $e, \mu$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	750 GeV	$m(\tilde{\chi}_1^0)>0.2 \times m(\tilde{\chi}_1^\pm), A_{121}\neq 0$	1405.5086	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu$ + $\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	$m(\tilde{\chi}_1^0)>0.2 \times m(\tilde{\chi}_1^\pm), A_{133}\neq 0$	1405.5086	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}q$	0	6-7 jets	-	20.3	$\tilde{g}$	917 GeV	$\text{BR}(h)=\text{BR}(h)=\text{BR}(c)=0\%$	1502.05686	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}q$	0	6-7 jets	-	20.3	$\tilde{g}$	870 GeV	$m(\tilde{\chi}_1^0)=600 \text{ GeV}$	1502.05686	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b\tilde{s}$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{g}$	850 GeV	-	1404.250	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	0	2 jets + 2 $b$	-	20.3	$\tilde{t}_1$	100-308 GeV	-	ATLAS-CONF-2015-026	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$	2 $e, \mu$	2 $b$	-	20.3	$\tilde{t}_1$	0.4-1.0 TeV	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/\mu)/\mu>20\%$	ATLAS-CONF-2015-015		
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 $c$	Yes	20.3	$\tilde{c}$	490 GeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}$	1501.01325	

10<sup>-1</sup>

1

Mass scale [TeV]

$10^{-1}$

1

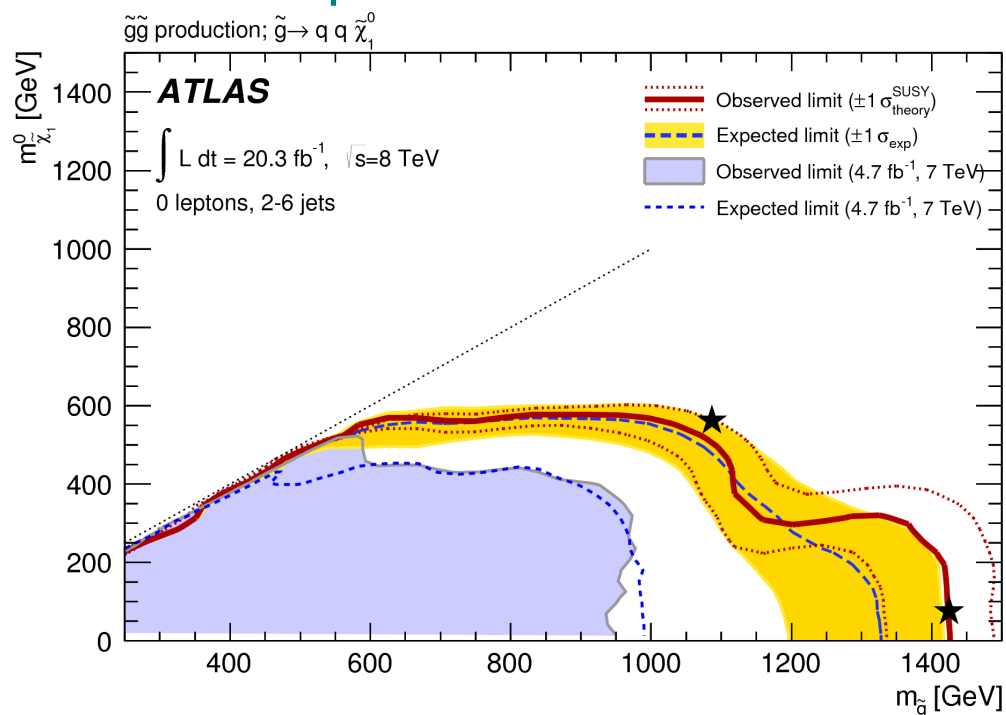
Mass scale [TeV]

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus  $1\sigma$  theoretical signal cross section uncertainty.

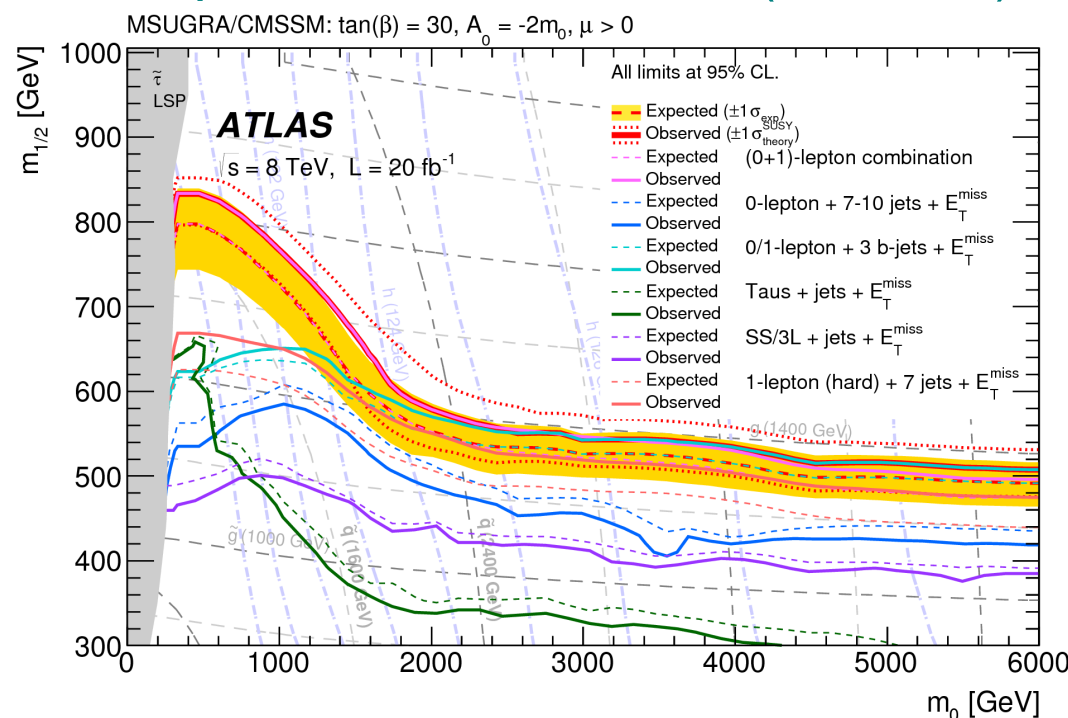
# Introduction

No significant signals found → have presented SUSY limits in:

## Simplified Models



## Specific SUSY Models (CMSSM)



*What is the impact of the full set of ATLAS searches on a broader set of SUSY models?*

# Phenomenological MSSM

Use 19-parameter pMSSM to scan the MSSM – we assume:

- Minimal flavor violation with no new source of CP violation
- Degenerate 1<sup>st</sup> and 2<sup>nd</sup> generation squarks and sleptons
- No R-parity violation and the LSP is the lightest neutralino

Generate pMSSM parameters randomly with flat prior and masses up to 4 GeV

Parameter	Min value	Max value
$m_{\tilde{L}_1} (= m_{\tilde{L}_2})$	90 GeV	4 TeV
$m_{\tilde{e}_1} (= m_{\tilde{e}_2})$	90 GeV	4 TeV
$m_{\tilde{L}_3}$	90 GeV	4 TeV
$m_{\tilde{e}_3}$	90 GeV	4 TeV
$m_{\tilde{Q}_1} (= m_{\tilde{Q}_2})$	200 GeV	4 TeV
$m_{\tilde{u}_1} (= m_{\tilde{u}_2})$	200 GeV	4 TeV
$m_{\tilde{d}_1} (= m_{\tilde{d}_2})$	200 GeV	4 TeV
$m_{\tilde{Q}_3}$	100 GeV	4 TeV
$m_{\tilde{u}_3}$	100 GeV	4 TeV
$m_{\tilde{d}_3}$	100 GeV	4 TeV
$ M_1 $	0 GeV	4 TeV
$ M_2 $	70 GeV	4 TeV
$ \mu $	80 GeV	4 TeV
$M_3$	200 GeV	4 TeV
$ A_t $	0 GeV	8 TeV
$ A_b $	0 GeV	4 TeV
$ A_\tau $	0 GeV	4 TeV
$M_A$	100 GeV	4 TeV
$\tan \beta$	1	60

500 million points sampled and apply constraints from:

- Precision EW and flavor measurements
- LEP SUSY searches
- The Higgs boson mass
- Dark Matter abundance and direct detection

Parameter	Minimum value	Maximum value
$\Delta\rho$	-0.0005	0.0017
$\Delta(g-2)_\mu$	$-17.7 \times 10^{-10}$	$43.8 \times 10^{-10}$
$\text{BR}(b \rightarrow s\gamma)$	$2.69 \times 10^{-4}$	$3.87 \times 10^{-4}$
$\text{BR}(B_s \rightarrow \mu^+\mu^-)$	$1.6 \times 10^{-9}$	$4.2 \times 10^{-9}$
$\text{BR}(B^+ \rightarrow \tau^+\nu_\tau)$	$66 \times 10^{-6}$	$161 \times 10^{-6}$
$\Omega_{\tilde{\chi}_1^0} h^2$	—	0.1208
$\Gamma_{\text{invisible(SUSY)}}(Z)$	—	2 MeV
Masses of charged sparticles	100 GeV	—
$m(\tilde{\chi}_1^\pm)$	103 GeV	—
$m(\tilde{u}_{1,2}, \tilde{d}_{1,2}, \tilde{c}_{1,2}, \tilde{s}_{1,2})$	200 GeV	—
$m(h)$	124 GeV	128 GeV

310,327  
models  
selected  
for this  
analysis

Generation and selection by T. Rizzo and collaborators similar to [Eur. 1215 Phys. J. C72 \(2012\) 2156](#)

# ATLAS Run-1 SUSY Searches

Reinterpret 22 ATLAS Run-1 searches on pMSSM

- Almost full set of 8 TeV searches for R-parity conserving SUSY
- More than 200 signal regions considered – “combined” by using the best expected signal region for exclusion

Inclusive searches	0-lepton + 2–6 jets + $E_T^{\text{miss}}$
	0-lepton + 7–10 jets + $E_T^{\text{miss}}$
	1-lepton + jets + $E_T^{\text{miss}}$
	$\tau(\tau/\ell)$ + jets + $E_T^{\text{miss}}$
	SS/3-leptons + jets + $E_T^{\text{miss}}$
	0/1-lepton + 3b-jets + $E_T^{\text{miss}}$
	Monojet
3 <sup>rd</sup> gen. searches	0-lepton stop
	1-lepton stop
	2-leptons stop
	Monojet stop
	Stop with Z boson
	2b-jets + $E_T^{\text{miss}}$
	$t\bar{b}$ + $E_T^{\text{miss}}$ , stop
EW searches	$\ell h$
	2-leptons
	2- $\tau$
	3-leptons
	4-leptons
	Disappearing Track
	Long-lived particle
	$H/A \rightarrow \tau^+ \tau^-$

Makes full use of ATLAS simulation, reconstruction and analysis

- 310,327 models analyzed
- >30 billion signal events generated for fast truth-based analysis evaluations
- 44,559 models simulated and reconstructed (>600 million events) for precise analysis evaluation

Most comprehensive results from ATLAS on SUSY to date



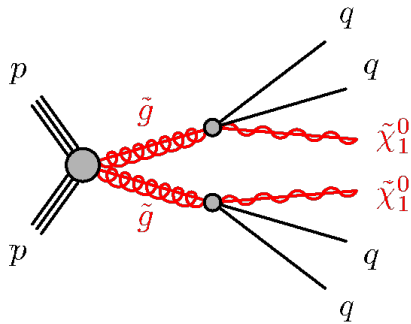
# Results – Gluinos

Present results as fraction of excluded models as a function of various parameters, such as sparticle masses

- Black means 100% excluded – white is no models generated

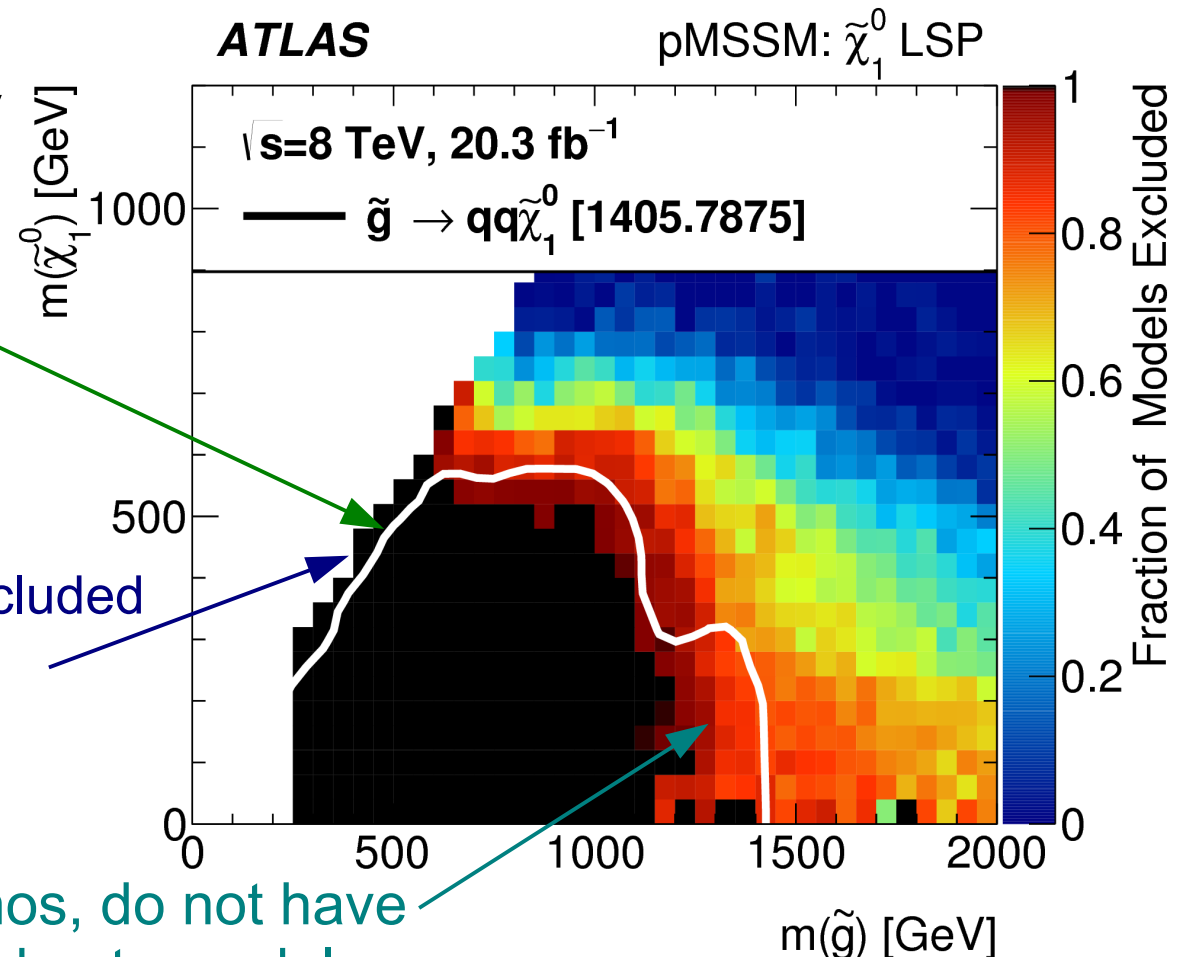
Exclude almost all models with  $m(\tilde{g}) < 1$  TeV and  $m(\tilde{\chi}_1^0) < 0.5$  TeV

Good agreement with the gluino simplified model limit from 0-lepton + 2-6 jets  $E_t^{\text{miss}}$  analysis



Diagonal excluded by mono-jet analysis

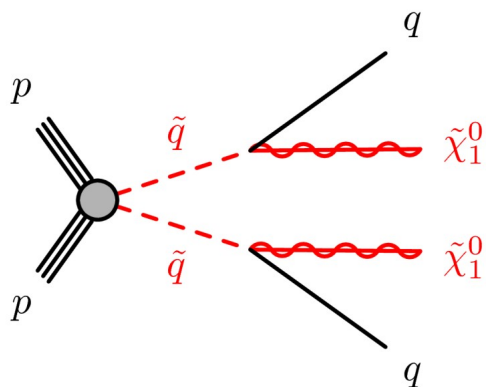
For heavier gluinos, do not have 100% exclusion due to models with intermediate sparticles



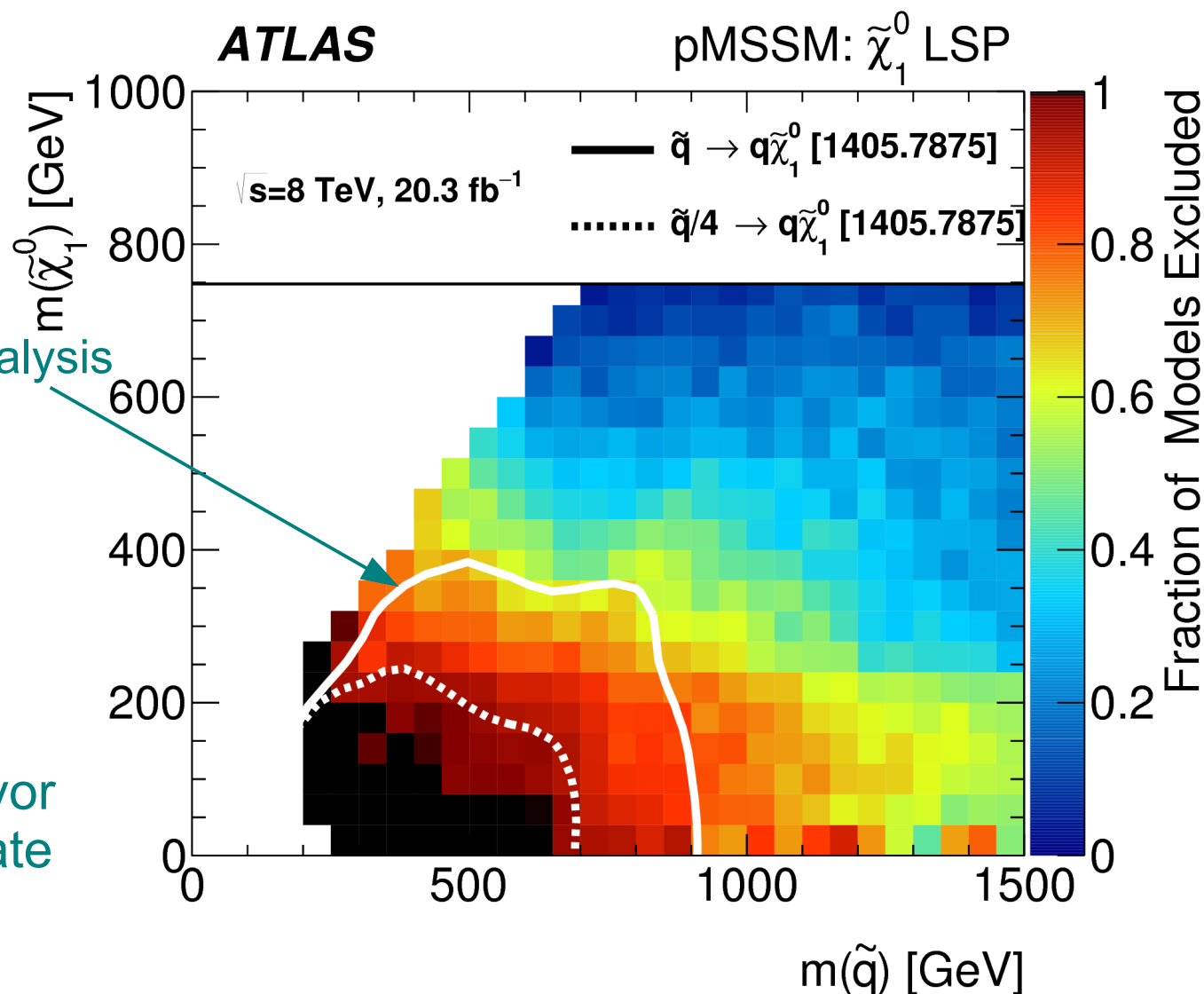
# Light-flavor Squarks

For light-flavor squarks, only  $m(\tilde{q}) < 250$  GeV fully excluded

Not in agreement with simplified model limit from 0-lepton + 2-6 jets  $E_t^{\text{miss}}$  analysis



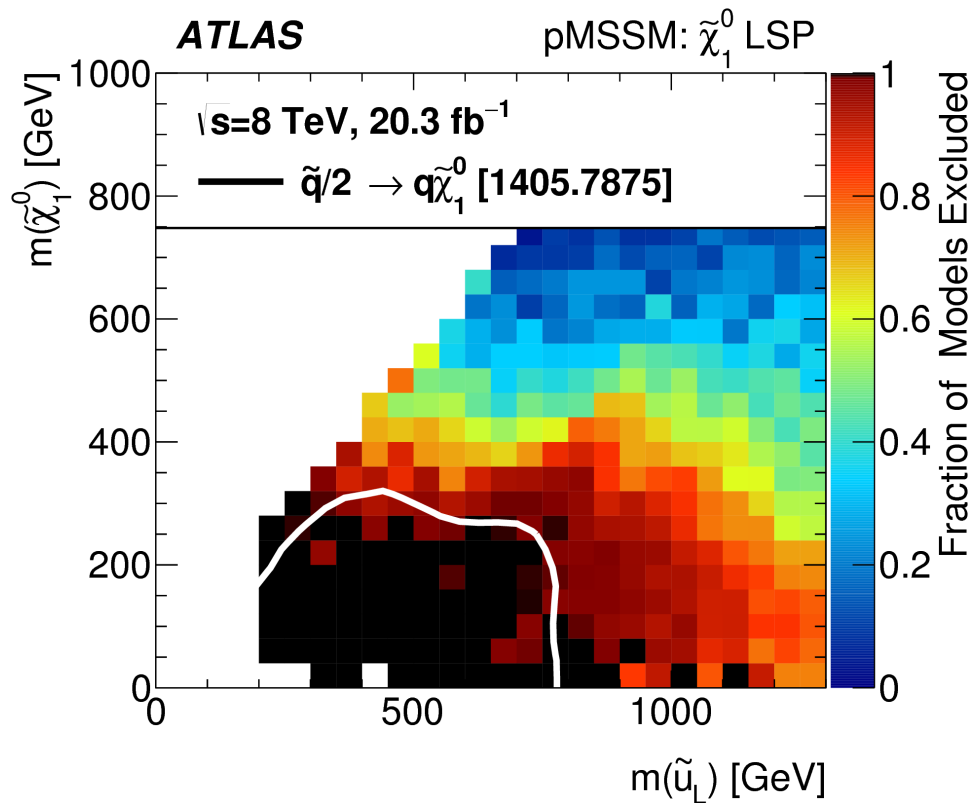
Due to not all 8 light-flavor squarks being degenerate in the pMSSM



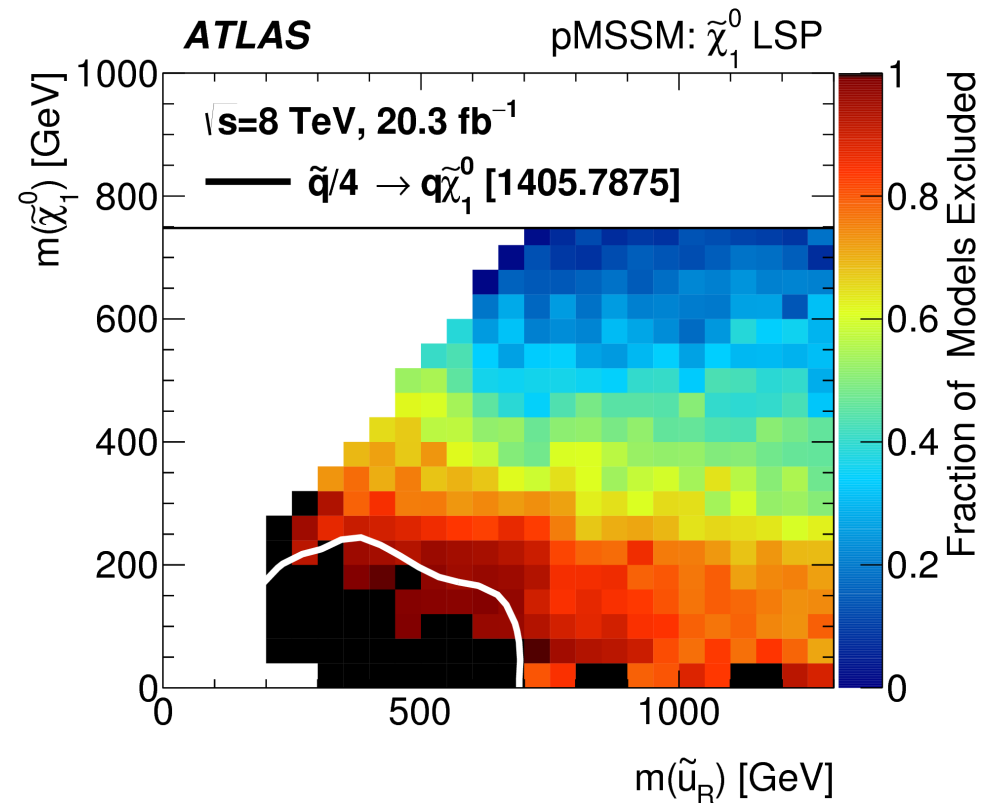
# Left/Right-handed Squarks

Splitting in left and right-handed quark partners  
restores good agreement with simplified model limits

$$m(\tilde{u}_L) \sim m(\tilde{d}_L) \sim m(\tilde{c}_L) \sim m(\tilde{s}_L)$$



$$m(\tilde{u}_R) \sim m(\tilde{c}_R)$$



Similar plot for  $m(\tilde{d}_R) \sim m(\tilde{s}_R)$



# 3<sup>rd</sup> Generation Squarks – stop

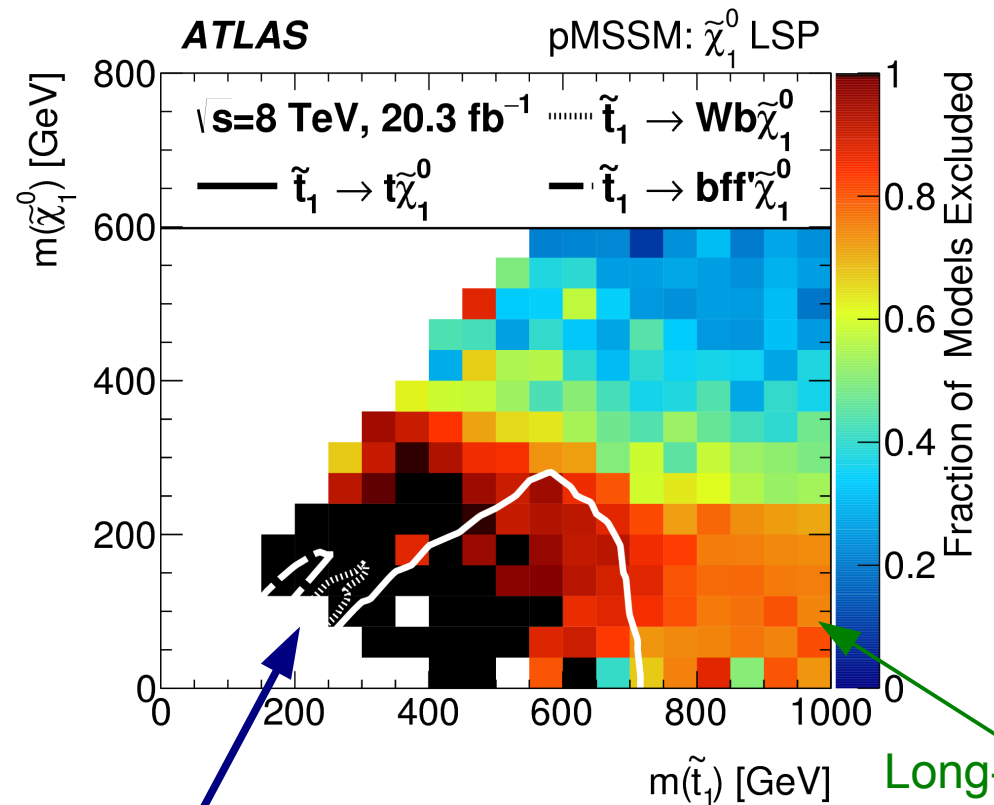
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Good exclusion reach for light stop

– sensitivity mostly from the dedicated 3<sup>rd</sup> generation searches

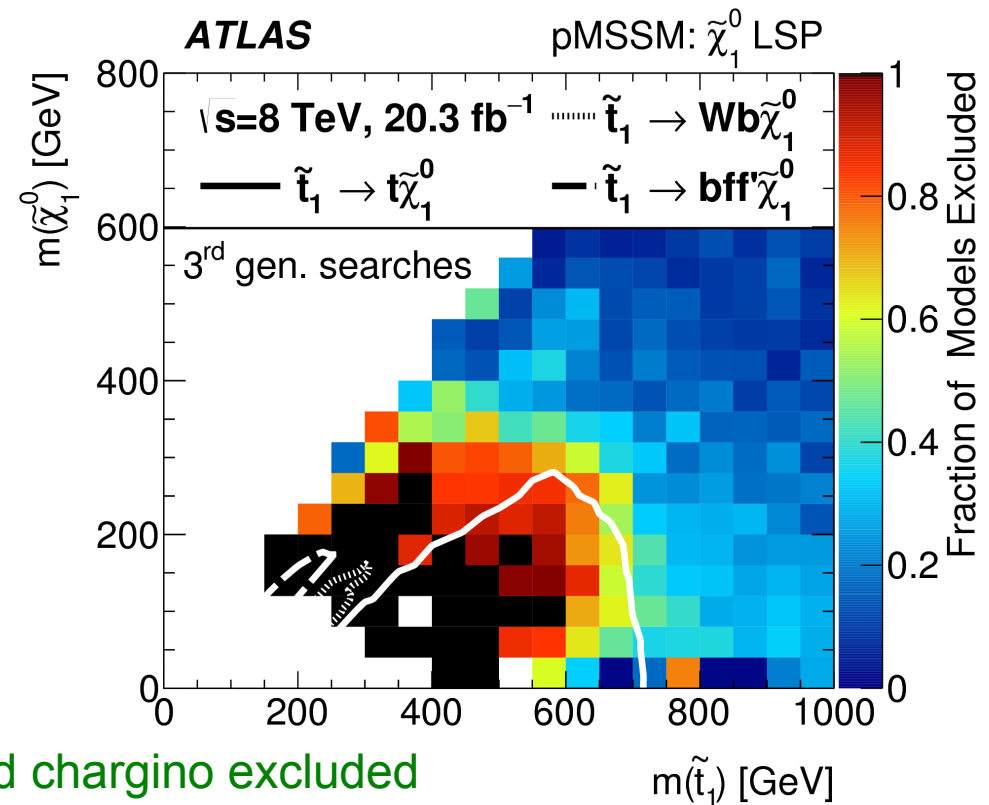
Simplified model with 100% BR for  $\tilde{t} \rightarrow t\tilde{\chi}_1^0$  overestimates mass reach

## All searches



Note: very few models with light stop due to Higgs mass constraint

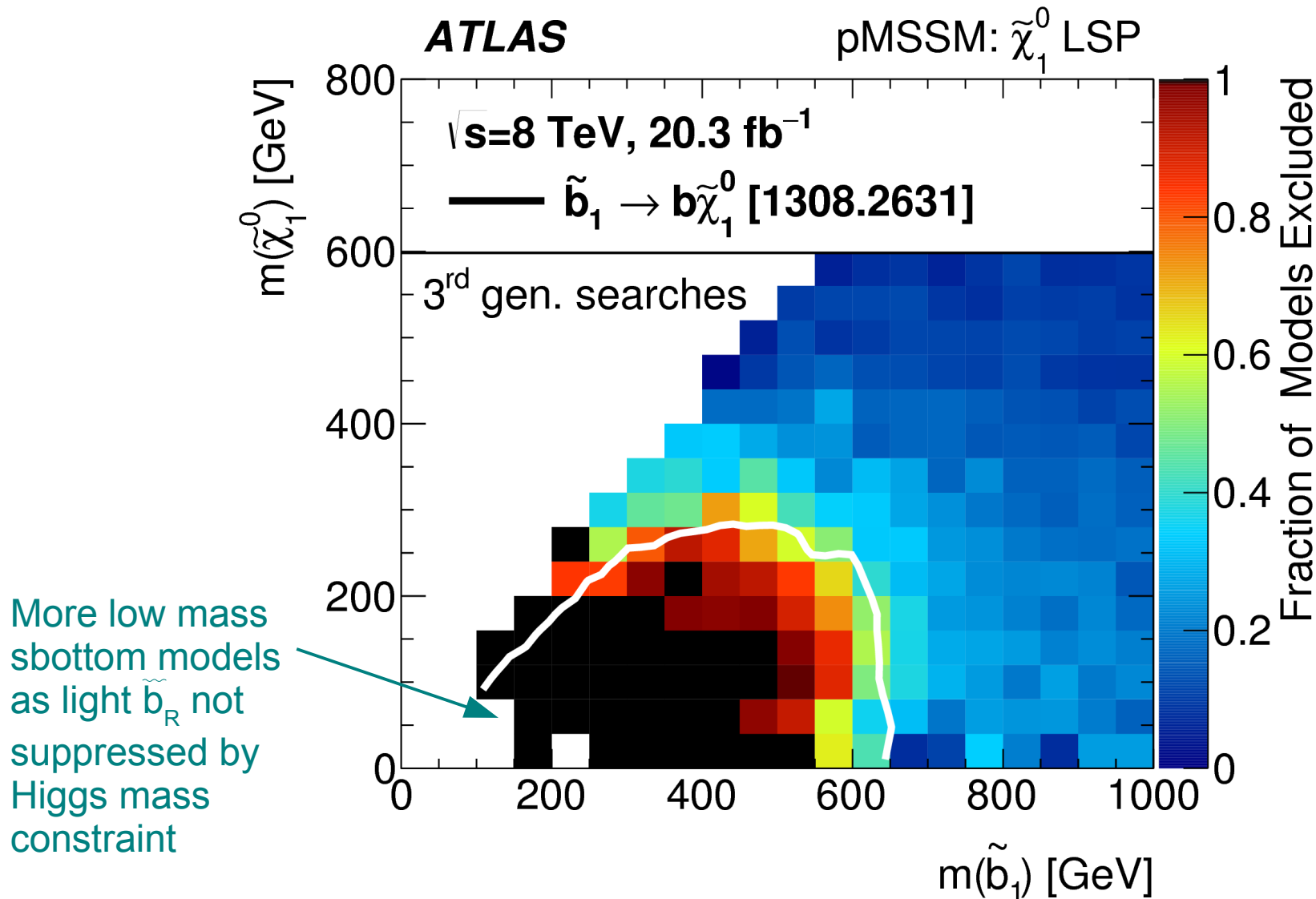
## Only 3<sup>rd</sup> gen. searches



Long-lived chargino excluded by disappearing track analysis

# 3<sup>rd</sup> Generation Squarks - sbottom

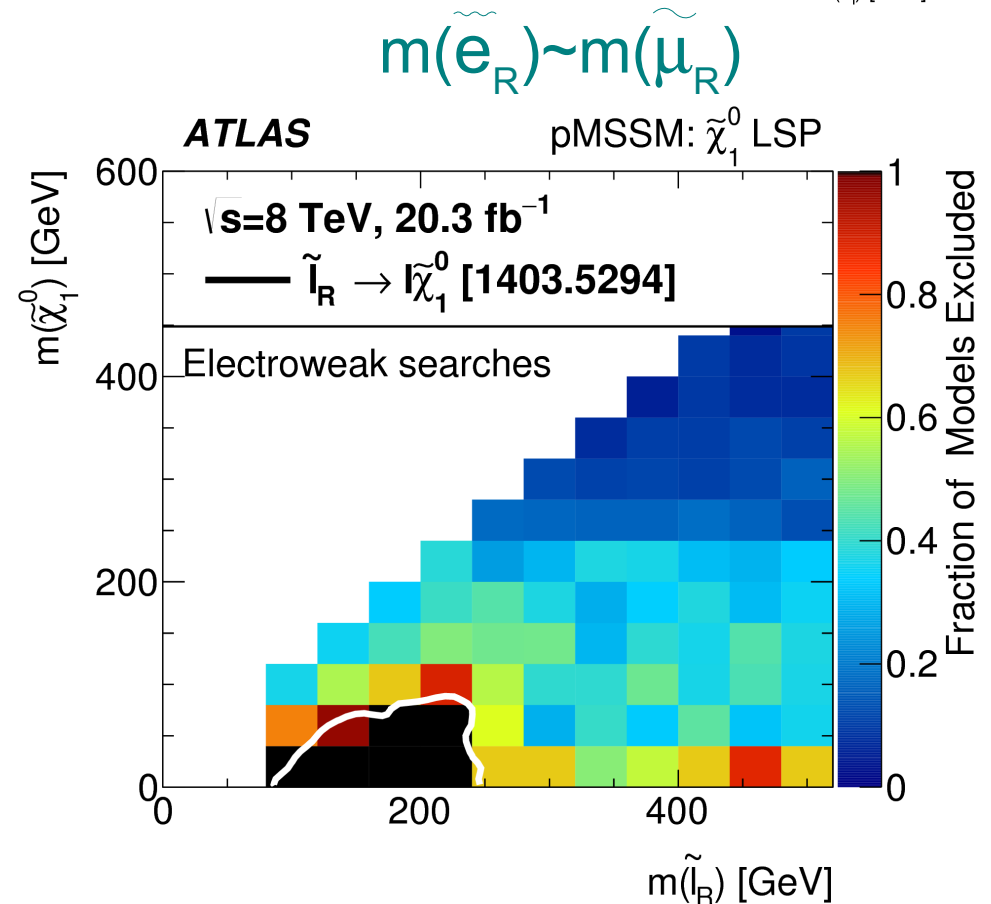
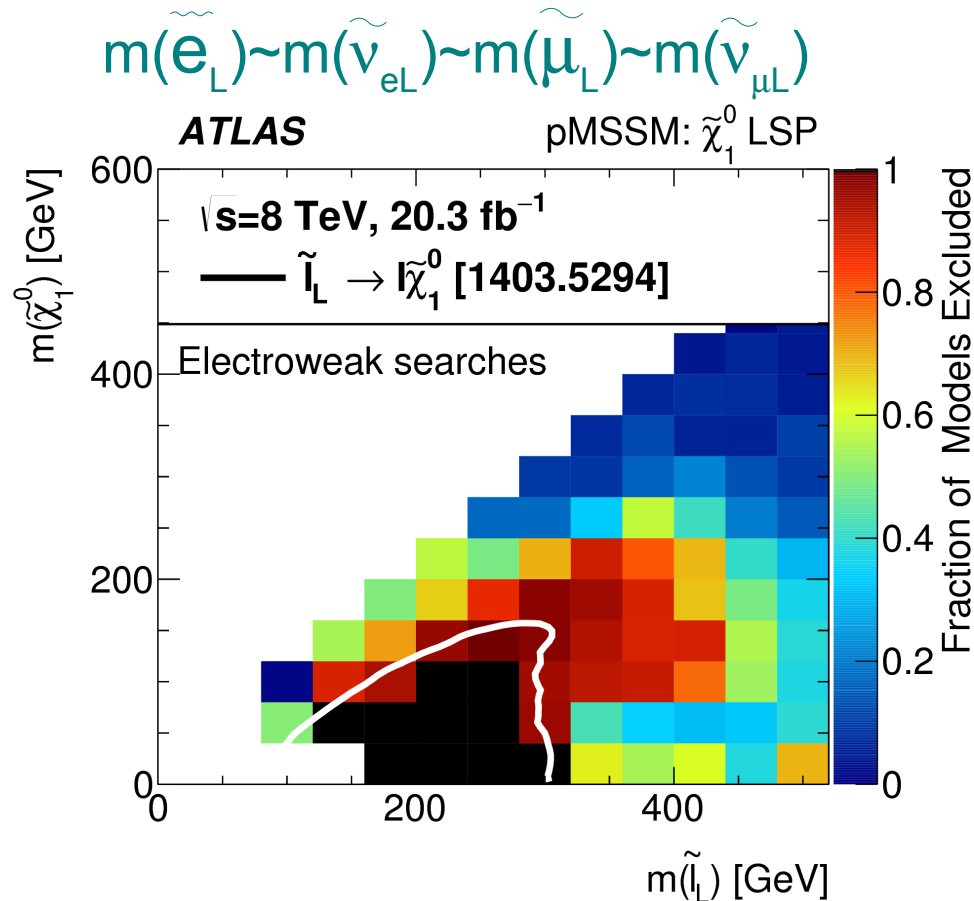
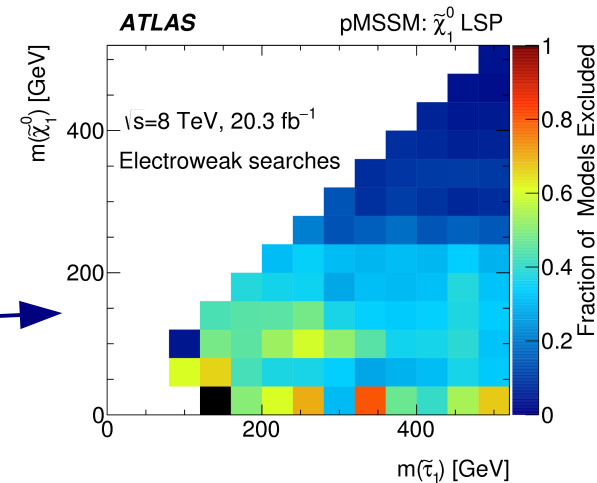
Similar conclusions for the sensitivity to sbottom production



# EW Production - Sleptons

Good agreement with simplified models when split in left and right-handed sleptons

Sensitivity to staus still rather limited due to the larger backgrounds



# Exclusion Strength per Analysis

Can also compare strength of different analysis for these pMSSM models

Absolute fractions very dependent on pMSSM scan range, but gives idea of relative sensitivity

Split by LSP type (dominant  $\tilde{\chi}_1^0$  component)

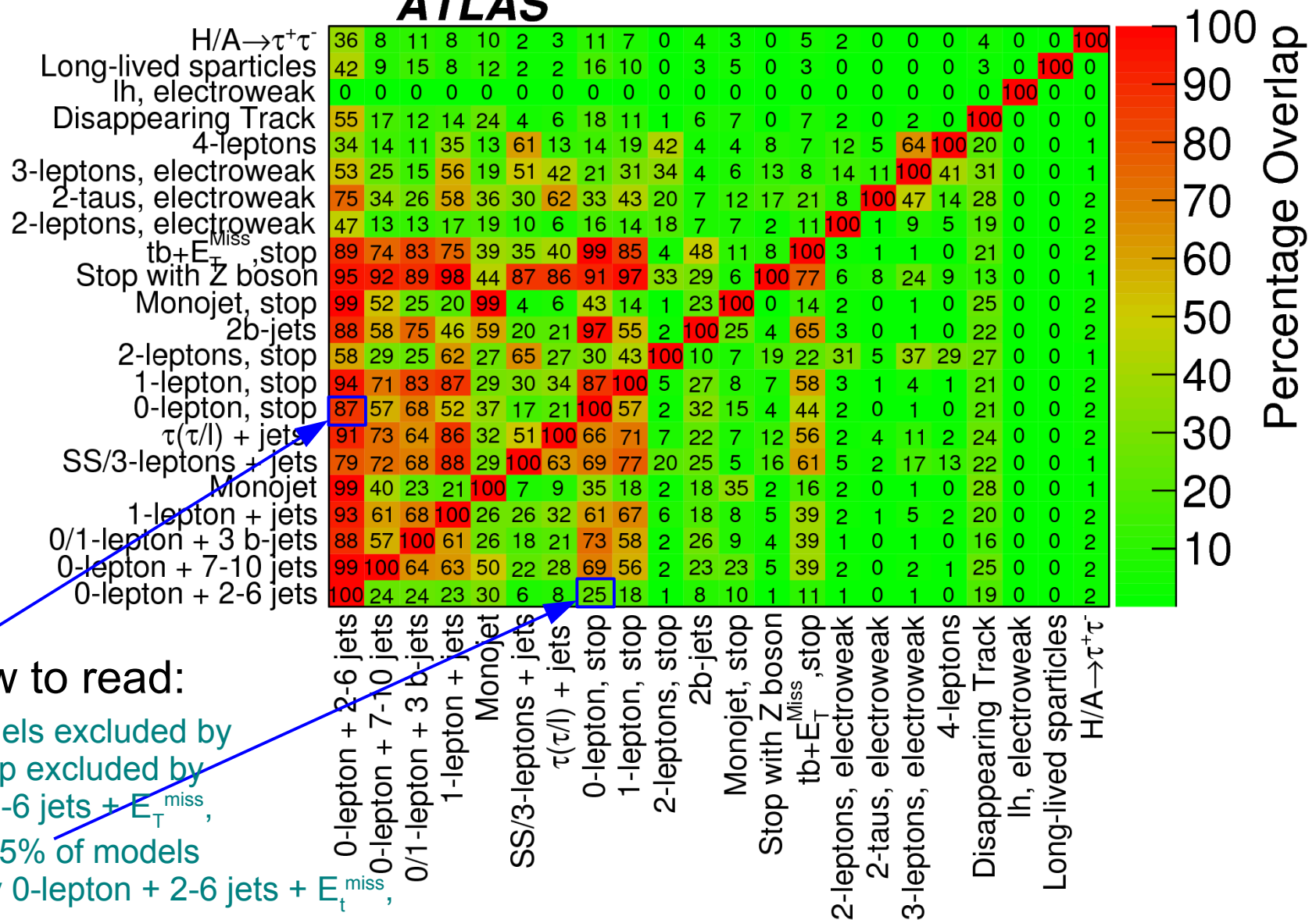
Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + $E_T^{\text{miss}}$	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + $E_T^{\text{miss}}$	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + $E_T^{\text{miss}}$	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + $E_T^{\text{miss}}$	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + $E_T^{\text{miss}}$	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + $E_T^{\text{miss}}$	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2%
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + $E_T^{\text{miss}}$	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
$t\bar{b} + E_T^{\text{miss}}$ , stop	4.2%	1.9%	3.1%	5.0%
$\ell h$ , electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2- $\tau$ , electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1%
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \rightarrow \tau^+ \tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

# Analysis Complementarity

Also looked in the overlap in exclusion between analysis

Apart the  $lh$  EW search, all analysis have unique contribution

## ATLAS



How to read:

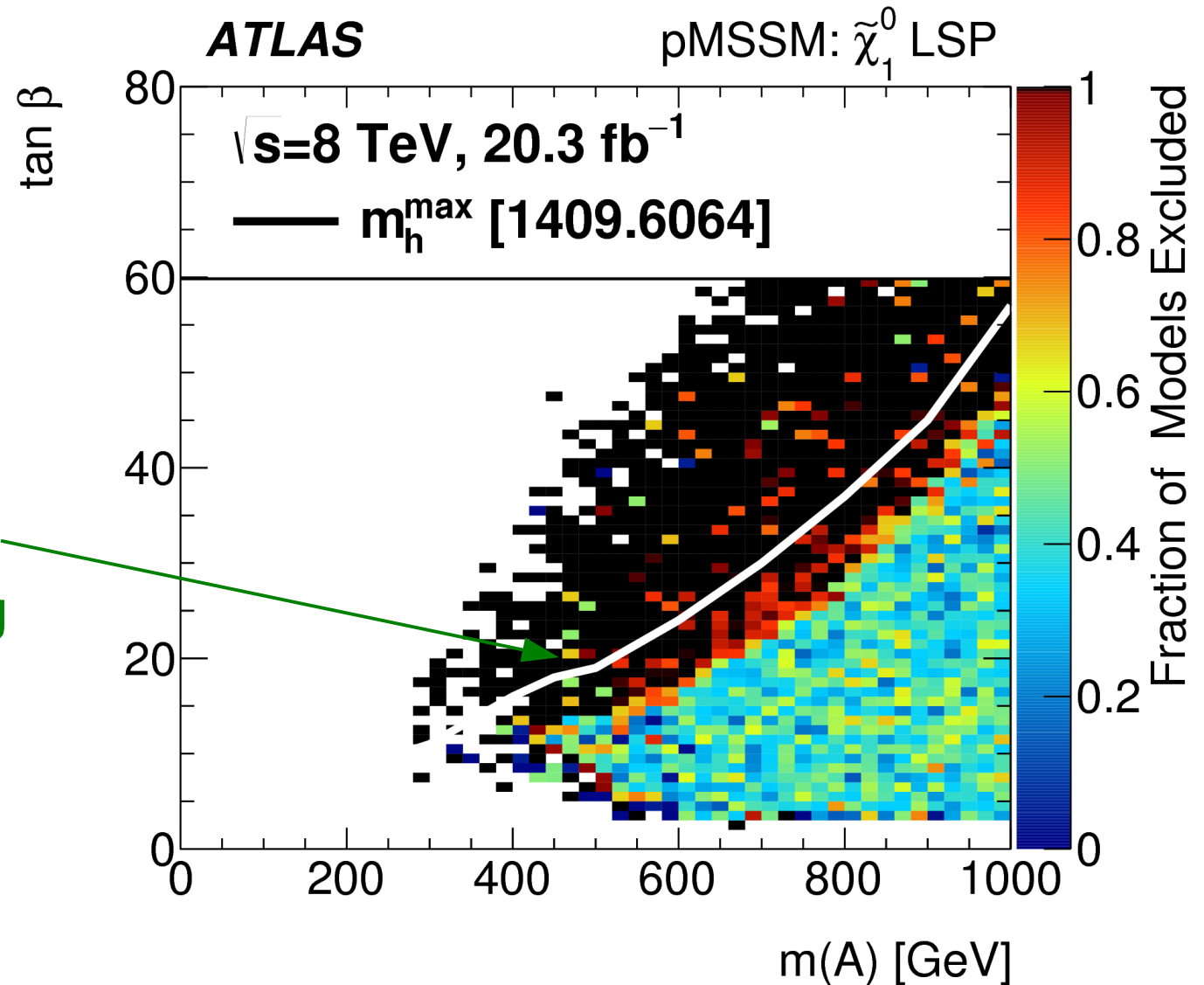
87% of models excluded by  
0-lepton, stop excluded by  
0-lepton + 2-6 jets +  $E_T^{\text{miss}}$ ,  
while only 25% of models  
excluded by 0-lepton + 2-6 jets +  $E_T^{\text{miss}}$ ,  
are excluded by 0-lepton stop

# Heavy Higgs Partner Search

Search for heavy (pseudo-)scalar H/A to  $\tau$ -pair included as well

Provide very high complementarity with direct SUSY searches (previous slide)

Exclusion mostly better than usual  $m_h^{\text{max}}$  scenario due to higher branching fraction in the pMSSM models



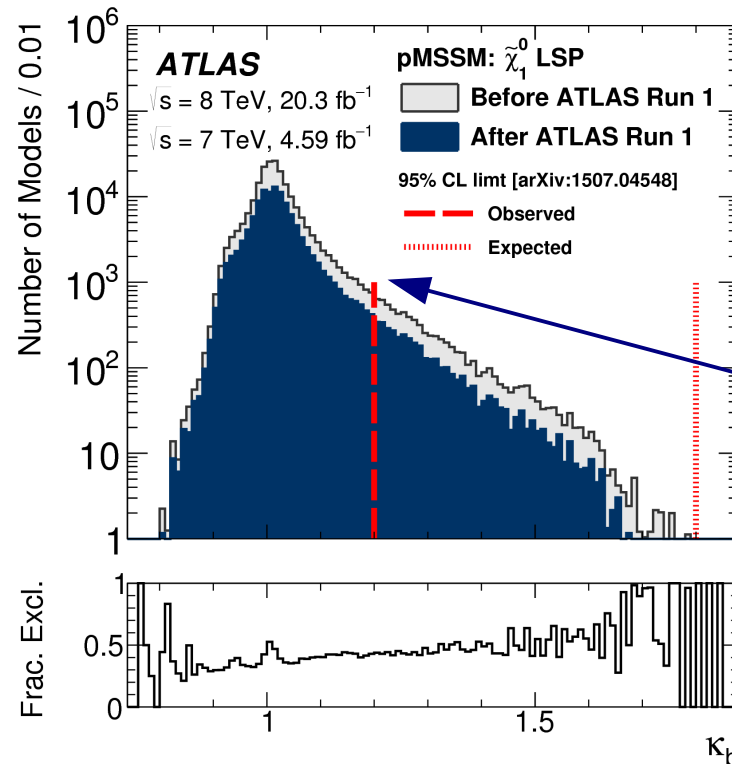
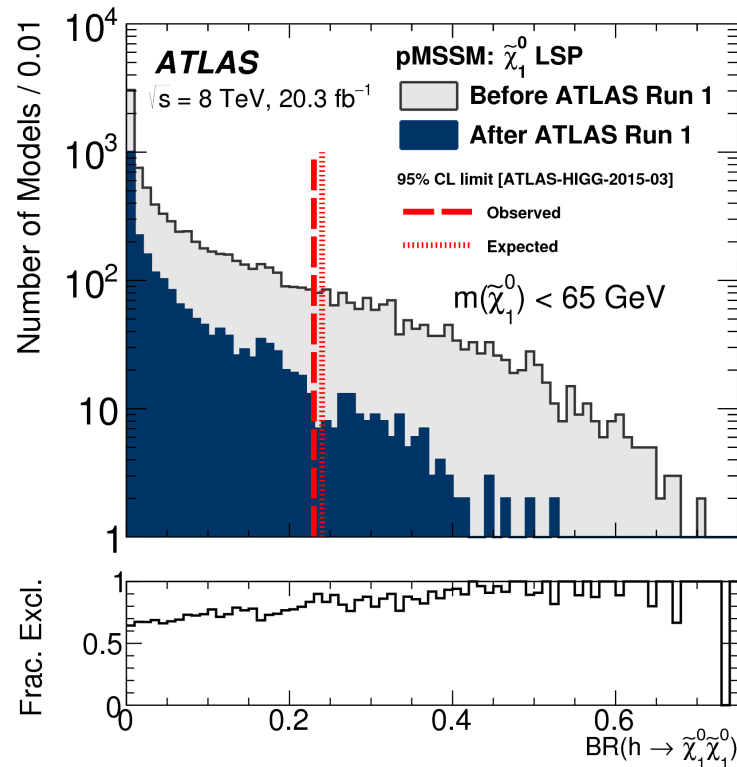


# Other Higgs Measurements

Higgs mass included in model constraints  
No dependence seen in allowed range

7% of the non-excluded models with  $m(\tilde{\chi}_1^0) < 65$  GeV are excluded  
by ATLAS  $\text{BF}(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 0.23$  measurement (arXiv:1509.00672)

$$\kappa_i = \sqrt{\frac{\Gamma_h}{\Gamma_{h,\text{SM}}} \times \frac{\text{BR}(h \rightarrow i + i)}{\text{BR}(h \rightarrow i + i)_{\text{SM}}}},$$



Other coupling measurements not expected to have sensitivity to these pMSSM models

$\kappa_b$  measurement (arXiv:1507.04548) is lower than expected and excludes 3.1% of the models at 95% CL

Also have impact of  $B_s \rightarrow \mu\mu$ ,  $b \rightarrow s\gamma$  and  $(g-2)_\mu$  measurements (in backup)

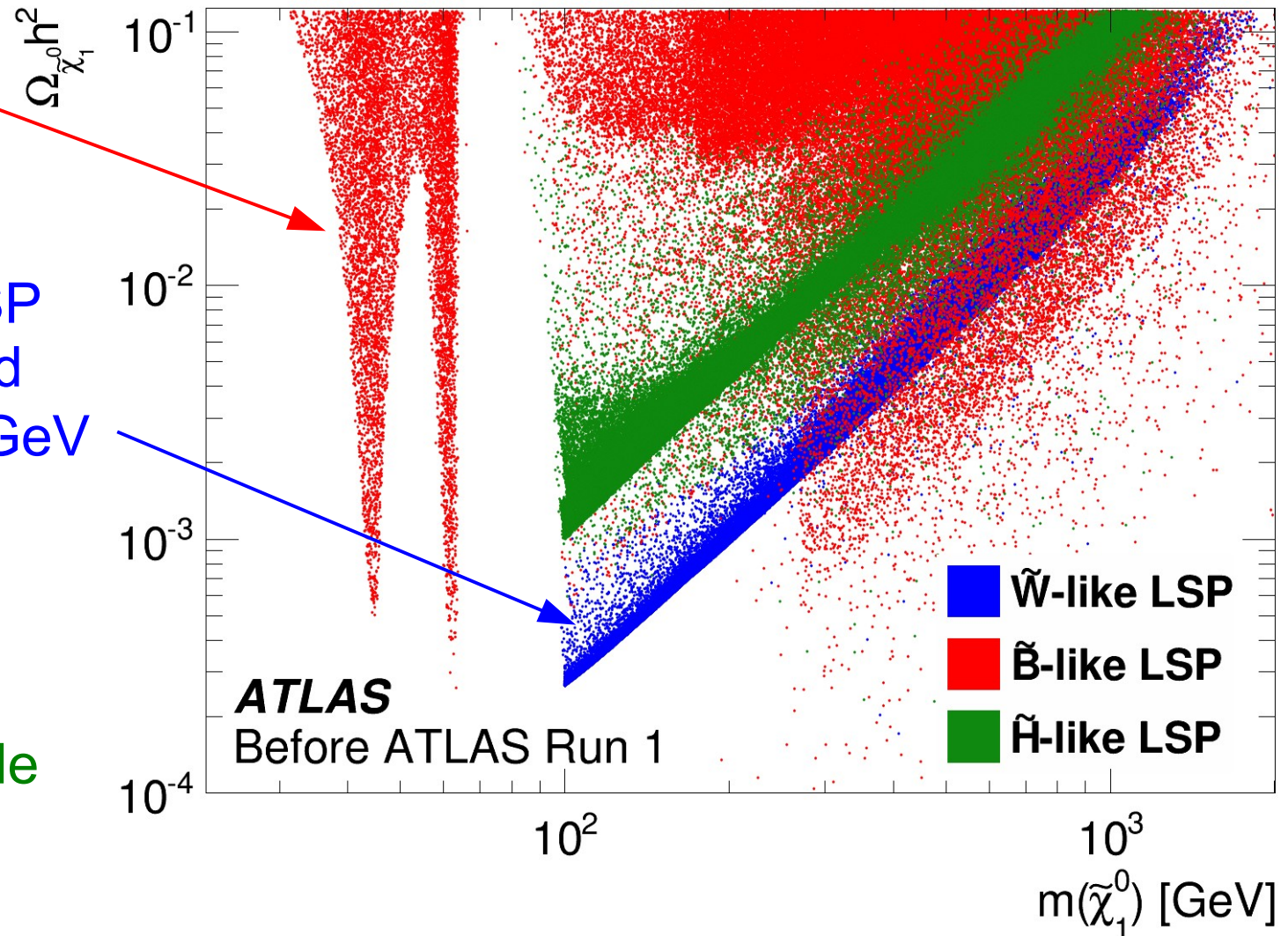
# Dark Matter Relic Abundance

Dark Matter relic abundance only applied as an upper bound

2/3 of models in  
Z and H funnel  
excluded

80% of Wino LSP  
models excluded  
for  $m(\tilde{\chi}_1^0) < 200$  GeV  
by disappearing  
track analysis

Higgsino LSP  
harder to exclude  
as chargino too  
short lived



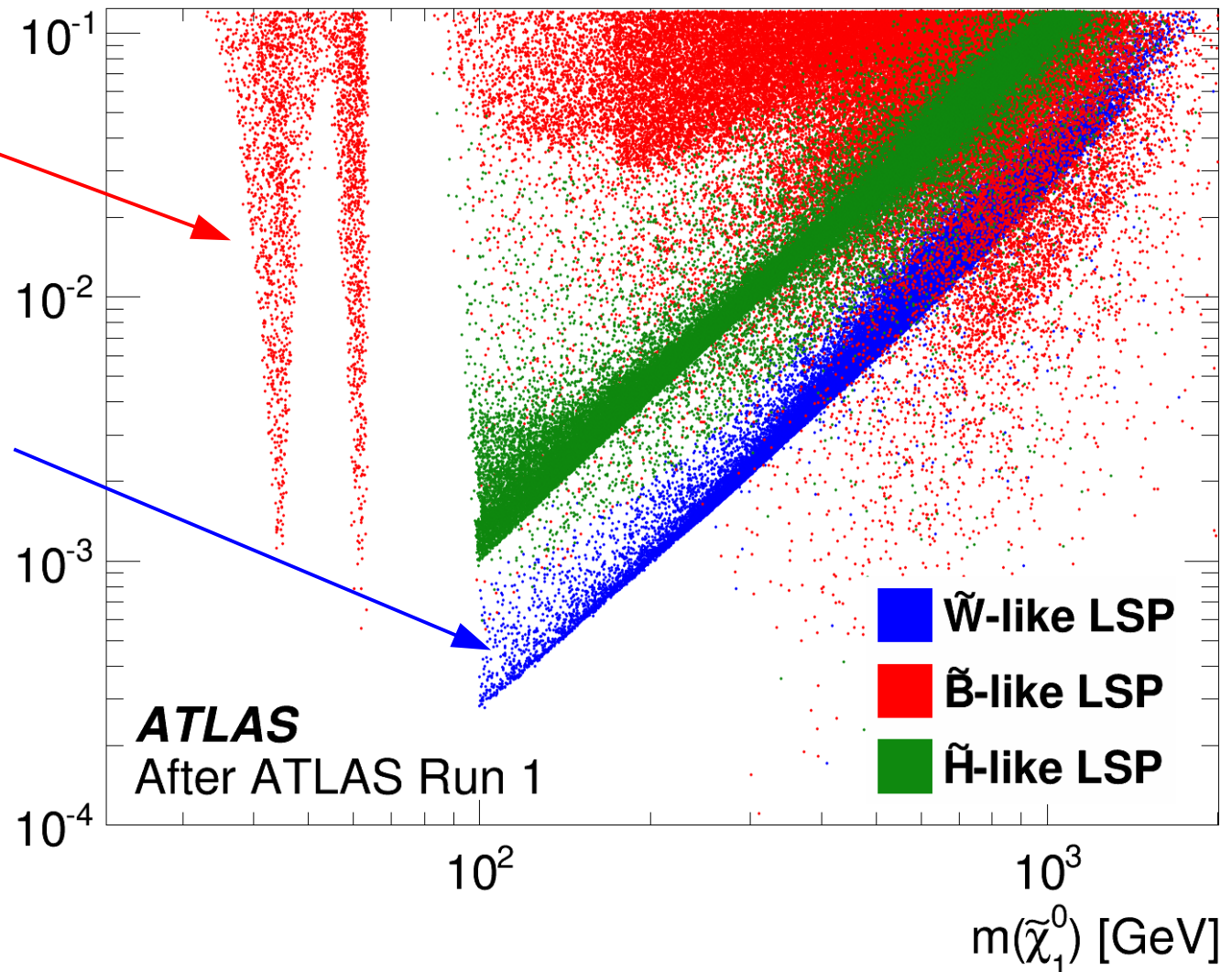
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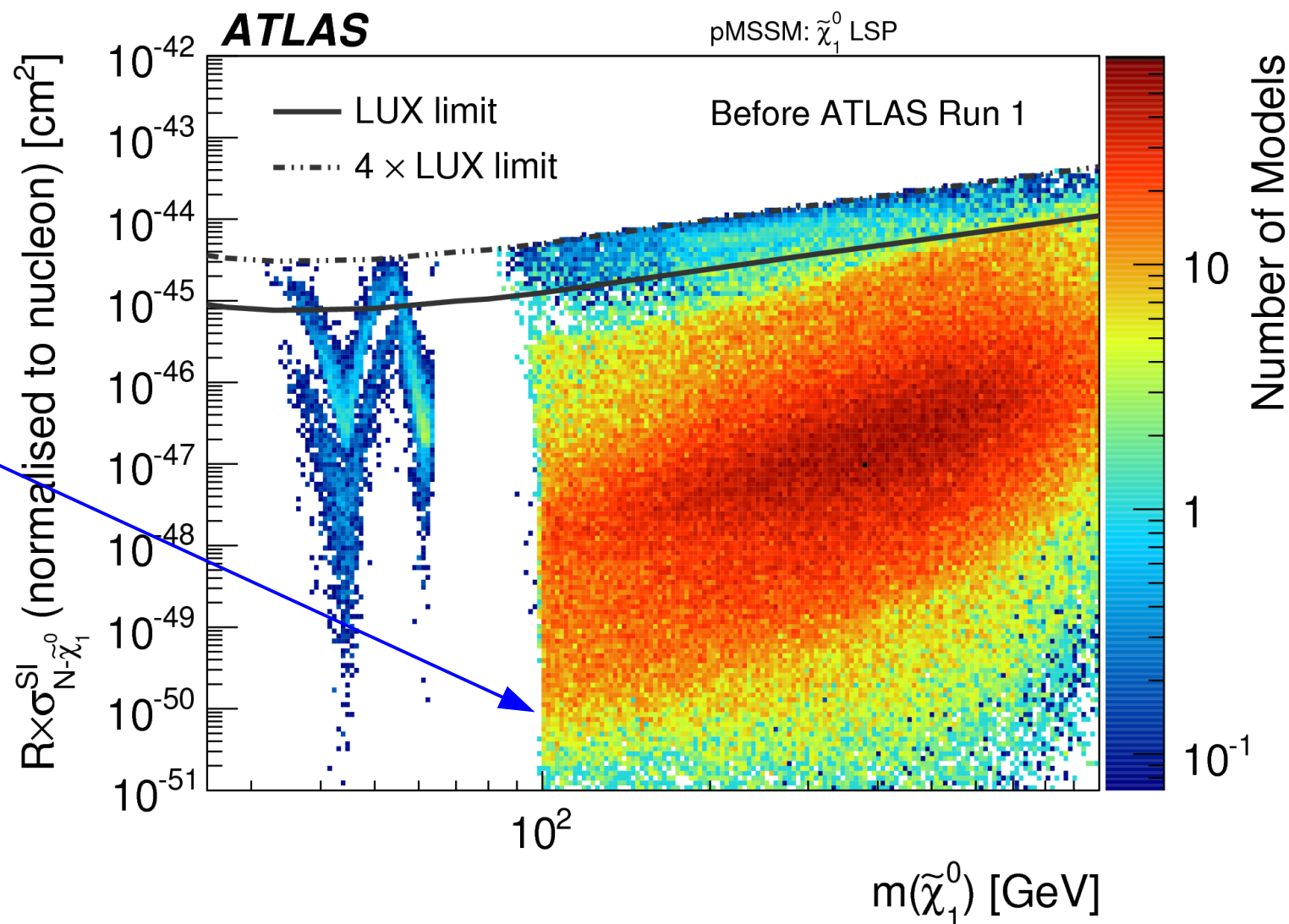
# Dark Matter Interaction Cross Section

Can also compare to DM direct detection experiments

- a loose constraint from LUX applied during model selection

Show good complementarity with direct detection experiments

Exclusion at very low cross sections again due to disappearing track analysis excluding light Wino charginos



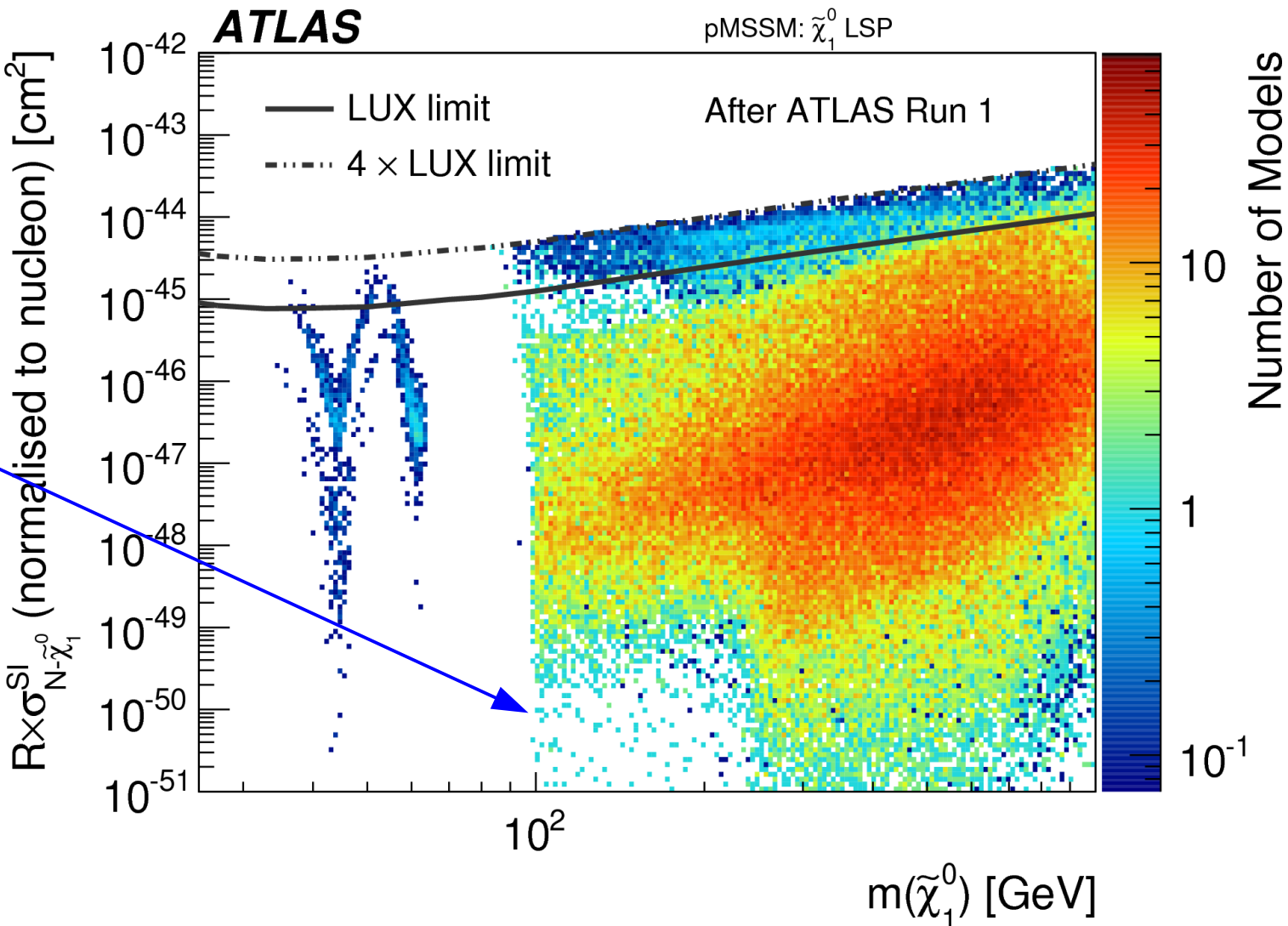


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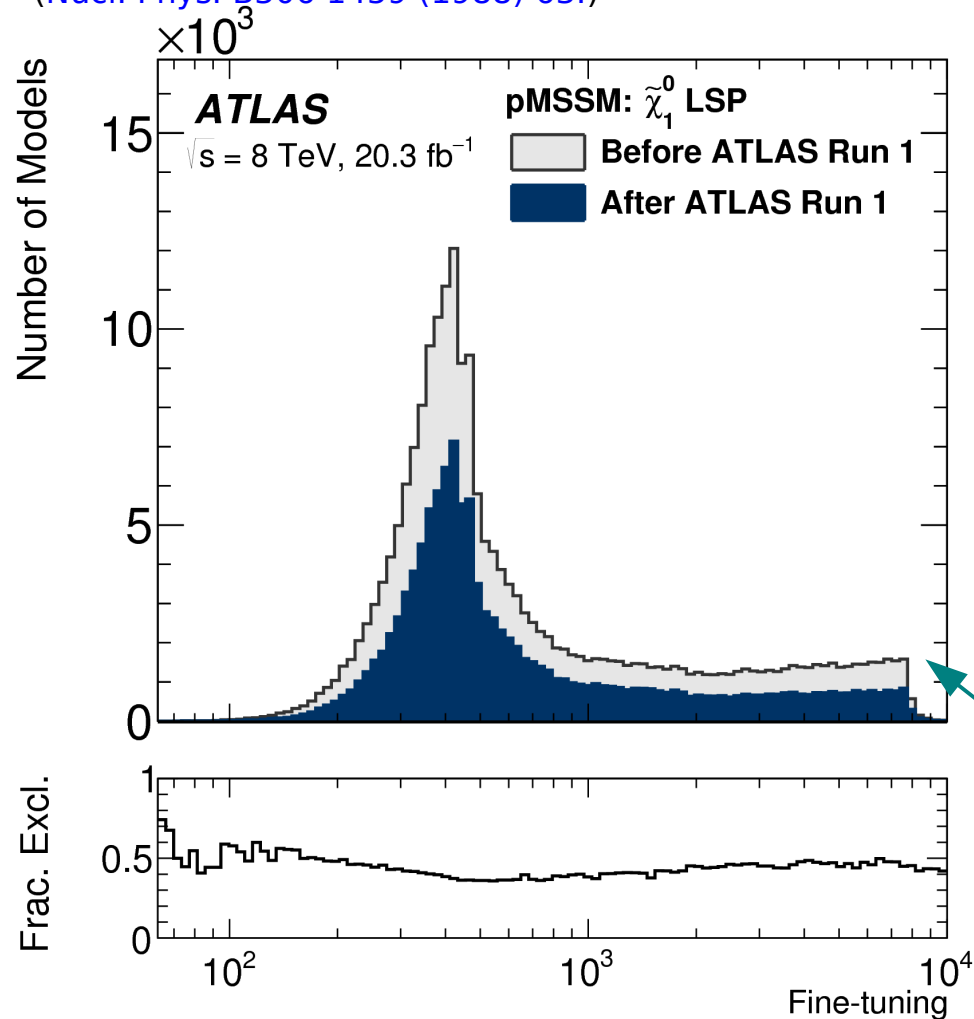
# Fine-tuning

No fine-tuning requirement applied during model selection  
 Little dependence on fine-tuning seen in the ATLAS exclusion  
 – mostly driven by  $\mu$  and  $A_t$  in the pMSSM models

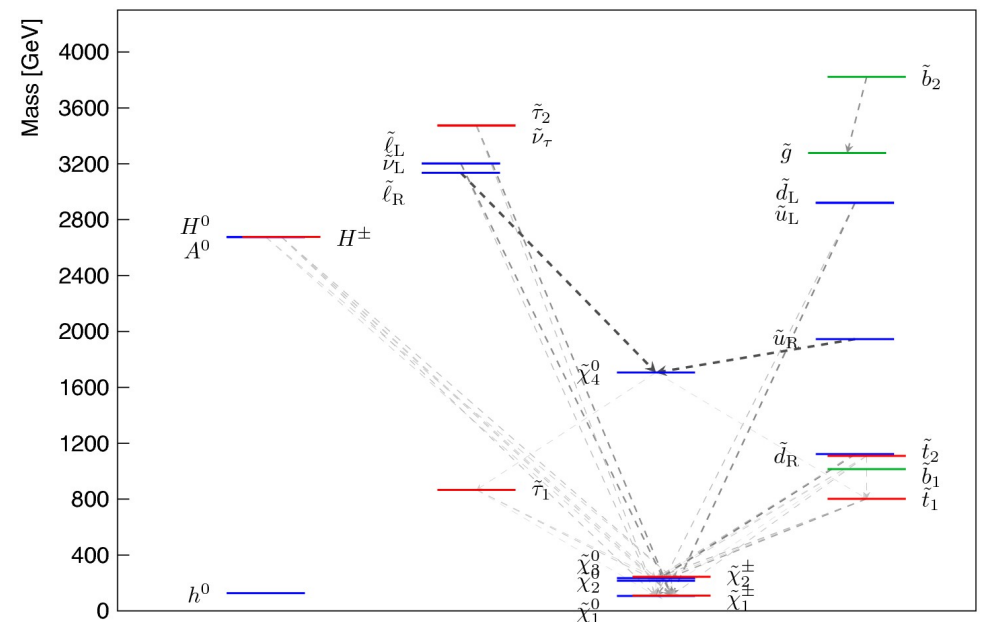
## Fine-tuning

(Barbieri and Giudice measure)

(Nucl. Phys. B306 1459 (1988) 63.)



## Model with lowest fine-tuning ( $O(2\%)$ )



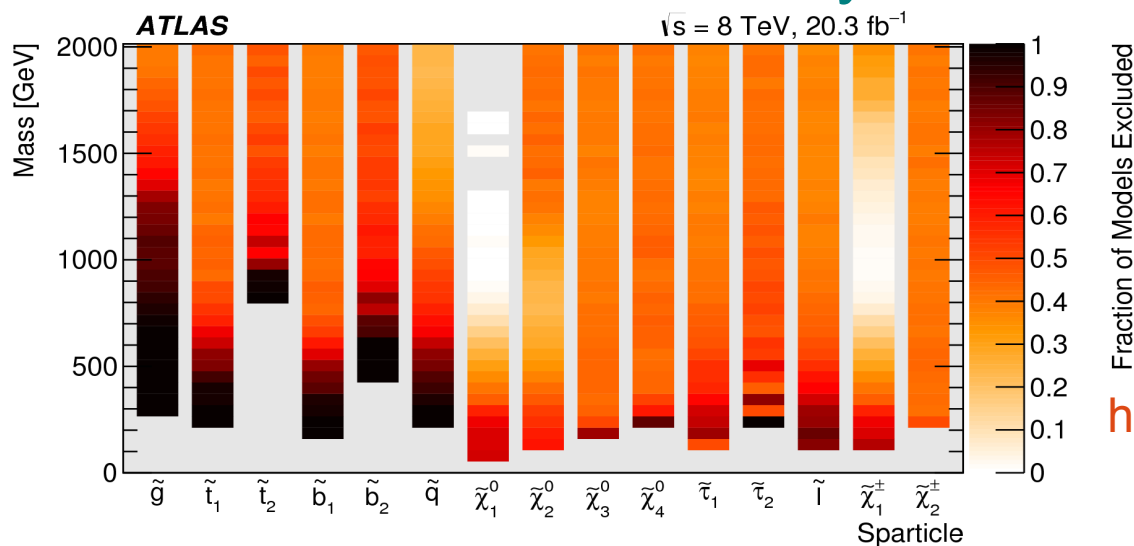
Upper bound due to upper bounds in the generated parameters



# Summary

- ATLAS Run-1 searches have been evaluated on a large set of varied pMSSM models
- Most sensitivity to strong production processes
- Simplified model shown to have good correspondence to the pMSSM models, but also differences observed
- Good complementarity shown between different searches and with direct detection experiments

## Exclusion summary



All models and information of the excluding analyses can be found at HepData:

<http://hepdata.cedar.ac.uk/view/ins1389857>

Backup

# Sampling by LSP Type

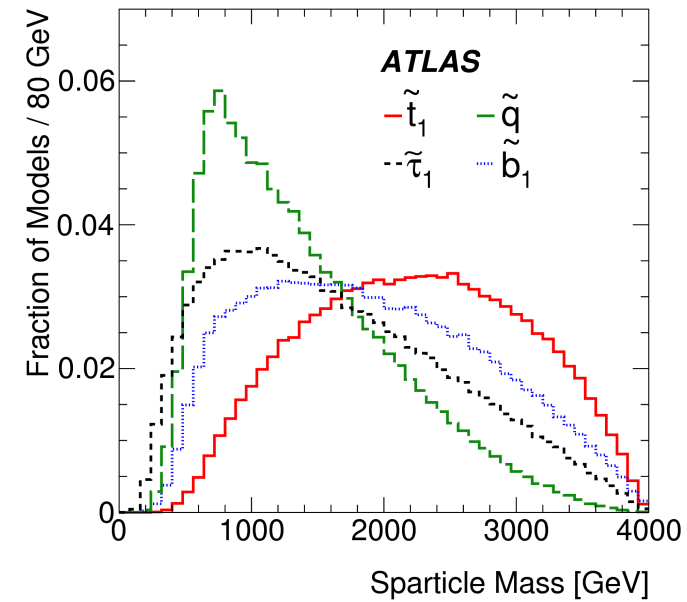
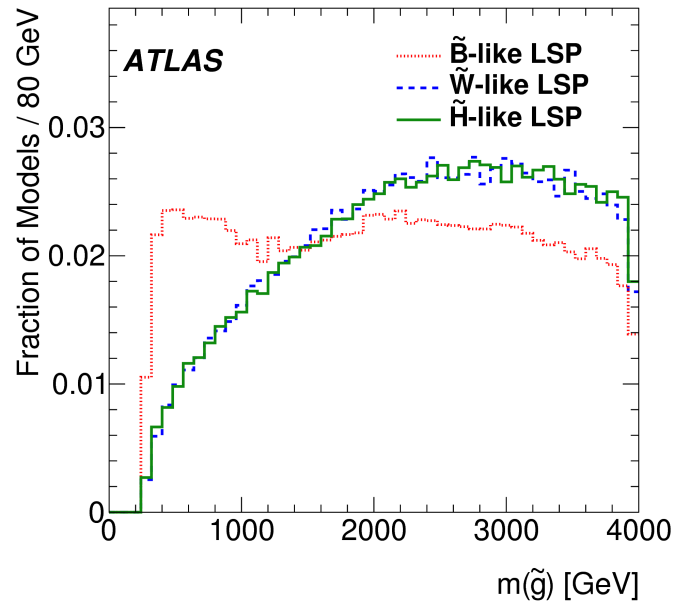
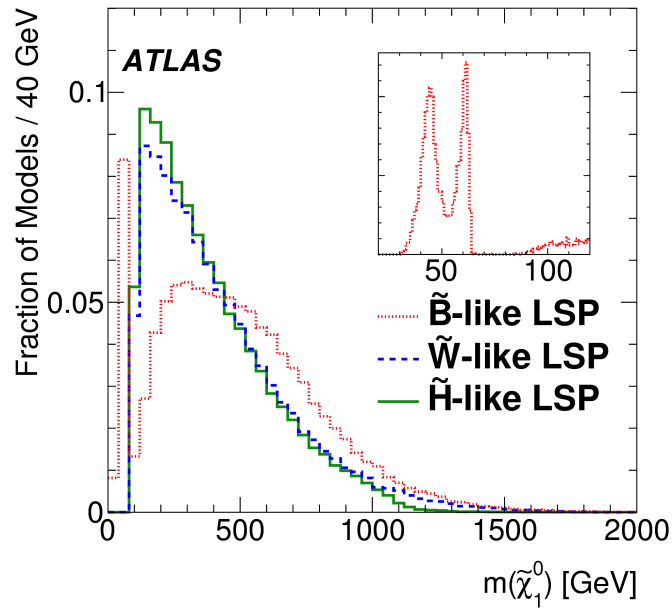
Bino LSP tends to overproduce DM, so disfavored by model selection  
 Bino LSP is also the only one type allowing for  $m(\tilde{\chi}_1^0)<100$  GeV  
 To ensure good precision, models with Bino LSP oversampled by a factor 24 – weighted by 1/24 in the combined plots

LSP type	Definition	Sampled	Simulated		Weight
			Number	Fraction	
‘Bino-like’	$N_{11}^2 > \max(N_{12}^2, N_{13}^2 + N_{14}^2)$	$480 \times 10^6$	103,410	35%	1/24
‘Wino-like’	$N_{12}^2 > \max(N_{11}^2, N_{13}^2 + N_{14}^2)$	$\left. \vphantom{\begin{matrix} N_{12}^2 > \max(N_{11}^2, N_{13}^2 + N_{14}^2) \end{matrix}} \right\} 20 \times 10^6 \left\{ \right.$	80,233	26%	1
‘Higgsino-like’	$(N_{13}^2 + N_{14}^2) > \max(N_{11}^2, N_{12}^2)$		126,684	39%	1
Total		$500 \times 10^6$	310,327		

$N_{ij}$  is neutralino mixing matrix

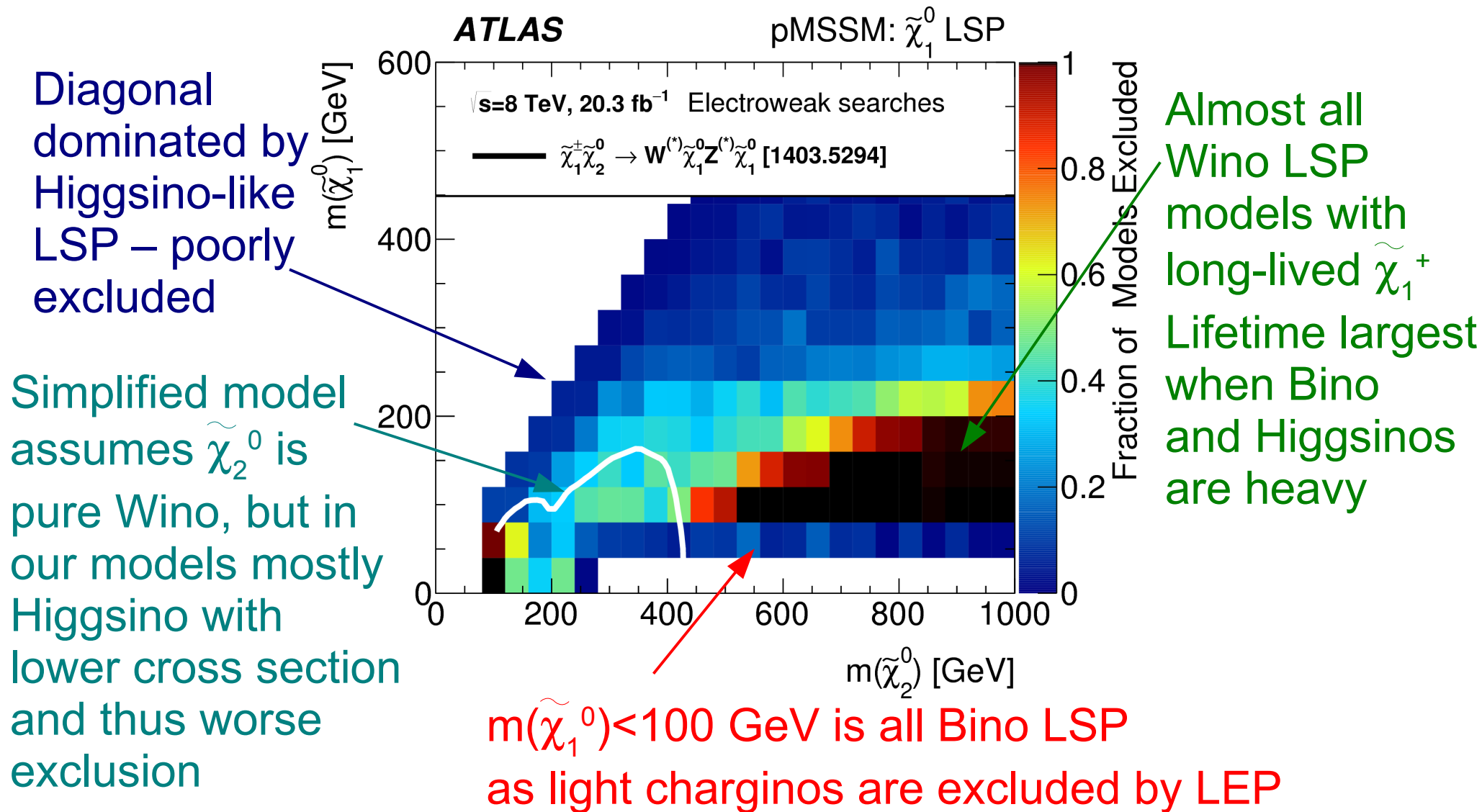
# Sparticle Distribution

Distributions before applying ATLAS Run-1 searches



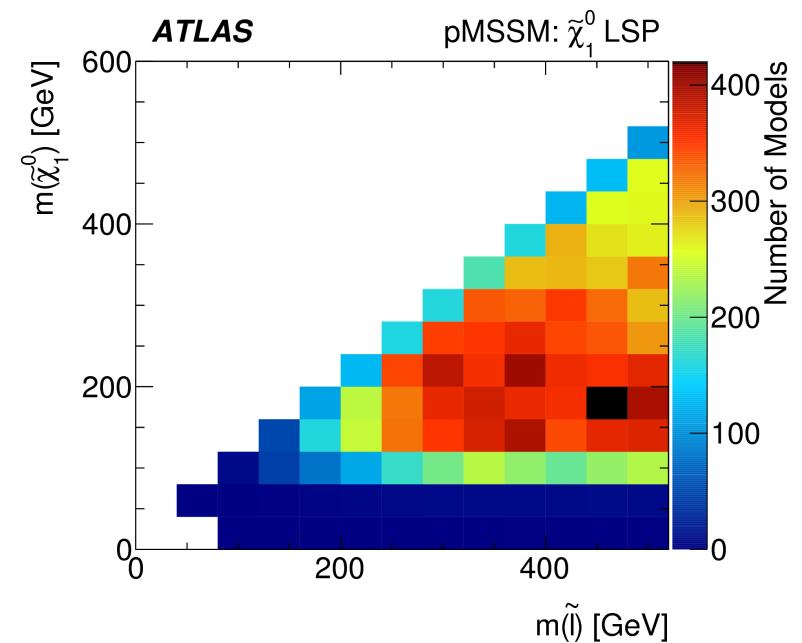
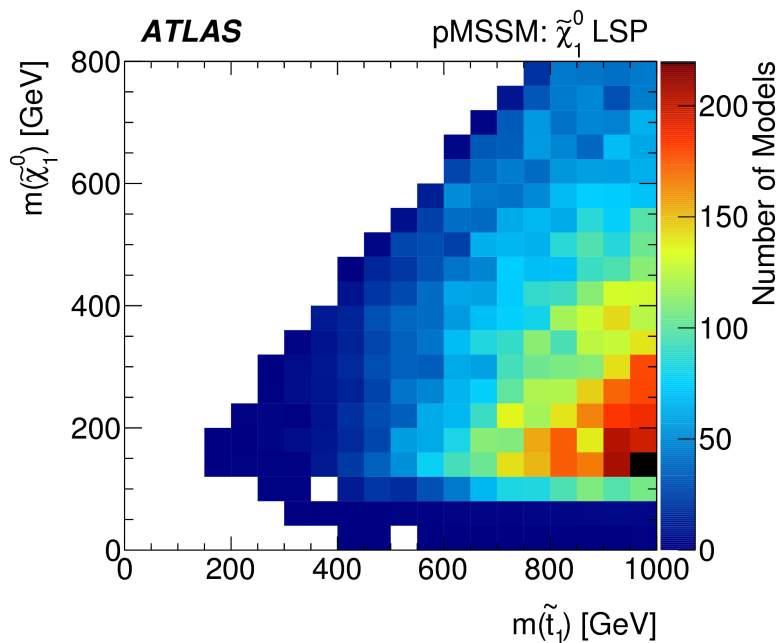
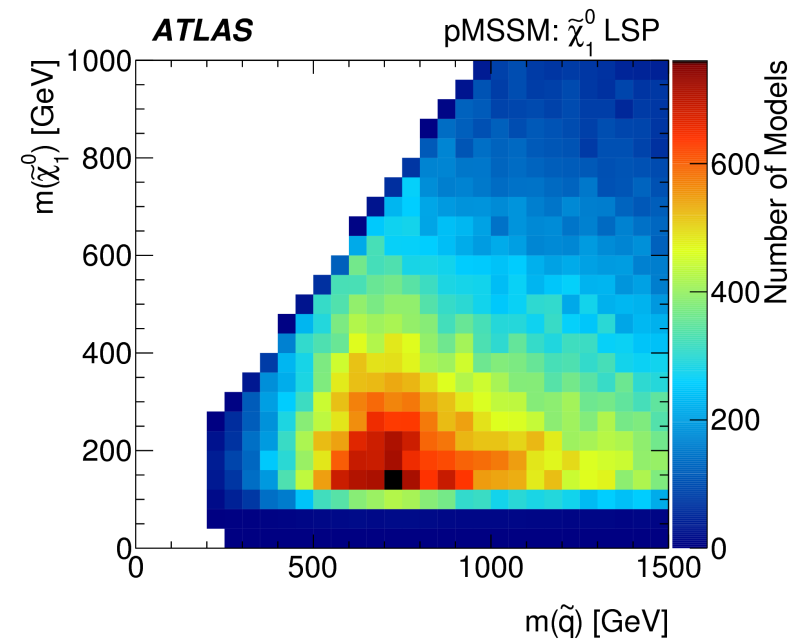
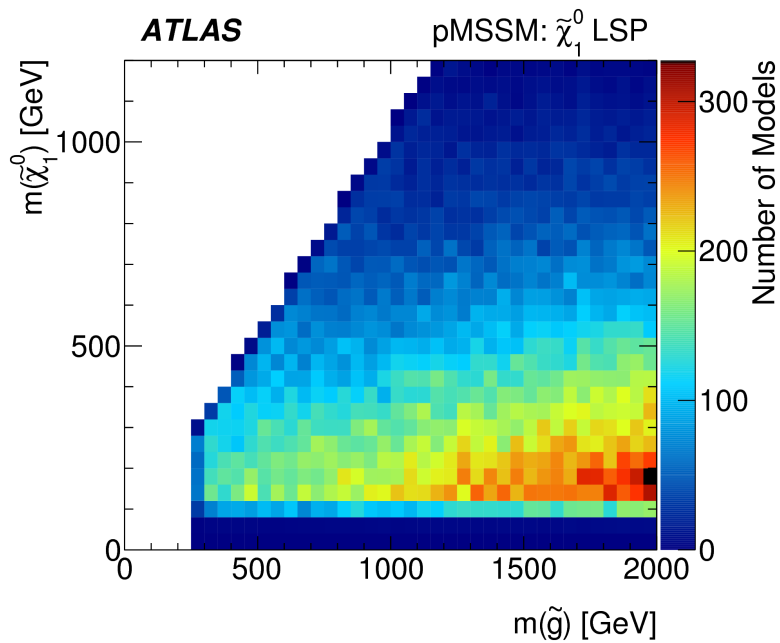
# EW Production – Electroweakinos

Electroweakino exclusion complicated due to strong dependence on the nature of LSP (Bino, Wino and Higgsino admixture)



# 2D Model Distributions

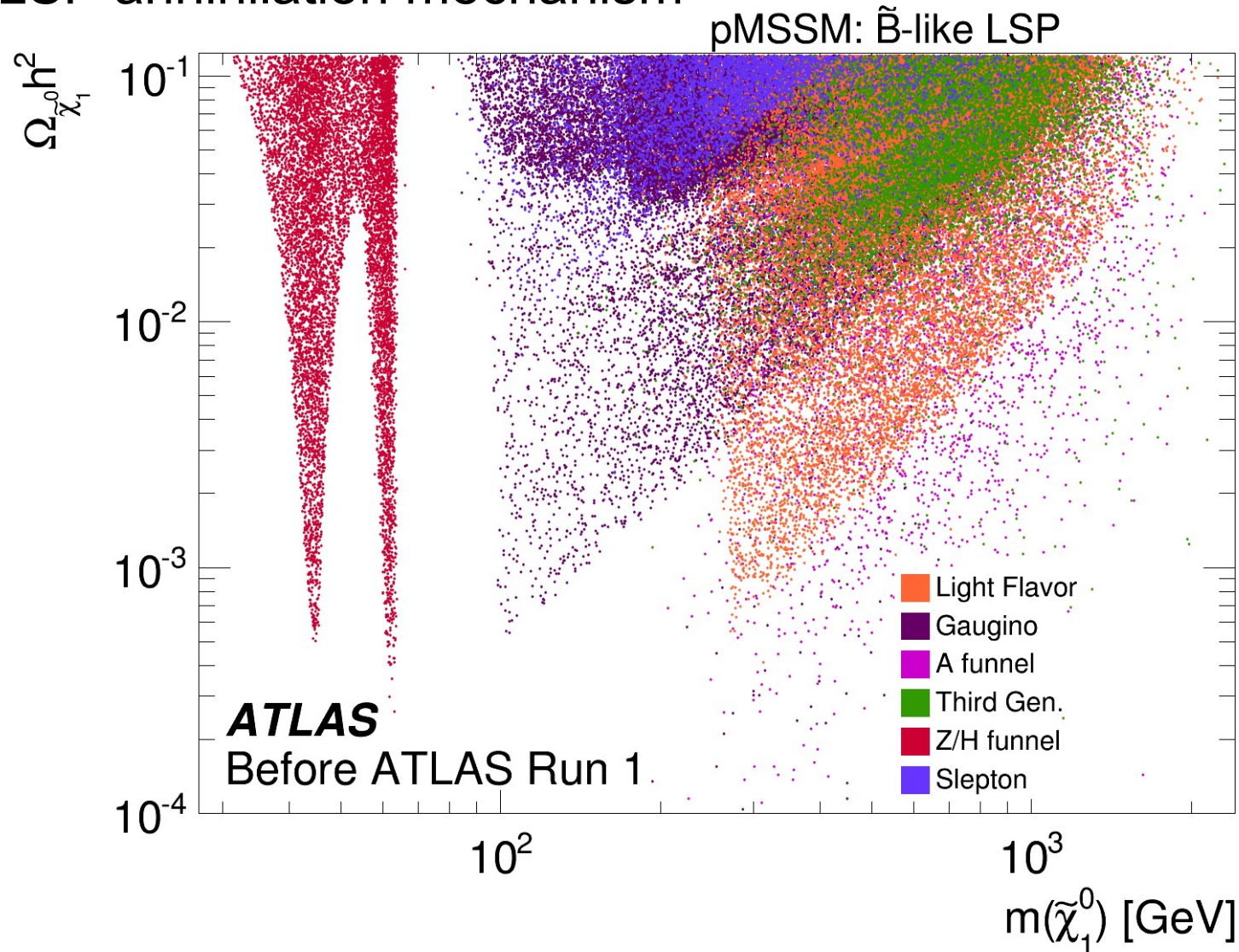
## Before ATLAS Run-1 Searches





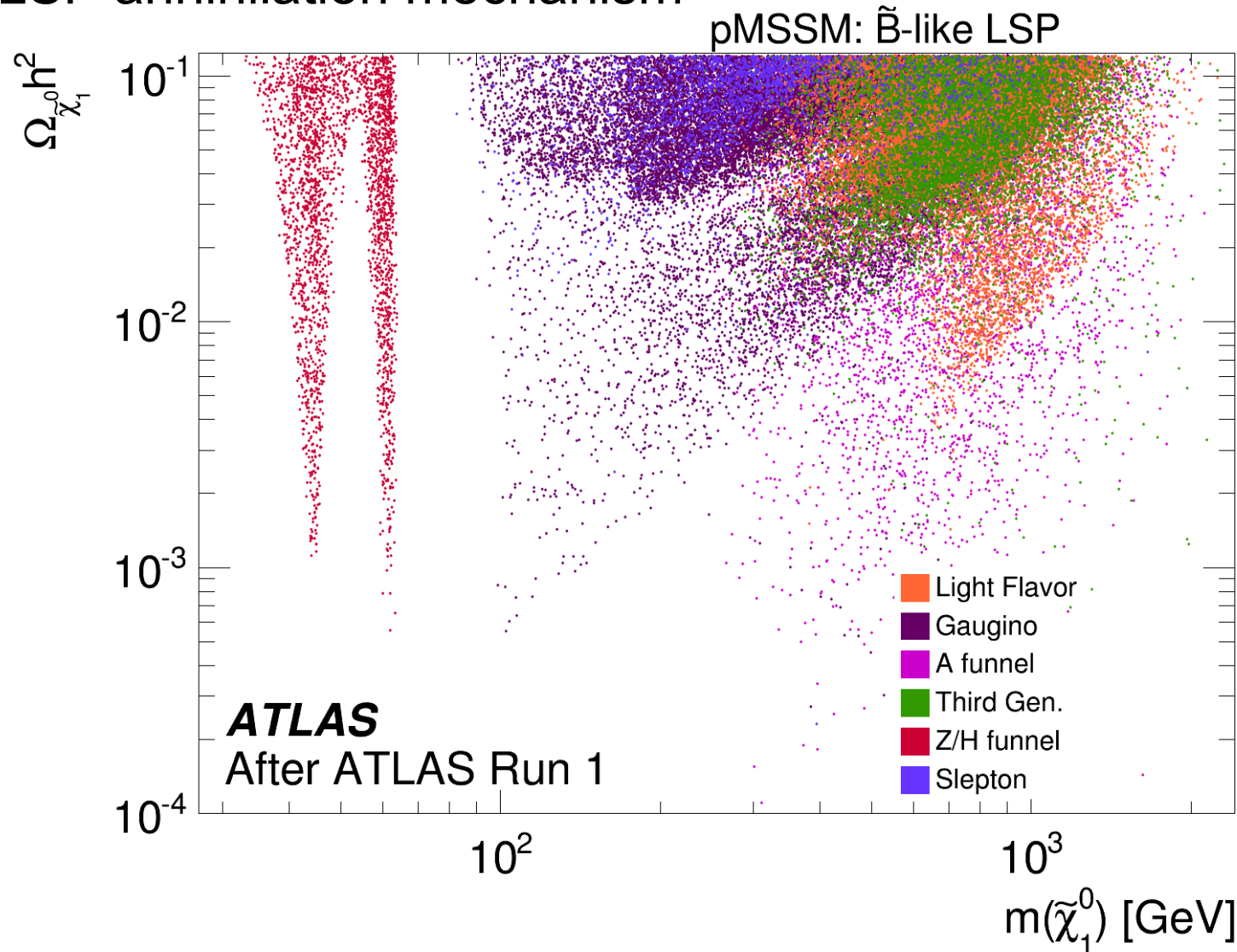
# DM by Annihilation Mechanism

For Bino LSP can split sample by dominant LSP annihilation mechanism



# DM by Annihilation Mechanism

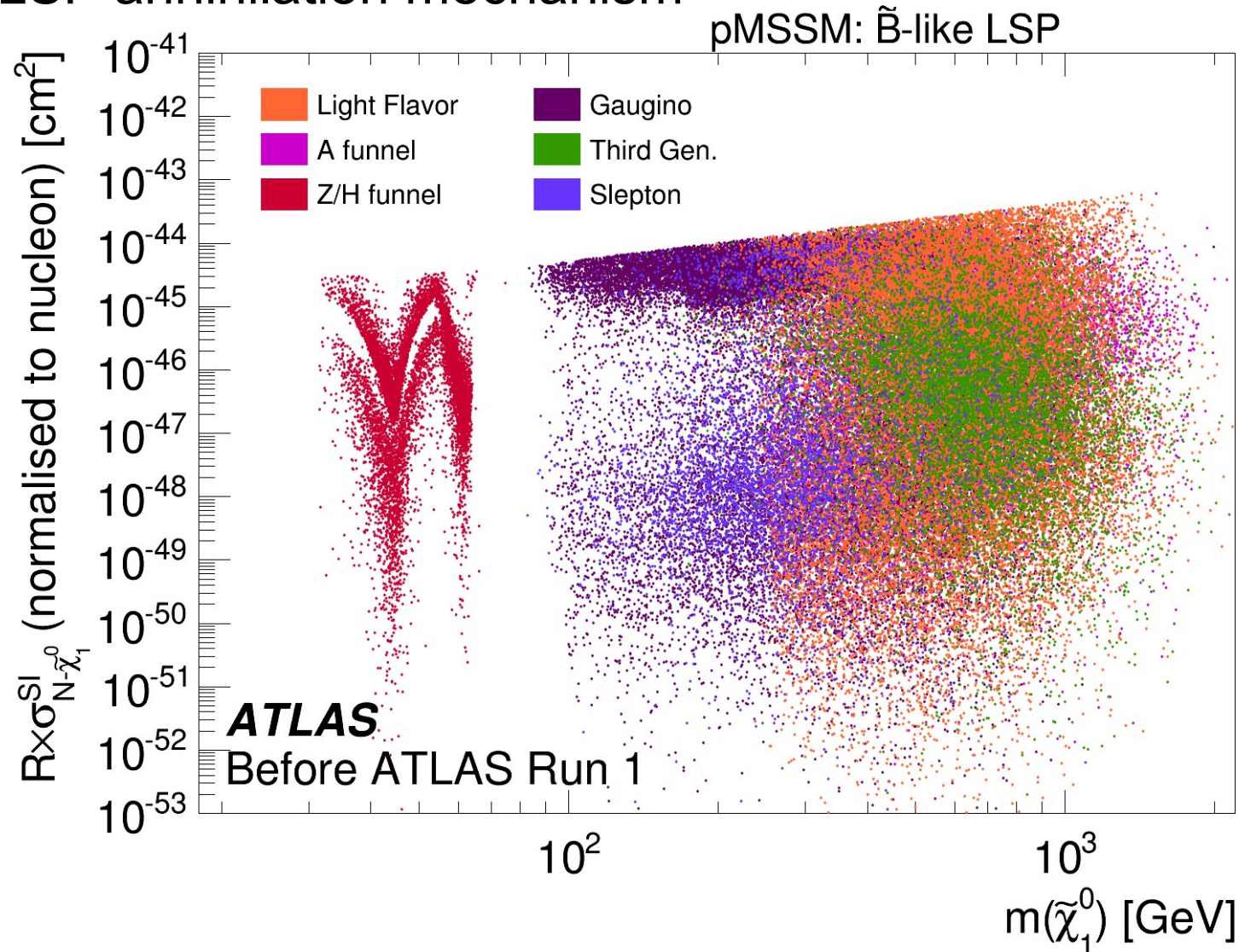
For Bino LSP can split sample by dominant LSP annihilation mechanism



# Direct Detection vs Annihilation Mechanism

29

For Bino LSP can split sample by dominant LSP annihilation mechanism

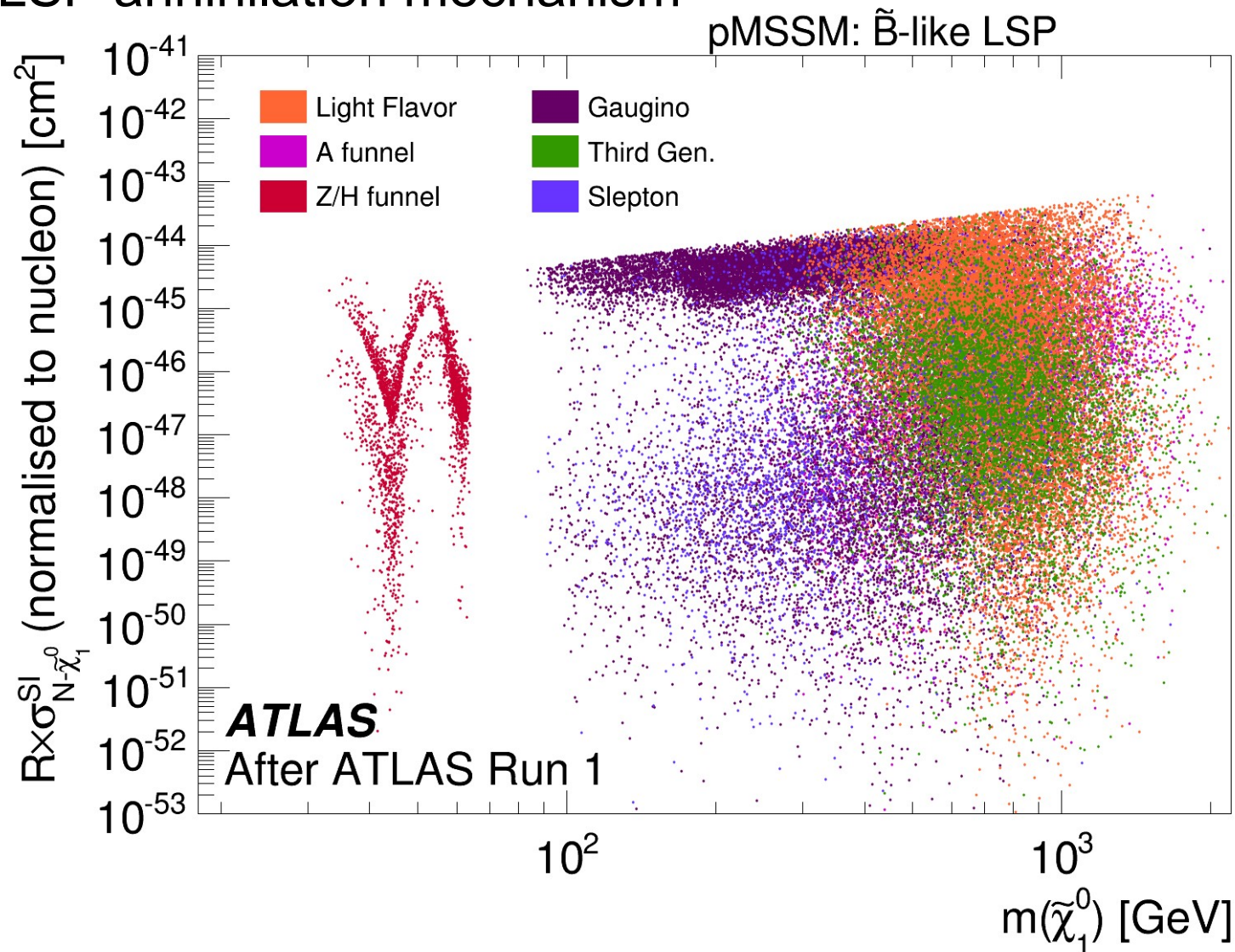




# Direct Detection vs Annihilation Mechanism

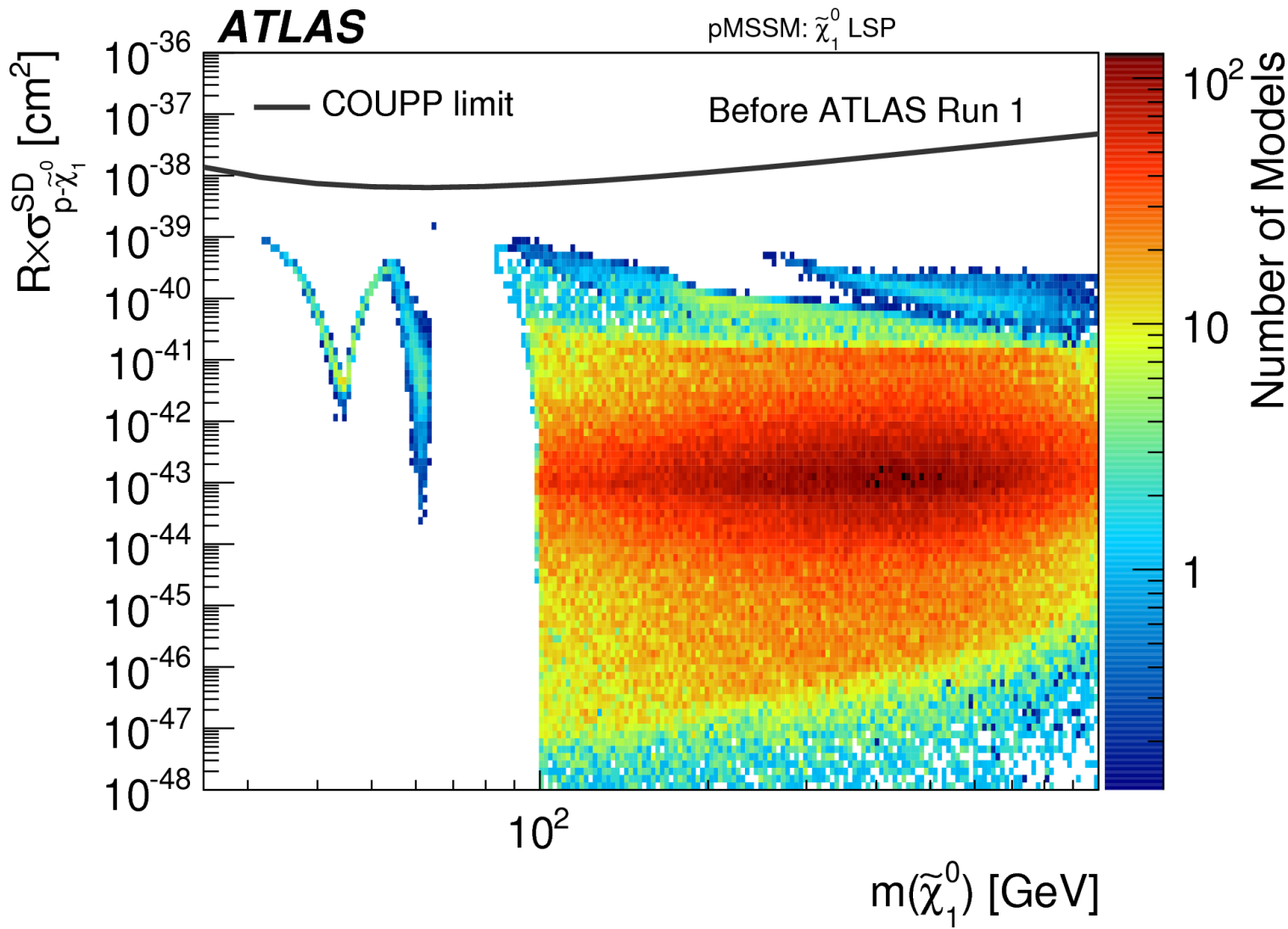
30

For Bino LSP can split sample by dominant LSP annihilation mechanism



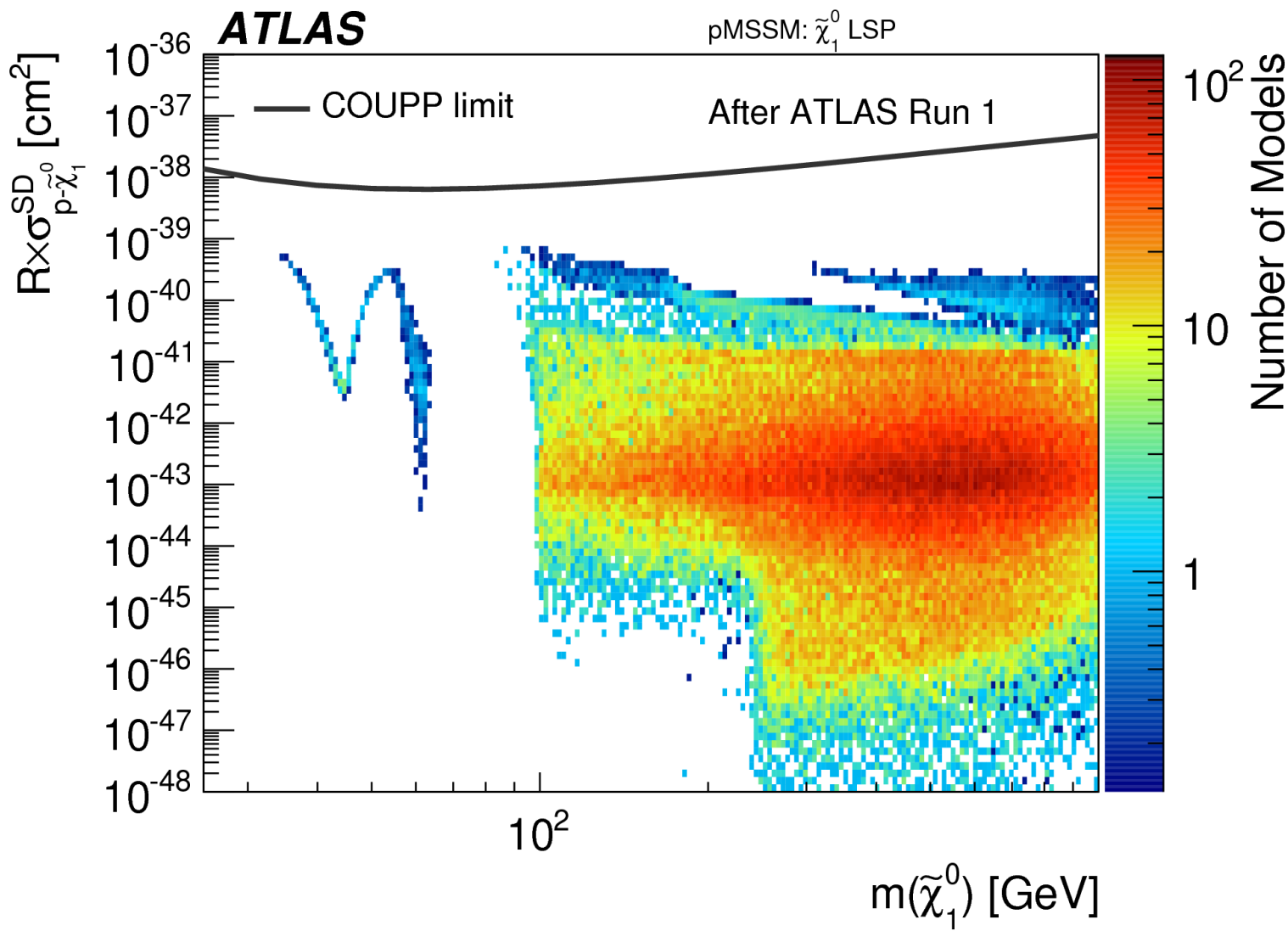
# Spin-dependent DM Cross Section

Limit from COUPP applied in model generation, but had no effect



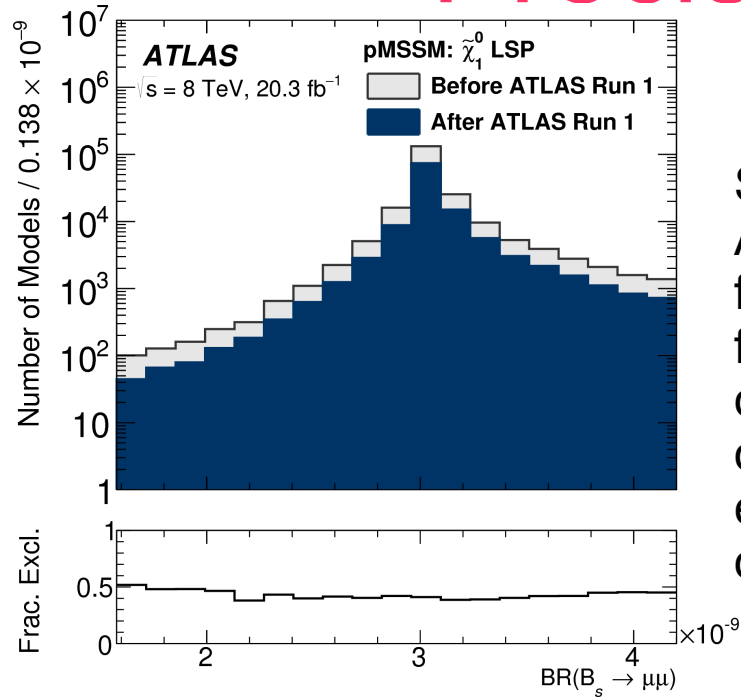
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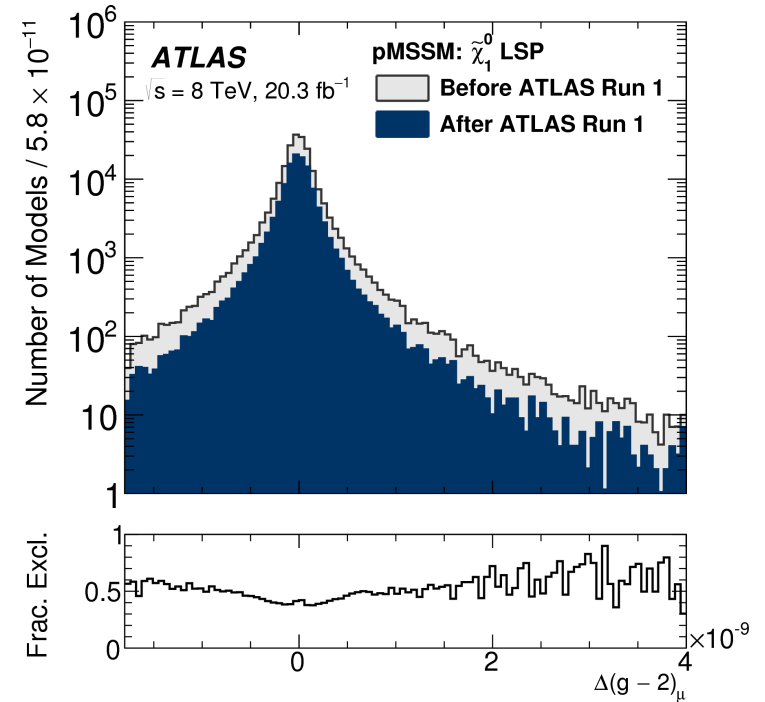
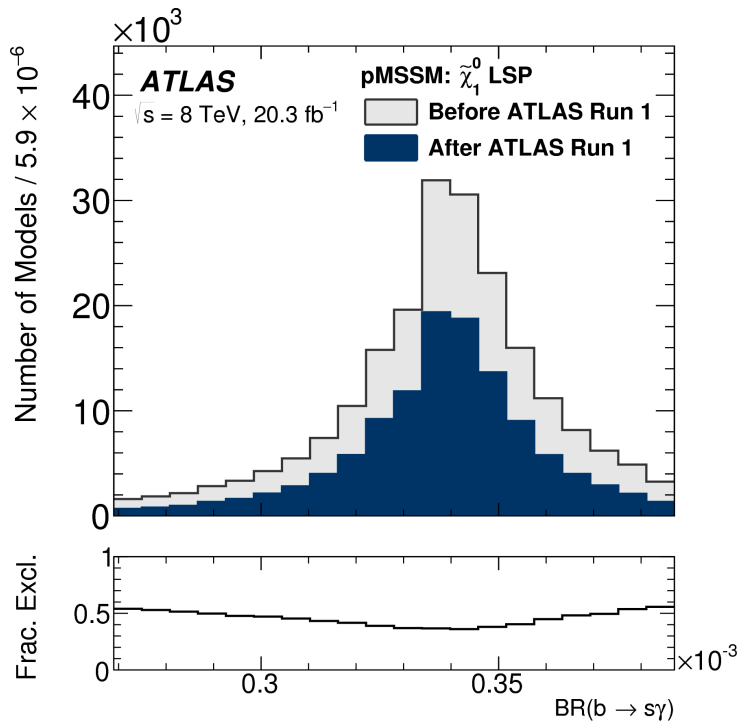
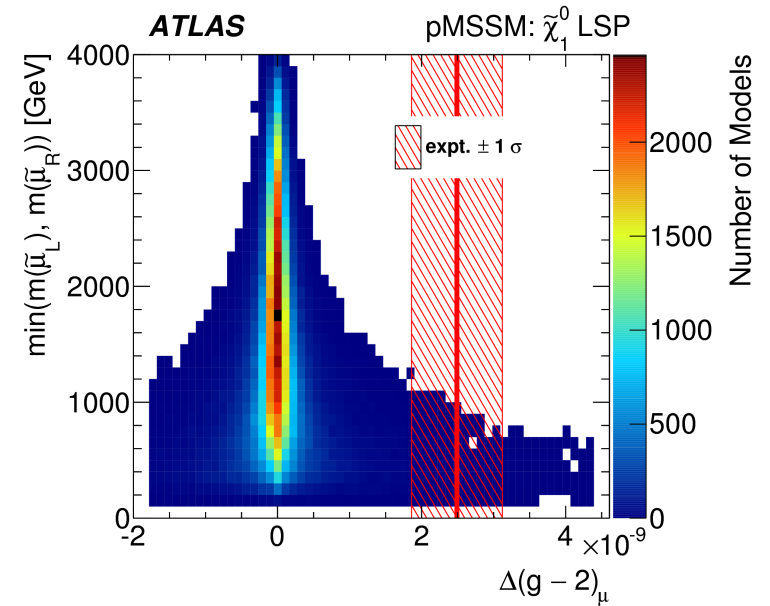




# Precision Observables

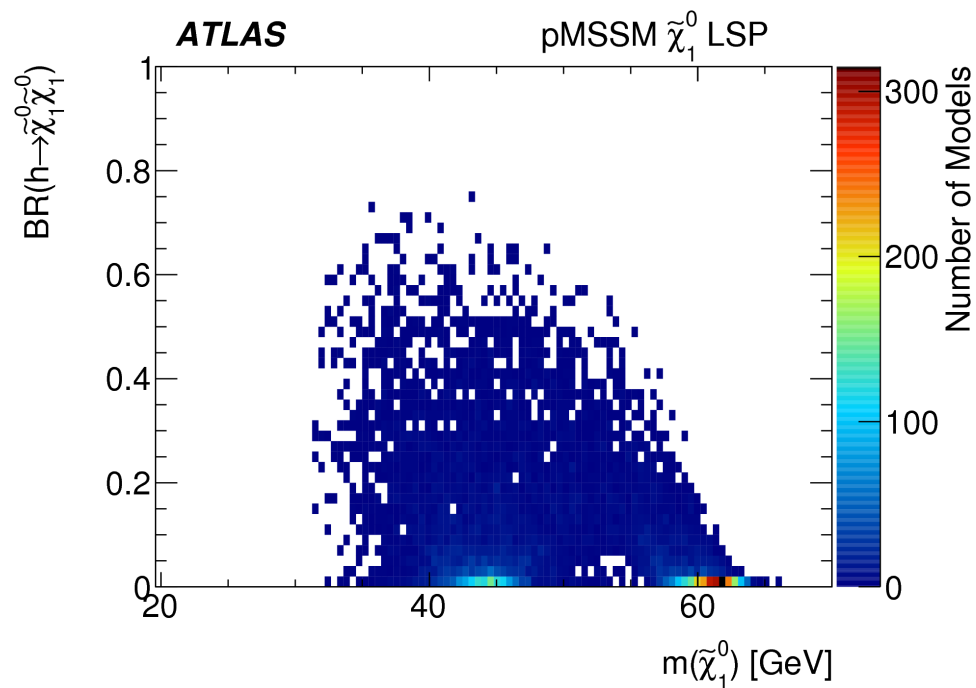


Slightly higher  
ATLAS exclusion  
for models furthest  
from the SM values  
of precision  
observables as that  
enhances presence  
of light sparticles

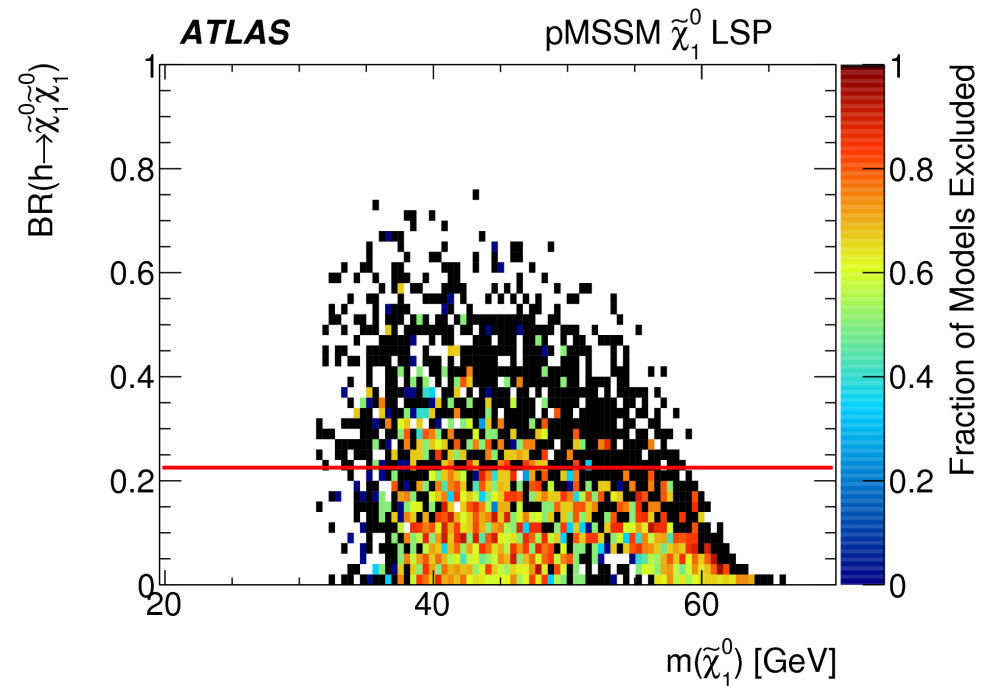


# Invisible Higgs

Models before ATLAS Run-1 Searches



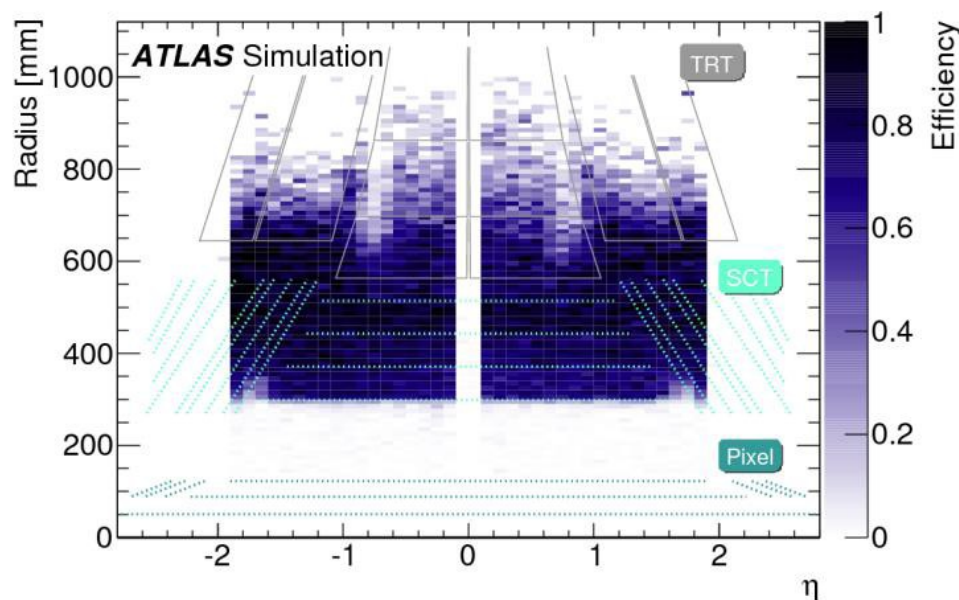
Exclusion by ATLAS Run-1 Searches



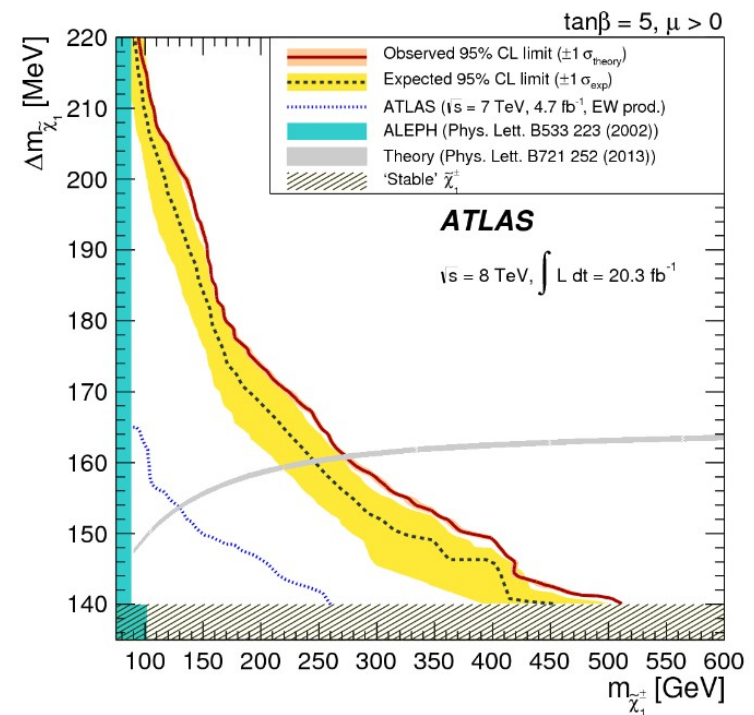
# Disappearing Track Analysis

- Motivated by anomaly-mediated SUSY breaking
- LSP almost pure-wino and mass degenerate with lightest chargino (typical mass splitting is  $\sim 160$  MeV)
- The chargino has a lifetime  $O(ns)$   $\rightarrow$  decay length of a few centimeters
- The chargino leaves a few hit in the tracker, then decay to the LSP and a soft, charged pion, which is not reconstructed
- Appear as “disappearing track” in the tracking system
- Paper: <http://journals.aps.org/prd/abstract/10.1103/PhysRevD.88.112006>

The efficiency for decaying charginos



Exclusion vs masses



# Model Evaluation

- Start with each of the 310,327 model points passing the pre-ATLAS Run 1 constraints
- Check if any production process pass minimum requirement
  - If not, the model is not excluded
- Generate a sample of events
  - Only at particle level
  - Detector inefficiency are estimated
- Expected event yield in each signal region ( $N_{sig}$ ) is calculated, then compare it to the model-independent 95% CL upper bound for the corresponding signal region ( $N_{max}^{95}$ )
  - If  $N_{sig}$  considerably larger than  $N_{max}^{95}$ , the model can't be excluded
  - If  $N_{sig}$  considerably smaller than  $N_{max}^{95}$ , the model is excluded
  - Otherwise, need full detector simulation and do CLs-method
  - The exact threshold depends on the signal region
- Model points with long-lived squarks, gluinos or sleptons with  $c\tau > 1mm$  are treated separately with long-lived search

Production mode	Minimum cross section [fb]	Fraction of models generated		
		Bino LSP	Wino LSP	Higgsino LSP
Strong	0.25	82.5%	74.9%	76.7%
Mixed	0.25	52.6%	42.1%	13.9%
Electroweak	7.5	38.3%	72.5%	75.0%
Slepton pair	0.75	9.6%	7.9%	9.5%

# Higgs Mass Dependence

No dependence  
in exclusion  
fraction on Higgs mass

