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

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On behalf of the ATLAS Collaboration

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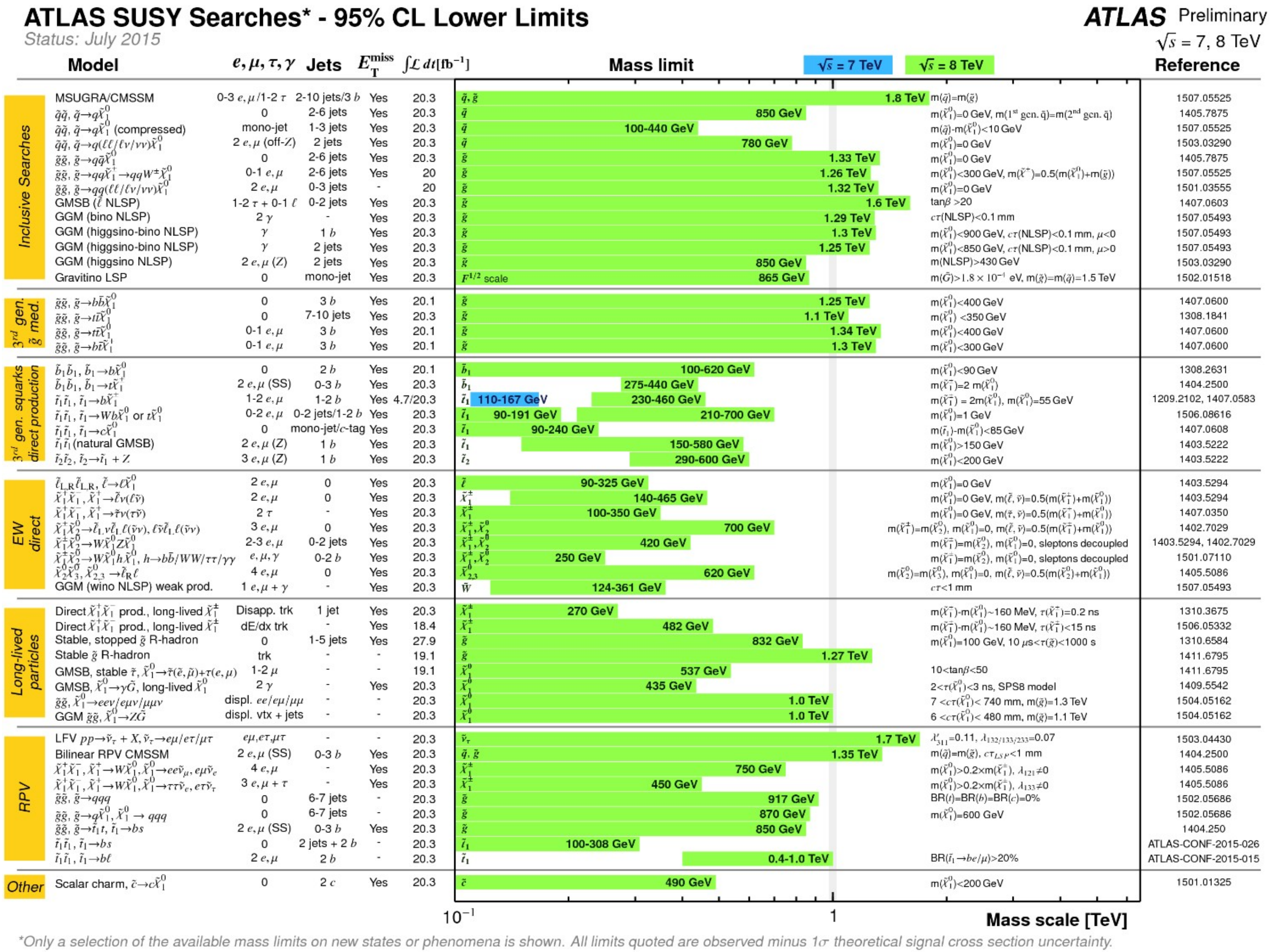
Submitted to JHEP

Introduction

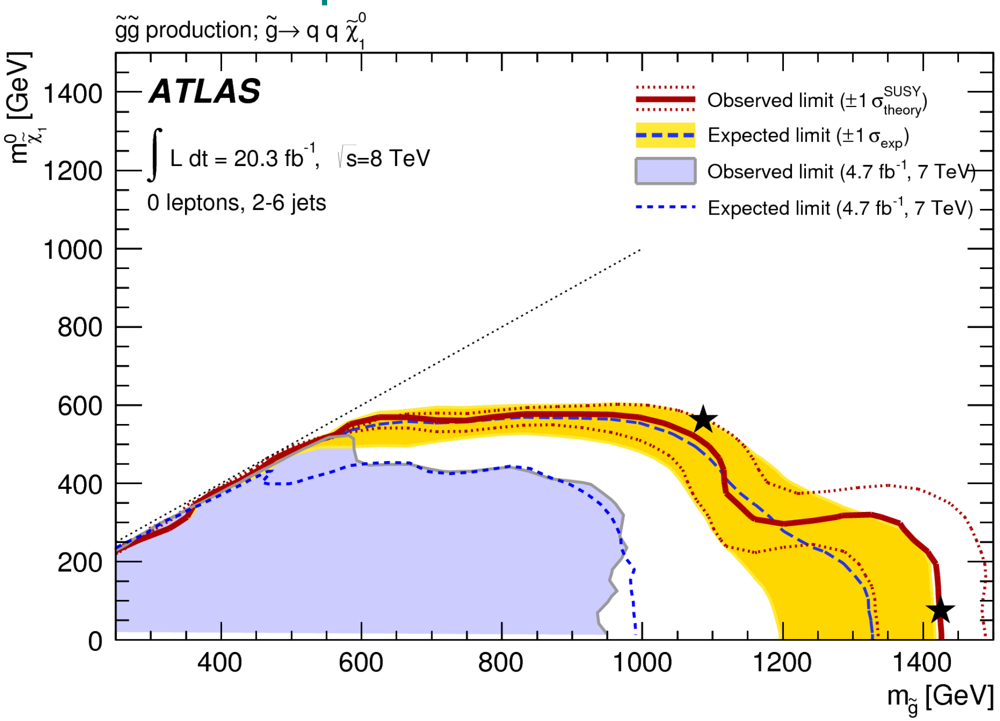
ATLAS has wide range of SUSY search results from Run-1



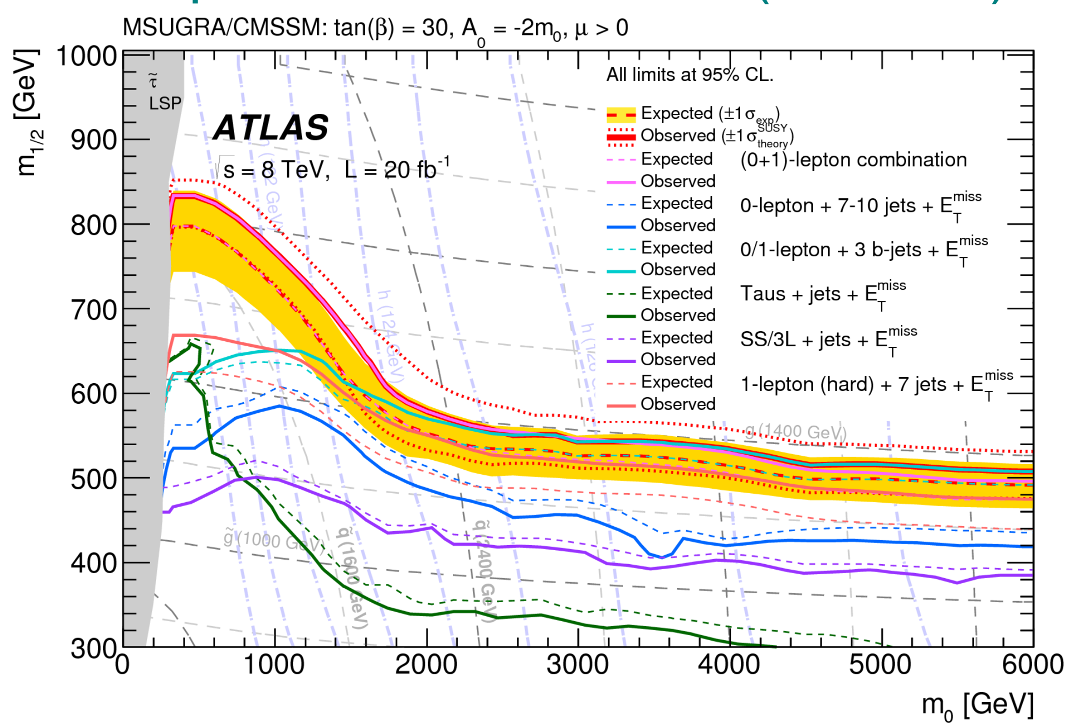
Introduction

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 1st and 2nd 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
$\lvert M_1\rvert$	0 GeV	4 TeV
$\lvert M_2\rvert$	70 GeV	4 TeV
$\lvert\mu\rvert$	80 GeV	4 TeV
M_3	200 GeV	4 TeV
$\lvert A_t\rvert$	0 GeV	8 TeV
$\lvert A_b\rvert$	0 GeV	4 TeV
$\lvert A_\tau\rvert$	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
$\Delta(g-2)_\mu$	-17.7×10^{-10}	43.8×10^{-10}
$\mathrm{BR}(b \to s\gamma)$	2.69×10^{-4}	3.87×10^{-4}
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	1.6×10^{-9}	4.2×10^{-9}
$\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$	66×10^{-6}	161×10^{-6}
$\Omega_{\tilde{\chi}^0_1} h^2$	—	0.1208
$\Gamma_{\mathrm{invisible(SUSY)}}(Z)$	—	2 MeV
Masses of charged sparticles	100 GeV	—
$m(\tilde{\chi}^\pm_1)$	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^{miss}
	0-lepton + 7–10 jets + E_T^{miss}
	1-lepton + jets + E_T^{miss}
	$\tau(\tau/\ell)$ + jets + E_T^{miss}
	SS/3-leptons + jets + E_T^{miss}
	0/1-lepton + 3b-jets + E_T^{miss}
	Monojet
3rd gen. searches	0-lepton stop
	1-lepton stop
	2-leptons stop
	Monojet stop
	Stop with Z boson
	2b-jets + E_T^{miss}
	tb+E_T^{miss}, stop
EW searches	ℓh
	2-leptons
	2-τ
	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

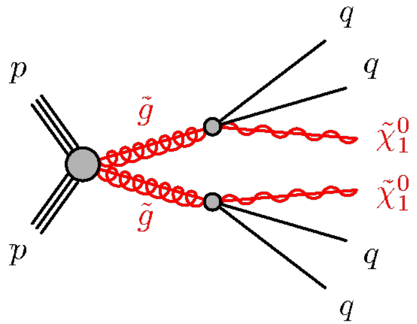
Results – Gluinos

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

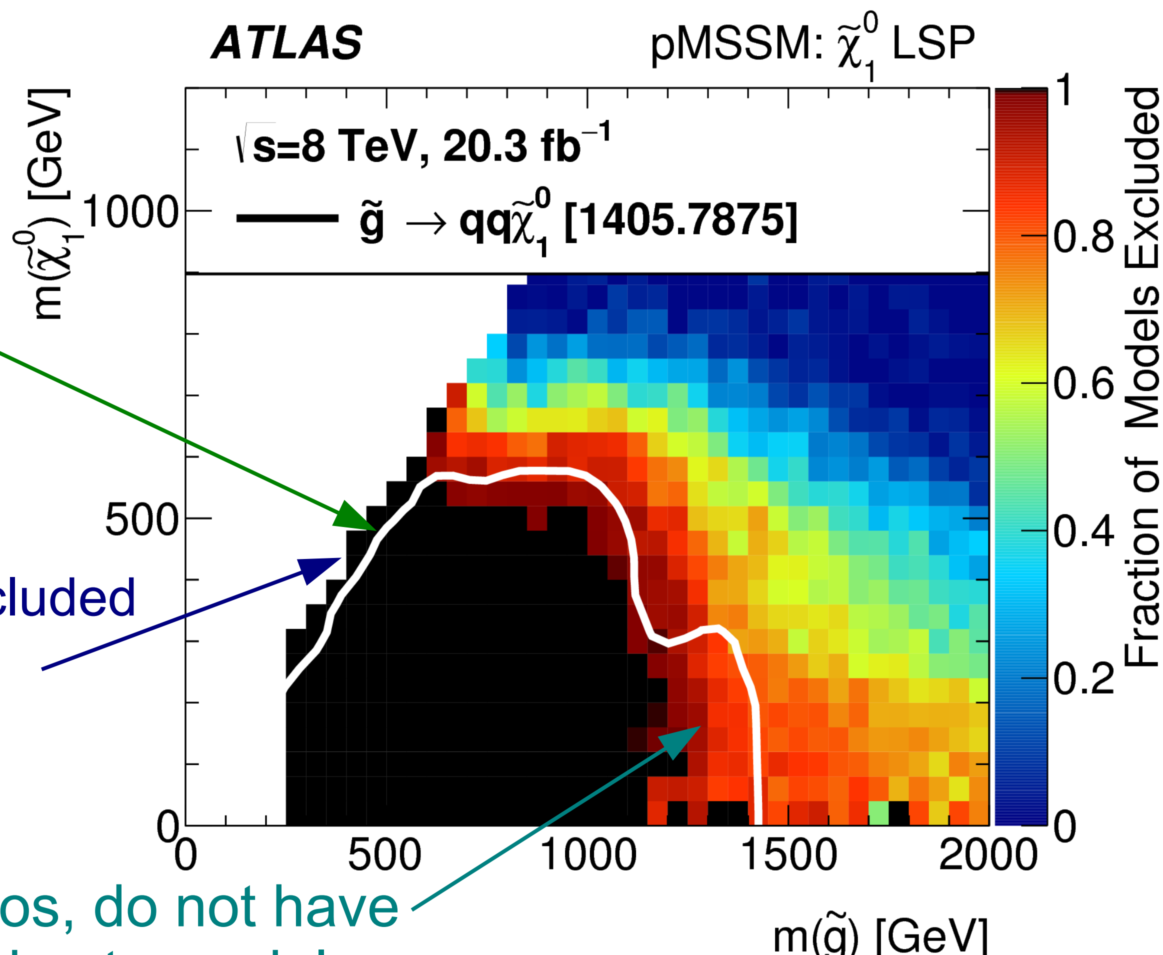
- Black means 100% excluded – white is no models generated

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^{miss} analysis



Diagonal excluded by mono-jet analysis

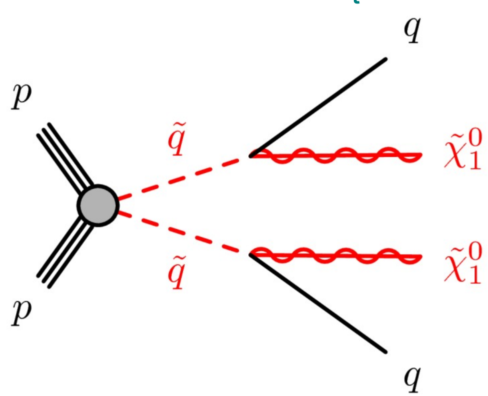


For heavier gluinos, do not have 100% exclusion due to models with intermediate sparticles

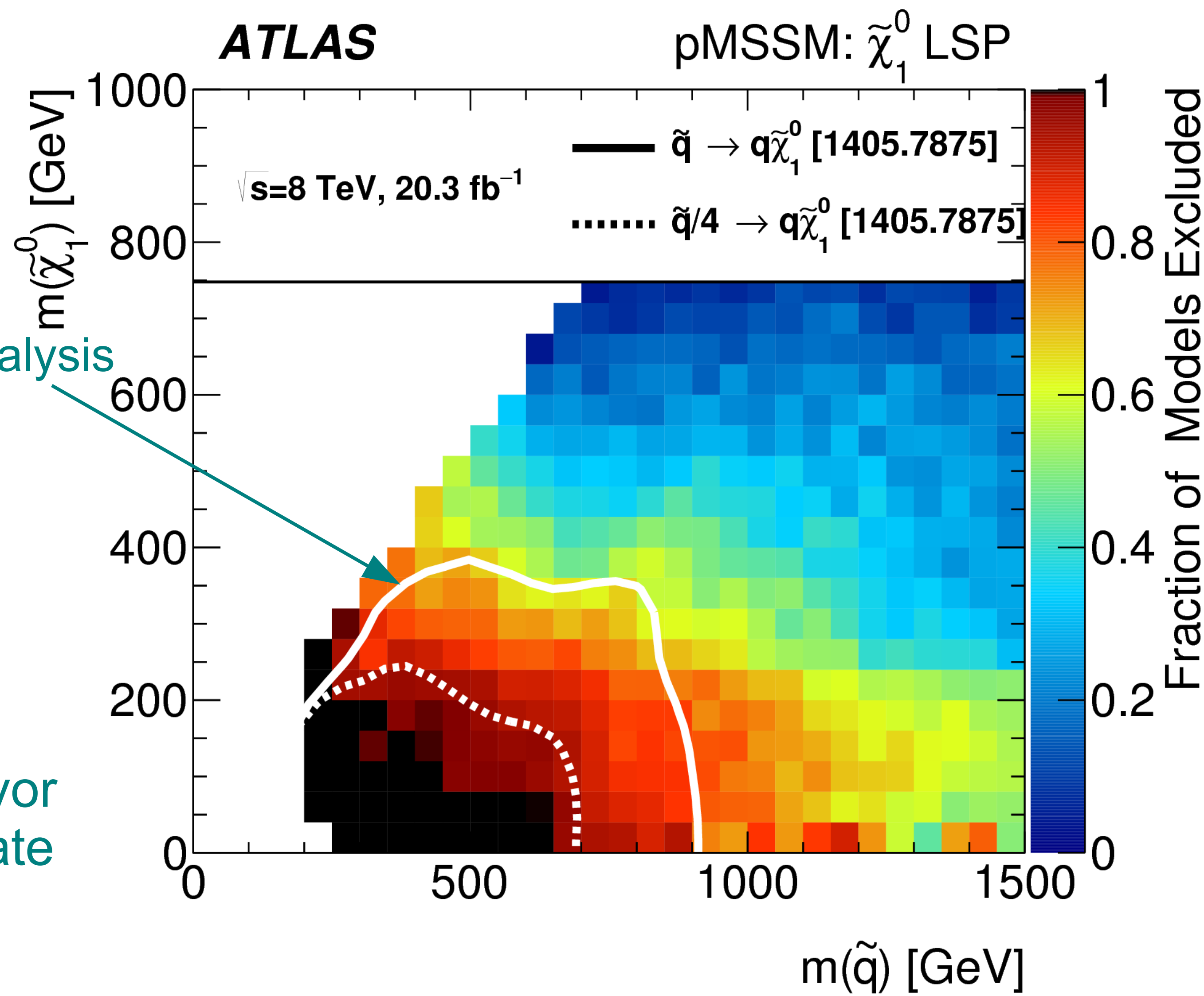
Light-flavor Squarks

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^{miss} analysis



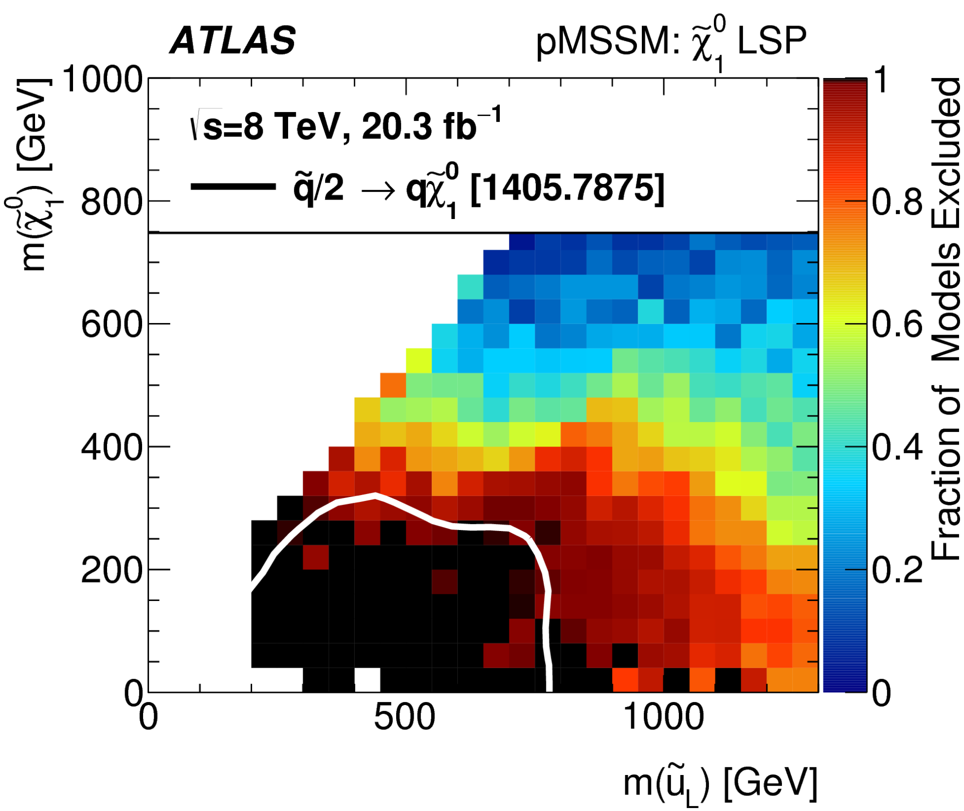
Due to not all 8 light-flavor squarks being degenerate in the pMSSM



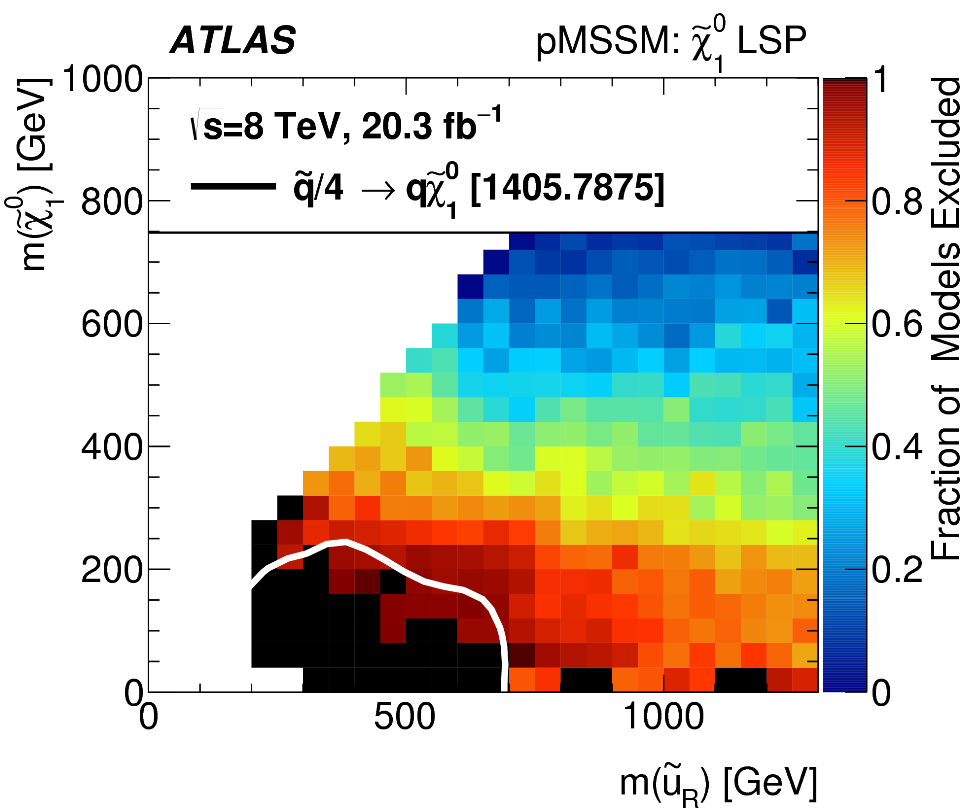
Left/Right-handed Squarks

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

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



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

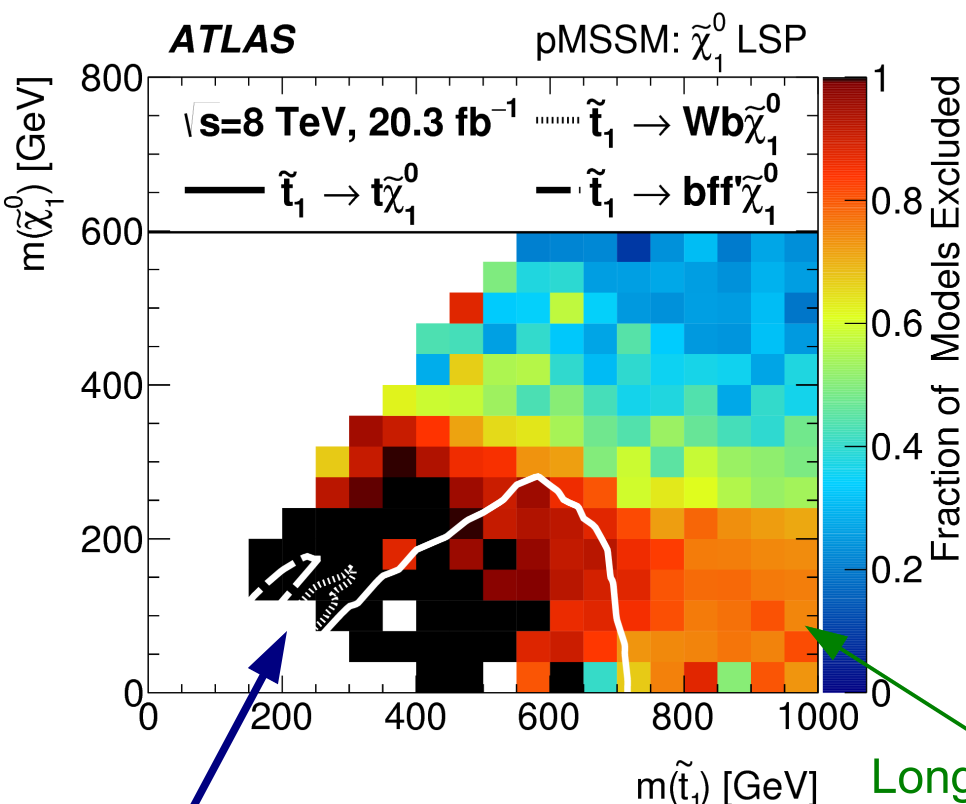


Similar plot for $m(\tilde{d}_R) \sim m(\tilde{s}_R)$

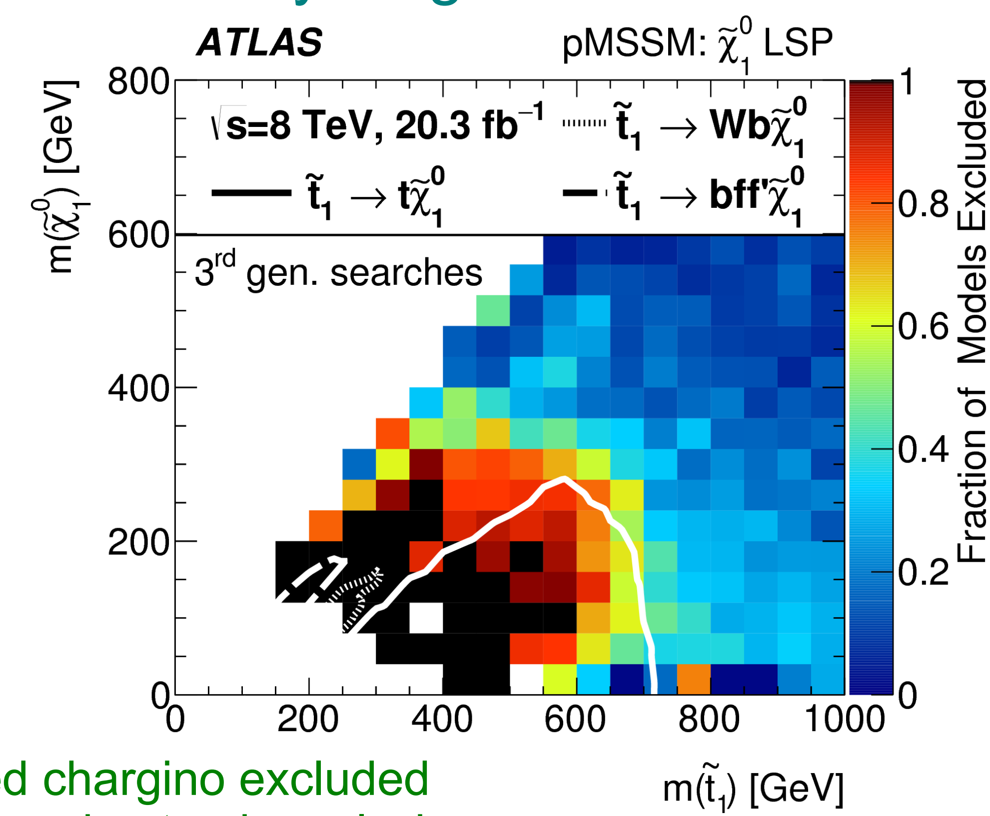
3rd Generation Squarks – stop

Good exclusion reach for light stop
– sensitivity mostly from the dedicated 3rd generation searches
Simplified model with 100% BR for $\tilde{t}\rightarrow t\tilde{\chi}_1^0$ overestimates mass reach

All searches



Only 3rd gen. searches

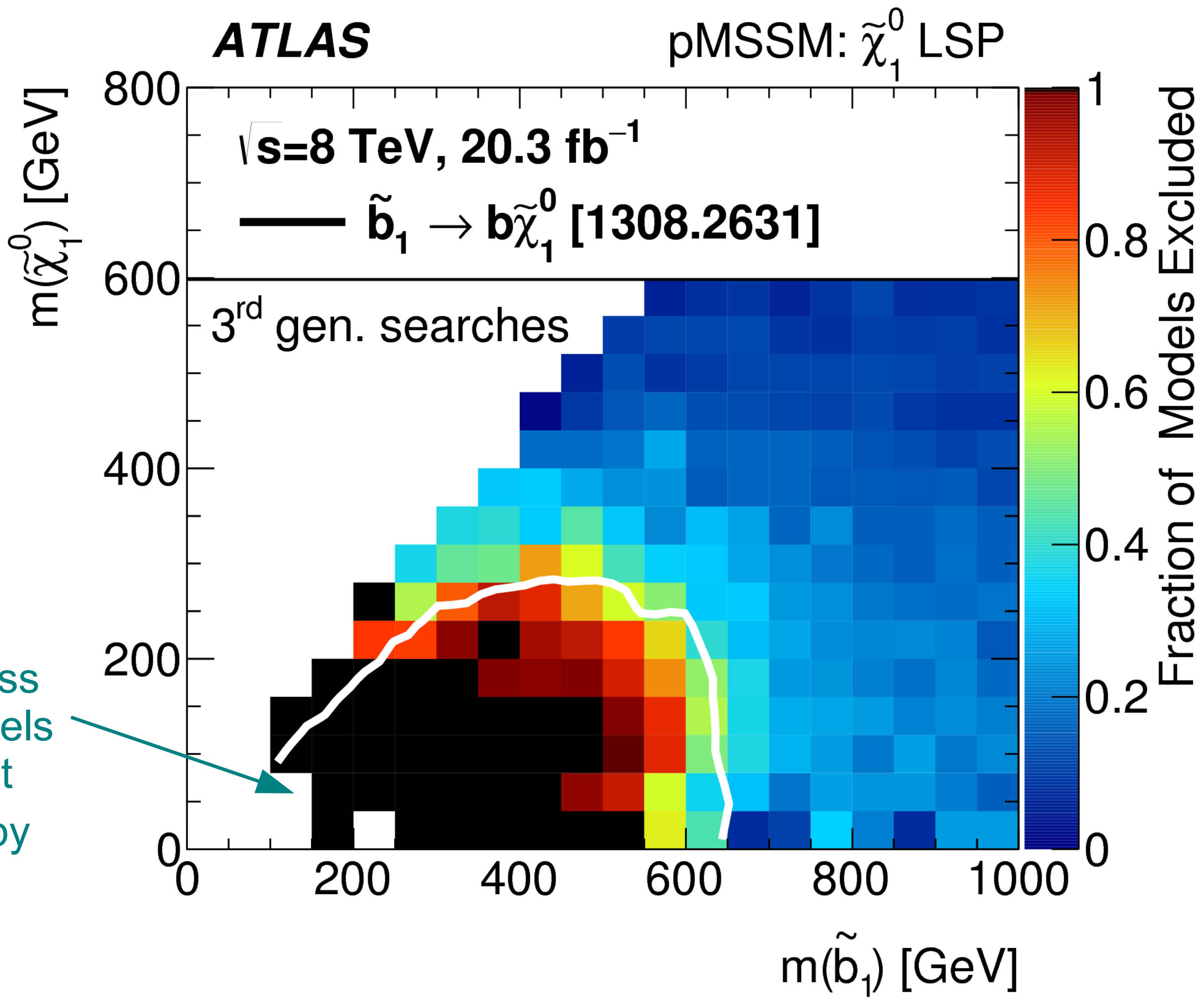


Long-lived chargino excluded by disappearing track analysis

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

3^{rd} Generation Squarks - sbottom

Similar conclusions for the sensitivity to sbottom production

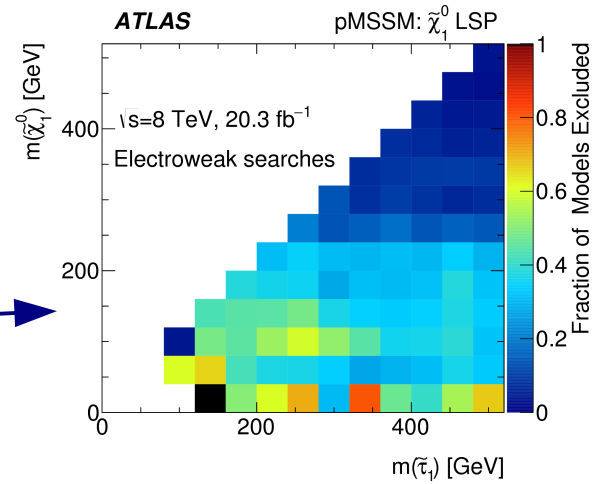


More low mass sbottom models as light $\tilde{b}_R$ not suppressed by Higgs mass constraint

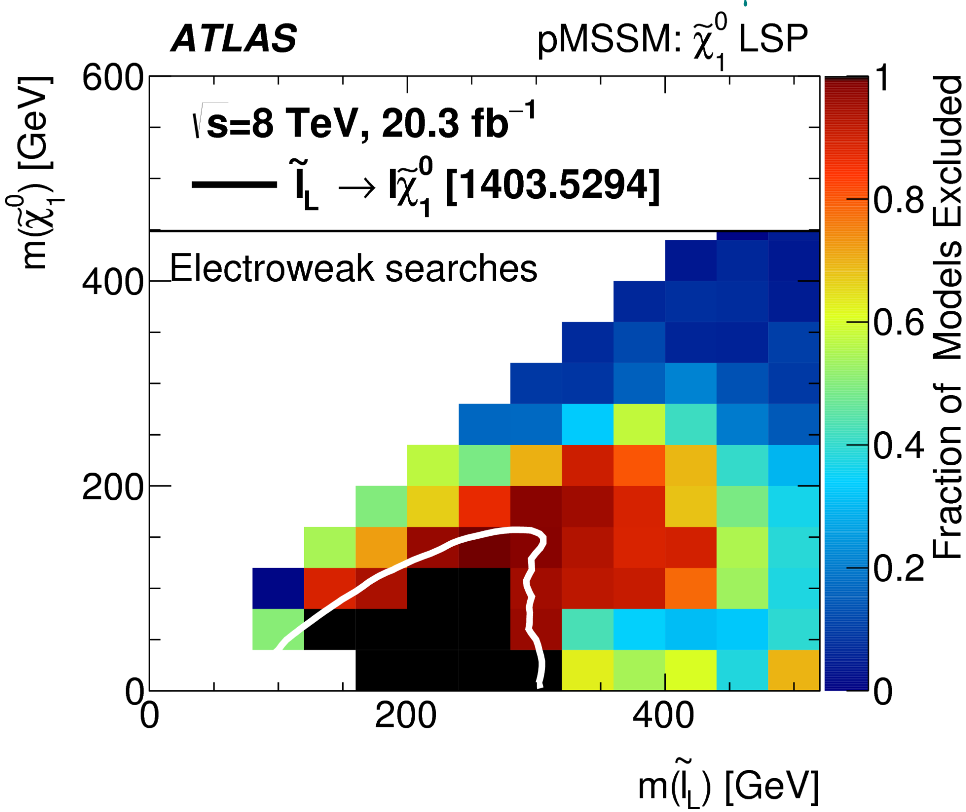
EW Production - Sleptons

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

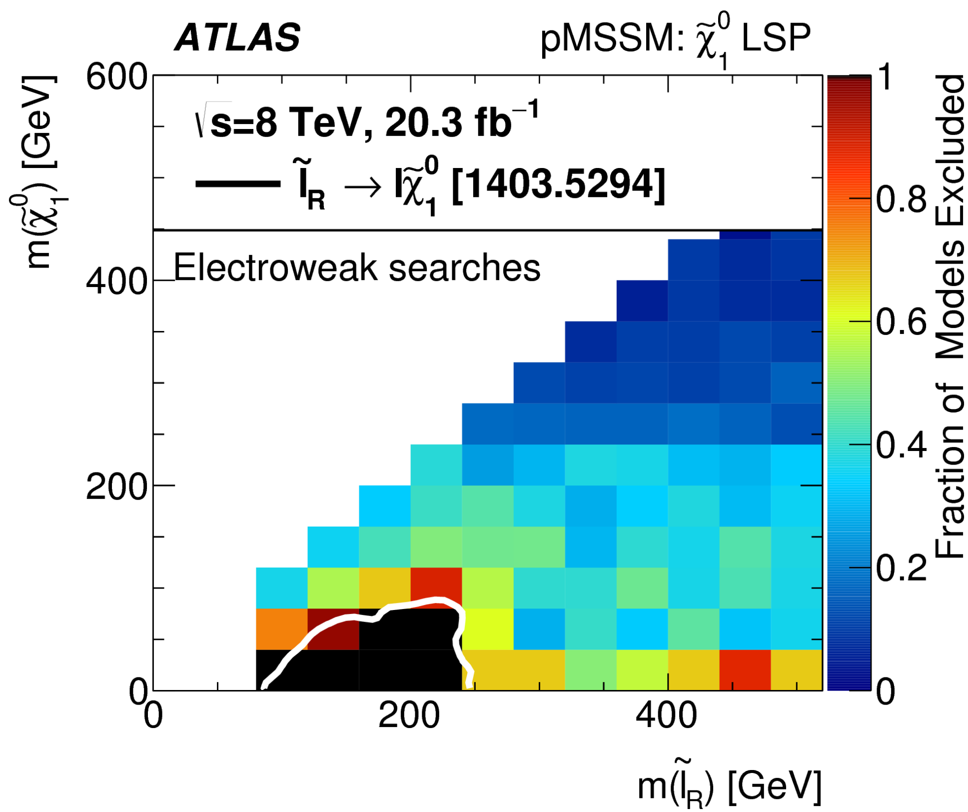
Sensitivity to staus still rather limited due to the larger backgrounds



$m(\tilde{e}_L)\sim m(\tilde{\nu}_{eL})\sim m(\tilde{\mu}_L)\sim m(\tilde{\nu}_{\mu L})$



$m(\tilde{e}_R)\sim m(\tilde{\mu}_R)$



Exclusion Strength per Analysis

Can also compare strength of different analysis for these pMSSM models

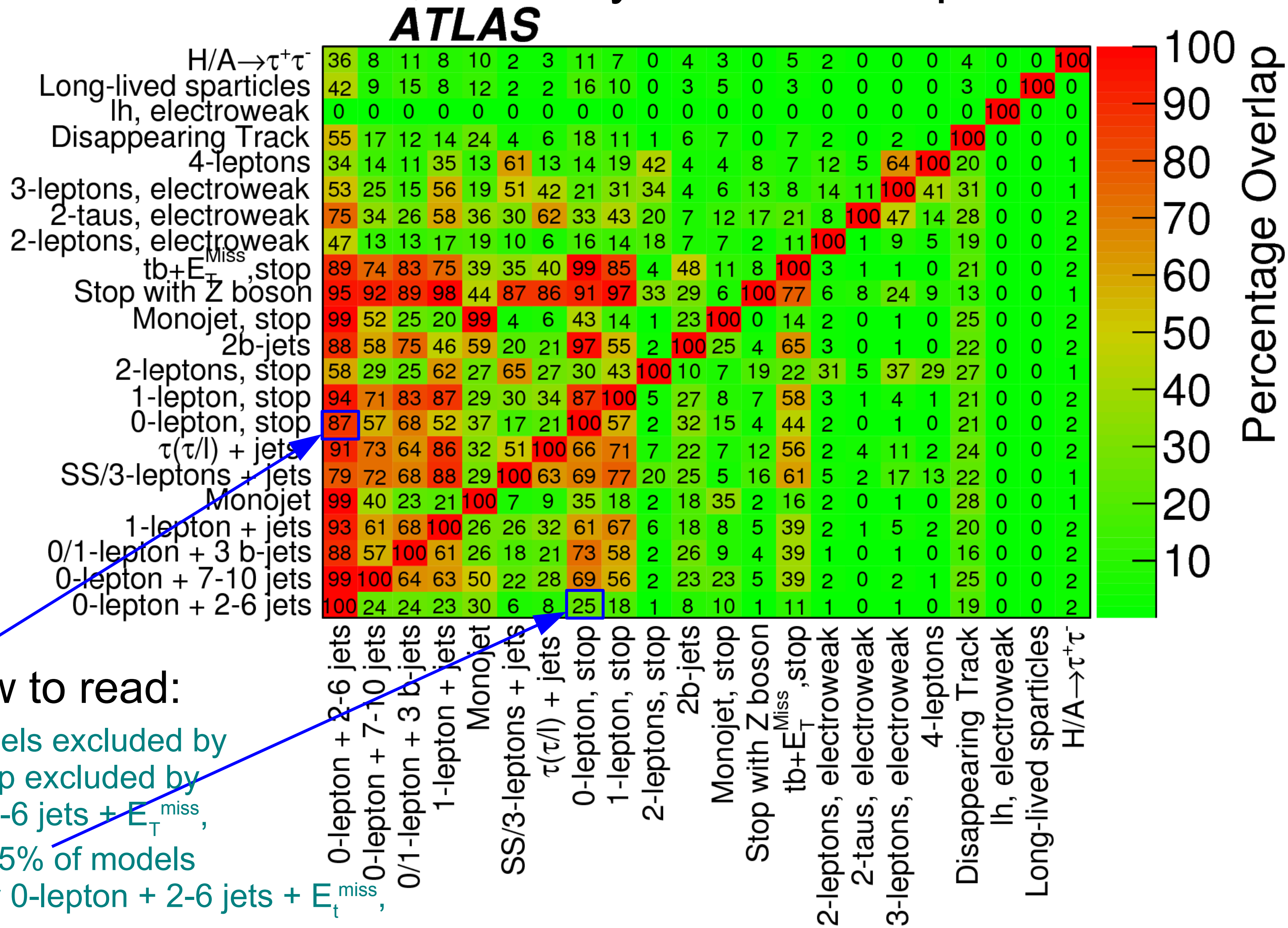
Absolute fractions very dependent on pMSSM scan range, but gives idea of relative sensitivity

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^{miss}	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + E_T^{miss}	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + E_T^{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^{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%
$tb+E_T^{miss}$, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, 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%
$H/A \to \tau^+\tau^-$	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



How to read:

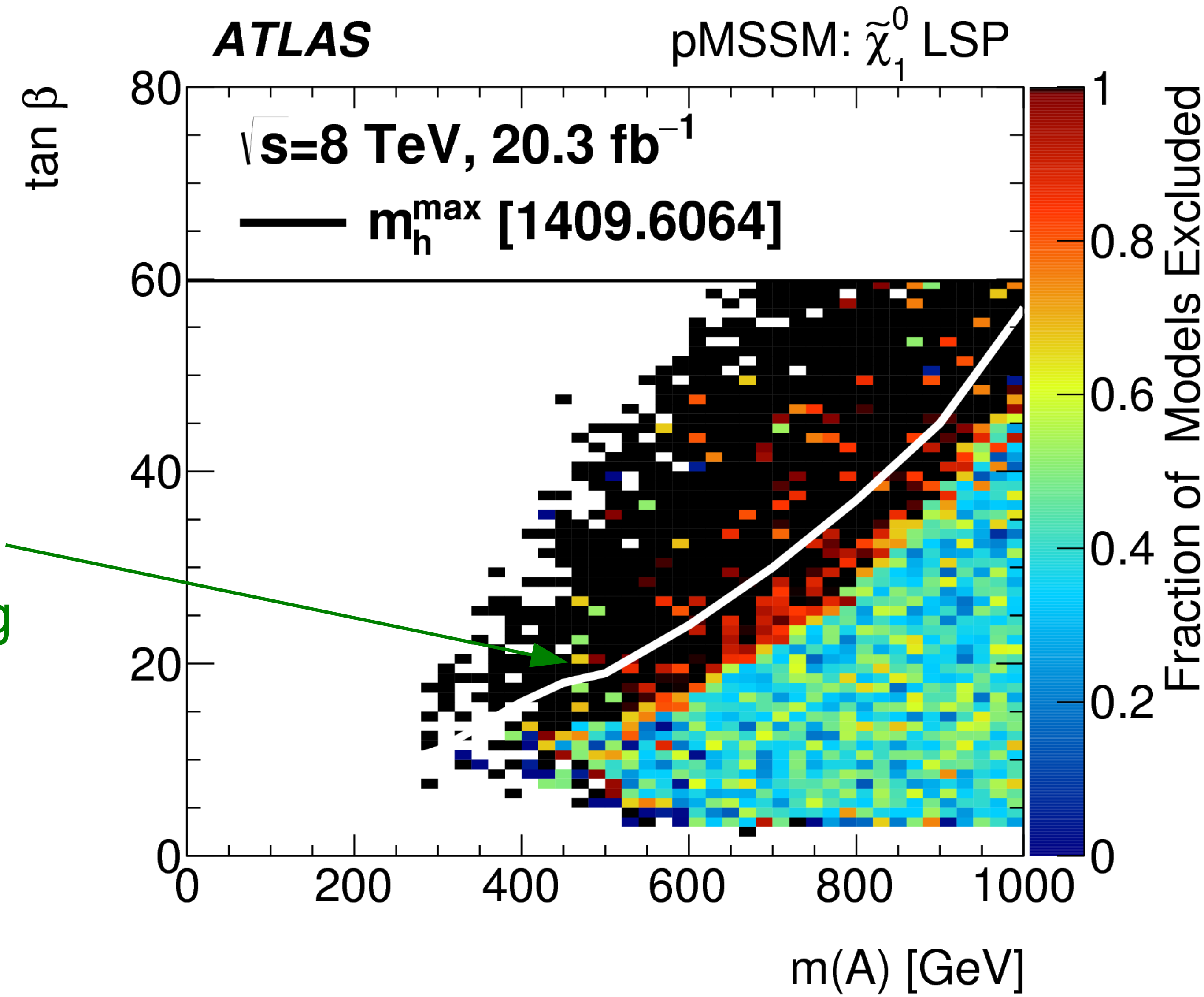
87% of models excluded by 0-lepton,stop excluded by 0-lepton + 2-6 jets + E_T^{miss}, while only 25% of models excluded by 0-lepton + 2-6 jets + E_t^{miss}, are excluded by 0-lepton stop

Heavy Higgs Partner Search

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

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

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

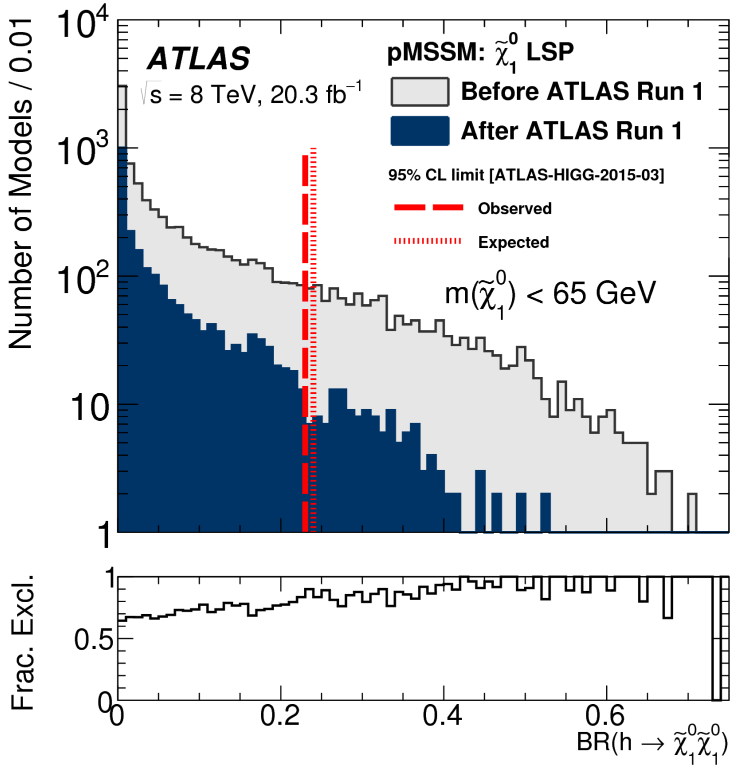


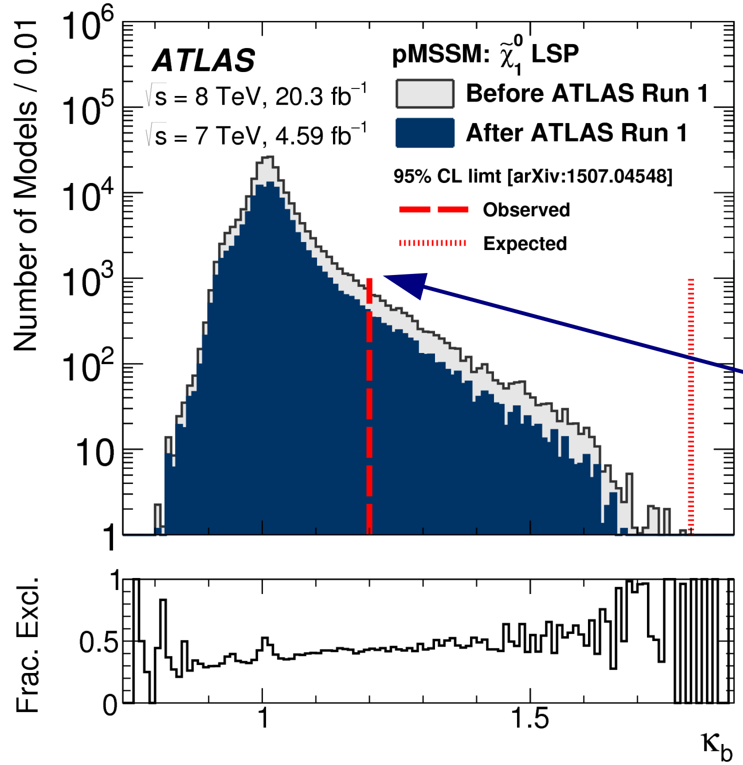
Other Higgs Measurements

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 BF$(h\rightarrow\tilde{\chi}_1^0\tilde{\chi}_1^0)<0.23$ measurement (arXiv:1509.00672)

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





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

κ_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)

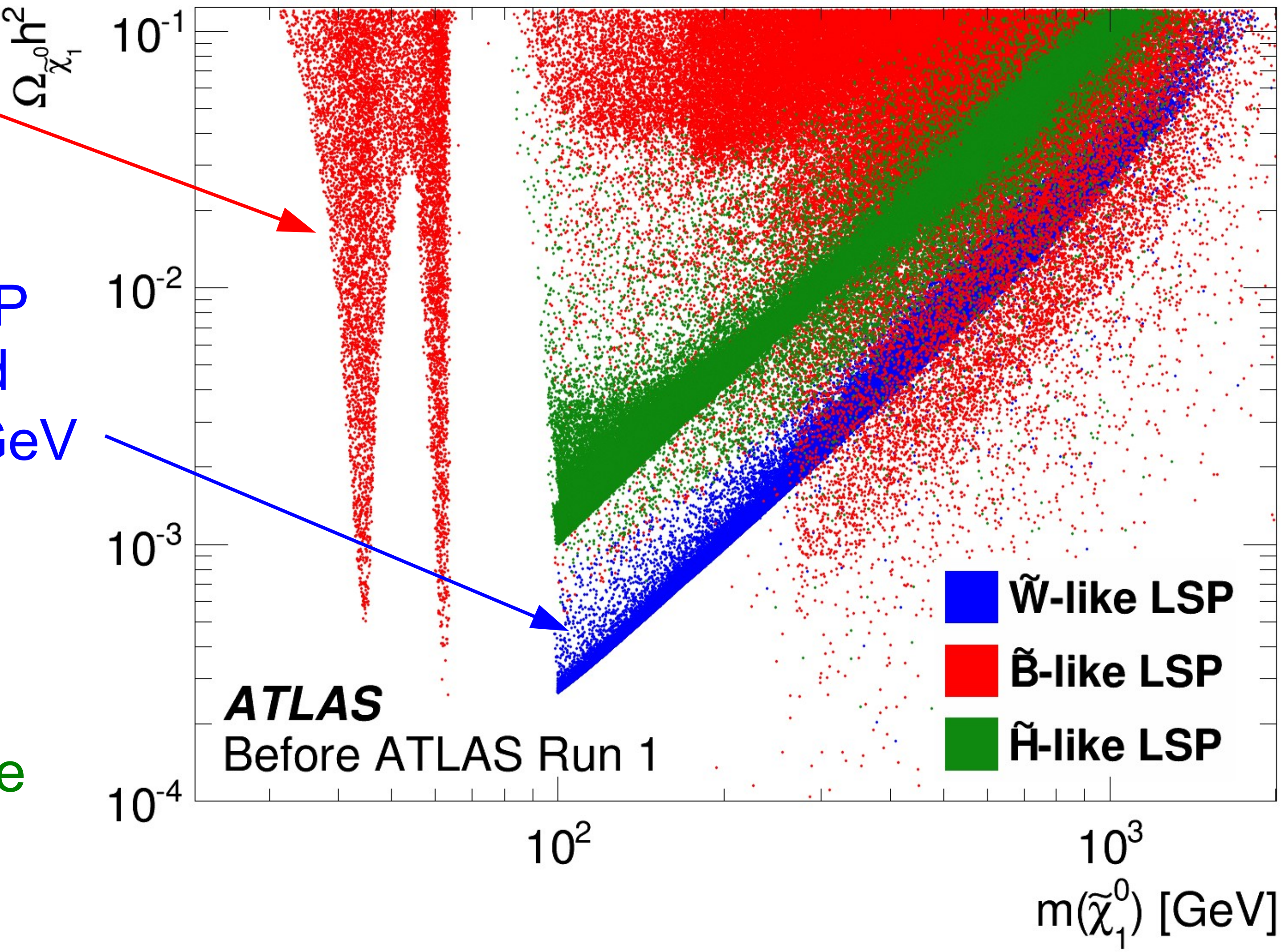
Dark Matter Relic Abundance

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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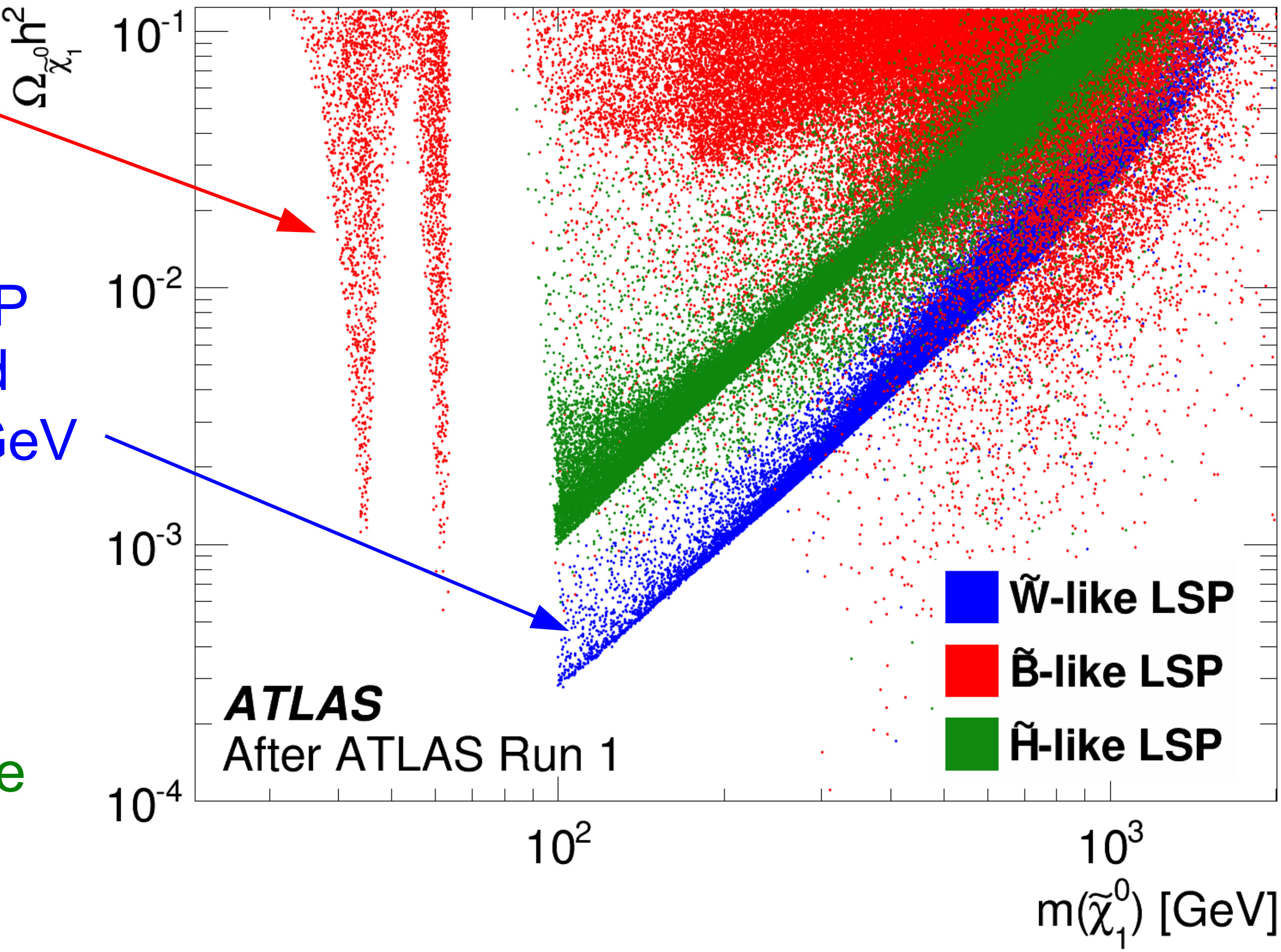
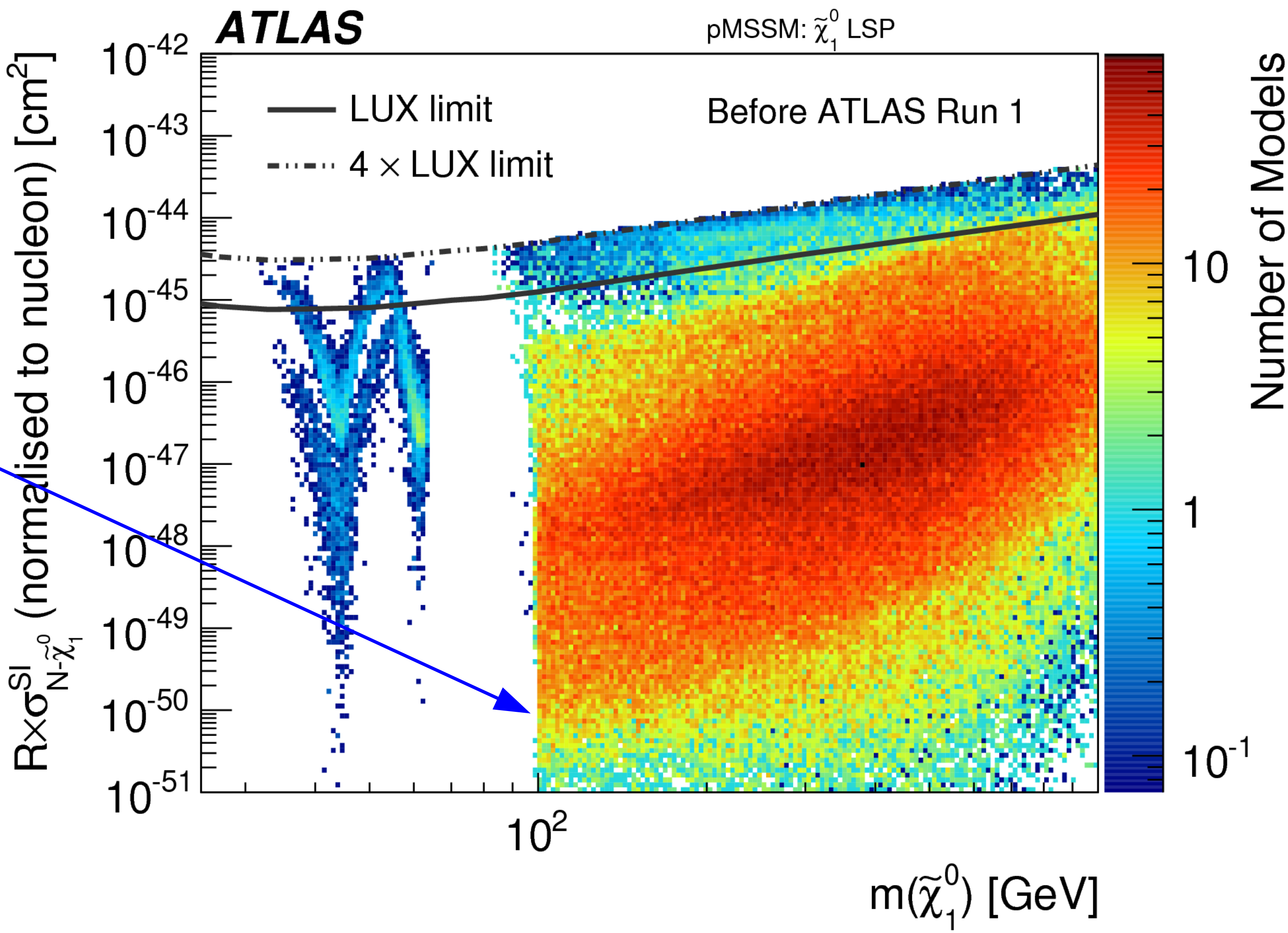


Dark Matter Interaction Cross Section

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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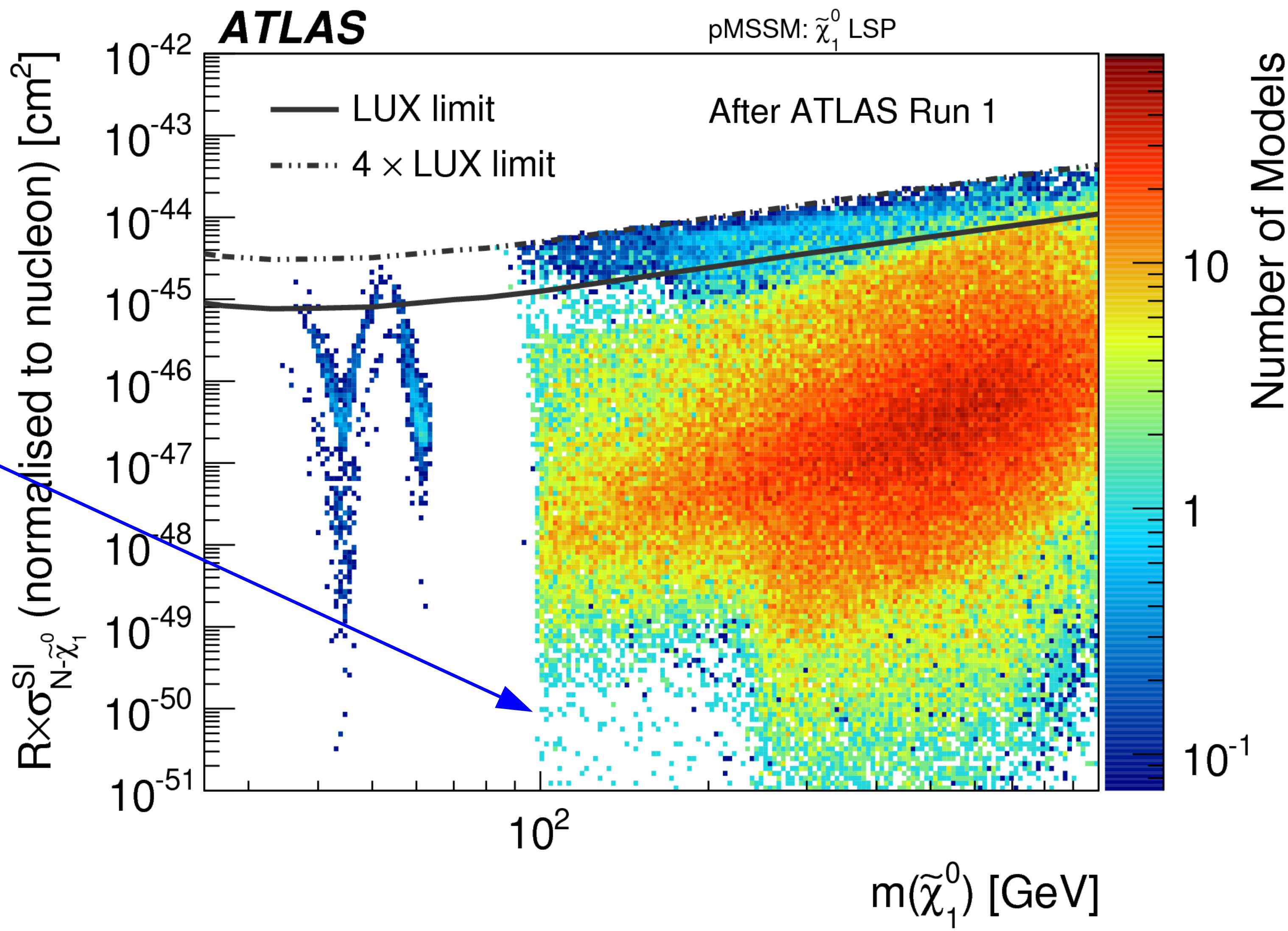


Fine-tuning

No fine-tuning requirement applied during model selection

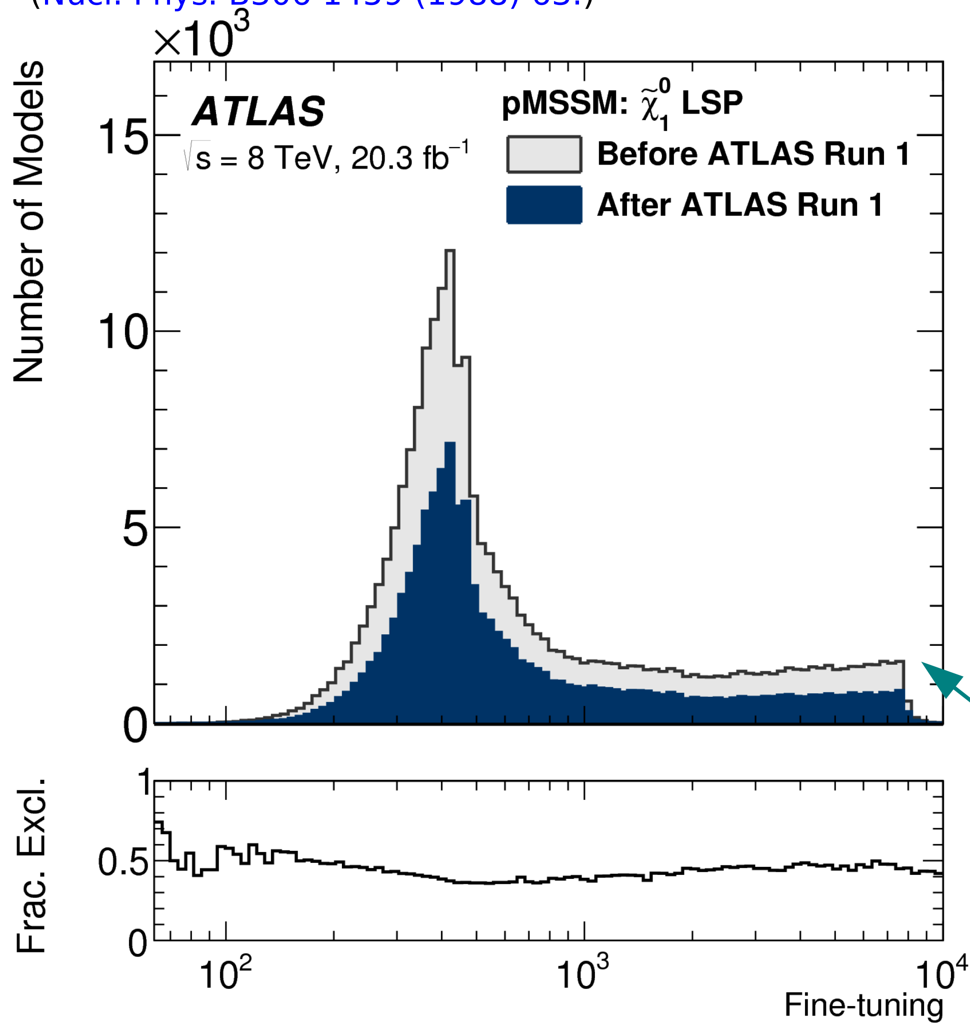
Little dependence on fine-tuning seen in the ATLAS exclusion

– mostly driven by μ and A_t in the pMSSM models

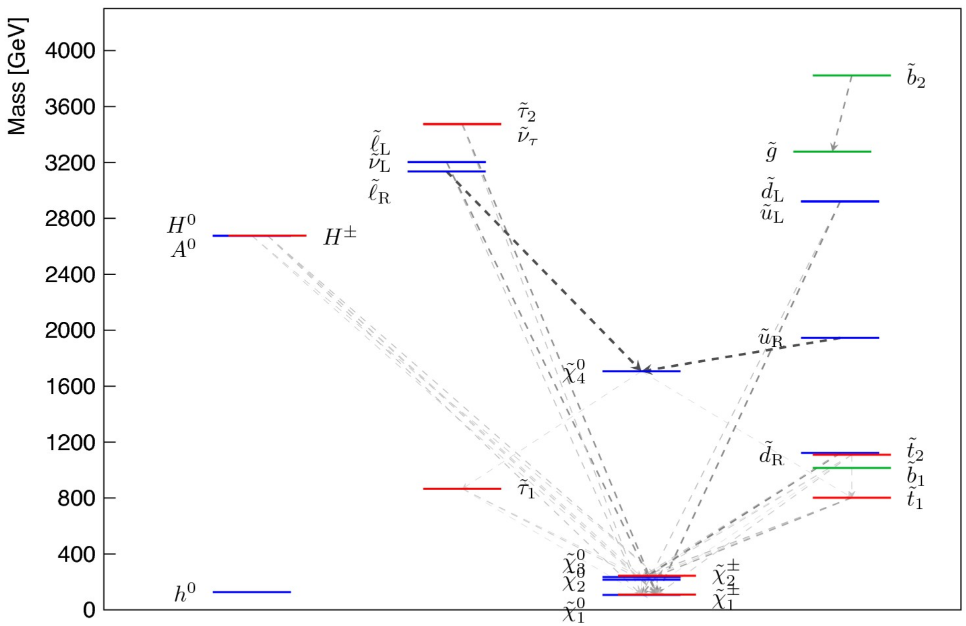
Fine-tuning

(Barbieri and Giudic measure)

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



Model with lowest fine-tuning (O(2%))

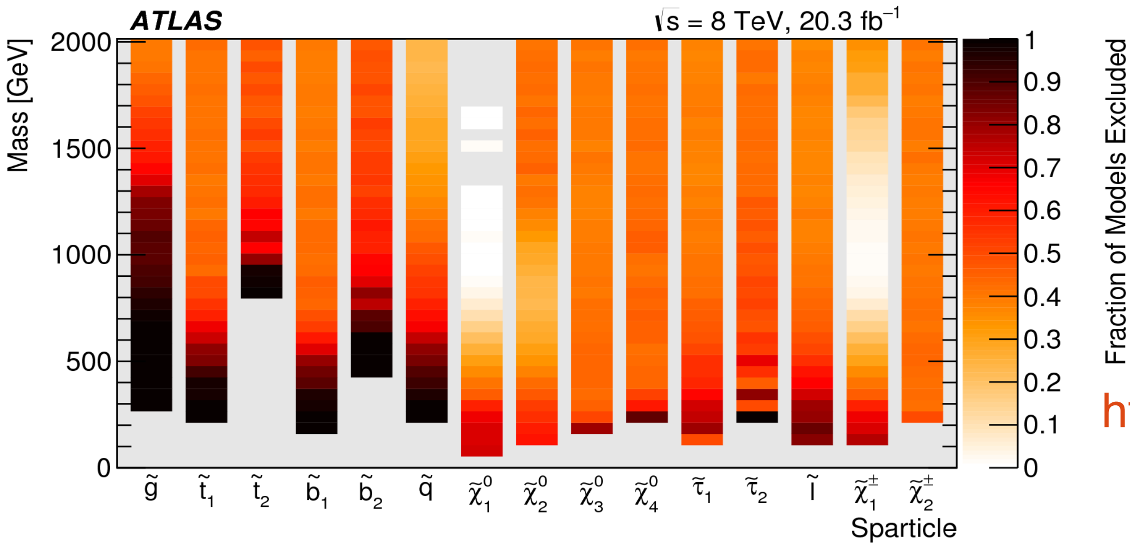


Upper bound due to upper bounds in the generated parameters

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

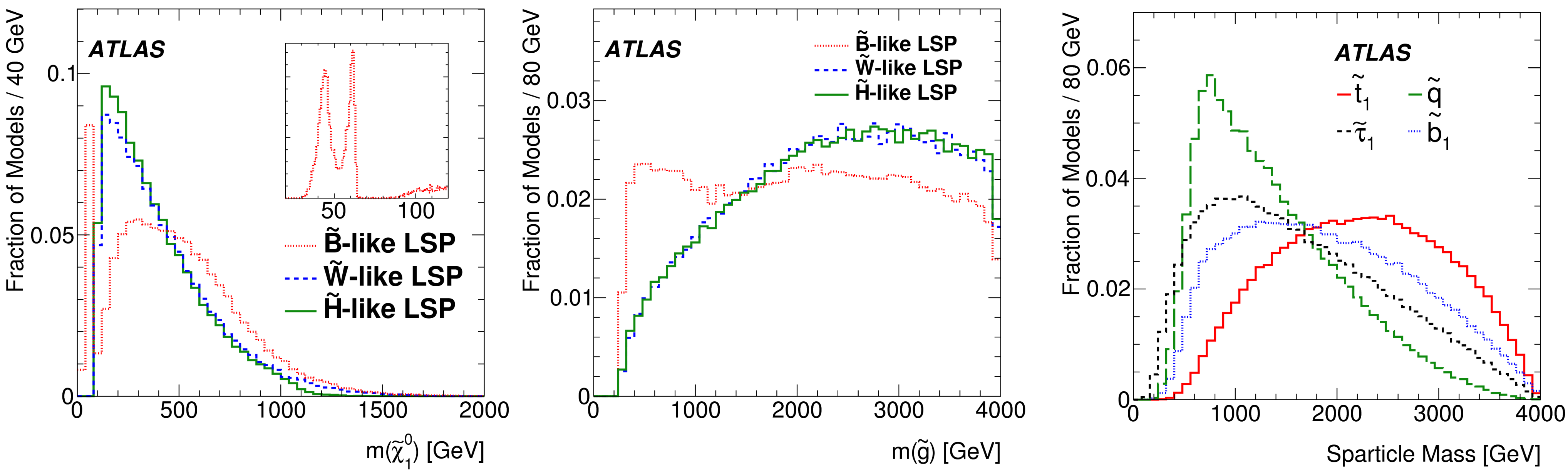
To ensure good precision, models with Bino LSP oversampled by a factor 24 – weighted by 1/24 in the combined plots

LSP type	Definition	Sampled	Simulated Number	Simulated Fraction	Weight
'Bino-like'	$N_{11}^2 > \max(N_{12}^2, N_{13}^2 + N_{14}^2)$	480×10^6	103,410	35%	1/24
'Wino-like'	$N_{12}^2 > \max(N_{11}^2, N_{13}^2 + N_{14}^2)$	20×10^6 (Wino-like and Higgsino-like combined)	80,233	26%	1
'Higgsino-like'	$(N_{13}^2 + N_{14}^2) > \max(N_{11}^2, N_{12}^2)$		126,684	39%	1
Total		500×10^6	310,327		

N_{ij} is neutralino mixing matrix

Sparticle Distribution

Distributions before applying ATLAS Run-1 searches

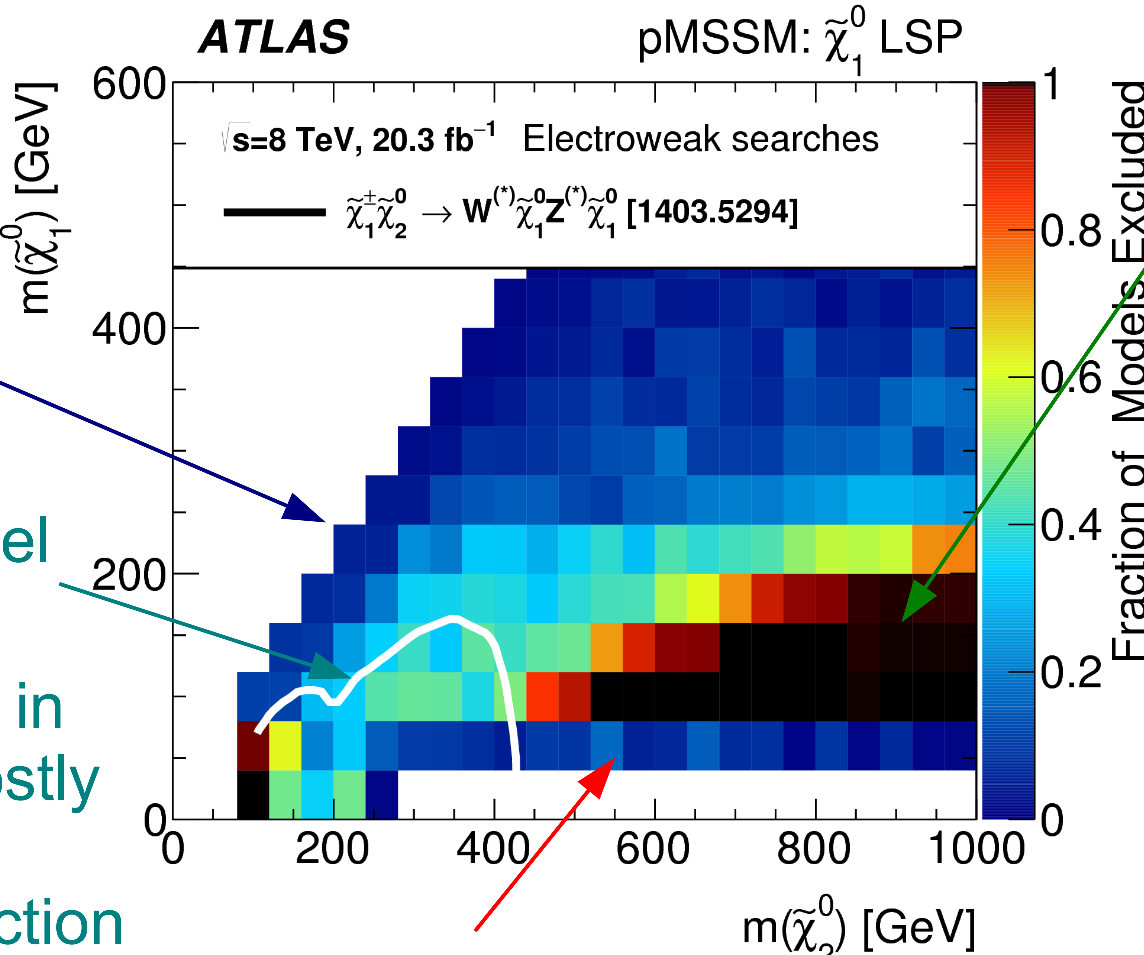


EW Production – Electroweakinos

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

Diagonal dominated by Higgsino-like LSP – poorly excluded

Simplified model assumes $\tilde{\chi}_2^0$ is pure Wino, but in our models mostly Higgsino with lower cross section and thus worse exclusion

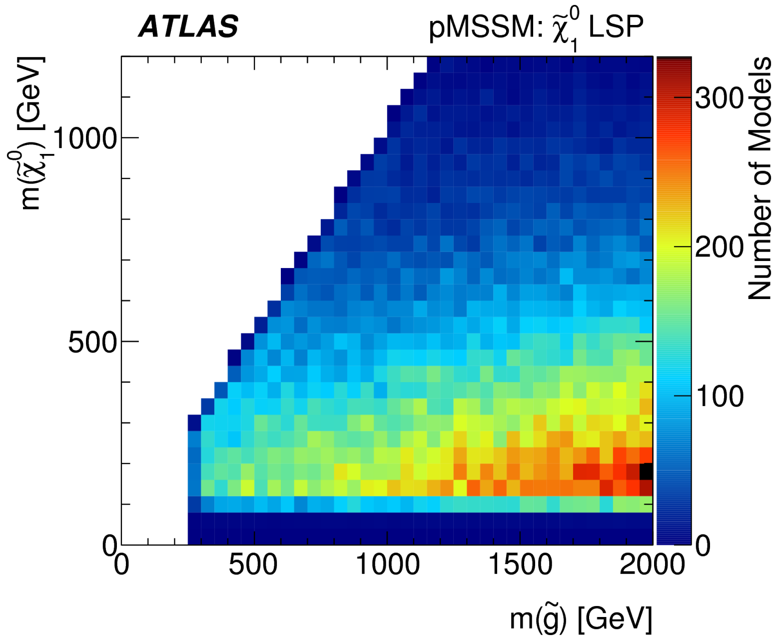


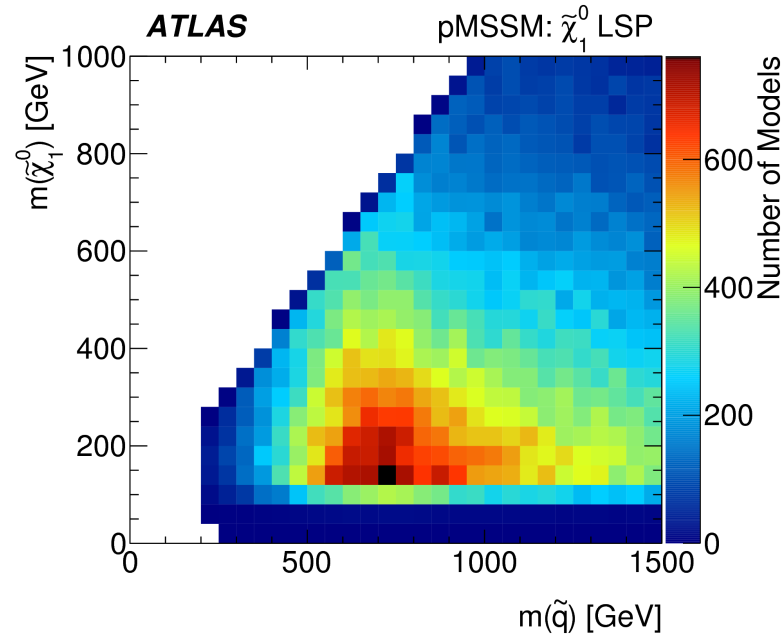
Almost all Wino LSP models with long-lived $\tilde{\chi}_1^+$ Lifetime largest when Bino and Higgsinos are heavy

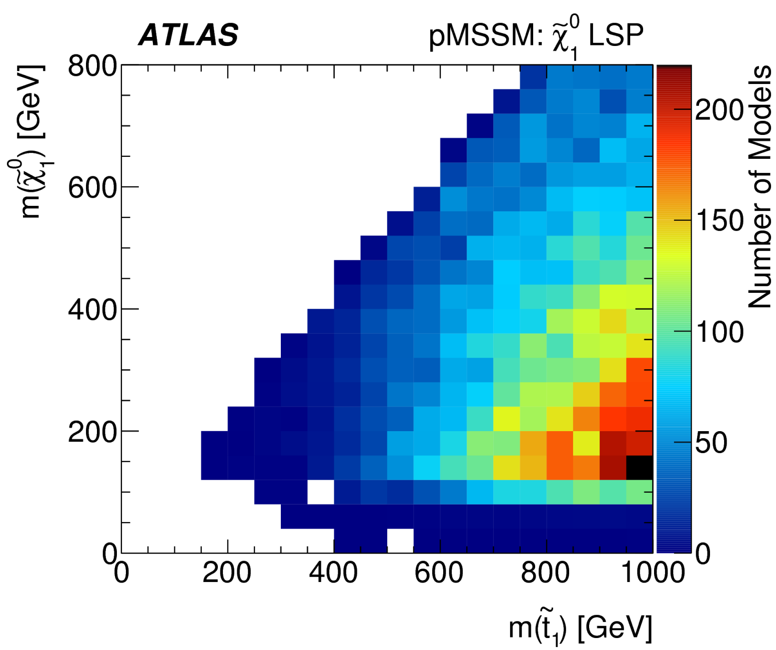
$m(\tilde{\chi}_1^0)$<100 GeV is all Bino LSP as light charginos are excluded by LEP

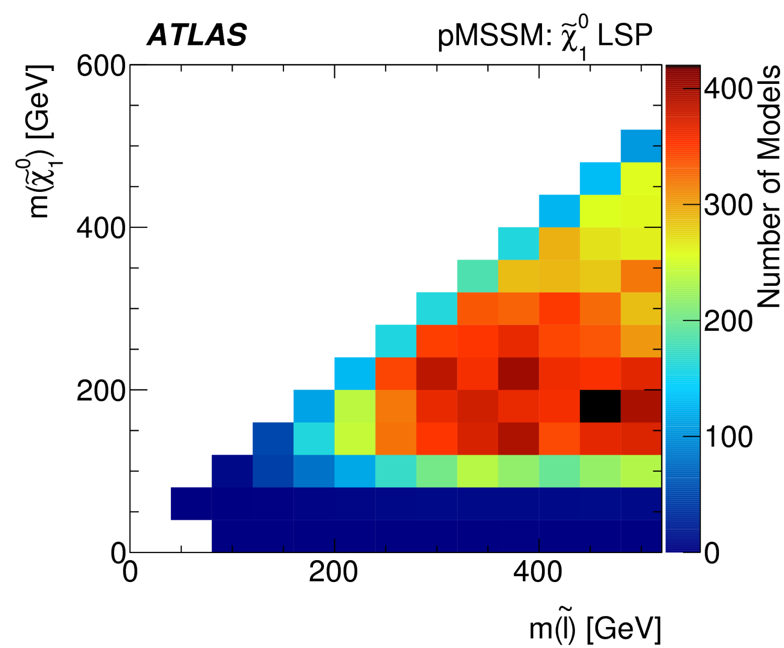
2D Model Distributions

Before ATLAS Run-1 Searches



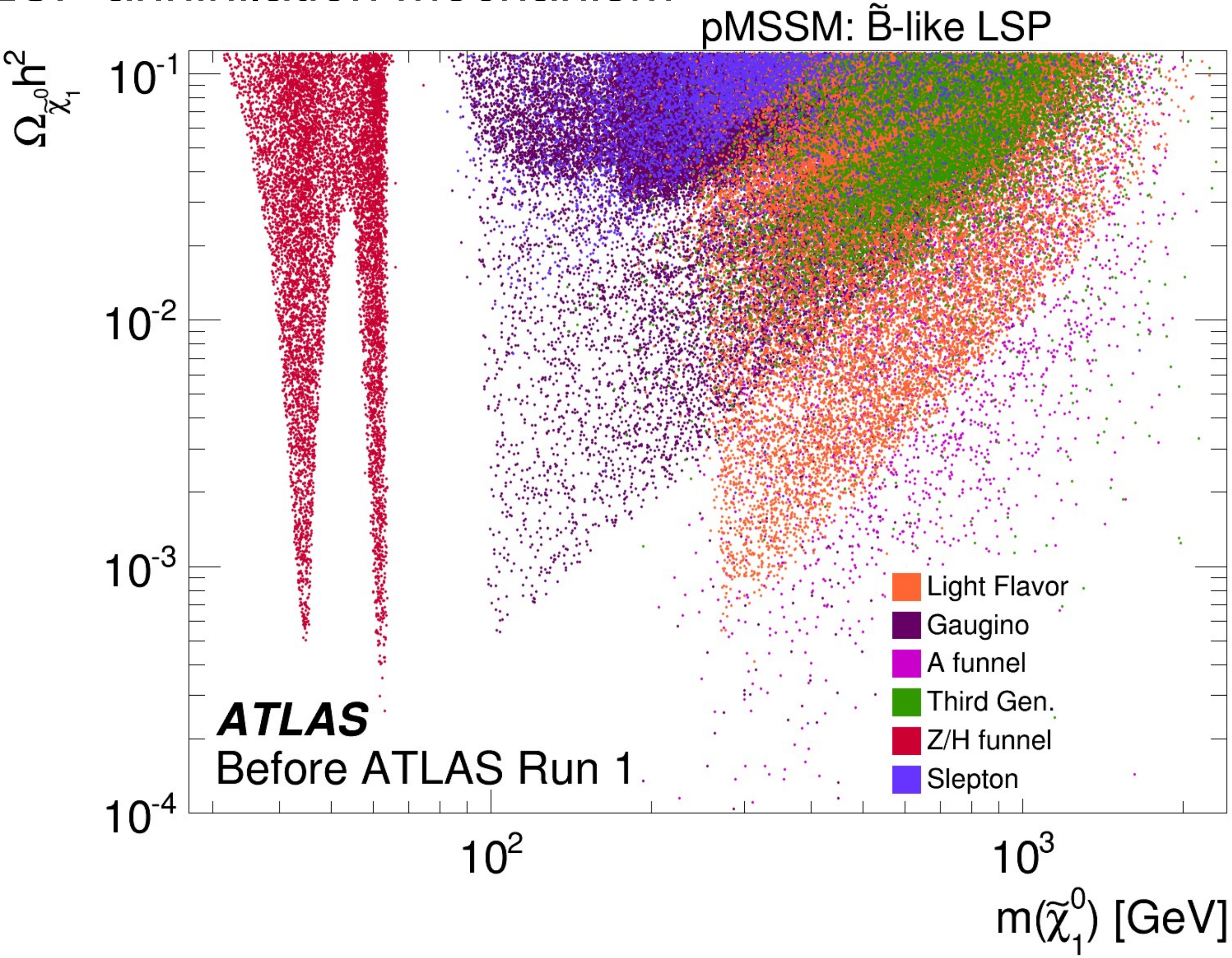






DM by Annihilation Mechanism

For Bino LSP can split sample by dominant LSP annihilation mechanism



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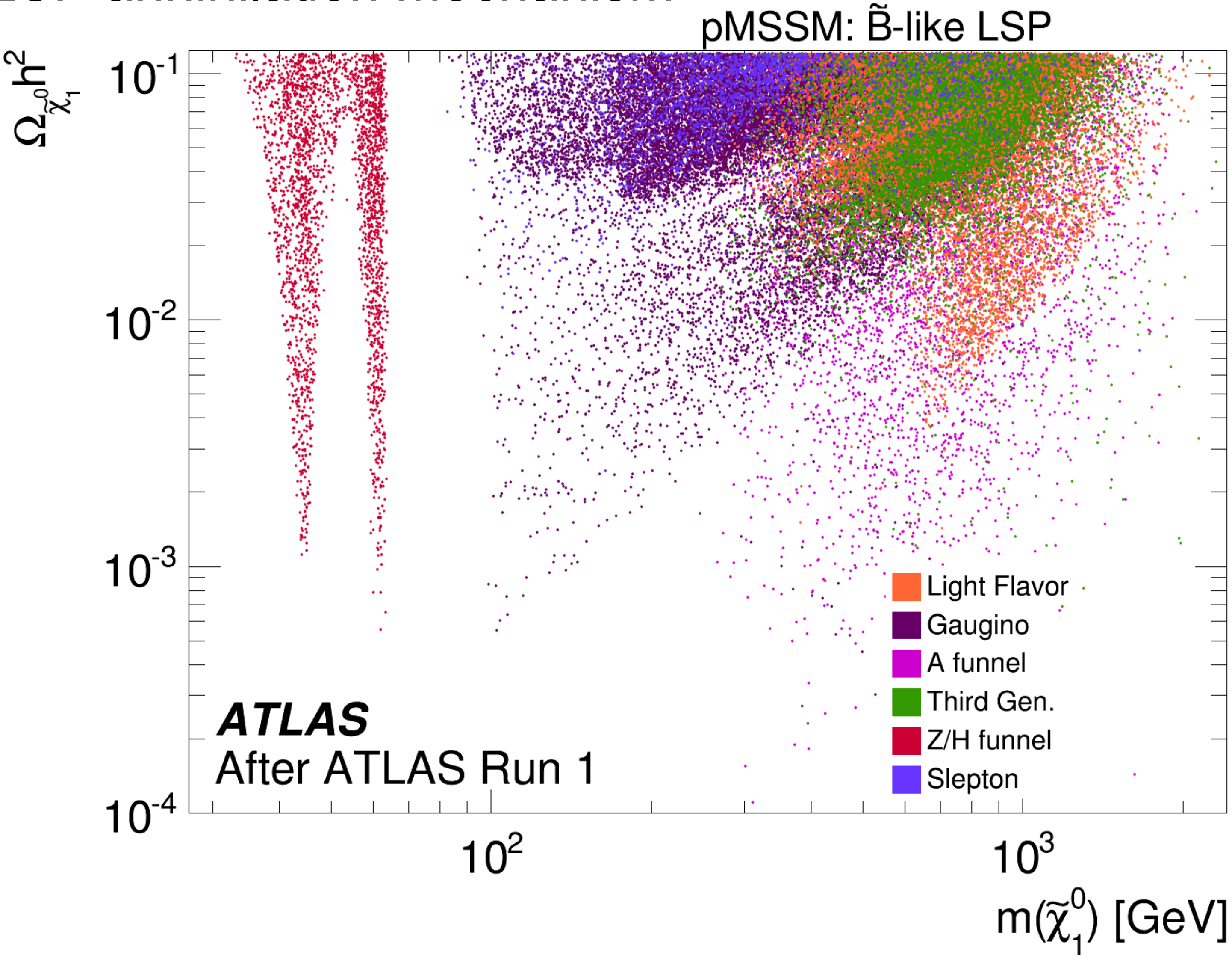

Direct Detection vs Annihilation Mechanism

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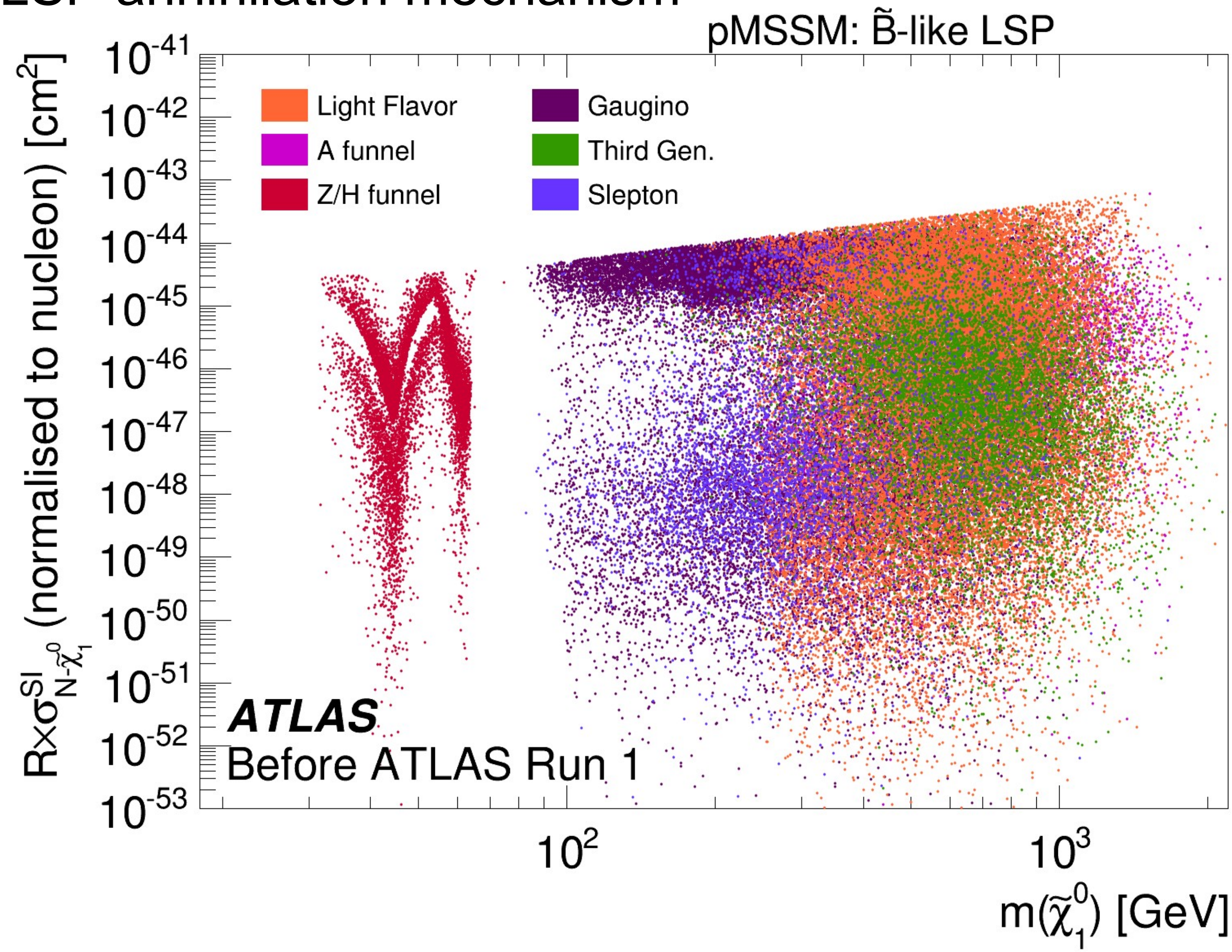

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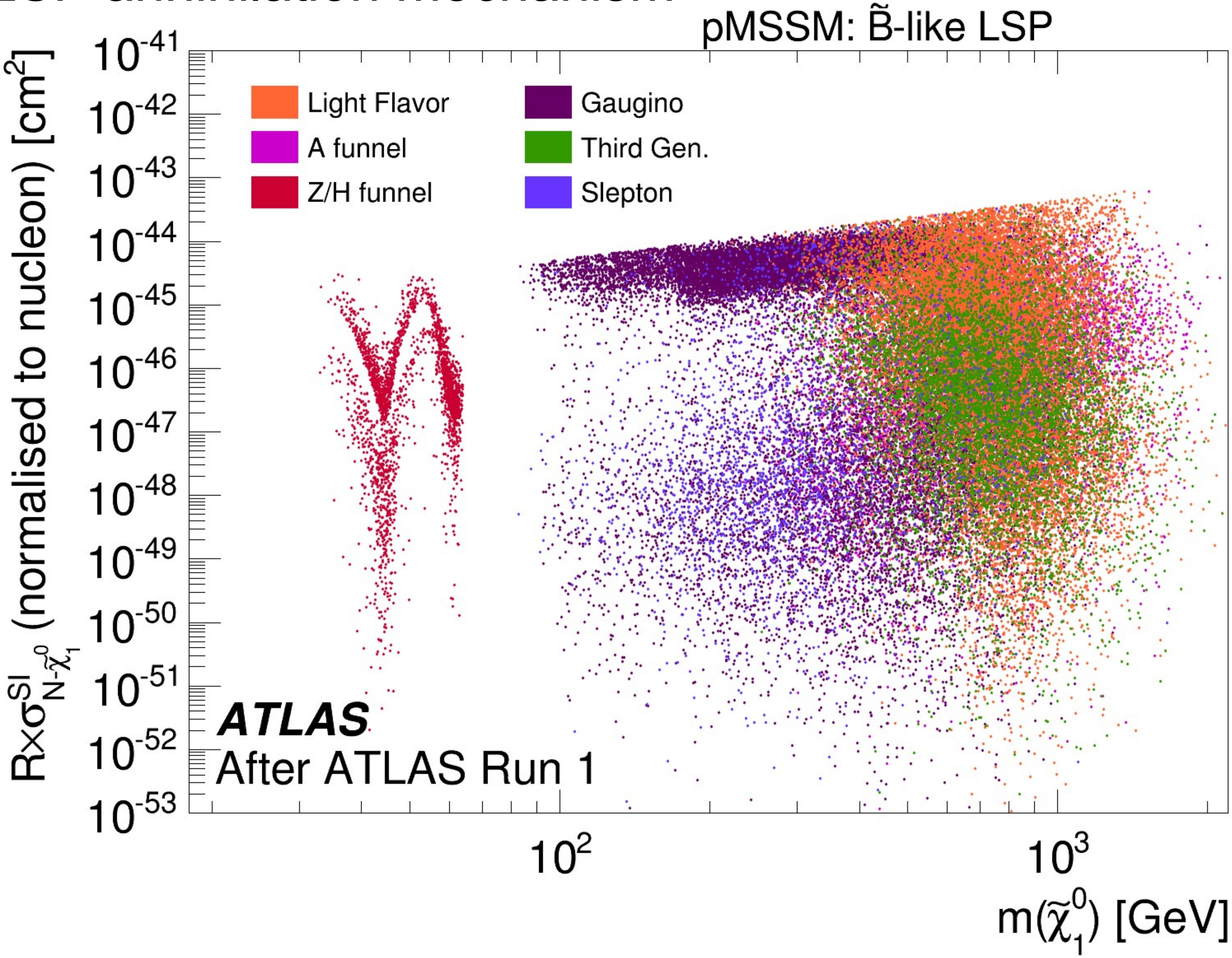
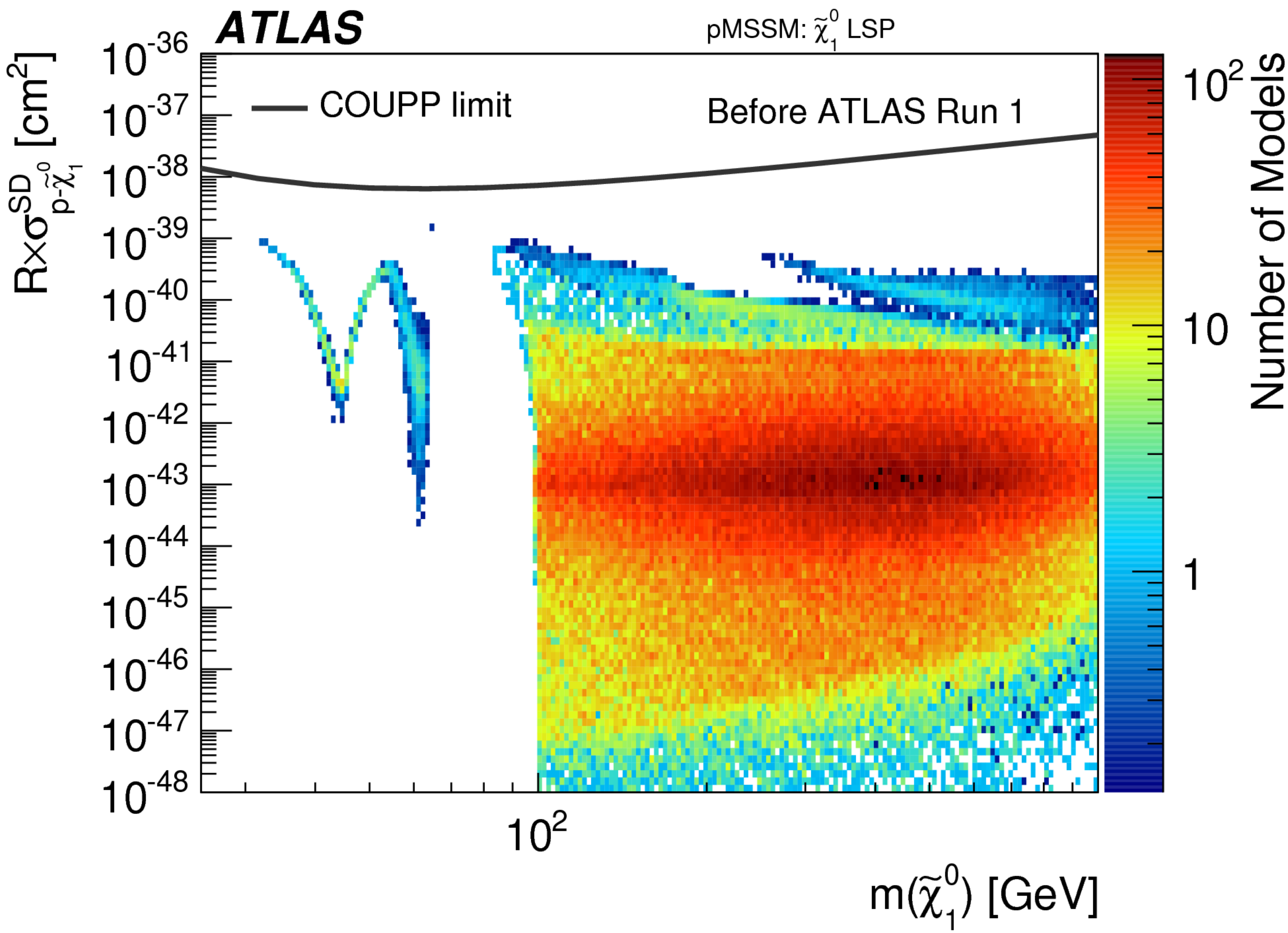


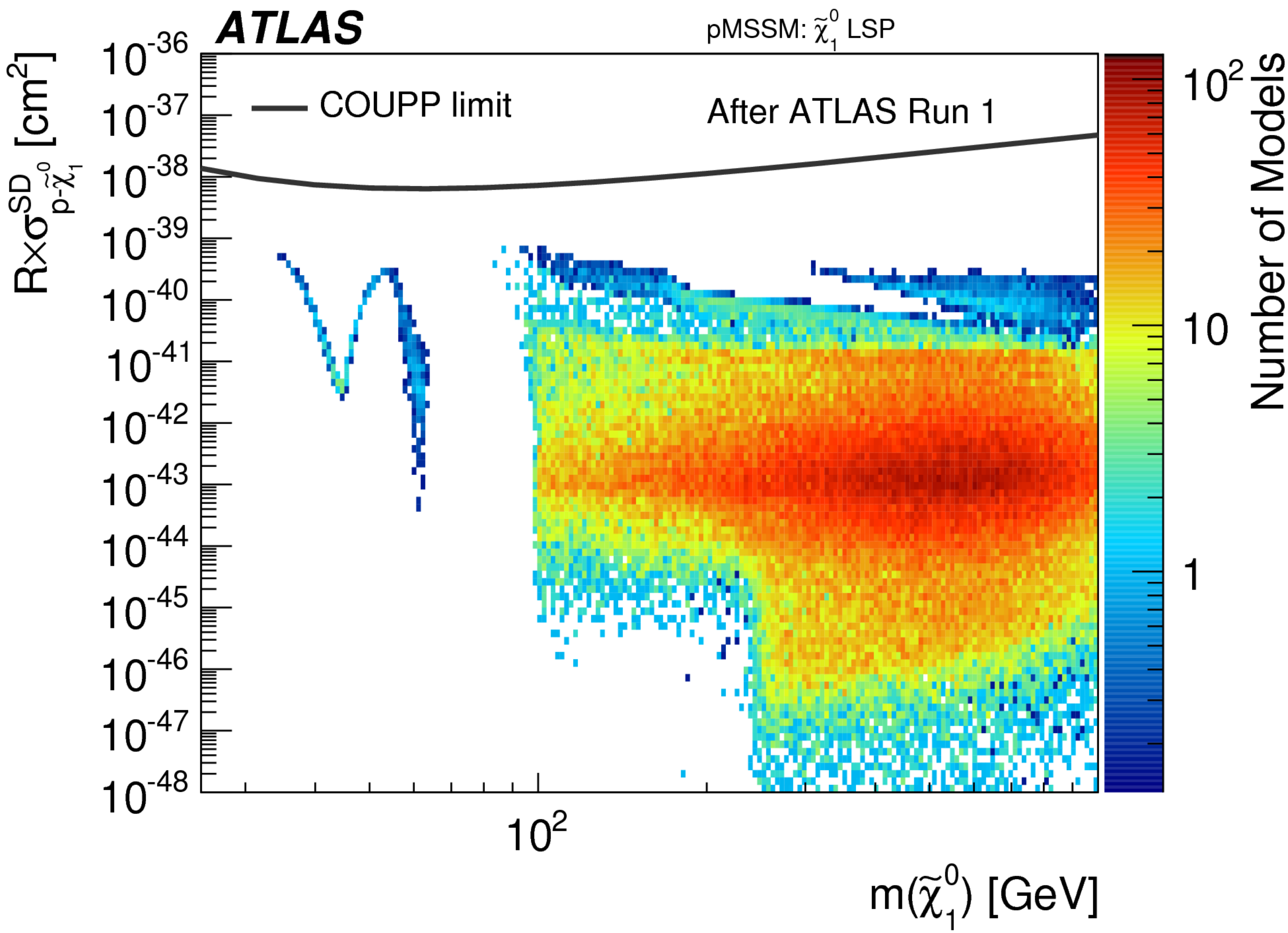
Spin-dependent DM Cross Section

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

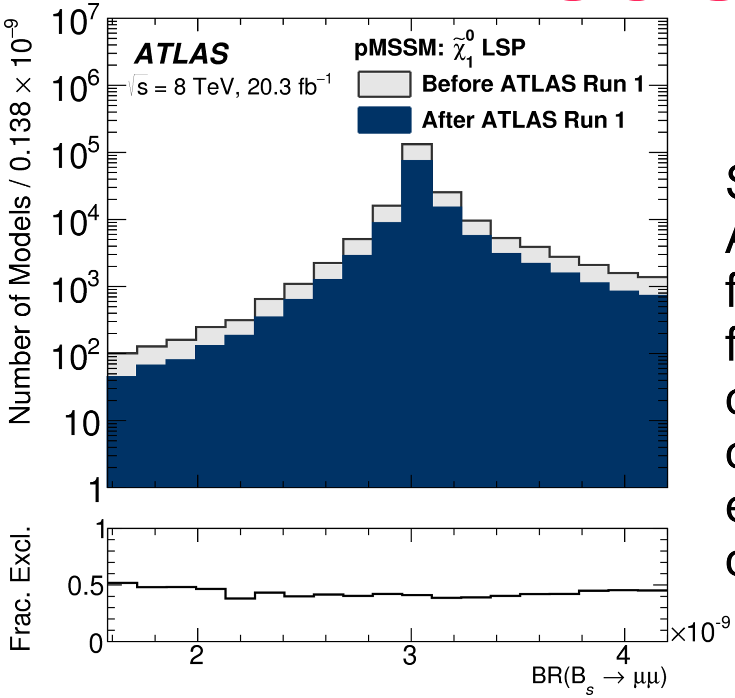


Spin-dependent DM Cross Section

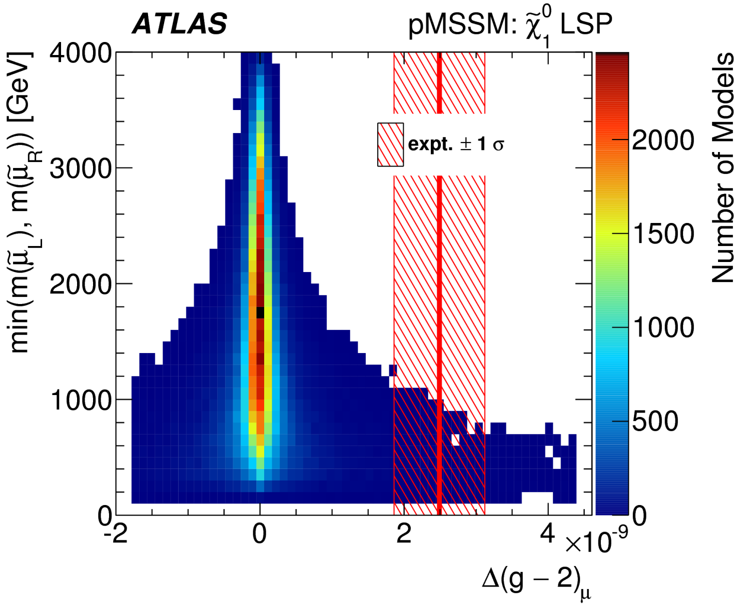
Limit from COUPP applied in model generation, but had no effect

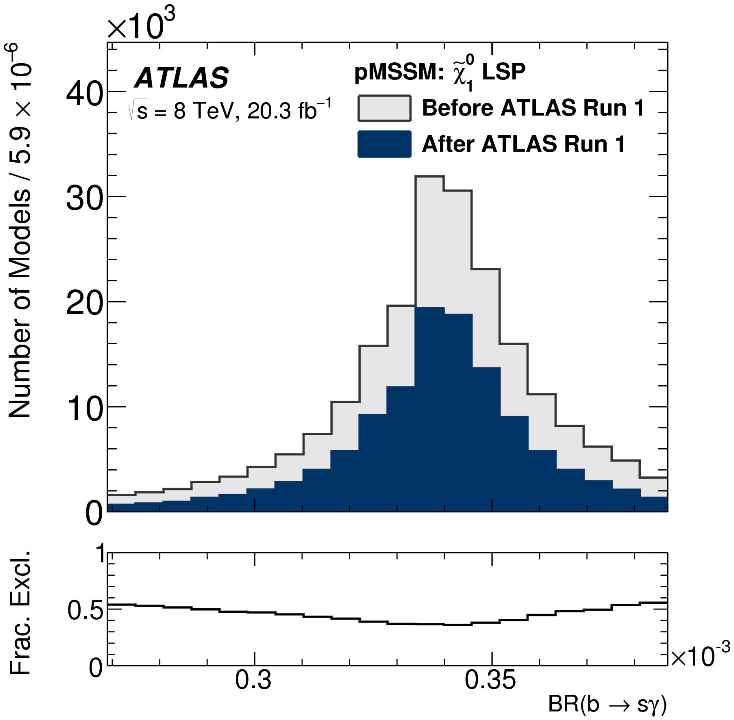


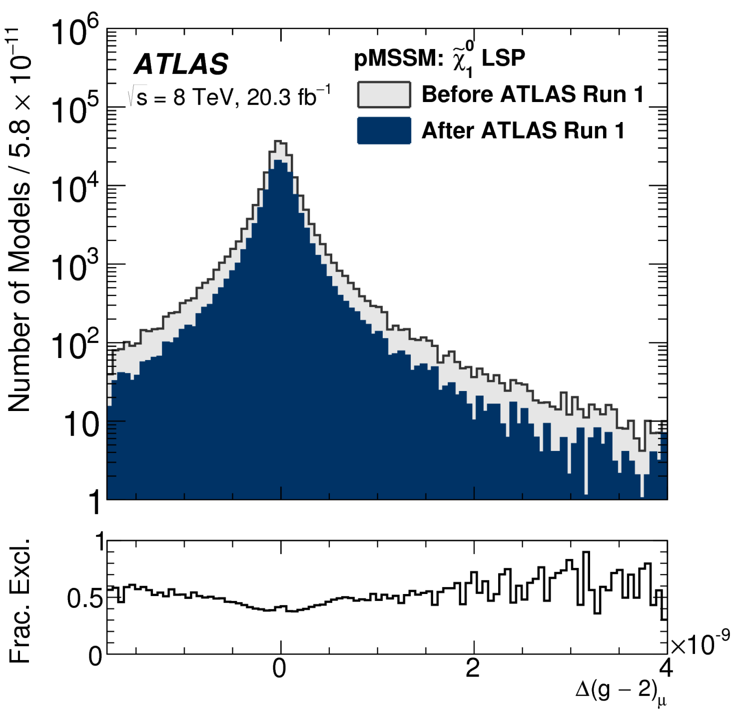
Precision Observables



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

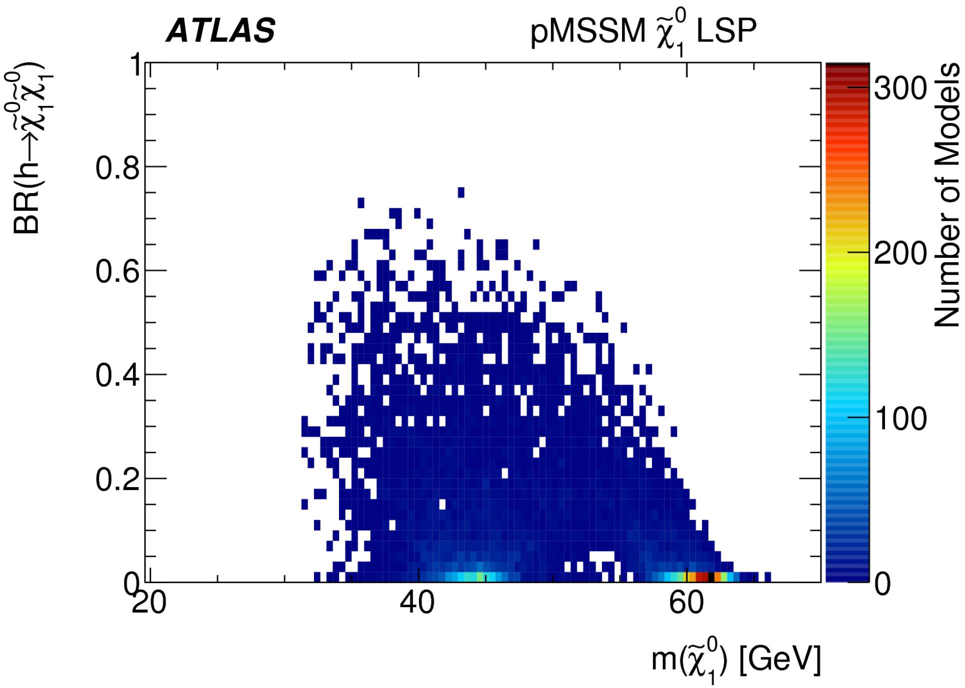




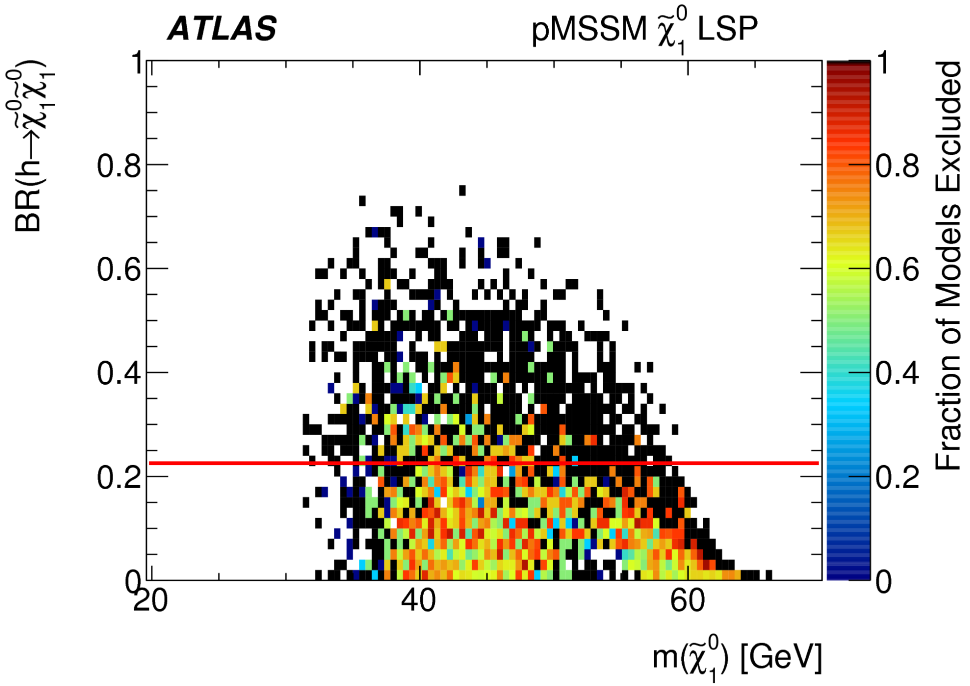


Invisible Higgs

Models before ATLAS Run-1 Searches



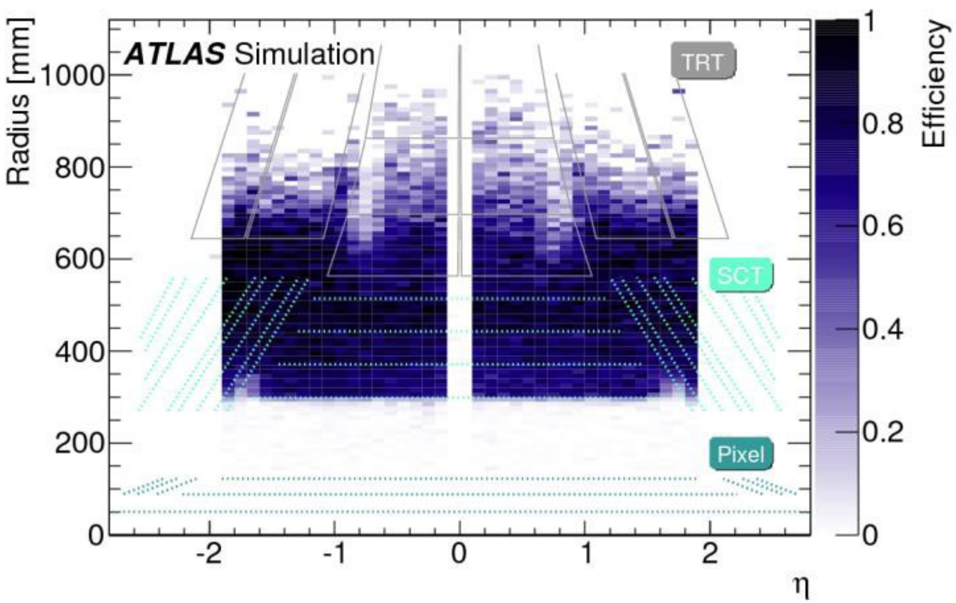
Exclusion by ATLAS Run-1 Searches



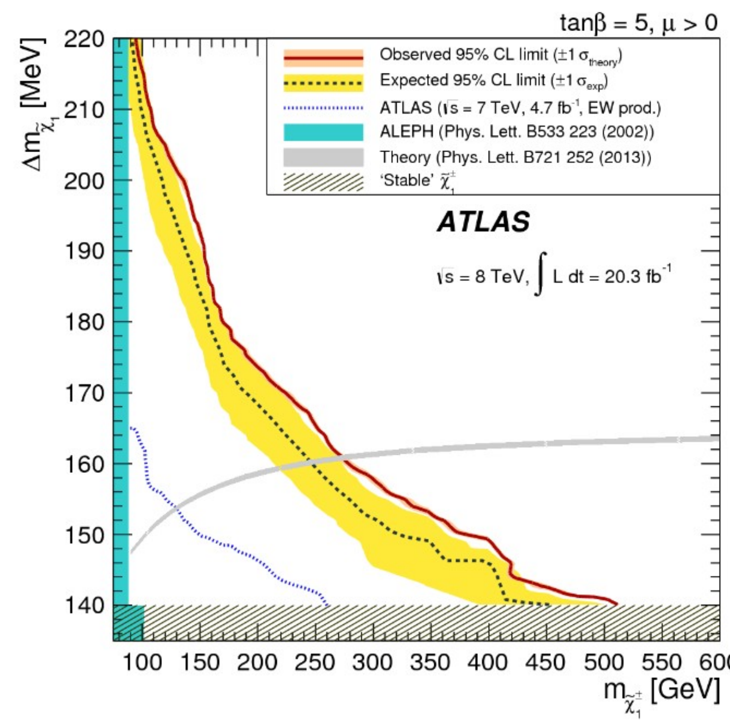
Disappearing Track Analysis

- Motivated by anomaly-mediated SUSY breaking
- LSP almost pure-wino and mass degenerate with lightest chargino (typical mass spitting is ~160 MeV)
- The chargino has a lifetime O(ns) → 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

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%

- 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 $Nsig$ 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

Higgs Mass Dependence

No dependence
in exclusion
fraction on Higgs mass