The effect of ATLAS Run-1 supersymmetric searches in the pMSSM

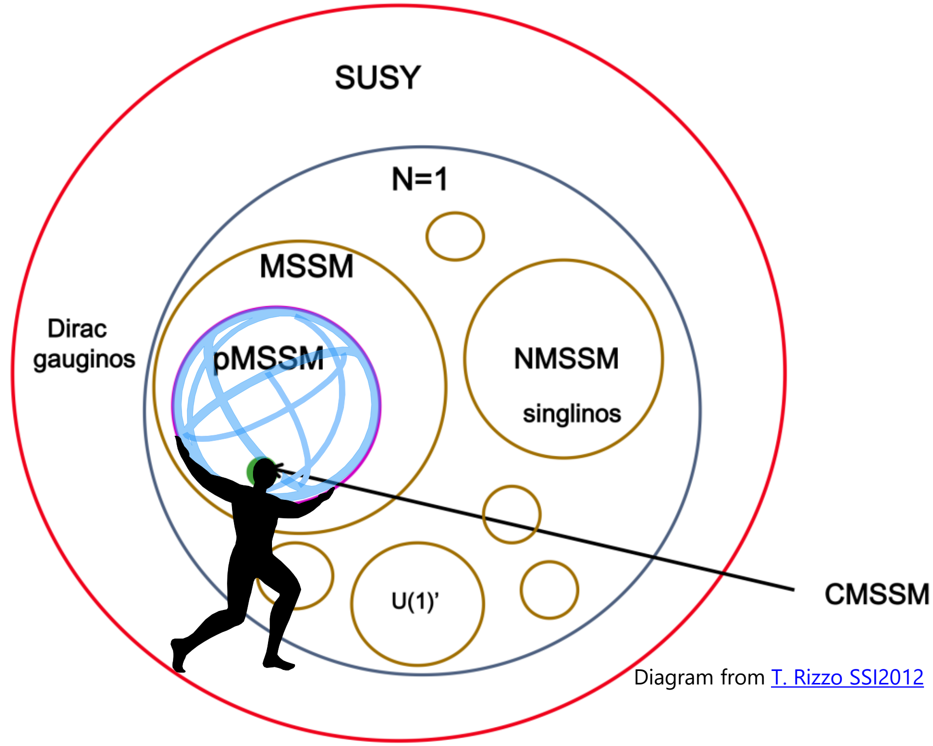

Diagram from T. Rizzo SSI2012

Based on the paper "Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM". arXiv:1508.06608

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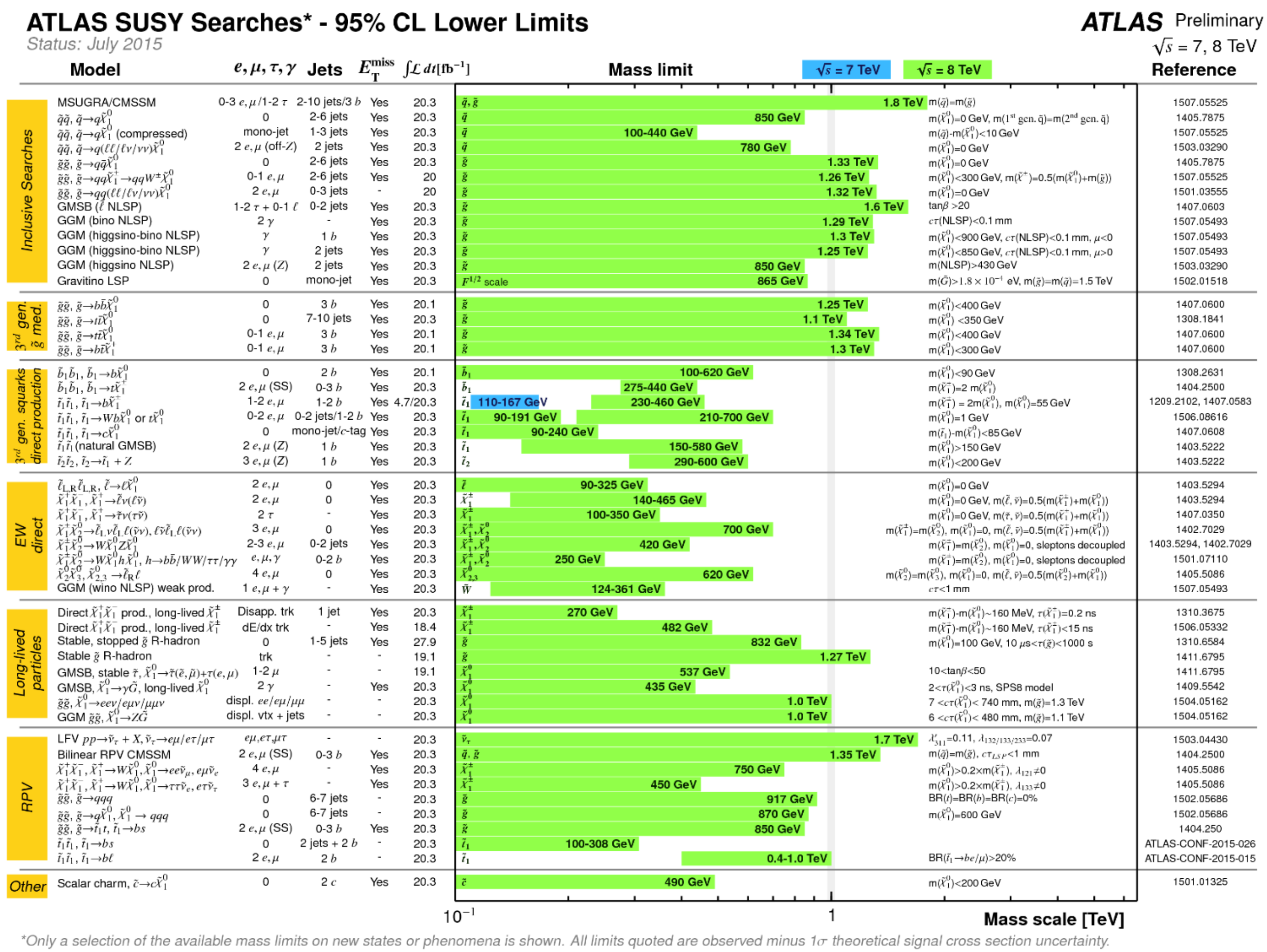
On behalf of the ATLAS Collaboration

SUSY with ATLAS Run 1

- ATLAS has a very wide range of SUSY searches, but usually uses simplified models (ATLAS SUSY Results)
- MSSM has 105 free parameters. Would like to use these searches to explore large part of it



Run 1 Summary with pMSSM

- pMSSM uses well-motivated reductions but still covers a broad spectrum of parameter space
- Assume
  - R-parity conservation
  - Neutralino LSP
  - $1^{st}/2^{nd}$ generation squark with the same quantum number are mass degenerate

Scanned full set of 19 pMSSM parameters up to masses of 4 TeV

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 models

Apply constraints from
- Precision EW and flavor
- DM abundance
- LEP, Tevatron
- Higgs mass

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}
$\Omega_{\tilde{\chi}_1^0}h^2$	—	0.1208
$\Gamma_{\mathrm{invisible(SUSY)}}(Z)$	—	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

Run 1 Summary with pMSSM

- Make full use of ATLAS simulation, reconstruction, and analysis tools

22

searches with over

200

signal regions

Inclusive	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	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	ℓh
	2-leptons
	2-τ
	3-leptons
	4-leptons
	Disappearing Track
	Long-lived particles
	$H/A \to \tau^+\tau^-$

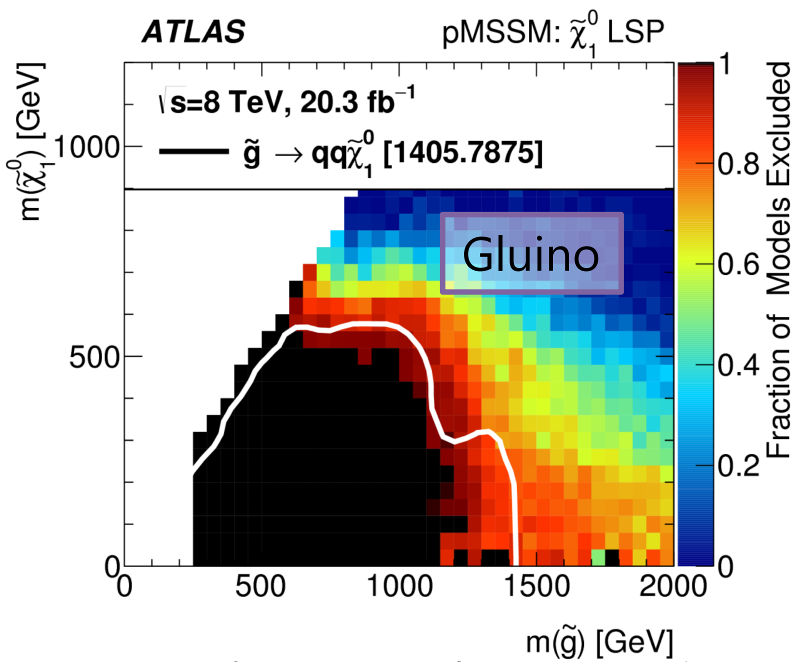
Details of each analysis linked in backup

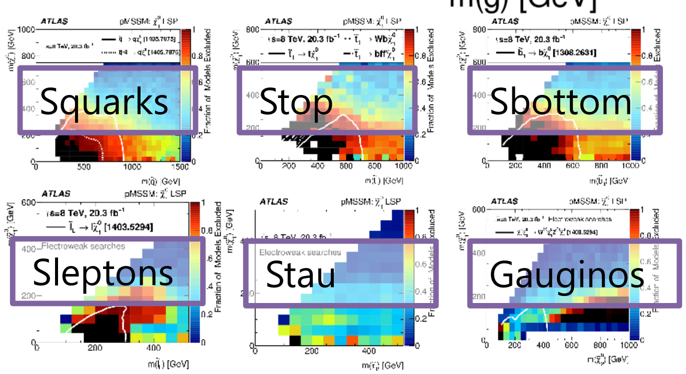
- 310,327 models analyzed
- 30 billion signal events generated
- 44,559 models fully reconstructed with 600 million signal events total

The most comprehensive results from ATLAS on SUSY to date

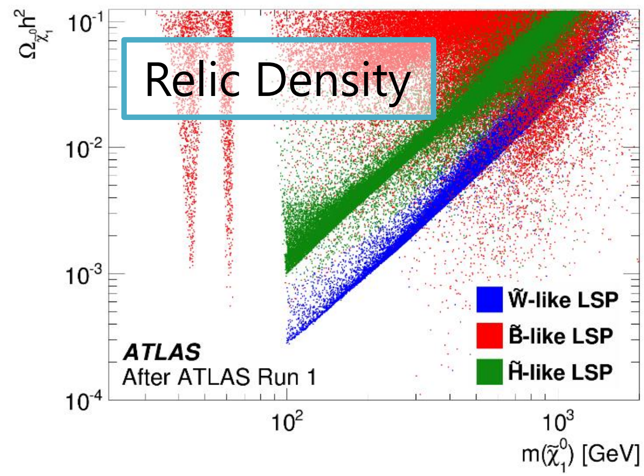
Outline

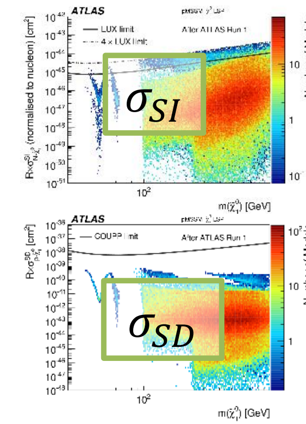
Mass Limits



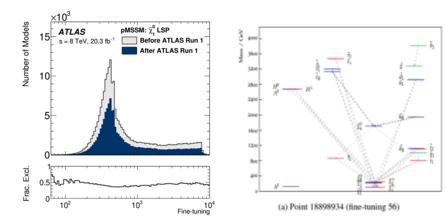


Dark Matter

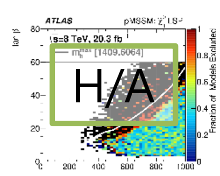


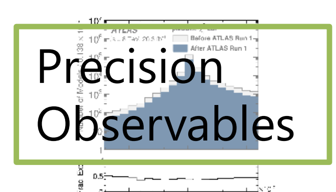


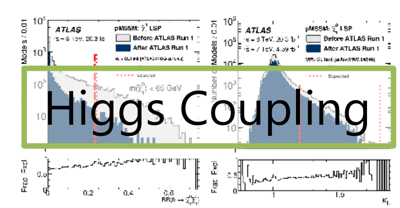
Naturalness

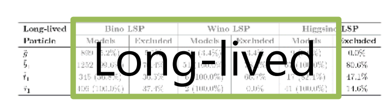


And many others…



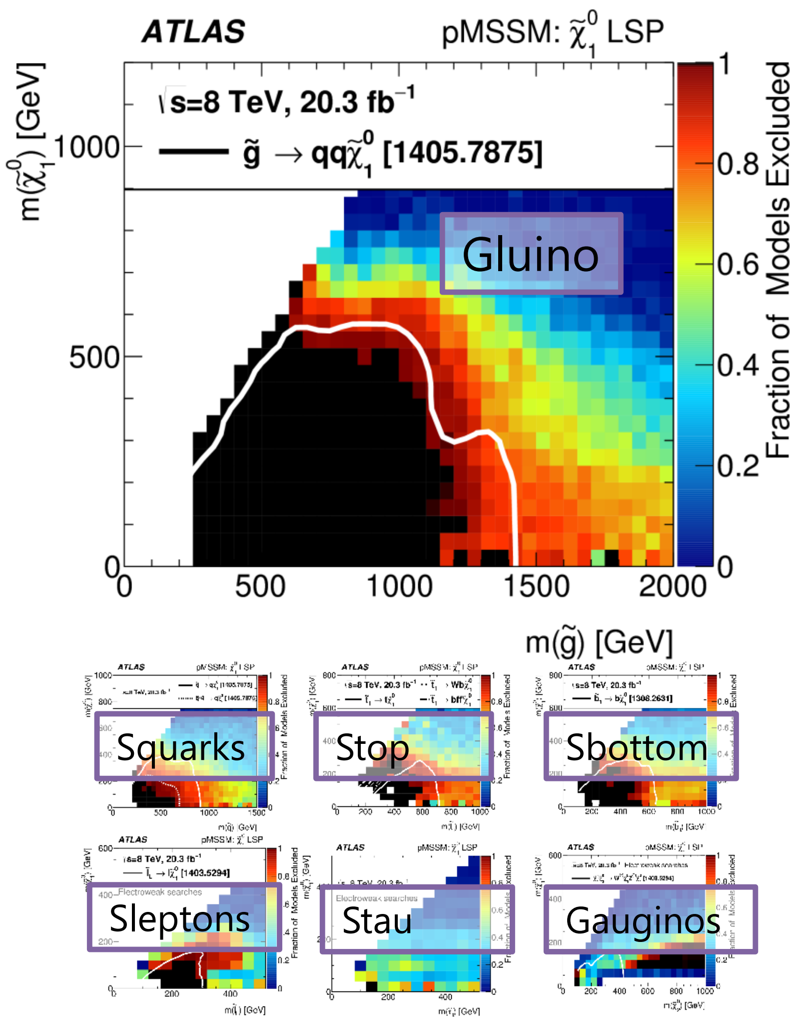




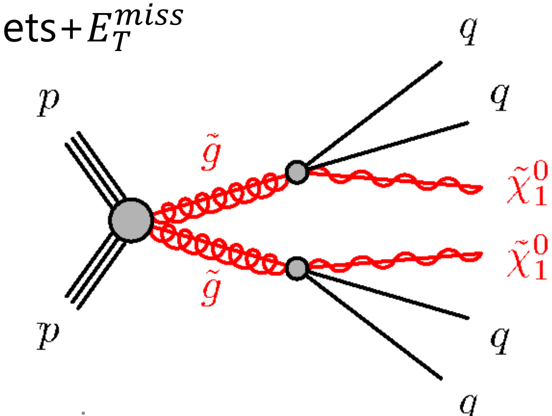


Outline

Mass Limits



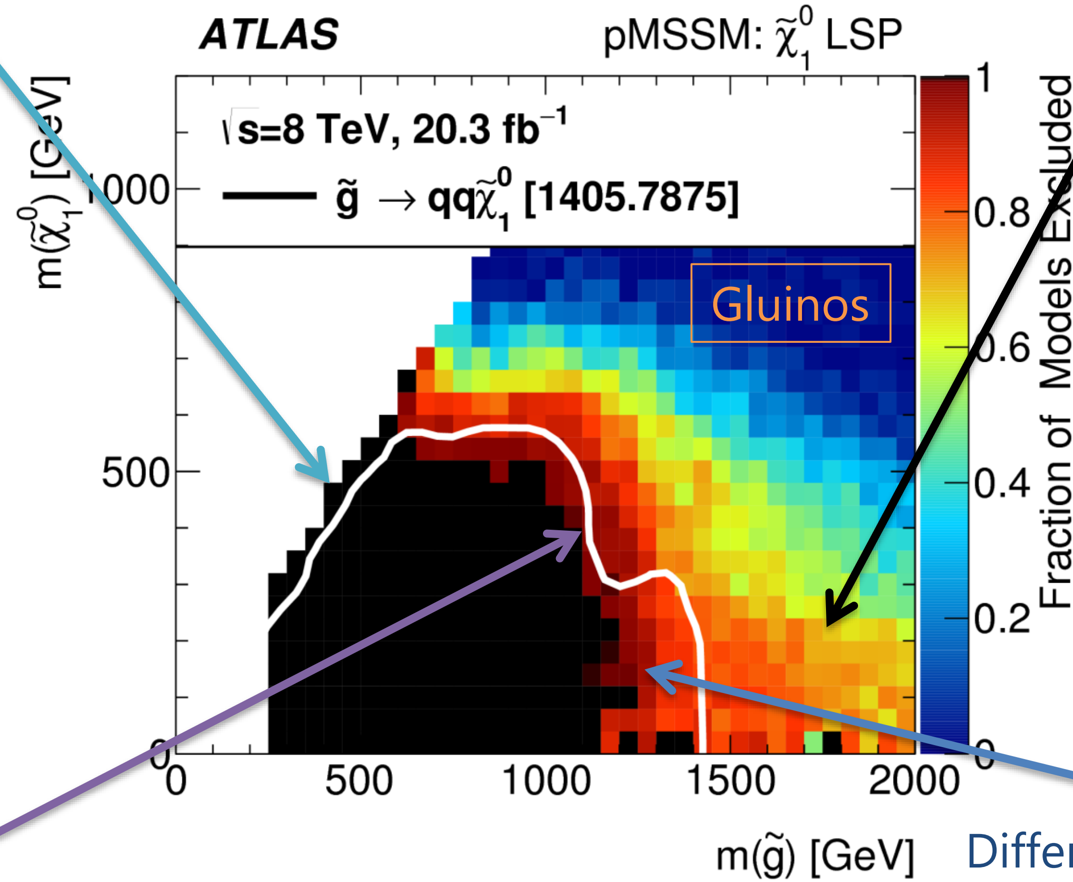
- 2D plot showing fraction of models excluded
  - Usually in mass plane of two sparticles
  - Color scale represents fraction of models excluded
    - Black is 100% excluded
    - White means no model point that pass pre-ATLAS Run 1 constraints
    - Fraction excluded depends on the choice of parameters' scan ranges
  - White line is 95% CL limit from a simplified model
- Example on the left:
  - Simplified model limit from 0L+2-6jets+E_T^{miss}



Gluinos

Good sensitivity from monojet search

Band of sensitivity for model with $\chi_1^{\pm} \rightarrow$ wino-like LSP model from disappearing track search

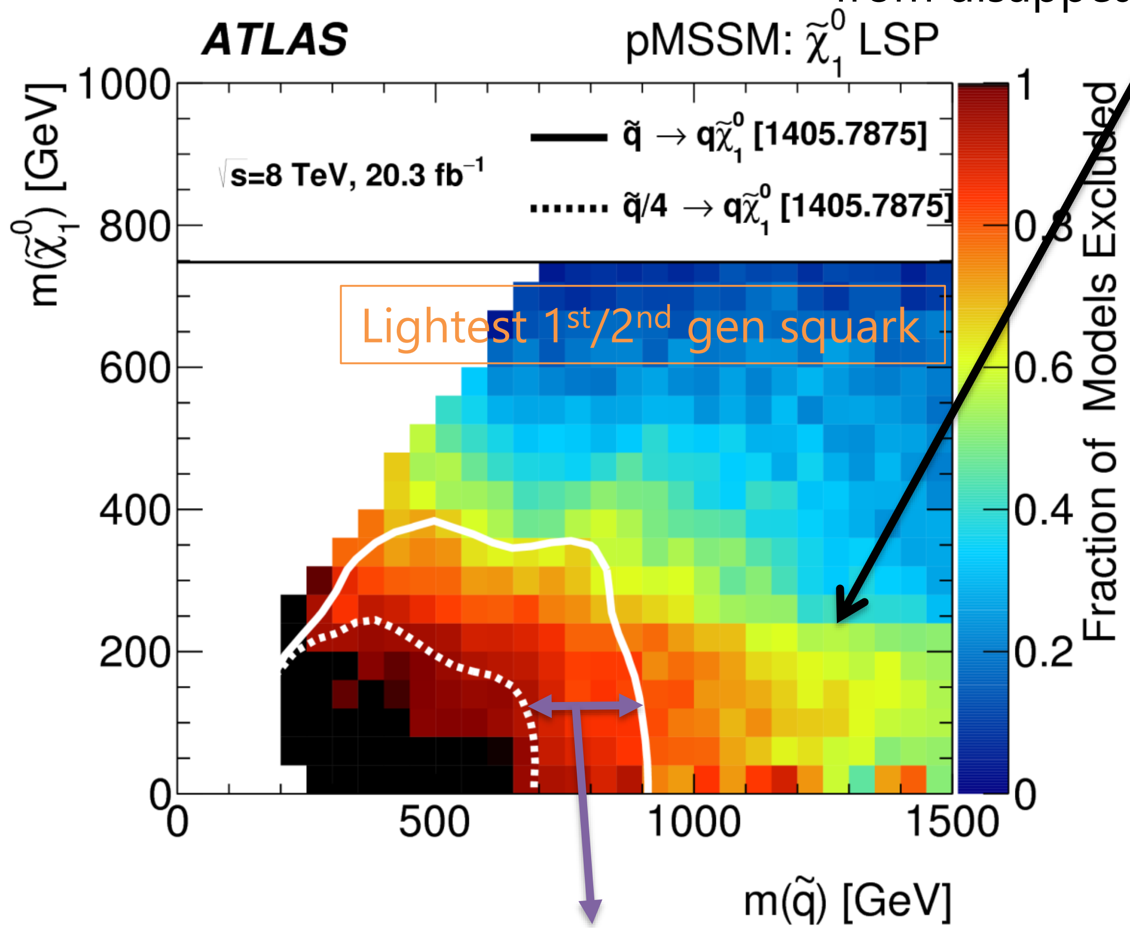


Simplified model limit from 0L+2-6jets+E_T^{miss} search

Difference from an intermediate sparticle with mass between $\tilde{g}$ and LSP

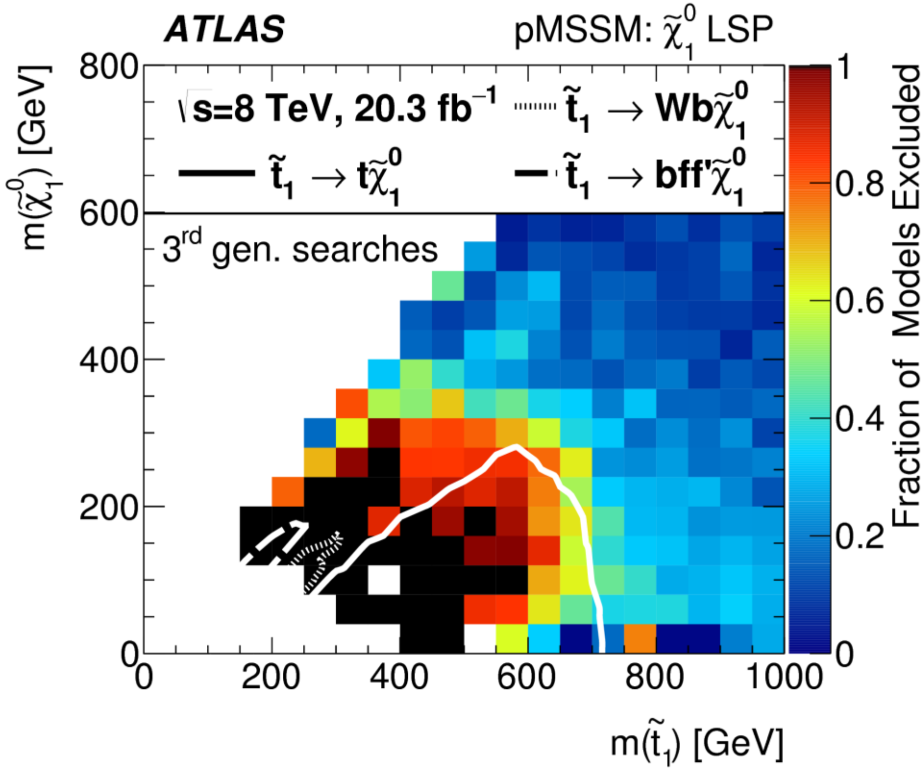
Light Flavor Squarks

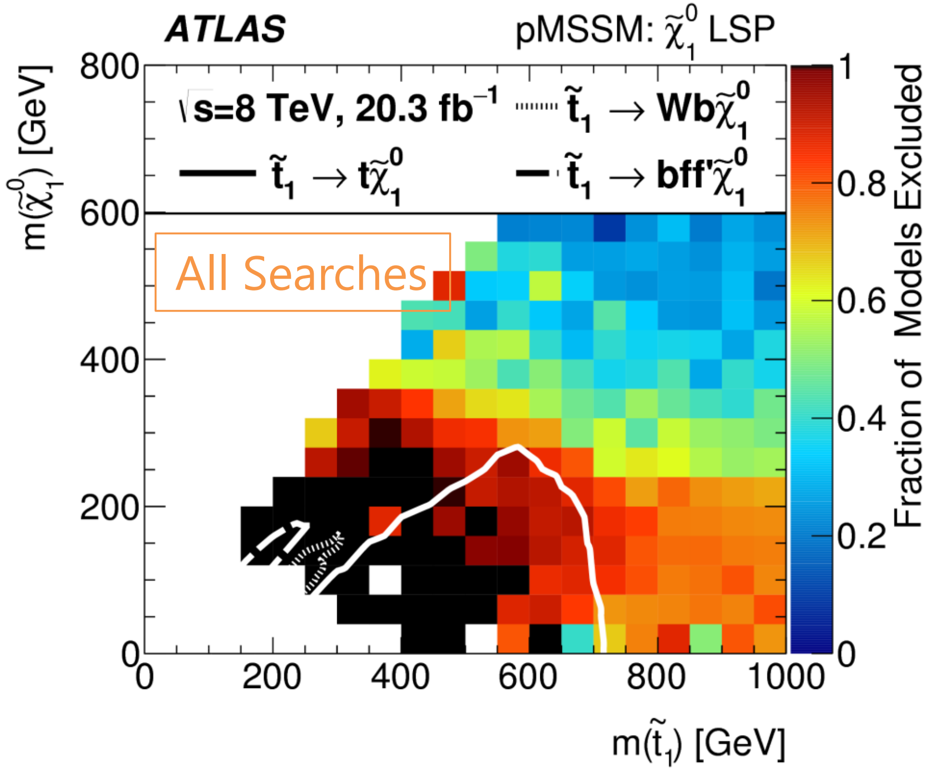
Band of sensitivity for model with $\chi_1^{\pm} \rightarrow$ wino-like LSP model from disappearing track search



Difference due to assumption of eight-fold squark mass degeneracy. Dashed line shows limit when cross-section for squark production reduced by 4 to simulate only two-fold degeneracy

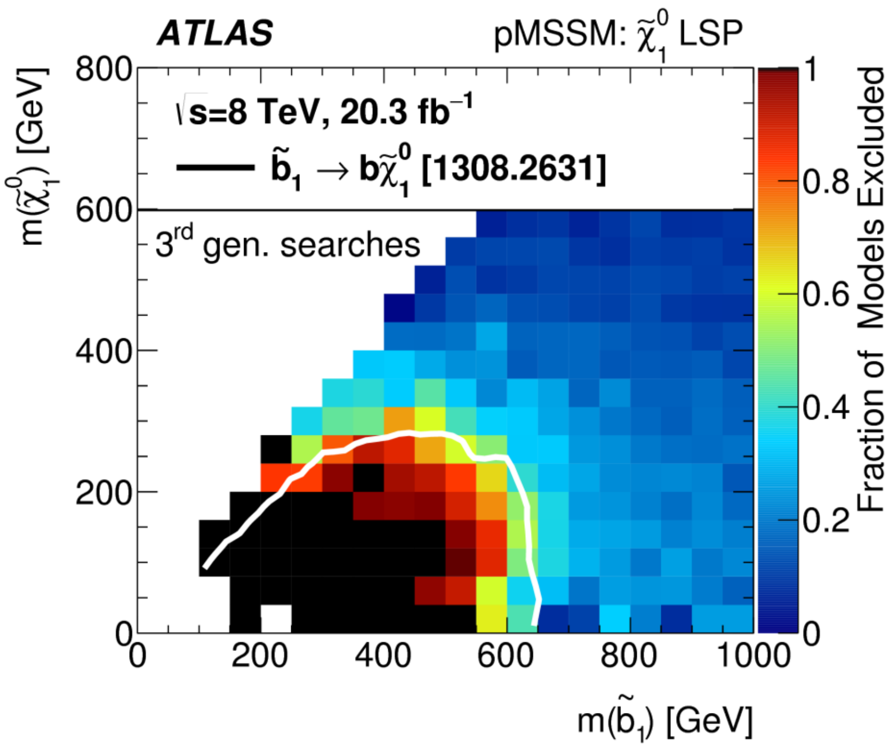
3rd Gen—Stop

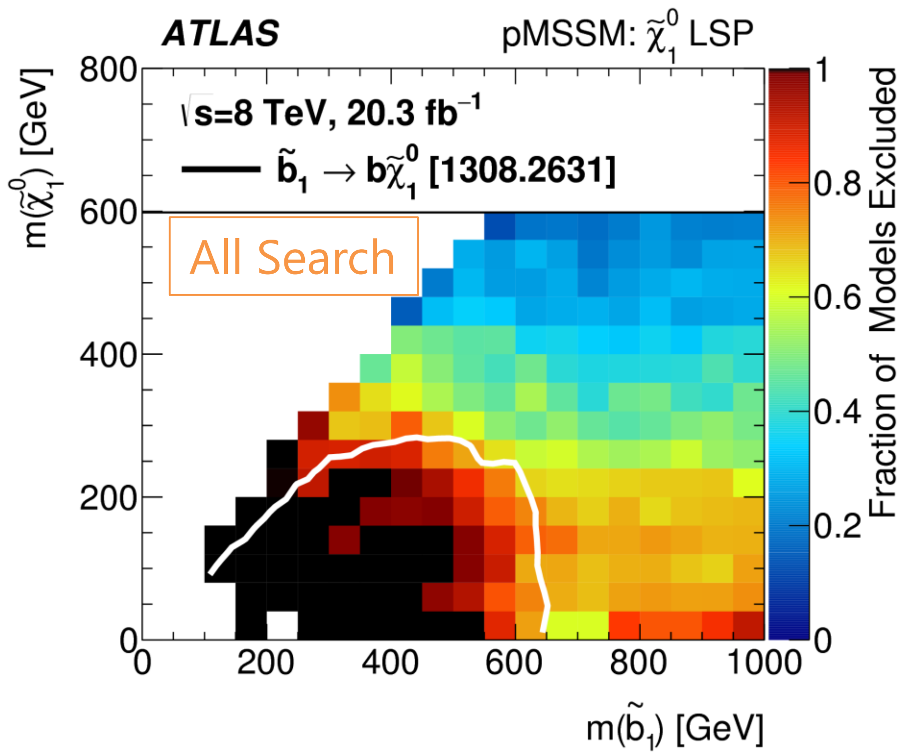




- ATLAS 3rd generations searches show good coverage in general
  - Complemented by disappearing track search for $m(\tilde{\chi}_1^0)$ < 200 GeV
- Difference in mass reach for pMSSM models results from 100% $\tilde{t}_1 \to t + \tilde{\chi}_1^0$ BR assumption in the simplified models

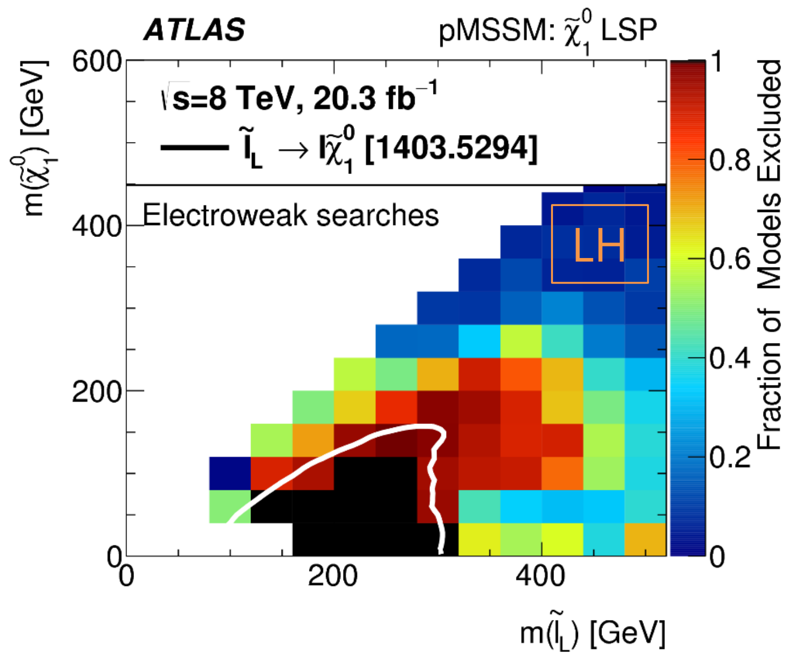
3rd Gen—Sbottom

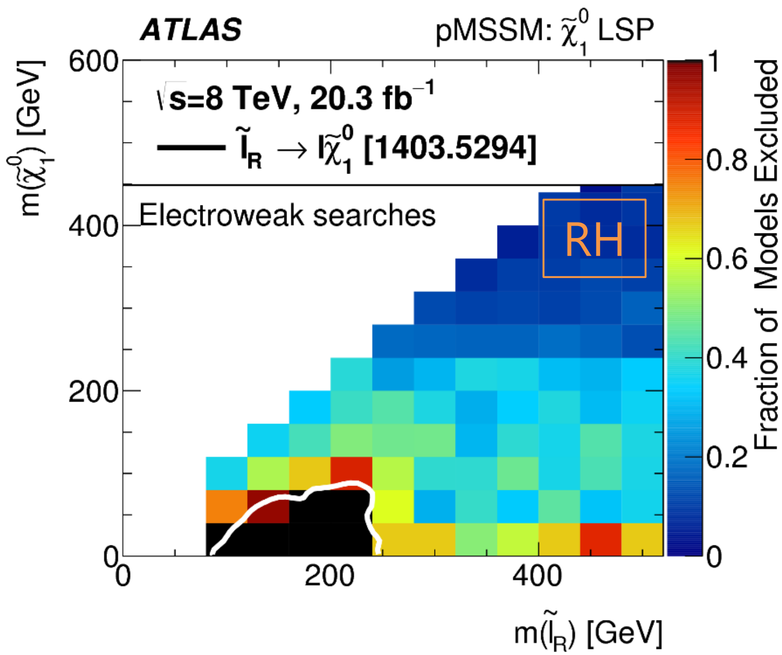




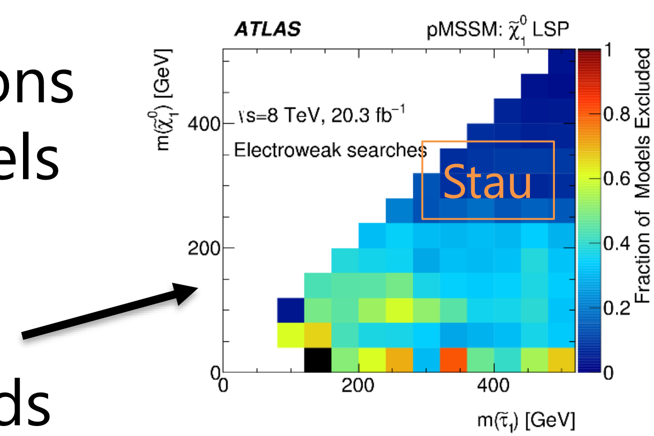
- For sbottom, the sensitivity is well-captured by the limit from simplified models

EW Sleptons



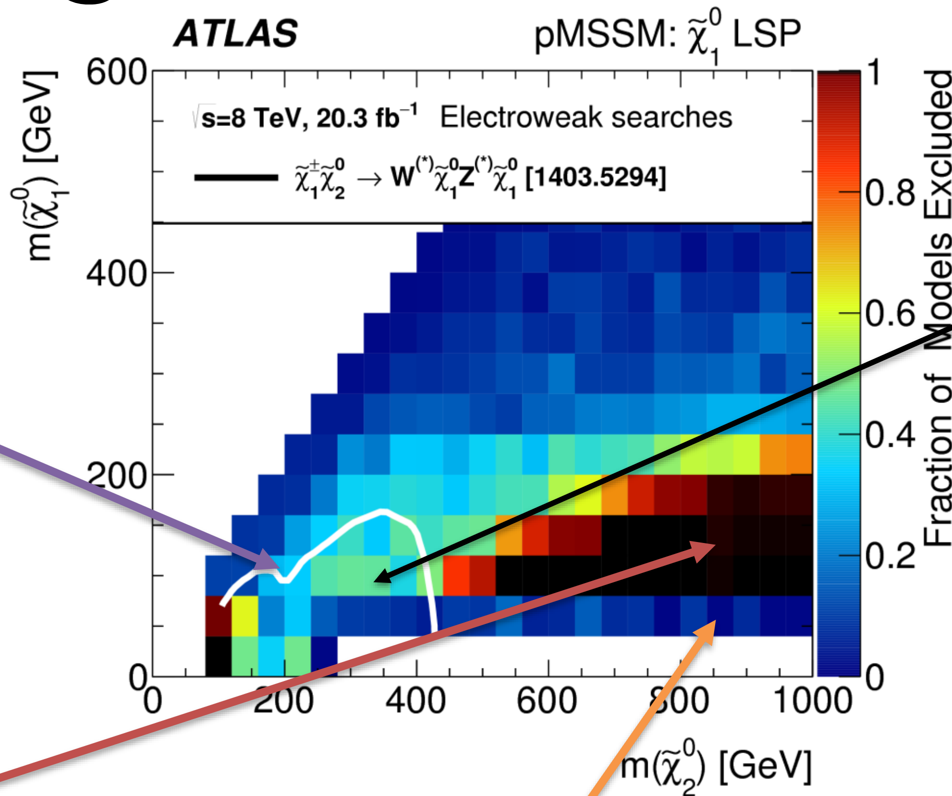


- When compared with simplified models which assume either only LH or RH sleptons are produced, sensitivity to pMSSM models are well-represented
- Limited sensitivity to stau due to the difficulty to trigger and larger backgrounds



ATLAS constraints from LHC Run 1

EW Gauginos



Limit from pure-wino $\tilde{\chi}_1^{\pm} + \tilde{\chi}_2^0$ production

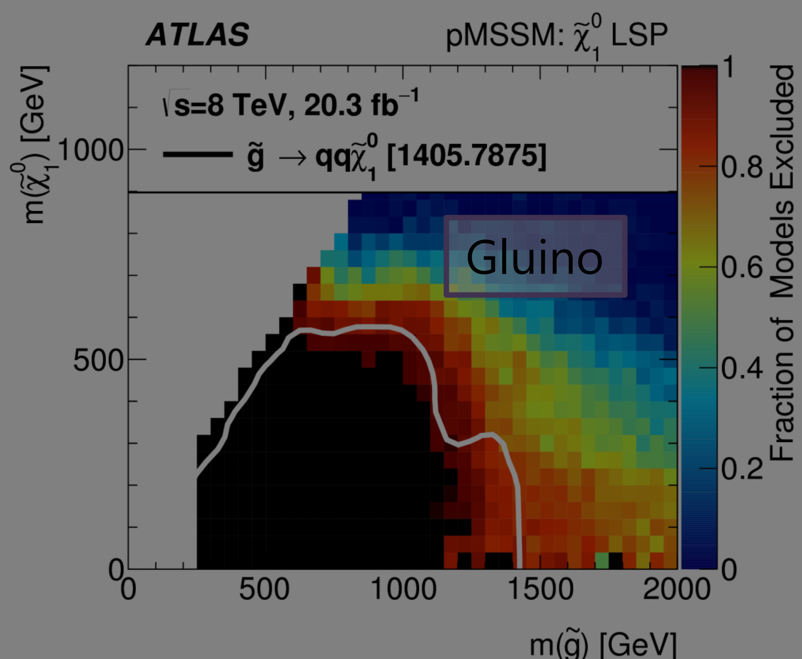
Best sensitivity from multi-lepton searches, but still many viable models due to low cross-section because $\tilde{\chi}_2^0$ is Higgsino-like

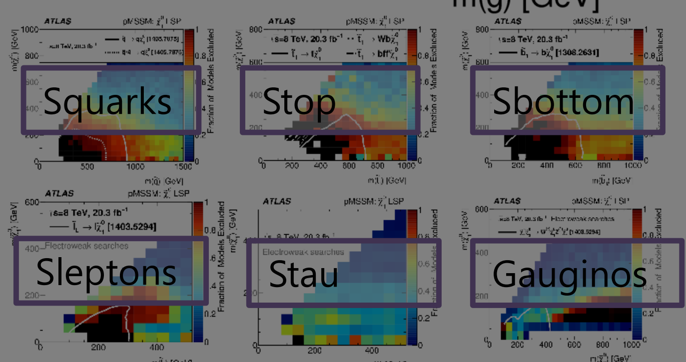
Exclusion from disappearing track analysis. Strongest when LSP is wino-like. Complements the direct search nicely

This band is dominated by bino-like LSP due to the relic density limit controlled by Z and h “funnels”

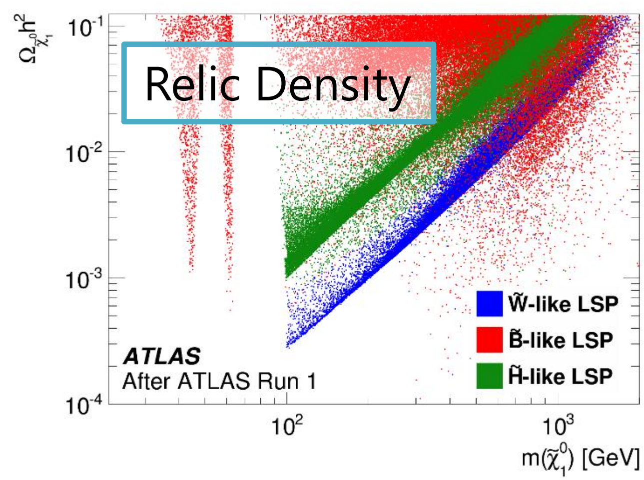
Outline

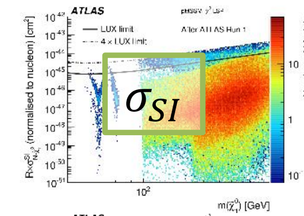
Mass Limits

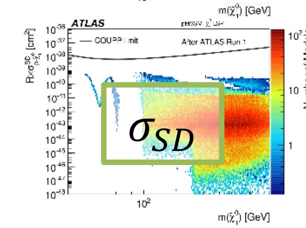




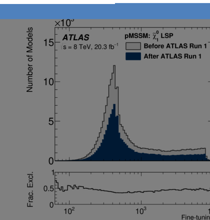
Dark Matter

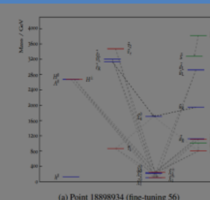




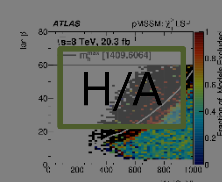


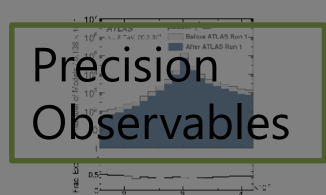
Naturalness

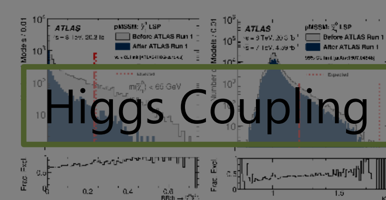


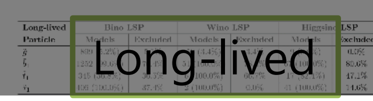


And many others…

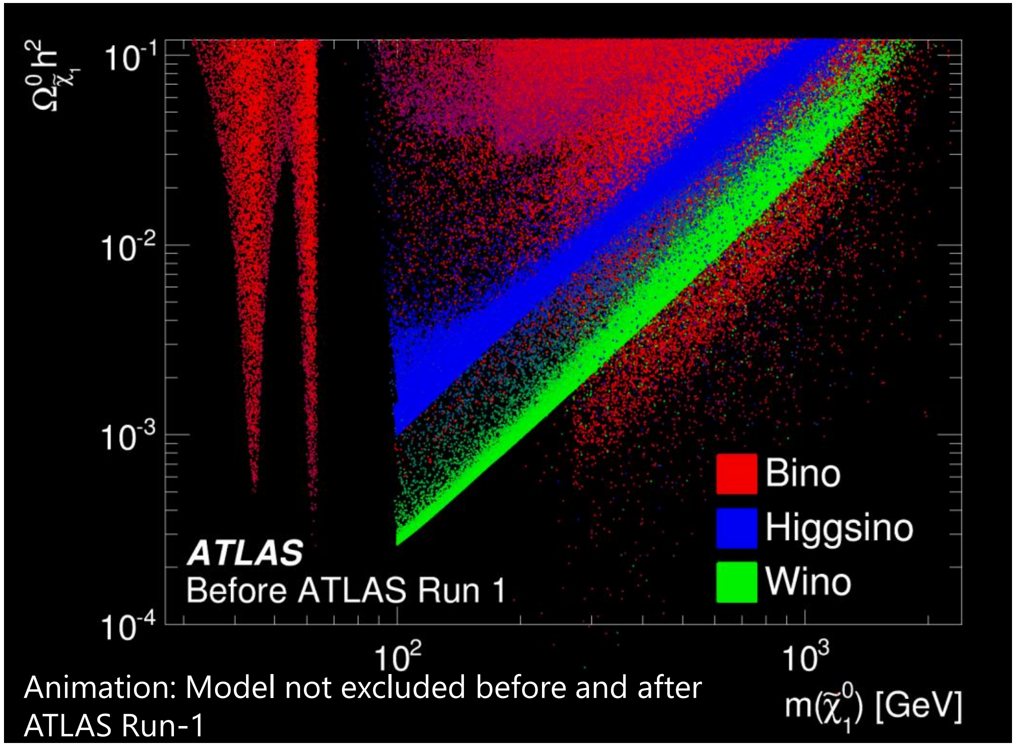




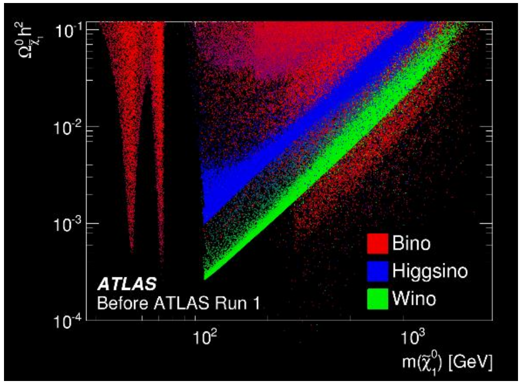


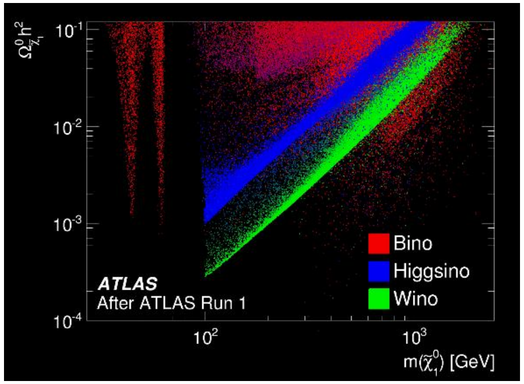


Relic Abundance



Same plot, static versions
Before (top) and after (bottom)

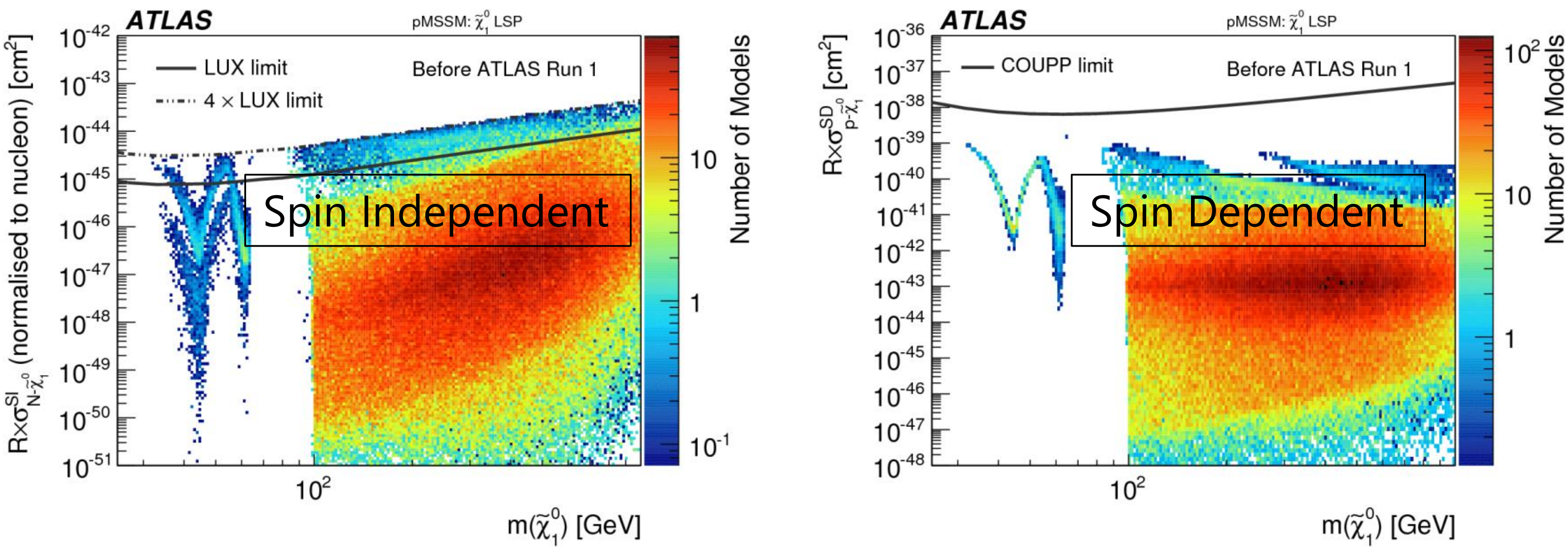




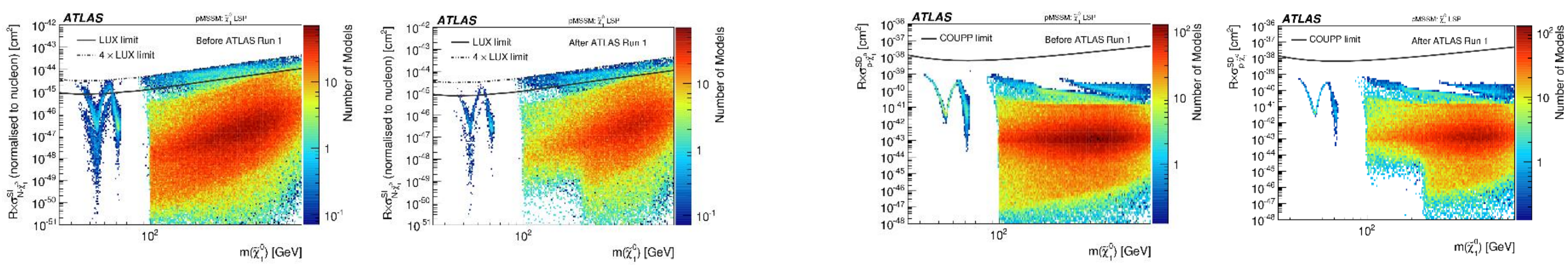
- Bino models:
  - Z and h funnel can be seen and about 2/3 are excluded
  - ATLAS searches has sensitivity up to $m(\tilde{\chi}_1^0) \lesssim$ 800 GeV
- Wino models:
  - Again up to $m(\tilde{\chi}_1^0) \lesssim$ 800 GeV. Especially good below 200 GeV where 80% are excluded
  - Dominated by disappearing track analysis
- Higgsino models:
  - Charged higgsino lifetime is too short for disappearing track analysis

DM Interaction Cross Section

Interaction cross section



Animation: Model not excluded before and after ATLAS Run-1

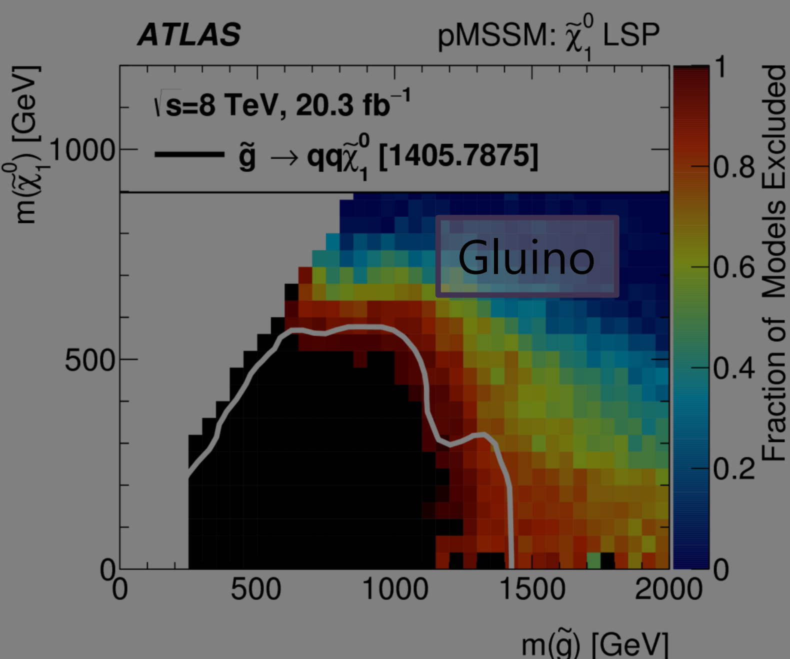


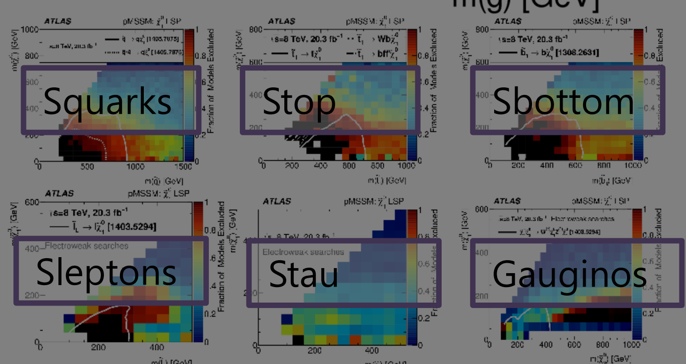
Same plots. Static version

- The box of excluded regions are dominated by almost-pure wino LSP models which are constrained by disappearing track analysis

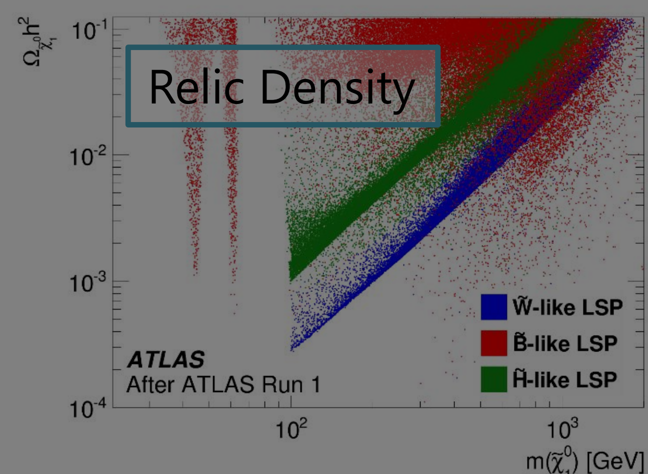
Outline

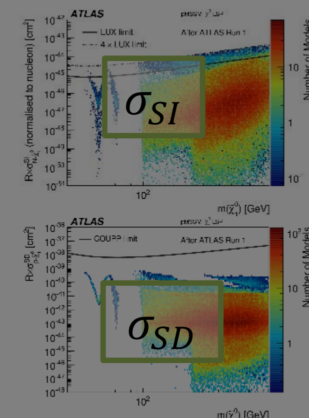
Mass Limits



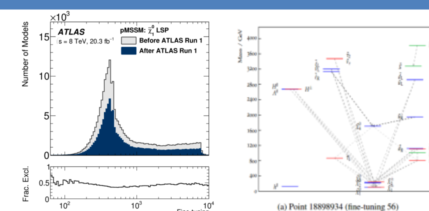


Dark Matter

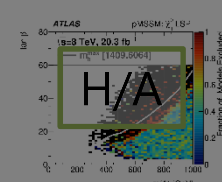


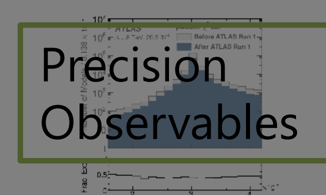


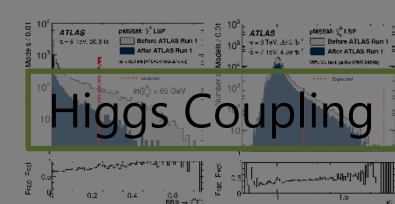
Naturalness

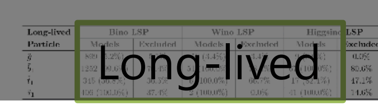


And many others...



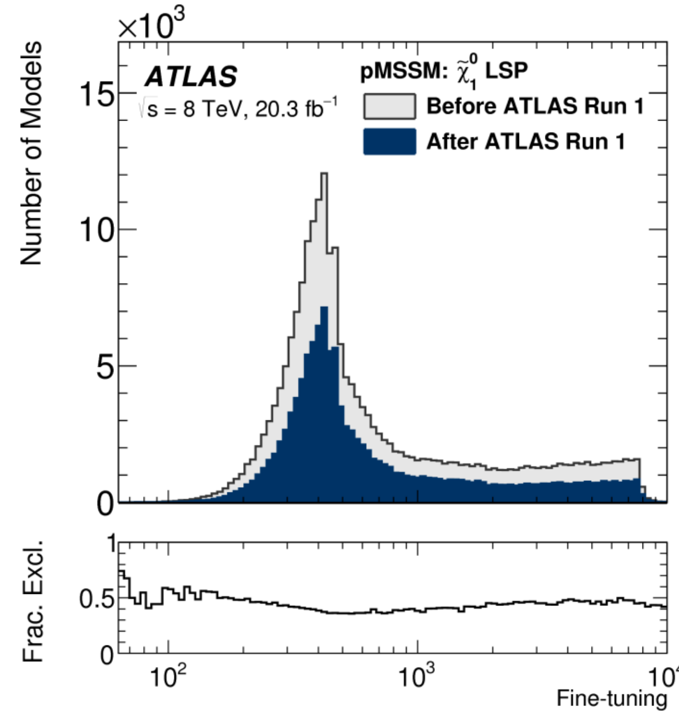


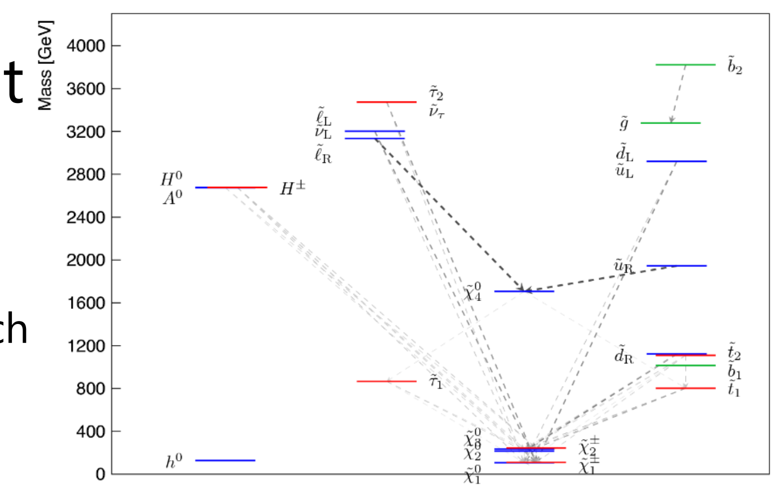




Naturalness of models

- Check the sensitivity as a function of fine tuning
  - No naturalness requirement in model selections
  - The fine-tuning parameter = 10 means cancellation of parameters up to an order of magnitude
  - we employ the definition of Barbieri and Giudic (Nucl. Phys. B306 1459 (1988) 63.)
- ATLAS Run 1 searches' sensitivity mostly independent of fine-tuning
- The mass spectrum of the lowest fine-tuned model (~O(2%)) surviving all constraints is shown on the right plot
  - Wino-like LSP, which only slightly lighter than its charge partner, evading disappearing track search
  - Stop just beyond Run 1 reach
  - Gluino and left-squark also just beyond Run 1 reach





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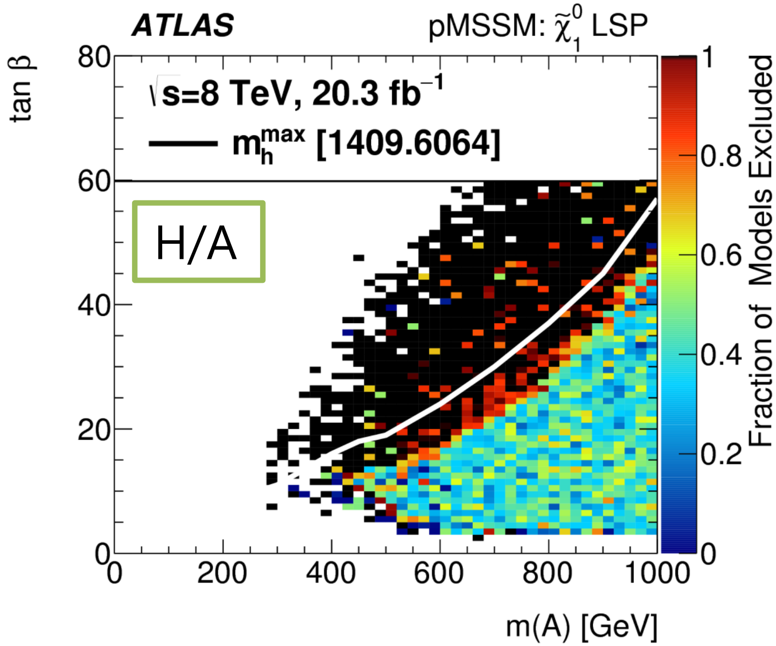
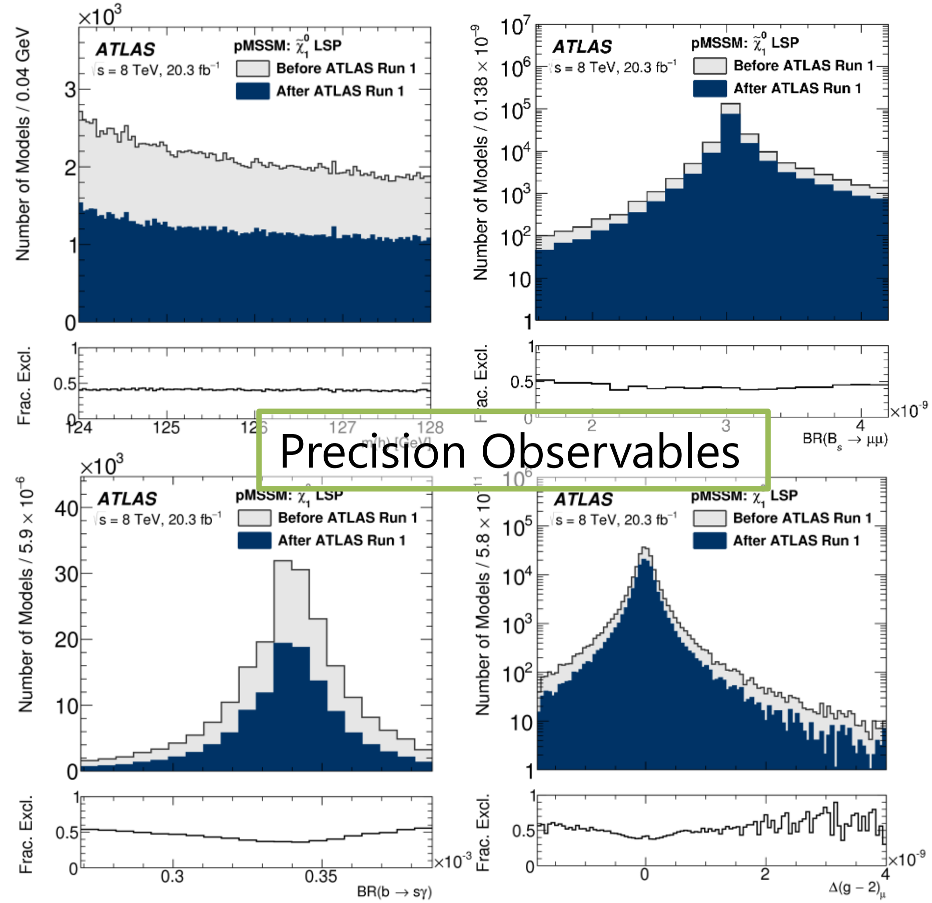
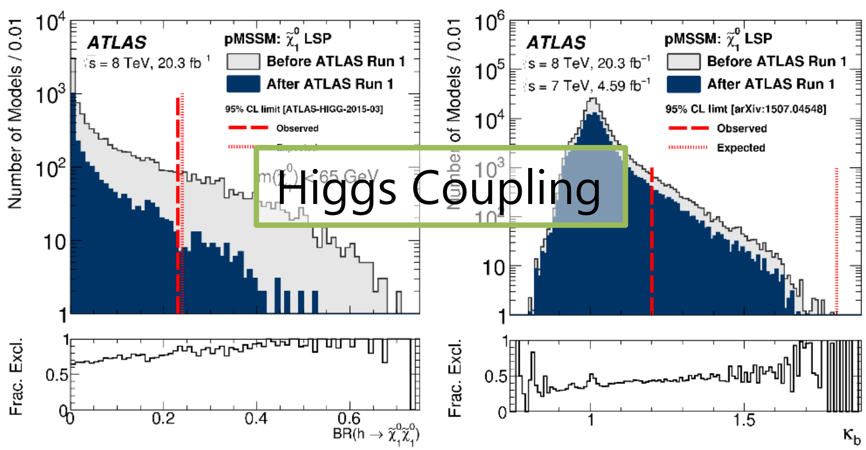




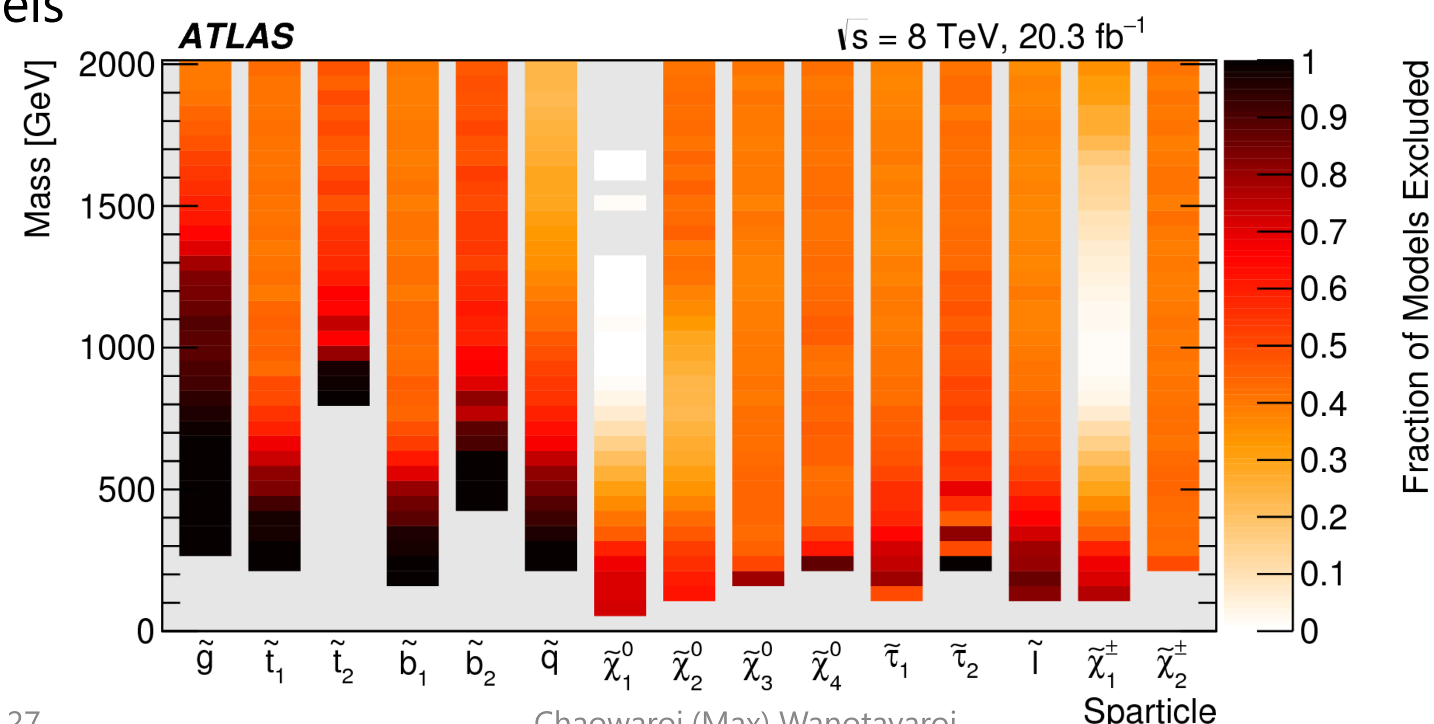


Long-lived

Long-lived Particle	Bino LSP Models	Bino LSP Excluded	Wino LSP Models	Wino LSP Excluded	Higgsino LSP Models	Higgsino LSP Excluded
$\tilde{g}$	899 (5.2%)	5.1%	58 (3.4%)	3.4%	9 (0.0%)	0.0%
$\tilde{b}_1$	1252 (99.6%)	76.4%	51 (100.0%)	78.4%	67 (100.0%)	80.6%
$\tilde{t}_1$	345 (56.8%)	36.5%	6 (100.0%)	66.7%	17 (82.4%)	47.1%
$\tilde{\tau}_1$	406 (100.0%)	37.4%	2 (100.0%)	0.0%	41 (100.0%)	14.6%

Conclusions

- ATLAS Run 1 searches are most effective for strongly interacting particles
- Sensitivity to simplified models have been shown to have a fairly good correspondence to the sensitivity to pMSSM models, but significant differences are observed in certain regions
- Good complementarity to dark matter detection experiments
- Models and the corresponding ATLAS exclusions will be publicly available
- Additional sensitivity in Run 2 will have a final say on lower fine-tuned models



Backup

pMSSM

- The minimal supersymmetric extension of the Standard Model (MSSM) has over a hundred free parameters
- Typically, a simplified model with a few varying parameters is presented in context of an ATLAS search
  - The effect of multiple production channels and decay modes are usually lost
- A set of assumptions reduces MSSM to 19 free parameters called phenomenological MSSM (pMSSM) [Ref 1, 2, 3]
  - Motivated by experiment results or possible SUSY breaking mechanism
    - R-parity is exactly conserved
    - No new source of CP–violation
    - No flavor changing neutral currents parameters
    - The first two generations of squarks and sleptons with the same quantum numbers are mass degenerate, and their Yukawa couplings are too small to affect sparticle production or precision observables
    - Lightest neutralino is the LSP

Parameter	Min value	Max value	Note
$m_{\tilde{L}_1}(=m_{\tilde{L}_2})$	90 GeV	4 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde{e}_1}(=m_{\tilde{e}_2})$	90 GeV	4 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde{L}_3}$	90 GeV	4 TeV	Left-handed stau doublet mass
$m_{\tilde{e}_3}$	90 GeV	4 TeV	Right-handed stau mass
$m_{\tilde{Q}_1}(=m_{\tilde{Q}_2})$	200 GeV	4 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde{u}_1}(=m_{\tilde{u}_2})$	200 GeV	4 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde{d}_1}(=m_{\tilde{d}_2})$	200 GeV	4 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde{Q}_3}$	100 GeV	4 TeV	Left-handed squark (third gen.) mass
$m_{\tilde{u}_3}$	100 GeV	4 TeV	Right-handed top squark mass
$m_{\tilde{d}_3}$	100 GeV	4 TeV	Right-handed bottom squark mass
$\|M_1\|$	0 GeV	4 TeV	Bino mass parameter
$\|M_2\|$	70 GeV	4 TeV	Wino mass parameter
$\|\mu\|$	80 GeV	4 TeV	Bilinear Higgs mass parameter
M_3	200 GeV	4 TeV	Gluino mass parameter
$\|A_t\|$	0 GeV	8 TeV	Trilinear top coupling
$\|A_b\|$	0 GeV	4 TeV	Trilinear bottom coupling
$\|A_\tau\|$	0 GeV	4 TeV	Trilinear τ lepton coupling
M_A	100 GeV	4 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

pMSSM free parameters and their scan range

ATLAS Searches

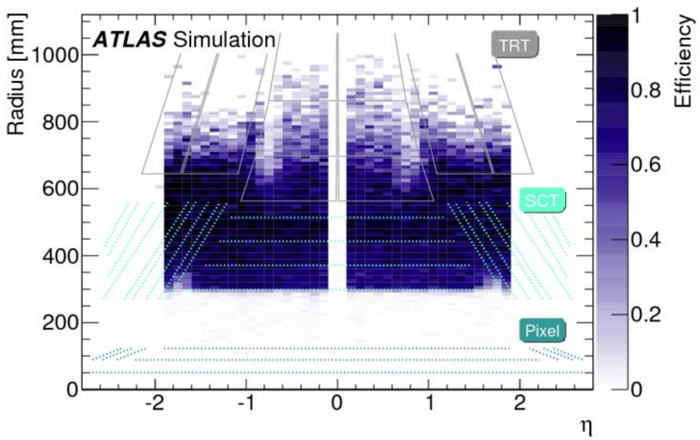
- 22 distinct ATLAS searches represent a wide range of strategies
- Each has many signal regions
  - Most regions are considered, but some are left out due to practical reasons
  - Almost 200 signal regions total
- 4 general categories of analyses
  1. Inclusive: Prompt decay of first two generations squarks or gluinos, including cascade decays
  2. 3rd Gen: Direct production of top and bottom squarks (stop and sbottom)
  3. Electroweak: Production of electroweakinos (neutralinos and charginos) and sleptons
  4. Other: Long-live particles and heavy Higgs

Analysis	Ref.	Category
0-lepton + 2–6 jets + E_T^{miss}	Link	Inclusive
0-lepton + 7–10 jets + E_T^{miss}	Link	
1-lepton + jets + E_T^{miss}	Link	
$\tau(\tau/\ell)$ + jets + E_T^{miss}	Link	
SS/3-leptons + jets + E_T^{miss}	Link	
0/1-lepton + 3b-jets + E_T^{miss}	Link	
Monojet	Link	
0-lepton stop	Link	hird generation
1-lepton stop	Link	
2-leptons stop	Link	
Monojet stop	Link	
Stop with Z boson	Link	
2b-jets + E_T^{miss}	Link	
tb+E_T^{miss}, stop	Link	
ℓh	Link	Electroweak
2-leptons	Link	
2-τ	Link	
3-leptons	Link	
4-leptons	Link	
Disappearing Track	Link	
Long-lived particle	1, 2	Other
$H/A \to \tau^+\tau^-$	Link	

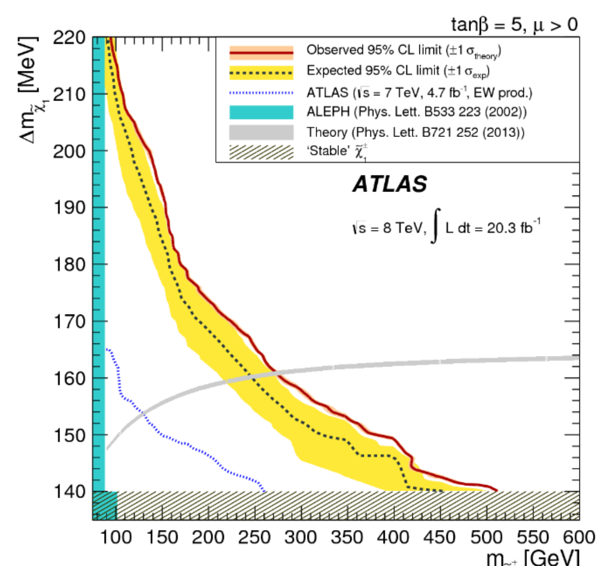
Lepton (ℓ) refers specifically to e± and μ± states, except in the cases of the electroweak 3-leptons and 4-leptons analyses where τs are also included.

Disappearing Track Search

- Motivated by anomaly-mediated SUSY breaking
- LSP almost pure-wino
- LSP almost mass degenerated with the lightest chargino due to radiative correction involving EW gauge bosons
- Typical mass spitting is ~160 MeV
- The chargino has a lifetime of a fraction of nanosecond
- Decay length of a few centimeters
- The chargino left a few hit in the tracker, then decay to LSP and 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 with the disappearing-track selection. Vertical and horizontal axes are the radius and η of the decay, respectively. Sensitive layers and areas of the pixel, SCT and TRT detectors are also indicated in the figure.



Model Points

- Upper bound on all sparticles mass is 4 TeV
  - Accessible for the LHC Run 1
  - This choice has direct effect on fraction of model excluded
- Randomly pick values for the 19 parameters within the ranges
  - 500 million models
- Further constrain the models by precision EW and flavor, dark matter abundance, LEP results, and Higgs mass
  - 310,327 models
  - Will be referred to as pre-ATLAS Run 1 constraints
- Importance sampling by LSP type
  - Models with bino-like LSP tends to over-produced dark matter but they are important
    - Observable LSP at 8 TeV and available decay modes
  - From the 500 millions models, use the first 20 millions to pick wino and Higgsino-like LSP models
  - Use the rest to pick Bino-like LSP models
  - Weight them to account for the bias

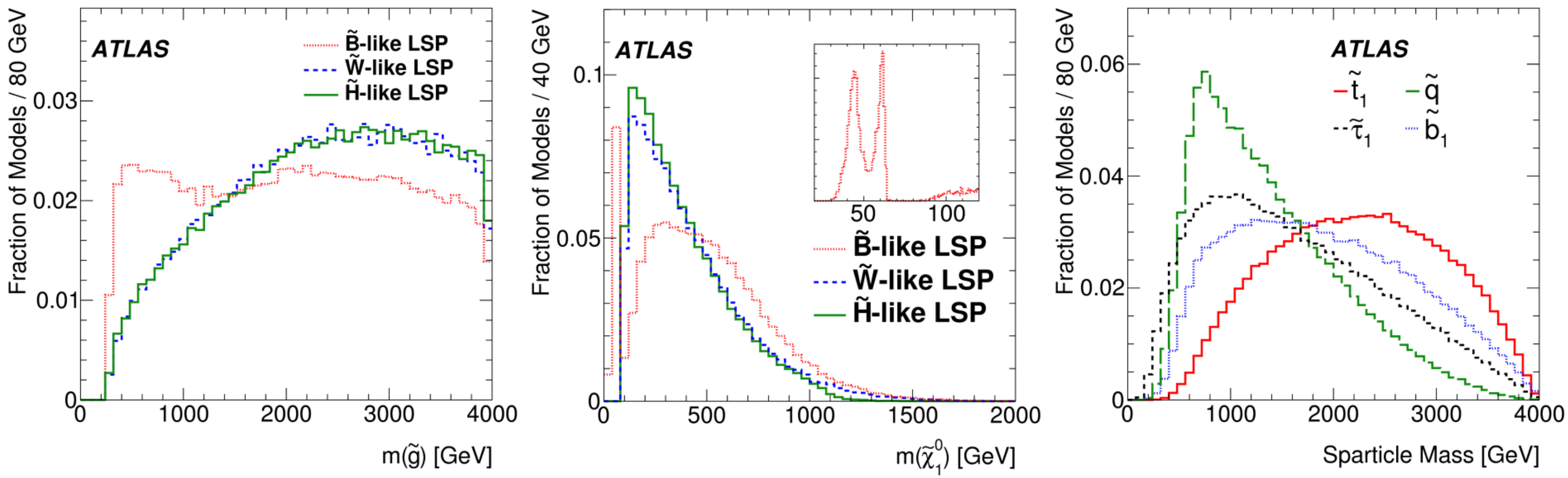
Constrains on acceptable pMSSM points

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}
$\Omega_{\tilde{\chi}_1^0}h^2$	—	0.1208
$\Gamma_{\mathrm{invisible(SUSY)}}(Z)$	—	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

LSP type of sample models

LSP type	Definition	Sampled	Simulated		Weight
			Number	Fraction	
'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	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		

Model Properties



- Distributions of gluino and LSP mass in the models before ATLAS Run 1 search applied is shown on the left and middle plot
- Mass distributions of various sparticles in the model sample before ATLAS Run 1 search shown on the right plot

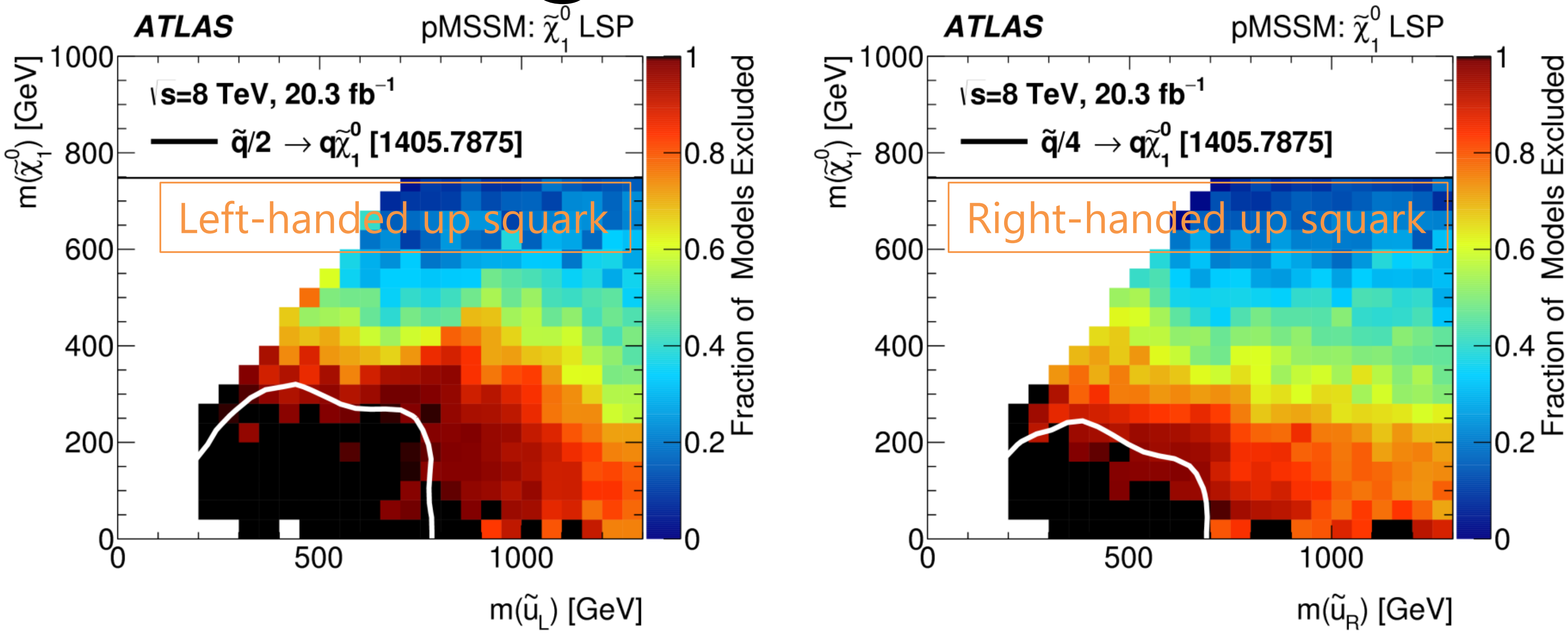
Evaluating Models

- 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 is can't be excluded

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%

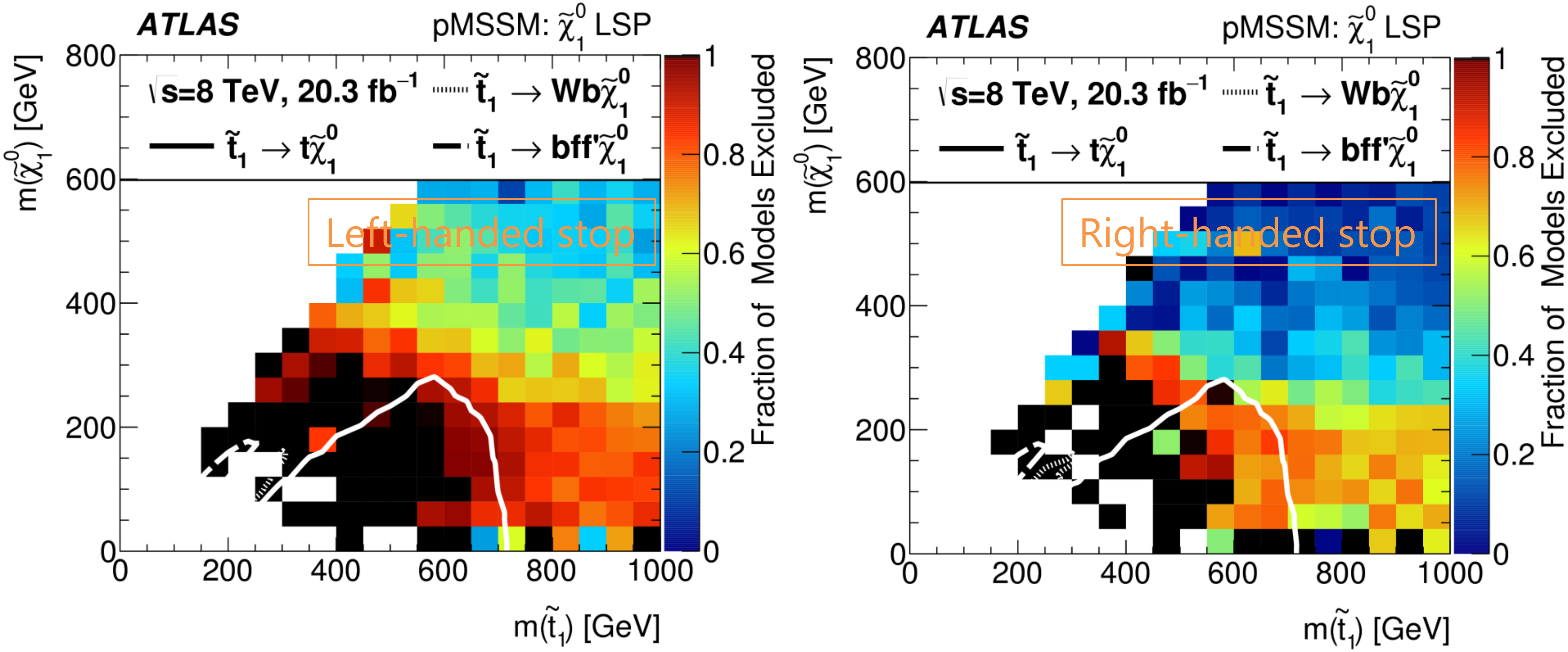
- Generate a sample of events
  - Only at particle level
  - Detector inefficiency are estimated
- Expected event yield in each signal region (N_{sig}) is calculated, then compare it to the model-independent 95% CL upper bound for the corresponding signal region (N_{max}^{95})
  - If N_{sig} considerably 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

Left- and Right-handed



- Search reach for left-handed and right-handed lightest squark
  - LH up and down type squarks form an SU(2) doublet so they are mass degenerate, effectively increasing production cross section
  - RH squarks lack weak coupling and have small Yukawa coupling
- LH and RH equivalent sensitivity assumption is not justified in context of pMSSM

3rd Gen—Stop



- Similar to the light-flavor squark, left-right chirality has non-trivial effect on the sensitivity in context of pMSSM

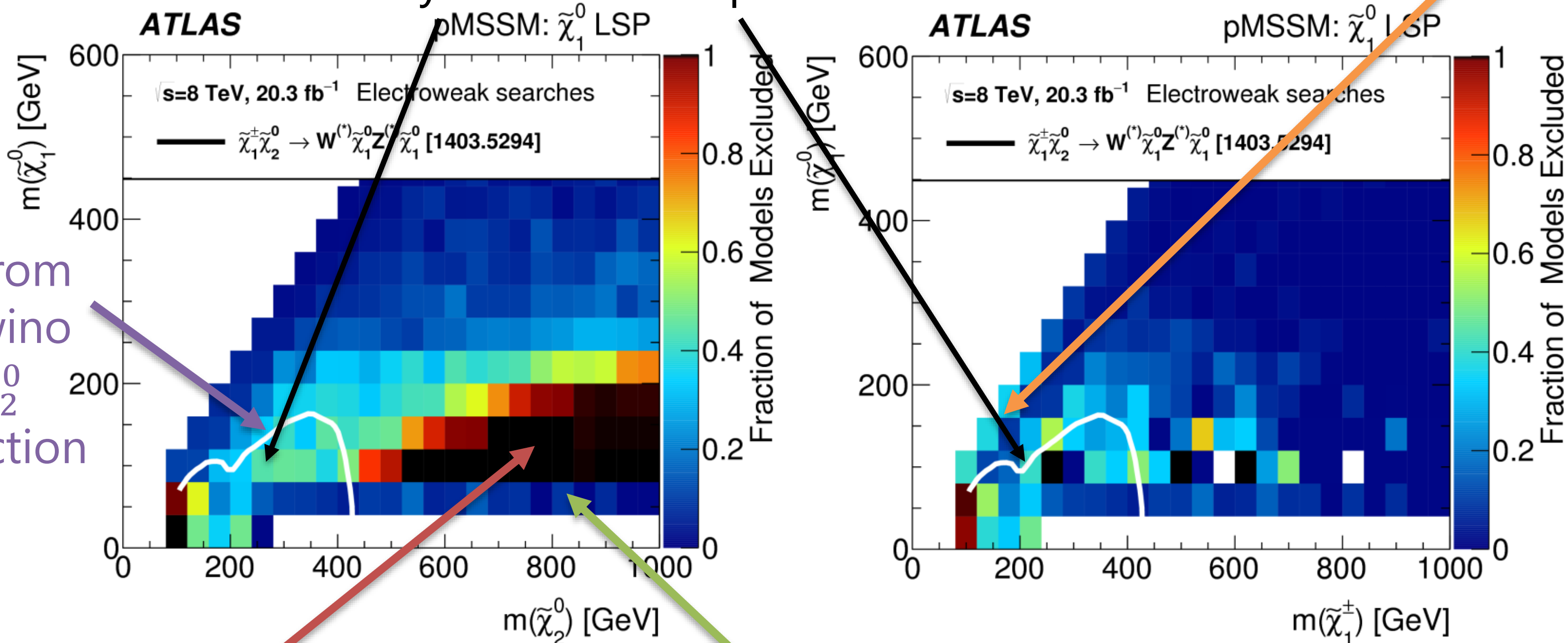
ATLAS constraints from LHC Run 1

EW Gauginos

Best sensitivity from multi-lepton searches

Some sensitivity from disappearing track

Limit from pure-wino $\tilde{\chi}_1^{\pm} + \tilde{\chi}_2^0$ production



Exclusion from Disappearing track analysis. Strongest when LSP is wino-like

This band is dominate by bino-like LSP due to the relic density limit controlled by Z and h funnels

- pMSSM sensitivity from electroweak searches on the $\tilde{\chi}_1^0 - \tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm} - \tilde{\chi}_1^0$ plane

Long-lived Particles

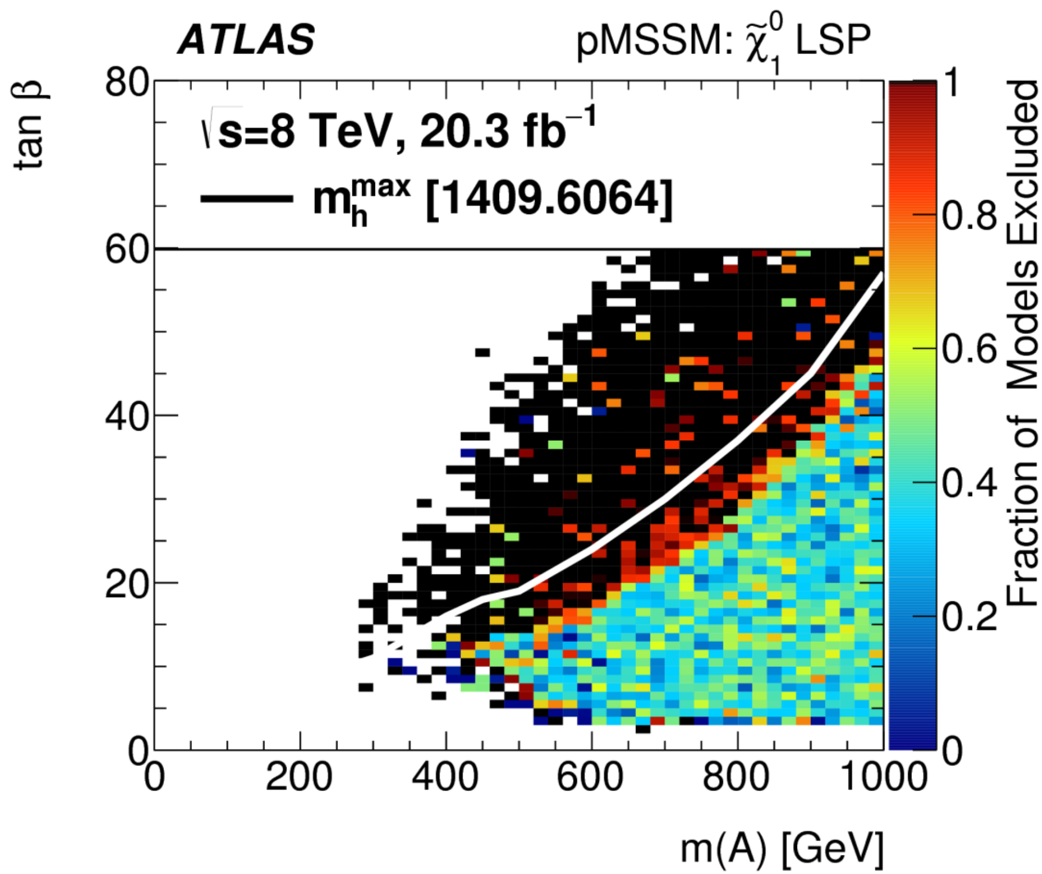
- Model with long-lived squarks, gluinos, and sleptons are considered using Long-lived particle searches only
- Particularly good at sbottom, bad at gluinos

Long-lived	**Bino LSP**		**Wino LSP**		**Higgsino LSP**	
Particle	**Models**	**Excluded**	**Models**	**Excluded**	**Models**	**Excluded**
$\tilde{g}$	899 (5.2%)	5.1%	58 (3.4%)	3.4%	9 (0.0%)	0.0%
$\tilde{b}_1$	1252 (99.6%)	76.4%	51 (100.0%)	78.4%	67 (100.0%)	80.6%
$\tilde{t}_1$	345 (56.8%)	36.5%	6 (100.0%)	66.7%	17 (82.4%)	47.1%
$\tilde{\tau}_1$	406 (100.0%)	37.4%	2 (100.0%)	0.0%	41 (100.0%)	14.6%

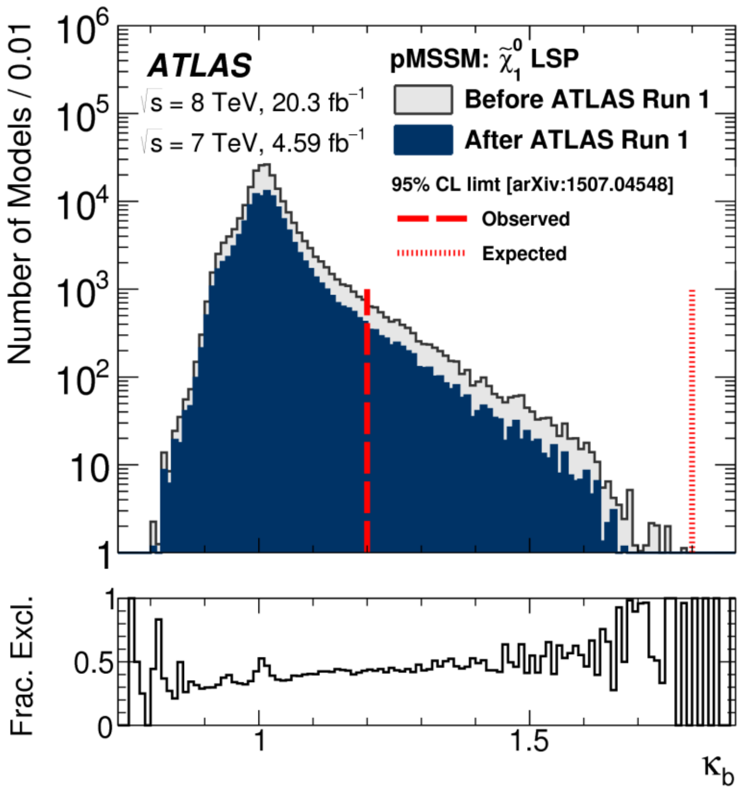
Number of model points with long-lived particles and their exclusion fraction. The percentages in parenthesis are the fractions of these model points where the long-lived particle has a lifetime long enough to traverse the full detector.

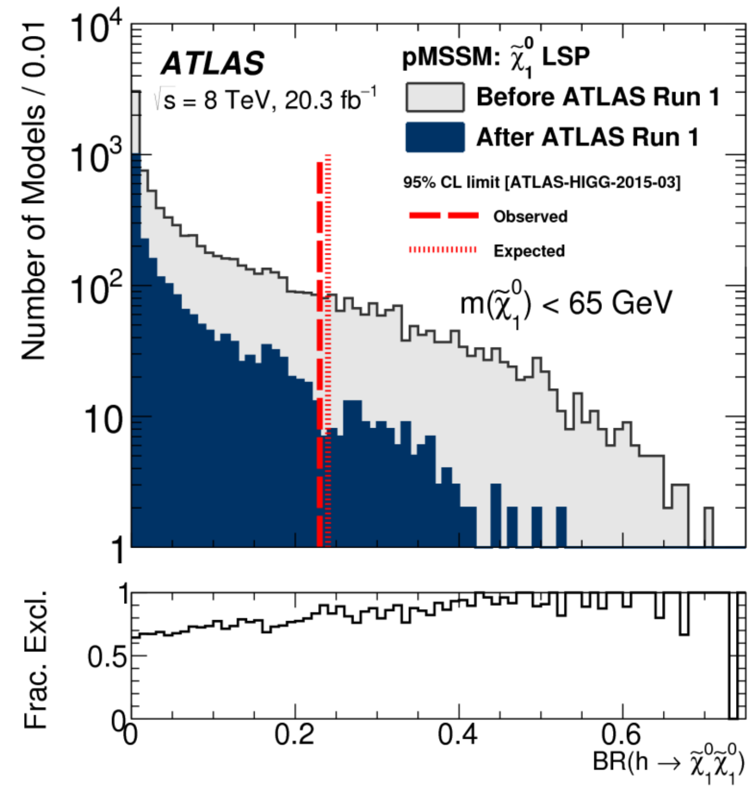
Heavy Higgs

- Search for Neutral Heavy Higgs, *H* or *A*, to $\tau\tau$
- Good correspondence observed. Simplified limit slightly underestimates the pMSSM result due to lighter electroweakinos



Effect of Higgs Coupling





- The current expected limit on the coupling to b-quark (κ_b) is too loose
- The observed limit disfavors about 3.1% of pMSSM models
- If LSP is light enough, $h \to$ invisible will be enhanced
  - Only bino models can have LSP this light and still satisfy pre-ATLAS Run 1 constraints
- Disfavor ~6.6% of bino models, which is ~0.03% of all points

Precision observables

- In general, ATLAS Run 1 search rules out models uniformly across the range of observables
- The “tail” models are slightly more sensitive since they usually have a light SUSY particle contributing via loop diagram
- The ranges of each plots correspond to the one used in model selection