pMSSM Studies with ATLAS and CMS

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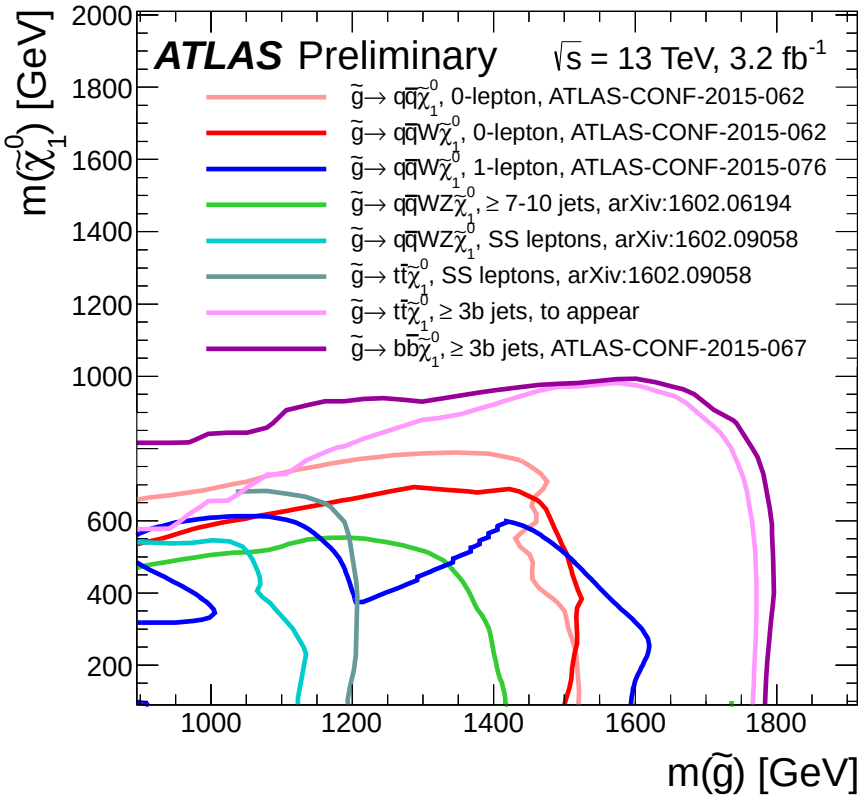
On behalf of the ATLAS and CMS collaborations

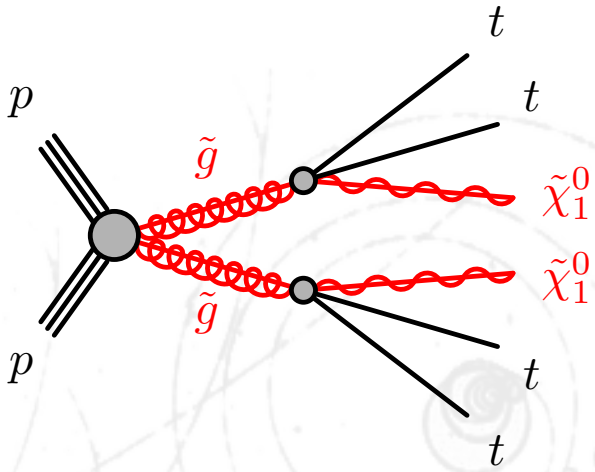
14 June 2016

How do we interpret the impact of experimental searches on SUSY?

Simplified Models



- Most searches interpret results in terms of simplified models
- These consider a single production and decay process
- Not representitive of more complex SUSY phenomenology



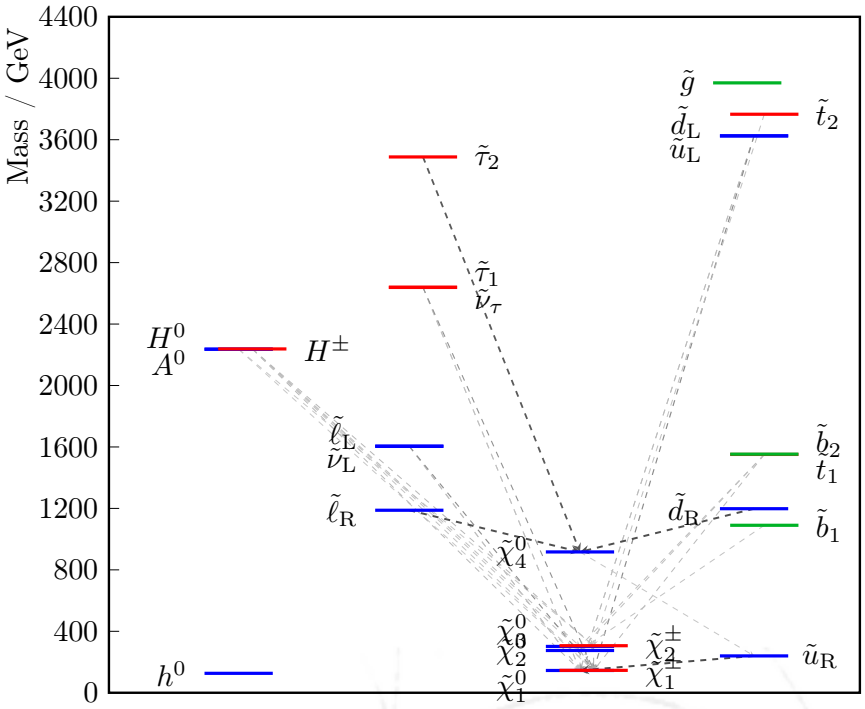
Is there a more generic way of understanding limits on SUSY?

The Phenomenological MSSM

Subset of 120 parameter MSSM

Key Constraints

- 1st gen. sfermion degenerate with corresponding 2nd gen. sfermion
- No CP violation beyond CKM
- No FCNC



- Constraints are motivated by experiments
- No assumption made about nature of SUSY breaking
- ATLAS and CMS use the 19-parameter pMSSM
- Lightest neutralino, $\tilde{\chi}_1^0$ is the LSP

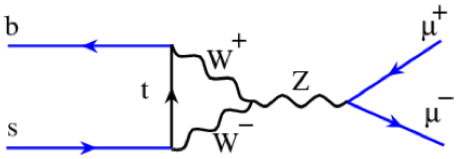
ATLAS and CMS

- Both ATLAS and CMS have produced large scale studies summarising the impact of Run-1 SUSY searches:
  ATLAS: JHEP 10 (2015) 134
  CMS: CMS-PAS-SUS-15-010
  New today! 1606.03577 (update of PAS note)

- Find points in pMSSM space: sets of parameters

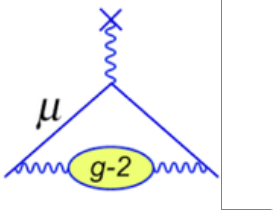
- Both apply relevant experimental constraints, such as:

Heavy Flavour ✔



Higgs Mass ✔

Precision Measurement ✔



Similarities and Differences

- Both employed flat priors to restrict the parameter space, eg all sparticles have mass less that 4 (3) TeV for ATLAS (CMS)

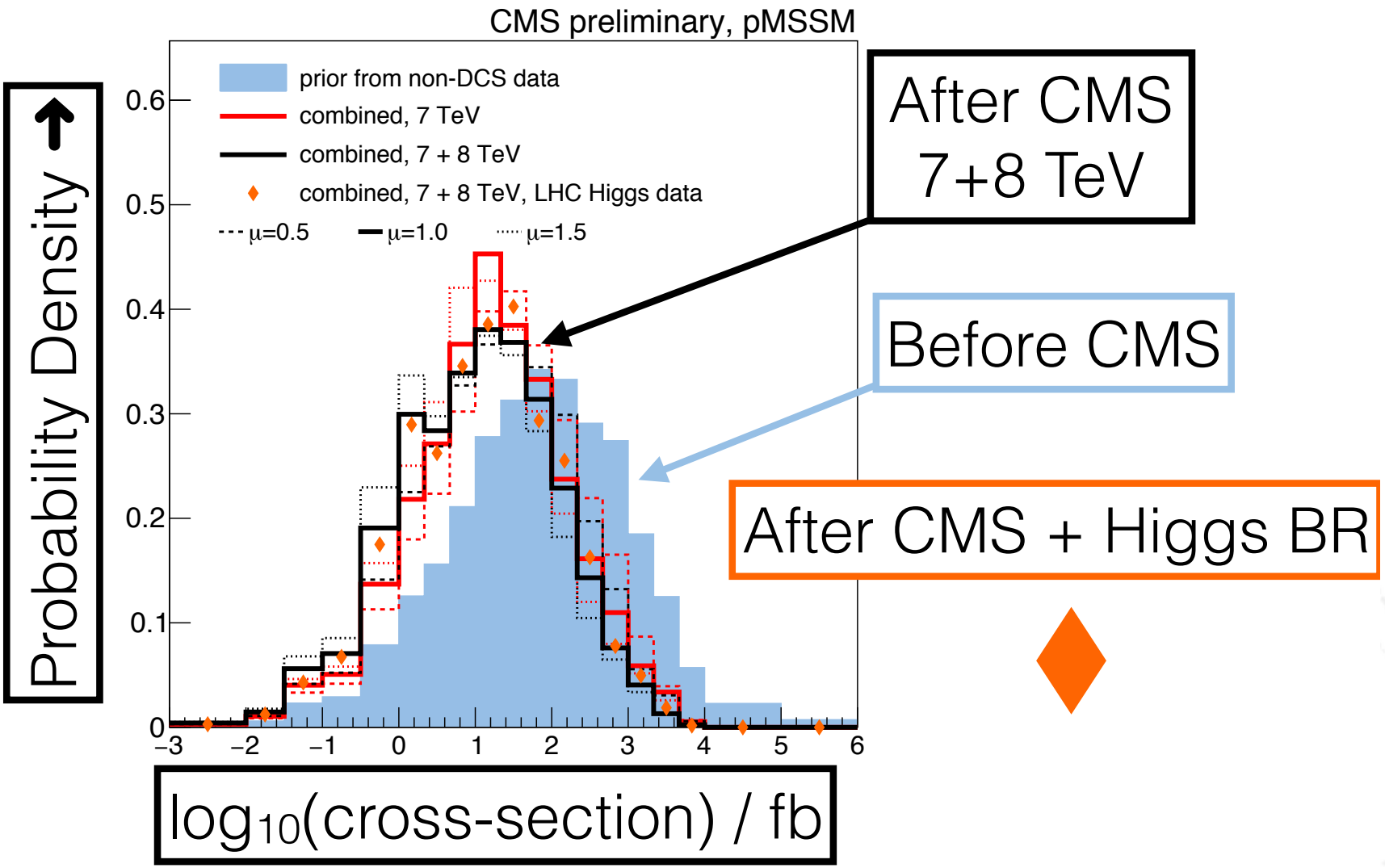
ATLAS

- Employed uniform sampling
- Sampled 500×10^6 points
- Dark Matter constraint: $\Omega h^2(\tilde{\chi}_1^0) <$Planck
- Simulated 300k models
- Combined 22 searches

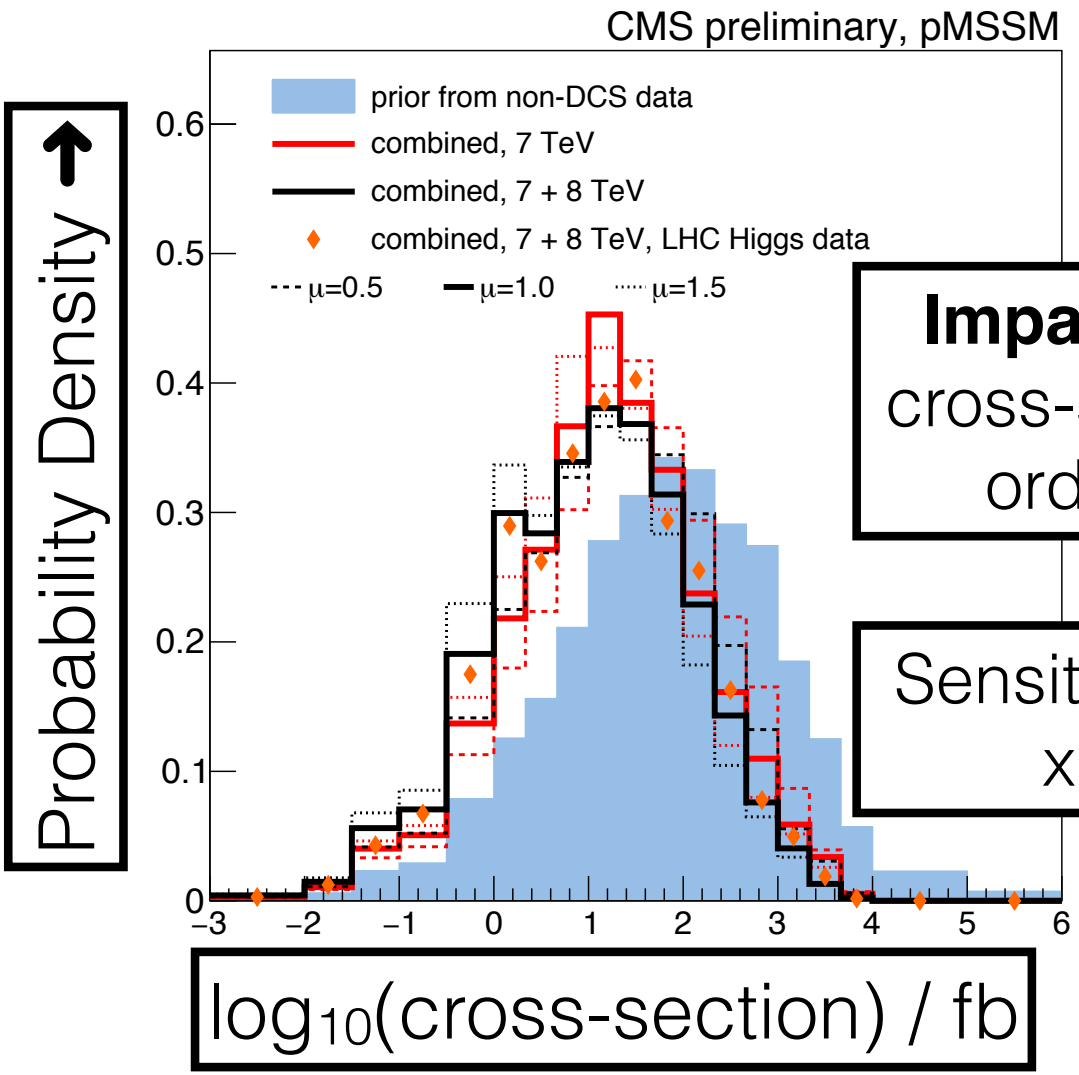
CMS

- Bayesian approach & MCMC
- Sampled 20×10^6 points
- No DM constraint
- Simulated 7k models
- Combined 11 searches

Results (CMS)


CMS preliminary, pMSSM
prior from non-DCS data
combined, 7 TeV
combined, 7 + 8 TeV
combined, 7 + 8 TeV, LHC Higgs data
μ=0.5
μ=1.0
μ=1.5
Probability Density
0.6
0.5
0.4
0.3
0.2
0.1
0
−3
−2
−1
0
1
2
3
4
5
6
log10(cross-section) / fb
After CMS 7+8 TeV
Before CMS
After CMS + Higgs BR

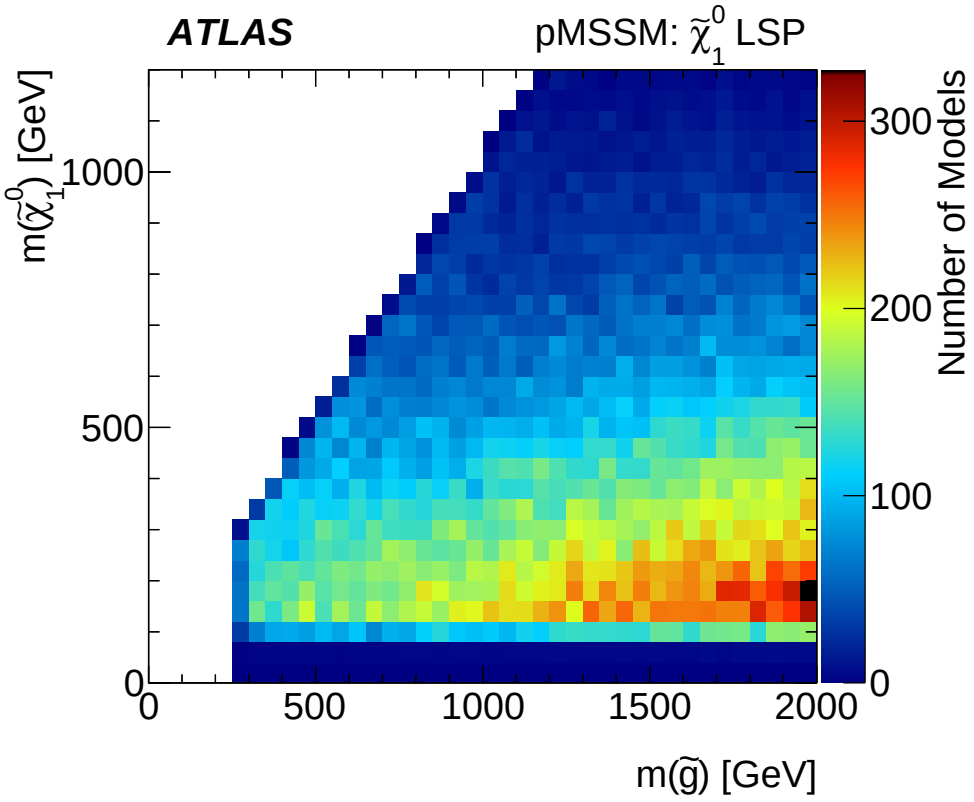
Cross-section

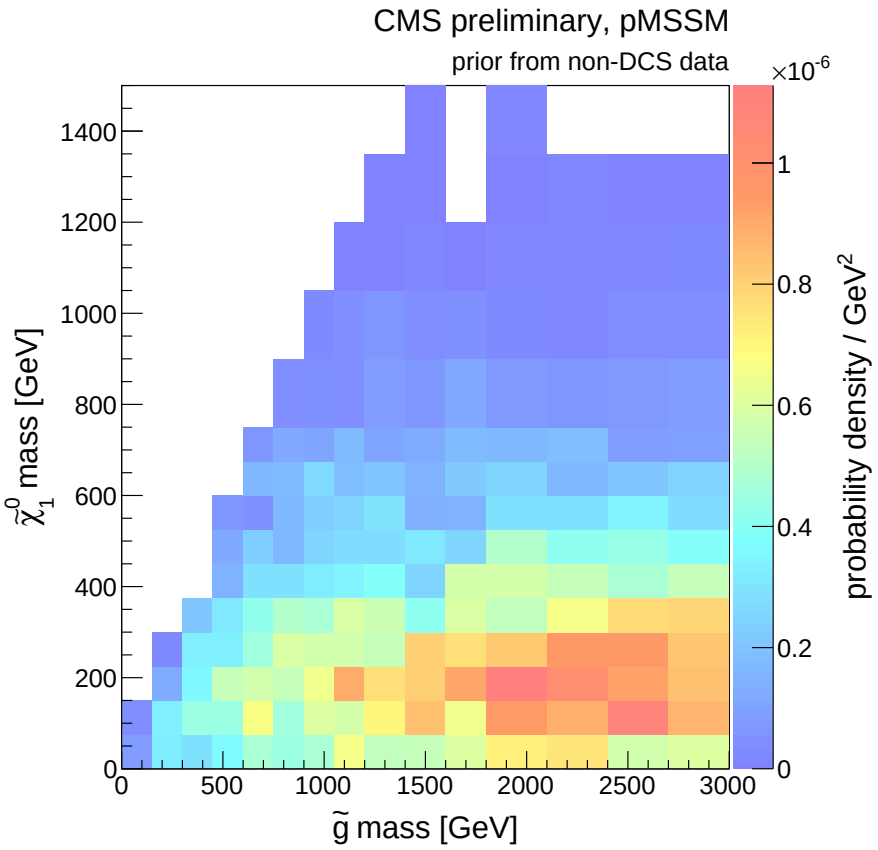


Impact: Most probable cross-section reduced by order of magnitude

Sensitivity to models with x-section of 1fb

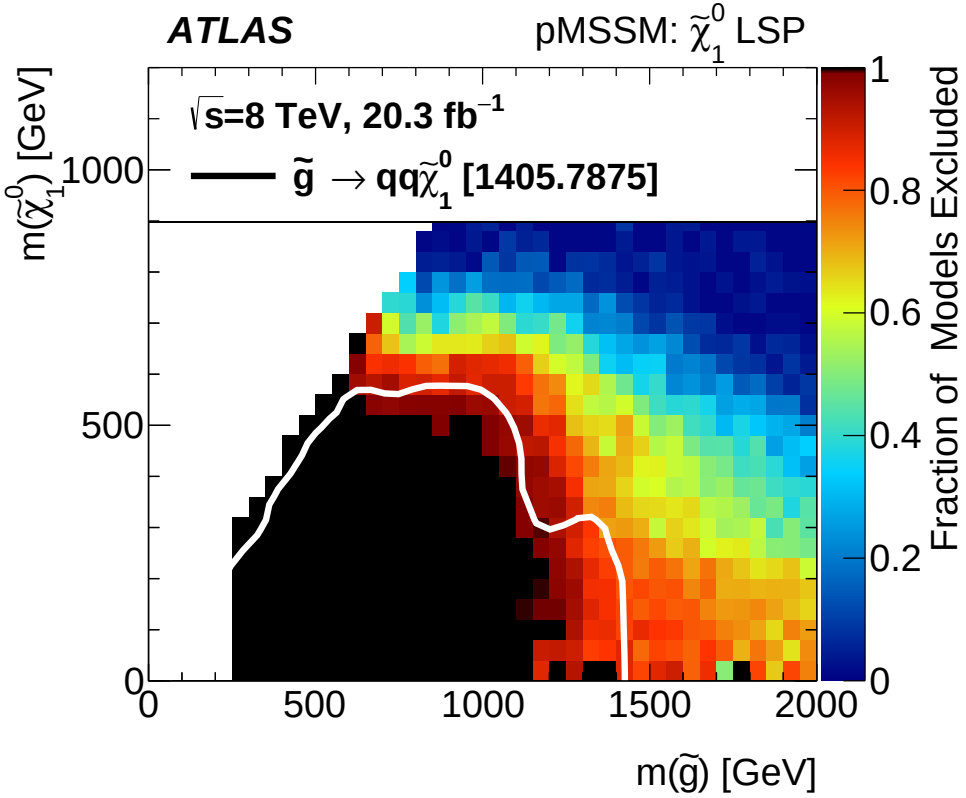
Gluinos: Before LHC

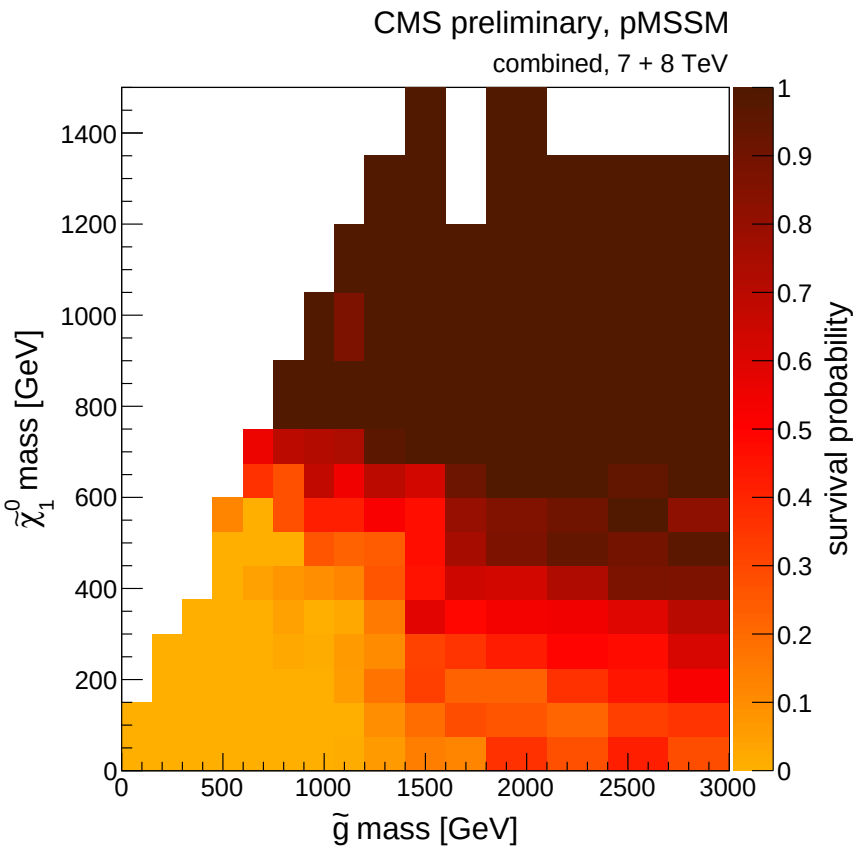




- Model density (prior)
- White squares mean no models
- Similarity between the two approaches

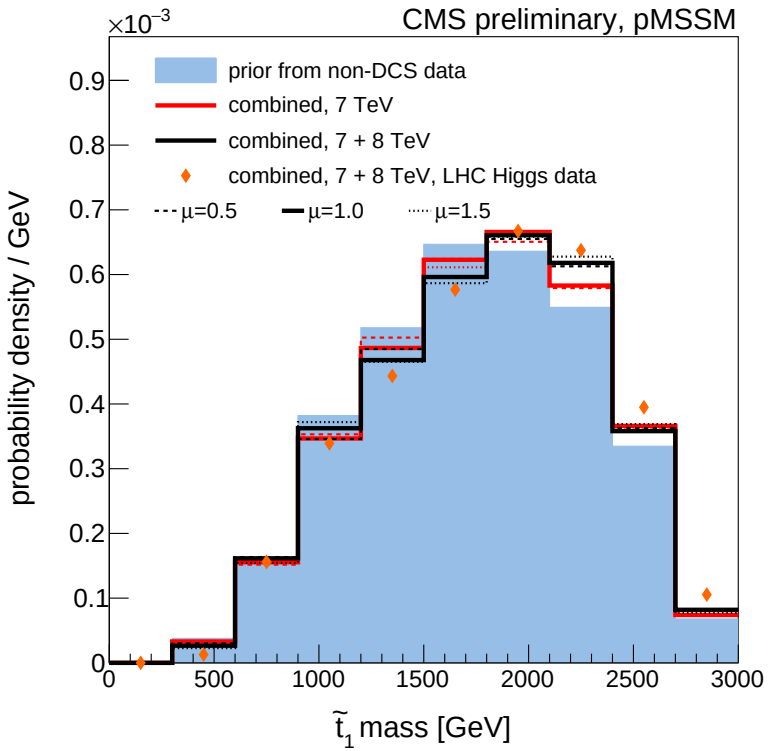
Gluinos: After LHC

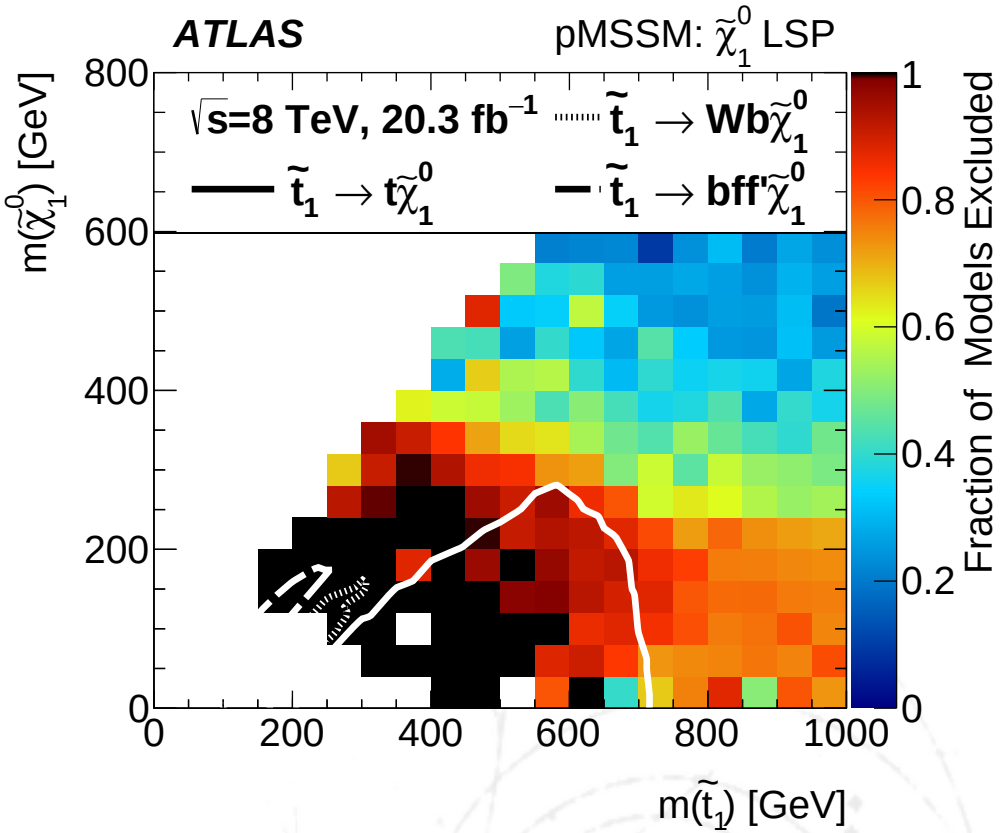




- Impact of searches
- No models with $m(\tilde{g}) < 500$ GeV remain

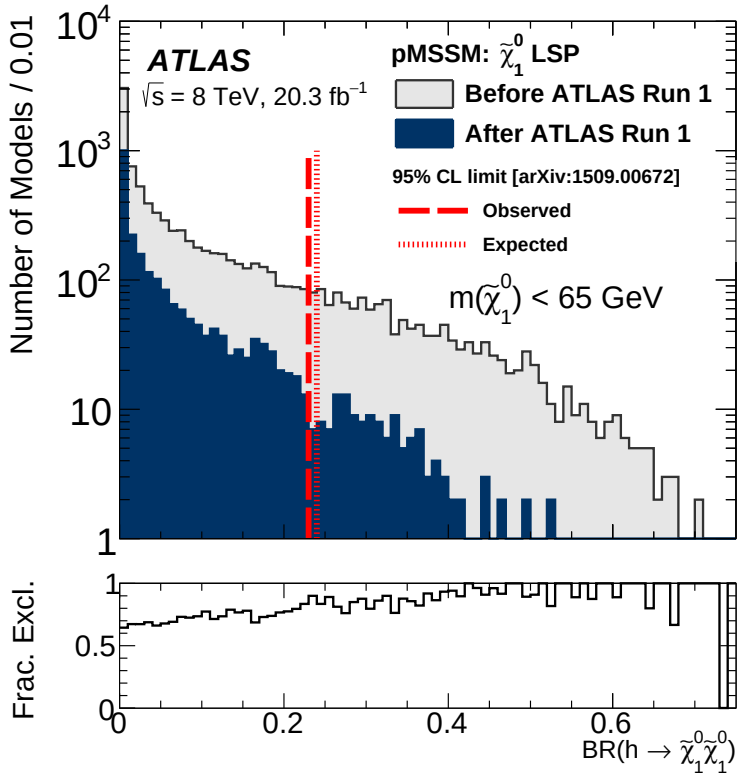
Stops

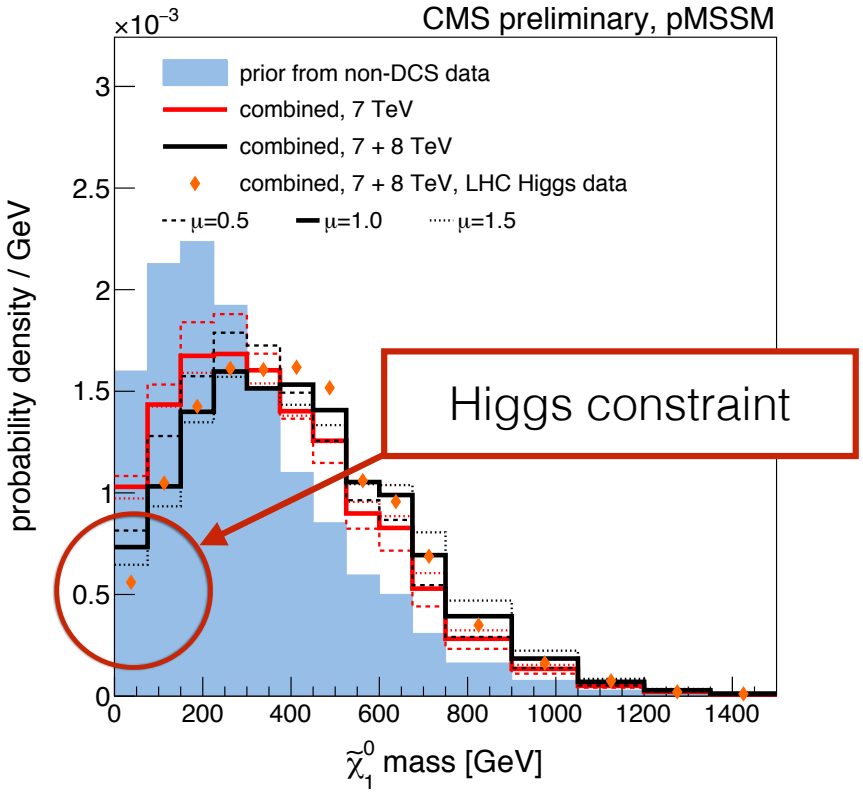




- Models with $m(\tilde{t}_1) < 500$ GeV are rare in the pMSSM
- Rare due to requirement $m(h) \approx 125$ GeV
- Models with light stops are still viable

Higgs to Invisibles

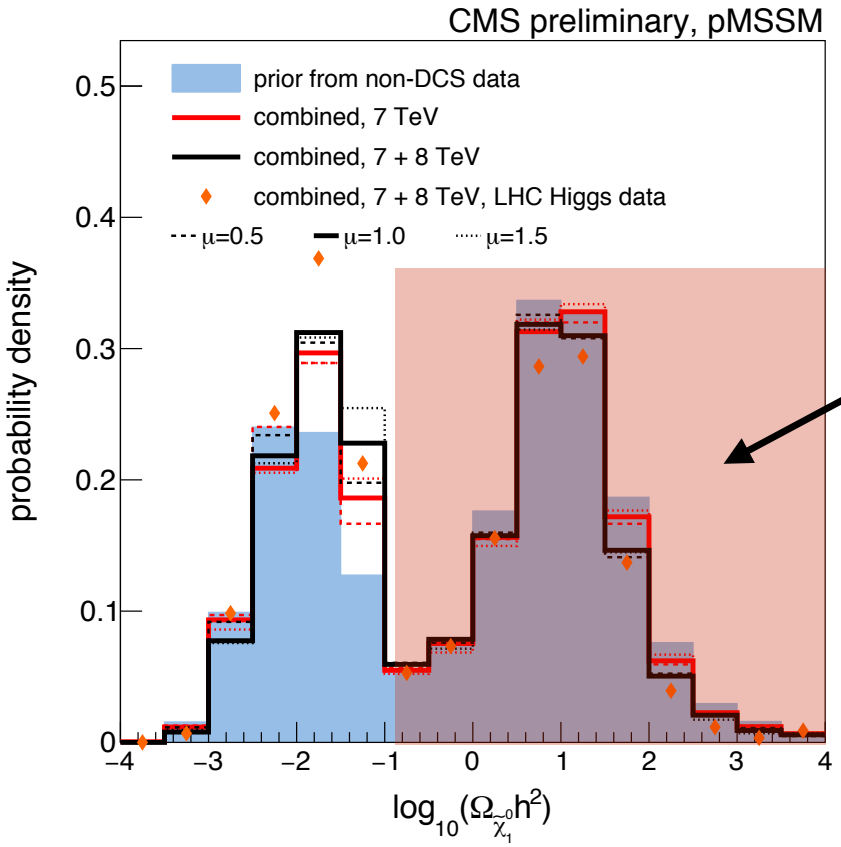




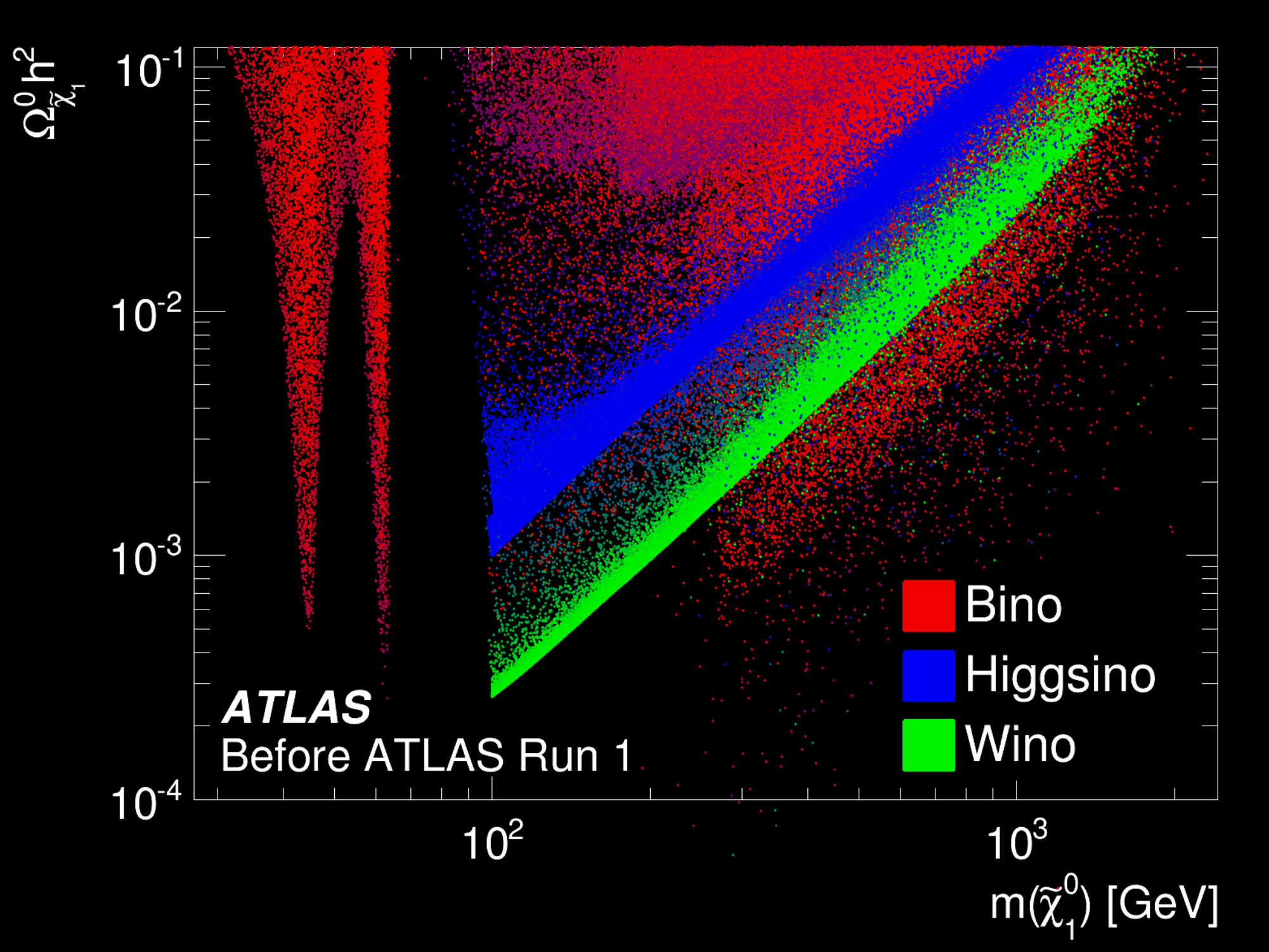
- If $m(\tilde{\chi}_1^0) \lesssim \frac{1}{2}m(h)$ then (invisible) $h \to \tilde{\chi}_1^0\tilde{\chi}_1^0$ occours
- Light neutralinos under threat from Higgs branching ratio constraints

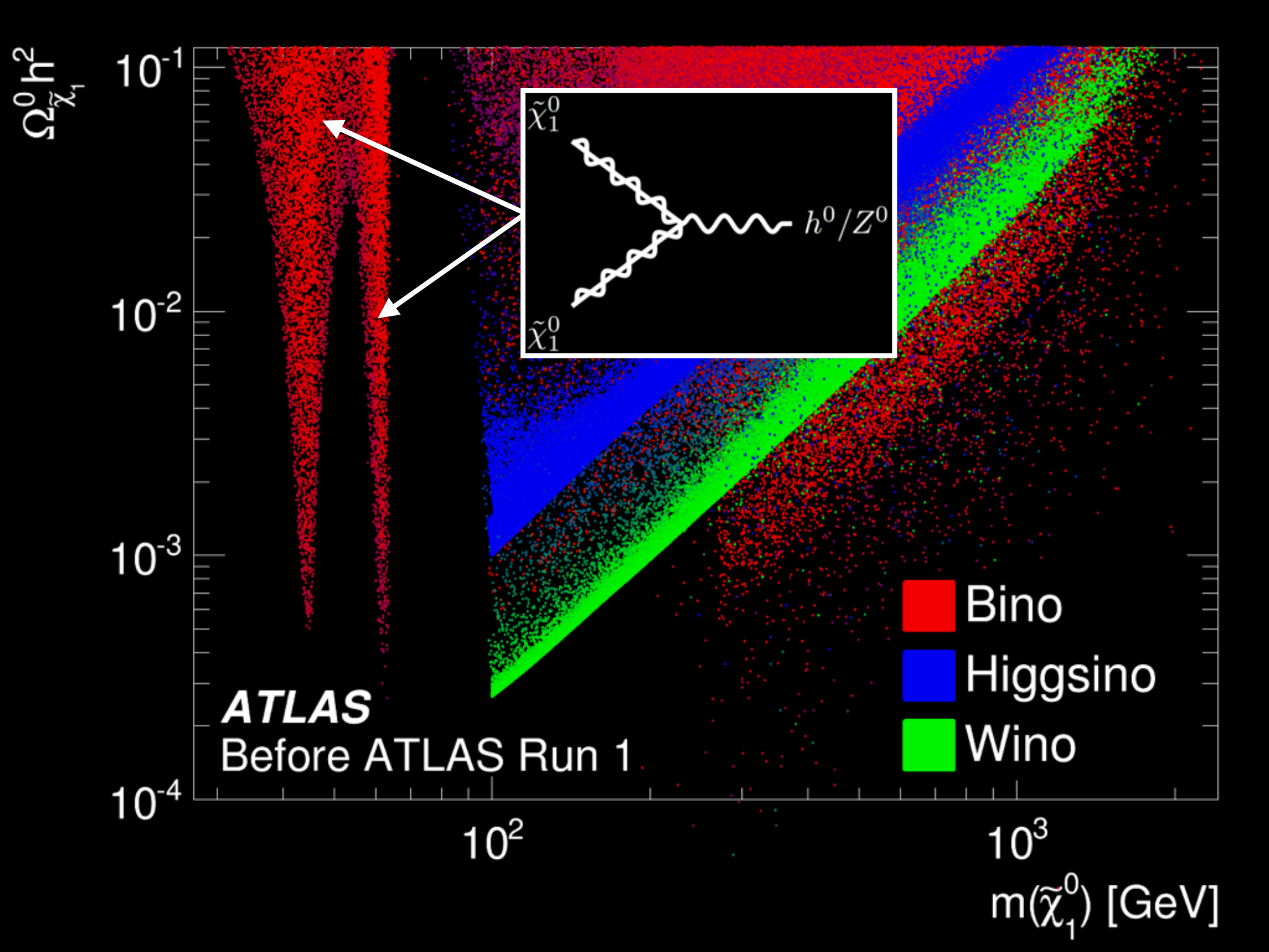
Dark Matter

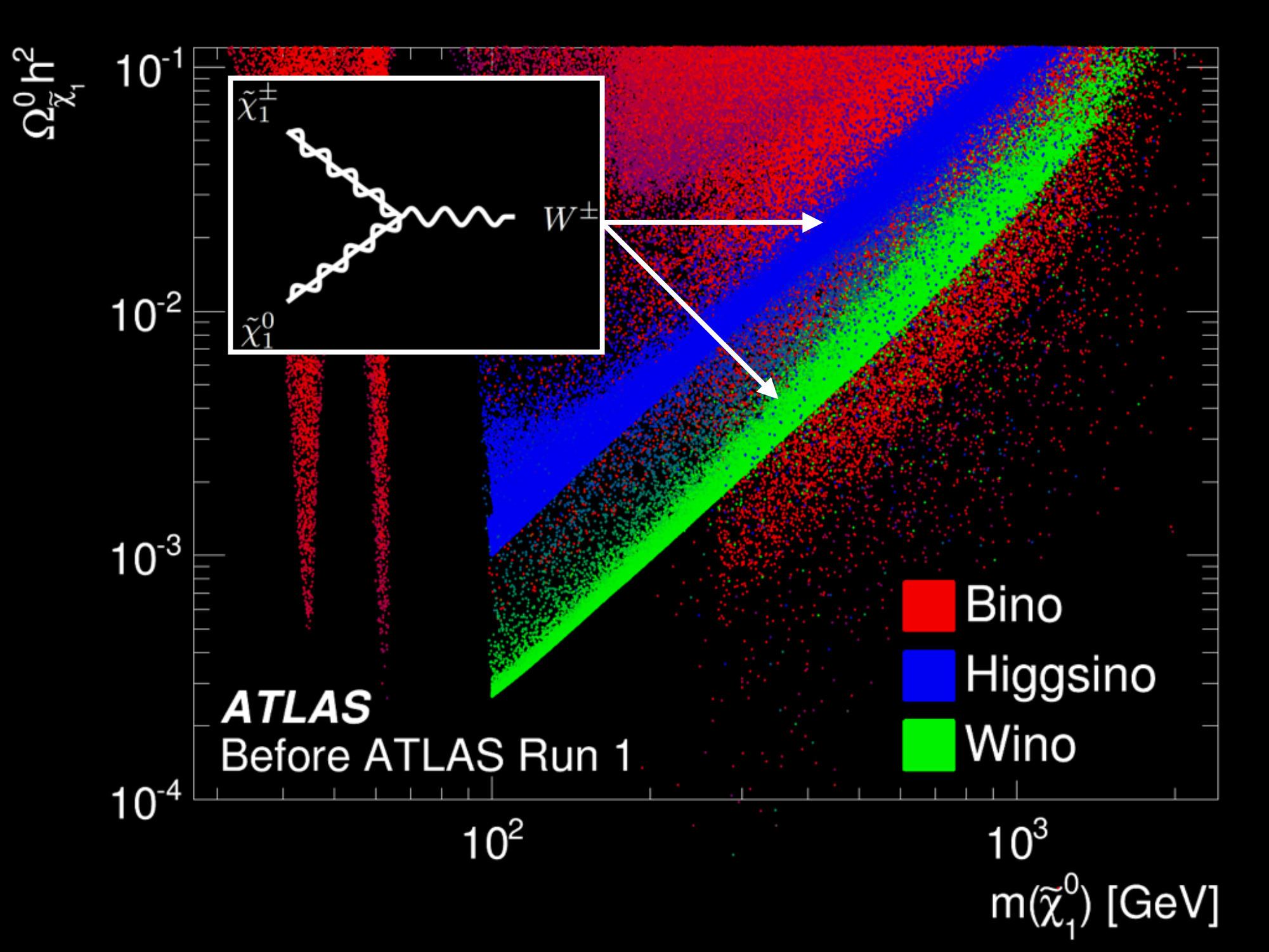
Key difference between the ATLAS and CMS approaches:
Constraint from PLANCK: $\Omega_{CDM}h^2 < 0.1208$

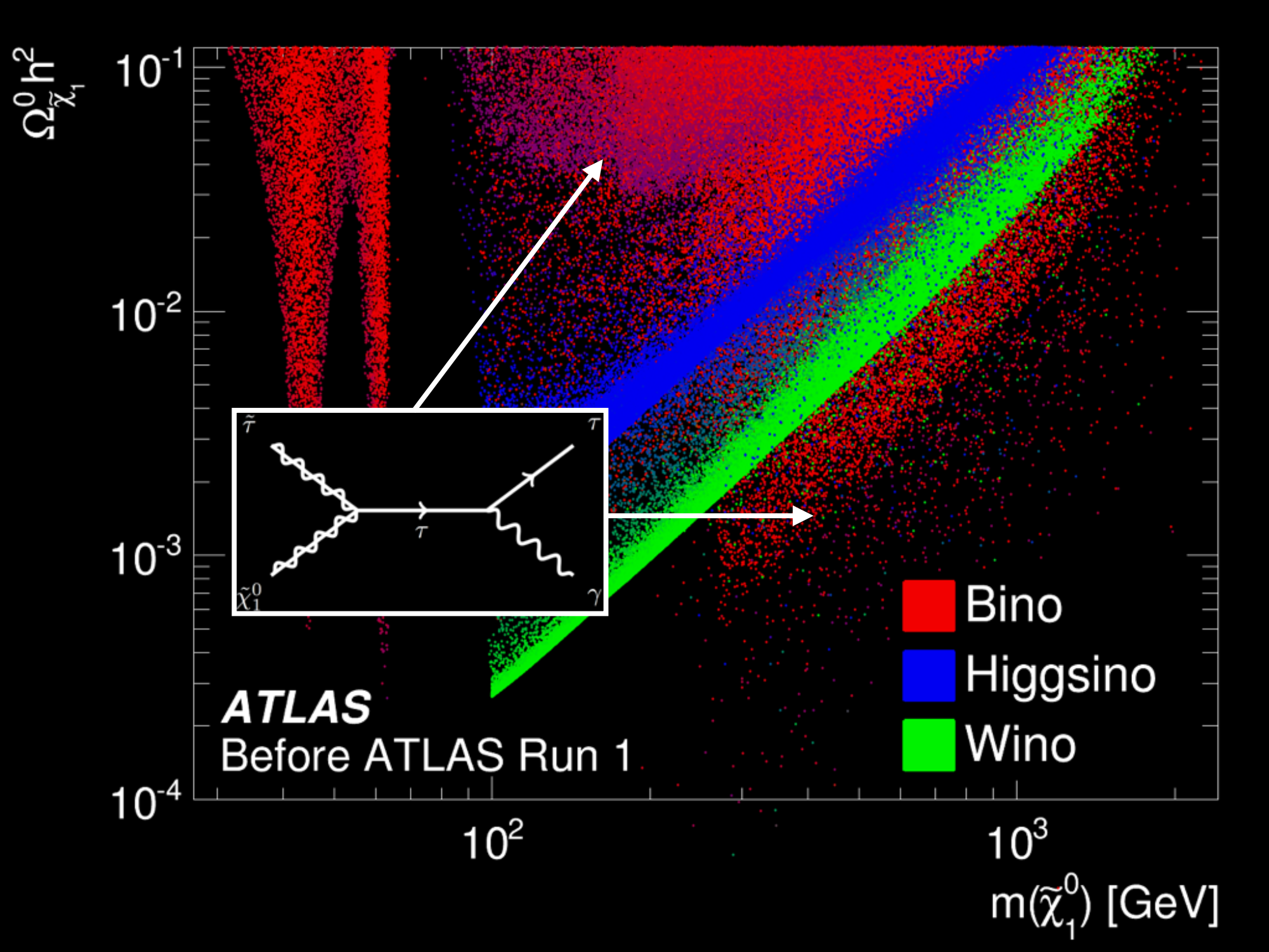


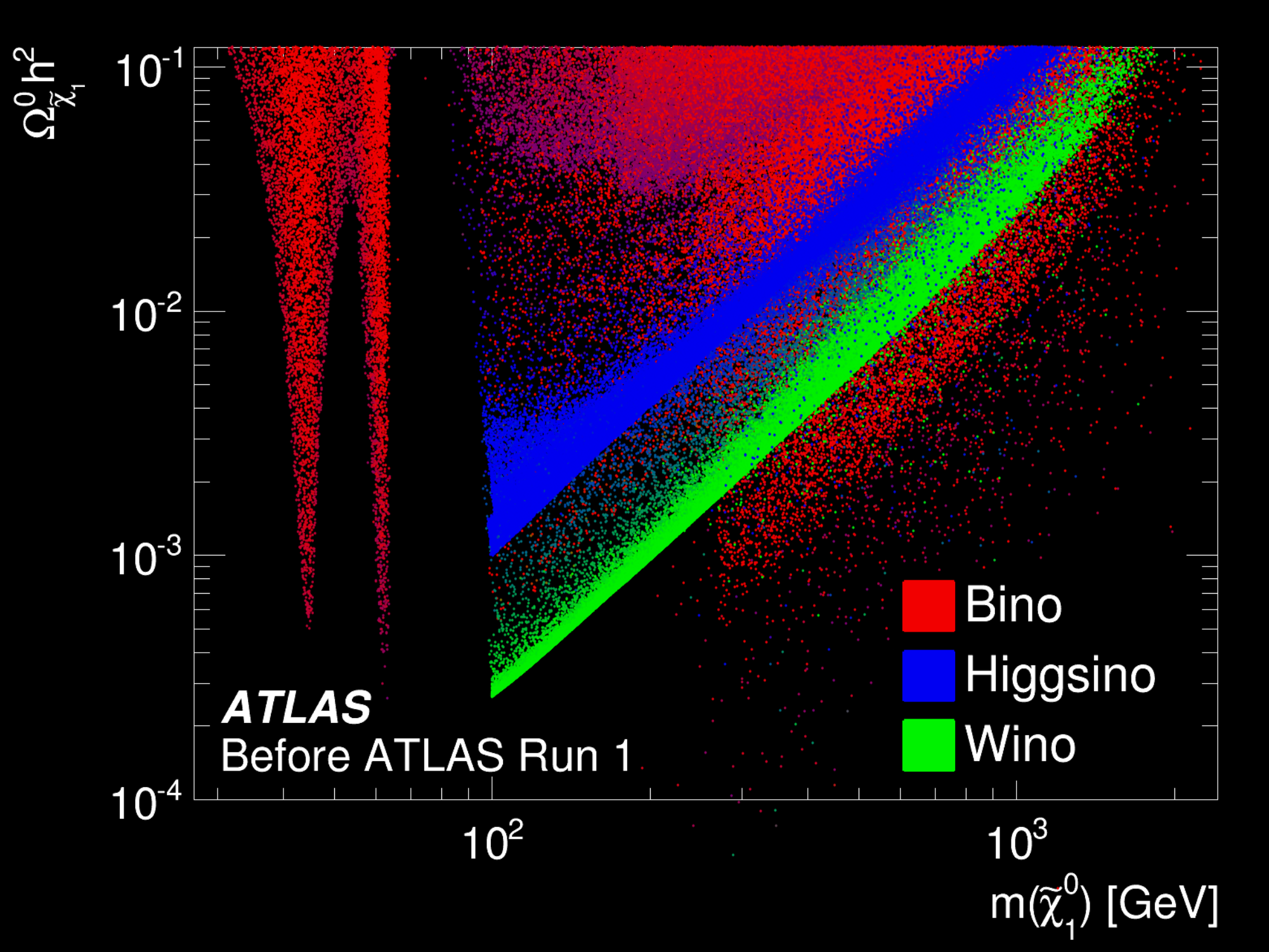
These models are not considered by ATLAS

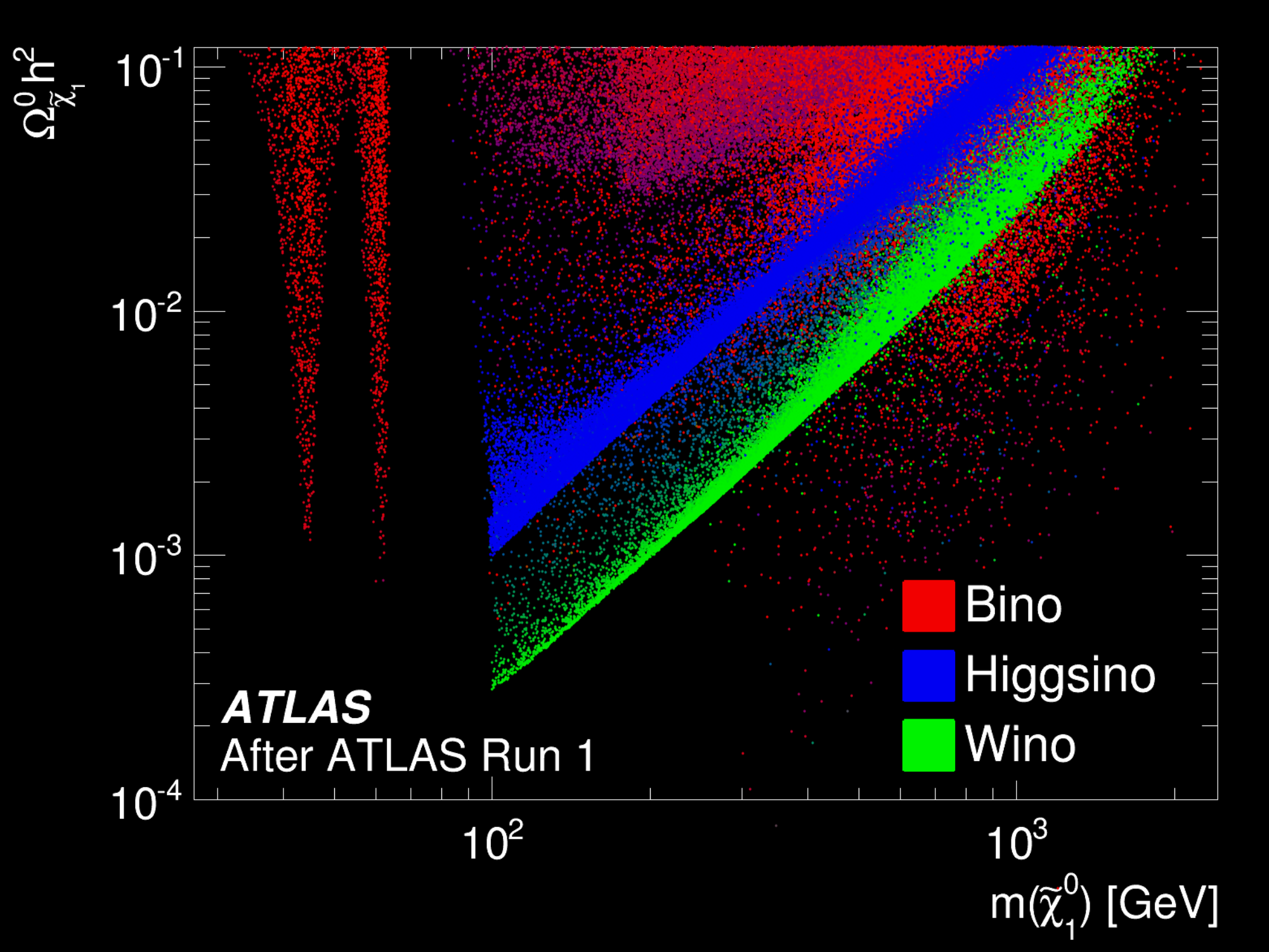

$\Omega^0_{\tilde{\chi}_1} h^2$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^2
10^3
$m(\tilde{\chi}^0_1)$ [GeV]
Bino
Higgsino
Wino
ATLAS
Before ATLAS Run 1


$\Omega^0_{\tilde{\chi}_1} h^2$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^2
10^3
$m(\tilde{\chi}^0_1)$ [GeV]
$\tilde{\chi}^0_1$
$\tilde{\chi}^0_1$
h^0/Z^0
Bino
Higgsino
Wino
ATLAS
Before ATLAS Run 1

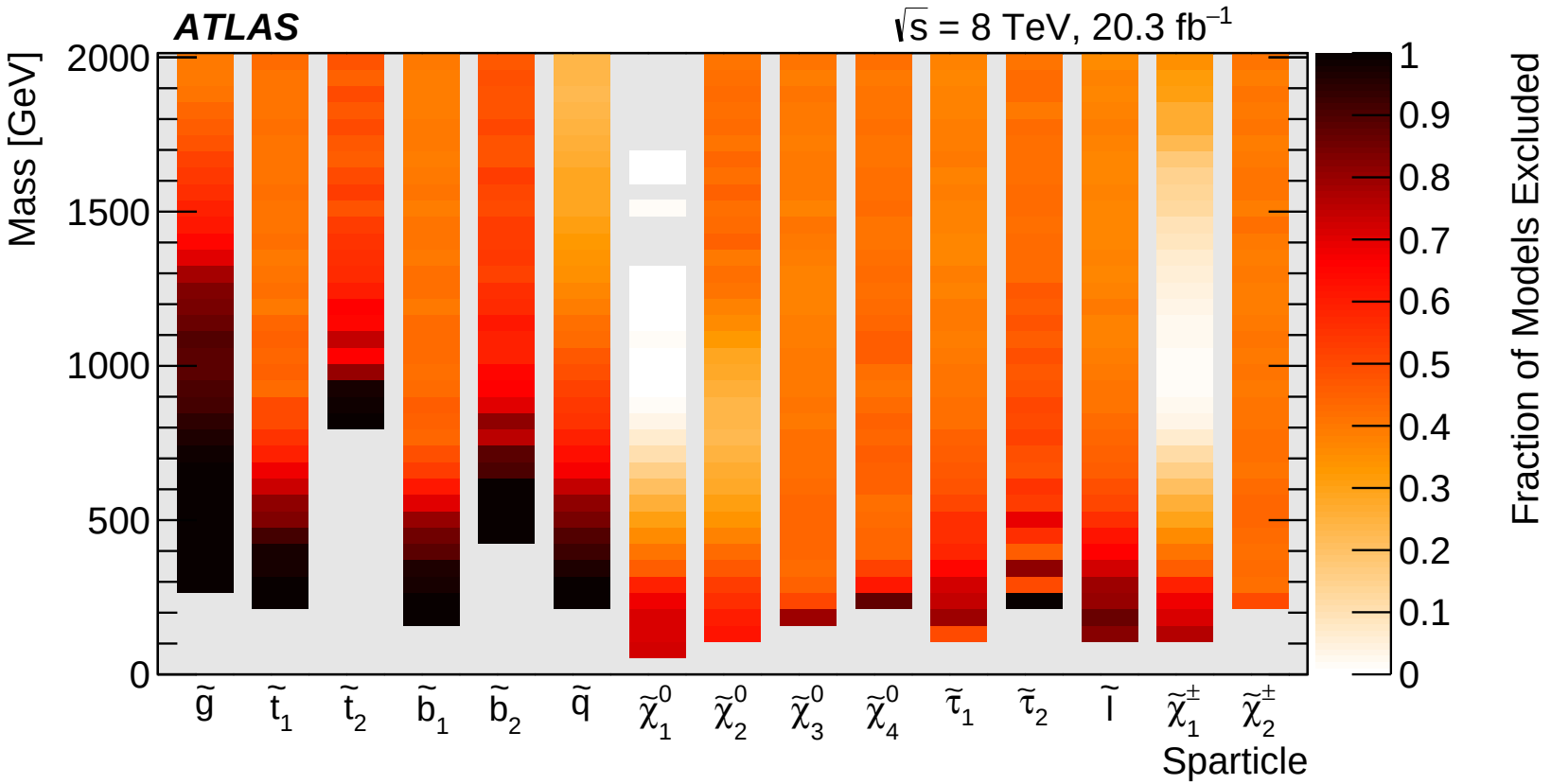

$\Omega^0_{\tilde{\chi}_1} h^2$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\tilde{\chi}_1^{\pm}$
$W^{\pm}$
$\tilde{\chi}_1^0$
Bino
Higgsino
Wino
ATLAS
Before ATLAS Run 1
10^2
10^3
$m(\tilde{\chi}_1^0)$ [GeV]


$\Omega^0_{\tilde{\chi}_1} h^2$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^2
10^3
$m(\tilde{\chi}^0_1)$ [GeV]
$\tilde{\tau}$
τ
τ
$\tilde{\chi}^0_1$
γ
Bino
Higgsino
Wino
ATLAS
Before ATLAS Run 1


$\Omega^0_{\tilde{\chi}_1} h^2$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^2
10^3
$m(\tilde{\chi}^0_1)$ [GeV]
Bino
Higgsino
Wino
ATLAS
Before ATLAS Run 1


$\Omega^0_{\tilde{\chi}_1} h^2$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^2
10^3
$m(\tilde{\chi}^0_1)$ [GeV]
Bino
Higgsino
Wino
ATLAS
After ATLAS Run 1

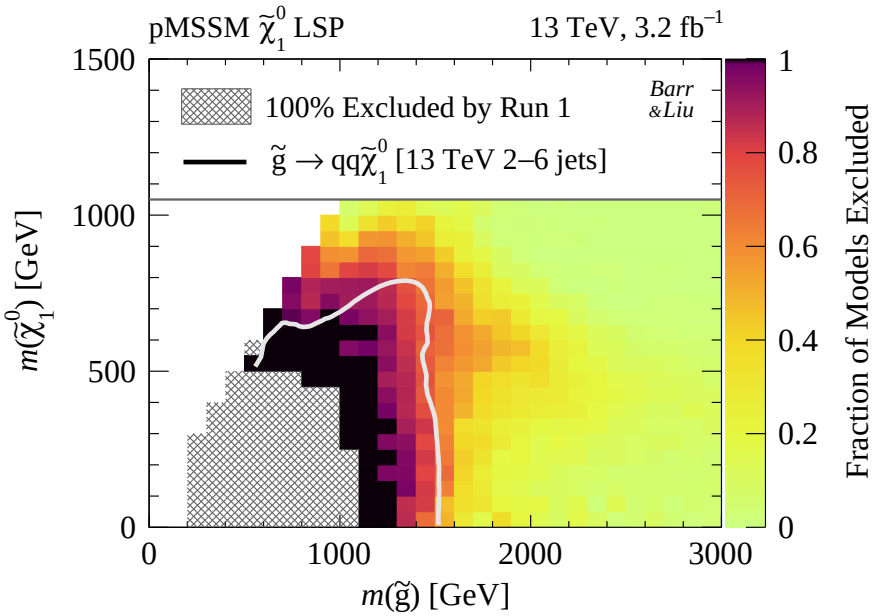
pMSSM: summary

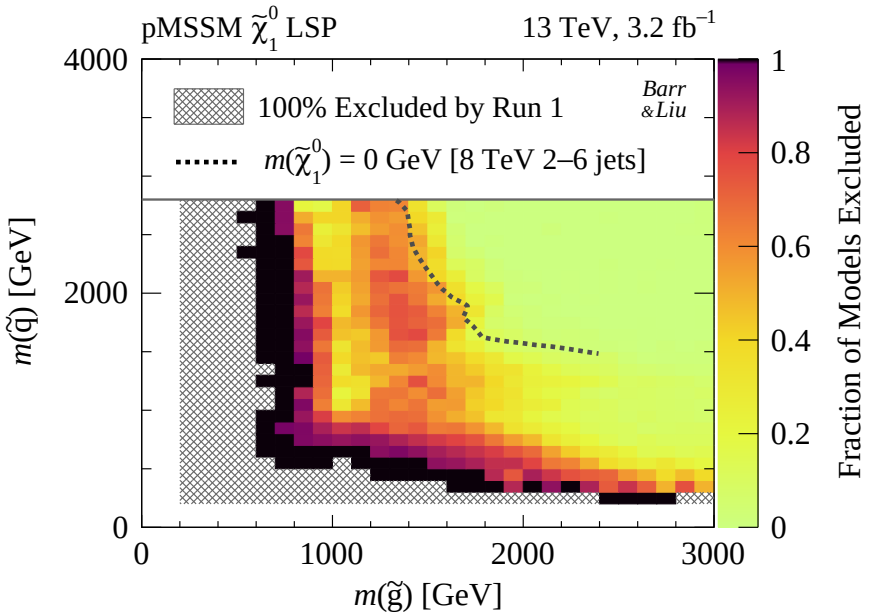


First interpretation of 13 TeV results

Uses ATLAS model information

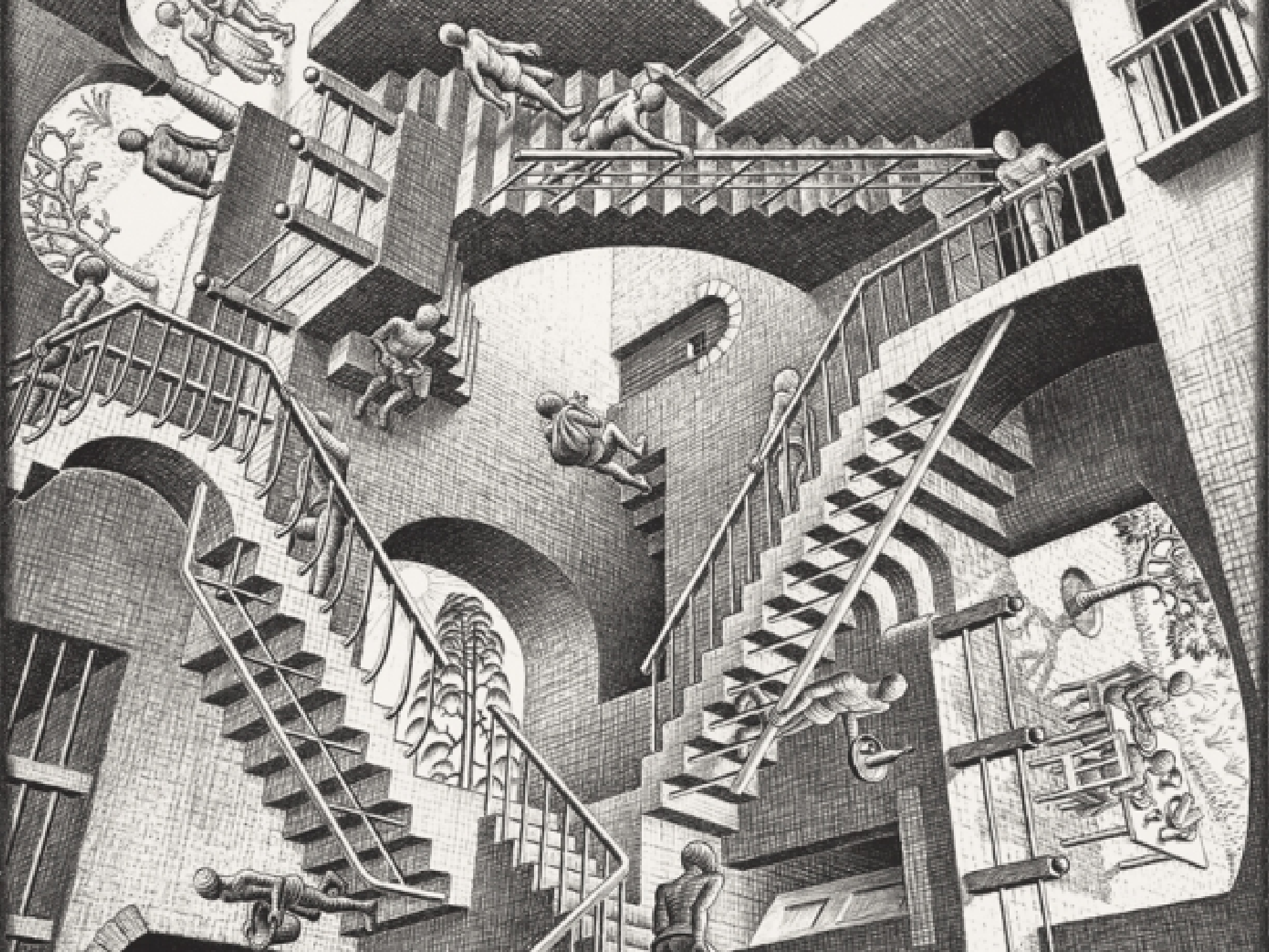
- Theorists have combined 6 ATLAS 13 TeV searches
- Considerable sensitivity increase of Run-2 searches
- 1605.09502





Summary

- pMSSM captures of the phenomenology of the full MSSM
- ATLAS: random scan, CMS: Bayesian approach
- Large swathes of pMSSM parameter space untouched by searches
- Plenty of work to do in Run-2!

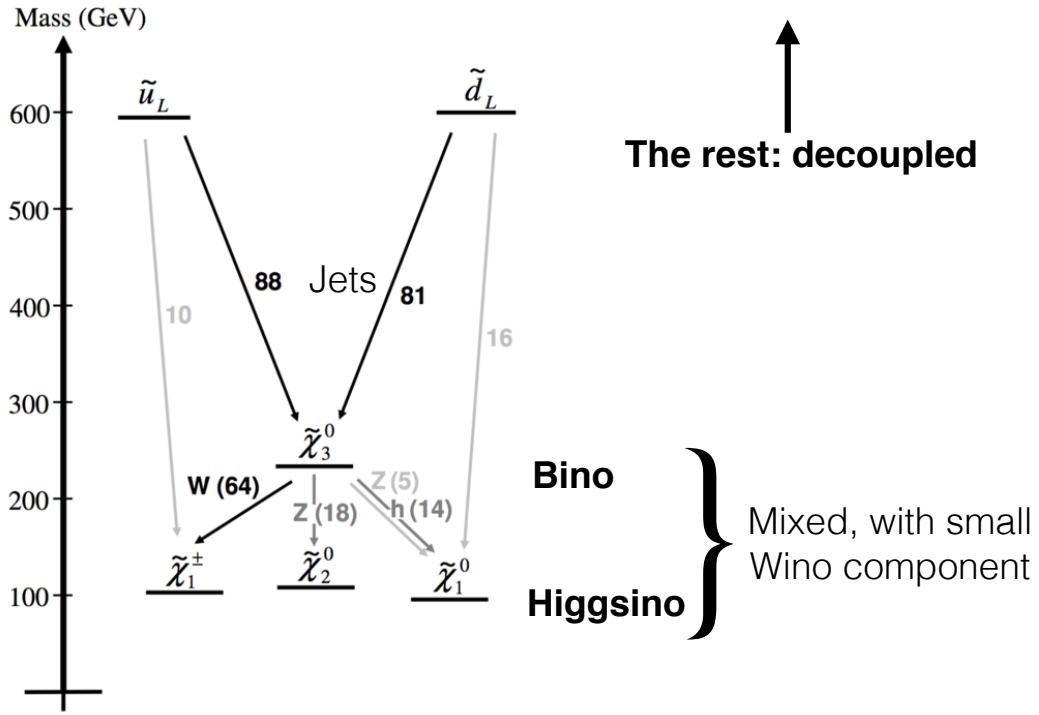


Backup

pMSSM and the Z+$E_{\mathrm{T}}^{\mathrm{miss}}$excess

Uses ATLAS model information

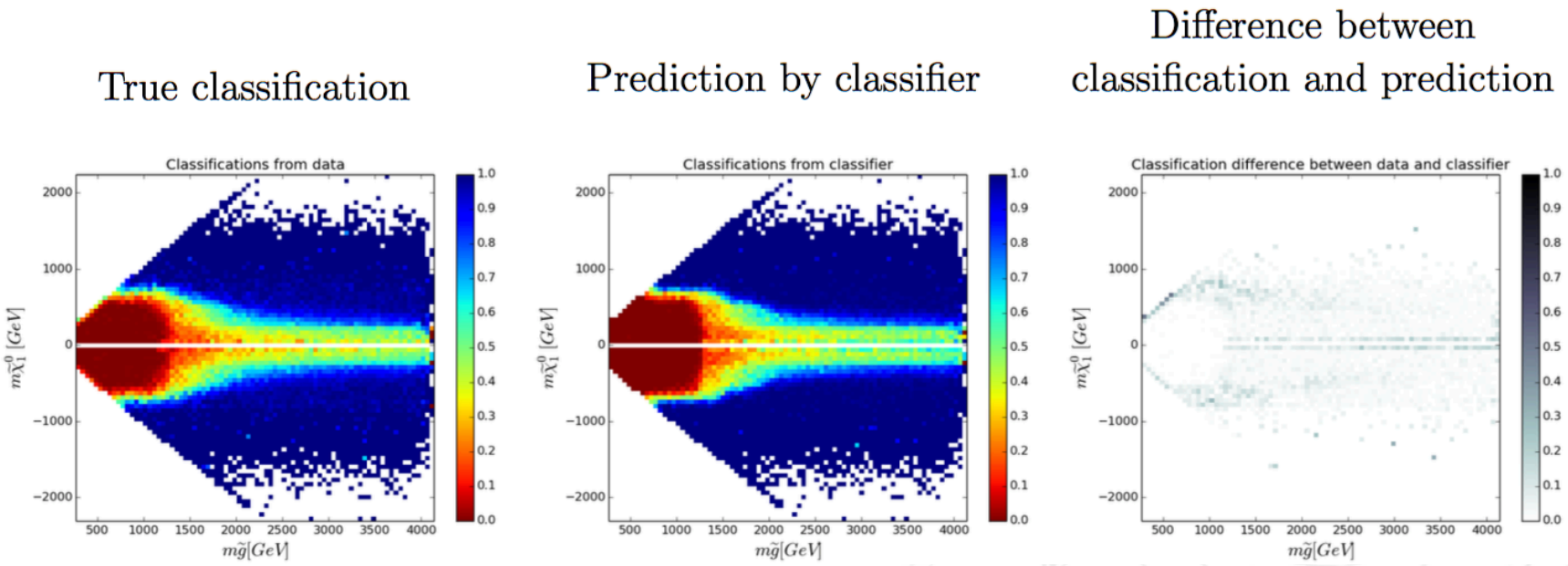
- 3σ excess in Z+jets+$E_{\mathrm{T}}^{\mathrm{miss}}$search (ATLAS) EPJC 75, 10, 463 (2015)
- Yet no excess from a similar CMS search JHEP 04 (2015) 124
- pMSSM can provide a candidate model: study using ATLAS pMSSM models 1604.02959



Machine Learning and the pMSSM

Uses ATLAS model information

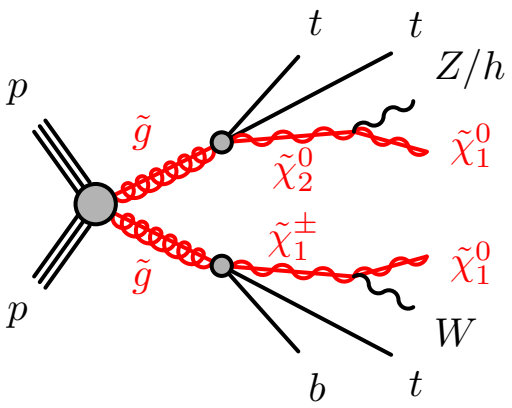
- Study done by theorists taking the ATLAS model set and using this as training for a Machine Learning Algorithm. "BSM AI project" 1605.02797
- Takes parameters of pMSSM model from SLHA input
- 93% accurate in determining if the model is excluded

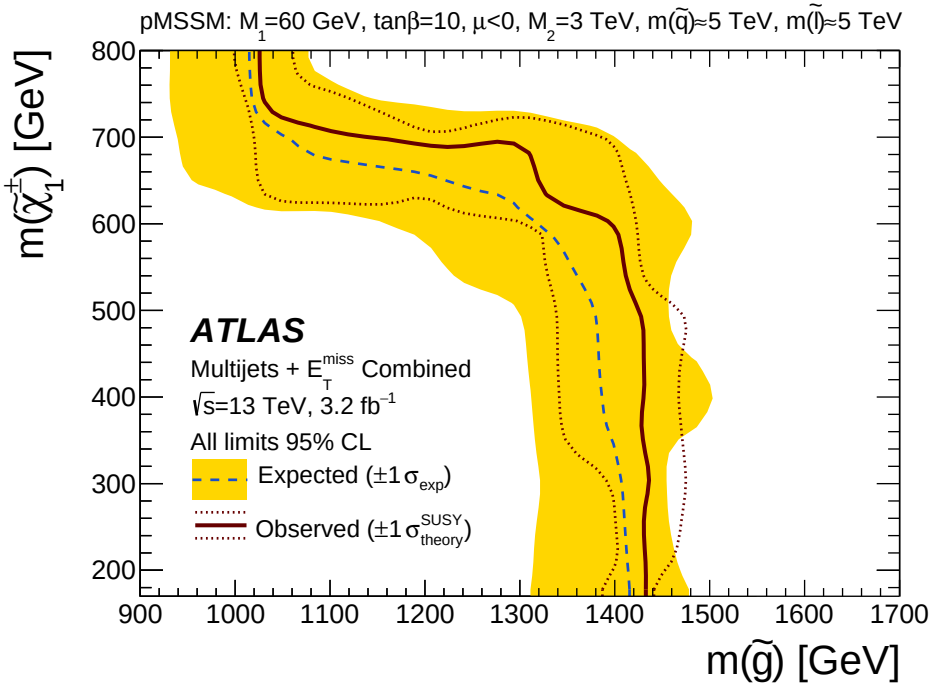


Models Evading Run-1: ATLAS

1602.06194

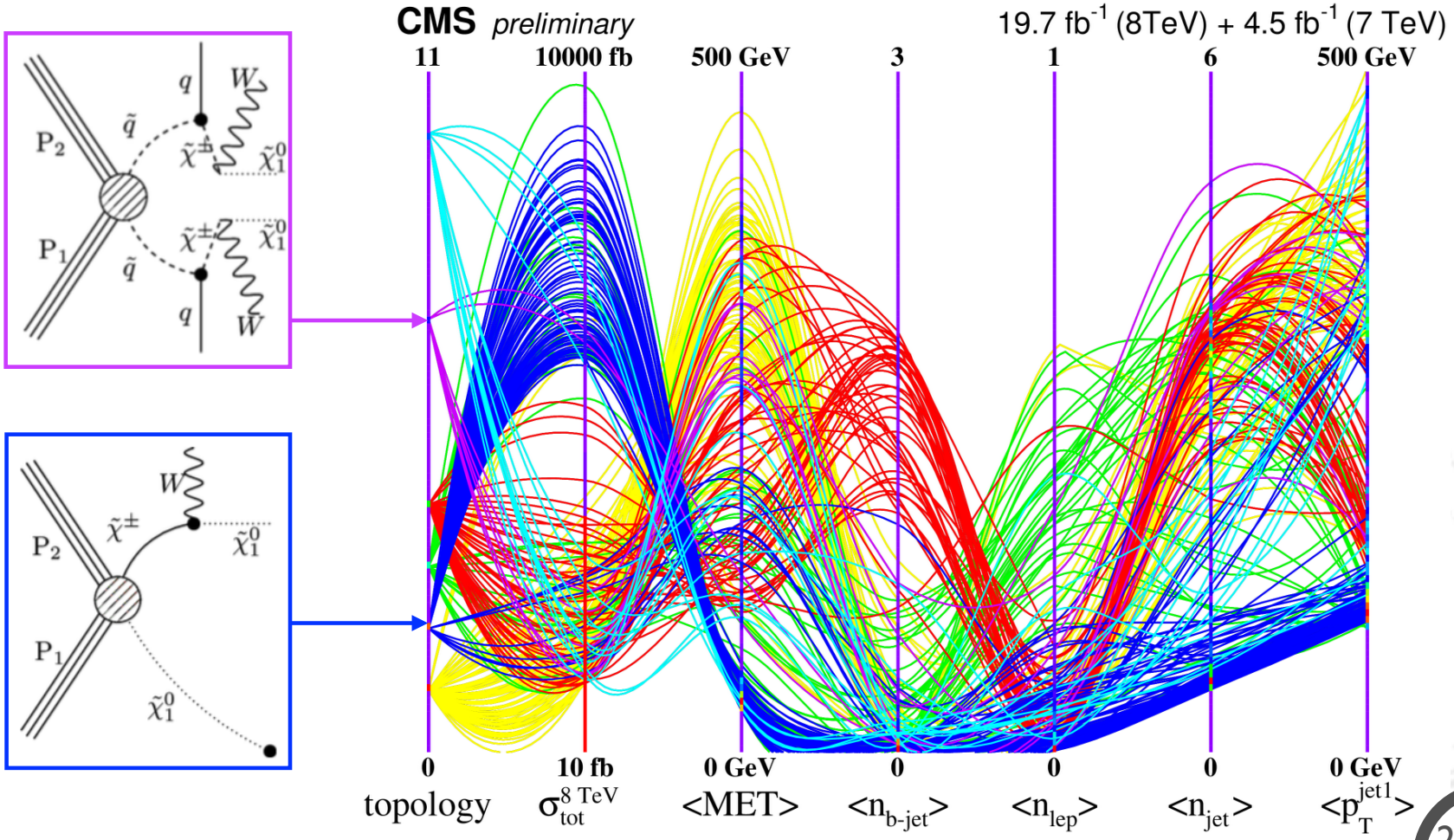
- ATLAS scan of the pMSSM revealed classes of models evading searches
- Built a simplified model to emulate this class
- Optimised a search to fill gap
- See Antonia's talk





Models Evading Run-1: CMS

- Set of "principal topologies" defined
- Most common production and decay modes
- Each colour corresponds to a different topology
- Each line a different model

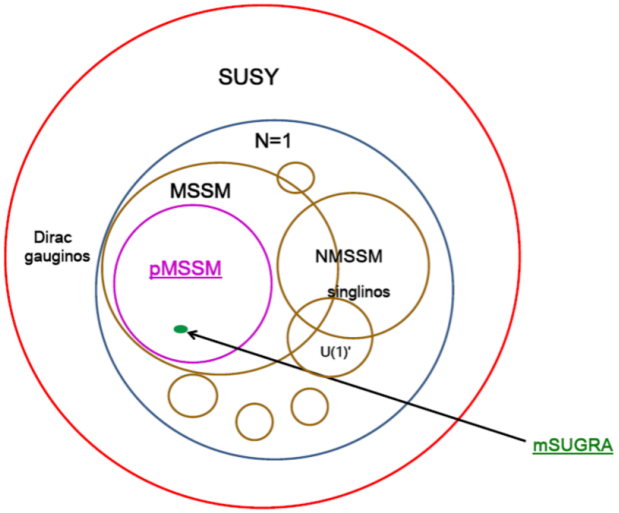


The pMSSM

The pMSSM is:

19 parameters subset of the 120 parameter MSSM

- MSSM too complex to explore directly
- Imposing following constraints:
  1. No CP violation beyond CKM
  2. No FCNC
  3. Degeneracy of $1^{st}/2^{nd}$ gen. squarks (& sleptons)
- Assume R-parity conservation
- neutralino-1 is the LSP



The pMSSM is small enough to explore with available computing resources but large enough to incorporate non-LHC constraints.

ATLAS: pMSSM Scan Range

Parameter	Range	Parameter	Range
M_1	[-4000:4000]	$m(\tilde{q}_{1L} = \tilde{q}_{2L})$	[200:4000]
M_2	[-4000:-70], [70:4000]	$m(\tilde{u}_R = \tilde{c}_R)$	[200:4000]
M_3	[200:4000]	$m(\tilde{d}_R = \tilde{s}_R)$	[200:4000]
μ	[-4000:-80], [80:4000]	$m(\tilde{q}_{3L})$	[100:4000]
$\tan\beta$	[1:60]	$m(\tilde{b}_R)$	[100:4000]
M_A	[100:4000]	$m(\tilde{t}_R)$	[100:4000]
A_τ	[-4000:4000]	$m(\tilde{e}_L = \tilde{\mu}_L)$	[90:4000]
A_b	[-4000:4000]	$m(\tilde{e}_R = \tilde{\mu}_R)$	[90:4000]
A_t	[-8000:8000]	$m(\tilde{\tau}_L)$	[90:4000]
		$m(\tilde{\tau}_R)$	[90:4000]

Table: pMSSM parameter scan ranges. Note mass units are in GeV.

Note, the upper bound of 4 TeV forces all sparticles to be below that limit and we therefore do not explore parts of the pMSSM where most particles are heavy, i.e. split SUSY like scenarios.

ATLAS: Non-ATLAS Search Constraints

Parameter	Constraint
$m(h)$	124–128 GeV
$g_\mu - 2$	$[-1.77 : 4.38] \times 10^{-9}$
$BF(b \to s\gamma)$	$[0.269 : 0.387] \times 10^{-3}$
$BF(B_d \to \mu\mu)$	$< 9.4 \times 10^{-10}$
$BF(B_s \to \mu\mu)$	$[1.6 : 4.2] \times 10^{-9}$
$BF(B^+ \to \tau\nu_\tau)$	$[64 : 161] \times 10^{-6}$
$\Gamma_{invis.}(Z)$	< 2 MeV
$\Delta\rho$	$[-0.0005 : 0.0017]$
Relic density	$\Omega h^2 <$ Planck + 10%
Direct SI	$< 4\times$ LUX
Direct SD, p	$< 4\times$ COUPP
Direct SD, n	$< 4\times$ Xenon
Charged sparticles	> 100 GeV
Chargino	> 103 GeV if: $m(\tilde{\nu}) > 160$ GeV and $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) > 2$ GeV

- Use 2σ union of expt.+theory uncertainty everywhere, ex. $g-2$
- For DM measurements, σ scaled down by a factor of 4 to account for nucleon form factor uncertainties
- Planck limit is upper bound only, models would be very different if lower bound applied
- $m(h)$ centered on 126 GeV (ATLAS value at time of model generation). Results insensitive to small change.
- We remove models outside the ranges and treat any model inside on equal footing

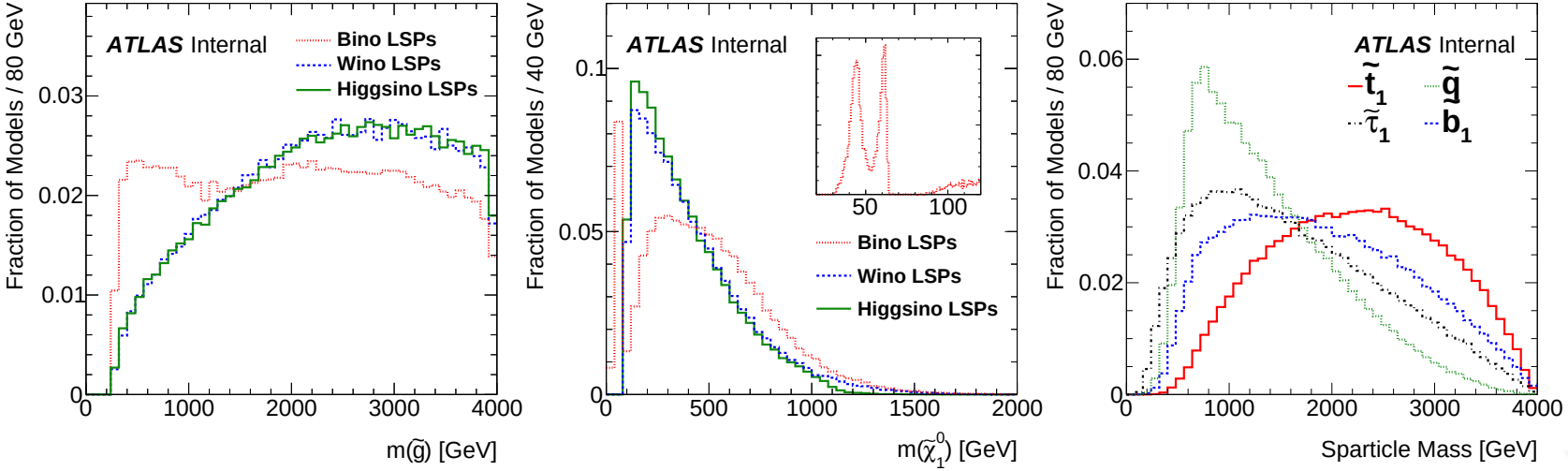
ATLAS: Sampling by LSP type

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	104,201	35%	$1/24$
'Wino-like'	$N_{12}^2 > \max(N_{11}^2,\ N_{13}^2 + N_{14}^2)$	$\}\ 20 \times 10^6\ \{$	80,239	26%	1
'Higgsino-like'	$(N_{13}^2 + N_{14}^2) > \max(N_{11}^2,\ N_{12}^2)$		126,769	39%	1
Total		500×10^6	311,209		

- Categorisation of the 311,209 models by the type of the LSP
- Split according to the neutralino mixing matrix parameters N_{ij}
  - first index indicates the neutralino mass eigenstate
  - second indicates its nature in the lexicographical order $(\tilde{B}, \tilde{W}, \tilde{H}_1, \tilde{H}_2)$

ATLAS: Resulting model distributions

Model distributions after other experimental and theoretical constraints, but before ATLAS searches



- Relic density constraint shapes these distributions
- E.g. two spikes in neutralino distribution for bino-LSP models "Z and h funnels"

ATLAS: Searches included

Analysis	Reference	Category
0ℓ, 2-6 jets	ATLAS-SUSY-2013-02	Inclusive
0ℓ, 7-10 jets	ATLAS-SUSY-2013-04	
1ℓ, 2-6 jets	ATLAS-SUSY-2013-20	
1–2τ, jets	ATLAS-SUSY-2013-10	
2ℓ SS/3ℓ	ATLAS-SUSY-2013-09	
3 b-jet	ATLAS-SUSY-2013-18	
Exotics mono-jet	ATLAS-EXOT-2013-13	
0ℓ, stop	ATLAS-SUSY-2013-16	Third generation
1ℓ, stop	ATLAS-SUSY-2013-15	
2ℓ, stop	ATLAS-SUSY-2013-19	
Stop to charm, monojet	ATLAS-SUSY-2013-21	
Stop with Z boson	ATLAS-SUSY-2013-08	
Two b-jet	ATLAS-SUSY-2013-05	
tb+MET,stop	TBA	
ℓh, electroweak	ATLAS-SUSY-2013-23	Electroweak
2ℓ, electroweak	ATLAS-SUSY-2013-11	
2τ, electroweak	ATLAS-SUSY-2013-14	
3ℓ, electroweak	ATLAS-SUSY-2013-12	
4ℓ	ATLAS-SUSY-2013-13	
Disappearing Track	ATLAS-SUSY-2013-01	
Long-lived sparticles	ATLAS-SUSY-2013-22	Other
	ATLAS-SUSY-2012-01	
$H/A \to \tau^+\tau^-$	ATLAS-HIGG-2013-31	

CMS: Searches included

Analysis	$\sqrt{s}$ [TeV]	L [fb^{-1}]	Likelihood
Hadronic HT + MHT search [46]	7	4.98	counts
Hadronic HT + MET + b-jets search [47]	7	4.98	counts
Leptonic search for EW prod. of $\tilde{\chi}^0, \tilde{\chi}^{\pm}, \tilde{l}$ [48]	7	4.98	counts
Hadronic HT + MHT search [49]	8	19.5	counts
Hadronic MT2 search [50]	8	19.5	counts
Hadronic HT + MET + b-jets search [51]	8	19.4	χ^2
Monojet searches [52, 53]	8	19.7	binary
Hadronic stop search [54]	8	19.4	counts
Opposite sign di-lepton (OS ll) search [55] (count experiment only)	8	19.4	counts
Like-sign di-leptoin (LS ll) search [56] (only channels w/o 3rd lepton veto)	8	19.5	counts
Leptonic search for EW prod. of $\tilde{\chi}^0, \tilde{\chi}^{\pm}, \tilde{l}$ [57] (only ss, 3l, and 4l channels)	8	19.5	counts
Combination of 7 TeV searches	7	-	binary
Combination of 8 TeV searches	8	-	binary
Combination of 7 and 8 TeV searches	7,8	-	binary

CMS prior (non-CMS constraints)

$$p^{\text{non-DCS}}(\theta) \propto \left[\prod_j L(D_j^{\text{non-DCS}}|\mu_j(\theta)\right] p(c\tau(\tilde{\chi}^{\pm}) < 10\text{mm}|\theta) p(\textbf{theory}|\theta) p_0(\theta)$$

$p_0(\theta)$: flat prior in scan range:

$$|M_1|, |M_2|, \mu \leq 3\,\text{TeV}$$
$$0 \leq M_3, M_A \leq 3\,\text{TeV}$$
$$2 \leq \tan\beta \leq 60$$
$$0 \leq \tilde{Q}_{1,2}, \tilde{U}_{1,2}, \tilde{D}_{1,2}, \tilde{L}_{1,2}, \tilde{E}_{1,2}, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3 \leq 3\,\text{TeV}$$
$$-7\,\text{TeV} \leq A_t, A_b, A_\tau \leq 7\,\text{TeV}$$

CMS prior

$p(\text{theory}|\theta)$ Imposes the following constraints:

- Spectrum free of tachyons
- No colour or charge breaking in the scalar potential
- EWSB is consistent and Higgs potential bounded from below
- LSP is lightest neutralino

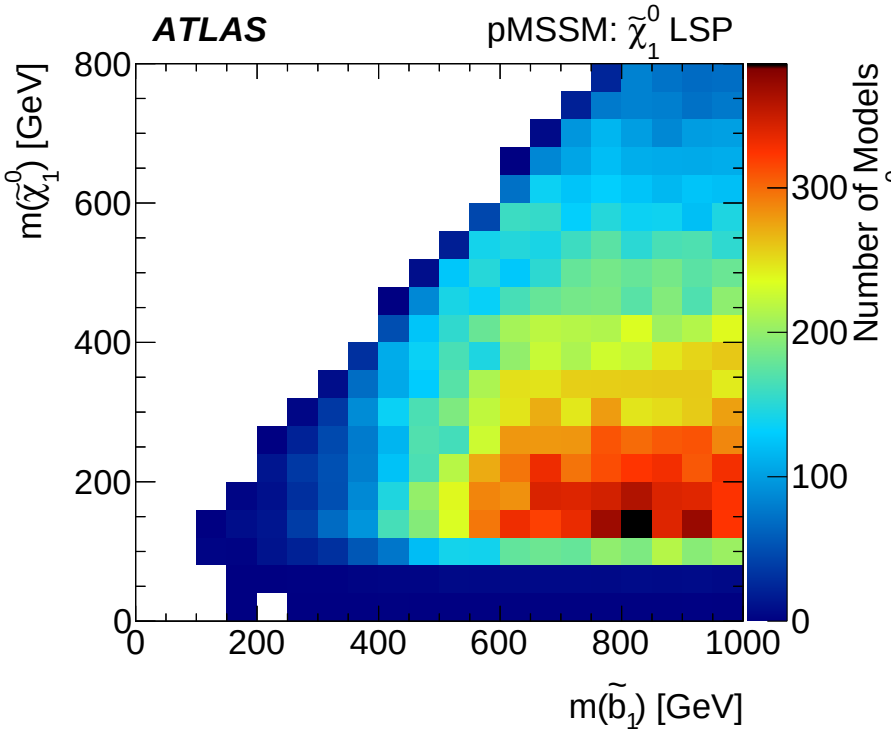
$p(c\tau(\tilde{\chi}^{\pm}) < 10\text{mm}|\theta)$ removes long-lived charginos

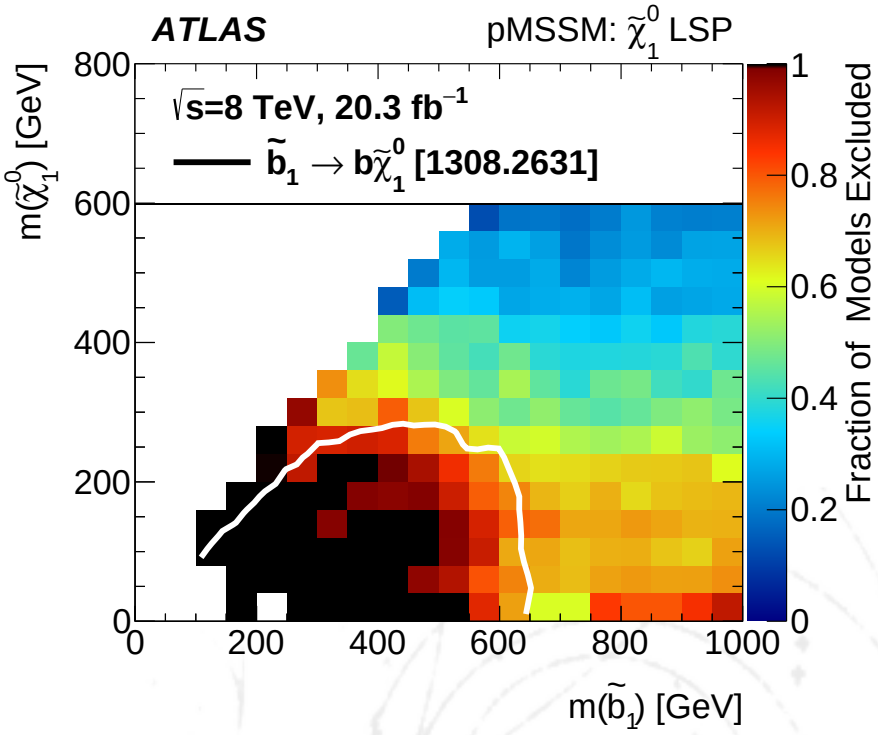
CMS prior

$L(D_j^{\text{non-DCS}}|\mu_j(\theta)$ Results from precision and pre-LHC measurements

i	Observable $\mu_i(\theta)$	Constraint $D_i^{\text{non-DCS}}$	Likelihood function $L(D_i^{\text{non-DCS}}\|\mu_i(\theta))$	comment
1	$BR(b \to s\gamma)$ [40]	$(3.43 \pm 0.21^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.07^{\text{sys}}) \times 10^{-4}$	Gaussian	reweight
2	$BR(B_s \to \mu\mu)$ [41]	$(2.9 \pm 0.7 \pm 0.29^{th}) \times 10^{-9}$	Gaussian	reweight
3	$R(B_u \to \tau\nu)$[40]	1.04 ± 0.34	Gaussian	reweight
4	Δa_μ [42]	$(26.1 \pm 6.3^{\text{exp}} \pm 4.9^{\text{SM}} \pm 10.0^{\text{SUSY}}) \times 10^{-10}$	Gaussian	
5	m_t [43]	$173.20 \pm 0.87^{\text{stat}} \pm 1.3^{\text{sys}}$ GeV	Gaussian	reweight
6	$m_b(m_b)$ [44]	$4.19^{+0.18}_{-0.06}$ GeV	Two-sided Gaussian	
7	$\alpha_s(M_Z)$ [44]	0.1184 ± 0.0007	Gaussian	
8	m_h	LHC: $m_h^{low} = 120$, $m_h^{up} = 130$	1 if $m_h^{low} \leq m_h \leq m_h^{up}$ 0 if $m_h < m_h^{low}$ or $m_h > m_h^{up}$	reweight
9	μ_h	CMS and ATLAS in LHC RunI, Tevatron	`Lilith1.01` [36, 37]	post-MCMC
10	sparticle masses	LEP [45] (via micrOMEGAs [29–31])	1 if allowed 0 if excluded	

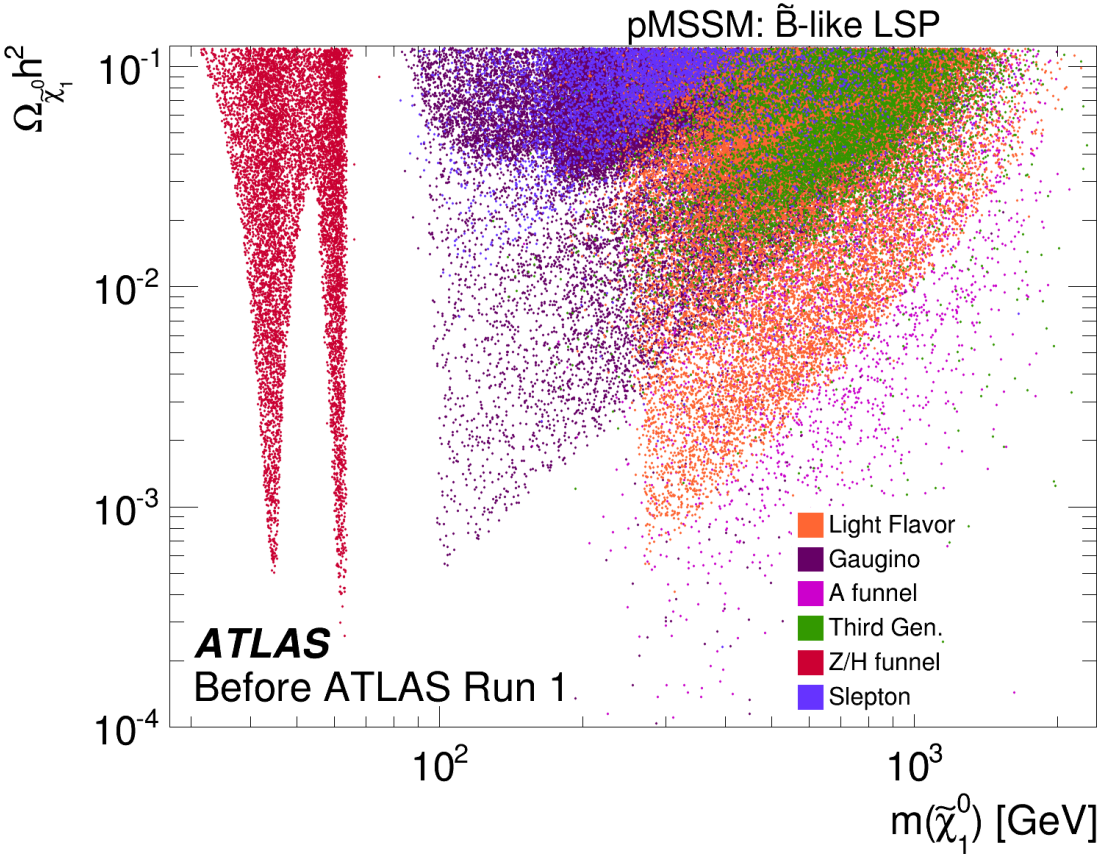
ATLAS: Sbottoms





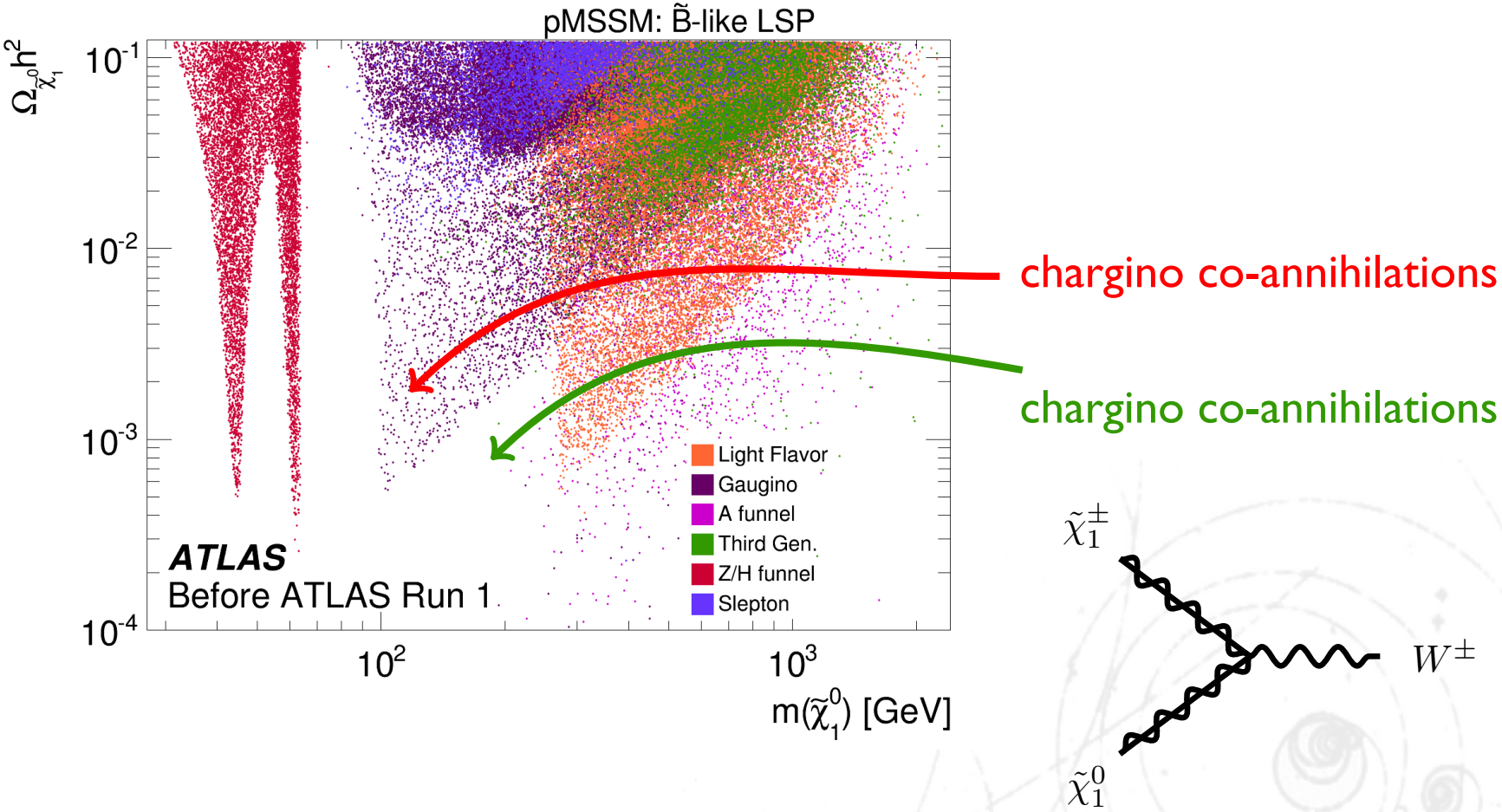
ATLAS: Dark Matter

SUSY models typically over-produce dark matter, unless there is some special mechanism to reduce the relic abundance.

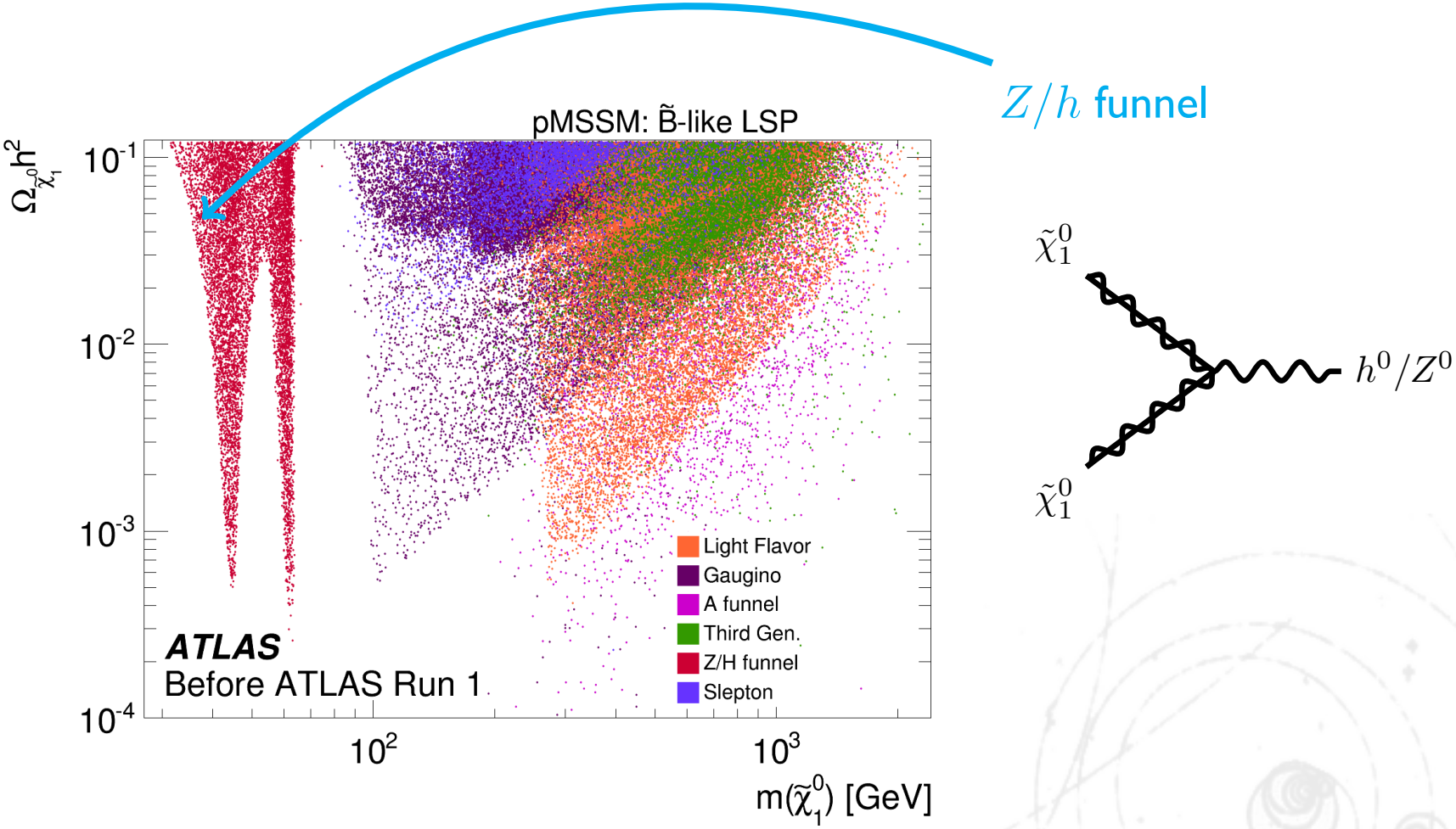


ATLAS: Dark Matter

Wino and Higgsino models get this special mechanism 'for free' as they have a compressed chargino.

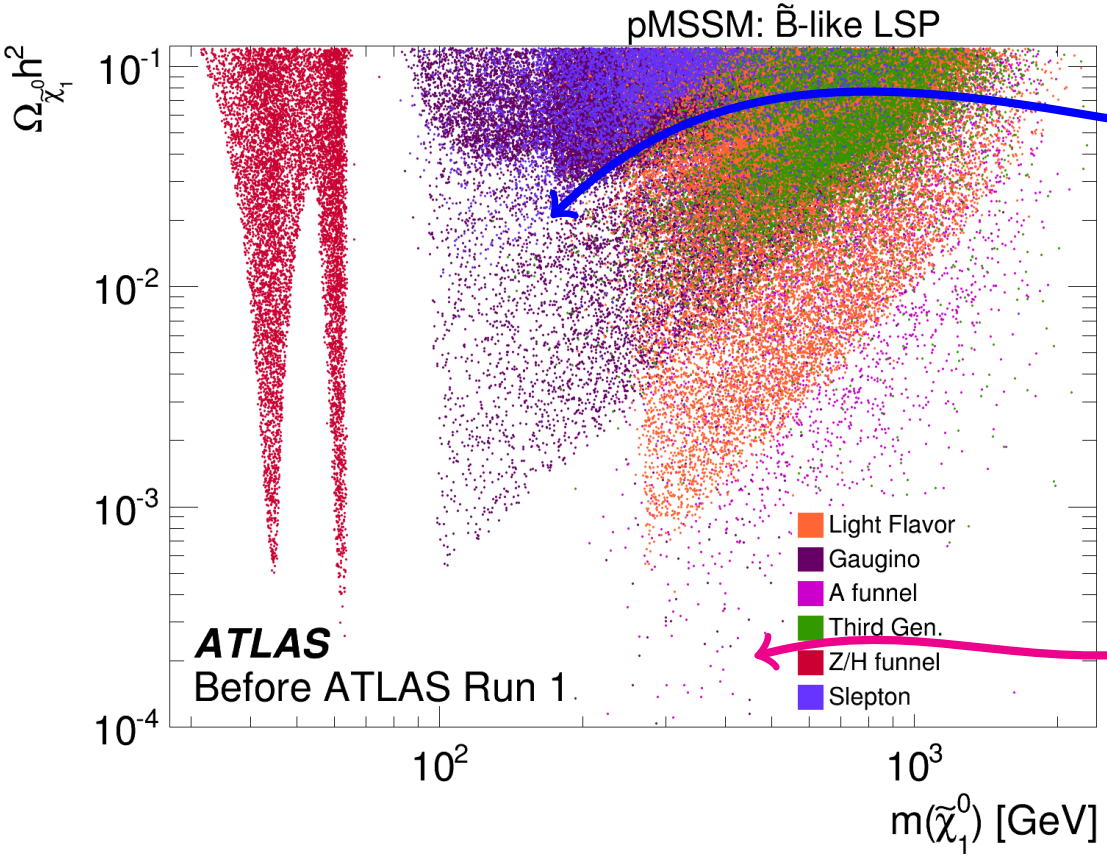


ATLAS: Dark Matter

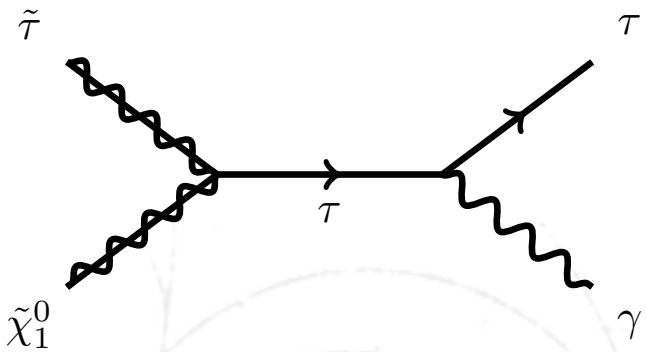


ATLAS: Dark Matter

Most bino-LSP models require a co-annihilator to reduce the relic abundance. This is models with mostly bino-LSPs have compressed sparticles.



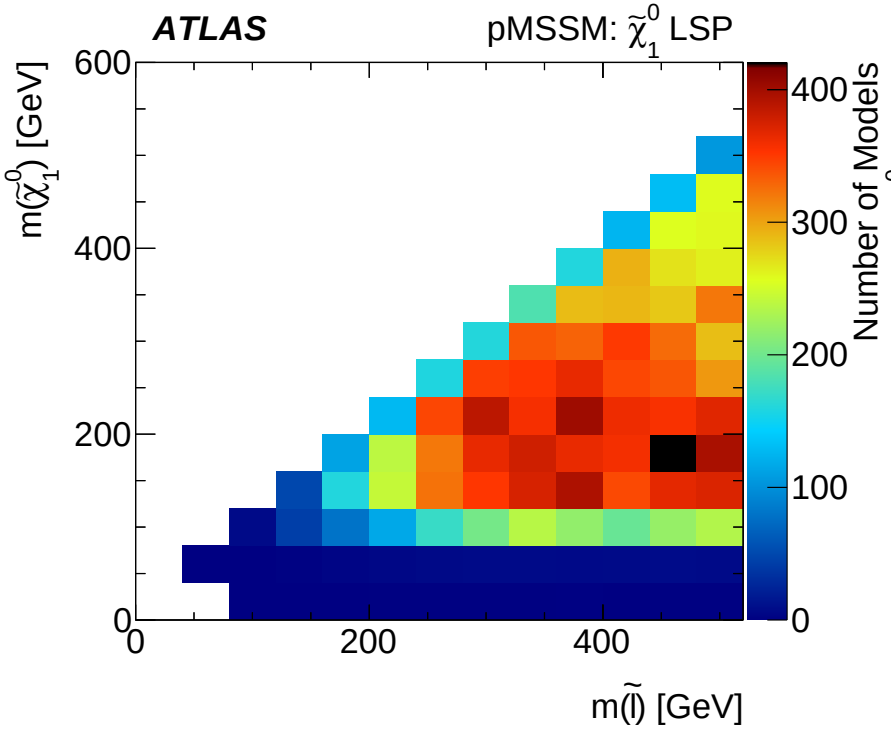
Co-annihilations

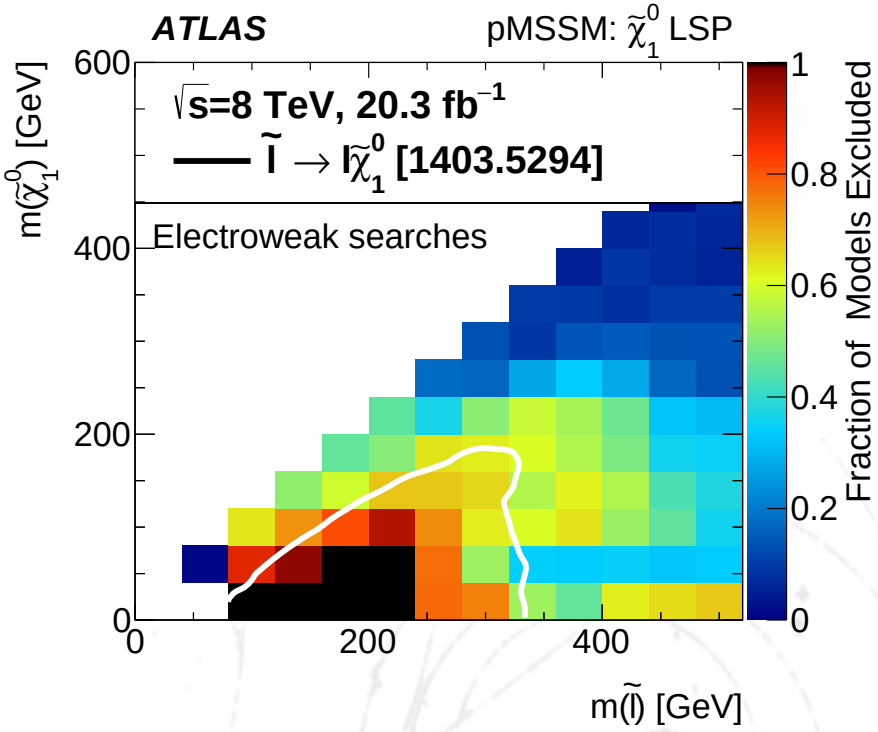


Multiple annihilators

ATLAS: Sleptons

Impact of electroweak searches only





ATLAS: Bino-LSP mass distribution