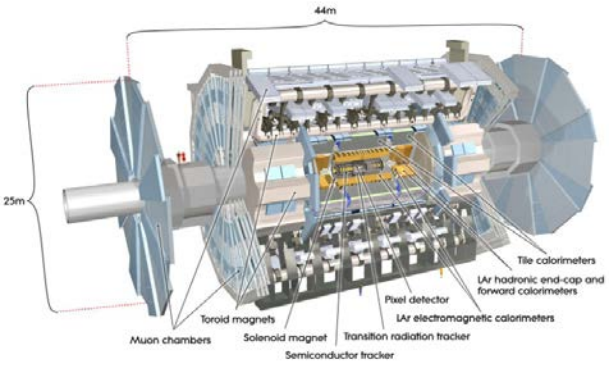
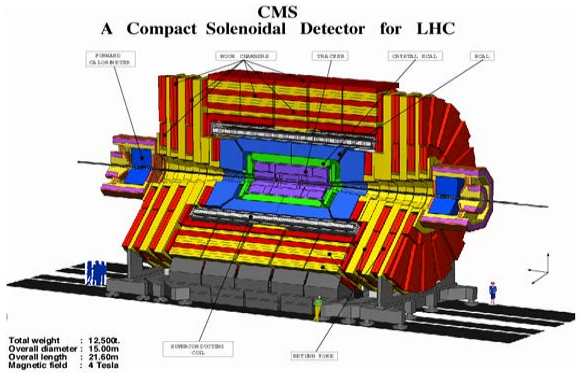
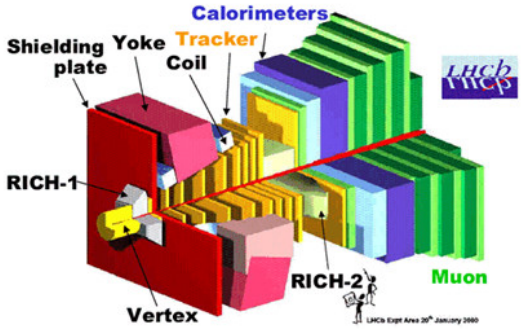
SUSY on the Frontier: LHC Searches with the pMSSM







1206.4321, 1206.5800, 1211.1981, 1211.7106, 1305.1605, 1305.2419, 1305.6921, ...

SLAC NATIONAL ACCELERATOR LABORATORY

M.W. Cahill-Rowley, J.L. Hewett, A. Ismail, T.G. Rizzo

5/31/13

The pMSSM SUSY Search Approach

- 19/20 parameter pMSSM is being used to study SUSY at 7, 8 & 14 TeV by duplicating 'ALL' ATLAS searches w/ fast MC to determine SUSY space coverage, look for unusual processes & ID weak areas needing more work

- Two large ~225k model sets with neutralino/gravitino LSPs

- Smaller 'designer' sets ~10k for low-FT study, etc, analyses

- Combine with other studies on DM searches, H properties, etc

- Here: (i) update χ^0_1 @ 7/8 TeV to all available as of 3/1/13
  (ii) first look at a new low-FT set

→14 TeV & Higgs studies for Snowmass ongoing

7 TeV Searches

Search	Reference	Fraction Excluded	
2-6 jets	ATLAS-CONF-2012-033	21.2%	
multijets	ATLAS-CONF-2012-037	1.6%	
1-lepton	ATLAS-CONF-2012-041	3.2%	
HSCP	1205.0272	4.0%	
Disappearing Track	ATLAS-CONF-2012-111	2.6%	
Gluino → Stop/Sbottom	1207.4686	4.9%	
Very Light Stop	ATLAS-CONF-2012-059	<0.1%	
Medium Stop	ATLAS-CONF-2012-071	0.3%	
Heavy Stop (0l)	1208.1447	3.7%	
Heavy Stop (1l)	1208.2590	2.0%	
GMSB Direct Stop	1204.6736	<0.1%	
Direct Sbottom	ATLAS-CONF-2012-106	2.5%	
3 leptons	ATLAS-CONF-2012-108	1.1%	
1-2 leptons	1208.4688	4.1%	
Direct slepton/gaugino (2l)	1208.2884	0.1%	
Direct gaugino (3l)	1208.3144	0.4%	
4 leptons	1210.4457	0.7%	✓
1 lepton + many jets	ATLAS-CONF-2012-140	1.3%	✓
1 lepton + γ	ATLAS-CONF-2012-144	<0.1%	✓
γ + b	1211.1167	<0.1%	✓
$\gamma\gamma$ + MET	1209.0753	<0.1%	✓
$B_s \to \mu\mu$	1211.2674	0.8%	✓
$A/H \to \tau\tau$	CMS-PAS-HIG-12-050	1.6%	✓

8 TeV Searches

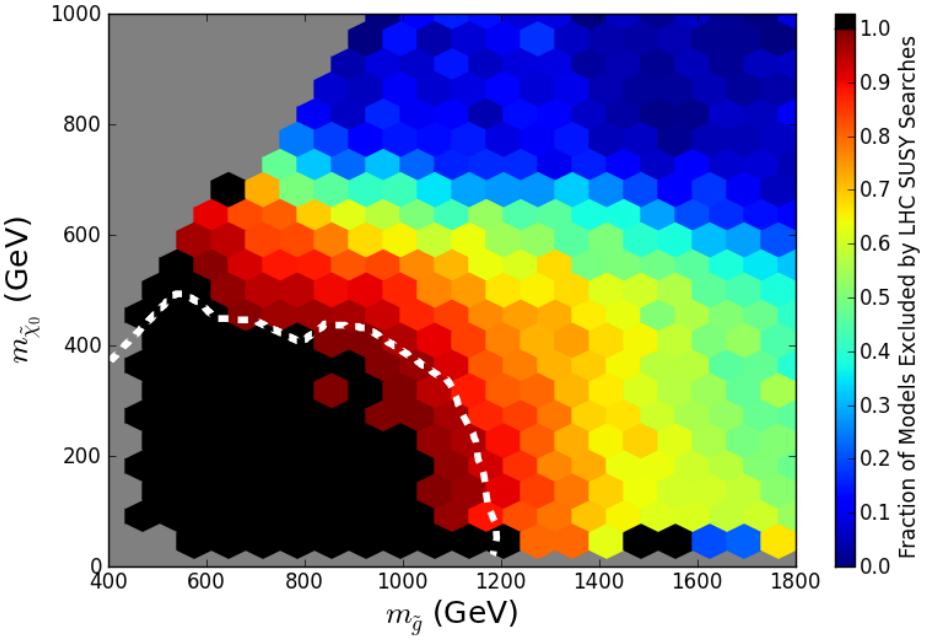
Search	Reference	Fraction Excluded	
2-6 jets	ATLAS-CONF-2012-109	26.7%	
multijets	ATLAS-CONF-2012-103	3.3%	
1-lepton	ATLAS-CONF-2012-104	3.3%	
SS dileptons	ATLAS-CONF-2012-105	4.9%	
Medium Stop (2l)	ATLAS-CONF-2012-167	0.6%	✓
Medium/Heavy Stop (1l)	ATLAS-CONF-2012-166	3.8%	✓
Direct Sbottom (2b)	ATLAS-CONF-2012-165	6.2%	✓
3rd Generation Squarks (3b)	ATLAS-CONF-2012-145	10.8%	✓
3rd Generation Squarks (3l)	ATLAS-CONF-2012-151	1.9%	✓
3 leptons	ATLAS-CONF-2012-154	1.4%	✓
4 leptons	ATLAS-CONF-2012-153	3.0%	✓
Z + jets + MET	ATLAS-CONF-2012-152	0.3%	✓

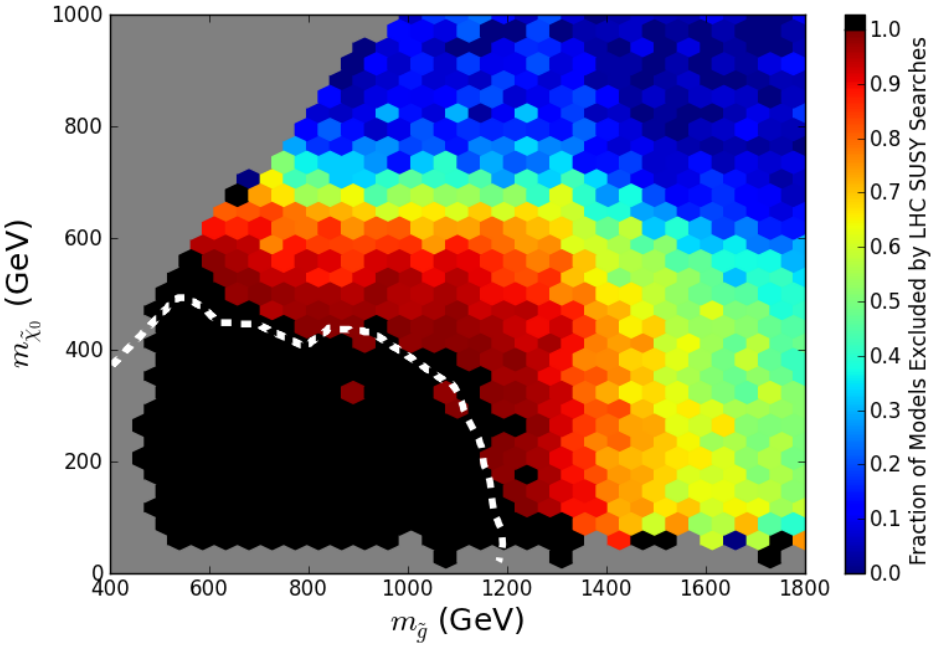
✓ = Newly added search

Total Excluded ~37% (was ~32% !)

No effect from $m_h = 126 \pm 3$ GeV cut

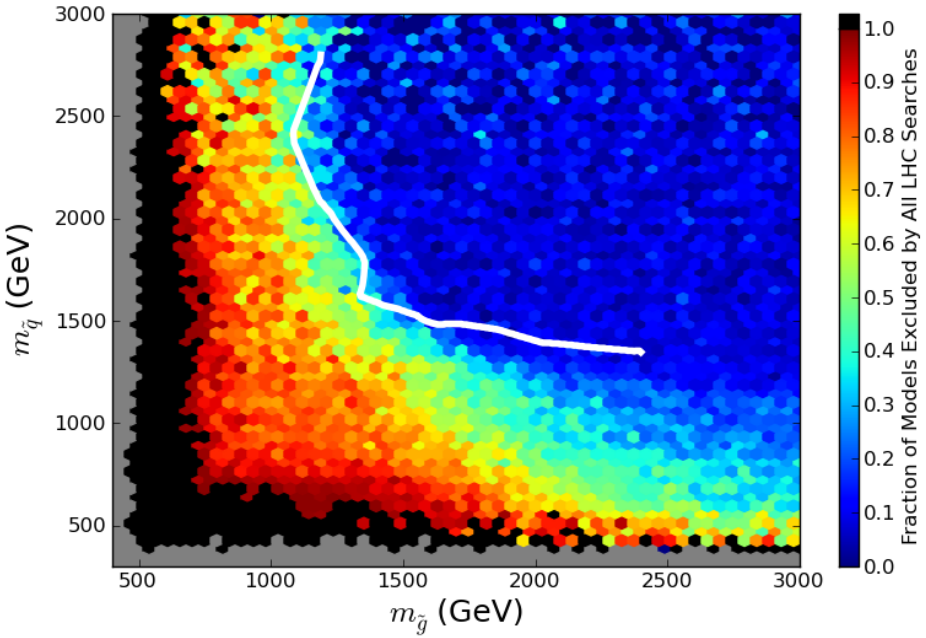
RESULTS ONLY !

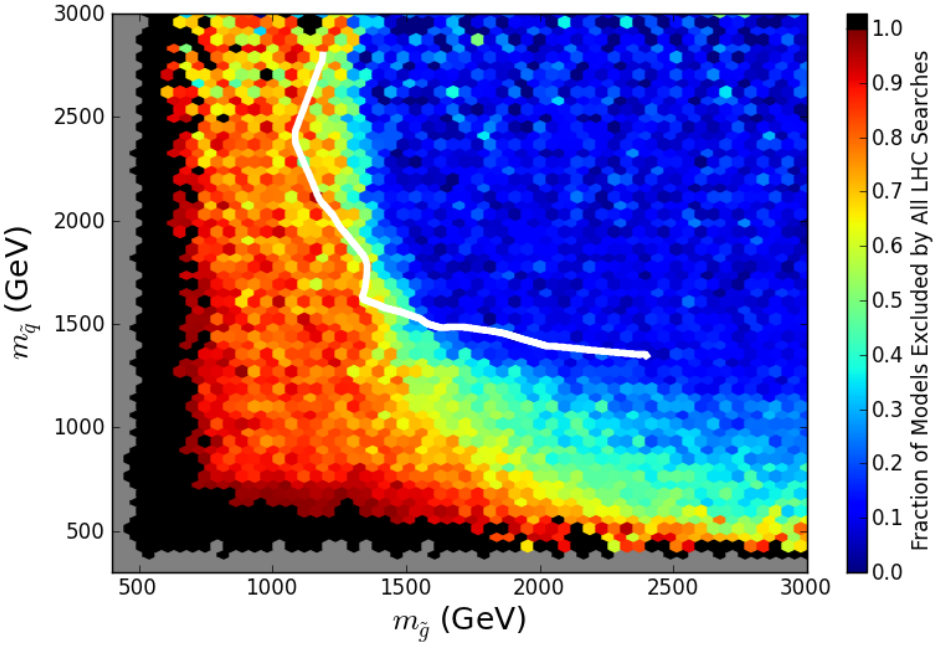


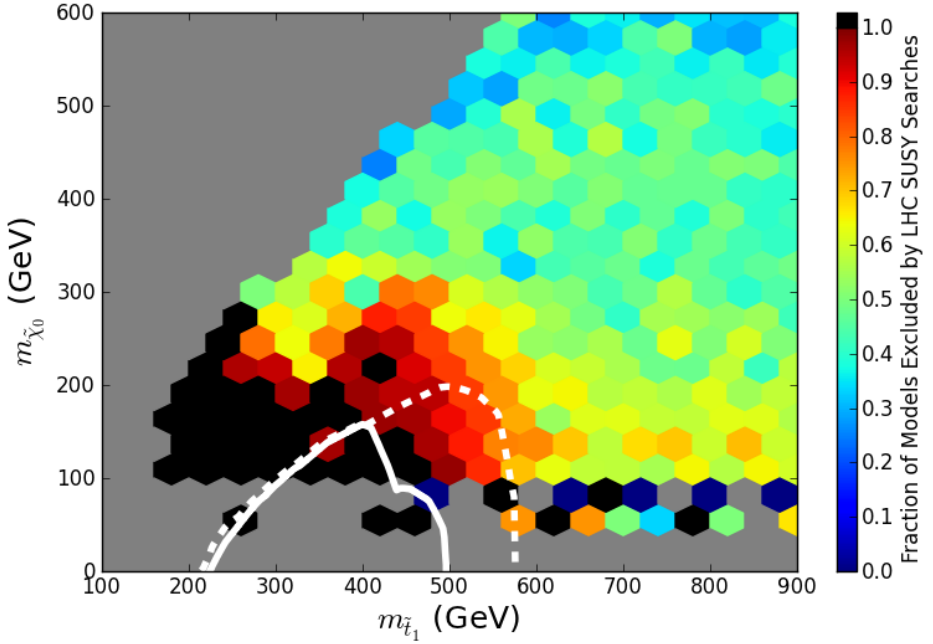


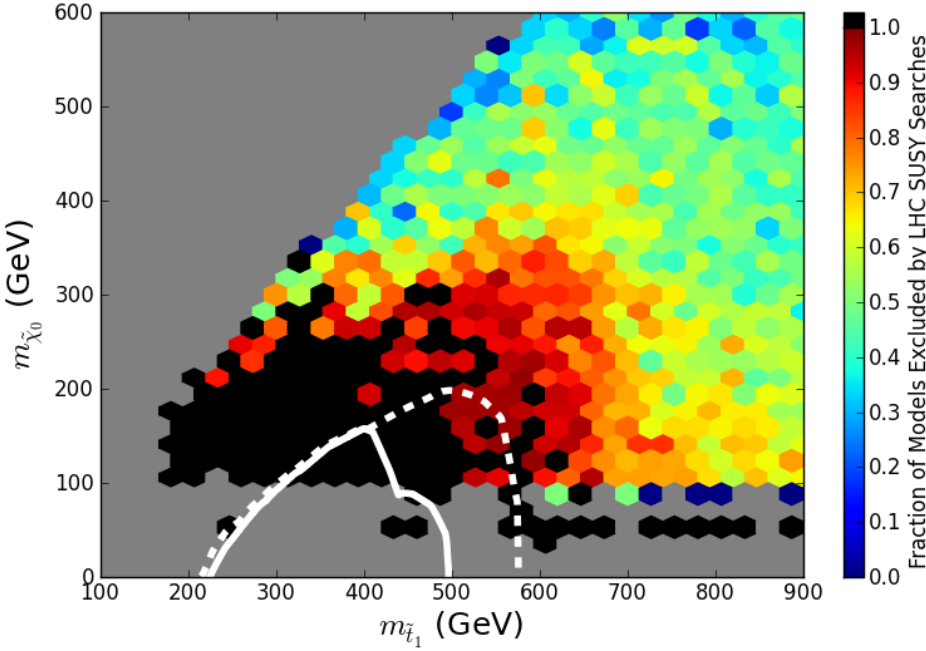
Before

After






$m_{\tilde{\chi}_0}$ (GeV)
$m_{\tilde{t}_1}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches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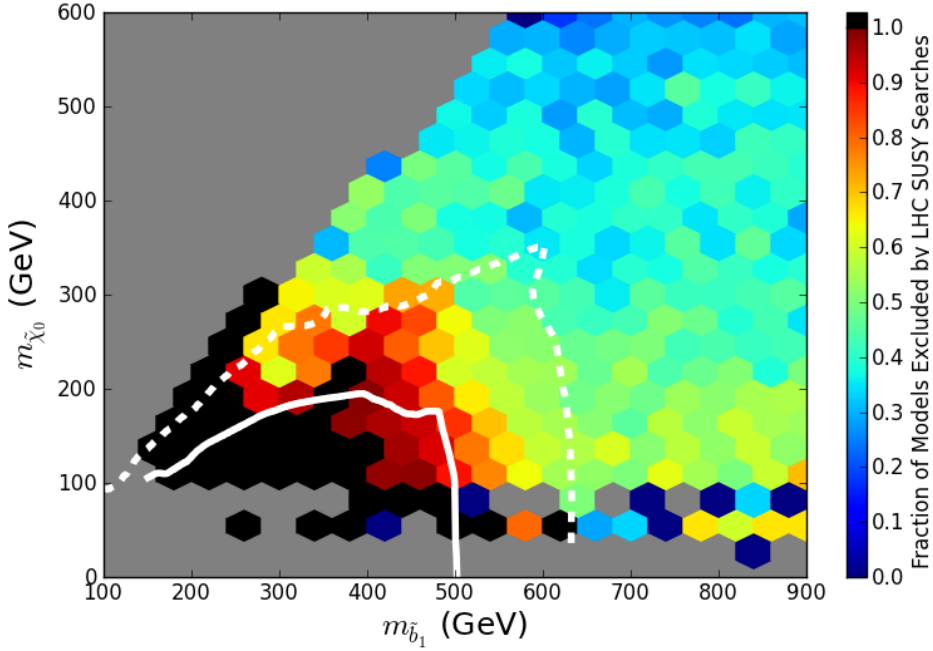
Fraction of Models Excluded by LHC SUSY Searches


$m_{\tilde{\chi}_0}$ (GeV)
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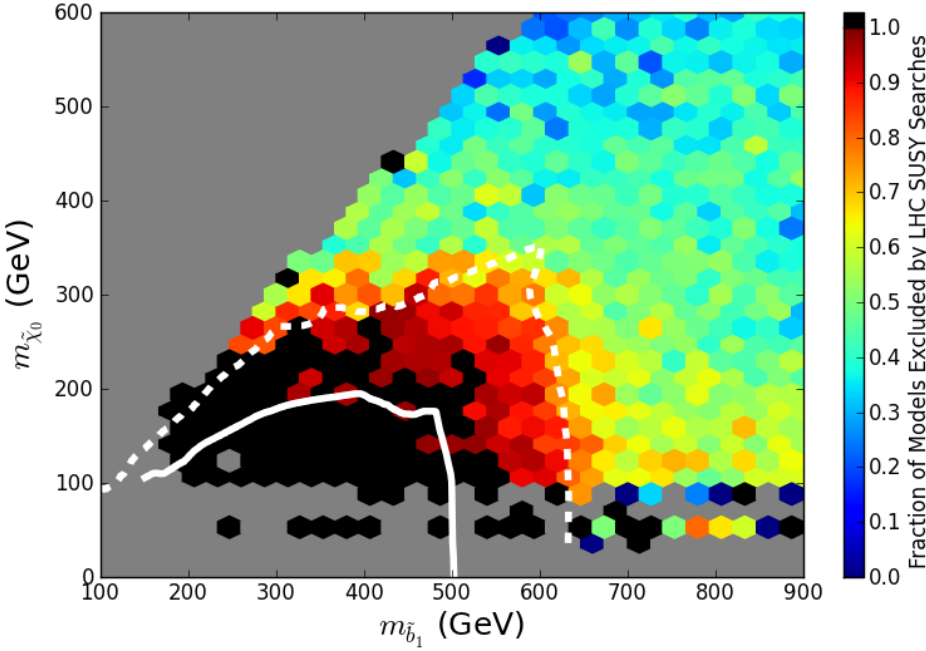
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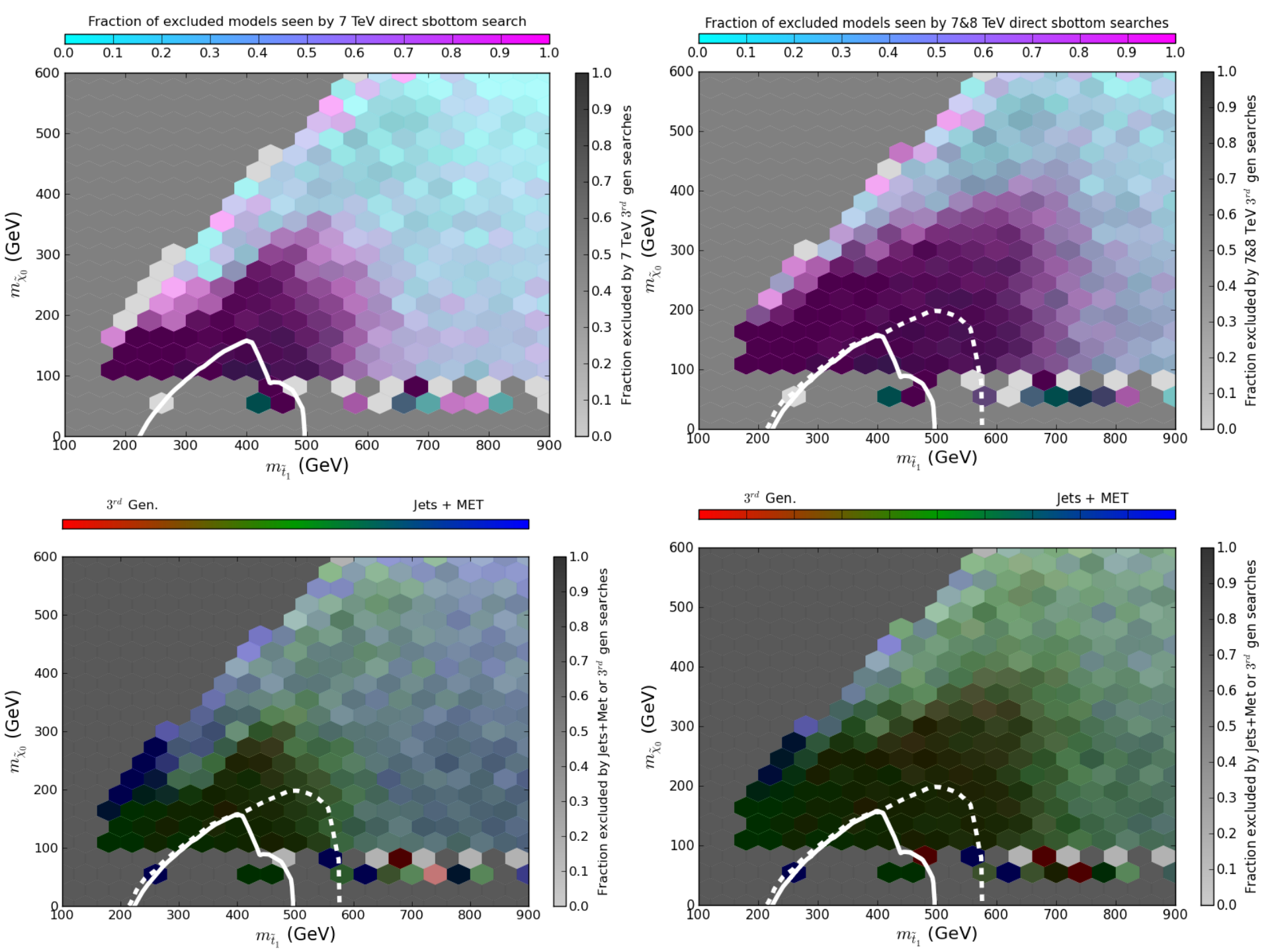
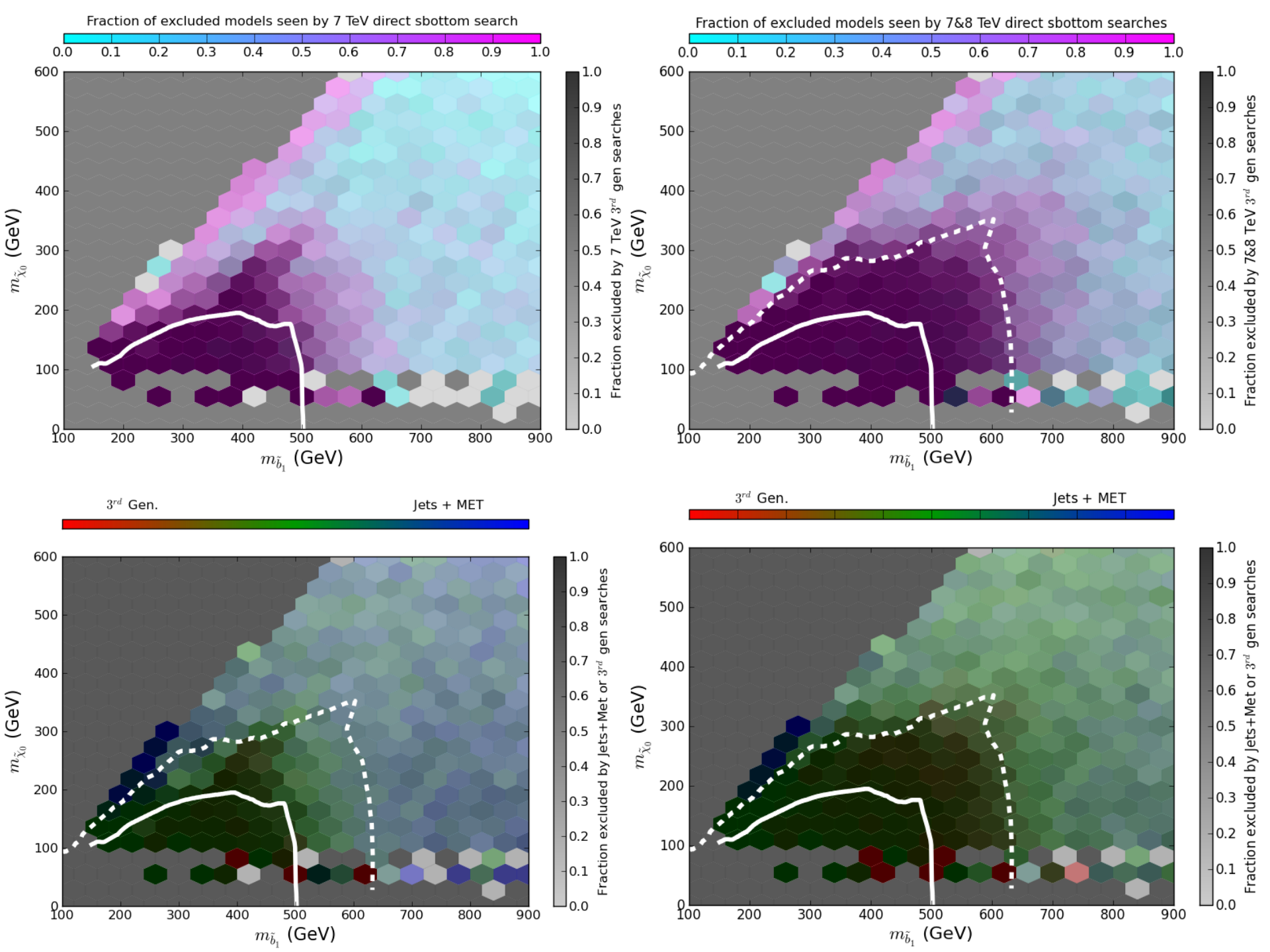
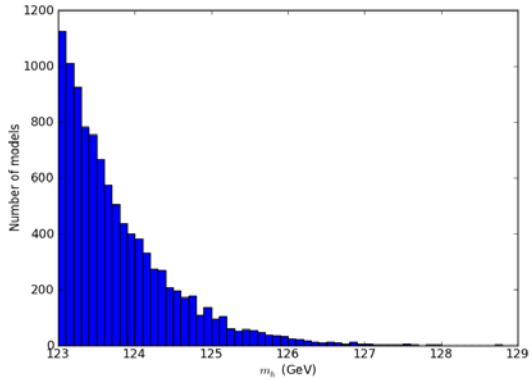
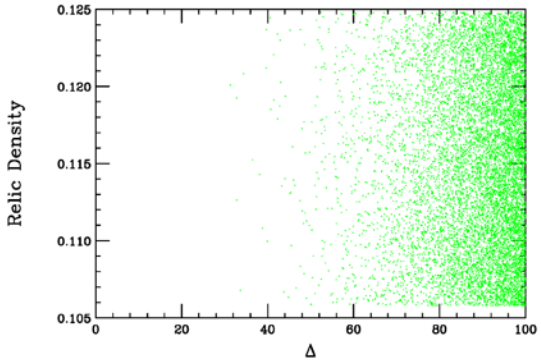

Fraction of excluded models seen by 7 TeV direct sbottom search
Fraction excluded by 7 TeV 3rd gen searches
Fraction of excluded models seen by 7&8 TeV direct sbottom searches
Fraction excluded by 7&8 TeV 3rd gen searches
3rd Gen.
Jets + MET
Fraction excluded by Jets+Met or 3rd gen searches
$m_{\tilde{\chi}_0}$ (GeV)
$m_{\tilde{t}_1}$ (GeV)

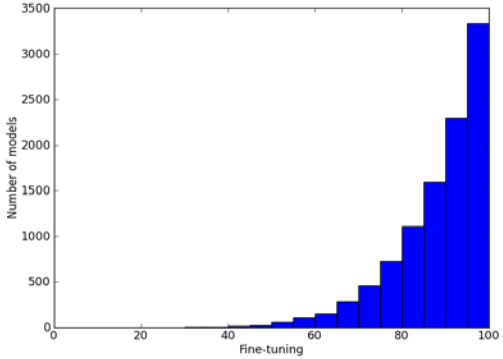

Fraction of excluded models seen by 7 TeV direct sbottom search
Fraction of excluded models seen by 7&8 TeV direct sbottom searches
3^{rd} Gen.
Jets + MET
$m_{\tilde{\chi}_0}$ (GeV)
$m_{\tilde{b}_1}$ (GeV)
Fraction excluded by 7 TeV 3^{rd} gen searches
Fraction excluded by 7&8 TeV 3^{rd} gen searches
Fraction excluded by Jets+Met or 3^{rd} gen searches

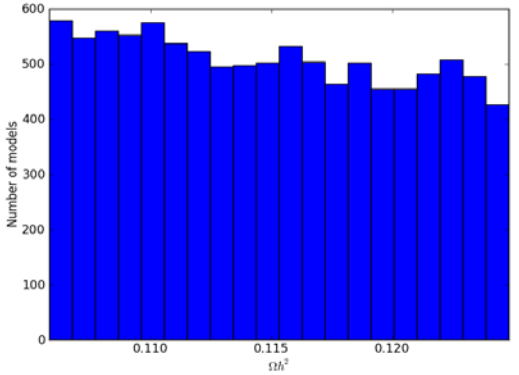
pMSSM Low-FT Neutralino LSP Model Set

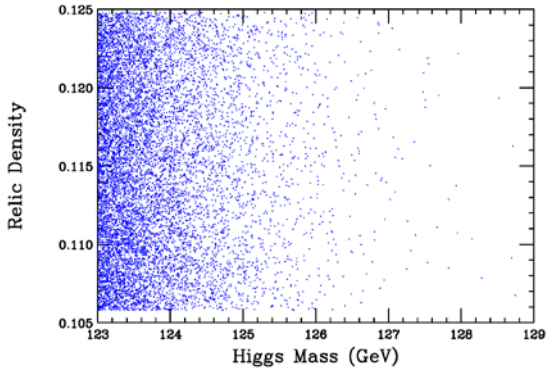
- 3.3 x 10^8 → ~10.2k models
- m_h = 126 ± 3 GeV
- WMAP/Planck ± 5σ
- FT better than 1% (Δ <100)
- expected to be very susceptible to ATLAS

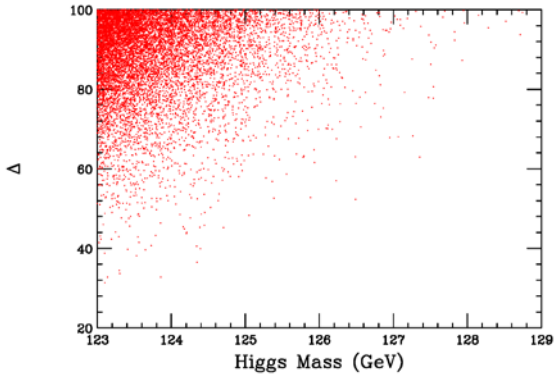


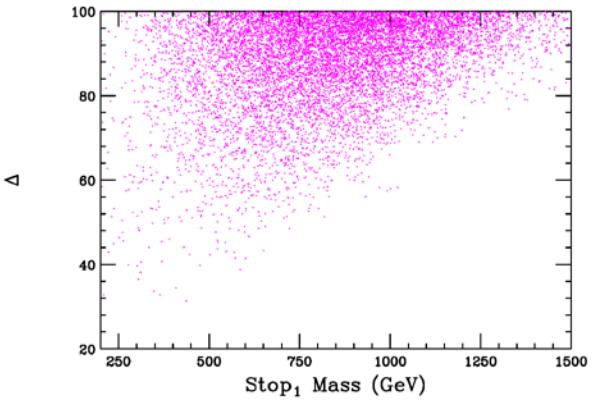


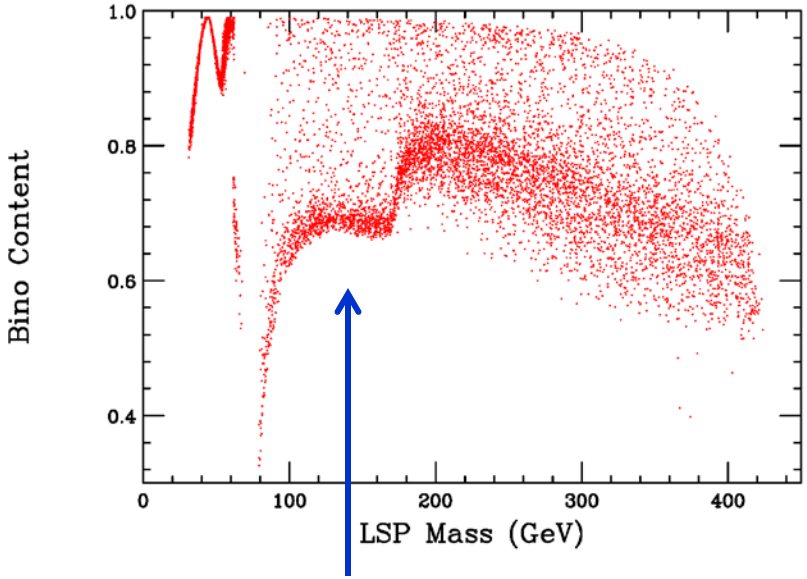




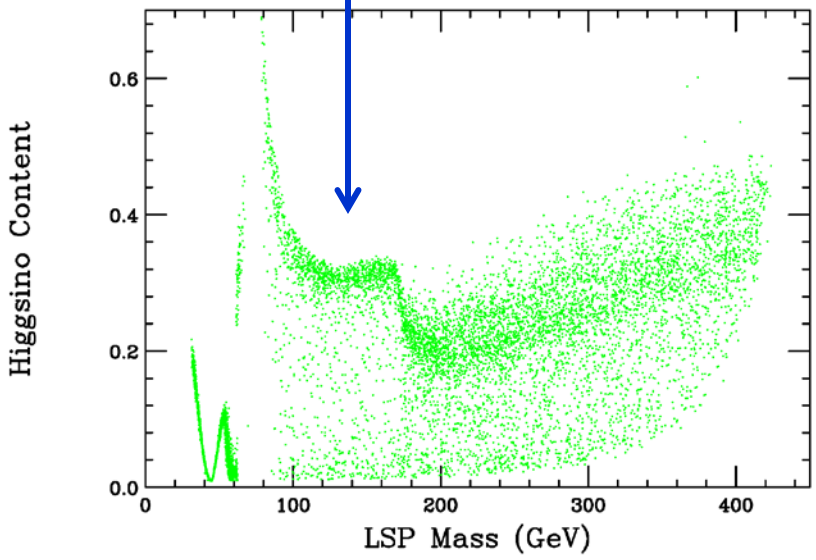






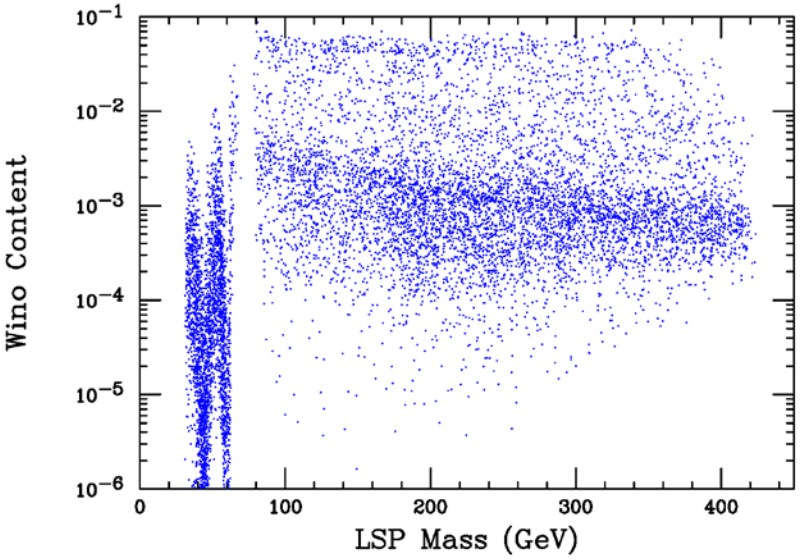


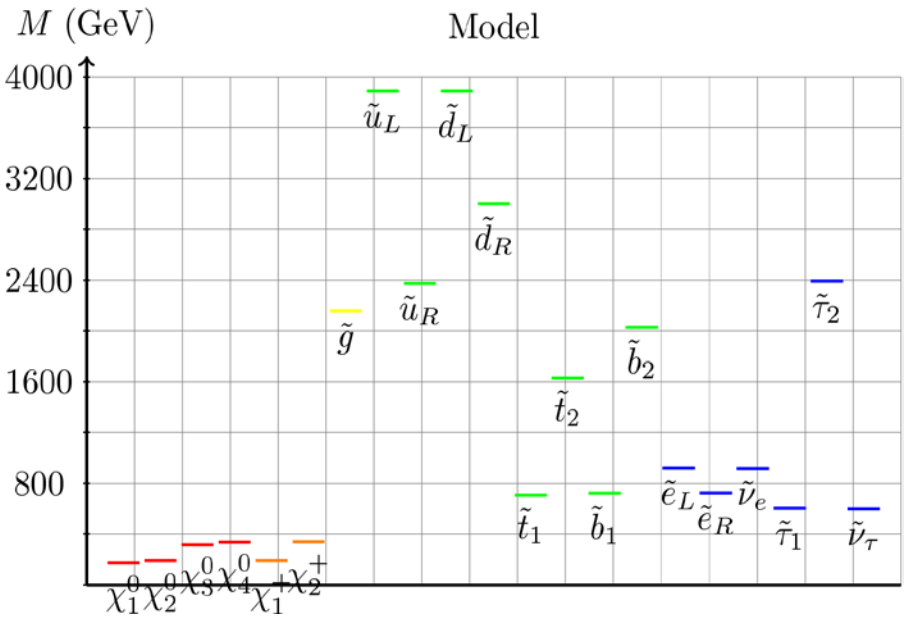
Essentially reflections !



LSPs are seen to be mostly bino-Higgsino admixtures as was expected w/ an occasional small wino component

There's lots of physics in the patterns here that there's no time to discuss(see backups)



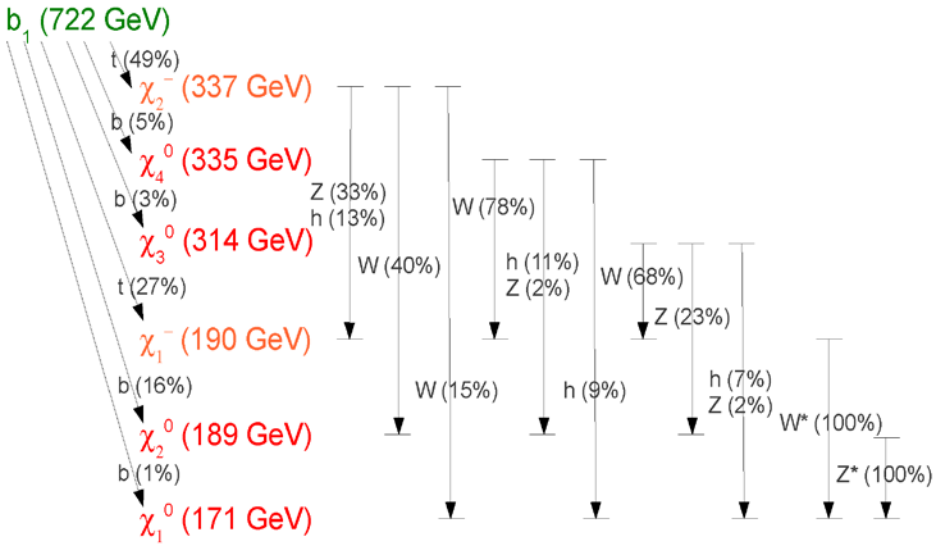


The necessity of both a light bino to get the right relic density & a light Higgsino for low-FT forces the stop decays to be quite complex !

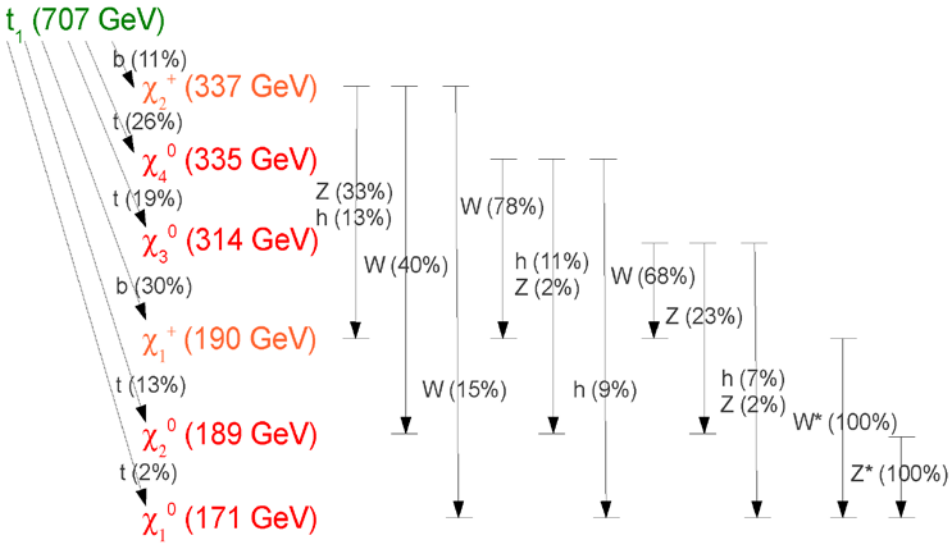
~ 60% of models also have winos below the stop/sbottom = leptons!

~ 30% also have a light slepton below stop (co-annihilators) = *more* leptons!

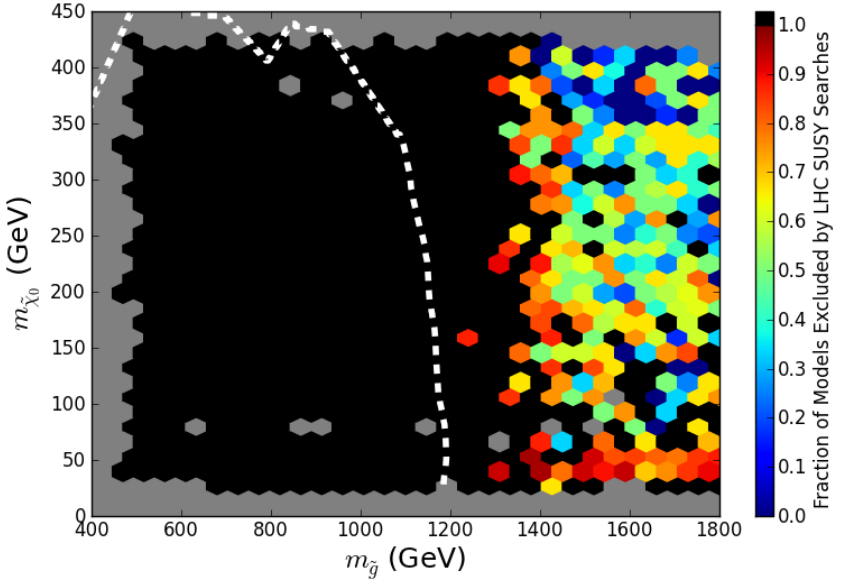
Model 3010059

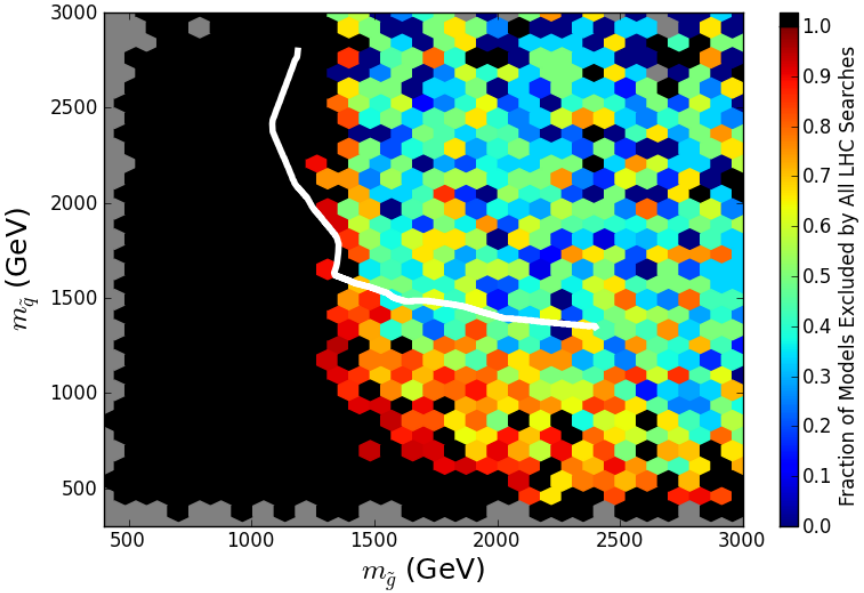


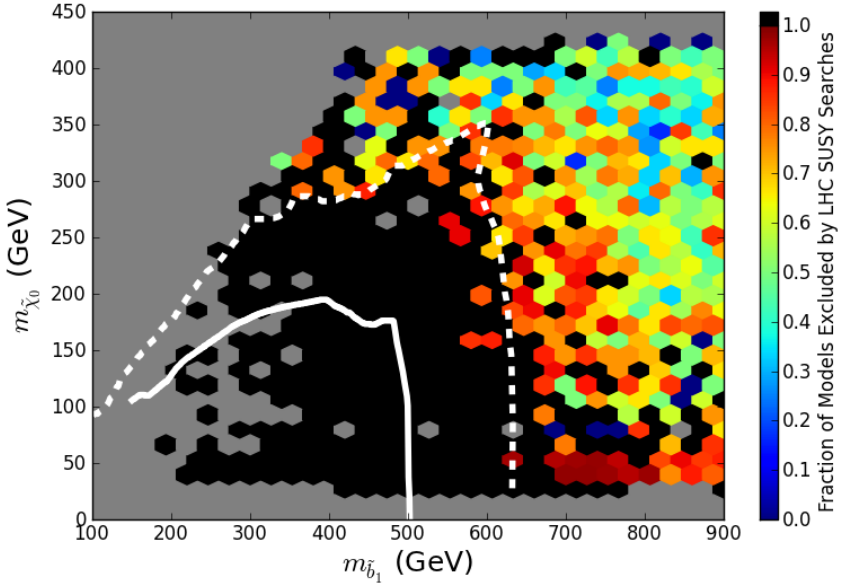
Model 3010059

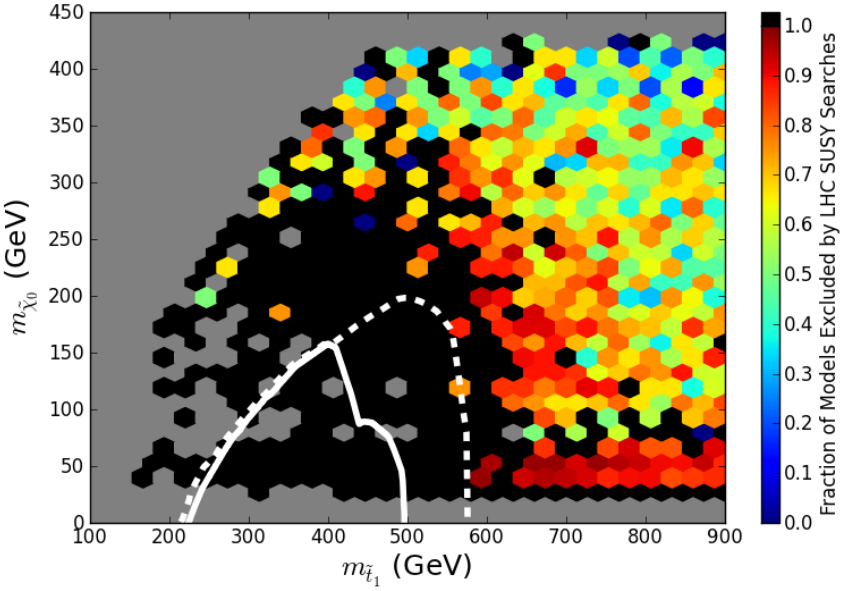


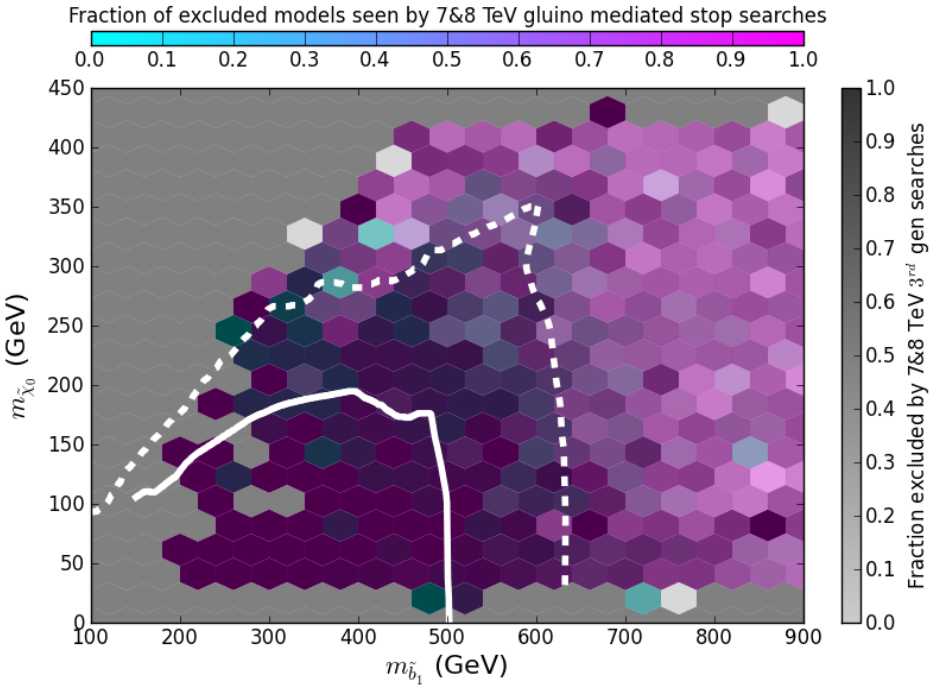
Coverage quite different than the more general set…..

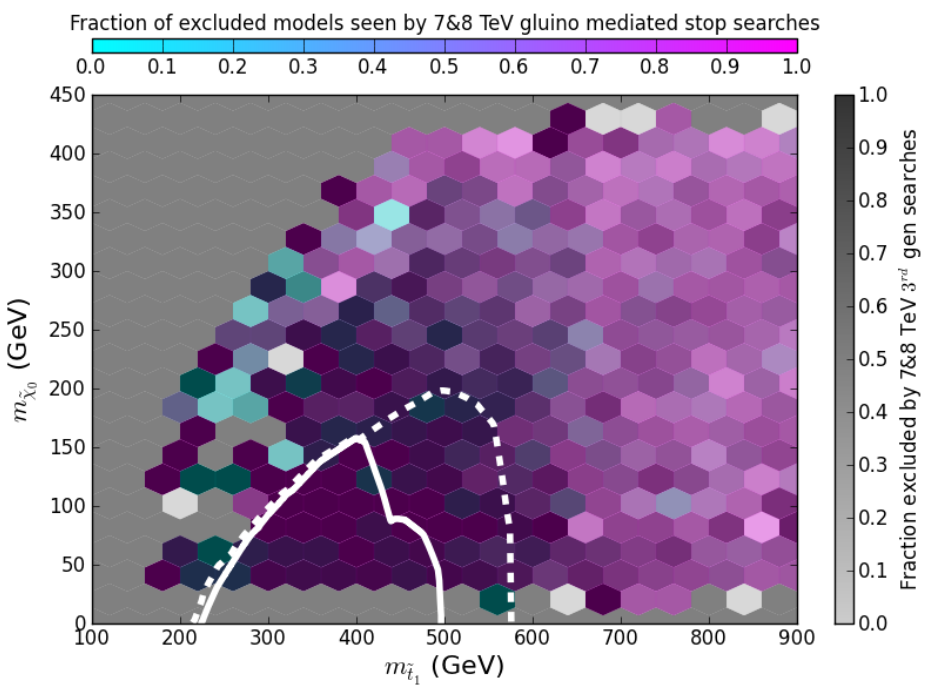









Fraction of excluded models seen by 7&8 TeV gluino mediated stop searches
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
$m_{\tilde{\chi}_0}$ (GeV)
$m_{\tilde{b}_1}$ (GeV)
Fraction excluded by 7&8 TeV 3^{rd} gen searches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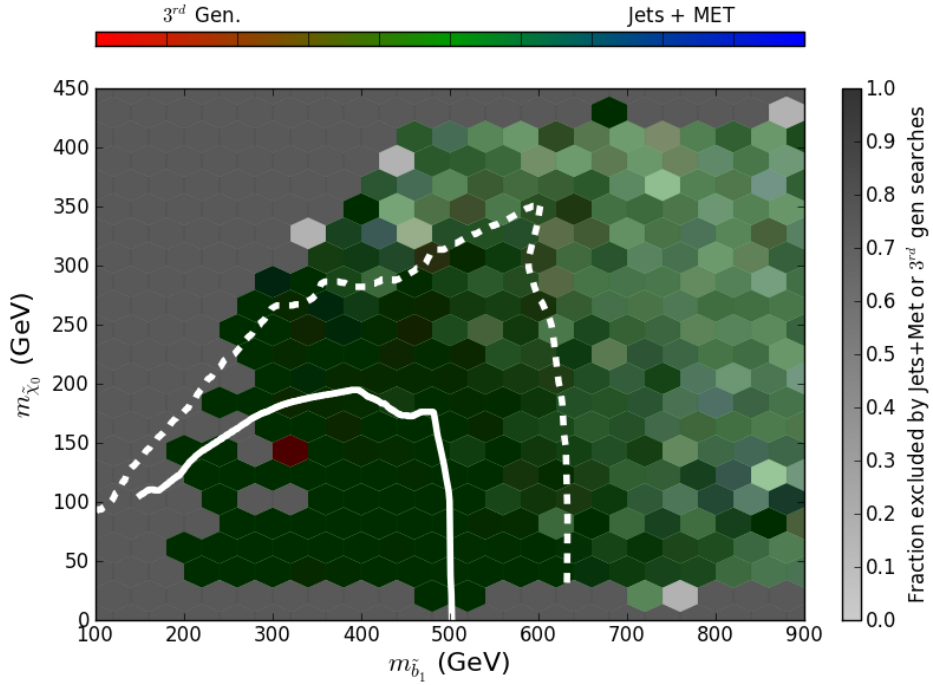
3^{rd} Gen.
Jets + MET
$m_{\tilde{\chi}_0}$ (GeV)
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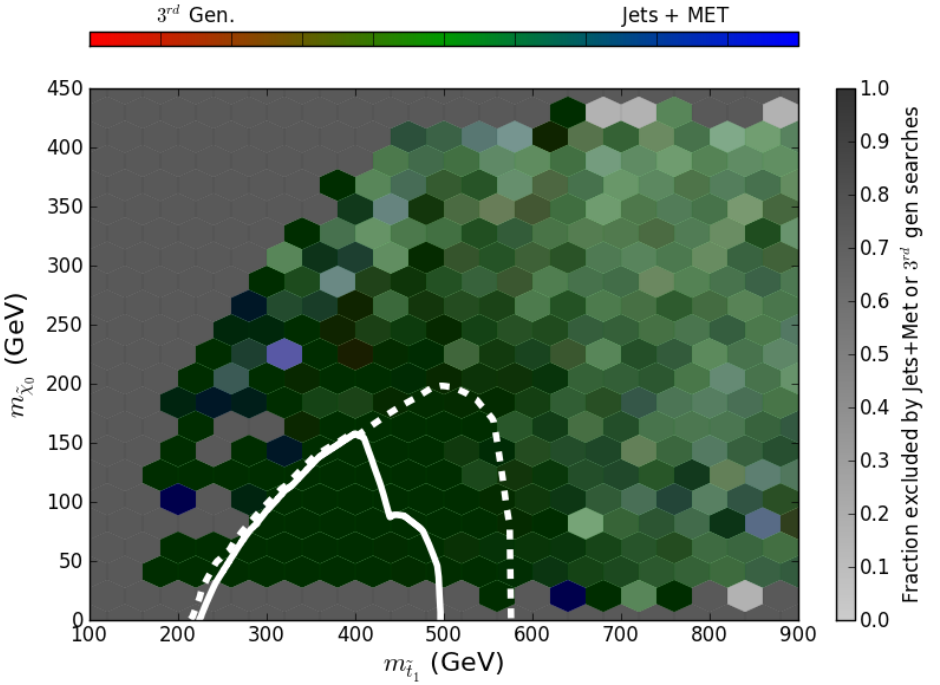
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Direct Sbottom (2b)	ATLAS-CONF-2012-165	17.4%
3rd Generation Squarks (3b)	ATLAS-CONF-2012-145	47.2%
3rd Generation Squarks (3l)	ATLAS-CONF-2012-151	32.8%
3 leptons	ATLAS-CONF-2012-154	38.5%
4 leptons	ATLAS-CONF-2012-153	52.4%
Z + jets + MET	ATLAS-CONF-2012-152	12.2%

Note: $B_s \rightarrow \mu\mu$ & $A \rightarrow \tau\tau$ constraints now applied during model generation

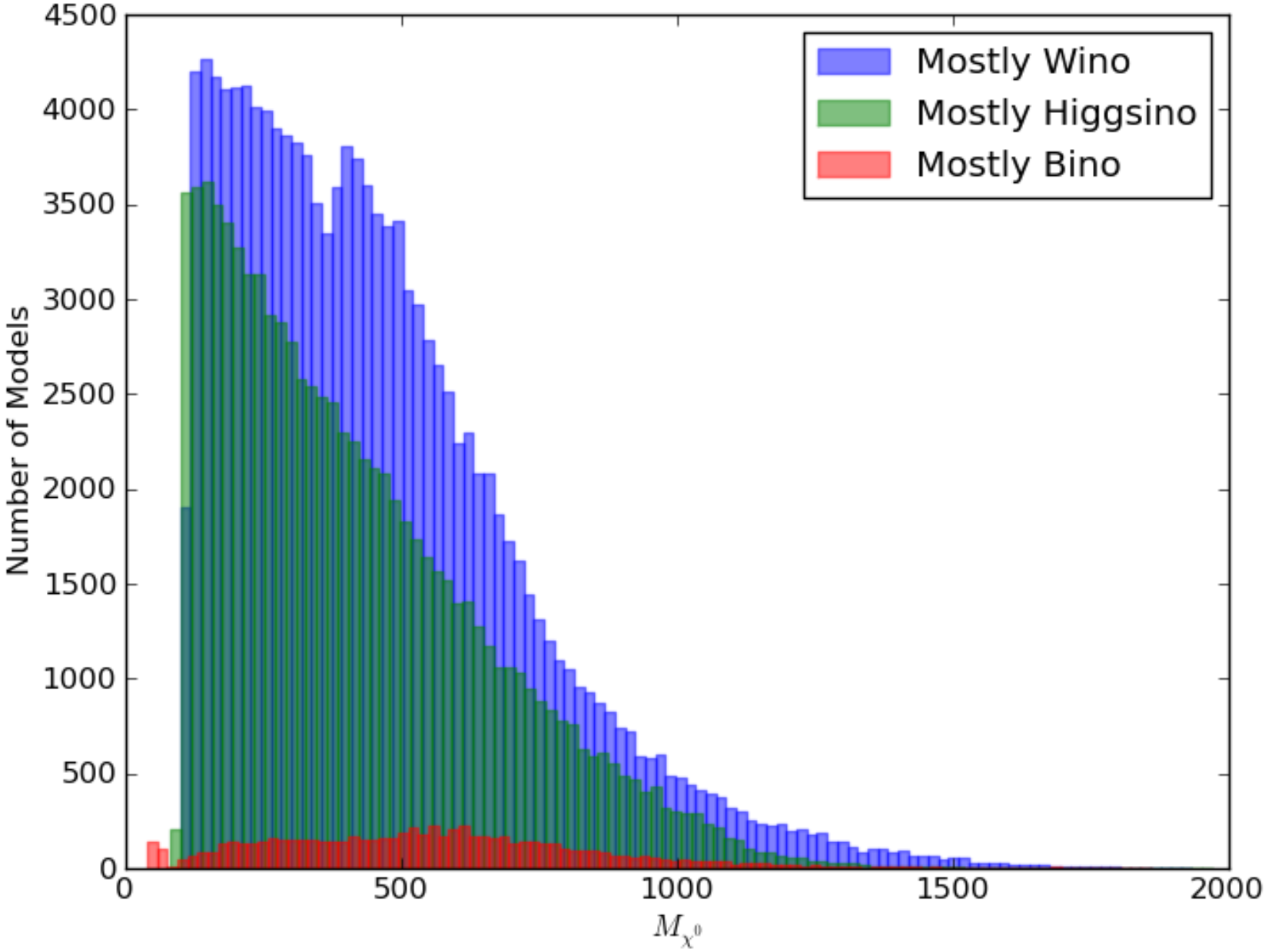
~73 % killed by searches !

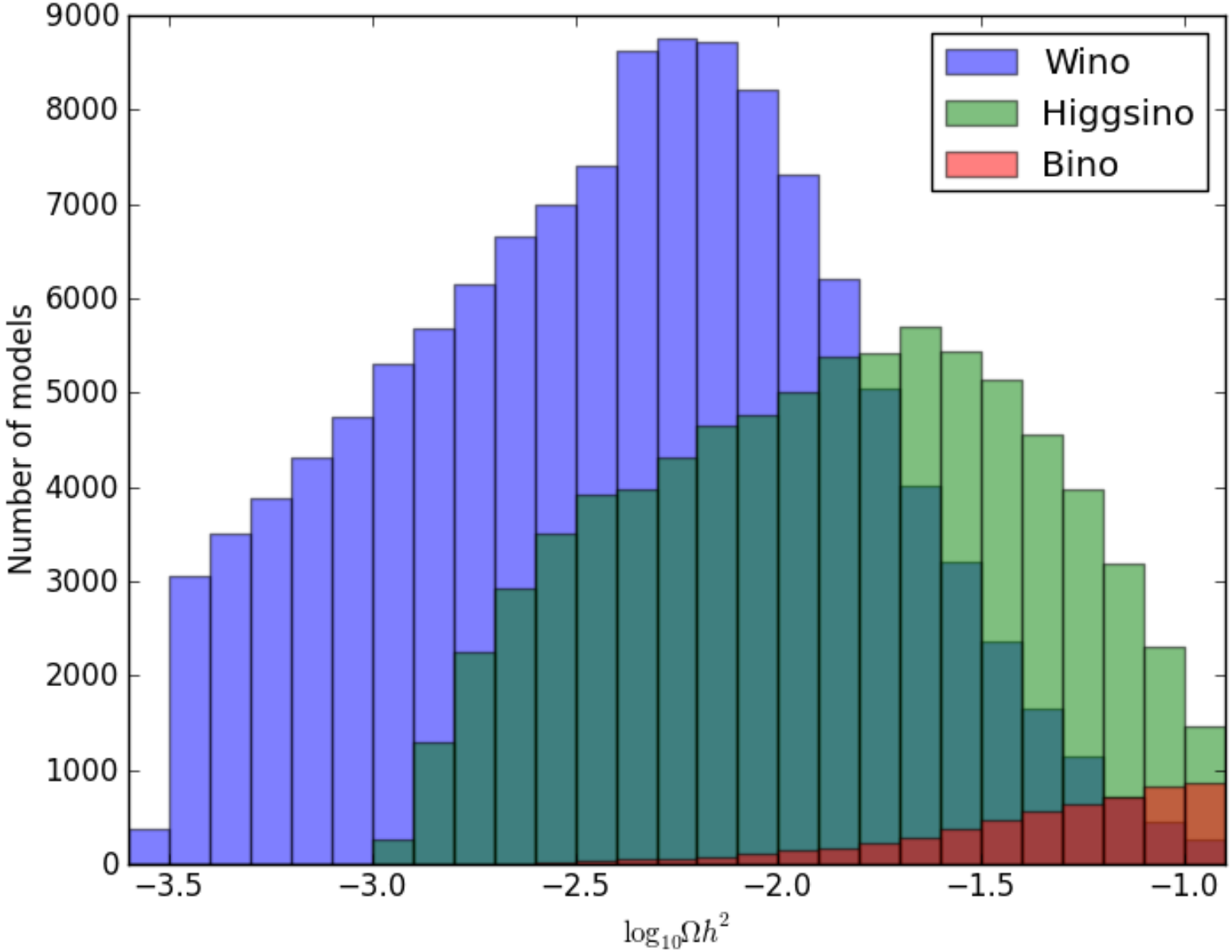
Summary

- Given time limitations this is only a brief overview of recent results

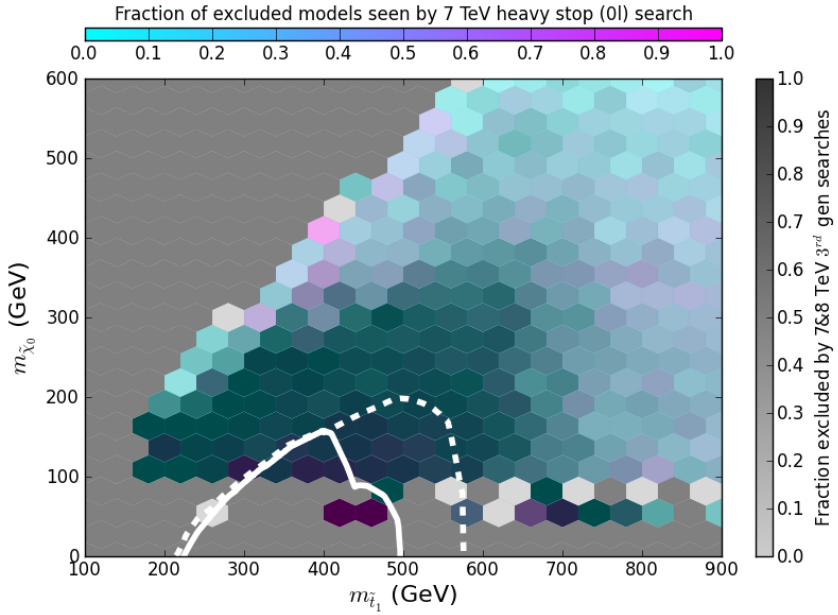
- Adding 15 new analyses (mostly 3rd gen + leptons) has an important impact on the coverage of the pMSSM neutralino set
- Low-FT models generally have complex stop/sbottom decays
- The coverage of models w/ low-FT is much more significant & the importance of 3rd generation & leptonic searches is quite obvious. The generation of a different new low-FT set is underway..
- Expect ~15 more analyses + gravitino set results for Snowmass
- Also : analysis @ 14 TeV as well as Higgs studies for Snowmass

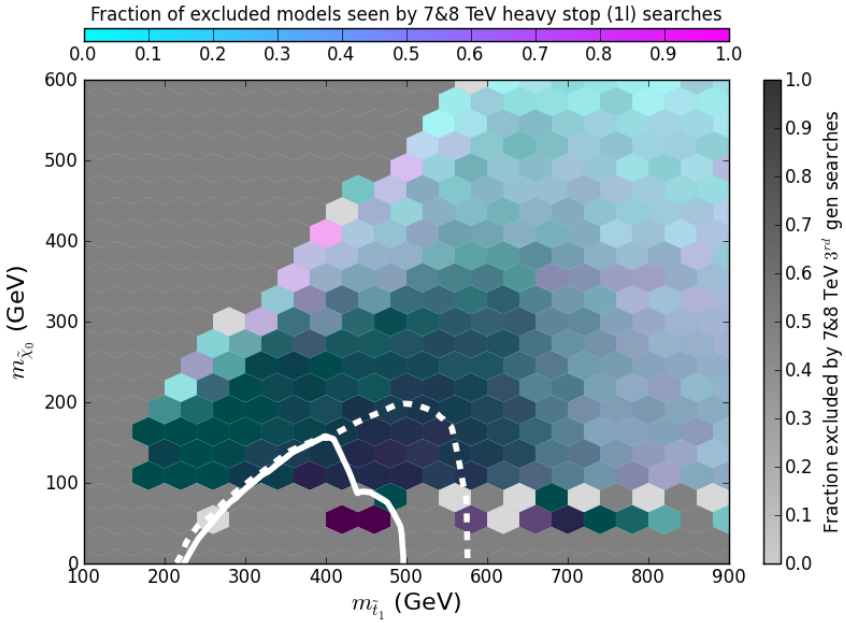
BACKUPS

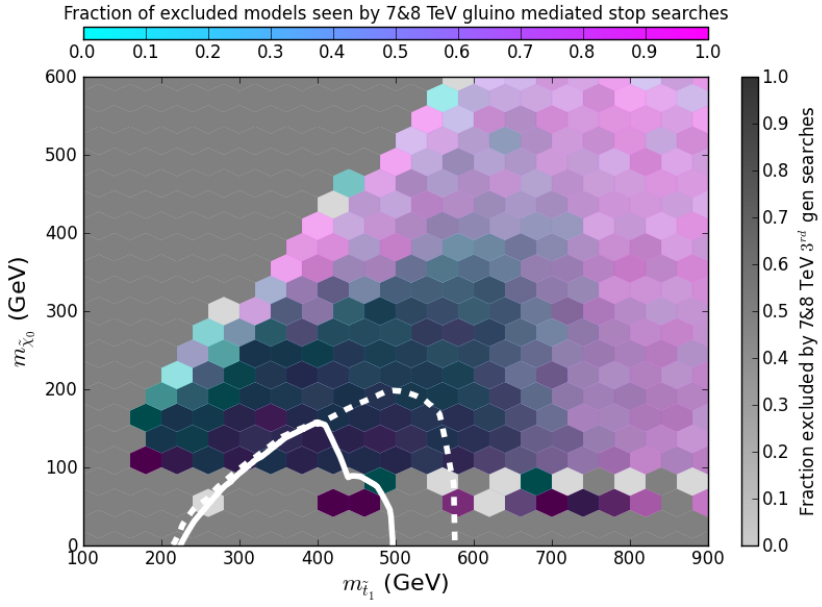

Mostly Wino
Mostly Higgsino
Mostly Bino
Number of Models
0
500
1000
1500
2000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
M_{χ^0}

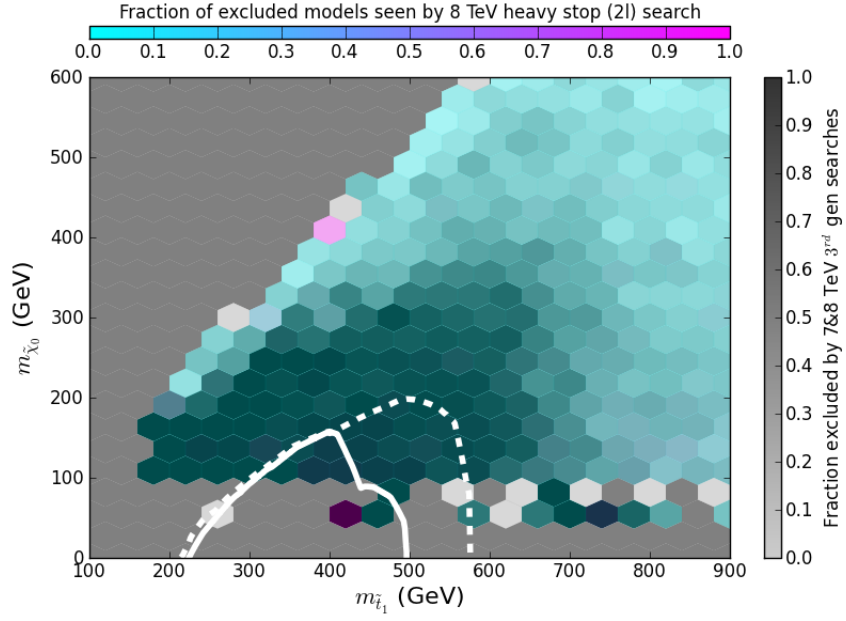

Wino
Higgsino
Bino
Number of models
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$\log_{10}\Omega h^2$

Comparison of Stop Search Effectiveness

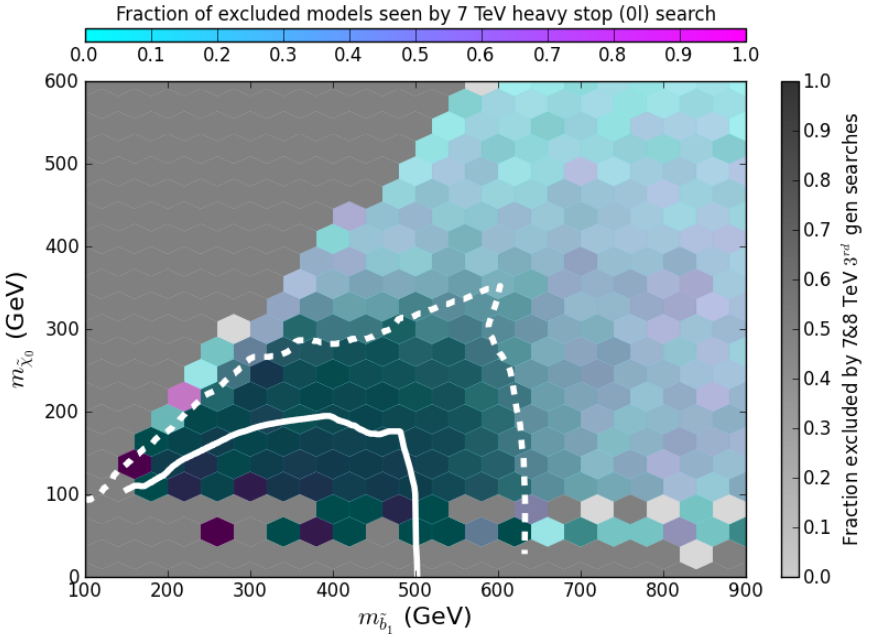


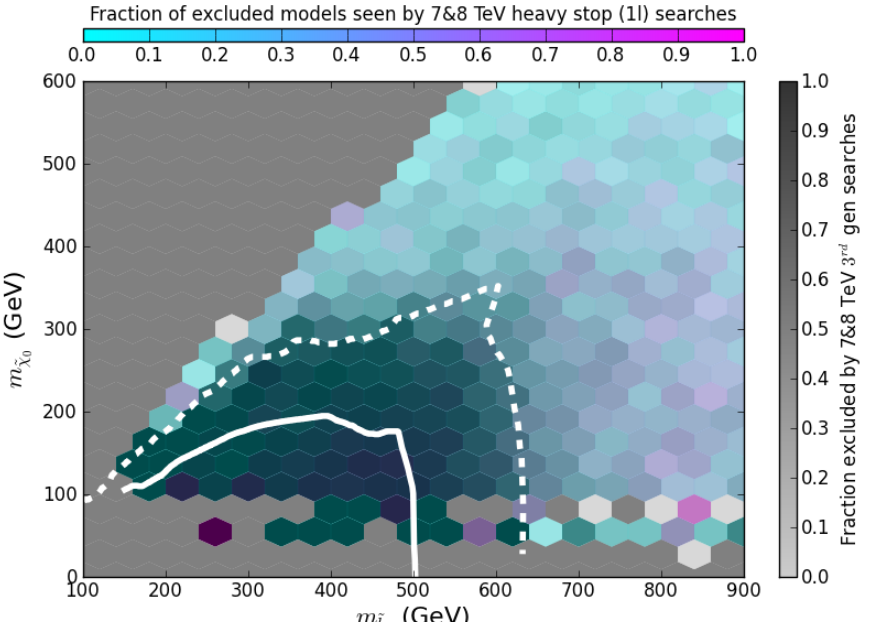


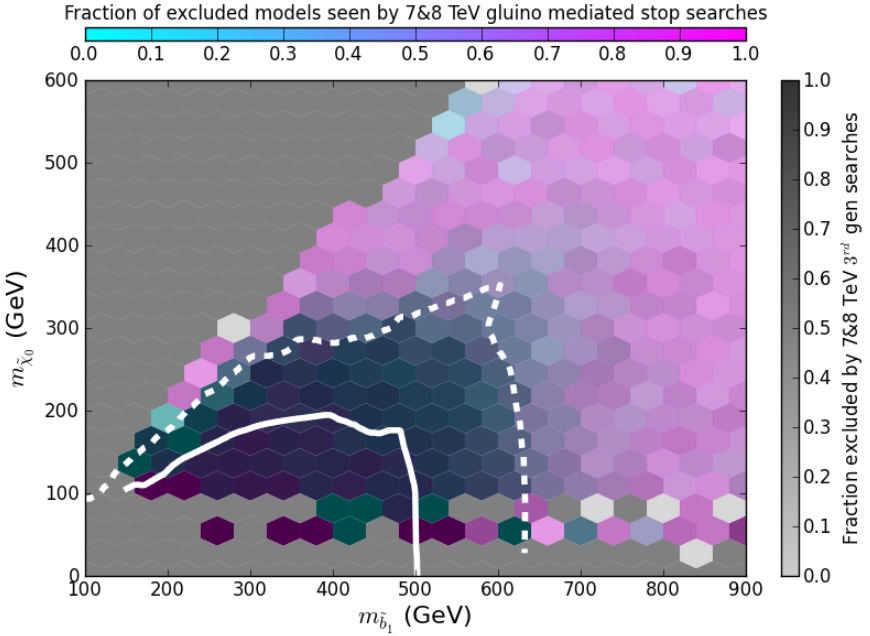


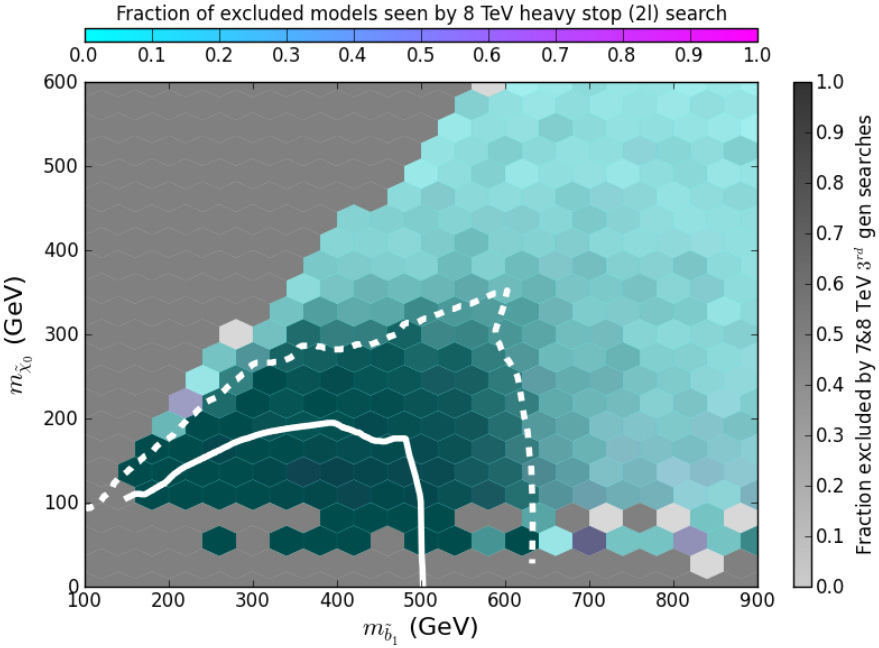


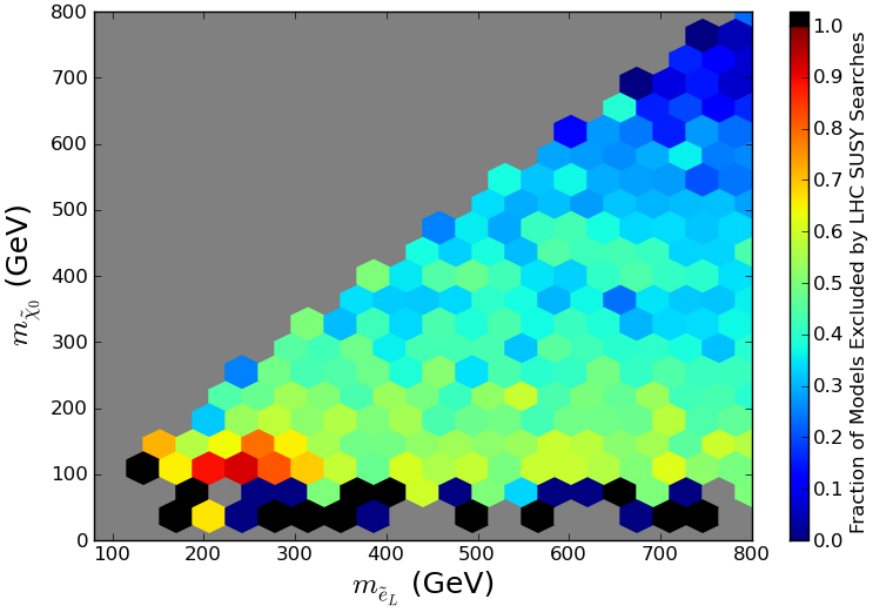
Comparison of Sbottom Search Effectiveness

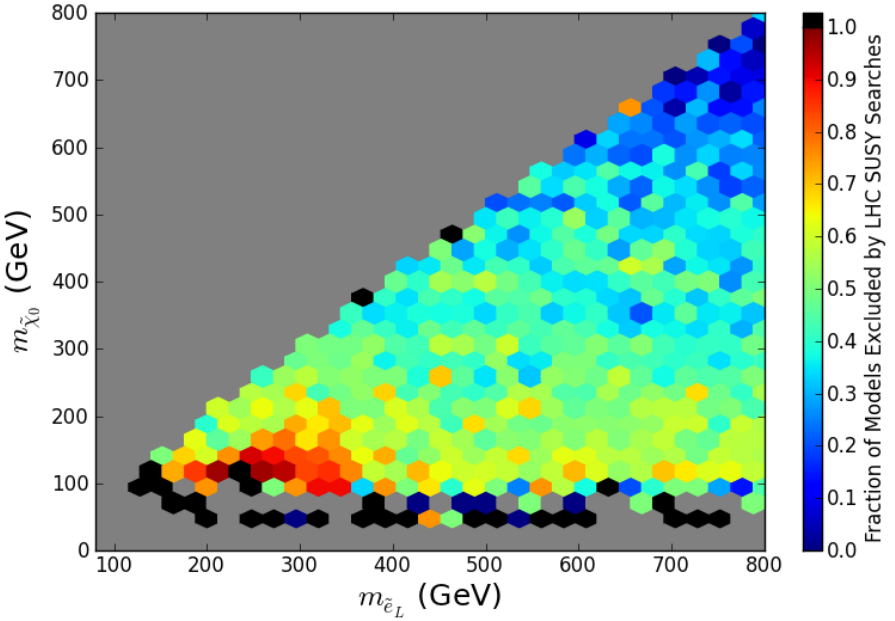






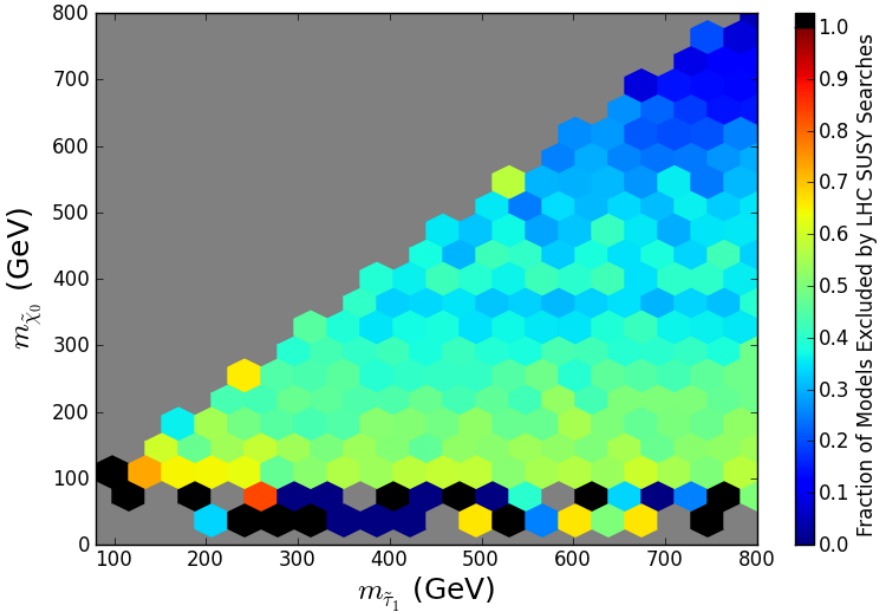


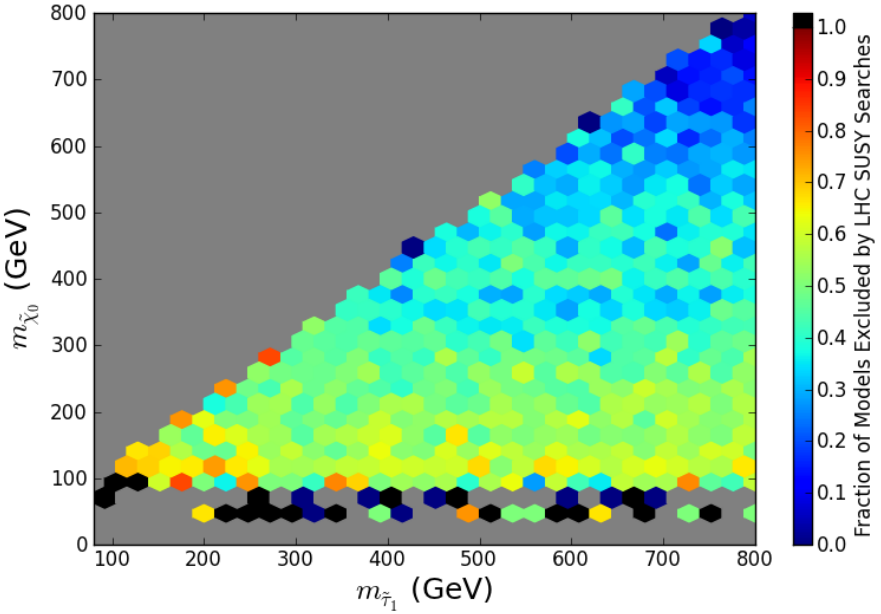




Before

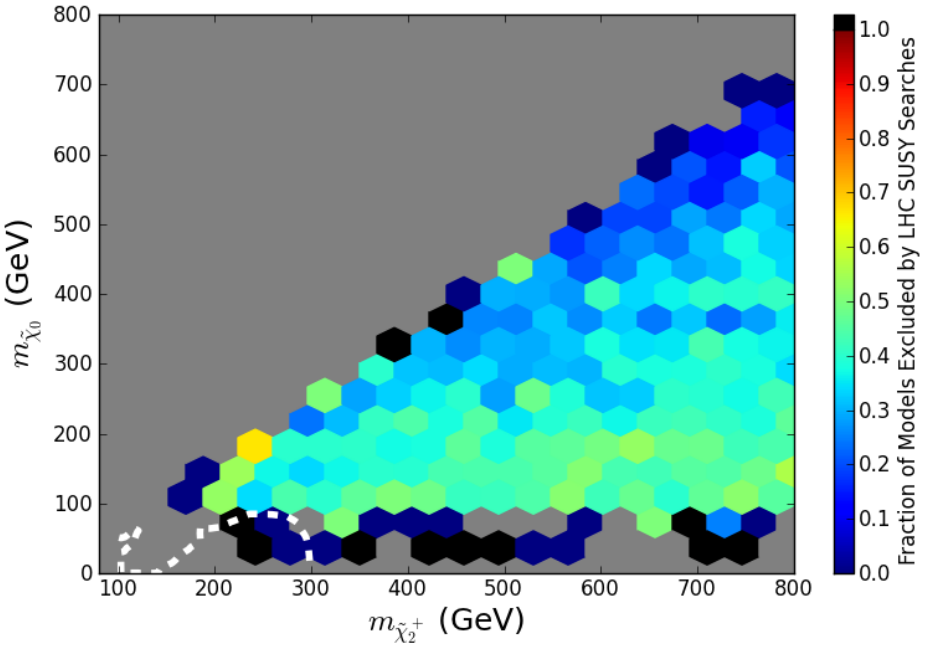
After

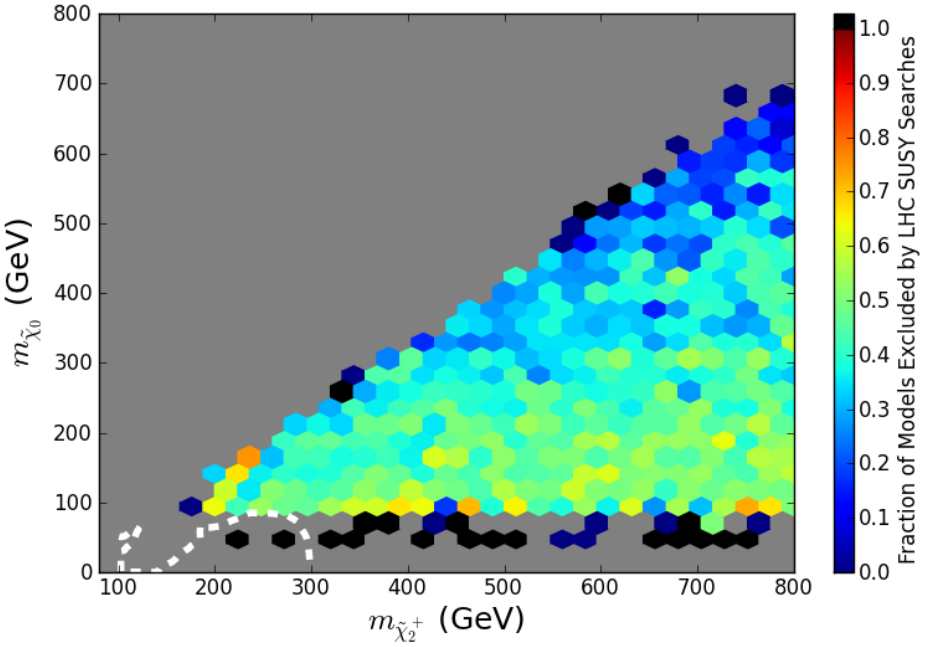




- Some improvement is seen for the case of gauginos likely due to the new leptonic searches + secondary sources which filter into these results

- However the sensitivity here remains rather weak but should improve when more lumi is added soon



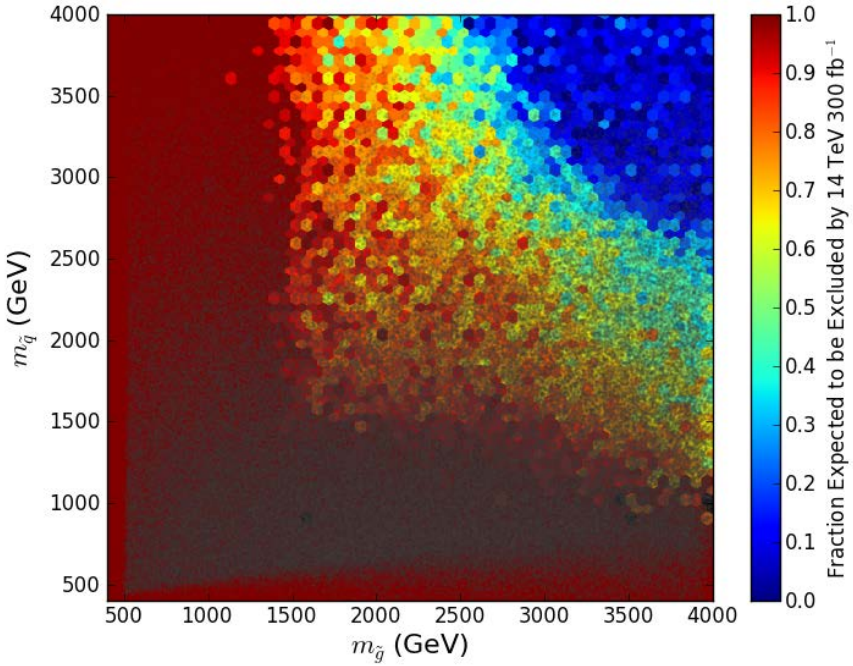


Extension of pMSSM Study to 14 TeV

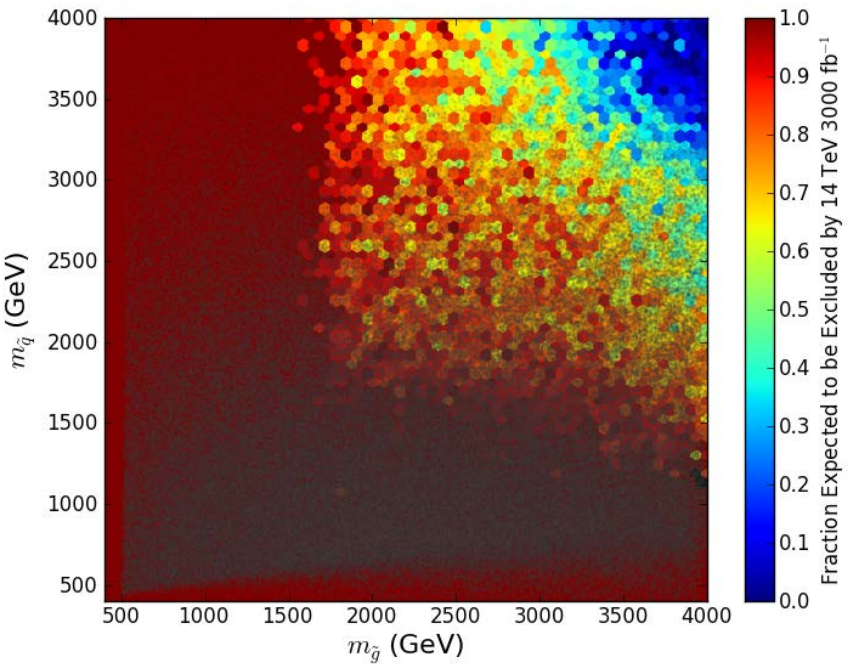
- Using naïve scaling arguments we can make some VERY VERY crude estimates of the pMSSM coverage @ 14 TeV

- With input from ATLAS we will perform analyses similar to those in the European Study Report for the pMSSM

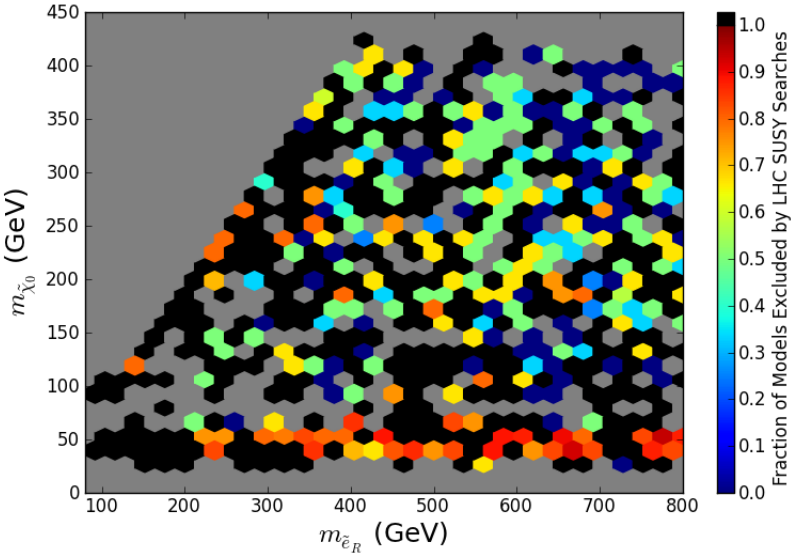
300 fb $^{-1}$

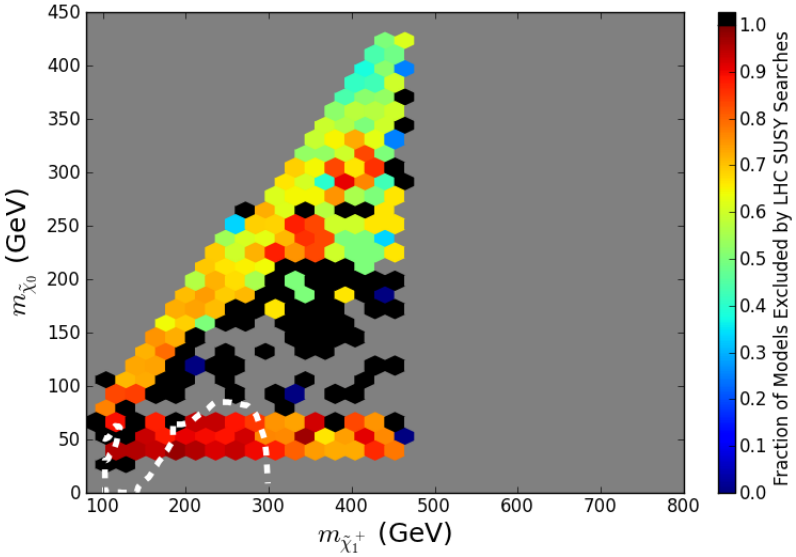


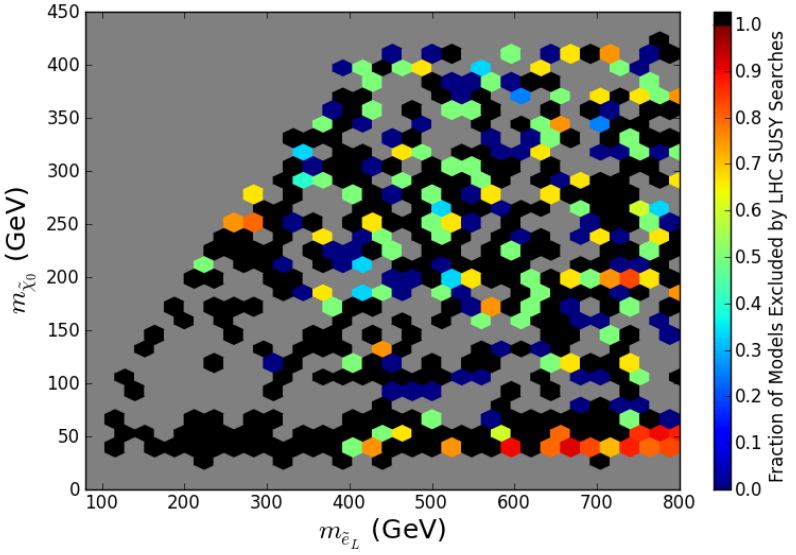
3 ab $^{-1}$

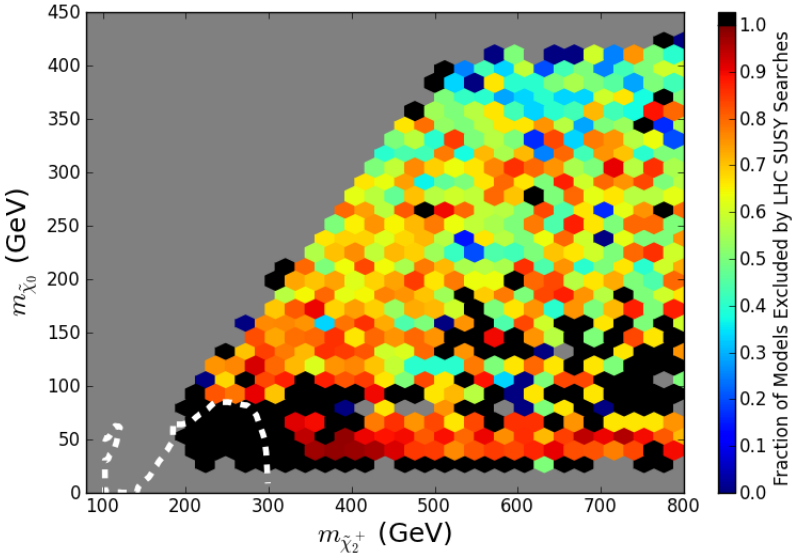


More Low-FT Results

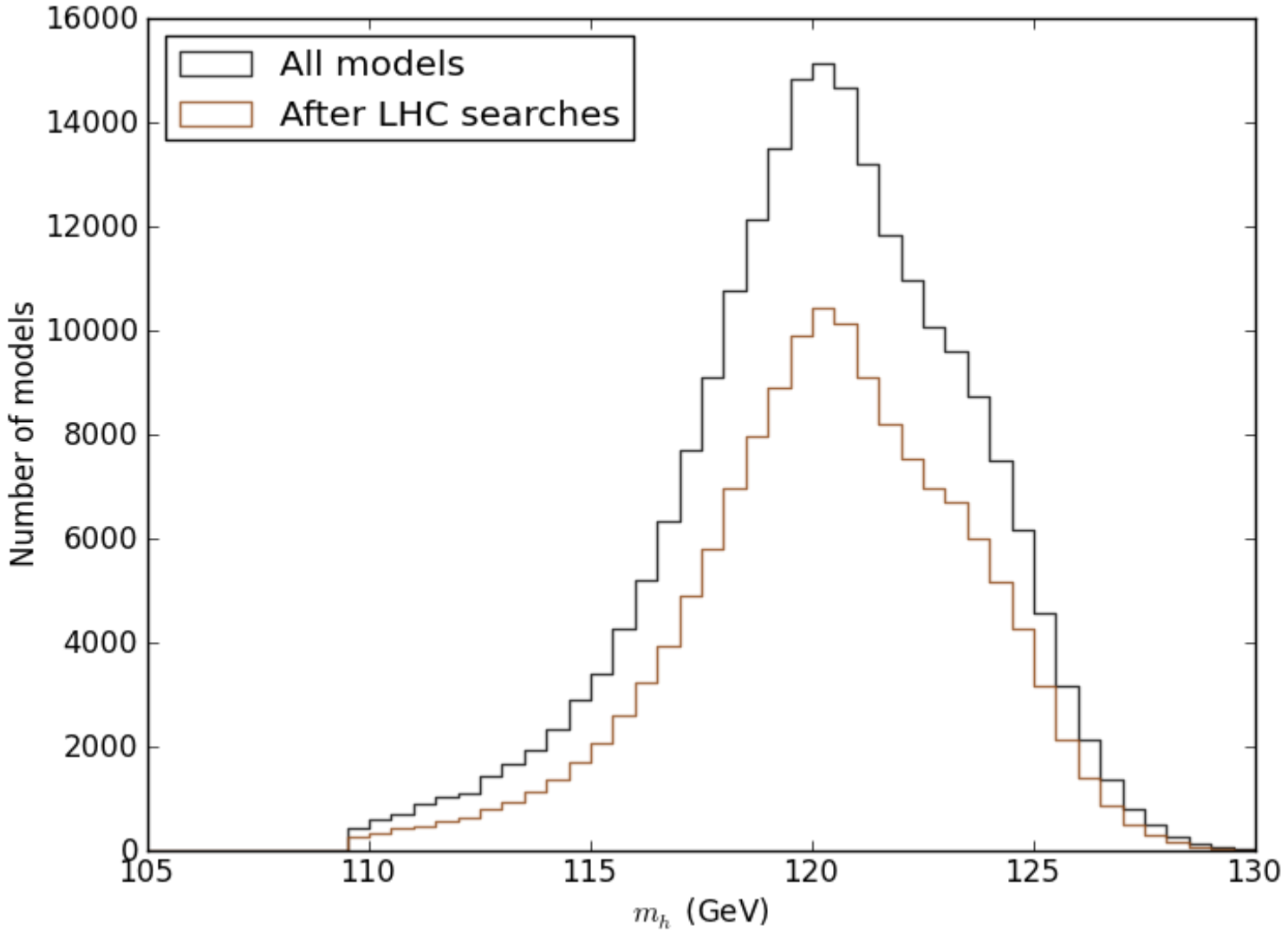








As the SUSY searches are roughly independent of the value of the Higgs mass, the predicted mass of the Higgs is roughly independent of the SUSY searches as well !



Low Fine-tuning in the pMSSM ?

- m_h ~ 125-6 GeV in the MSSM requires large stop masses and/or mixings which then → significant FT expected

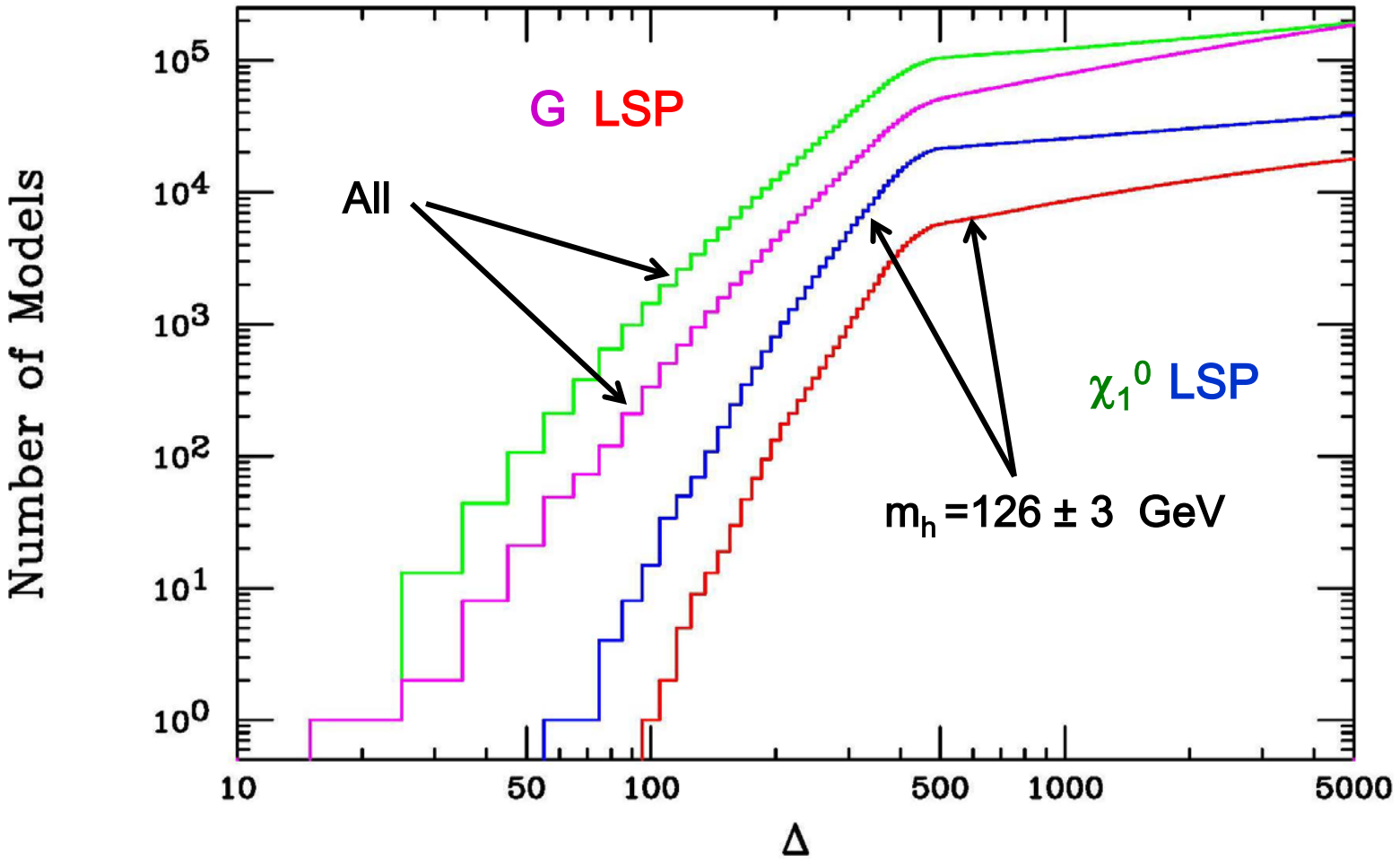
$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} + \mu^2$$

- To quantify FT we ask how the value of M_Z depends upon any of the 19 parameters , { p_i }, up to (in some cases) the 2-loop, NLL level (c/o Martin & Vaughn). We follow the traditional FT analysis of Ellis et.al. & Barbieri & Giudice :

$$A_i = |\partial \ln M_Z^2 / \partial \ln p_i| , \qquad \Delta = \max \{A_i\}$$

- How many models have Δ less than a specific value ?

Fine-tuning in the pMSSM



- As expected, the large Higgs mass 'cut' removes most of the models with the lowest FT values

Lessons Learned

- Completely random scans are seen to produce few models with low FT values
- Furthermore, as expected, the large Higgs mass 'cut' is seen to remove most of the models with the lowest FT values
- The spectra of these low-FT models can make them difficult to see w/ existing searches (see next 2 slides)
- This is an important class of models. It is certainly worth performing dedicated scans to produce sets of low-FT models under various physics assumptions so that they can be studied in detail.
- We got a start on this so let's have a look….

Some Constraints

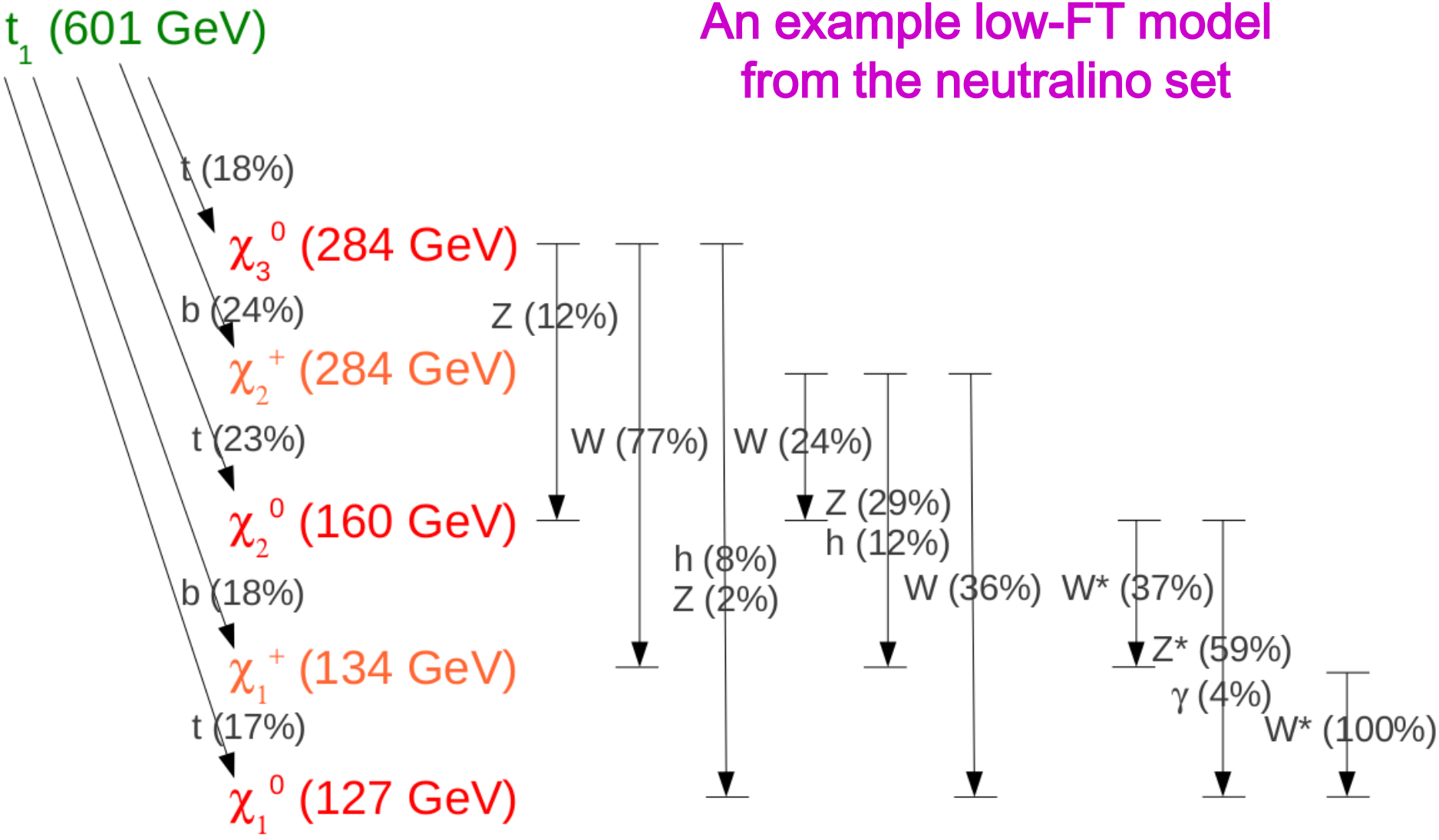
- $\Delta\rho$ / W-mass
- $b \to s\,\gamma$
- $\Delta(g\text{-}2)_\mu$
- $\Gamma(Z \to \text{invisible})$
- Meson-Antimeson Mixing
- $B \to \tau\nu$
- $B_s \to \mu\mu$

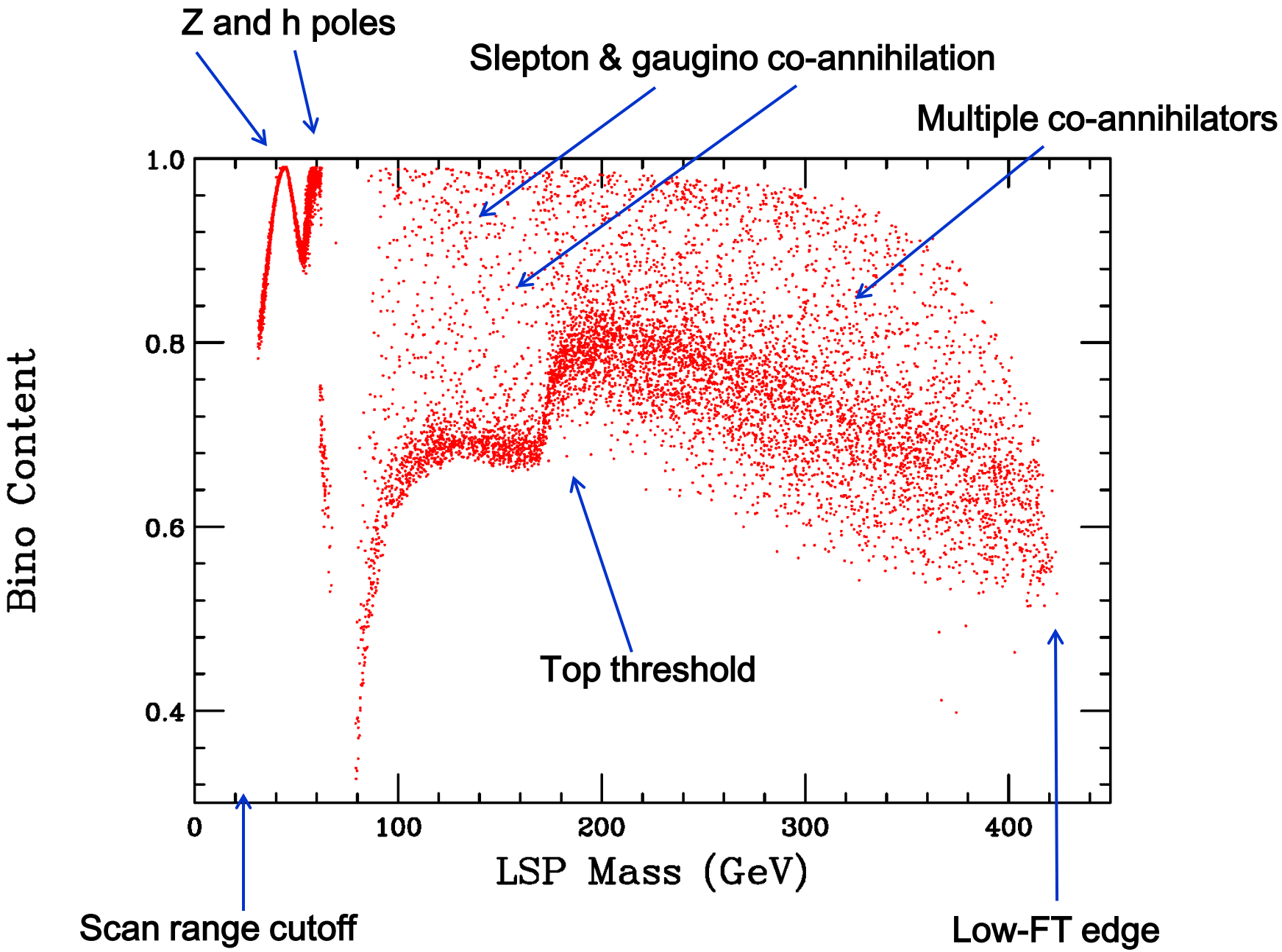
- Direct Detection of Dark Matter (SI & SD)
- WMAP Dark Matter density upper bound
- LEP and Tevatron Direct Higgs & SUSY searches
- LHC stable sparticle searches + $A \to \tau\tau$

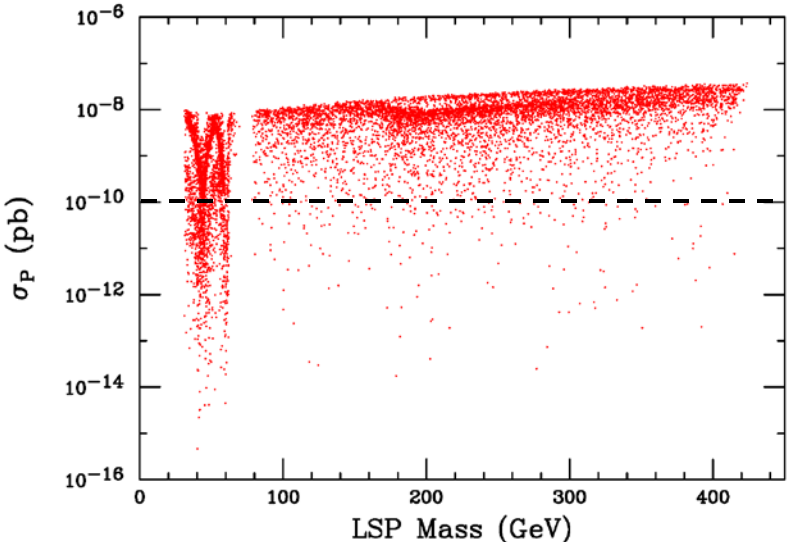
- BBN energy deposition for gravitinos
- Relic ν's & diffuse photon bounds

- No tachyons or color/charge breaking minima
- Stable vacua only

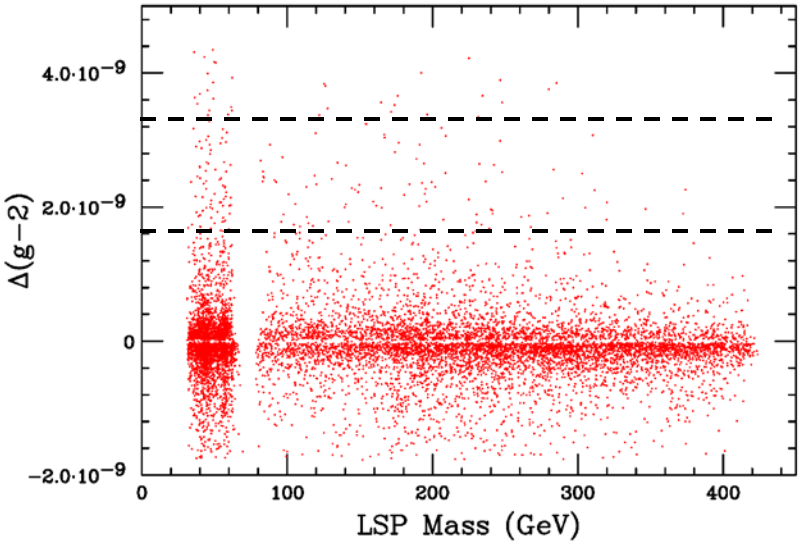
An example low-FT model from the neutralino set




Z and h poles
Slepton & gaugino co-annihilation
Multiple co-annihilators
Bino Content
1.0
0.8
0.6
0.4
0
100
200
300
400
LSP Mass (GeV)
Top threshold
Scan range cutoff
Low-FT edge



- SI direct detection cross sections for these models, since the LSP is mostly well-tempered, almost all lie within ~100 below the present limits & will be found (or not) by XENON-1T



- Δ(g-2) of the muon CAN be large for some of these models if there are also light sleptons which do appear in some cases to get DM co-annihilation to work

Our p(henomenological)MSSM

- General CP-conserving MSSM with R-parity
- MFV at the TeV scale (CKM)
- Lightest neutralino/gravitino is the LSP.
- 1st/2nd generation sfermions degenerate
- Ignore 1st/2nd generation A-terms &Yukawa's.
- No assumptions wrt SUSY-breaking
- WMAP used as upper bound on relic density

→ the pMSSM with 19/20 parameters

$50\ \text{GeV} \le |M_1| \le 4\ \text{TeV}$

$100\ \text{GeV} \le |M_2, \mu| \le 4\ \text{TeV}$

$400\ \text{GeV} \le M_3 \le 4\ \text{TeV}$

$1 \le \tan\beta \le 60$

$100\ \text{GeV} \le M_A, l, e \le 4\ \text{TeV}$

$400\ \text{GeV} \le q_1, u_1, d_1 \le 4\ \text{TeV}$

$200\ \text{GeV} \le q_3, u_3, d_3 \le 4\ \text{TeV}$

$|A_{t,b,\tau}| \le 4\ \text{TeV}$

$1\ \text{eV} \le m_{3/2} \le 1\ \text{TeV}$ (log prior)

Goal: obtain ~250k points in each of these 2 spaces satisfying existing data then study their signatures @ the LHC & elsewhere…

We're going for breadth not depth ! →→ New low-FT set(s)

The pMSSM SUSY Search Approach

- The pMSSM - reduces the # of MSSM parameters w/ experimentally motivated assumptions & is 'unprejudiced' wrt high-scale SUSY. Can lead to complex spectra & decay patterns, allows for correlations between various experiments & searches → less constrained SUSY. But is computationally challenging….

- The pMSSM can be used to combine all of the searches (even the non-MET ones !) to obtain a complete picture of the overall coverage of the SUSY parameter space

ATLAS SUSY Analyses @ 7 & 8 TeV

- Goal: implement the entire ATLAS SUSY suite w/ fast MC.
- Generate signal (only) events for every model for all ~85 SUSY processes & then scale w/ Prospino = CPU !
- Validate each signal region in every analysis using ATLAS benchmarks; use ATLAS backgrounds & limits as input
- Determine which models are excluded by every analysis & then combine them to determine the 'total' exclusion
- Note : we lag behind ATLAS

For us the 3 big questions are :

1st Question: How do each of the searches do in covering the pMSSM parameter space ?

2nd Question: When all the searches are combined what fraction of the space remains ?

3rd Question: Why are some models missed ?

Here

→ Update our set of 7 & 8 TeV analyses (+15) to include all ATLAS results as of 3/1/13. These are mostly 3rd gen & leptonic searches @ 13 fb $^{-1}$. Further updates will appear later this summer.

→ First look at the new low-FT model set

→ One Lesson: It is important to keep 'old', e.g., 7 TeV analyses even when 8 TeV ones are available as models can be missed by cut tightening. This may be especially important going to14 TeV.

pMSSM Low-FT Neutralino LSP Model Set

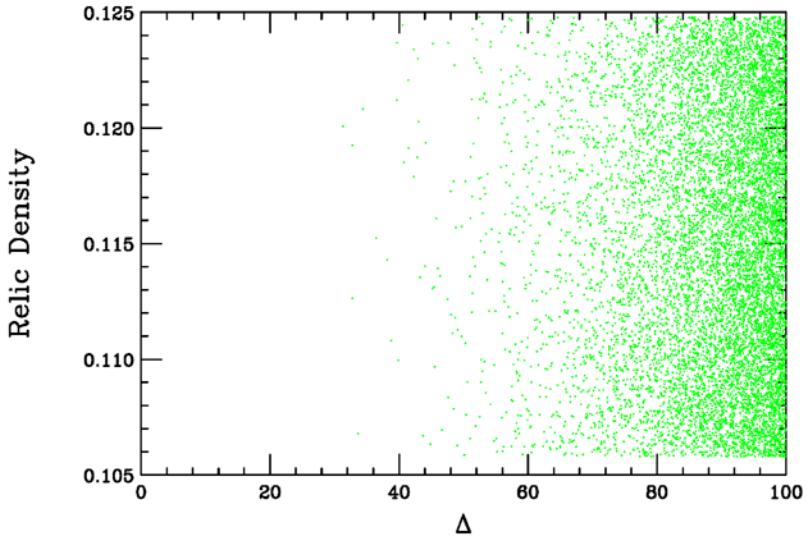
→→ Can we get models with the 'right' Higgs mass plus 'low'-FT & the 'right' relic density in the pMSSM ??

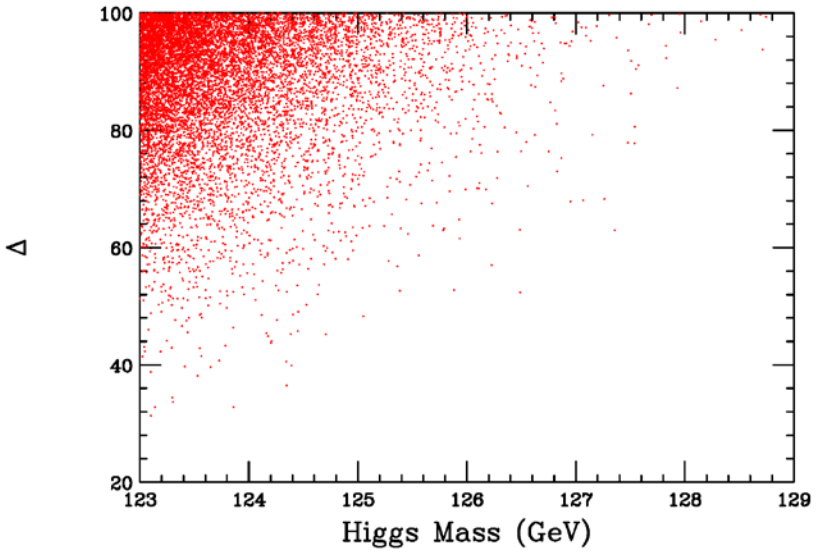
- Generate a low-FT set by adjusting the scan ranges of the more sensitive parameters (μ, A_t , m_{Q3} , m_{u3} , M_3 , $M_{1,2}$, etc.) such that the models already have low-FT < 100 & likely 'near correct' relic density: ~3.3 x 10^8 was 'sufficient'

- Impose an updated set of the usual flavor, precision, DD/ID, non-MET LHC, LEP, Tevatron & m_h constraints

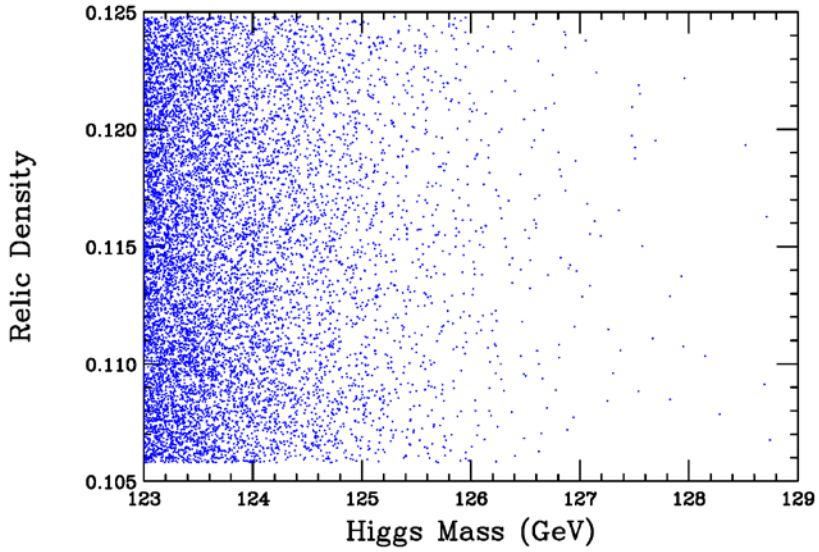
- Impose WMAP/Planck relic density ±5σ → ~10.2k models

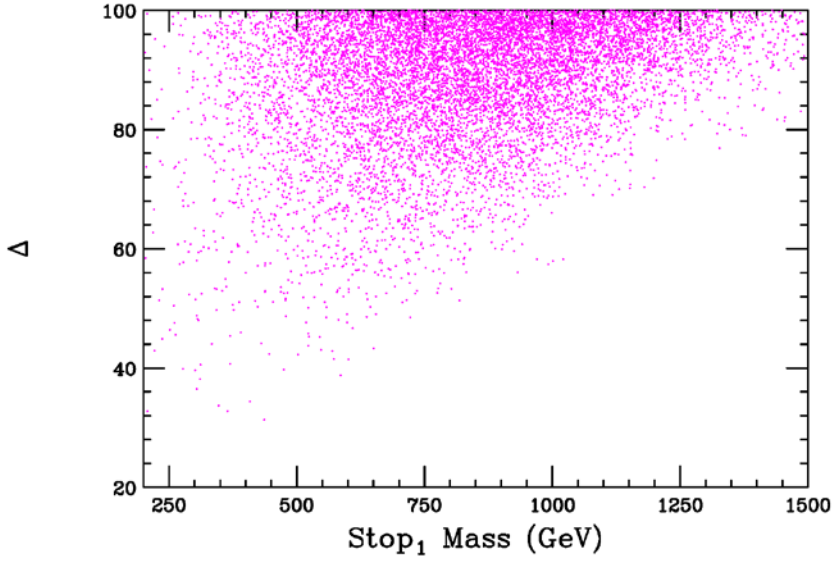
Pre-LHC MET analyses, what do these models look like?





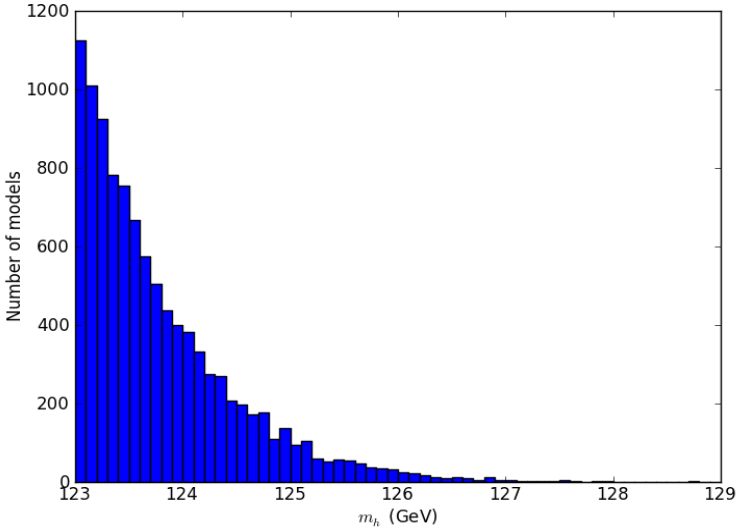
No correlation here with FT

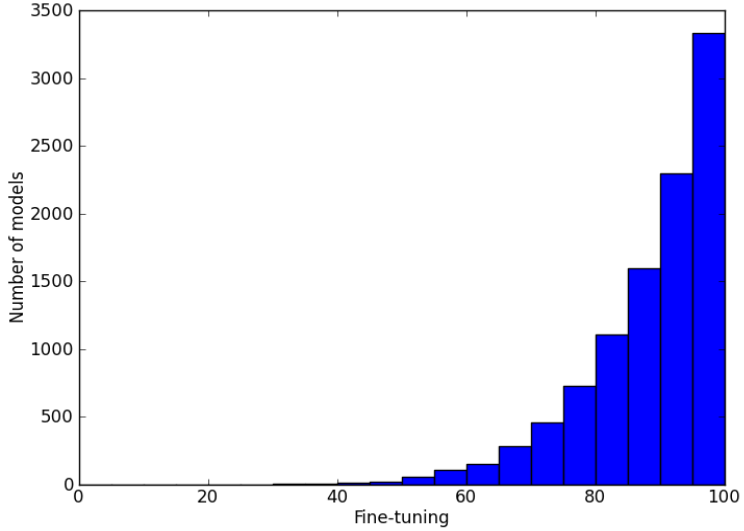


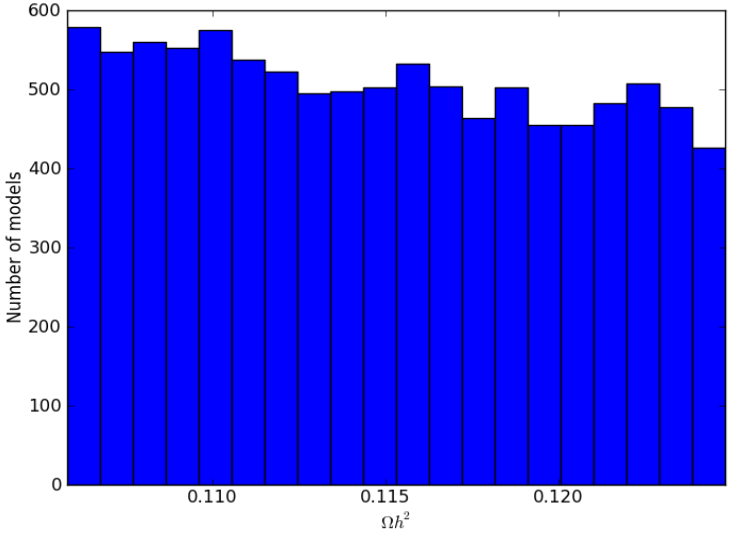


pMSSM Low-FT Neutralino LSP Model Set

- m_h = 126 ± 3 GeV
- $\Omega h^2|_{DM}$ = 0.1153 ± 0.0095
- FT better than 1% (Δ <100)
- ~10.2k model points



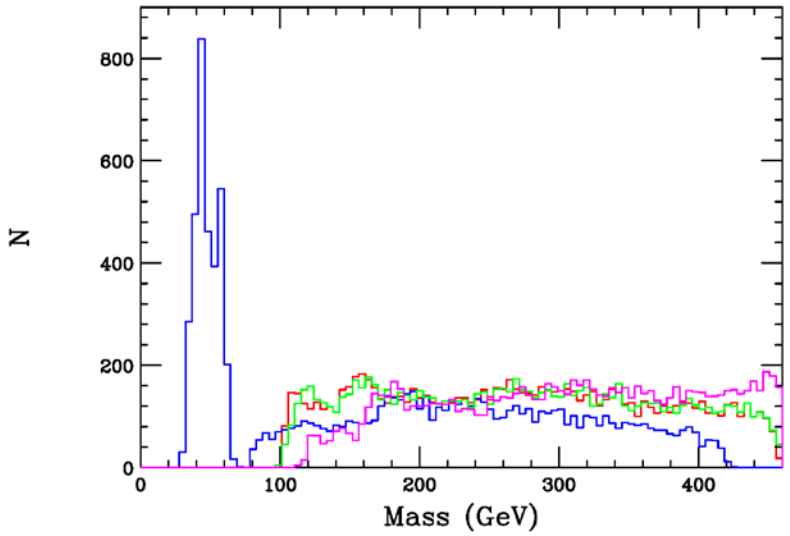


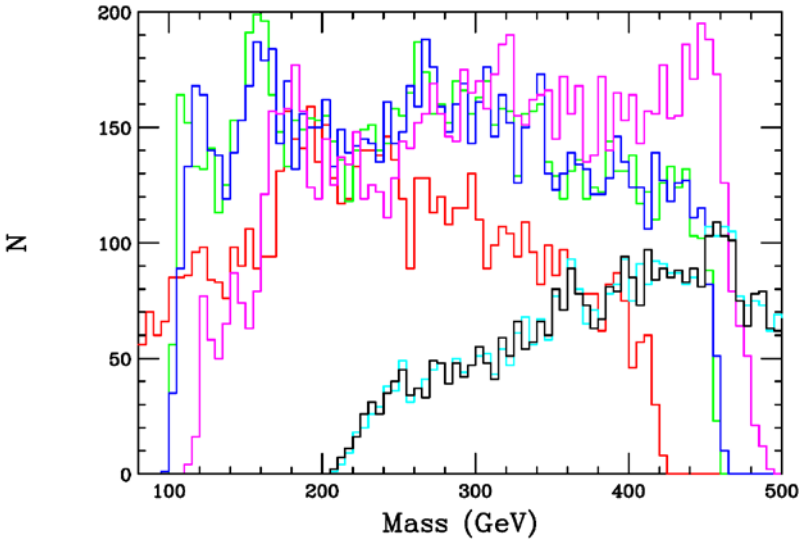


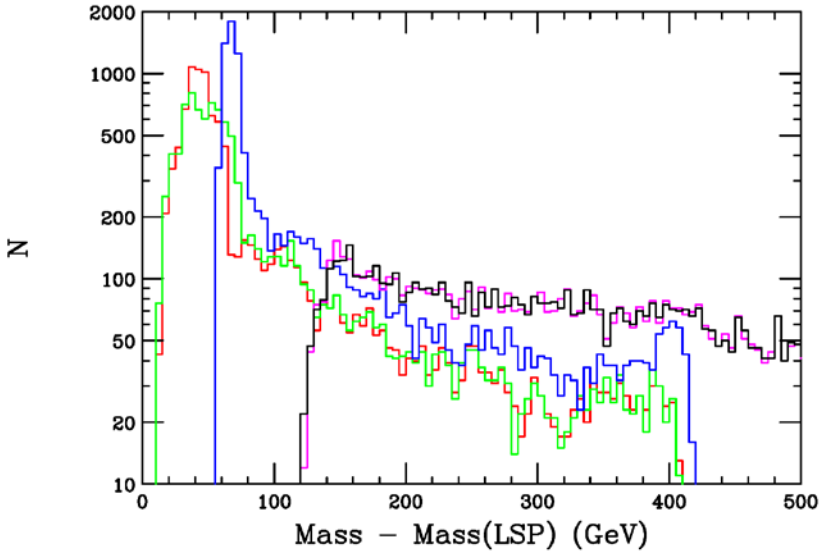
Some Numbers (again, pre-LHC MET Analyses !)

- ~1.4% of models have stop/sbottom BELOW the Higgsinos & winos. These are likely already excluded by the direct searches if sufficiently light unless compression occurs
- ~59.5% of models have all gauginos & Higgsinos below the lightest stop/sbottom. ~16.4% of models have the winos lighter than the Higgsinos.
- ~11.0% of models have a sbottom lighter than the stop
- ~30% of models have a light slepton of some kind below the stop/sbottom; it's most likely a mixed stau.
- ~15% of models have light squarks/gluinos below the stop or sbottom & so are likely excluded except for compression

Gaugino Mass spectra & splittings







Phenomenological MSSM c/o ATLAS

BR VS stop mass