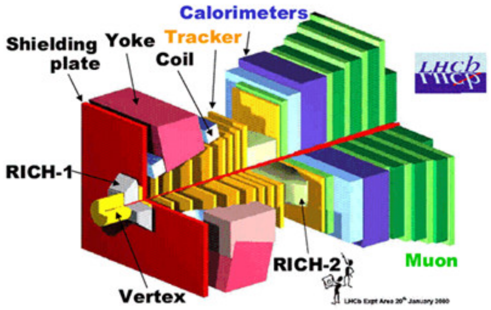
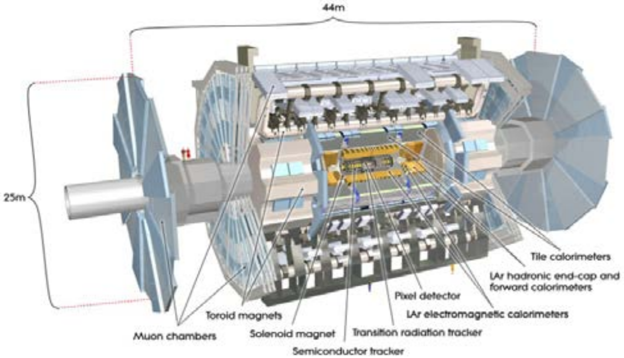
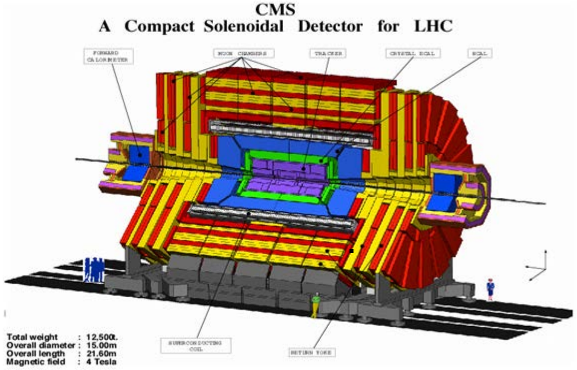
Status Report on pMSSM SUSY Searches @ the LHC







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

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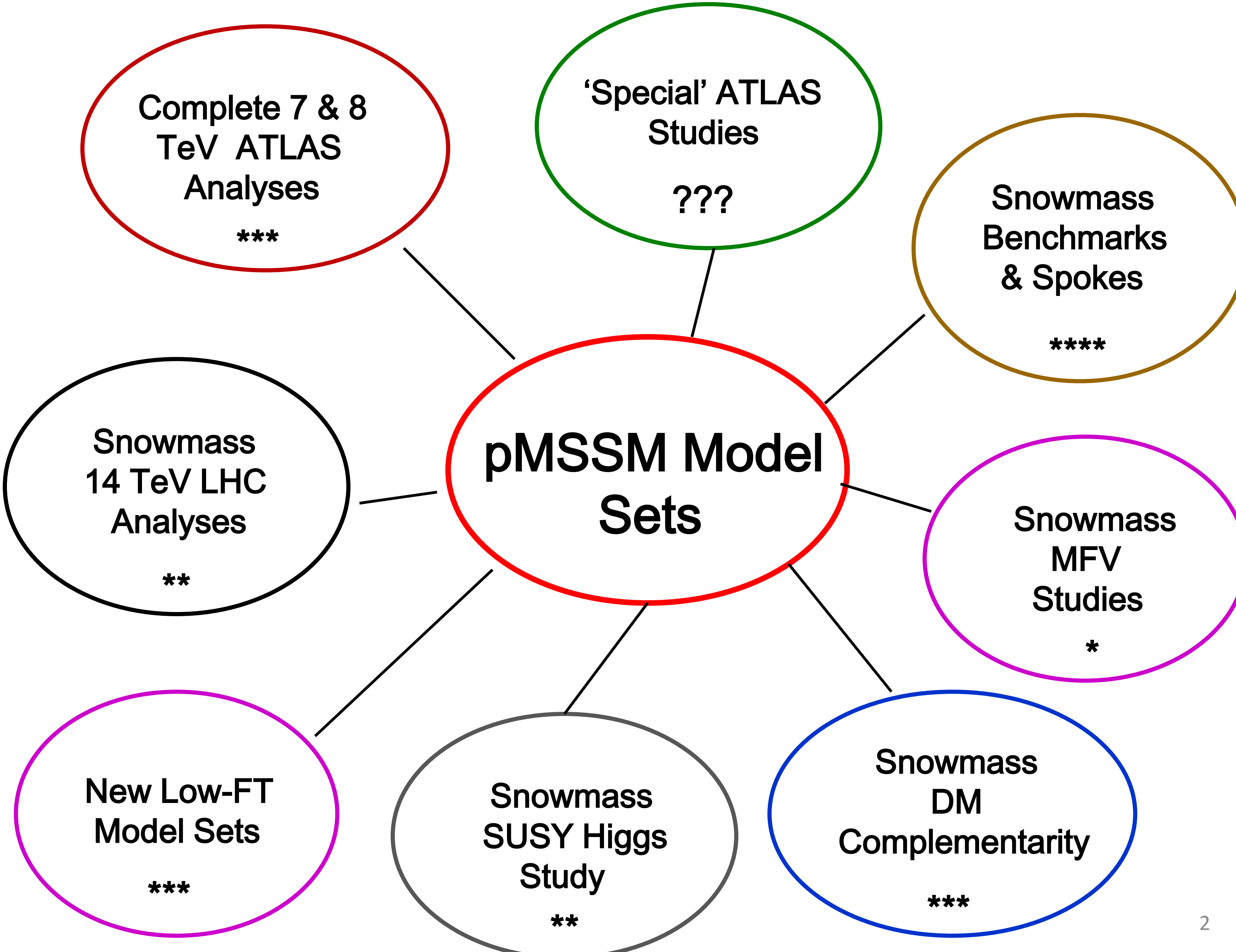
M.W. Cahill-Rowley, J.L. Hewett, A. Ismail, T.G. Rizzo

6/30/13


pMSSM Model Sets
Complete 7 & 8 TeV ATLAS Analyses ***
'Special' ATLAS Studies ???
Snowmass Benchmarks & Spokes ****
Snowmass 14 TeV LHC Analyses **
Snowmass MFV Studies *
New Low-FT Model Sets ***
Snowmass SUSY Higgs Study **
Snowmass DM Complementarity ***

Our pMSSM SUSY Search Strategy

- 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 & find other neat stuff.

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

- Smaller (~10k) dedicated sets 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) Low FT model set first results
  (iii) 14 TeV jets+MET a la the ES

→→ All studies are still ongoing

Preliminary Model Set Fractions Excluded by ATLAS Searches @ 7 TeV

Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-033	21.2%	17.8%	37.4%
multijets	ATLAS-CONF-2012-037	1.6%	2.3%	11.3%
1-lepton	ATLAS-CONF-2012-041	3.2%	5.3%	19.4%
HSCP	1205.0272	4.0%	16.9%	<0.1%
Disappearing Track	ATLAS-CONF-2012-111	2.6%	1.1%	<0.1%
Gluino $\to$ Stop/Sbottom	1207.4686	4.9%	4.1%	21.9%
Very Light Stop	ATLAS-CONF-2012-059	<0.1%	0.03%	0.3%
Medium Stop	ATLAS-CONF-2012-071	0.3%	4.9%	2.6%
Heavy Stop (0l)	1208.1447	3.7%	3.3%	17.9%
Heavy Stop (1l)	1208.2590	2.0%	2.3%	13.5%
GMSB Direct Stop	1204.6736	<0.1%	0.05%	0.8%
Direct Sbottom	ATLAS-CONF-2012-106	2.5%	2.8%	5.5%
3 leptons	ATLAS-CONF-2012-108	1.1%	5.9%	18.3%
1-2 leptons	1208.4688	4.1%	8.2%	21.3%
Direct slepton/gaugino (2l)	1208.2884	0.1%	1.2%	1.0%
Direct gaugino (3l)	1208.3144	0.4%	5.5%	8.0%
4 leptons	1210.4457	0.7%		15.5%
1 lepton + many jets	ATLAS-CONF-2012-140	1.3%		12.4%
1 lepton + γ	ATLAS-CONF-2012-144	<0.1%		<0.1%
γ + b	1211.1167	<0.1%		0.3%
$\gamma\gamma$ + MET	1209.0753	<0.1%		<0.1%
$B_s \to \mu\mu$	1211.2674	0.8%	3.1%	*
$A/H \to \tau\tau$	CMS-PAS-HIG-12-050	1.6%	0.07%	*

This is useful for comparing searches and model sets

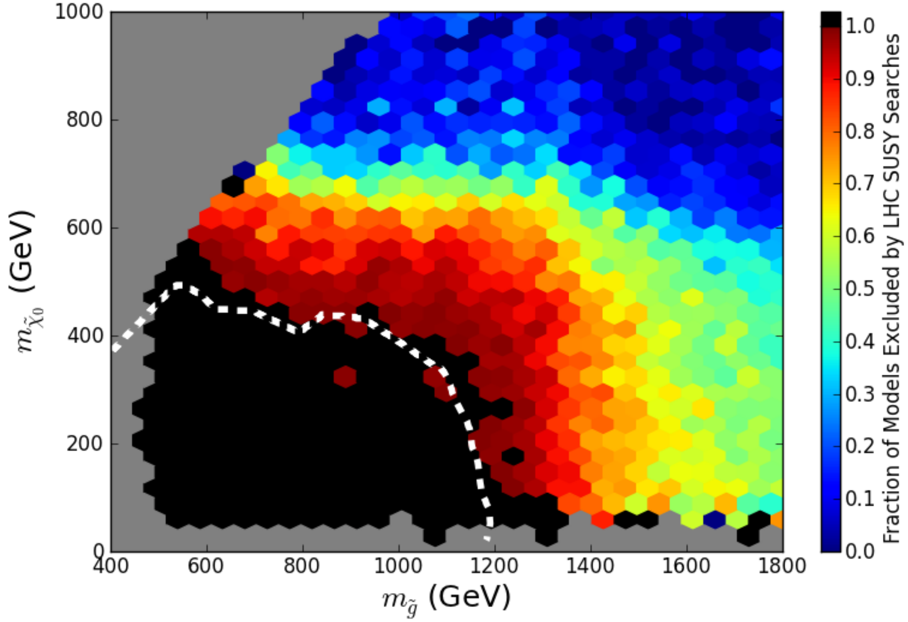
Preliminary Model Set Fractions Excluded by ATLAS Searches @ 8 TeV

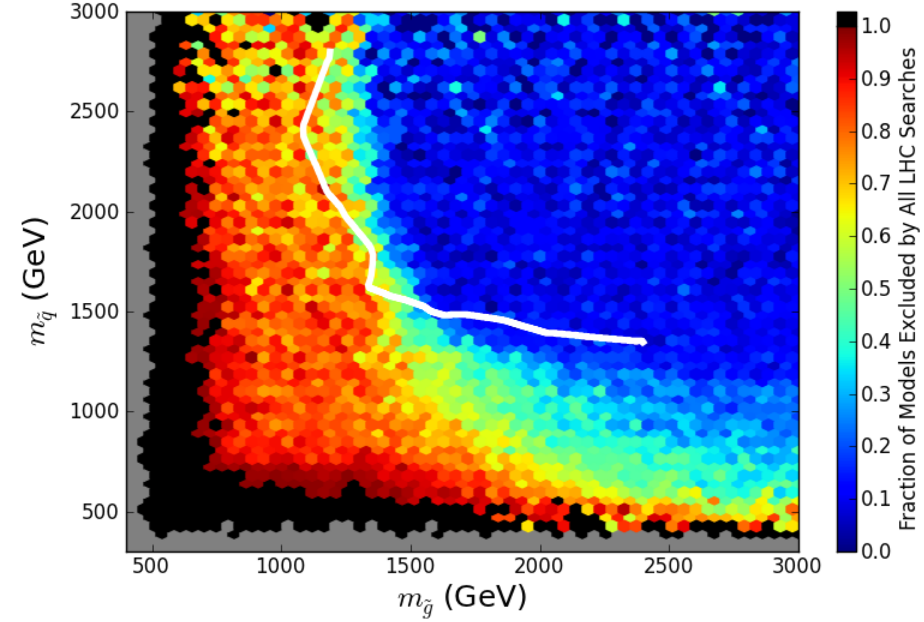
Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-109	26.7%	21.8%	49.8%
multijets	ATLAS-CONF-2012-103	3.3%	4.1%	27.0%
1-lepton	ATLAS-CONF-2012-104	3.3%	5.4%	27.7%
SS dileptons	ATLAS-CONF-2012-105	4.9%	11.5%	42.8%
Medium Stop (2l)	ATLAS-CONF-2012-167	0.6%		9.4%
Medium/Heavy Stop (1l)	ATLAS-CONF-2012-166	3.8%		28.7%
Direct Sbottom (2b)	ATLAS-CONF-2012-165	6.2%		17.4%
3rd Generation Squarks (3b)	ATLAS-CONF-2012-145	10.8%		47.2%
3rd Generation Squarks (3l)	ATLAS-CONF-2012-151	1.9%		32.8%
3 leptons	ATLAS-CONF-2012-154	1.4%		38.5%
4 leptons	ATLAS-CONF-2012-153	3.0%		52.4%
Z + jets + MET	ATLAS-CONF-2012-152	0.3%		12.2%

Total Exclusions: ~37% ~46% ~73%

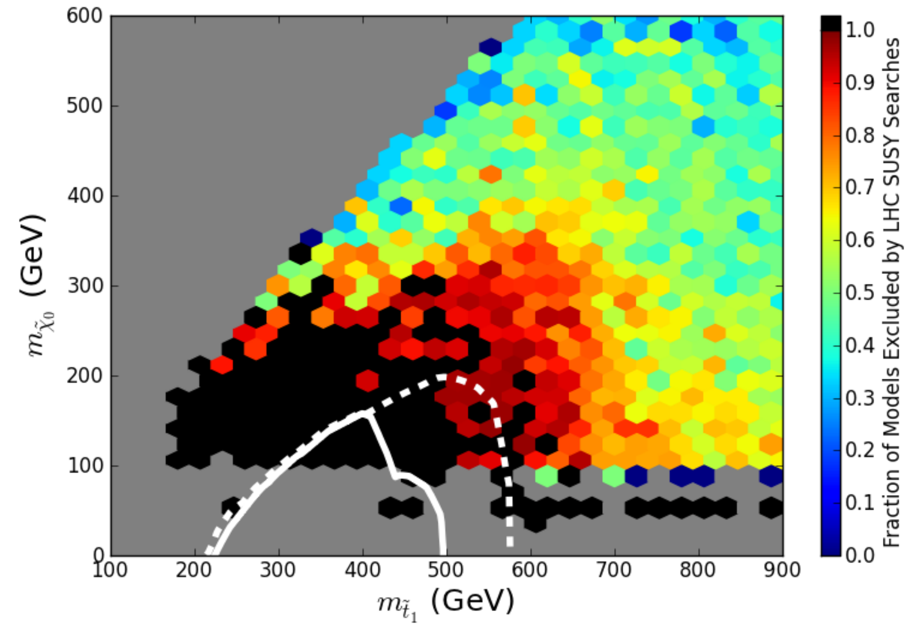
→ ~15 MORE analyses coming 'soon' bringing us up to date with all public ATLAS results as of 6/25/2013

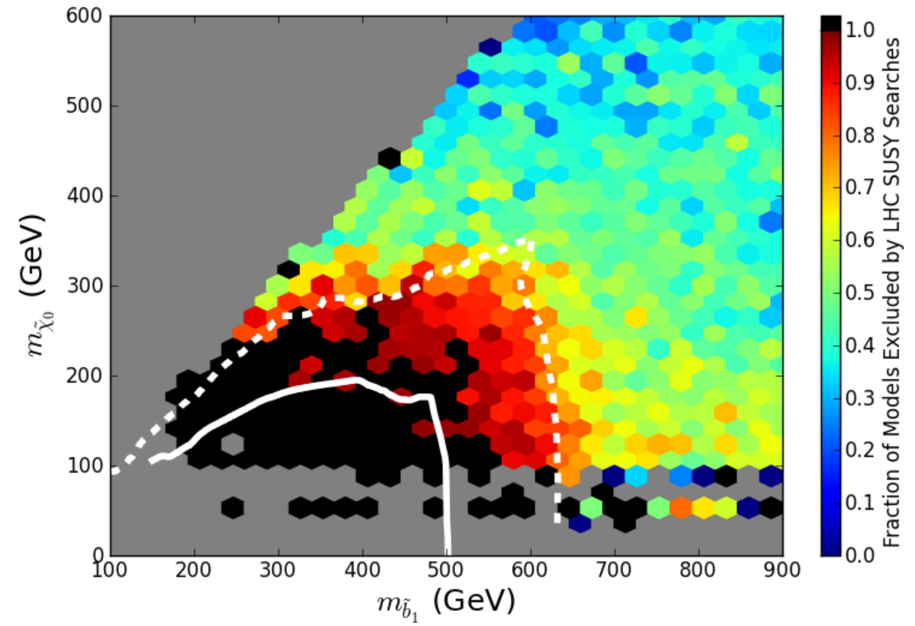
Of course search efficiency plots are much more interesting…

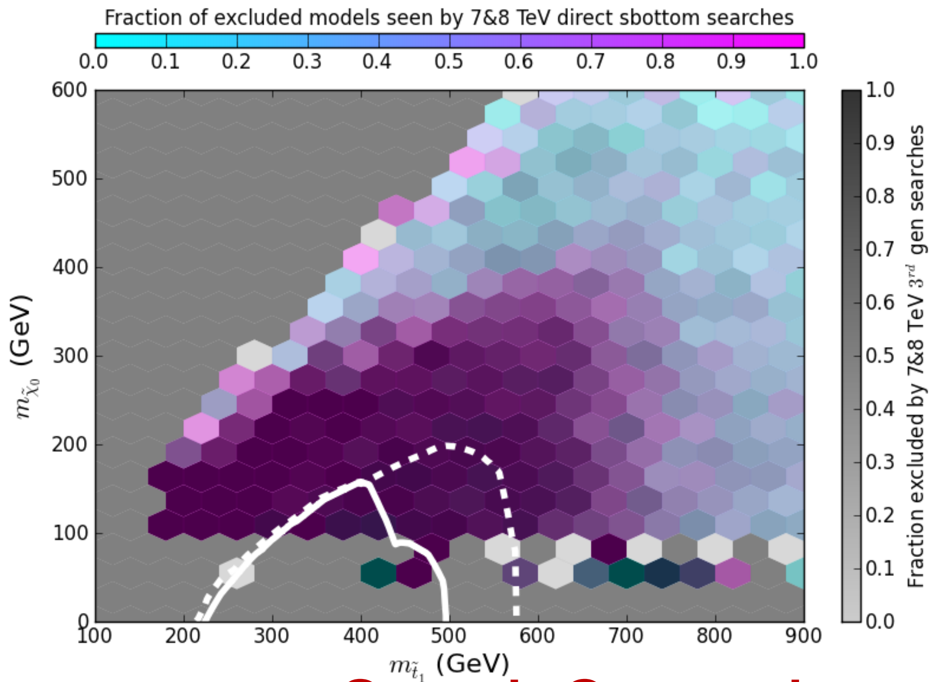


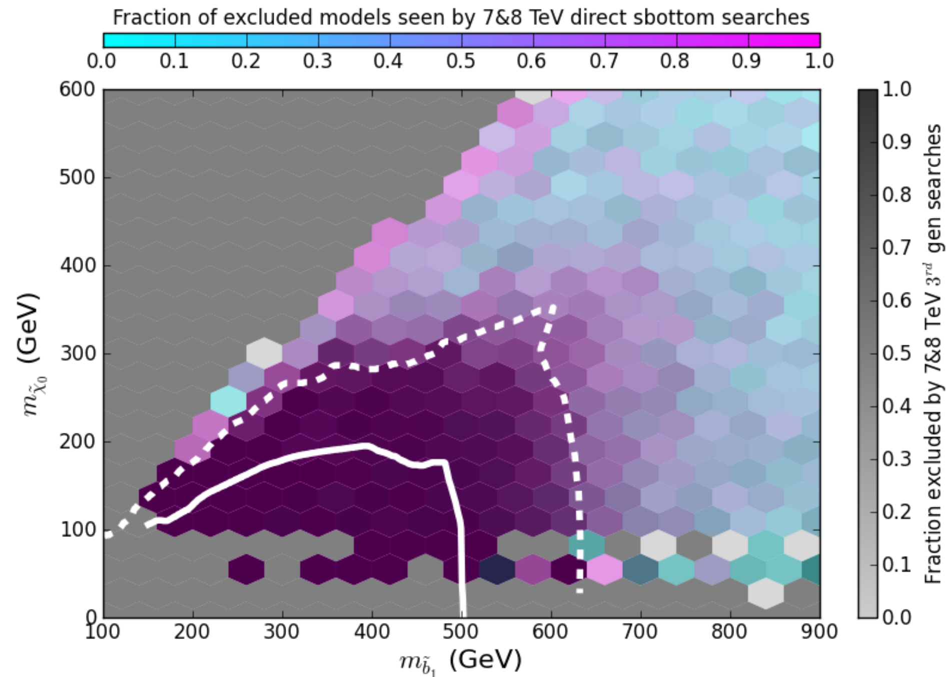


Search Efficiency for Neutralino LSP Set

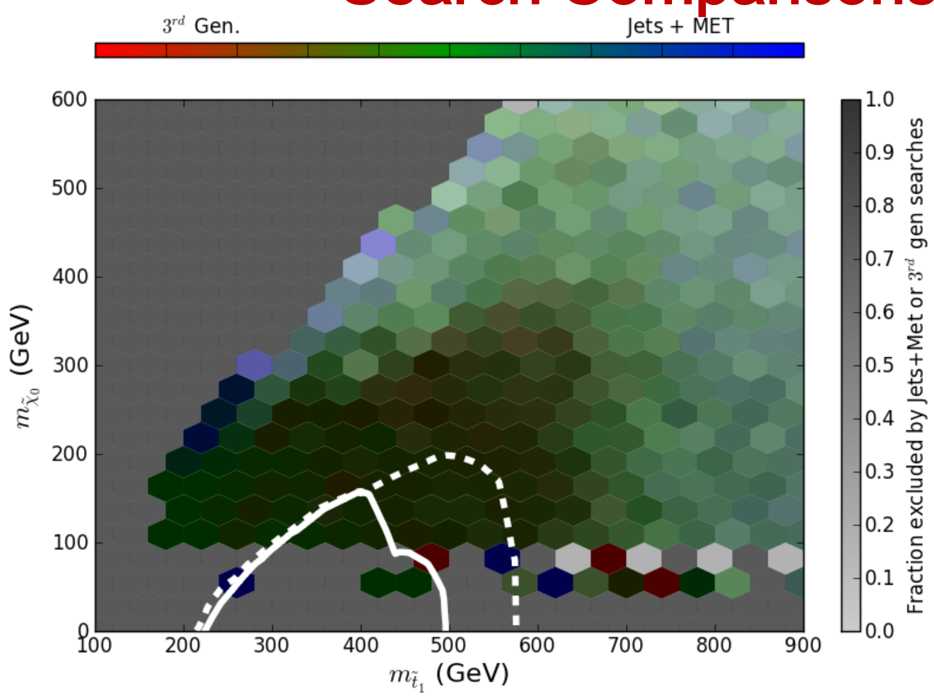


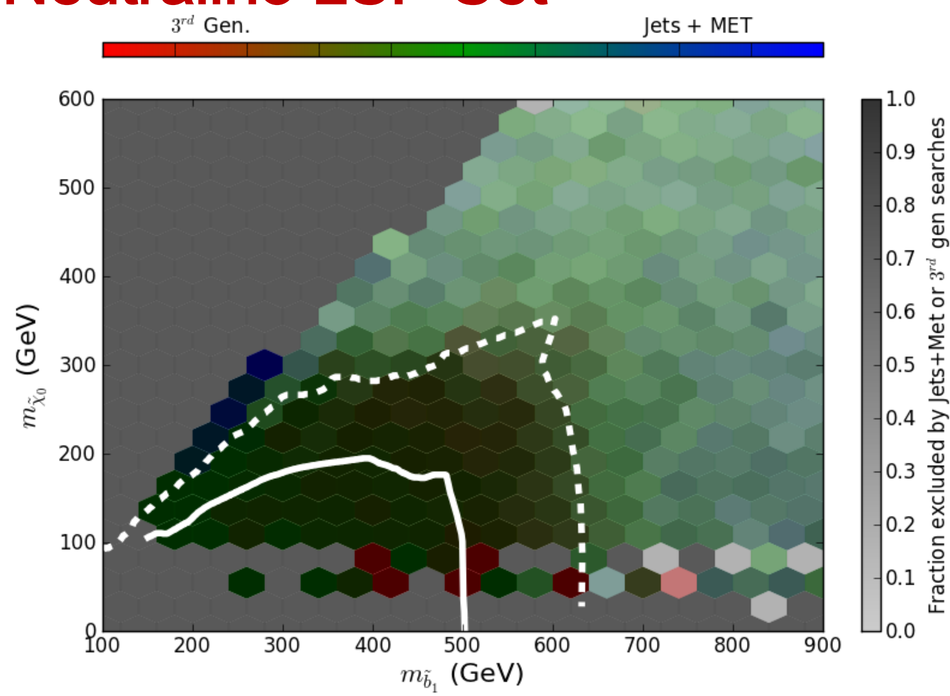






Search Comparisons: Neutralino LSP Set





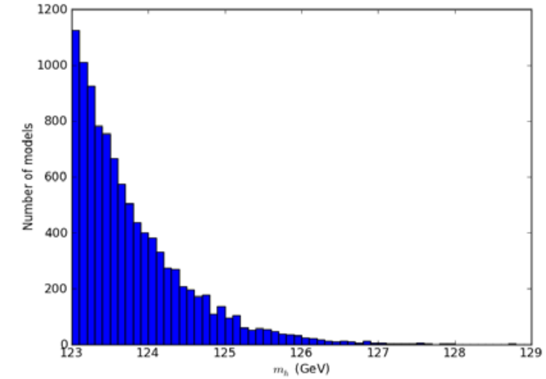
Neutralino Set LC Kinematic Accessibility Fractions

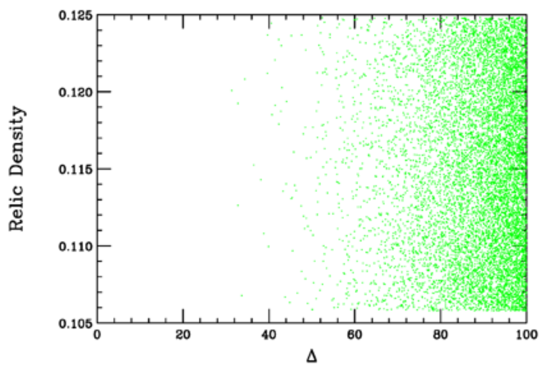
Sparticle	$\sqrt{s} = 250$ GeV	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 1$ TeV	$\sqrt{s} = 2$ TeV
$\tilde{\chi}_1^0$	3.3%	22.6%	58.1%	94.7%
$\tilde{\chi}_2^0$	1.3%	11.1%	30.0%	57.5%
$\tilde{\chi}_3^0$		0.7%	7.2%	25.5%
$\tilde{\chi}_1^\pm$	2.9%	22.2%	57.5%	93.6%
$\tilde{\chi}_2^\pm$		0.2%	4.8%	19.1%
$\tilde{e}_L$		0.1%	2.2%	12.7%
$\tilde{e}_R$		0.3%	3.2%	14.5%
$\tilde{\nu}_e$		0.1%	2.3%	12.8%
$\tilde{\tau}_1$		0.4%	4.7%	24.7%
$\tilde{\nu}_\tau$		0.2%	2.4%	13.2%
$\tilde{t}_1$			0.3%	10.4%
$\tilde{b}_1$			0.8%	16.7%

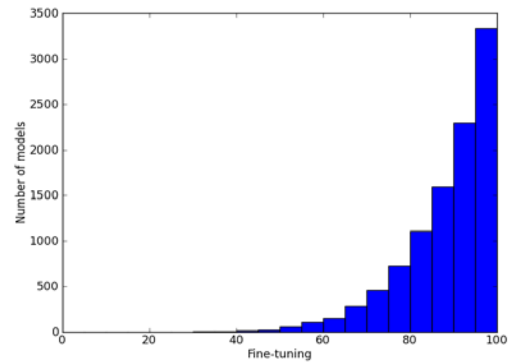
Table 9: Fraction (in percent) of viable pMSSM models with $m_h = 126 \pm 3$ GeV after the LHC searches that have kinematically accessible sparticles at an e^+e^- linear collider with various center of mass energies. The lack of an entry signals that the fraction is below 0.1%.

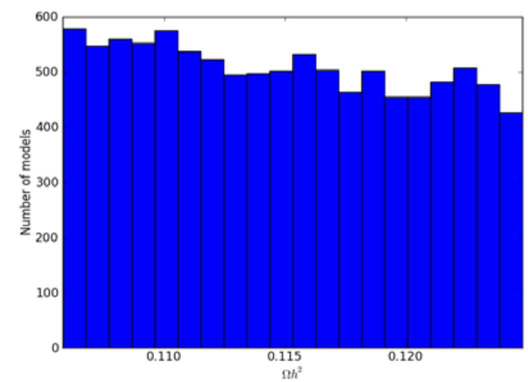
pMSSM Low-FT Neutralino LSP Model Set

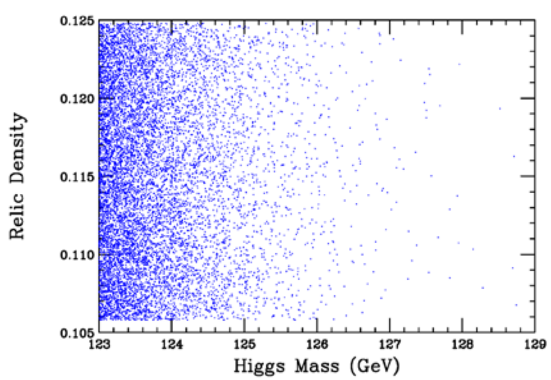
- 1/3 x 10^9 w/ low FT→ ~10.2k models
- m_h = 126 ± 3 GeV
- WMAP/Planck ± 5σ
- FT better than 1% (Δ <100)
- expected to be very susceptible to ATLAS

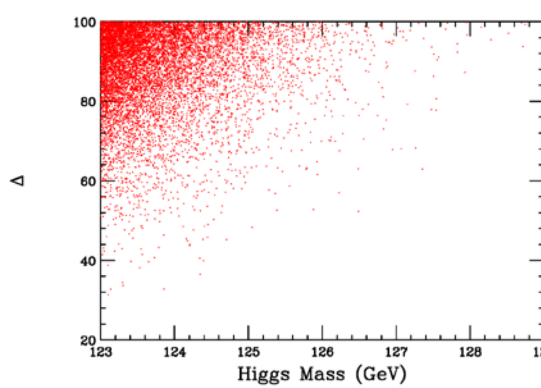


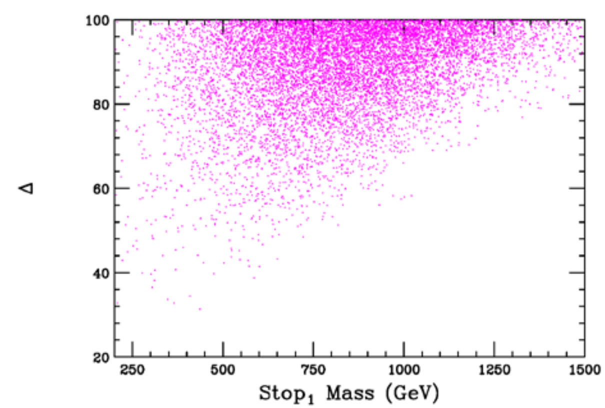


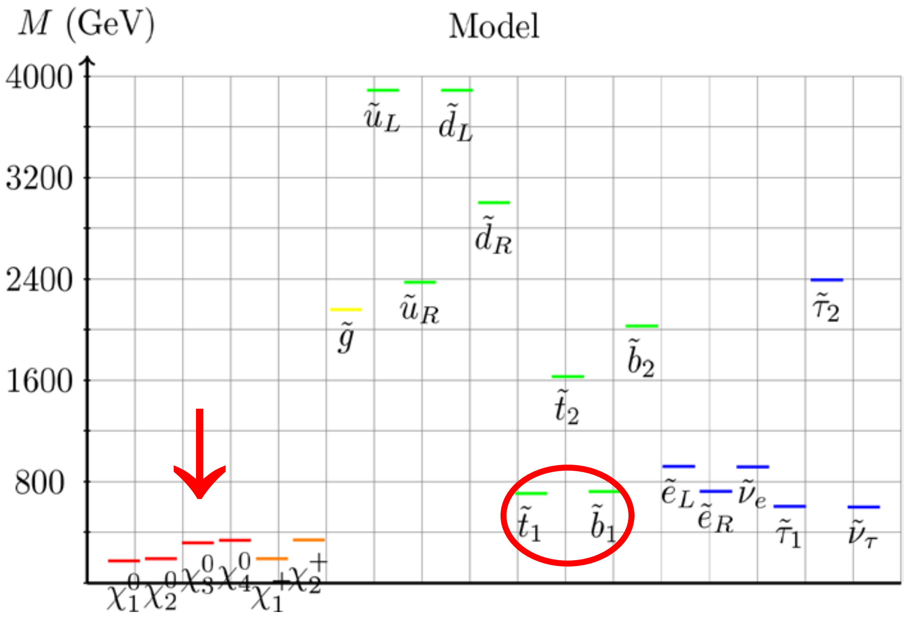










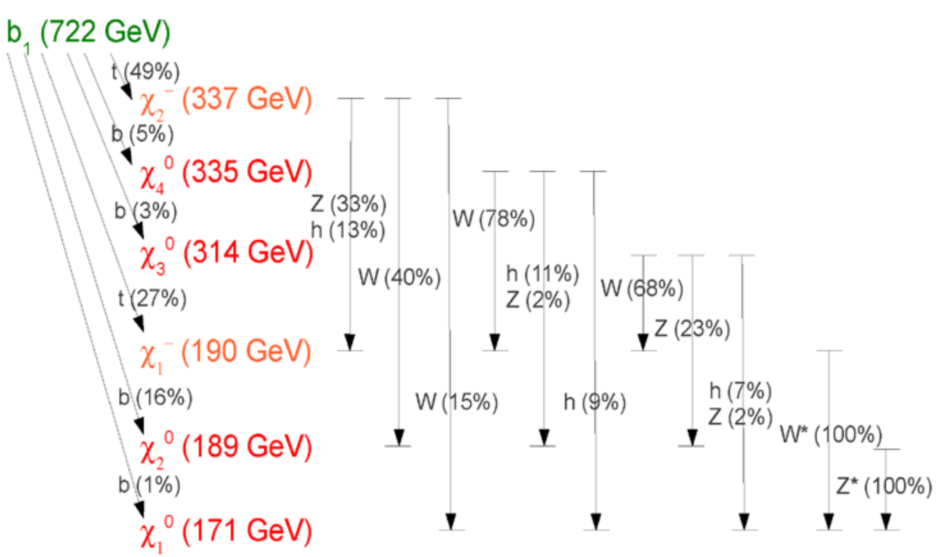


The necessity of both a light bino to get the right relic density & a light Higgsino for low-FT forces the stop decays to be quite complex !

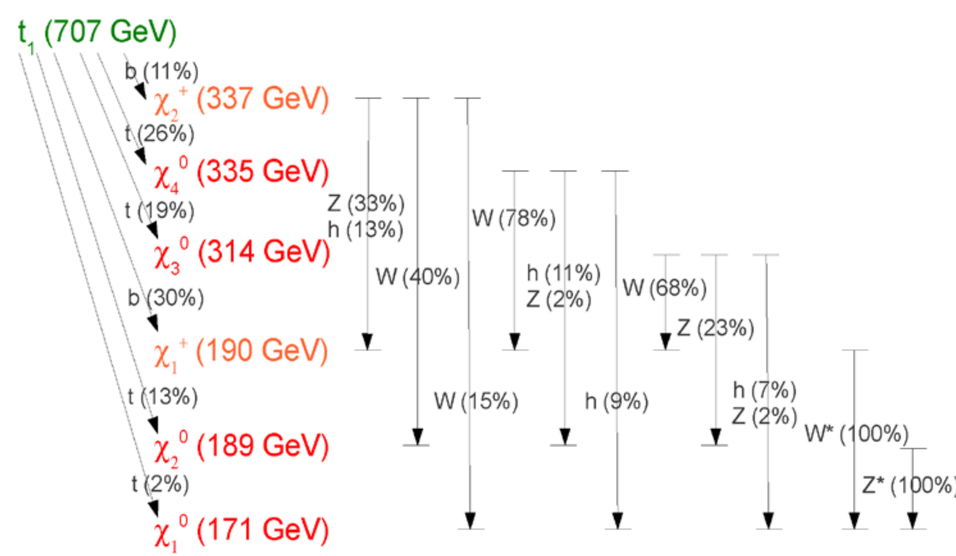
~ 60% of models also have winos below the stop/sbottom → leptons!

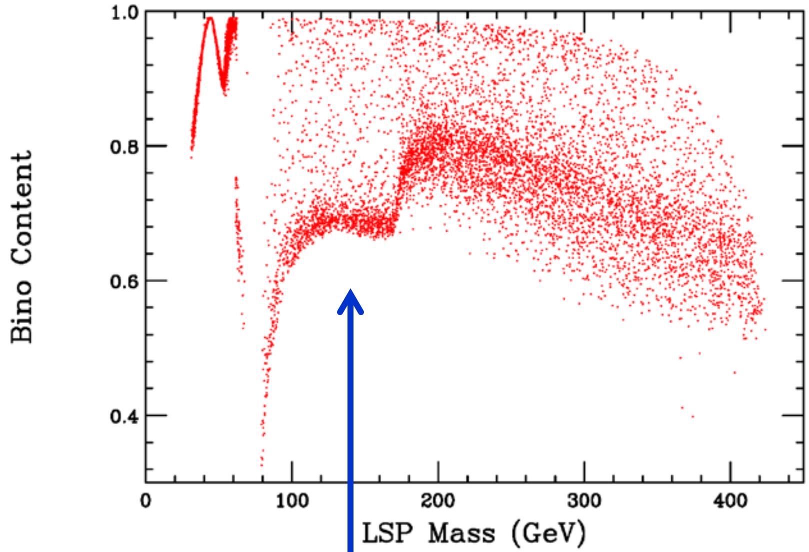
~ 30% also have a light slepton below stop (co-annihilators) → *more* leptons!

Model 3010059

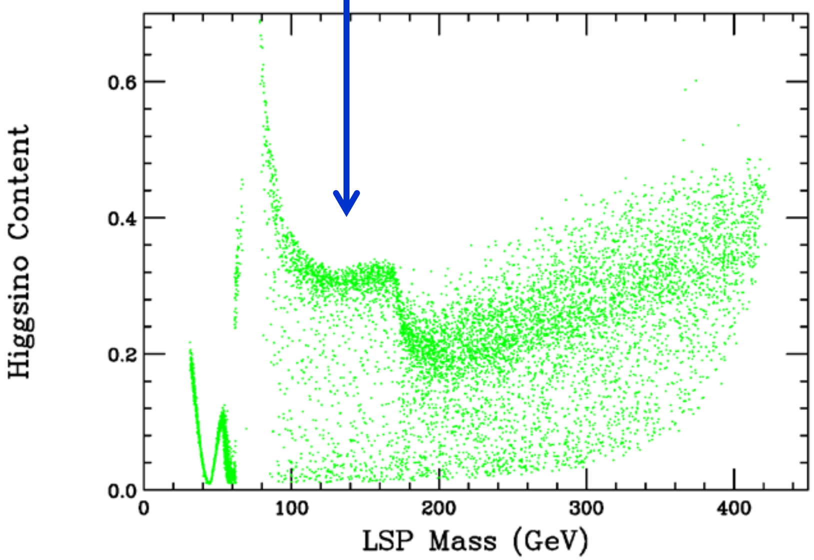


Model 3010059



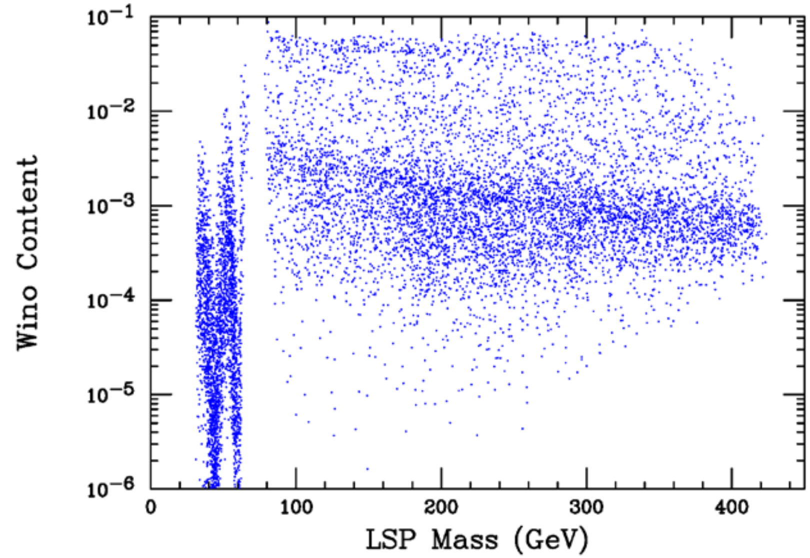


Essentially reflections !

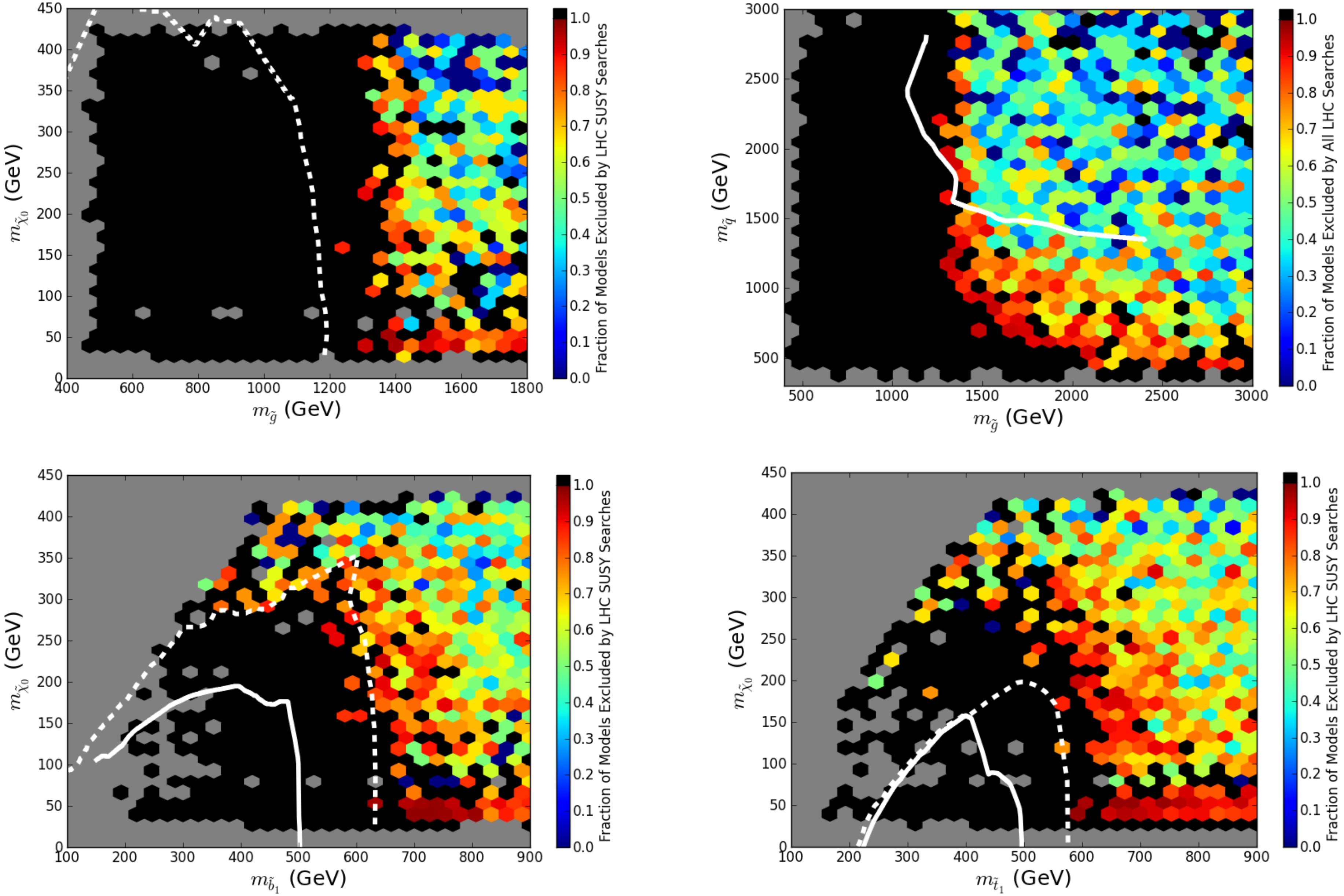


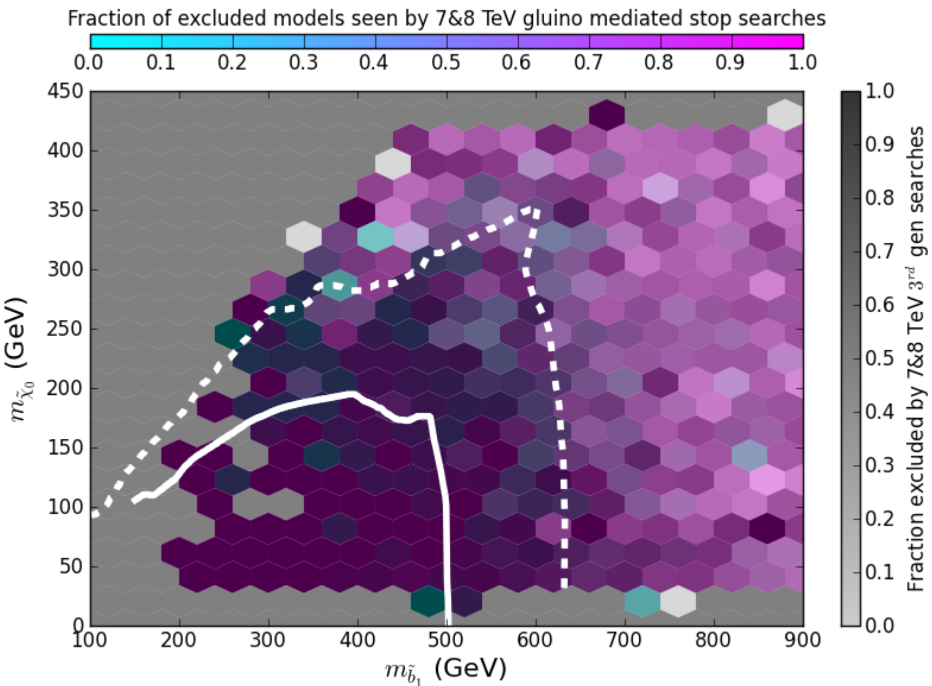
LSPs are seen to be mostly bino-Higgsino admixtures as was expected w/ an occasional small wino component

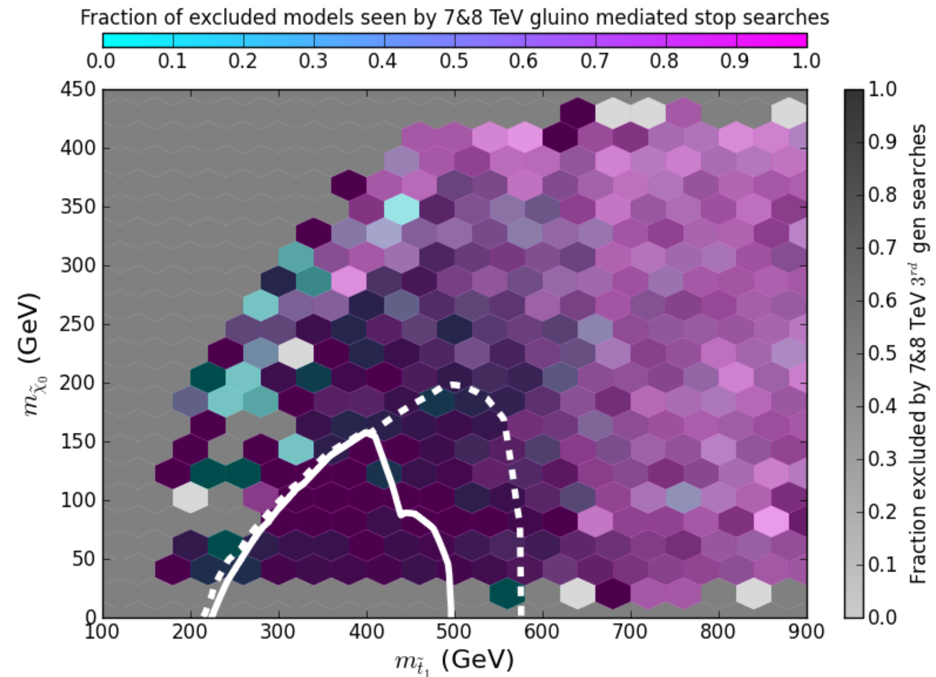
There's lots of physics in the patterns here that there's no time to discuss(see backups)



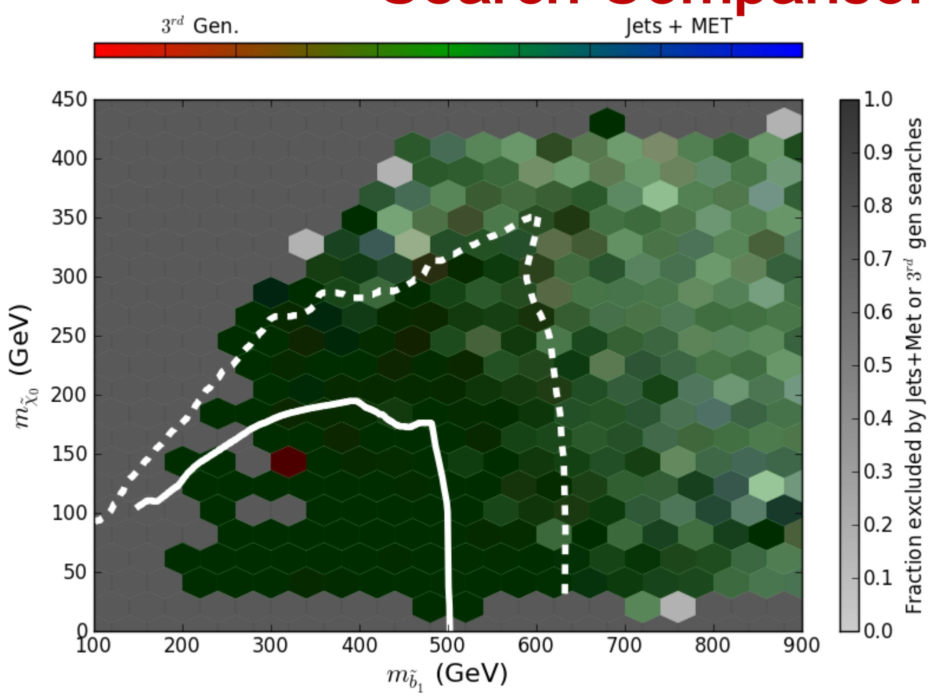
Coverage quite different than the more general set…..

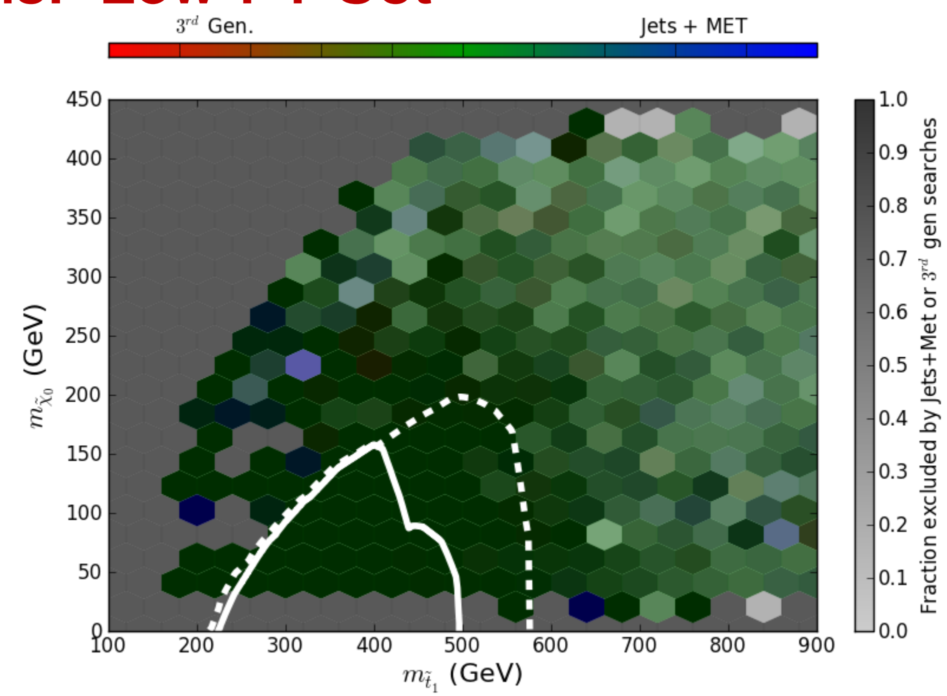






Search Comparisons: Low-FT Set





Low-FT Set LC Kinematic Accessibility Fractions

Sparticle	√s = 240	500	1000	1500 GeV
N1	0.38	0.69	1.00	1.00
N2	0.042	0.43	1.00	1.00
N3	0.002	0.30	1.00	1.00
N4	0.0	0.02	0.36	0.60
C1	0.05	0.43	1.00	1.00
C2	0.0	0.02	0.36	0.60
t1	0.0	0.003	0.08	0.37
b1	0.0	0.002	0.07	0.32

A reminder:

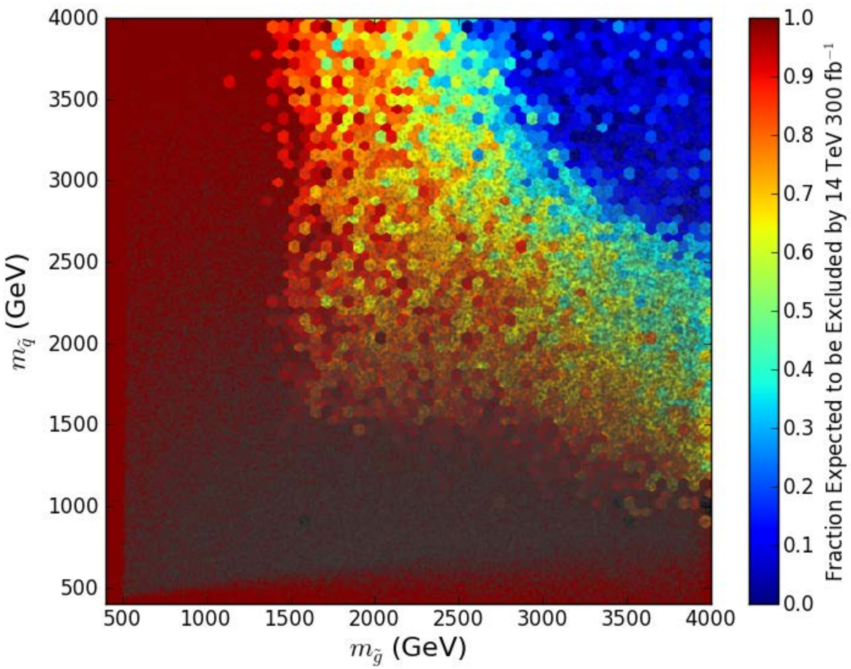
Extrapolation to 14 TeV

From Jan. 2013

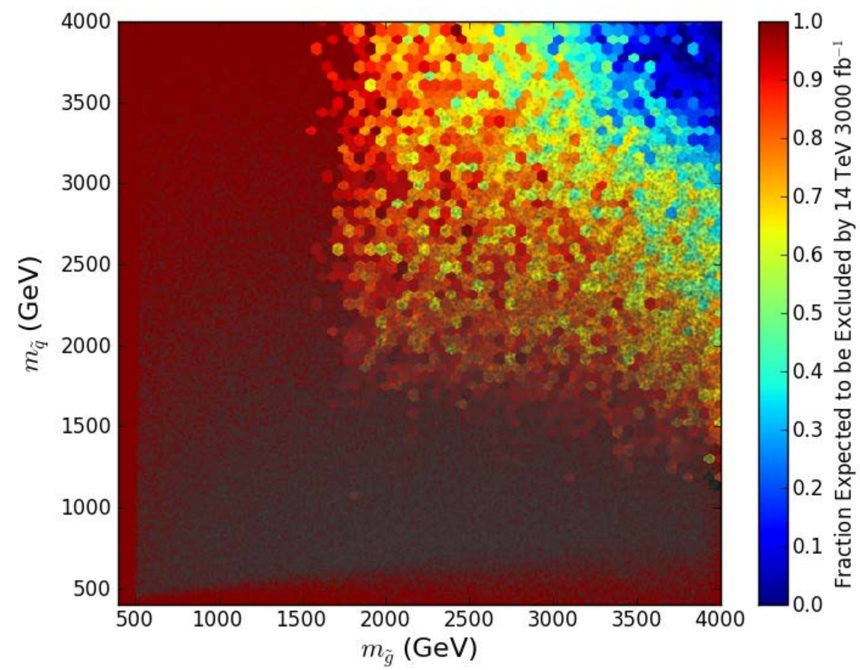
- Using naïve scaling arguments we can make some VERY VERY crude estimates of the pMSSM coverage @ 14 TeV

- We will perform analyses similar to those in the European Study Report for the pMSSM

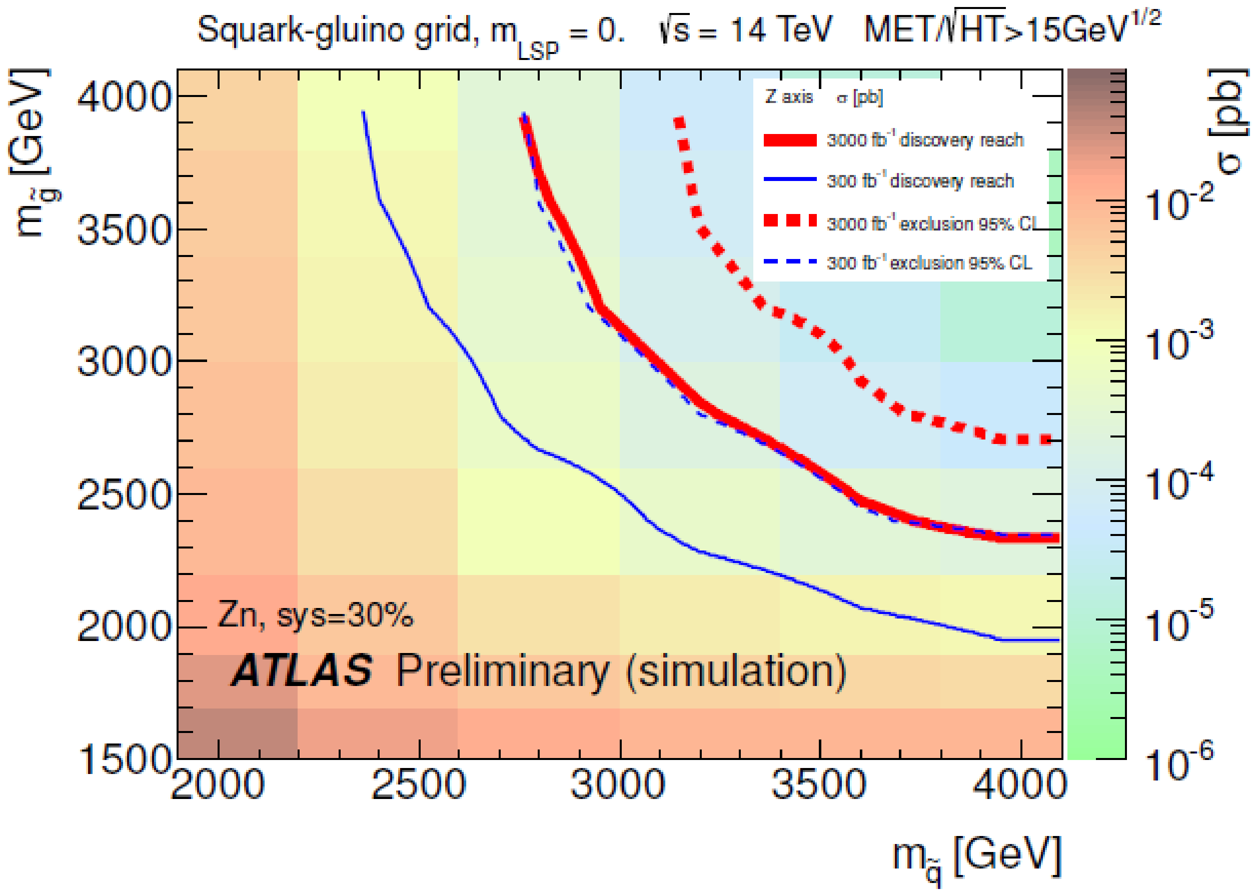
300 fb $^{-1}$



3 ab $^{-1}$



14 TeV: Jets plus MET Analysis From the ATLAS ES



Simplified Model Result

- Jets plus MET is a very powerful search covering a large portion of pMSSM space as was seen in the 7&8 TeV studies

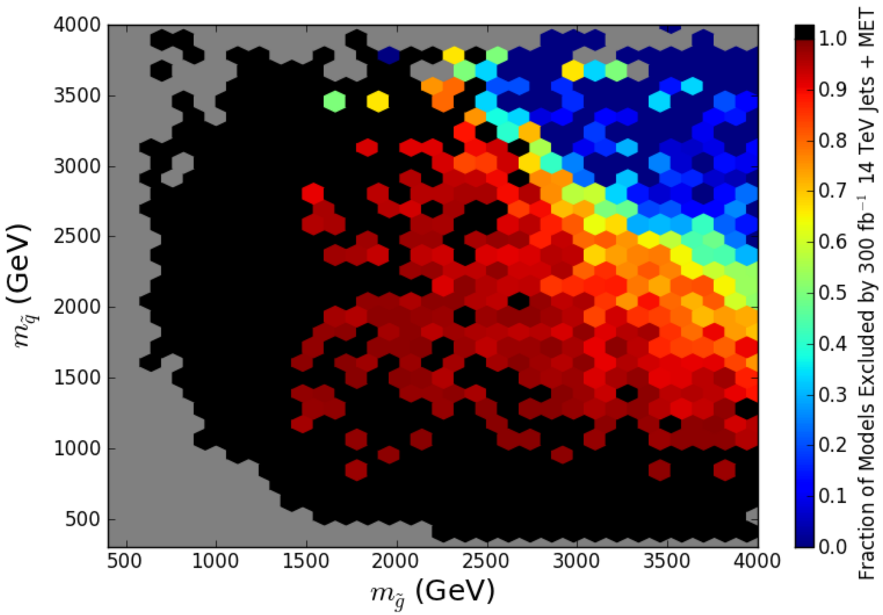
- We have ‘repeated’ this analysis @ 14 TeV so far ‘only’ for the ~30.7k surviving neutralino LSP models which predict a Higgs mass of 126±3 GeV & passing all the 7/8 TeV searches

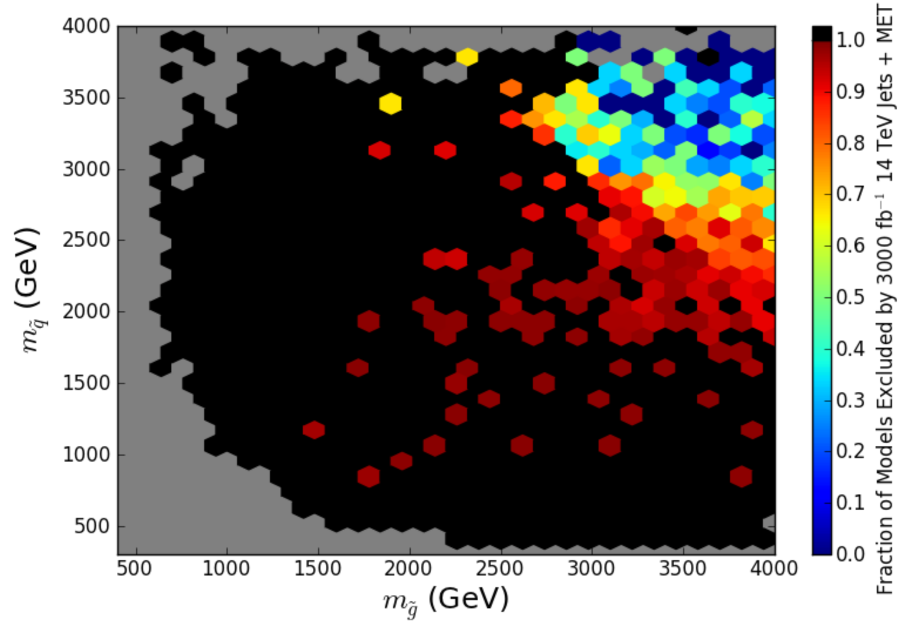
- The results are likely overestimates of coverage as proper background systematics not fully accounted for by ATLAS

- This was ‘expensive’ : ~1.5 x 10^6 core-hrs & was just now completed! The corresponding ~10k surviving gravitino models with the right Higgs mass as well those in the low-FT set will be run during July when more CPU is available

- At least one more 14 TeV ATLAS SUSY analysis (a 3rd generation search) might possibly be attempted by the time of the Snowmass write-ups if time/CPU exists (??) .

Some Preliminary 14 TeV Results

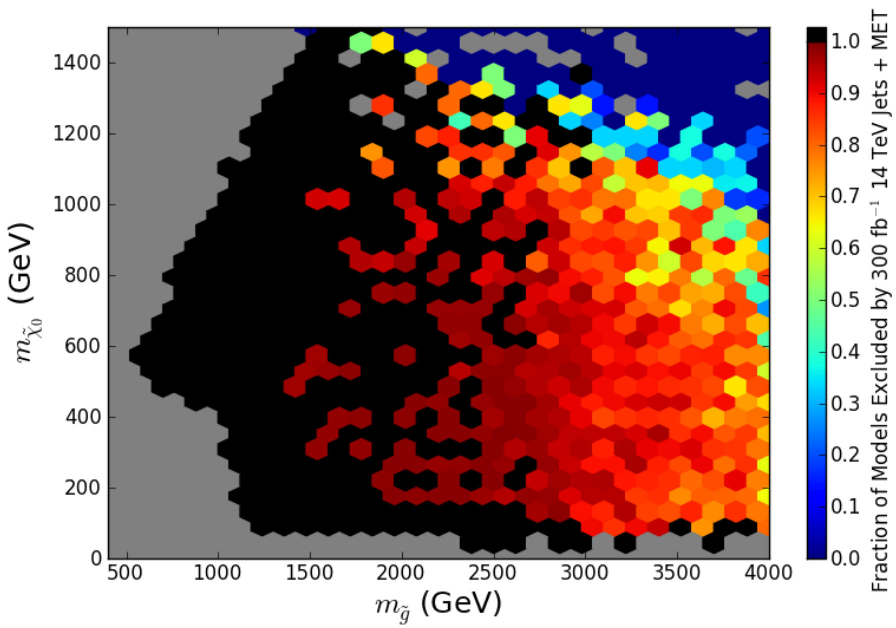


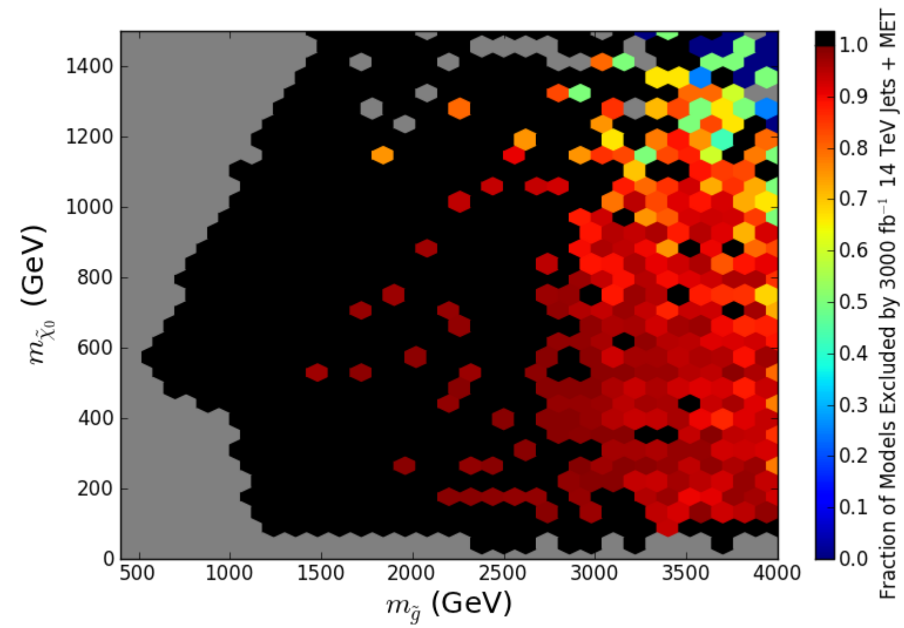


- For a luminosity of 300 (3000) fb^{-1} we find that 92.1(97.5)% of the models in the neutralino set surviving the 7/8 TeV searches are killed by jets + MET @ 14 TeV !

- Note lighter remnant 'stragglers' !

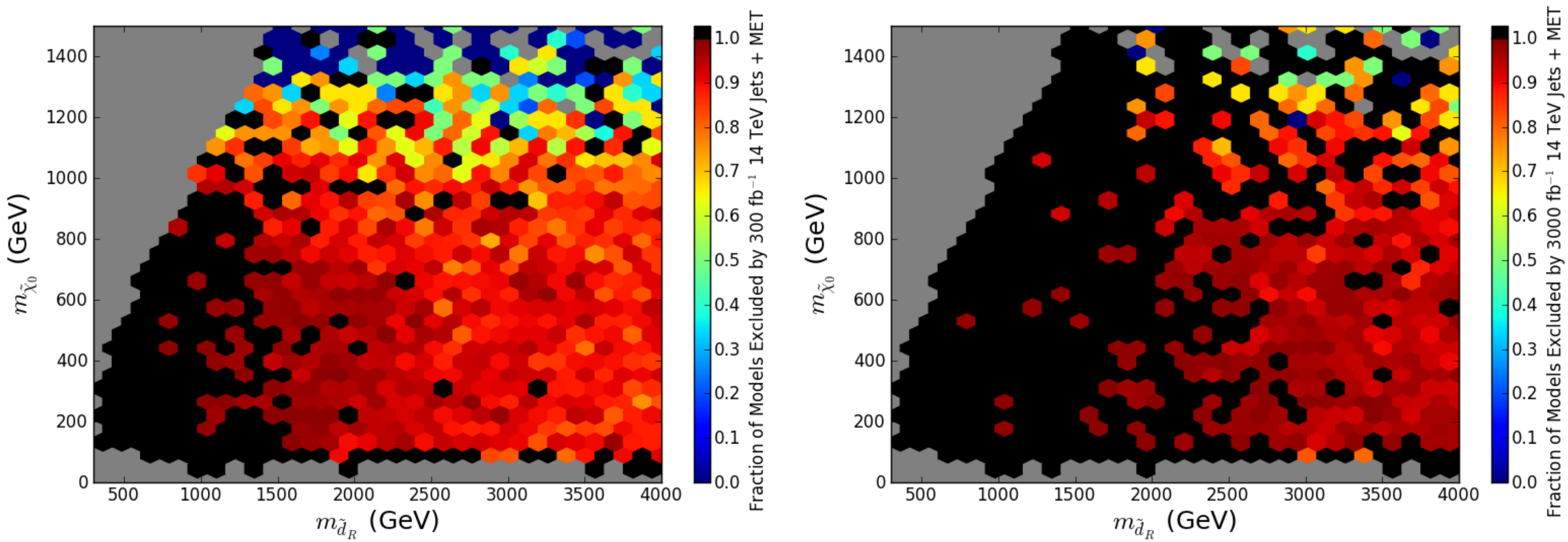
Some Preliminary 14 TeV Results (cont.)





- In the LSP-gluino mass plane, gluino masses below ~1.5 TeV are seen to be excluded but somewhat heavier stragglers still remain as we saw above.

Some Preliminary 14 TeV Results (cont.)



- Light RH-down squarks are the least constrained due to PDFs & being an iso-singlet & represent a 'worst-case' scenario. We see that some quite light guys remain…but this is only the results from a single analysis !

Summary

- Given time limitations this is only a brief overview of recent results
- Duplication of 'all' ATLAS SUSY analyses gives a more detailed perspective of model coverage
- Each model set has it's own properties & search sensitivities
- Low-FT models generally have complex stop/sbottom decays yet combining analyses fills in gaps yielding very significant coverage More low-FT studies are on-going.
- 14 TeV searches will produce very significant pMSSM coverage
- Expect ~15 more 8 TeV analyses + the gravitino set + 14 TeV results for Snowmass White Paper
- Results here also employed in both Higgs & DM studies

Michael Jackson prepares for Snowmass:

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updated 10:11 AM EDT, Fri June 21, 2013

CNN TRENDS *Canada flooding • James Gandolfini • U.S., Taliban talks • Racial Justice Act • Arizona b*

60 days with no sleep

CARL DE SOUZA/AFP/GETTY IMAGES

Final weeks of Michael Jackson's life detailed

Michael Jackson died while preparing to set a world record for the most successful concert run ever, but he unknowingly may have set another record that led to his death. FULL STORY

• Photos: Jackson trial who's who

BACKUPS

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

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

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

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

$1 \leq \tan\beta \leq 60$

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

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

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

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

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

Goal: obtain ~225k 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)

Some Constraints

- $\Delta\rho$ / W-mass
- $b \to s\,\gamma$
- $\Delta(g\text{-}2)_\mu$
- $\Gamma(Z \to$ 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

ATLAS SUSY Analyses @ 7, 8 & 14 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 usually by several months

For a VERY detailed pMSSM DM complementarity study see:

SLAC-PUB-15450
UCI-HEP-TR-2013-09

Complementarity and Searches for Dark Matter in the pMSSM

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[1]SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
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Abstract

The search for and identification of neutralino dark matter in supersymmetry requires a multi-pronged approach with important roles played by collider, direct and indirect dark matter detection experiments. In this report, we summarize the sensitivity of such searches at the 7, 8 (and eventually 14) TeV LHC, combined with those by *Fermi*, CTA, IceCube/DeepCore, COUPP and XENON1T, to such particles within the context of the 19-parameter p(henomenological)MSSM. This report provides an outline of the current status of our results and our expectations for future analyses.

1 Introduction and Overview of the pMSSM

One of the main motivations for R-parity conserving supersymmetry (SUSY) is the prediction that the lightest SUSY particle (LSP) is stable and may be identified as a candidate thermal dark matter (DM) particle if it is both electrically neutral and colorless. Quite commonly the role of the LSP is played by the lightest neutralino, χ_1^0, and this be will assumed in the discussion here. While DM searches are superficially focused on the nature of the LSP, the properties of all the other superparticles as well as those of the extended SUSY Higgs sector also come into play. Thus it is impossible to completely separate DM searches from searches for and the examination of the rest of the SUSY spectrum. However, even in the simplest SUSY scenario, the MSSM, the number of free parameters (~ 100) is too large to study in all generality. The traditional approach is to assume the existence of a high-scale

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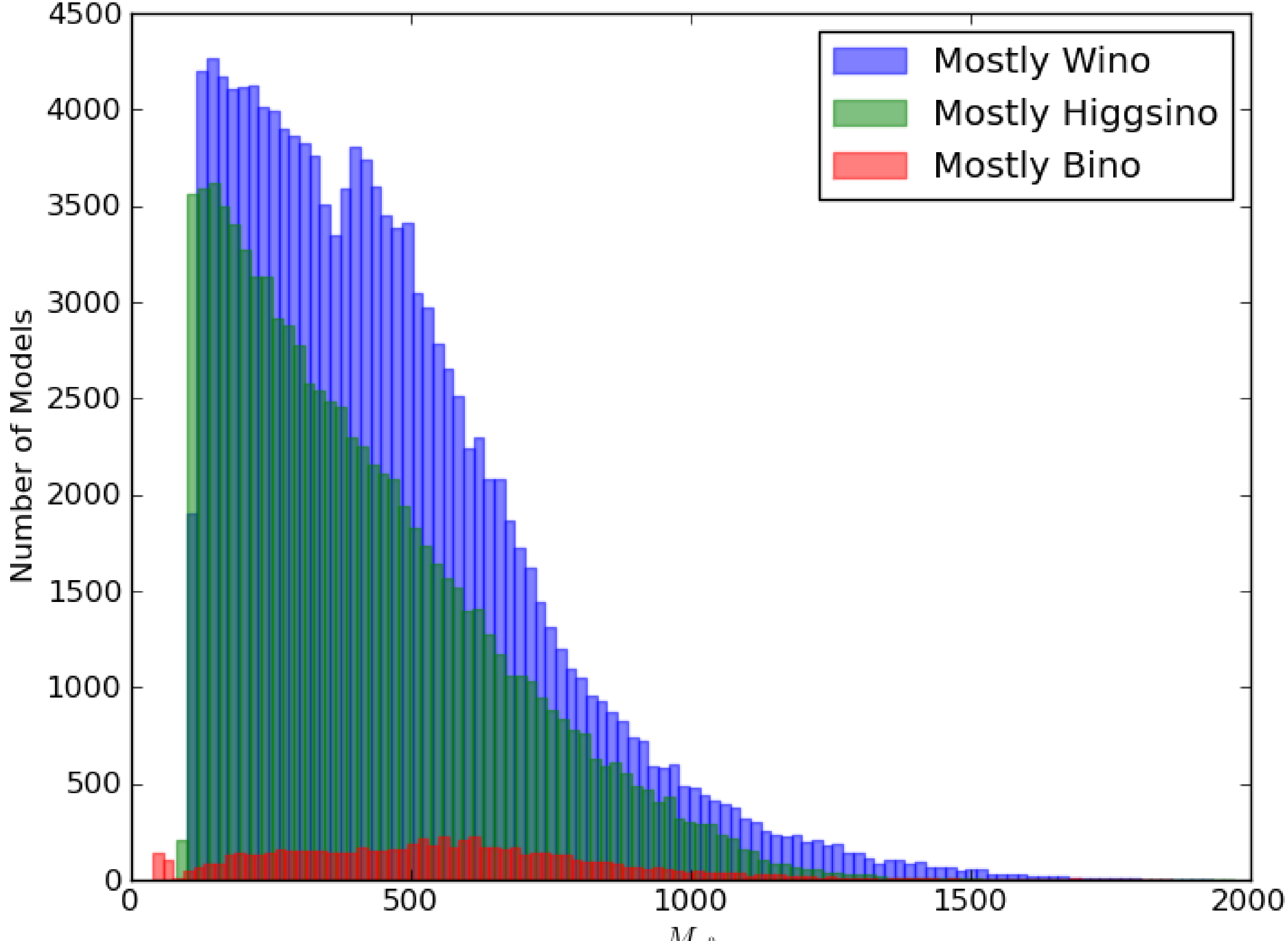
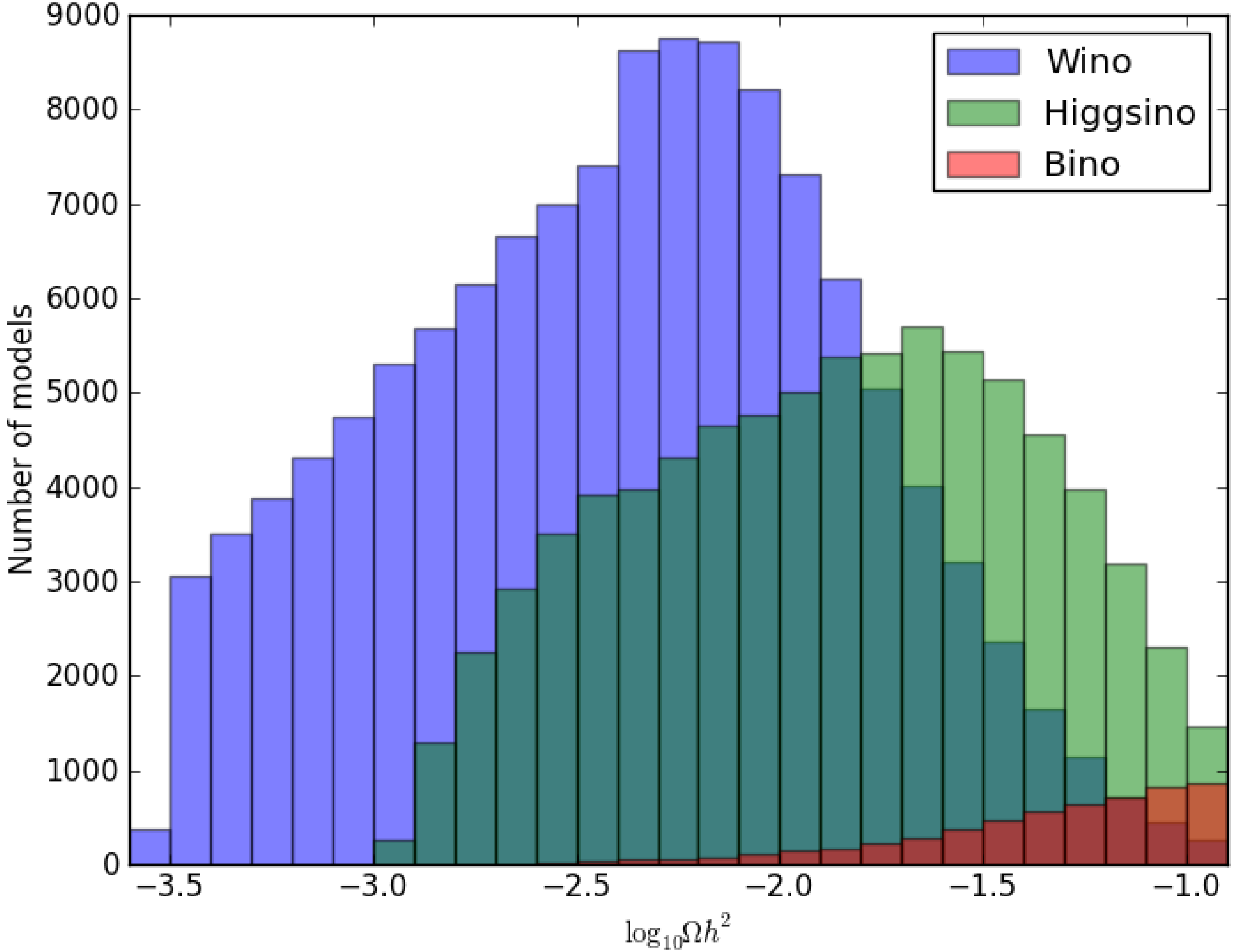
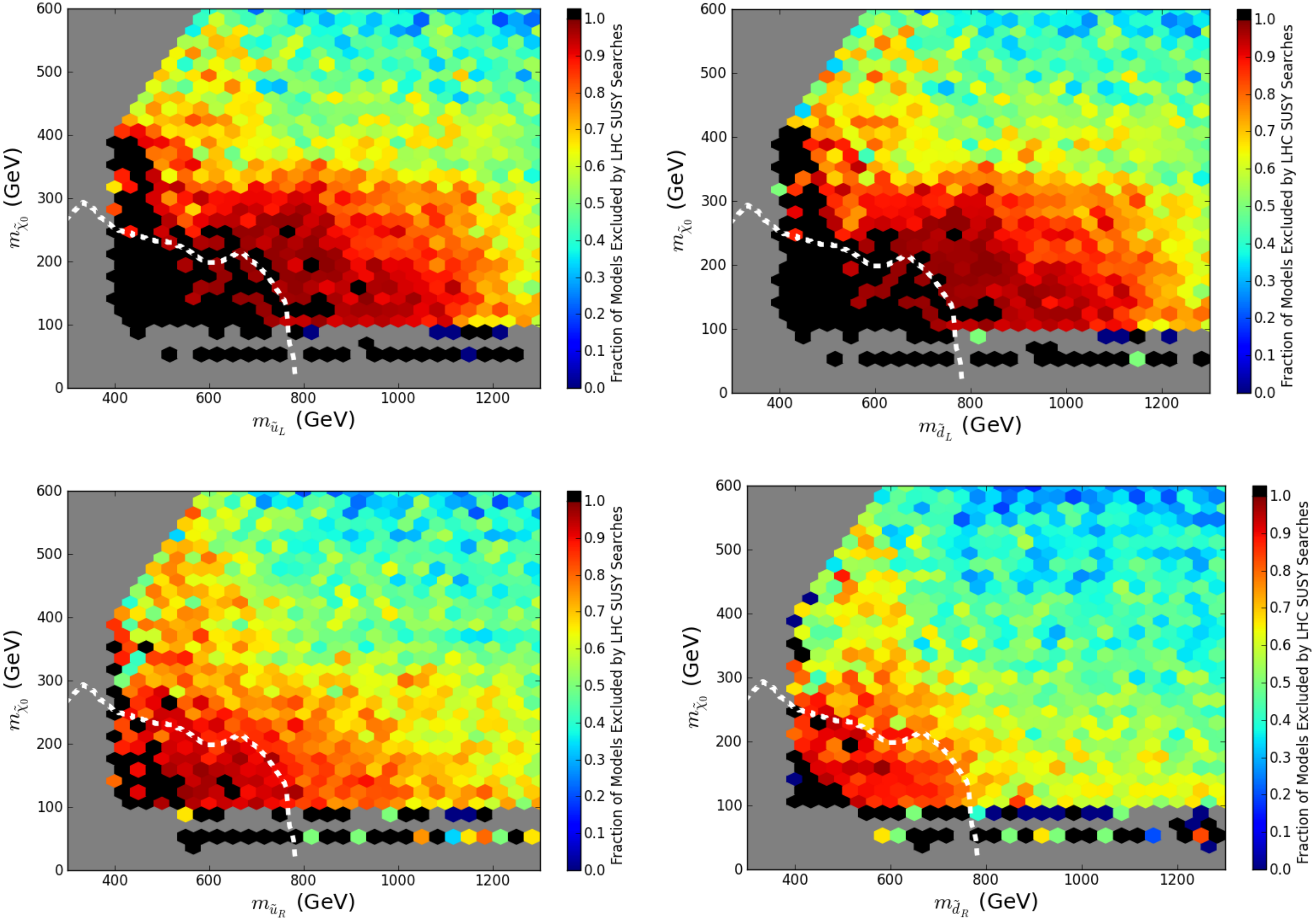


Mostly Wino
Mostly Higgsino
Mostly Bino
Number of Models
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
500
1000
1500
2000
M_{χ^0}

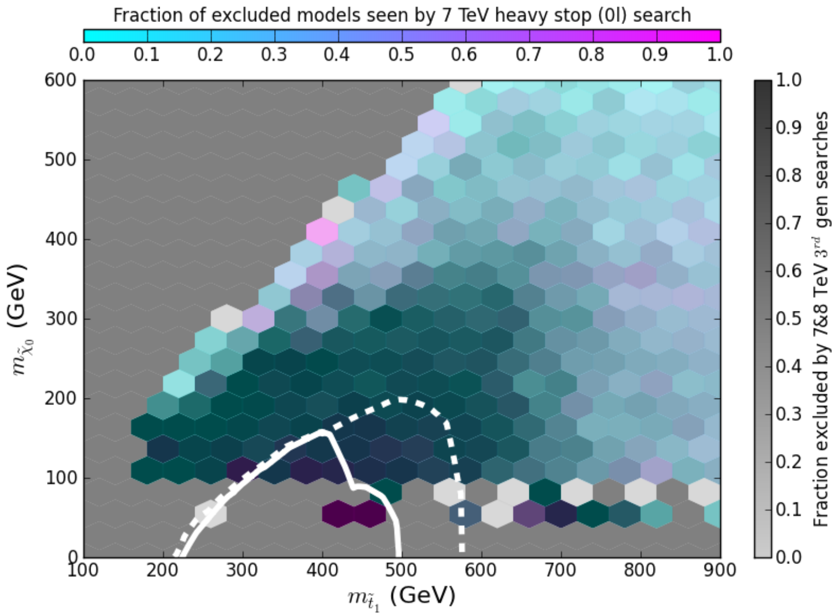


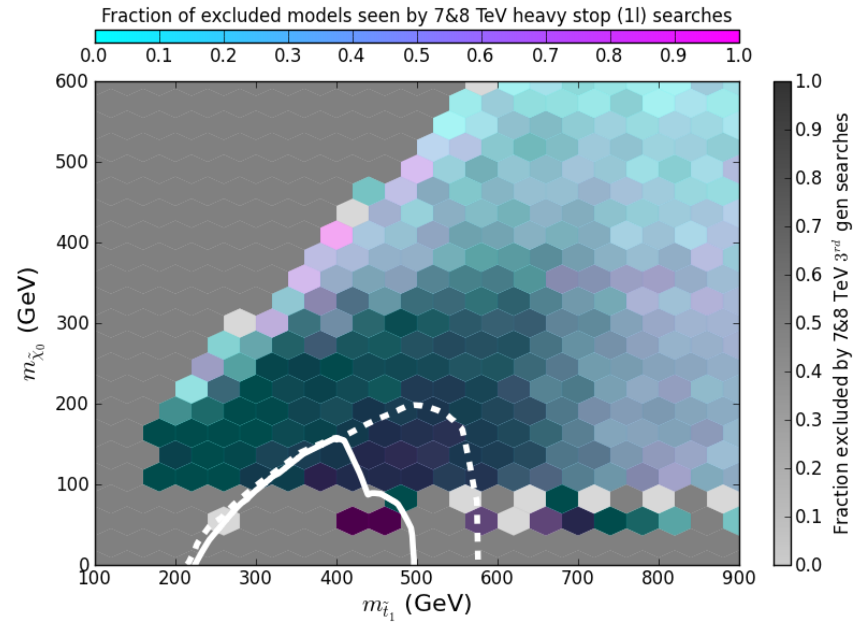
Wino
Higgsino
Bino
Number of models
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$\log_{10}\Omega h^2$

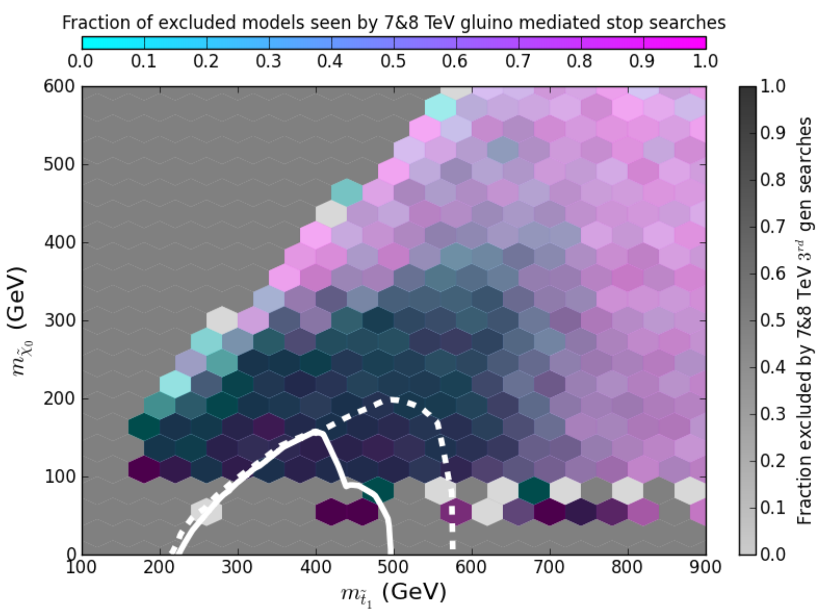
Neutralino Set Squark Results

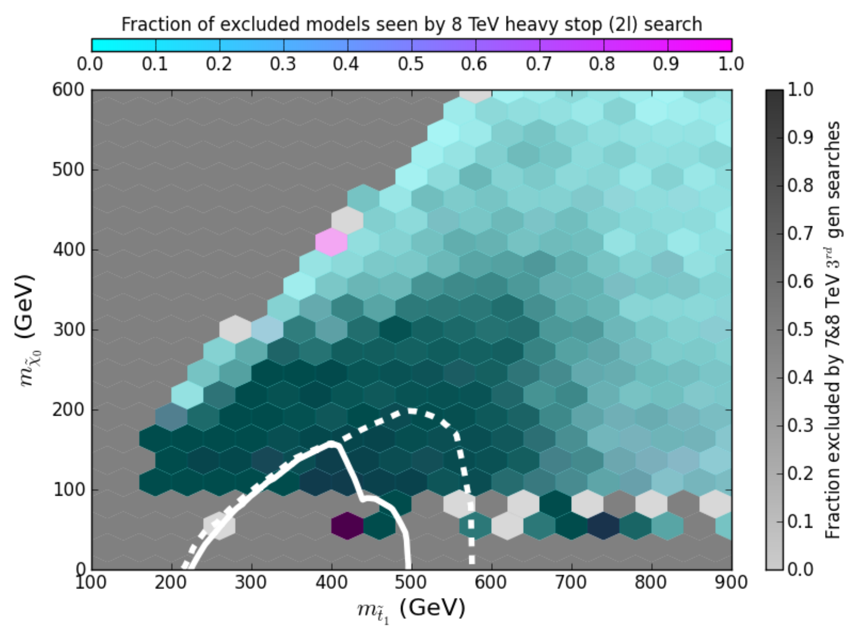


Comparison of Stop Search Effectiveness

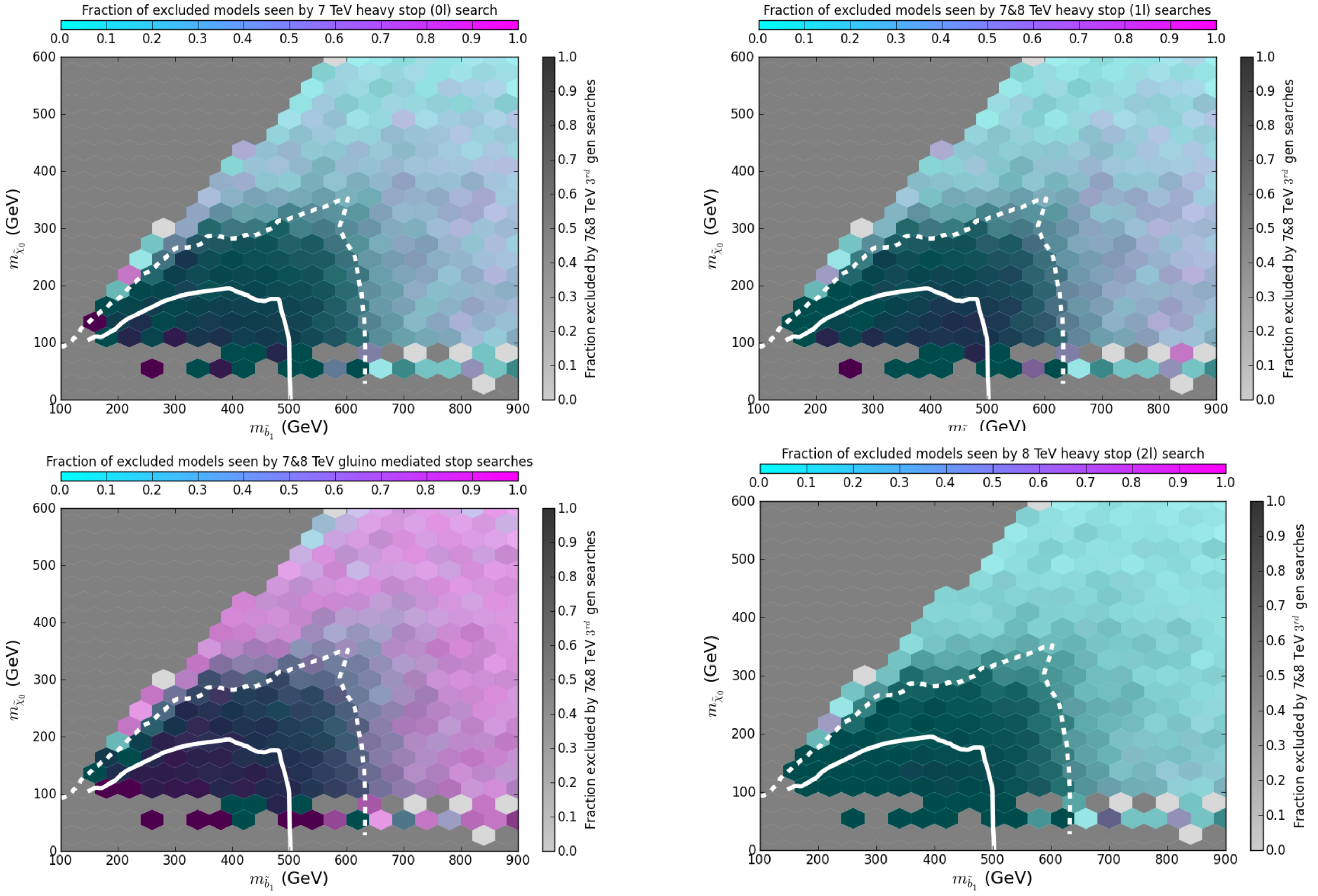


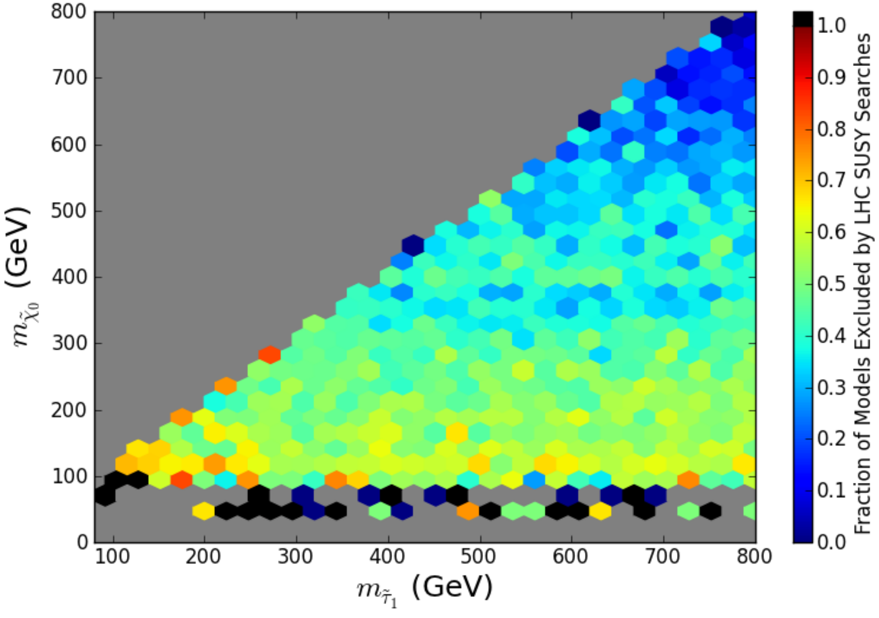




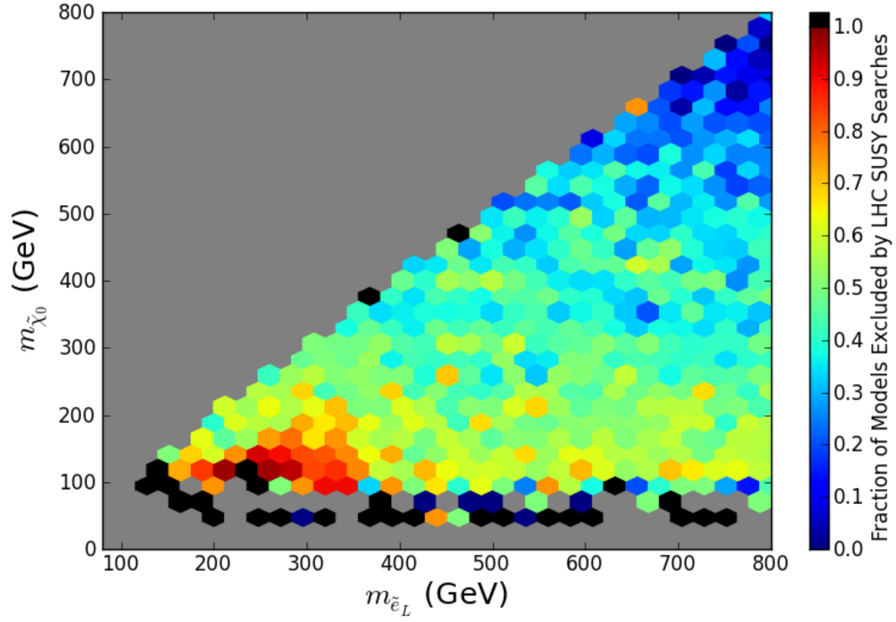


Comparison of Sbottom Search Effectiveness

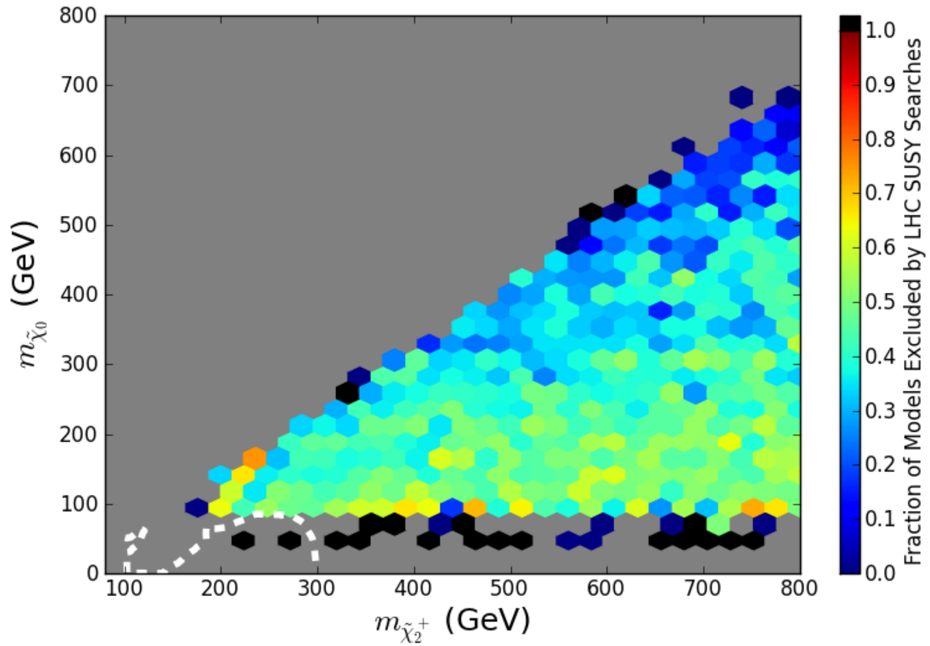




$m_{\tilde{\chi}^0}$ (GeV)
$m_{\tilde{\tau}_1}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches

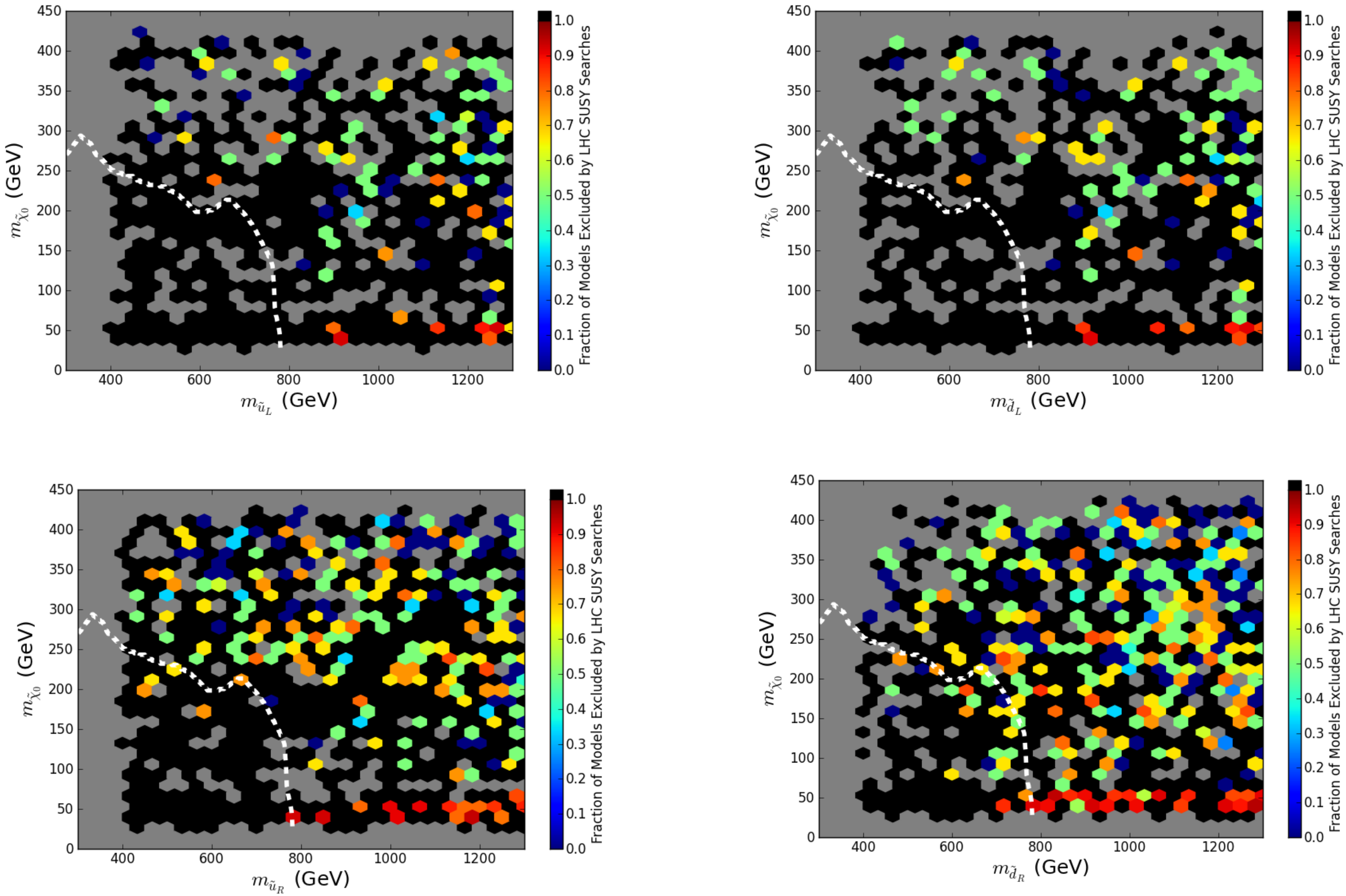


$m_{\tilde{\chi}^0}$ (GeV)
$m_{\tilde{e}_L}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches

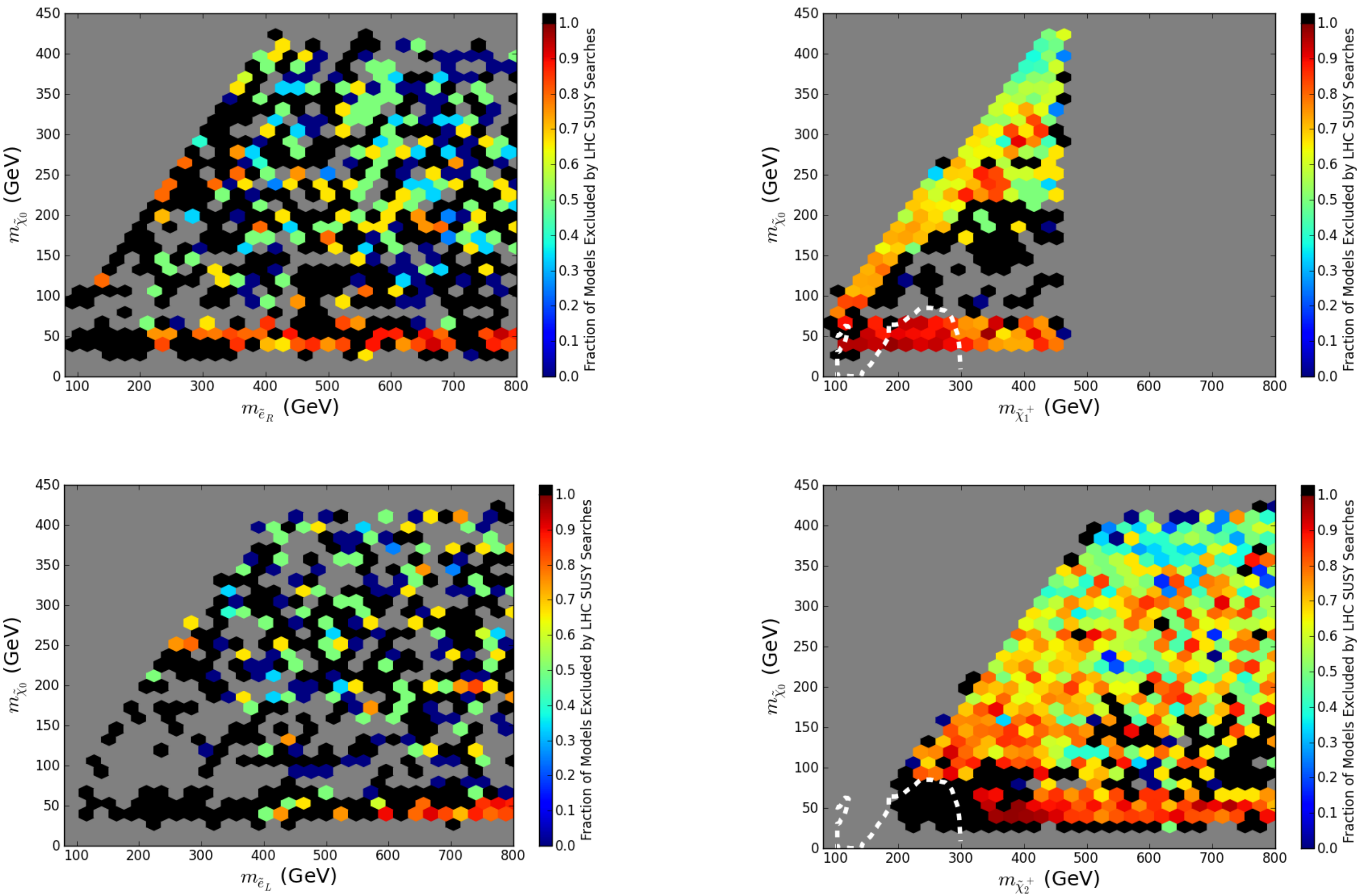


$m_{\tilde{\chi}^0}$ (GeV)
$m_{\tilde{\chi}_2^+}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches

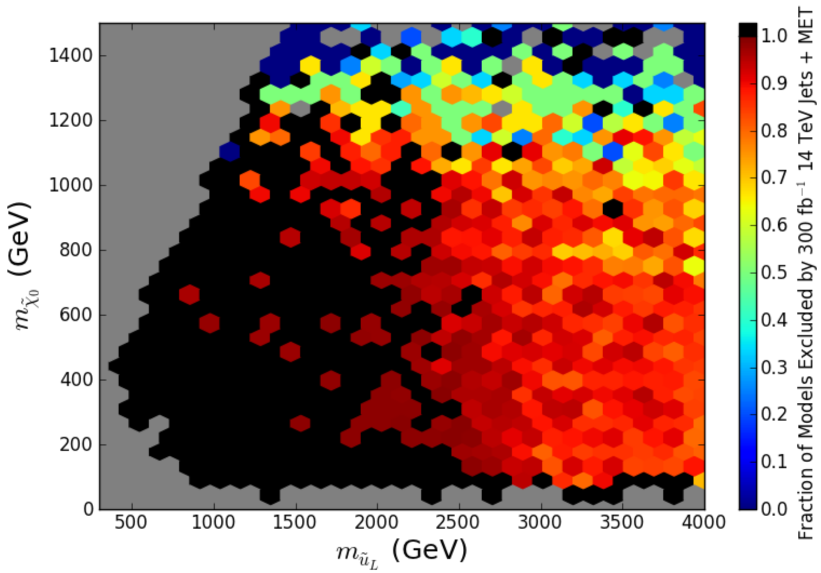
Low-FT Light Squark Results

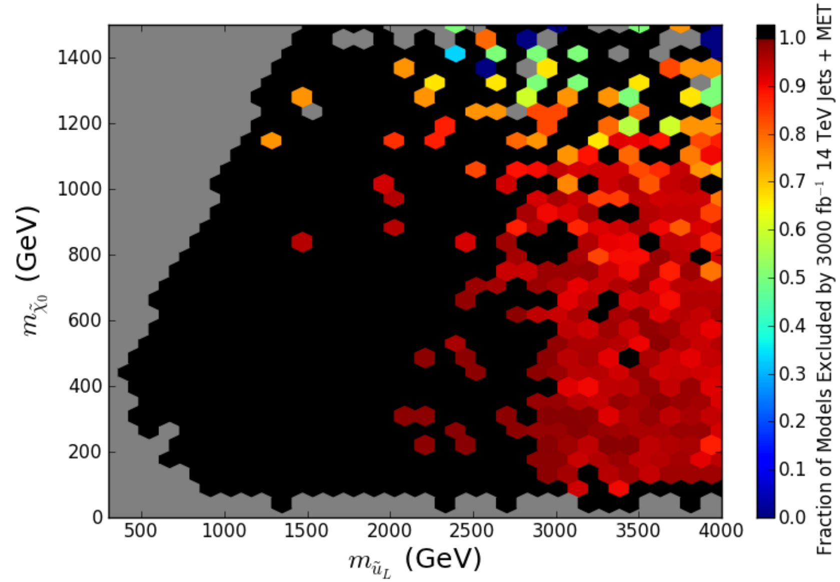


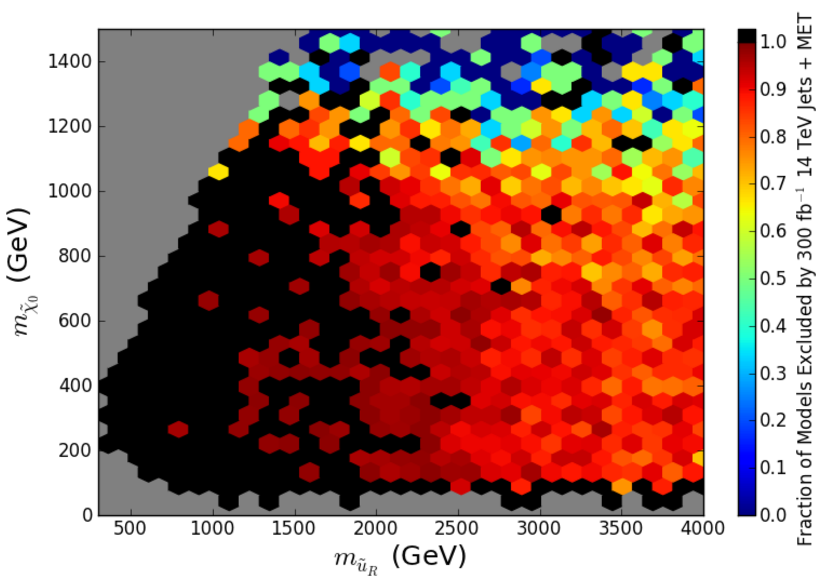
More Low-FT Results

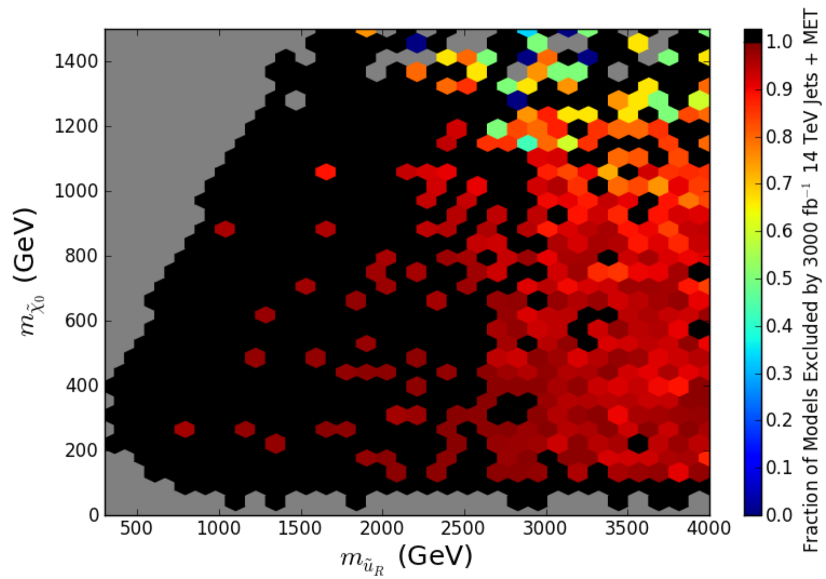


More 14 TeV Squark Results

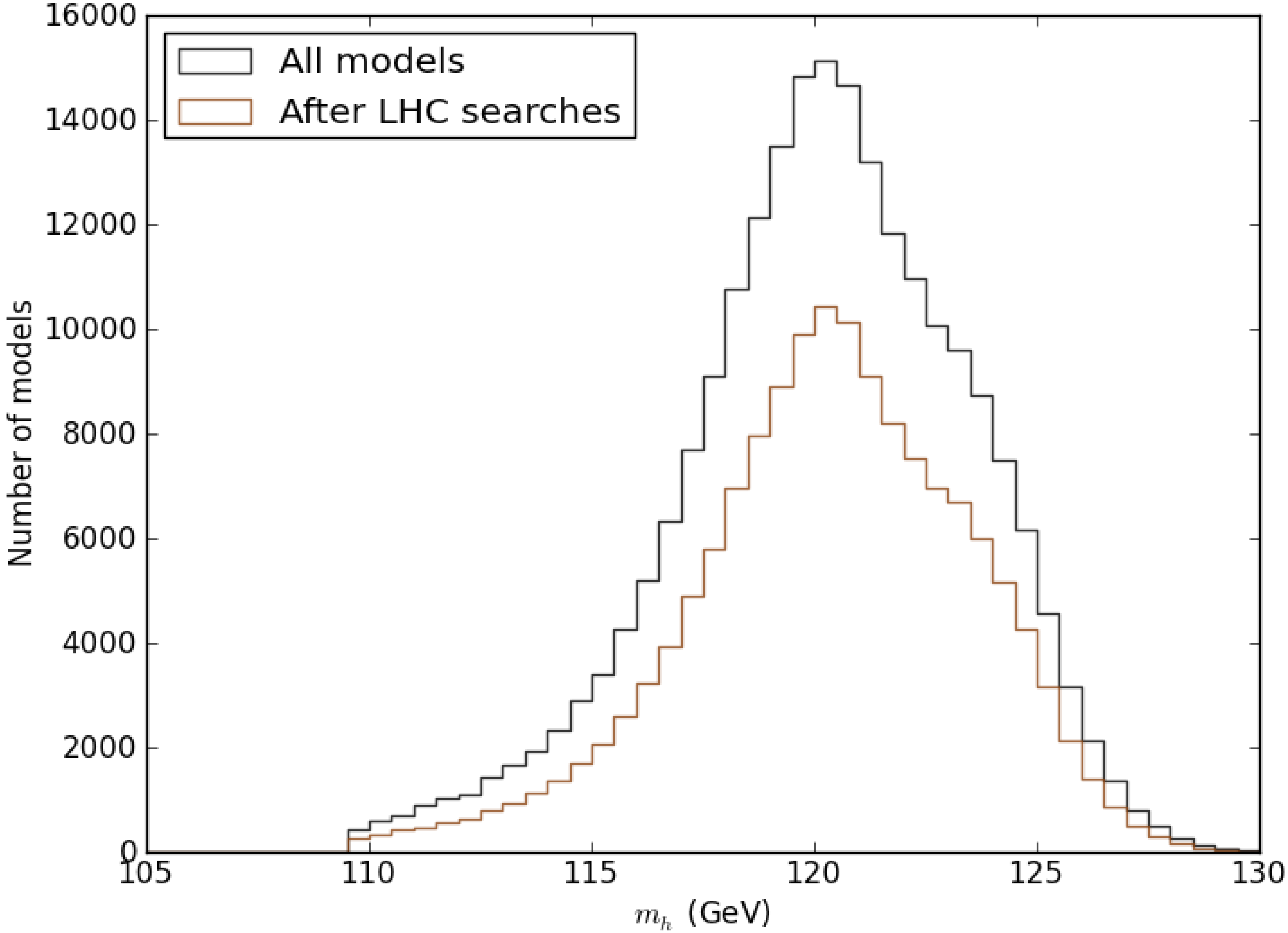








As the SUSY searches are roughly independent of the value of the Higgs mass, the predicted mass of the Higgs is roughly independent of the SUSY searches as well !



Low Fine-tuning in the pMSSM ?

- m_h ~ 126 GeV in the MSSM requires large stop masses and/or mixings which then $\rightarrow$ significant FT expected

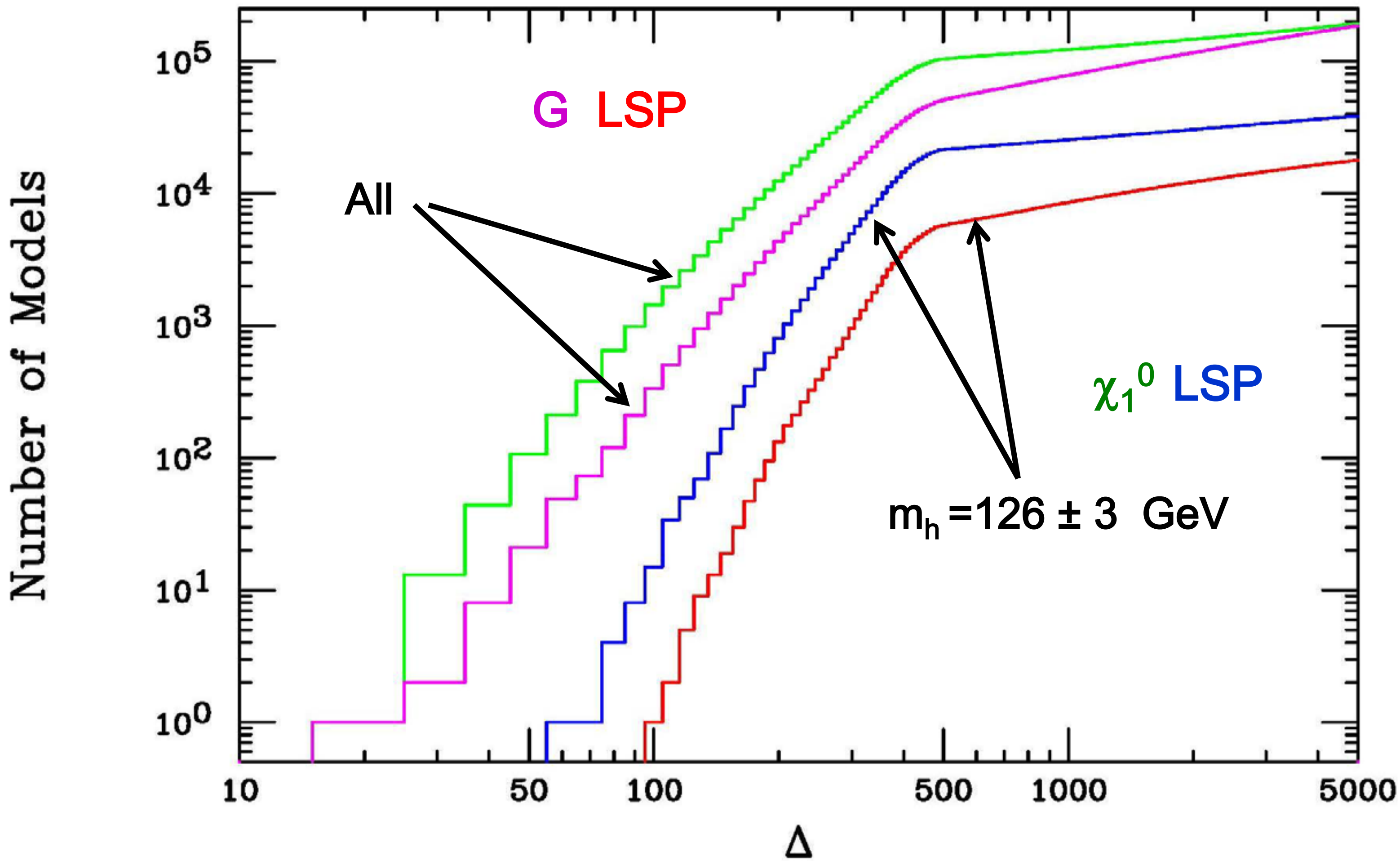
$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} + \mu^2$$

- 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 :

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

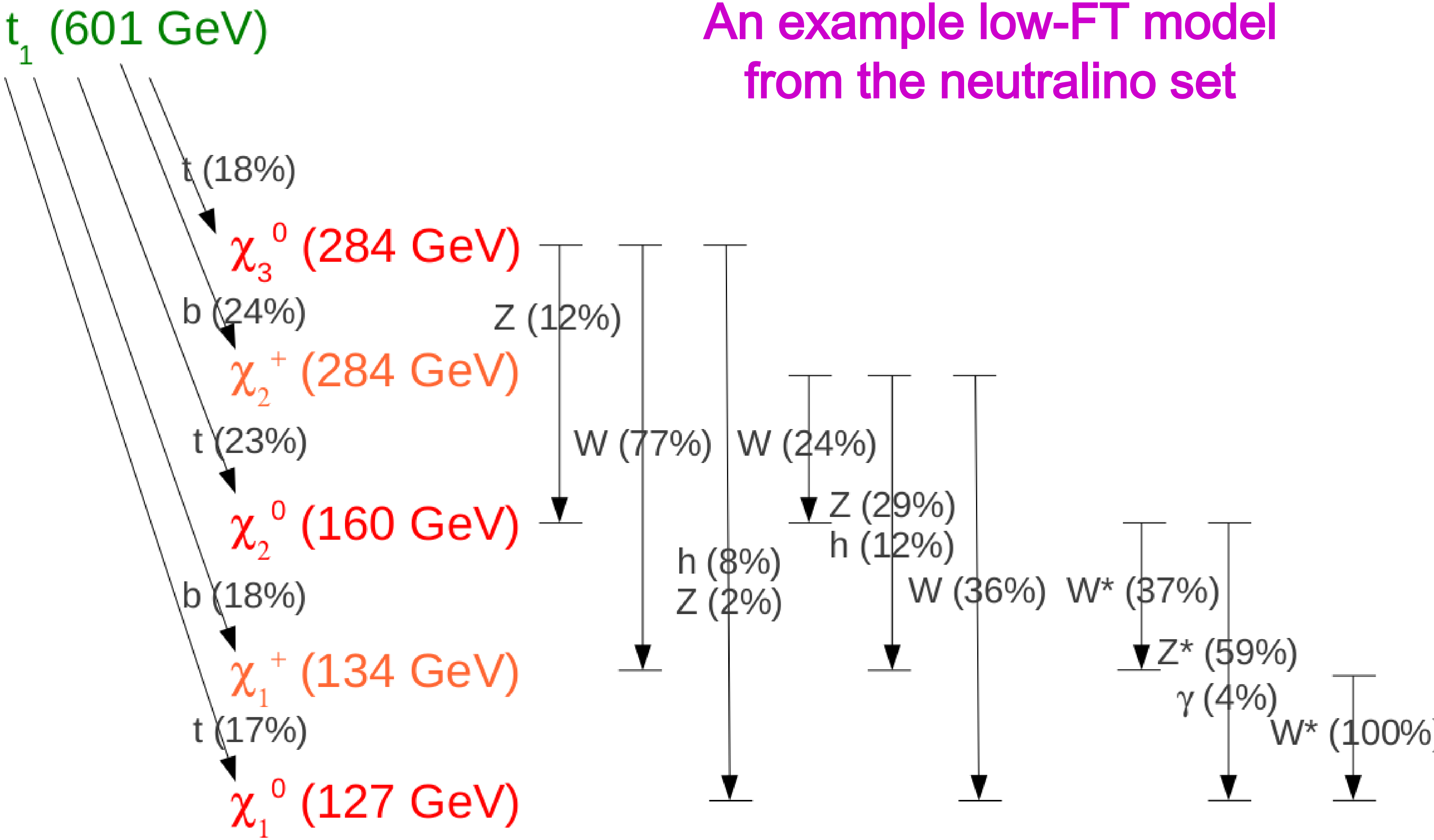
- How many models have Δ less than a specific value ?

Fine-tuning in the pMSSM



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

An example low-FT model from the neutralino set



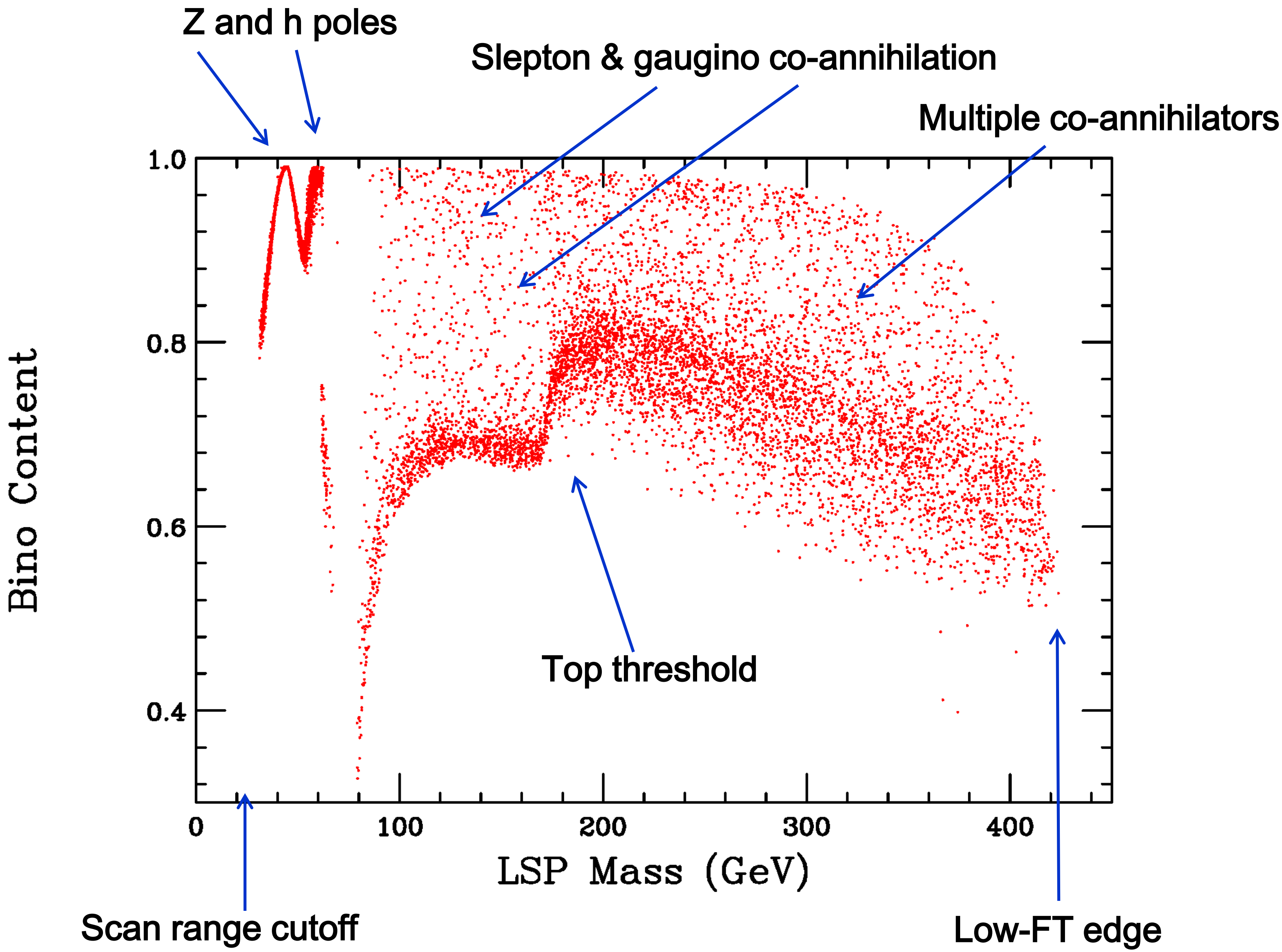
Lessons Learned

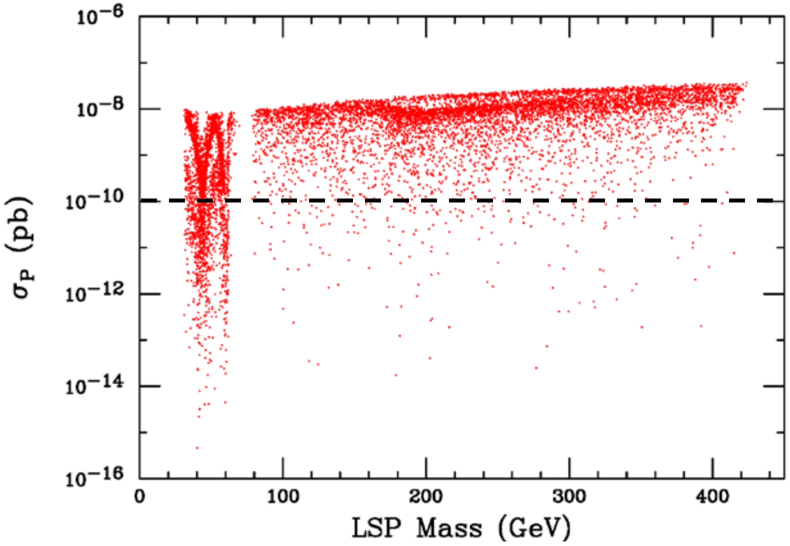
- Completely random scans are seen to produce few models with low FT values

- Furthermore, as expected, the large Higgs mass 'cut' is seen to remove most of the models with the lowest FT values

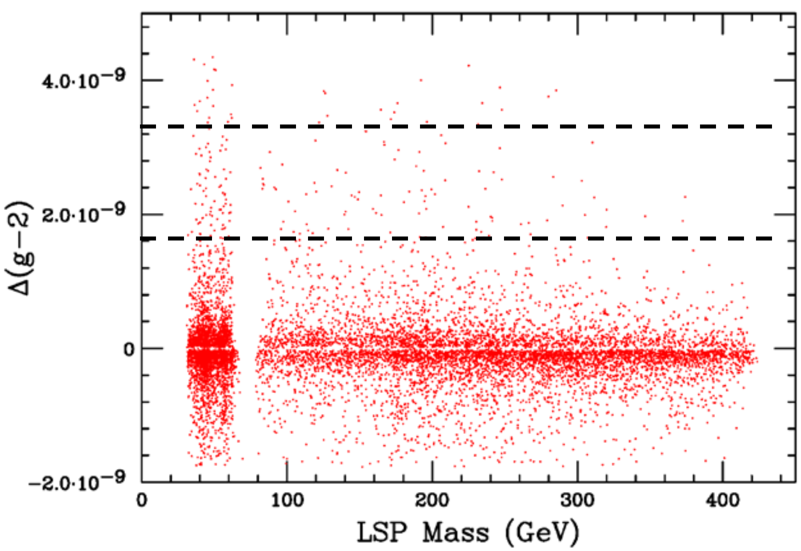
- The spectra of these low-FT models can make them difficult to see w/ any one existing search

- 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.


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



- 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

pMSSM Low-FT Neutralino LSP Model Set

$\rightarrow\rightarrow$ 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: ~3.3×10^8 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 $\pm 5\sigma$ $\rightarrow$ ~10.2k models

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

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

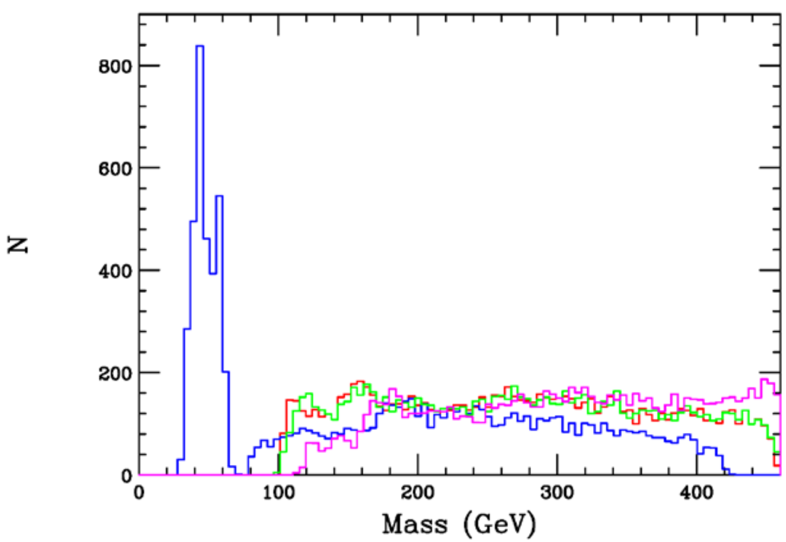
- ~59.5% of models have all gauginos & Higgsinos below the lightest stop/sbottom. ~16.4% of models have the winos lighter than the Higgsinos.

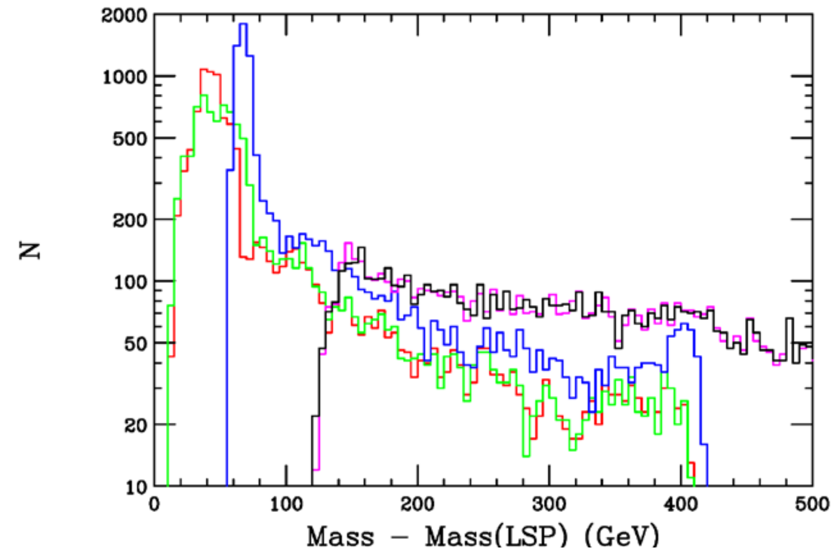
- ~11.0% of models have a sbottom lighter than the stop

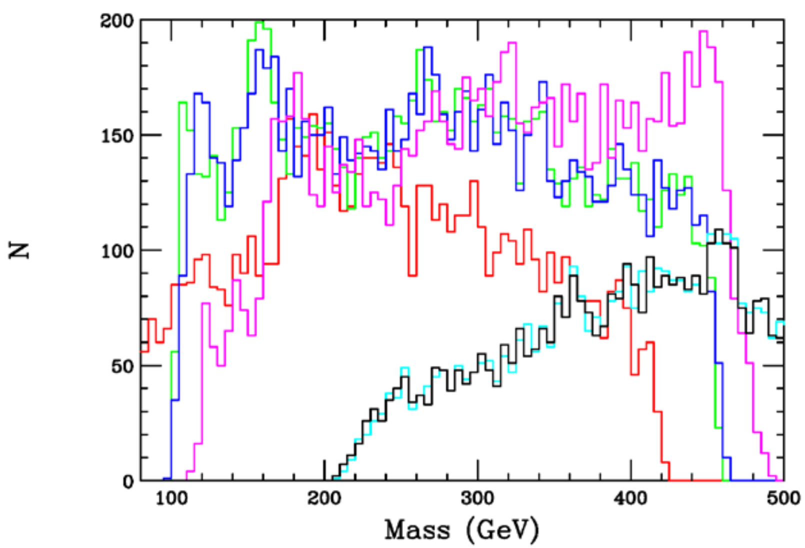
- ~30% of models have a light slepton of some kind below the stop/sbottom; it's most likely a mixed stau.

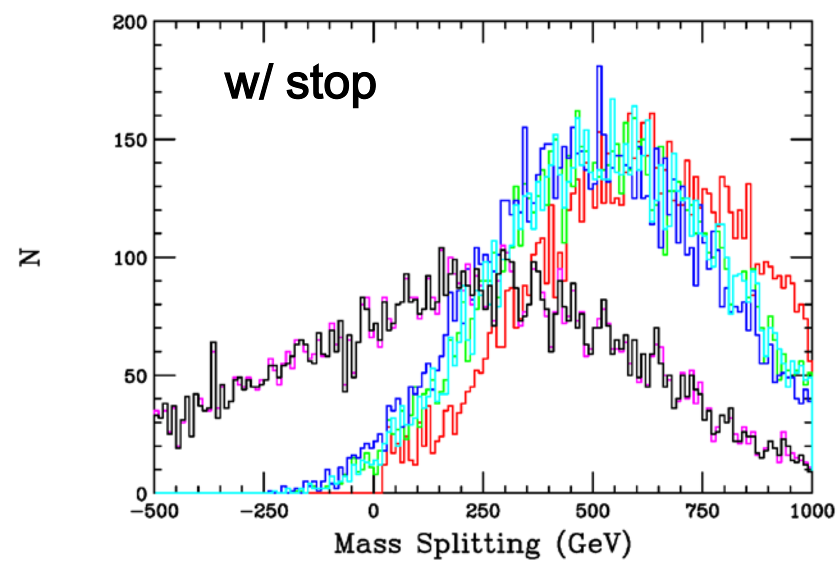
- ~15% of models have light squarks/gluinos below the stop or sbottom & so are likely excluded except for compression

Low-FT Model Gaugino Mass Spectra & Splittings



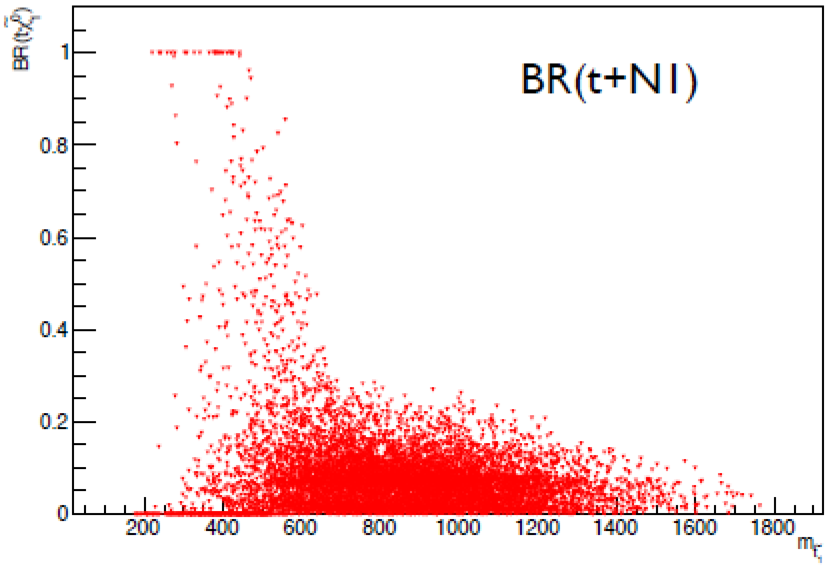


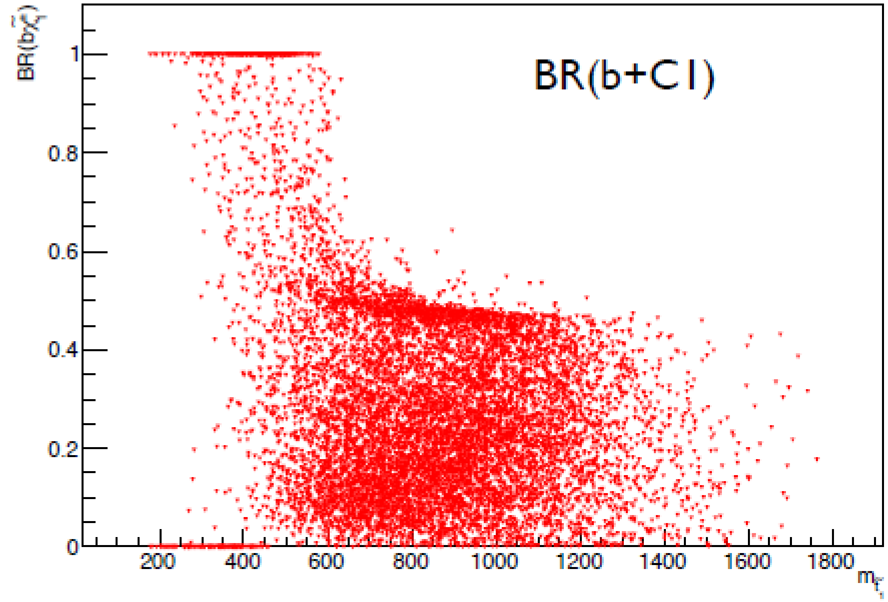


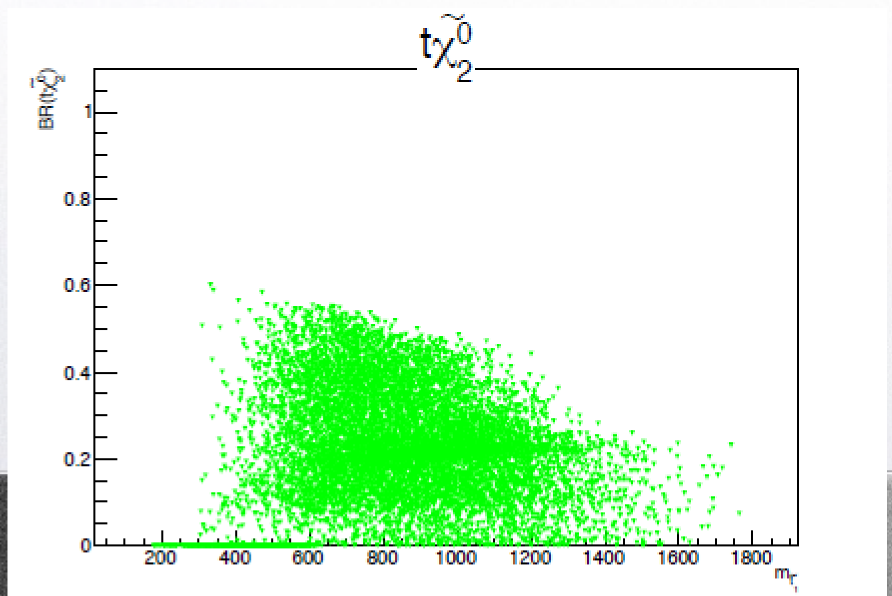


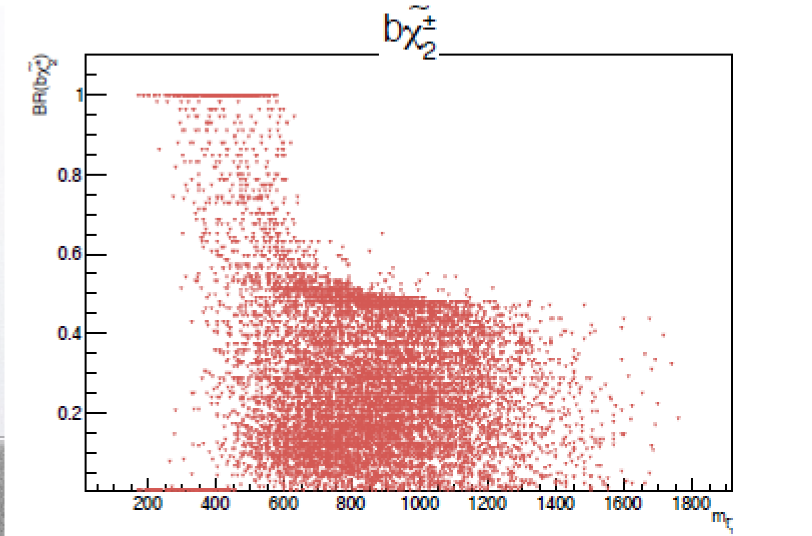
Phenomenological MSSM c/o ATLAS

BR VS stop mass





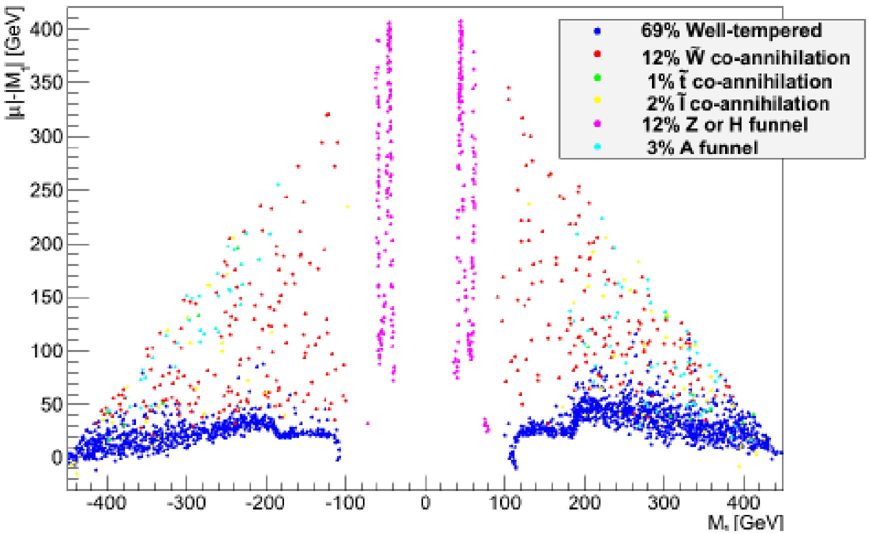




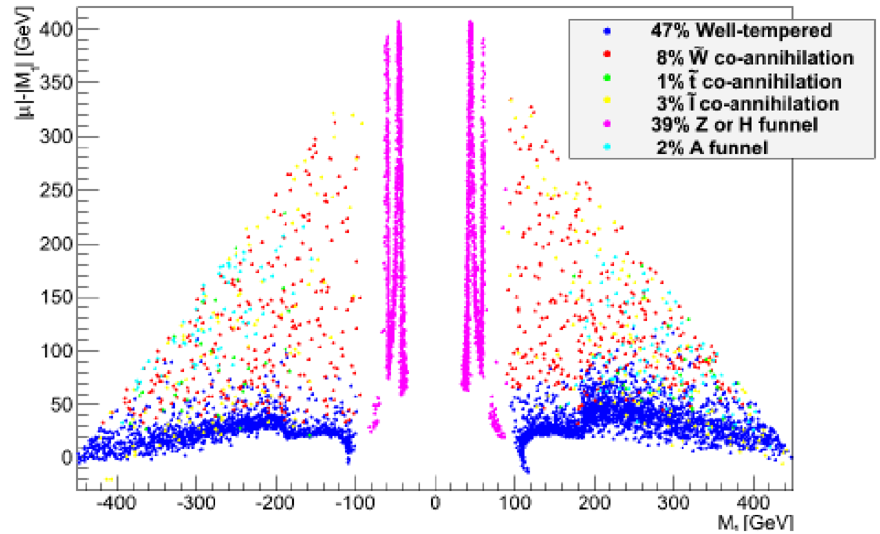
c/o ATLAS

Models allowed or excluded by LHC

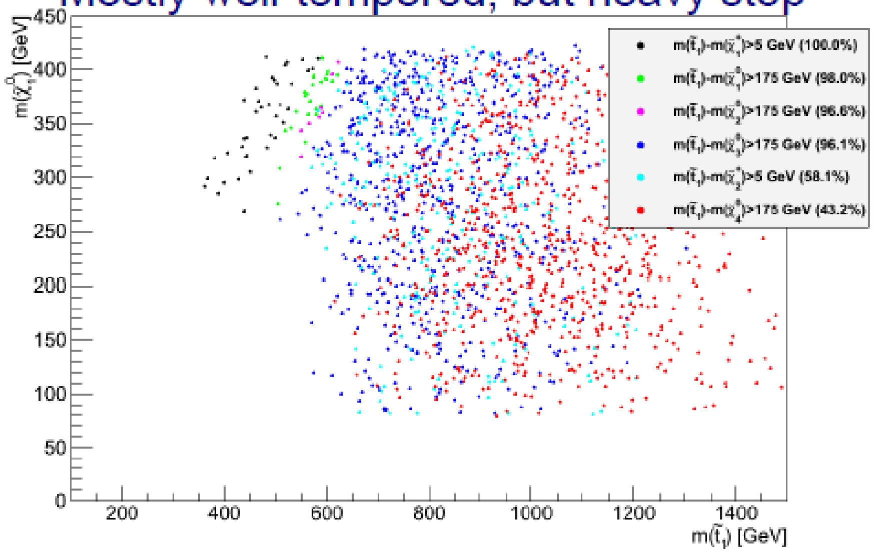
Allowed by LHC from SLAC emulation

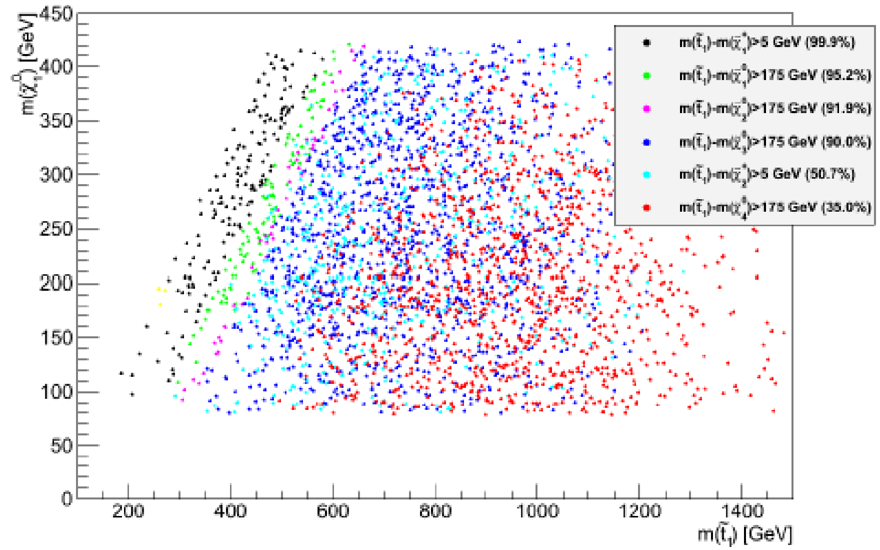


Excluded by LHC from SLAC emulation



Mostly well-tempered, but heavy stop





“Bino” ≡ $|N_{11}|^2 > .9$

- Significant Higgsino component in DM, since μ ≲ 450 GeV
- 172 models survive current collider limits and projected Xenon 1T limits