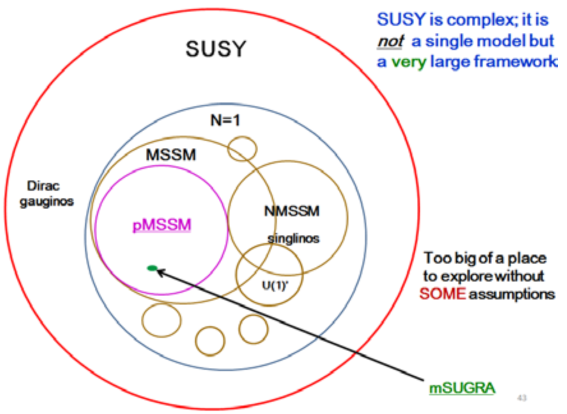
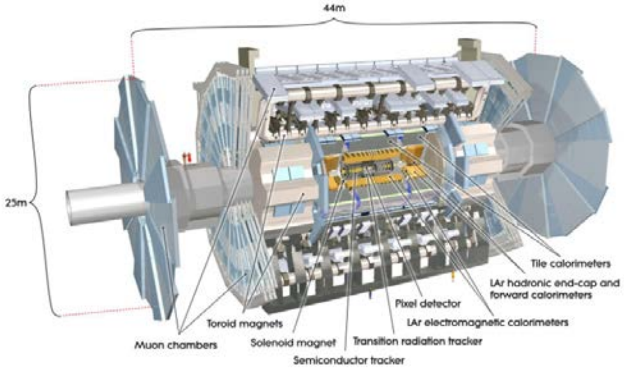
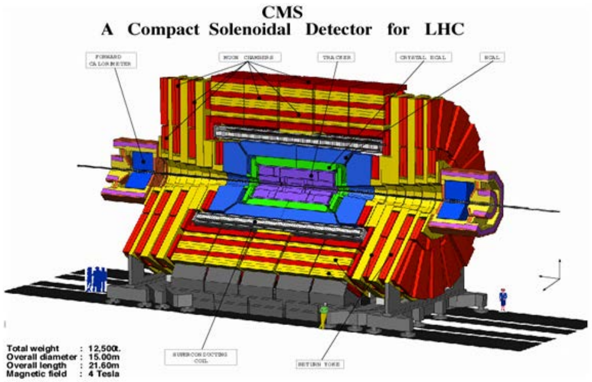
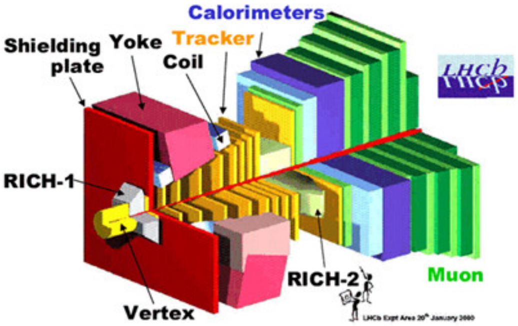
Simultaneous Constraints on Higgs Couplings & SUSY Partners in the pMSSM









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Direct searches for SUSY sparticles at the LHC as well as measurements of the properties of the Higgs boson both probe SUSY model parameter space

- What do (null?) SUSY searches tell us about the possible variations in the Higgs couplings ?

- What do precision measurements of the Higgs couplings tell us about the SUSY parameters & sparticle masses ?

→ Here we will use the pMSSM in various forms to address these questions quantitatively

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/Planck used as upper bound on thermal relic density

→ the pMSSM with 19/20 parameters

- Two large ~225k model sets with either a neutralino (19) or gravitino (20) LSP

- Smaller (~10k) dedicated set for low-FT studies & other analyses

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

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

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

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

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

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

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

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

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

There's a LOT of space here ; we're going for breadth not depth !

ATLAS SUSY Analyses @ 7 & 8 TeV

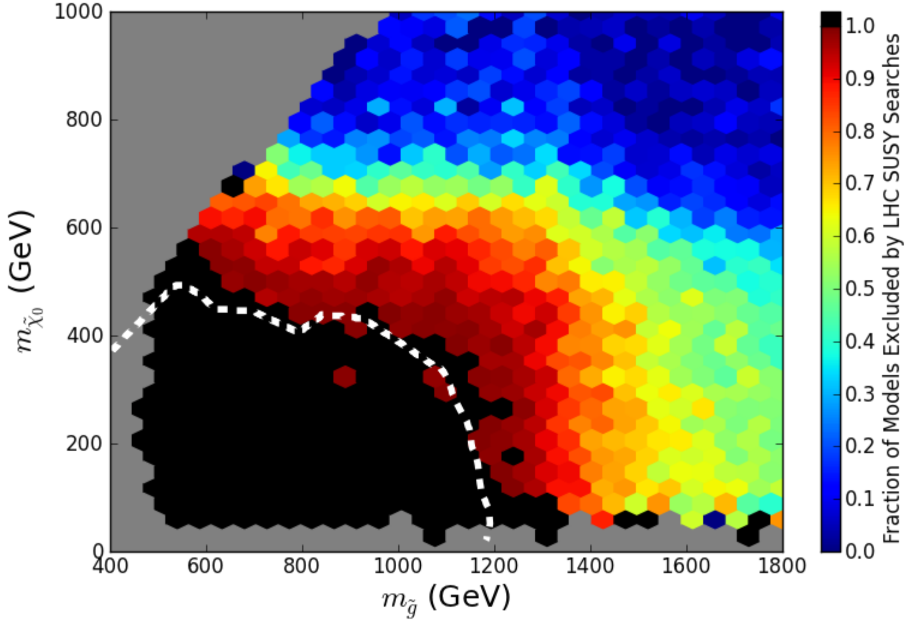
- We replicated the ATLAS analysis suite employing fast MC (SOFTSUSY, SDECAY, HDECAY, Madgraph & Pythia plus modified PGS) & validated using ATLAS MSSM benchmark points

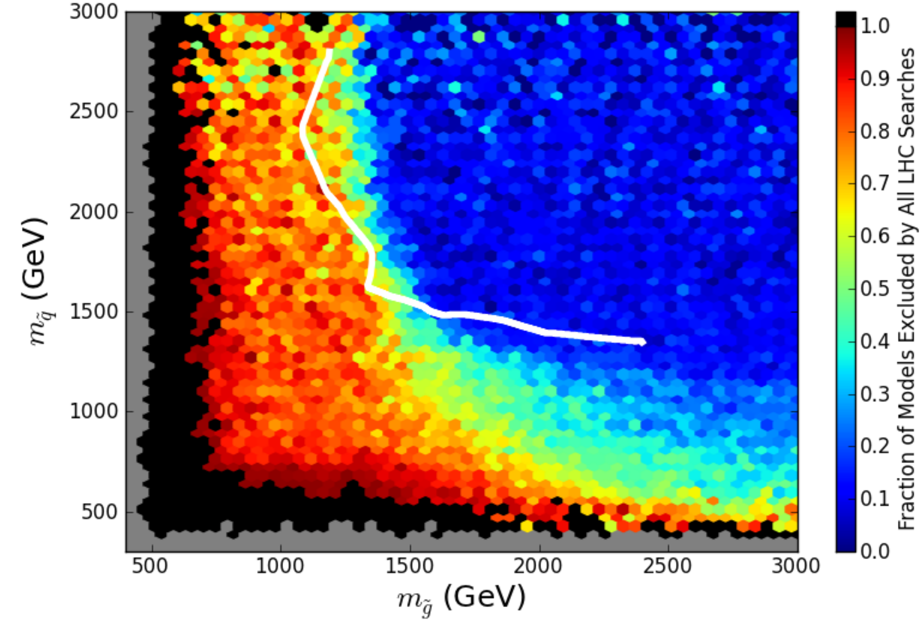
- We determine which models are excluded by each analysis & then combine them to determine the total exclusion. (ATLAS has now taken over for us!)

Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-033	21.2%	17.4%	36.5%
multijets	ATLAS-CONF-2012-037	1.6%	2.1%	10.6%
1 lepton	ATLAS-CONF-2012-041	3.2%	5.3%	18.7%
HSCP	1205.0272	4.0%	17.4%	<0.1%
Disappearing Track	ATLAS-CONF-2012-111	2.6%	1.2%	<0.1%
Muon + Displaced Vertex	1210.7451	-	0.5%	-
Displaced Dilepton	1211.2472	-	0.8%	-
Gluino $\to$ Stop/Sbottom	1207.4686	4.9%	3.5%	21.2%
Very Light Stop	ATLAS-CONF-2012-059	<0.1%	<0.1%	0.1%
Medium Stop	ATLAS-CONF-2012-071	0.3%	5.1%	2.1%
Heavy Stop (0ℓ)	1208.1447	3.7%	3.0%	17.0%
Heavy Stop (1ℓ)	1208.2590	2.0%	2.2%	12.6%
GMSB Direct Stop	1204.6736	<0.1%	<0.1%	0.7%
Direct Sbottom	ATLAS-CONF-2012-106	2.5%	2.3%	5.1%
3 leptons	ATLAS-CONF-2012-108	1.1%	6.1%	17.6%
1-2 leptons	1208.4688	4.1%	8.2%	21.0%
Direct slepton/gaugino (2ℓ)	1208.2884	0.1%	1.2%	0.8%
Direct gaugino (3ℓ)	1208.3144	0.4%	5.4%	7.5%
4 leptons	1210.4457	0.7%	6.3%	14.8%
1 lepton + many jets	ATLAS-CONF-2012-140	1.3%	2.0%	11.7%
1 lepton + γ	ATLAS-CONF-2012-144	<0.1%	1.6%	<0.1%
γ + b	1211.1167	<0.1%	2.3%	<0.1%
$\gamma\gamma$ + MET	1209.0753	<0.1%	5.4%	<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%	<0.1%	*

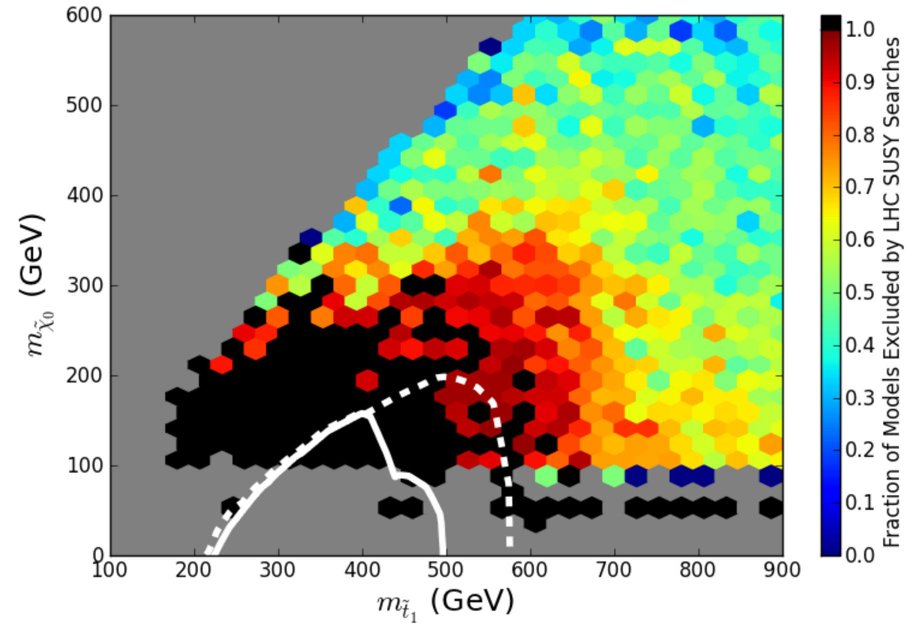
Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-109	26.7%	22.5%	44.9%
multijets	ATLAS-CONF-2012-103	3.3%	5.6%	20.9%
1 lepton	ATLAS-CONF-2012-104	3.3%	6.0%	20.9%
SS dileptons	ATLAS-CONF-2012-105	4.9%	12.5%	35.5%
2-6 jets	ATLAS-CONF-2013-047	38.0%	31.1%	56.5%
HSCP	1305.0491	-	23.0%	-
Medium Stop (2ℓ)	ATLAS-CONF-2012-167	0.6%	8.1%	4.9%
Medium/Heavy Stop (1ℓ)	ATLAS-CONF-2012-166	3.8%	4.5%	21.0%
Direct Sbottom (2b)	ATLAS-CONF-2012-165	6.2%	5.1%	12.1%
3rd Generation Squarks (3b)	ATLAS-CONF-2012-145	10.8%	9.9%	40.8%
3rd Generation Squarks (3ℓ)	ATLAS-CONF-2012-151	1.9%	9.2%	26.5%
3 leptons	ATLAS-CONF-2012-154	1.4%	8.8%	32.3%
4 leptons	ATLAS-CONF-2012-153	3.0%	13.2%	46.9%
Z + jets + MET	ATLAS-CONF-2012-152	0.3%	1.4%	6.8%

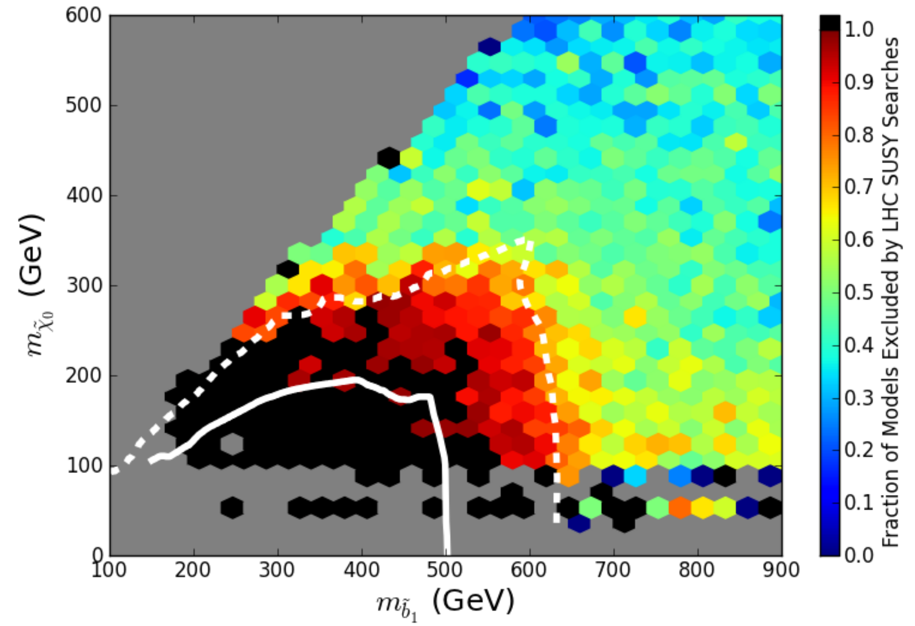
$\to$ many of the models are now excluded by LHC searches: (45.5, 61.3, 74.0) %



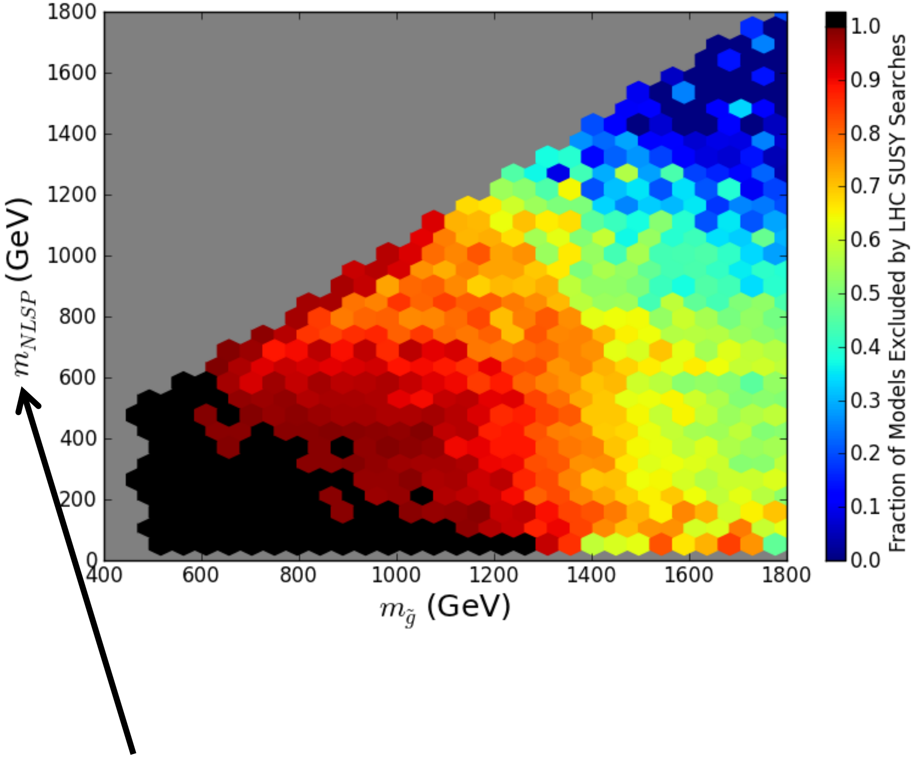


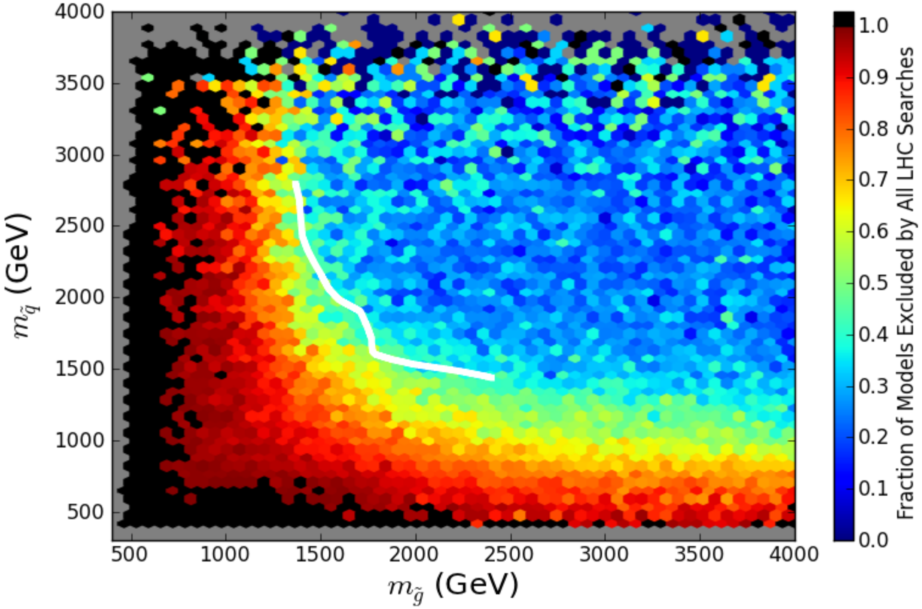
Search Efficiency for Neutralino LSP Set





Search Efficiency for Gravitino LSP Set

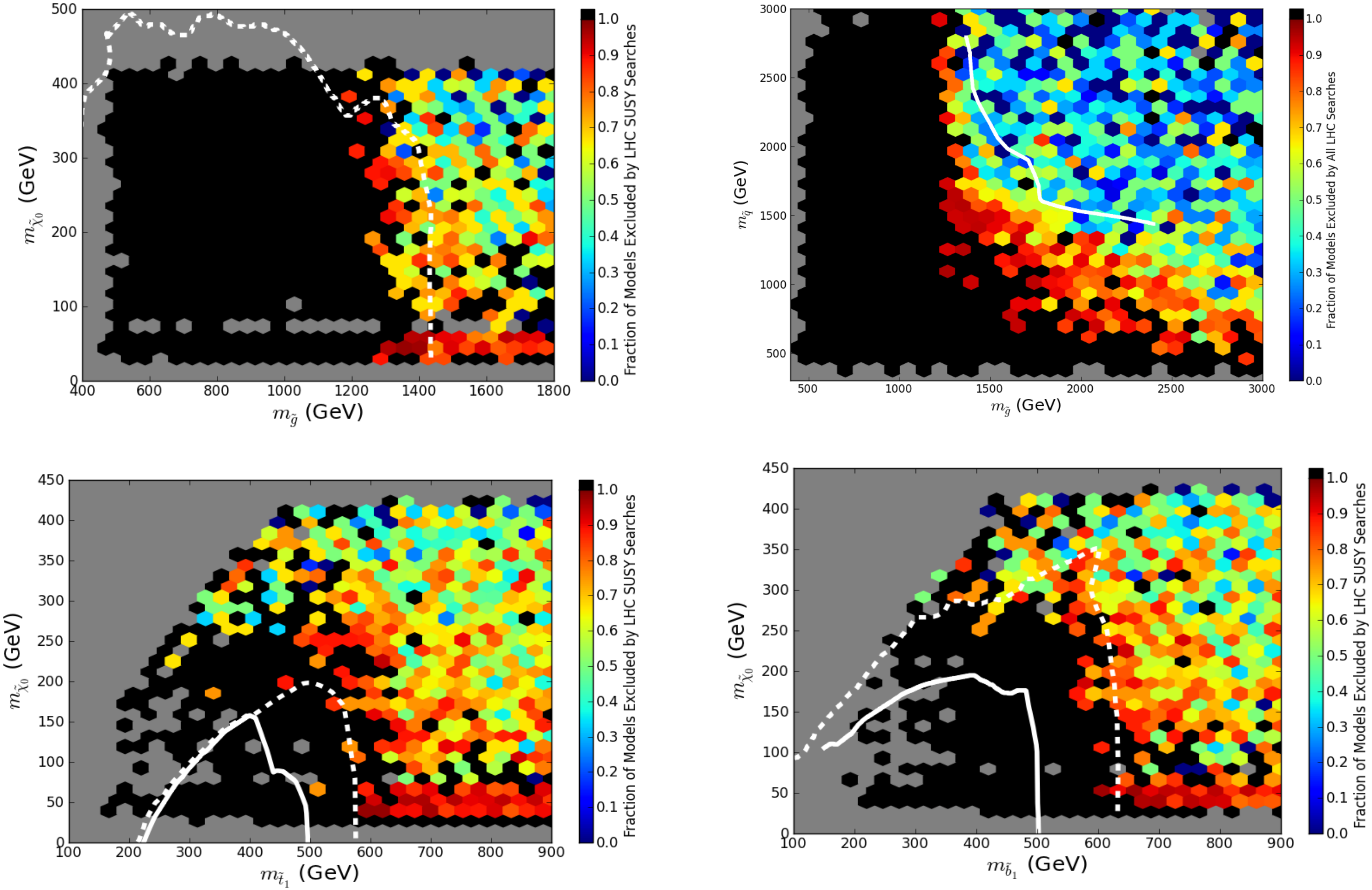




Note this is the NLSP mass!

Due to the large number of long-lived NLSPs in this set MET-based searches are less effective.. but these are more than compensated for by the specialized searches

Search Efficiency for Neutralino LSP Set



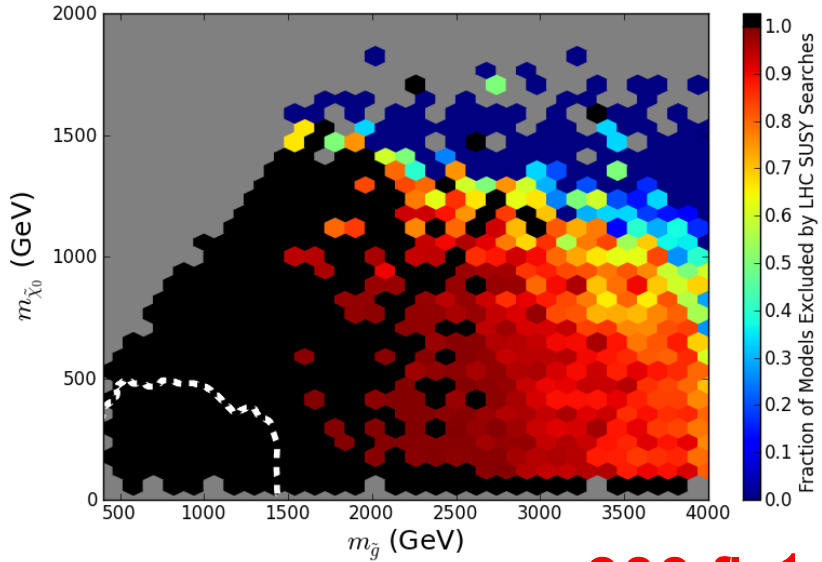
ATLAS SUSY Analyses @ 14 TeV

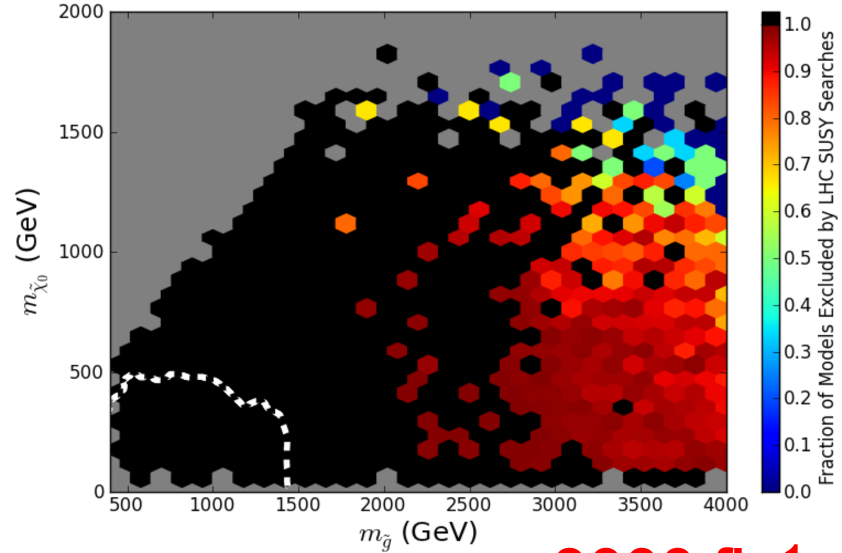
Not many ATLAS searches are publically available for us to replicate but just these few are very powerful :

Search	Lumi	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	300 fb^{-1}	ATLAS-PHYS-PUB-2013-002	90.74%	79.58%	97.35%
Stop (0l)	300 fb^{-1}	ATLAS-PHYS-PUB-2013-011	3.88%	5.03%	1.90%
Stop (1l)	300 fb^{-1}	ATLAS-PHYS-PUB-2013-011	16.98%	33.43%	52.09%
2-6 jets	3000 fb^{-1}	ATLAS-PHYS-PUB-2013-002	97.08%	90.57%	99.96%
Stop (0l)	3000 fb^{-1}	ATLAS-PHYS-PUB-2013-011	18.81%	14.9%	39.27%
Stop (1l)	3000 fb^{-1}	ATLAS-PHYS-PUB-2013-011	43.45%	61.77%	93.43%

- With 300 (3000) fb^{-1} that 90.8 (97.2)% of the neutralino models are probed. For the low-FT set these rise to 97.4 (100) % ! Smaller numbers result in the gravitino case, 79.7(90.7)%, since these are all MET-based searches.

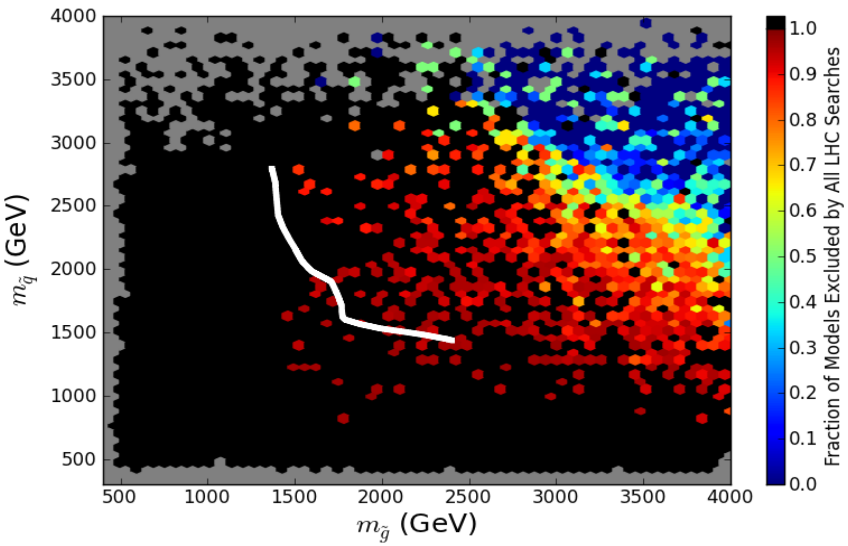
14 TeV Neutralino Set Results

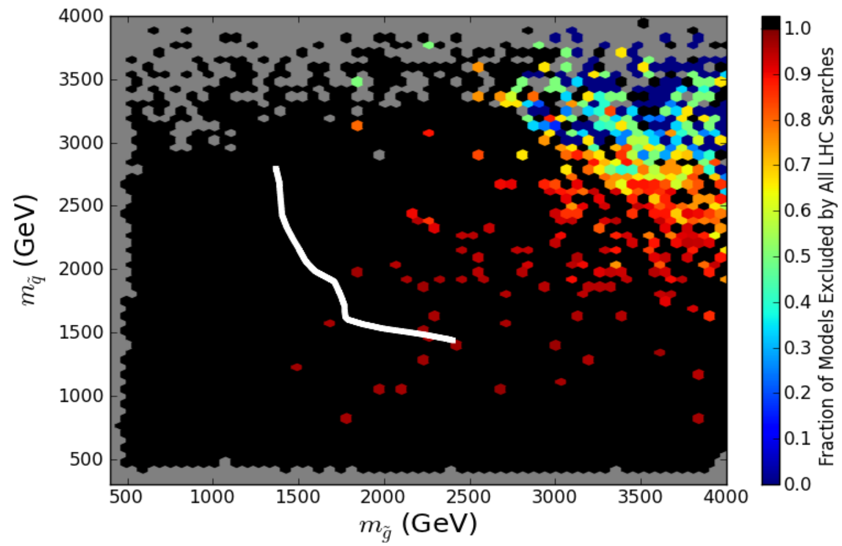




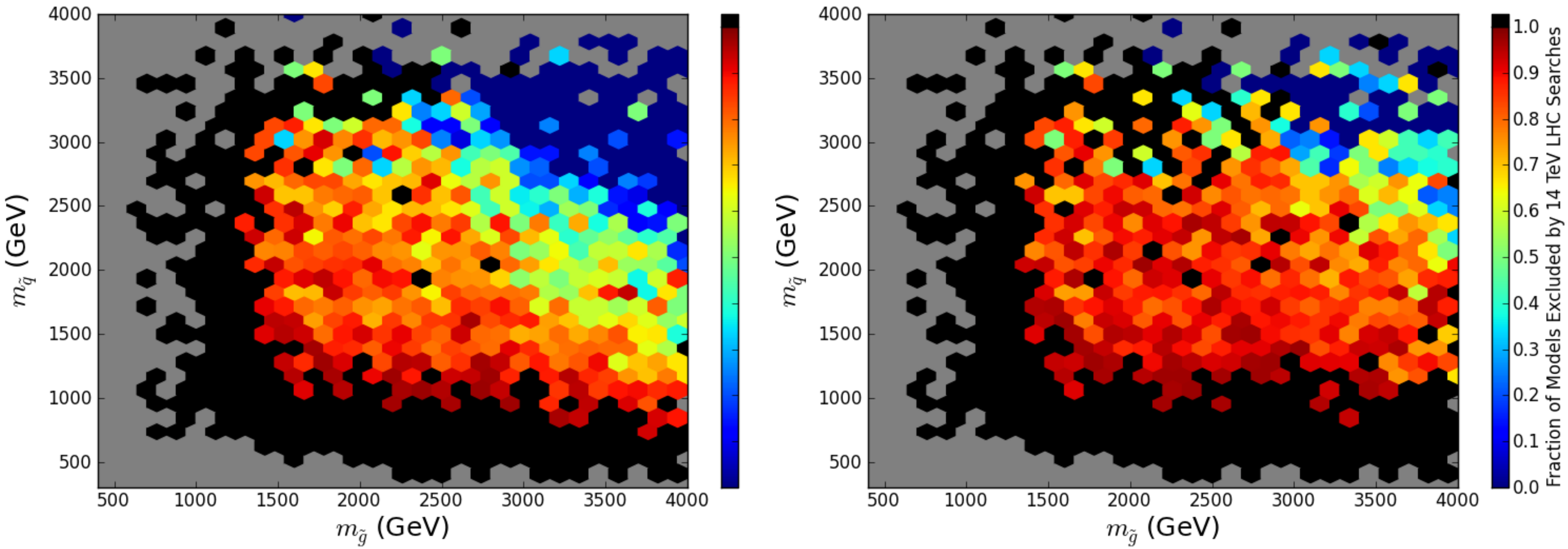
300 fb^{-1}

3000 fb^{-1}





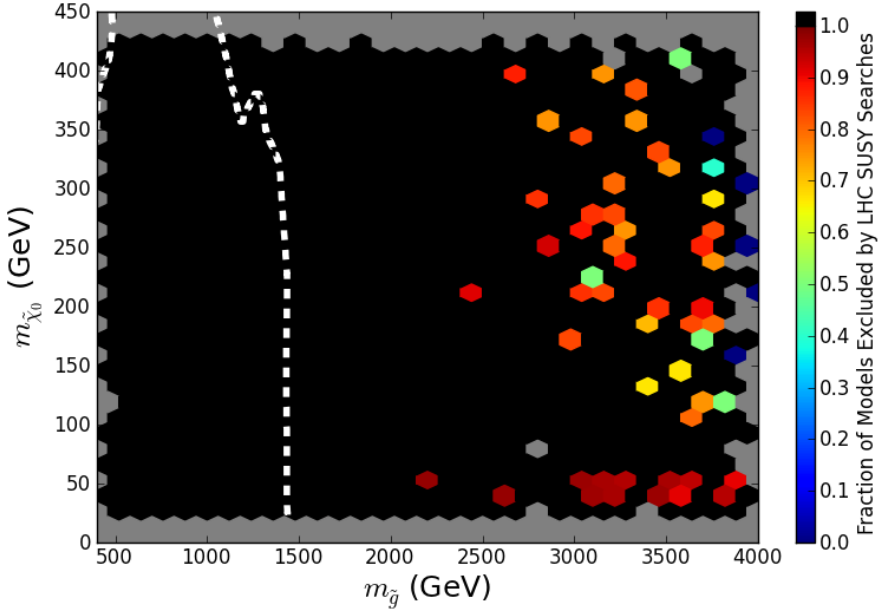
14 TeV Gravitino Set Results

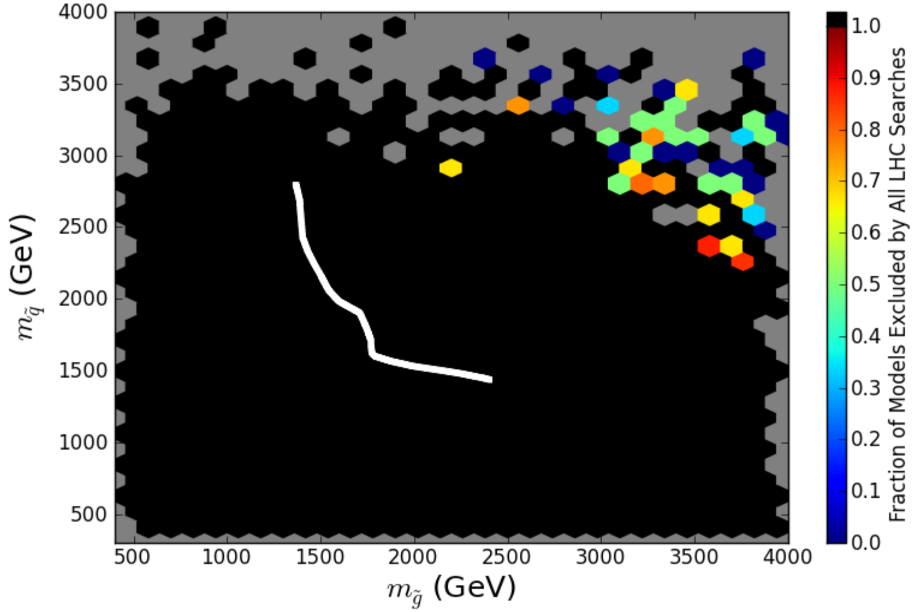


Being MET-based these 14 TeV searches are less powerful for the case of gravitino LSPs . The addition of searches for long-lived states would be very useful here.

14 TeV Results for the Low-FT Model Set

300 fb^{-1}





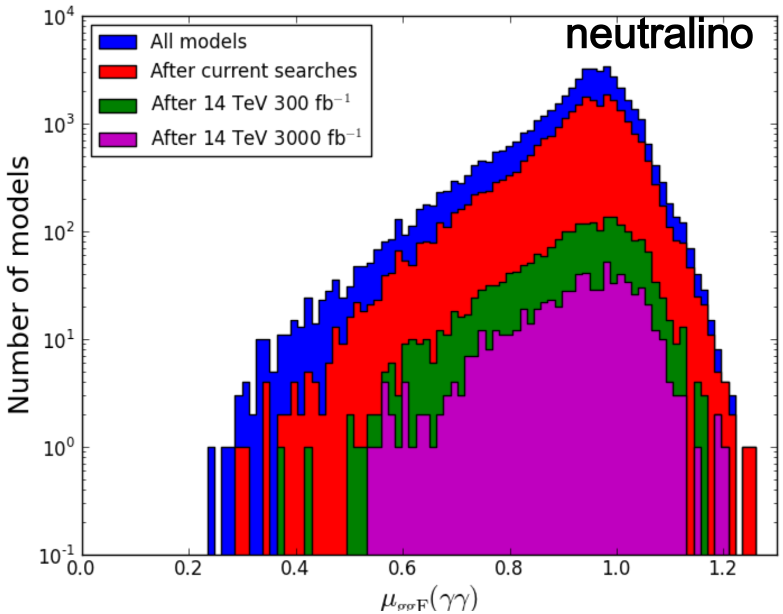
None of these models remain to be shown after the HL-LHC !

Precision Higgs Confronts the pMSSM

- Present measurements of the Higgs couplings do not stress the pMSSM models here…this will no longer be true in the future w/ LHC data @14 TeV & the ILC

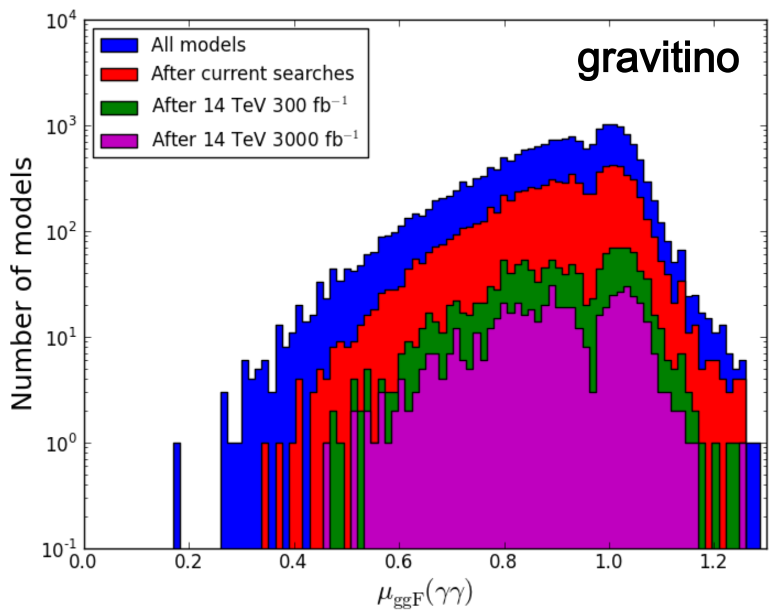
- We employ the LHC, HL-LHC, ILC500 & ILC lumi upgrade estimates of future constraints on the Higgs couplings as given in the Snowmass Higgs Working Group report, i.e., Dawson etal., 1310.8361

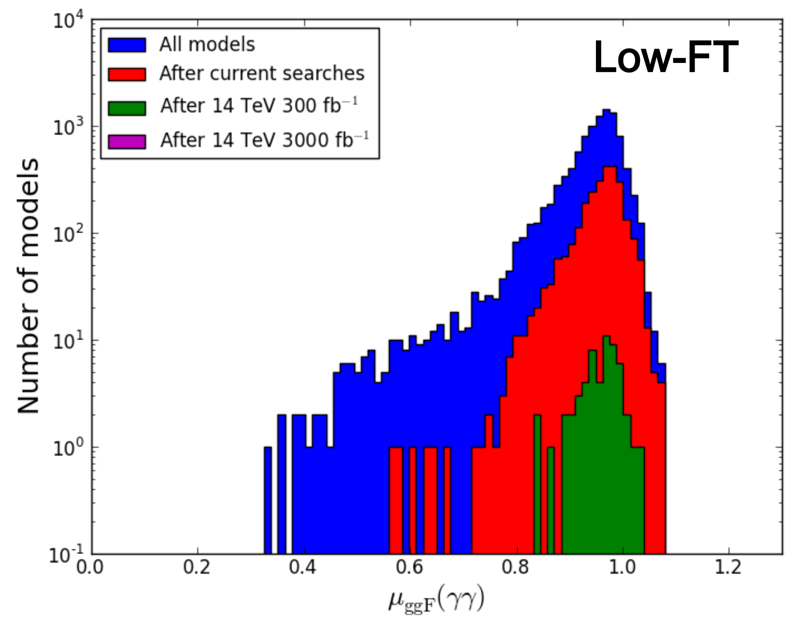
- We can then compare the constraints coming from bounds on the signal strength parameters, μ_i , as well as the ratios of squared couplings, r_i , to those from the SUSY searches for each model set (HDECAY5.11)

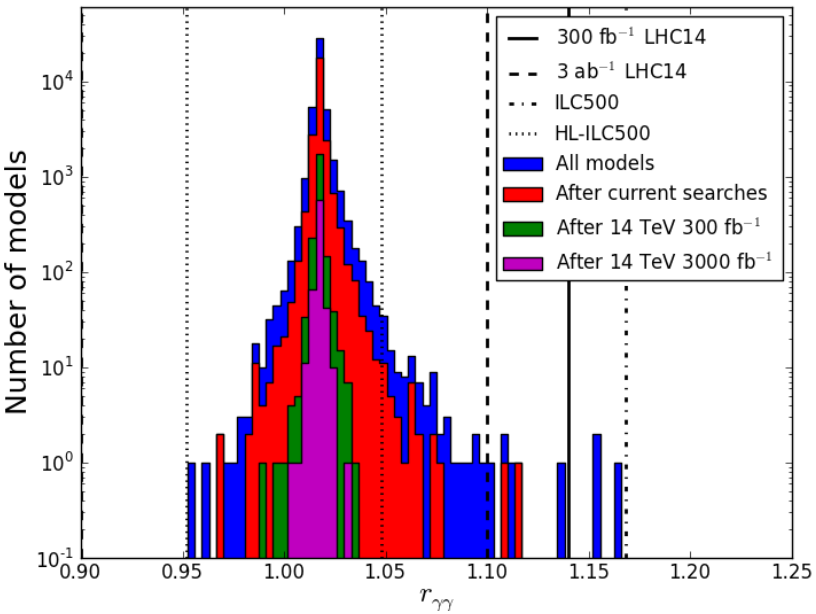


Example: these are the signal strength distributions for the di-photon final state produced in gg fusion.

LHC searches reduce statistics but do not change the shapes in a significant way

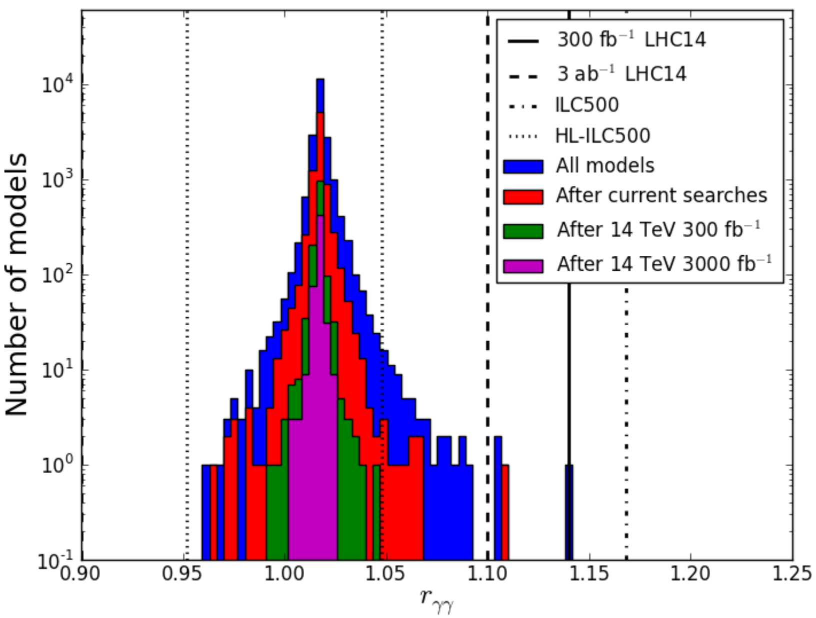


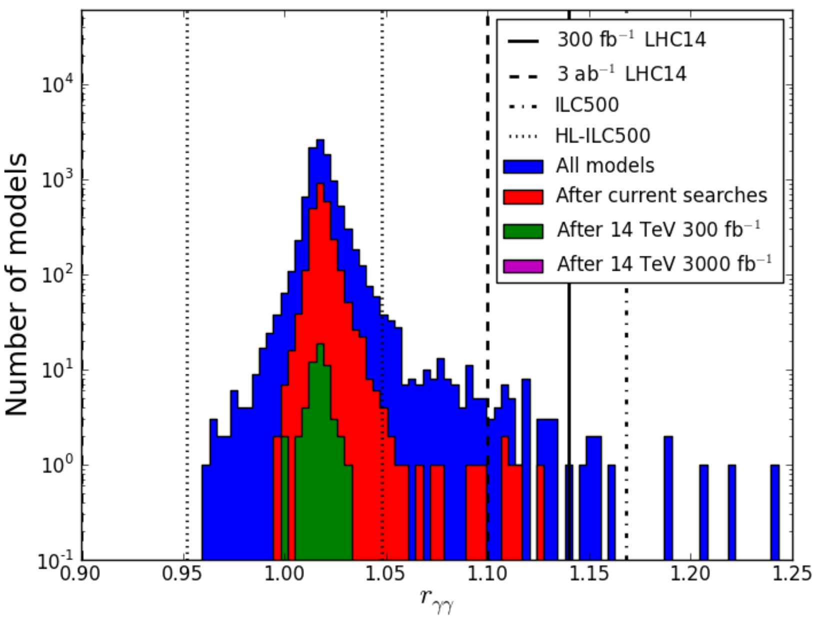


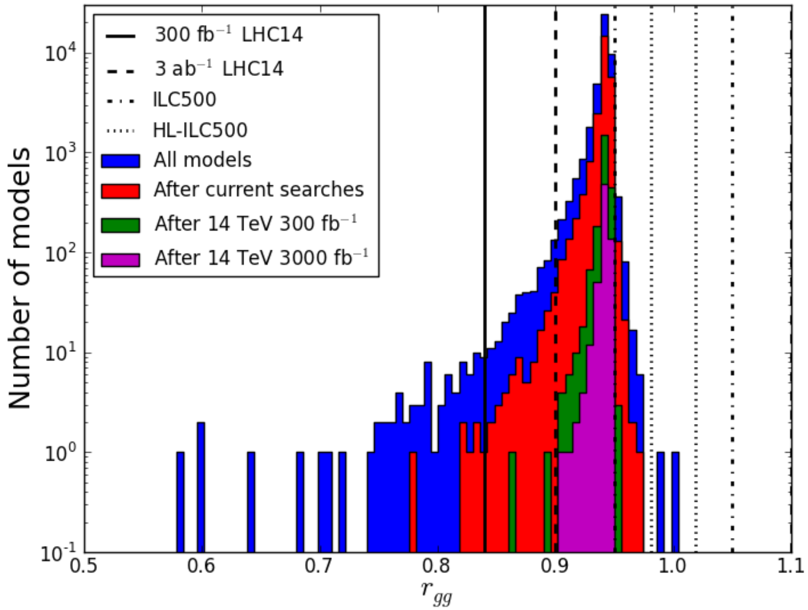


While neutralino & gravitino cases are very similar, the low-FT set is different (ie, wider) as it contains light stops & charginos that can contribute significantly in loops

Note the peak is slightly (~2%) above unity in all cases arising from the large stop mixing necessary to get a ~126 GeV Higgs mass

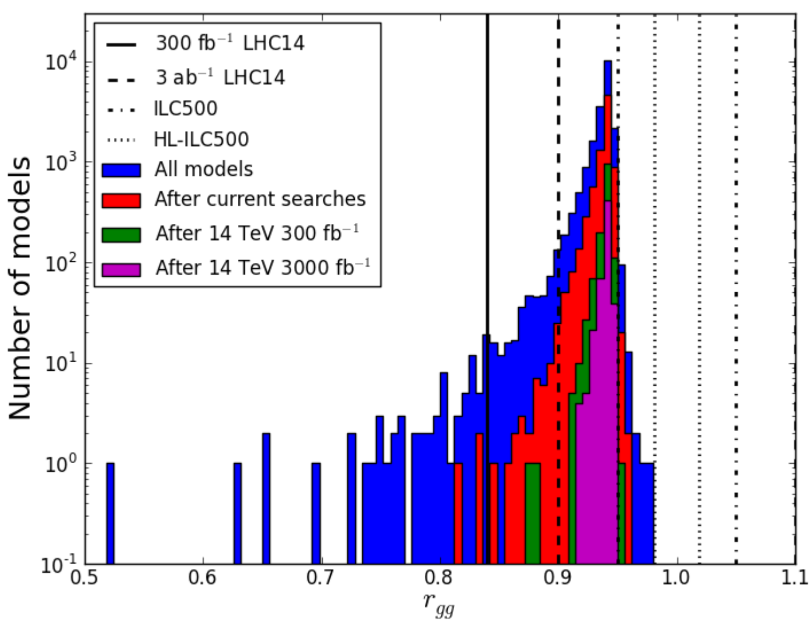


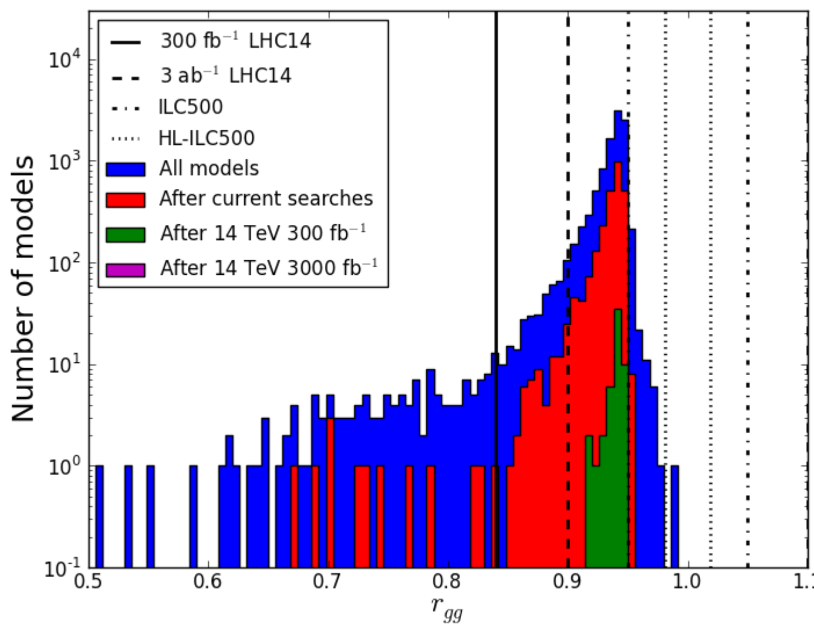


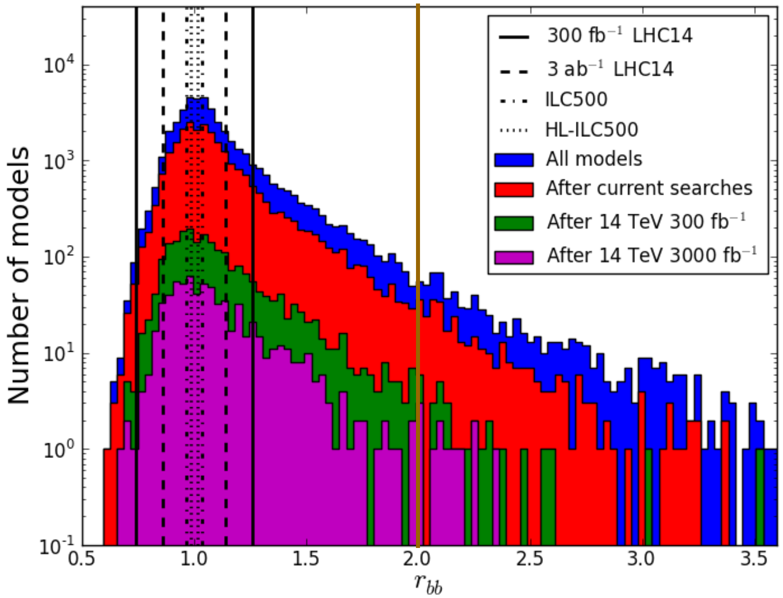


Note the peak here is somewhat below 1 in all cases arising from the large stop mixing necessary to get a ~126 GeV Higgs mass. Again the low-FT set is somewhat different.

The suppression here is ~3x larger than the correlated enhancement for the γγ final state.



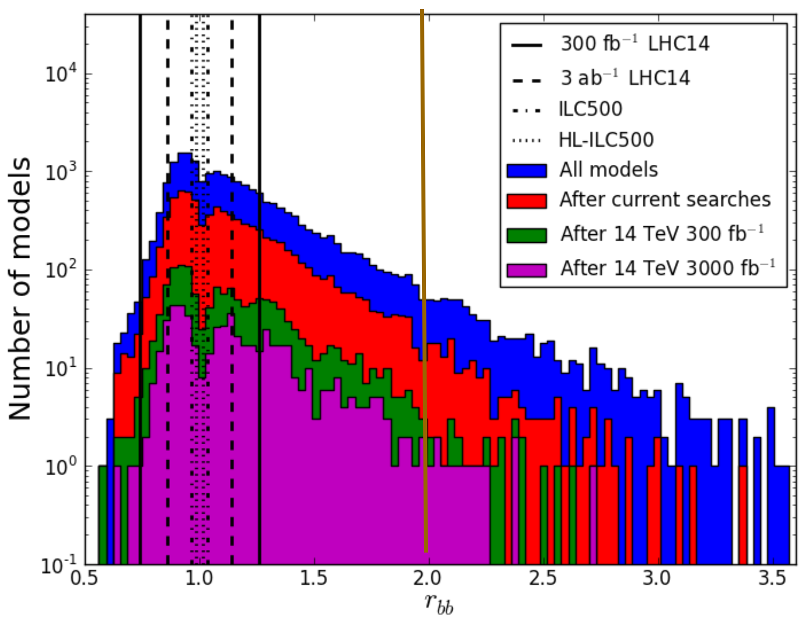


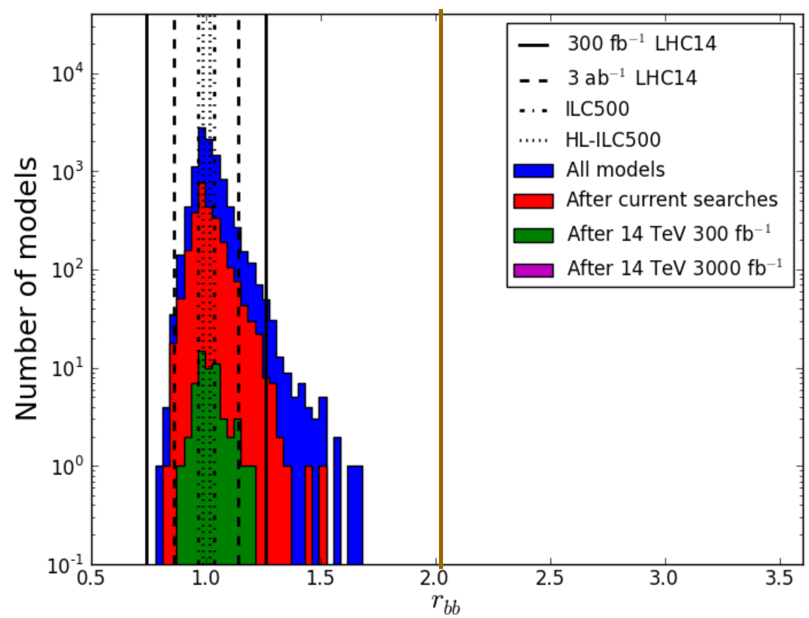


Large non-decoupling effects can appear in the bottom coupling mostly from, e.g., sbottom-gluino loops with large sbottom mixing even when all sparticle masses are large.

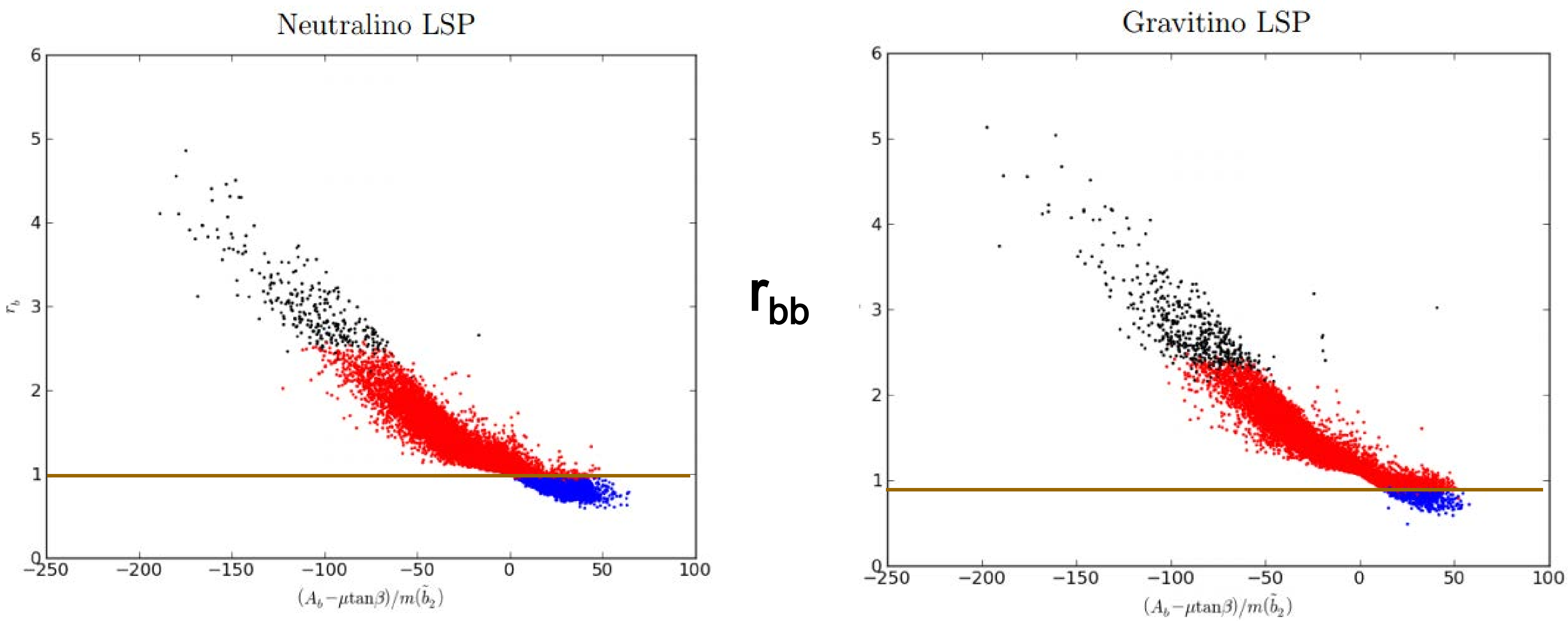
Enhancement or suppression is correlated with the sign of this mixing

μ is small in the low-FT set to the effect is reduced

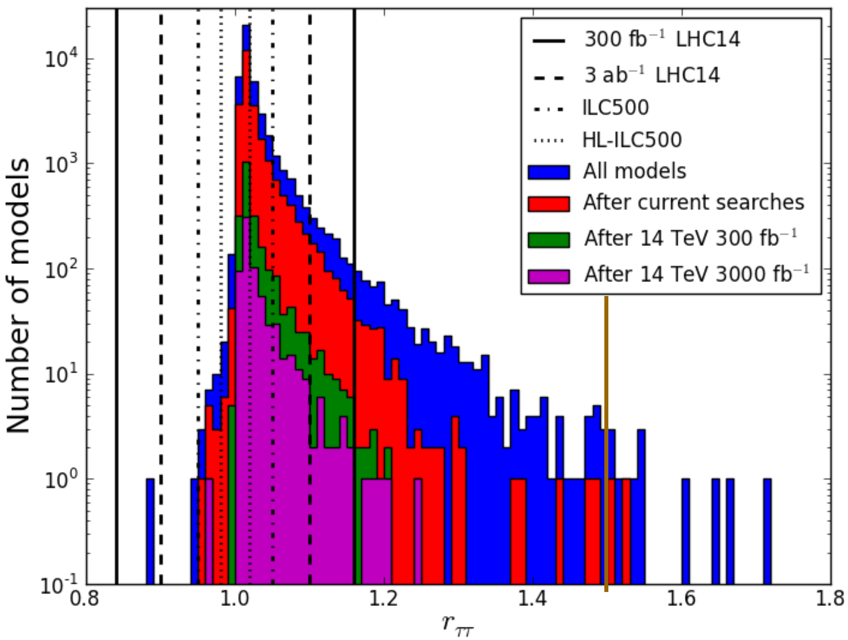




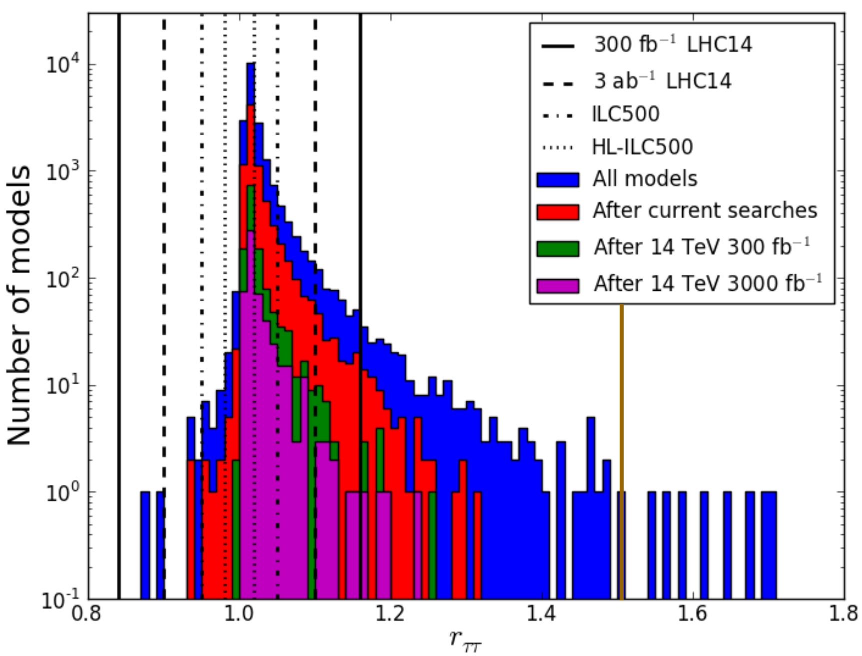
Sizeable modifications in the bottom couplings are directly correlated with large sbottom mixing & its sign. This effect is much less in the low-FT set as there $|\mu|$ must be small.

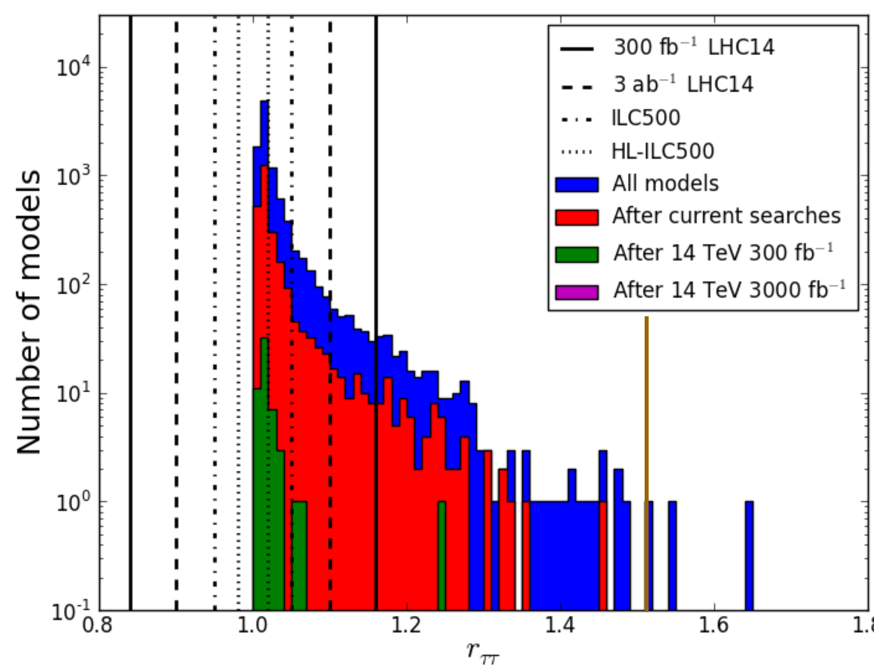


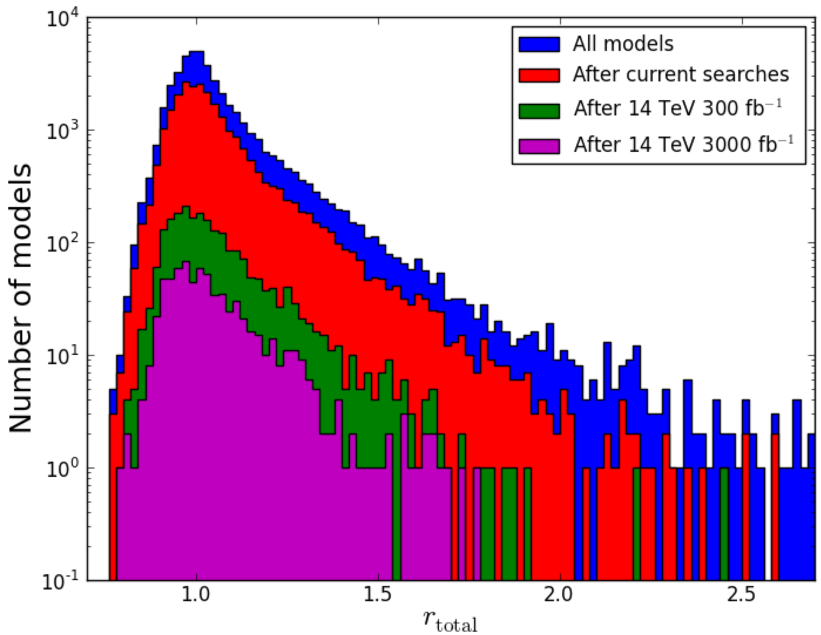
$(A_b - \mu \tan\beta) / m_{b2}$



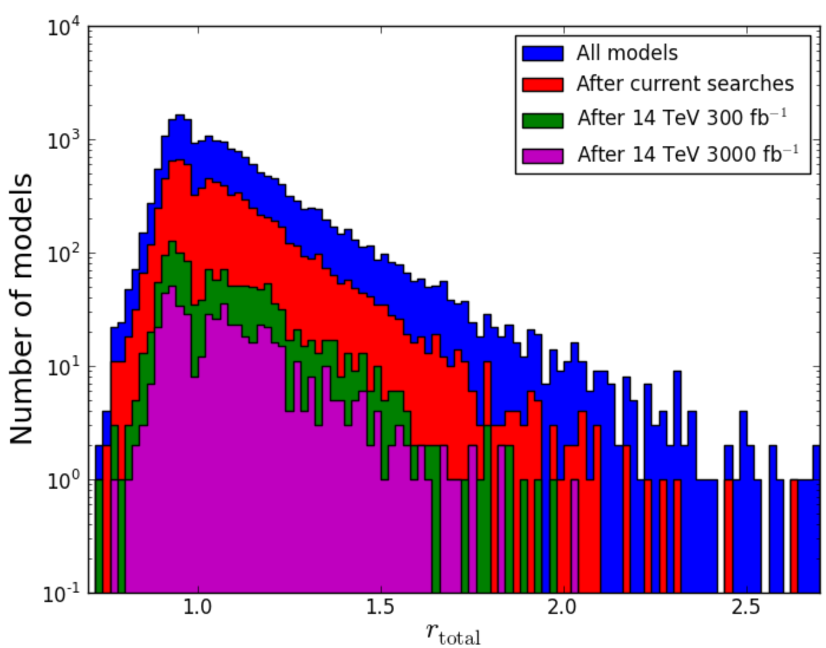
Similar non-decoupling effects due to stau mixing can also influence Higgs to τ couplings but to a somewhat lesser extent since now they can only go through EWK gaugino loops

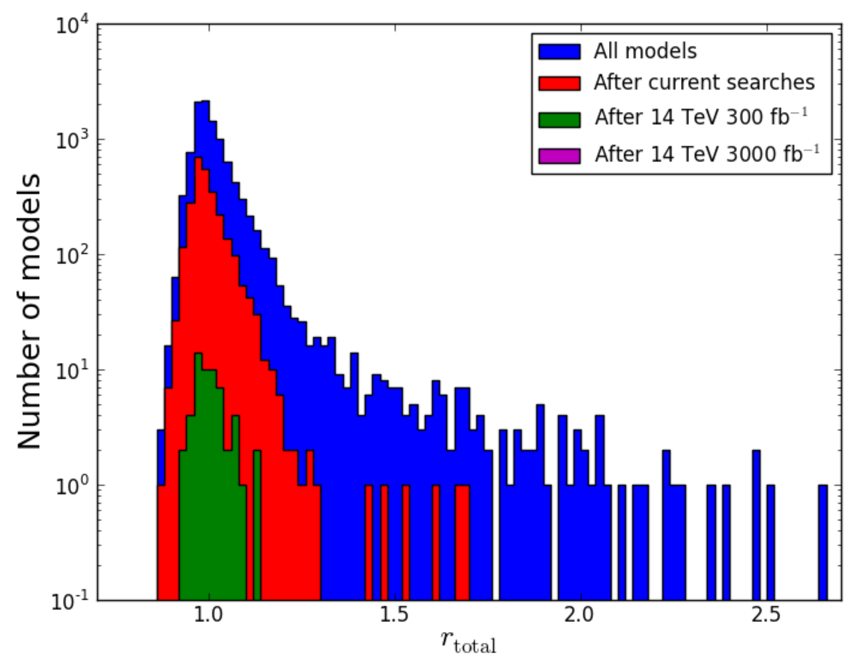


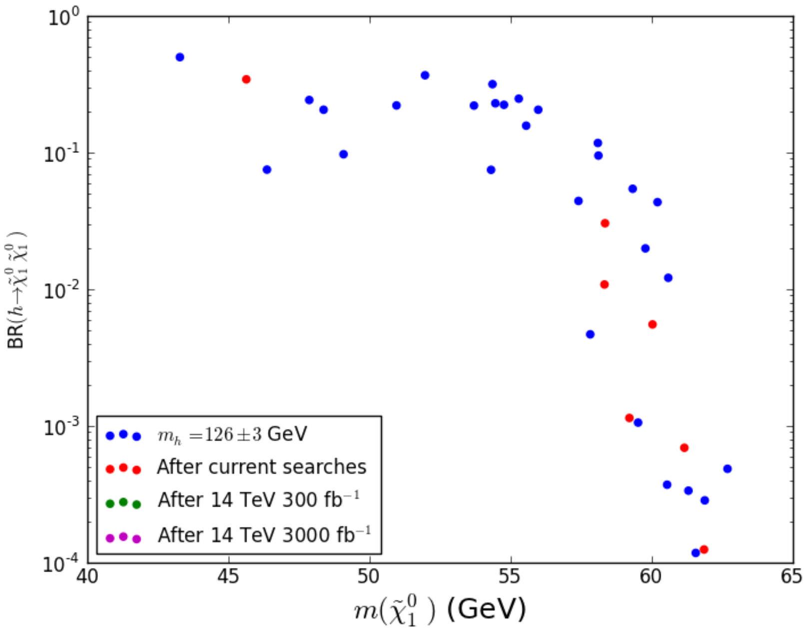




Since $\Gamma(h \to bb)$ is the largest partial width, a significant modification there can have a sizeable impact on the Higgs total width … but we are still safely under the new CMS upper bound < 4.2.



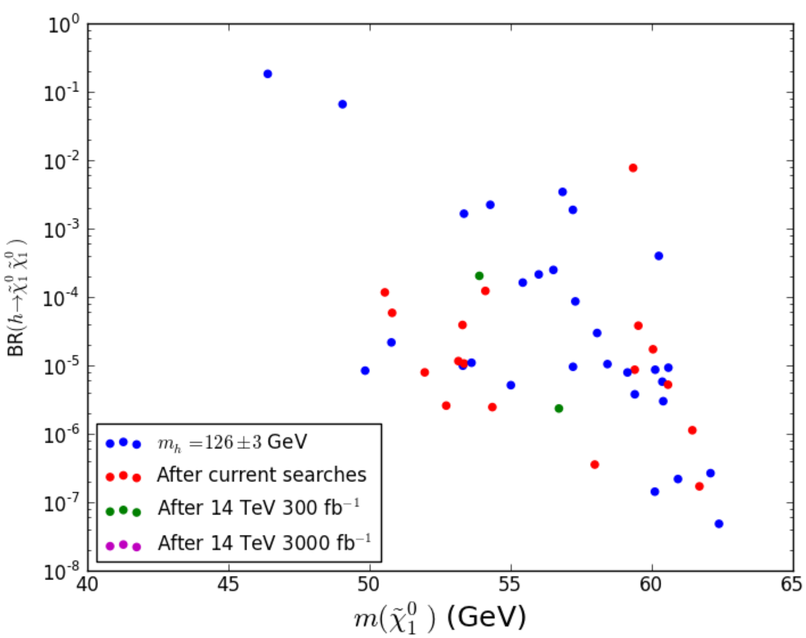


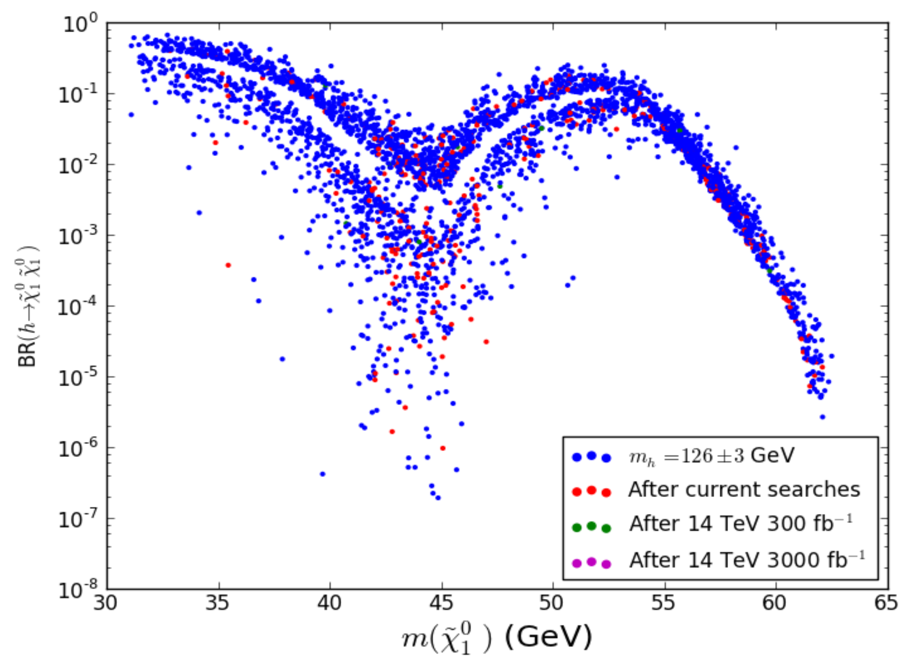


The invisible final state occurs through decays to neutralinos that are either stable (in neutralino LSP models) or long-lived (in gravitino models).

The low-FT set has many bino-Higgsino models with light LSPs to get the relic density right, leading to significant BFs (note sign μ sensitive !)

None of these are excluded as B < 0.5



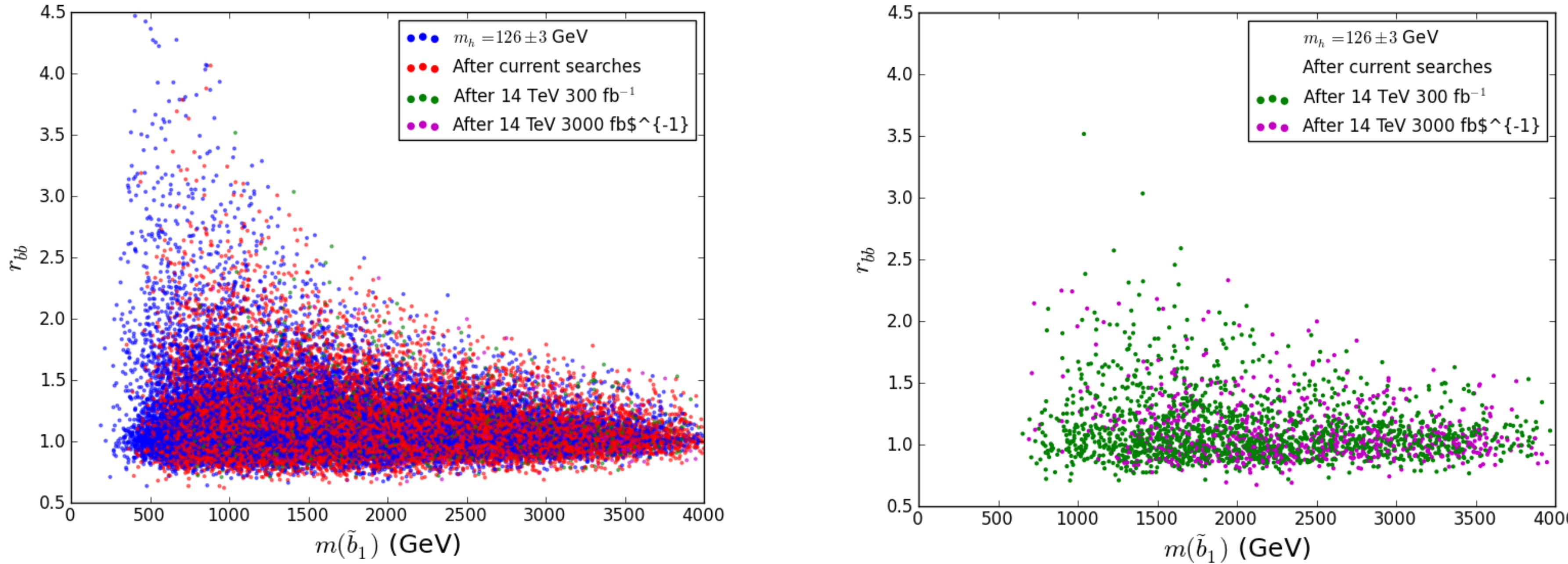


Will, e.g., measurements of r_{bb} near ~1 impose any constraint on the lightest sbottom mass ??

Not really…but large ratio values will require relatively light sbottoms so that null searches might narrow the expected range for r_{bb} . But note (see below) values >2 are still possible after the HL-LHC.

Similar results are found to hold for the gravitino LSP set

Neutralino Model set



- Clearly measurements of the various Higgs couplings will put significant constraints on the pMSSM…. But how much?

- No matter where the measured r_i central values end up, if their errors are small a large fraction of models will be excluded

- HOWEVER, the number of models & their identities WILL depend on what these values are..

- To proceed further we have to make some assumption about this. We will assume, for purposes of demonstration, that the r_i end up at their SM values in all future measurements

- Other (randomly chosen?) values are possible & interesting but are more difficult to justify

What do we find comparing the direct SUSY searches with the Higgs coupling measurements ?

Out of the presently surviving models, what fractions will the Higgs measurements be sensitive to assuming SM central values ?

Channel	300 fb^{-1} LHC	3 ab^{-1} LHC	500 GeV ILC	HL 500 GeV ILC
bb	16.6 (27.7, 0.5)	33.4 (48.5, 5.5)	78.4 (88.8, 49.1)	91.1 (95.8, 77.3)
$\tau\tau$	0.7 (0.8, 2.9)	3.1 (2.7, 5.7)	11.5 (9.9, 11.9)	36.9 (34.2, 32.9)
gg	0.02 (0.04, 0.5)	0.5 (0.6, 3.1)	99.4 (99.7, 99.7)	100.0 (100.0, 100.0)
$\gamma\gamma$	0.02 (0.07, 0)	0.02 (0.09, 0.2)	0.02 (0.07, 0)	0.1 (0.2, 0.6)
Invisible	0 (0, 0)	0 (0, 0)	0.01 (0.01, 6.2)	0.02 (0.01, 7.5)
All	17.1 (28.2, 3.8)	34.9 (49.6, 11.1)	99.8 (99.96, 99.92)	100.0 (100.0, 100.0)

Table 4: The fraction in percent of neutralino (gravitino, low-FT) models with the correct Higgs mass remaining after the current 7 and 8 TeV LHC searches that are expected to be excluded by future Higgs coupling measurements, *assuming* that the SM values for these couplings are obtained.

… and after the 300 fb^{-1} SUSY searches ?

Channel	300 fb^{-1} LHC	3 ab^{-1} LHC	500 GeV ILC	HL 500 GeV ILC
bb	20.5 (31.7, 0)	39.1 (53.0, 5.4)	82.6 (92.6, 46.4)	93.1 (97.5, 75.0)
$\tau\tau$	0.5 (0.7, 1.8)	3.3 (2.3, 1.8)	12.9 (9.9, 5.4)	38.9 (32.6, 23.2)
gg	0 (0, 0)	0.09 (0.1, 0)	99.9 (99.93, 100.0)	100.0 (100.0, 100.0)
$\gamma\gamma$	0 (0, 0)	0 (0, 0)	0 (0, 0)	0 (0, 0)
Invisible	0 (0, 0)	0 (0, 0)	0 (0, 10.7)	0 (0, 16.1)
All	20.8 (31.9, 1.8)	40.6 (53.7, 5.4)	99.91 (100.0, 100.0)	100.0 (100.0, 100.0)

Table 5: Same as Table 4 above but now for the subset of models expected to remain after the ATLAS 14 TeV 0l jets + MET and 0l and 1l stop searches with 300 fb^{-1} of data.

Why are some couplings more restrictive than others ???

- hbb covers a very wide range so that any precision measurement is likely to exclude many models & thus it is the strongest at the LHC independently of its measured value. The high precision possible at the ILC makes it quite powerful there as well

- hgg is particularly sensitive to the stop mixing required to get the ~126 GeV Higgs mass & is always below the SM value. Thus a measurement yielding the SM value with small errors, as is possible at the ILC, will kill almost everything! Of course if r_{gg} was 0.97 with the same error this measurement at the ILC would only exclude 2.7% of the neutralino models

- $h\tau\tau$ is also helpful but clearly plays a secondary role

… and after the 3 ab^{-1} SUSY searches ?

Channel	300 fb^{-1} LHC	3 ab^{-1} LHC	500 GeV ILC	HL 500 GeV ILC
$b\bar{b}$	19.6 (32.6, —)	38.4 (54.5, —)	82.9 (94.9, —)	93.4 (98.4, —)
$\tau\tau$	0.7 (0.7, —)	3.3 (2.5, —)	14.7 (10.7, —)	41.6 (35.3, —)
gg	0 (0,—)	0 (0, —)	100.0 (100.0, —)	100.0 (100.0, —)
$\gamma\gamma$	0 (0, —)	0 (0, —)	0 (0, —)	0 (0, —)
Invisible	0 (0, —)	0 (0, —)	0 (0, —)	0 (0, —)
All	29.9 (32.8, —)	39.3 (55.4, —)	100.0 (100.0, —)	100.0 (100.0, —)

Table 6: Same as Table 4 above but now for the subset of models expected to remain after the ATLAS 0l jets + MET and 0l and 1l stop searches with 3 ab^{-1} of data. The entries for the low-FT set in this table are blank because no models survive the 3 ab^{-1} LHC searches.

Here we see that the Higgs coupling measurements are very powerful in terms of parameter space coverage & will even exclude/discover some models to which the HL-LHC will not have access

Summary & Conclusions

- Higgs coupling measurements provide an ‘orthogonal’ set of constraints on the SUSY parameter space in comparison to direct searches.
- Direct (null) SUSY searches have qualitatively little influence over the possible ranges of Higgs couplings
- However, constraints on Higgs couplings can exclude or discover models that are not accessible to the HL-LHC
- The identity of the excluded models will depend on where the measurements end up but are particularly powerful for the SM case
- Hopefully a discovery will happen soon after LHC14 turn-on !

BACKUPS

Low Fine-tuning in the pMSSM ?

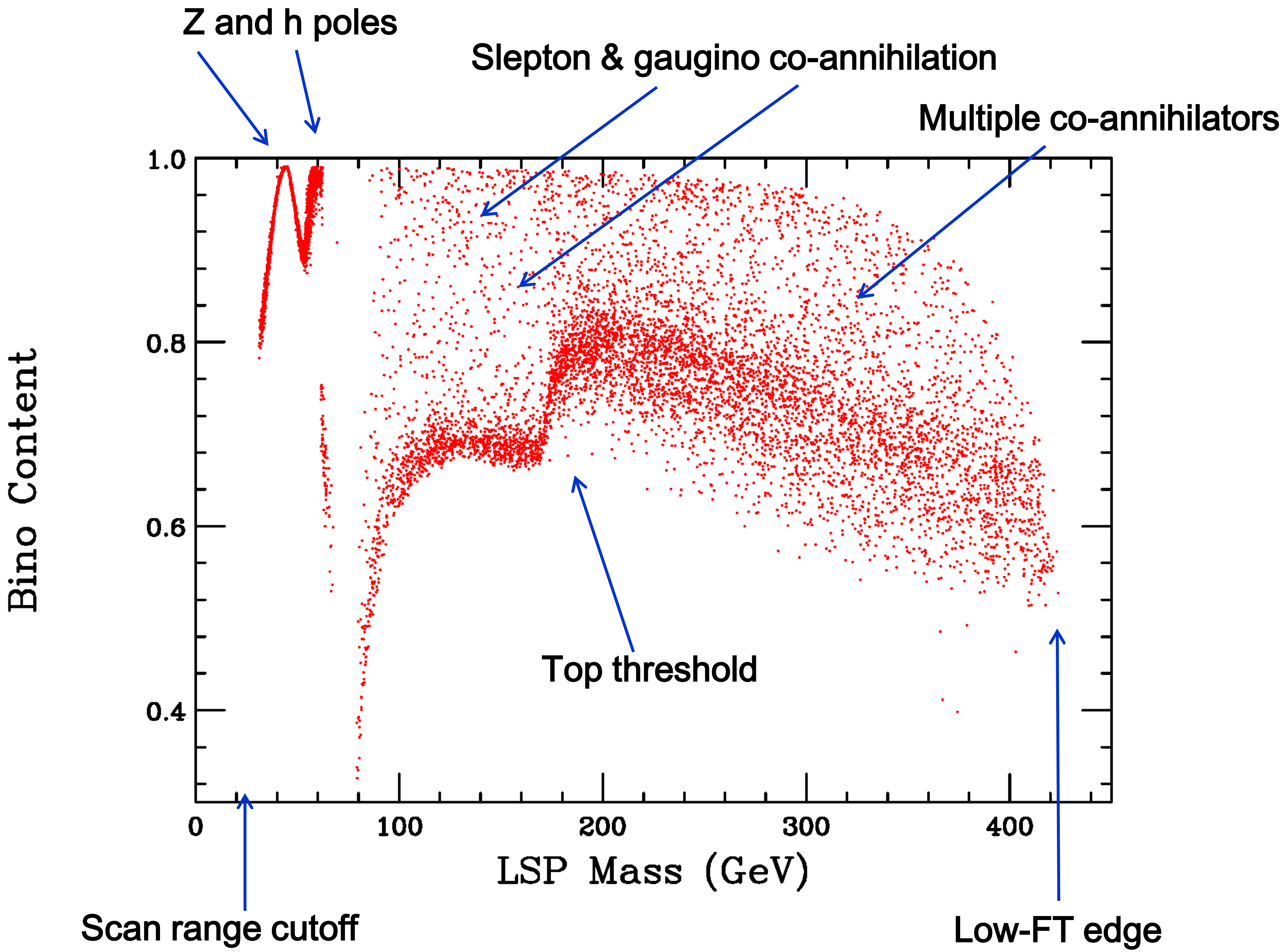
- m_h ~ 126 GeV in the MSSM requires large stop masses and/or mixings which then $\rightarrow$ significant FT expected

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

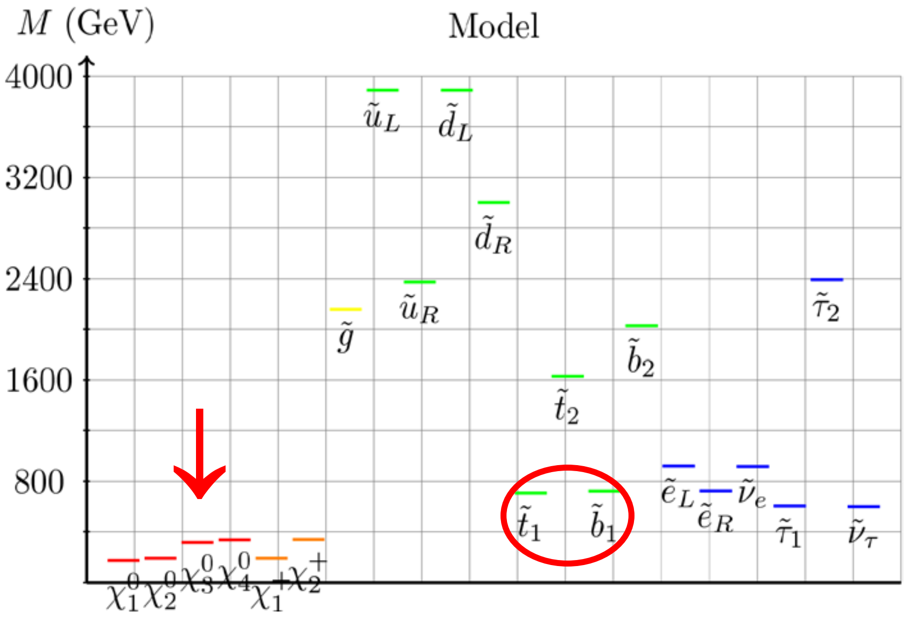
- To quantify FT we ask how the value of M_Z depends upon any of the 19 parameters , { p_i }, up to (in some cases) the 2-loop, NLL level (c/o Martin & Vaughn). We follow the traditional FT analysis of Ellis et.al. & Barbieri & Giudice :

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

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



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

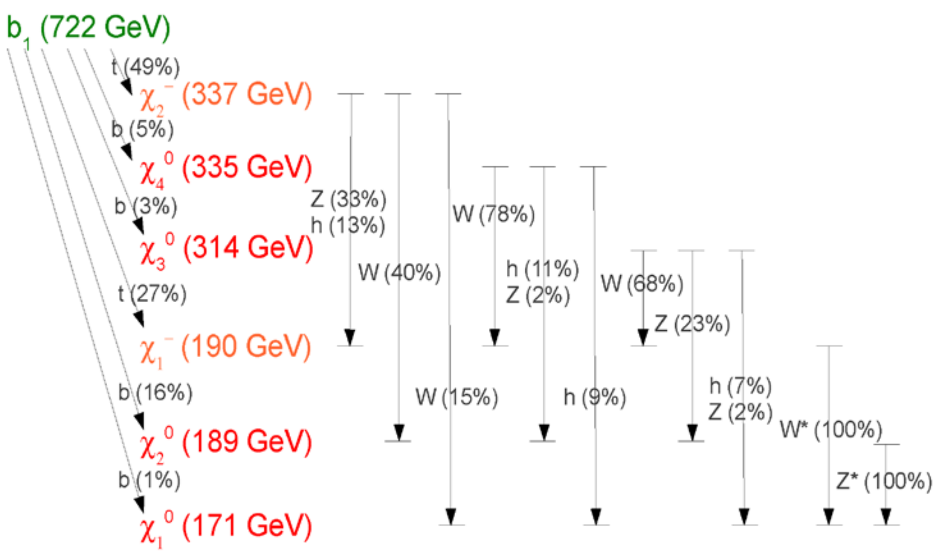


The necessity of both a light bino to get the right relic density & a light Higgsino for low-FT forces the stop decays to be quite complex !

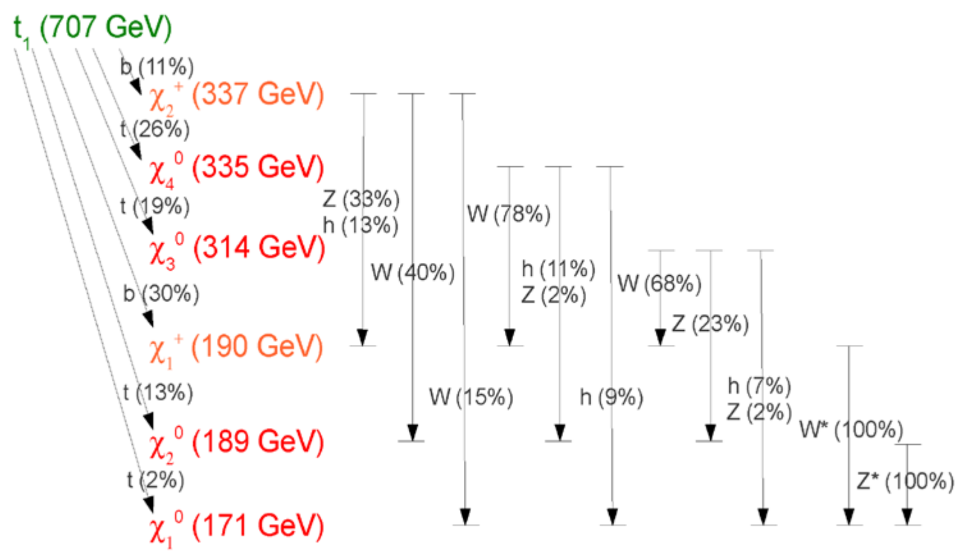
~ 60% of models also have winos below the stop/sbottom → leptons!

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

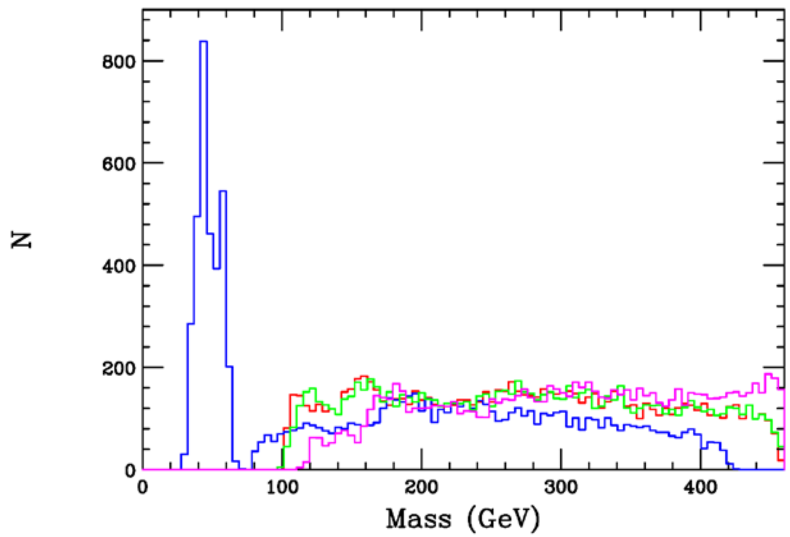
Model 3010059

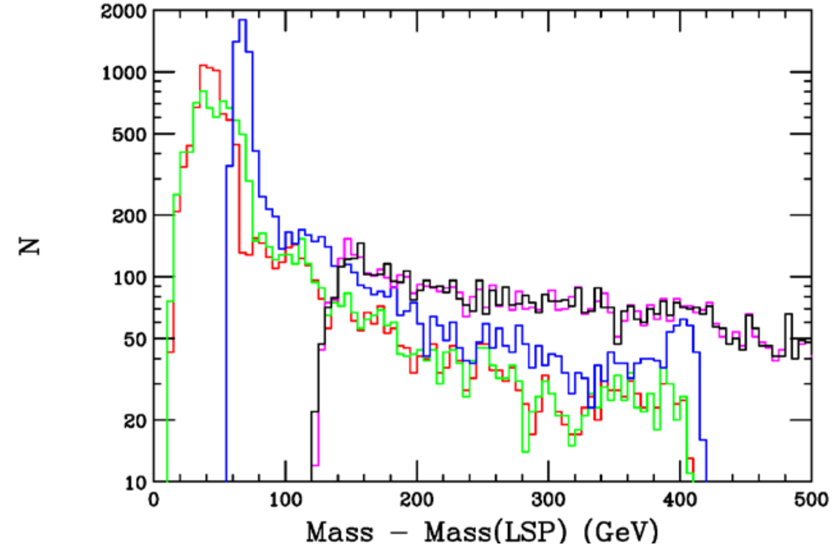


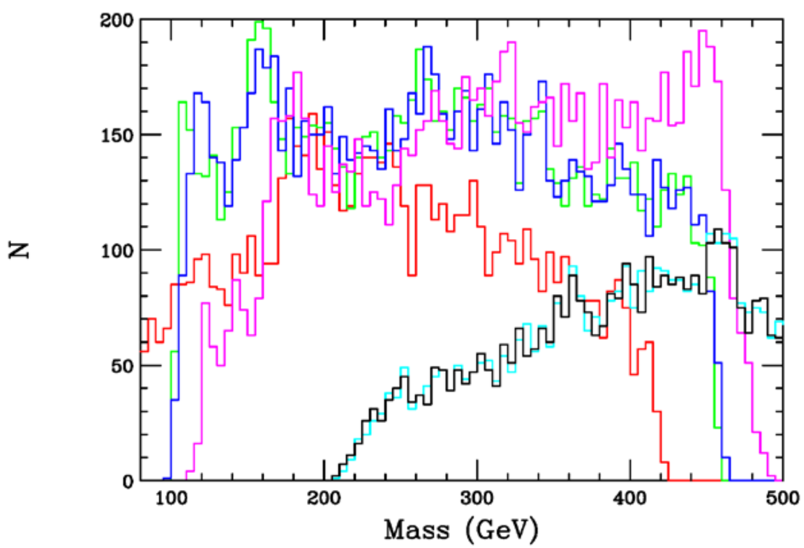
Model 3010059

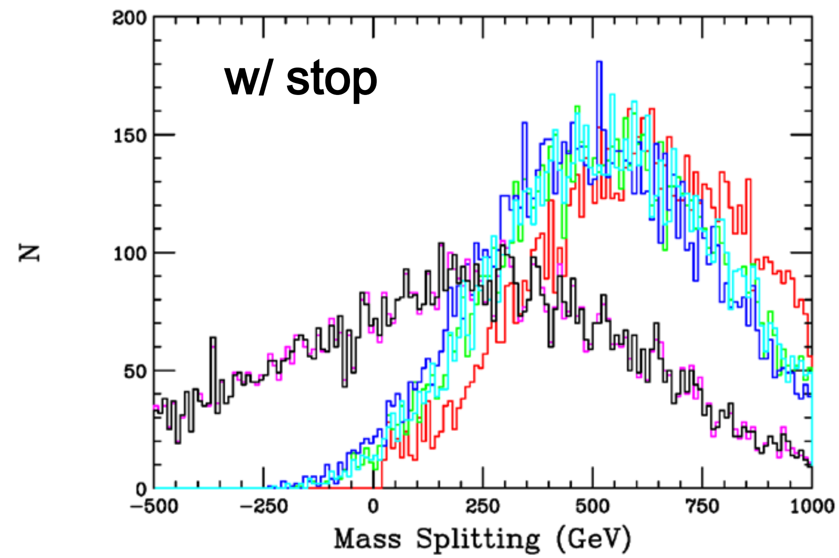


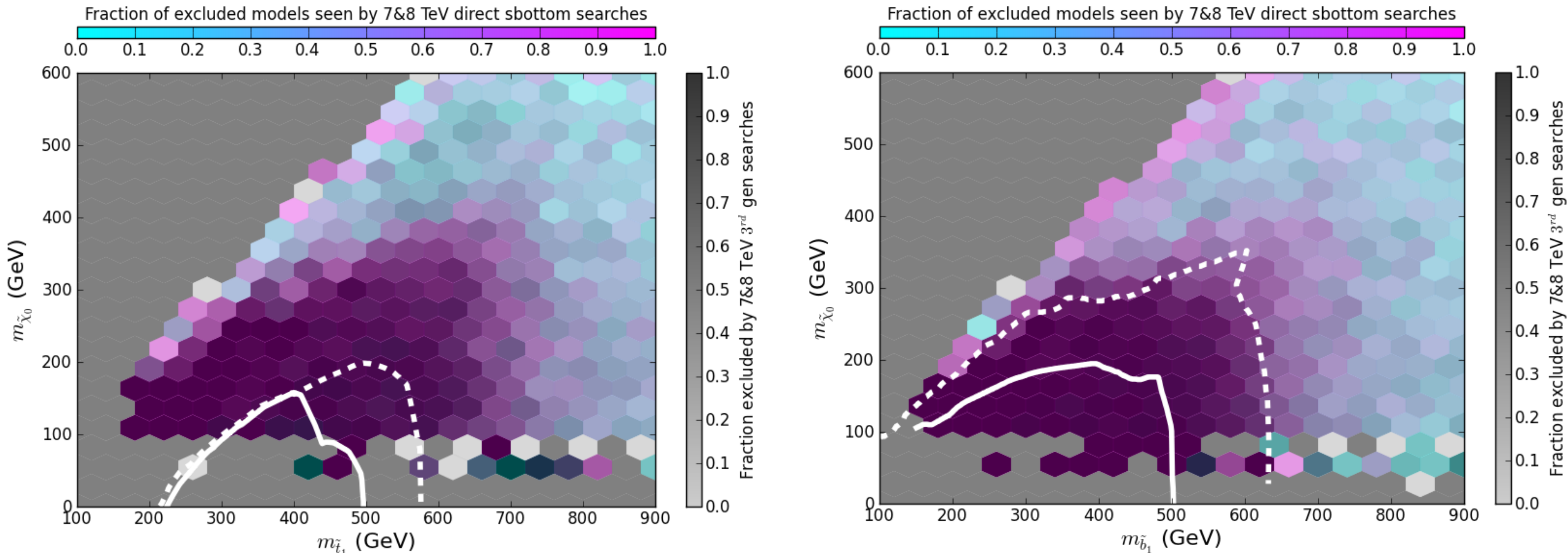
Low-FT Model Gaugino Mass Spectra & Splittings



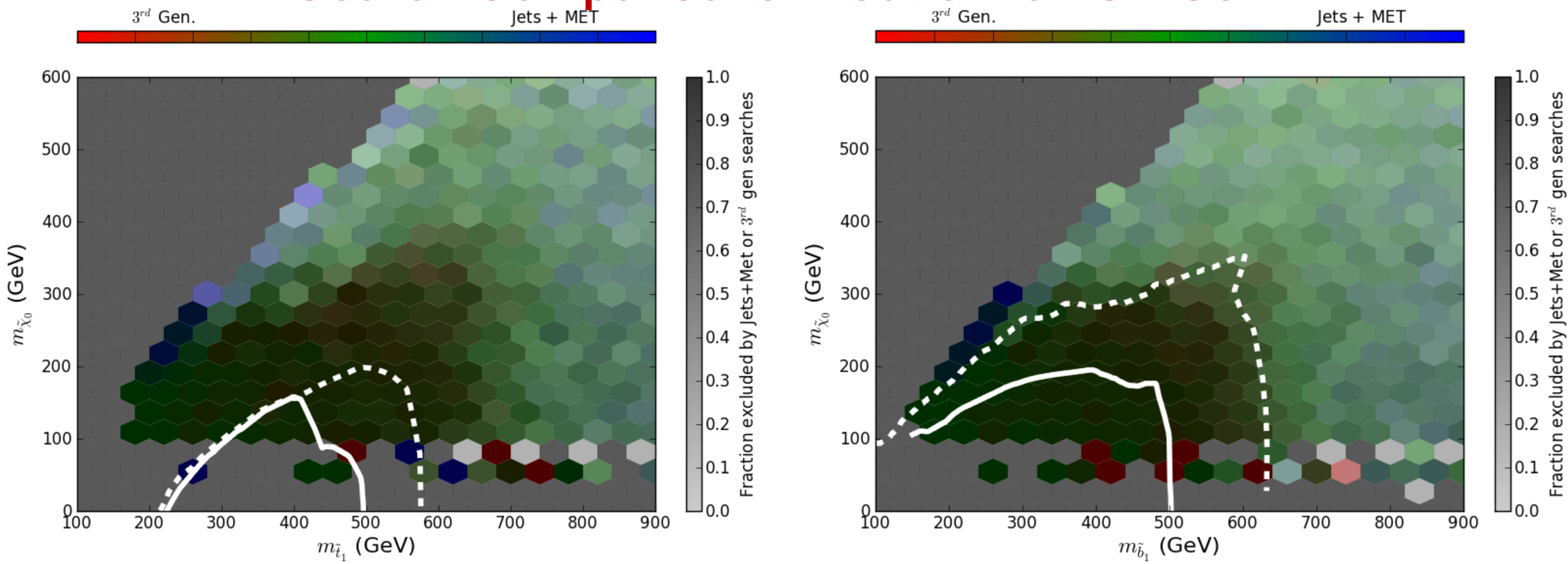


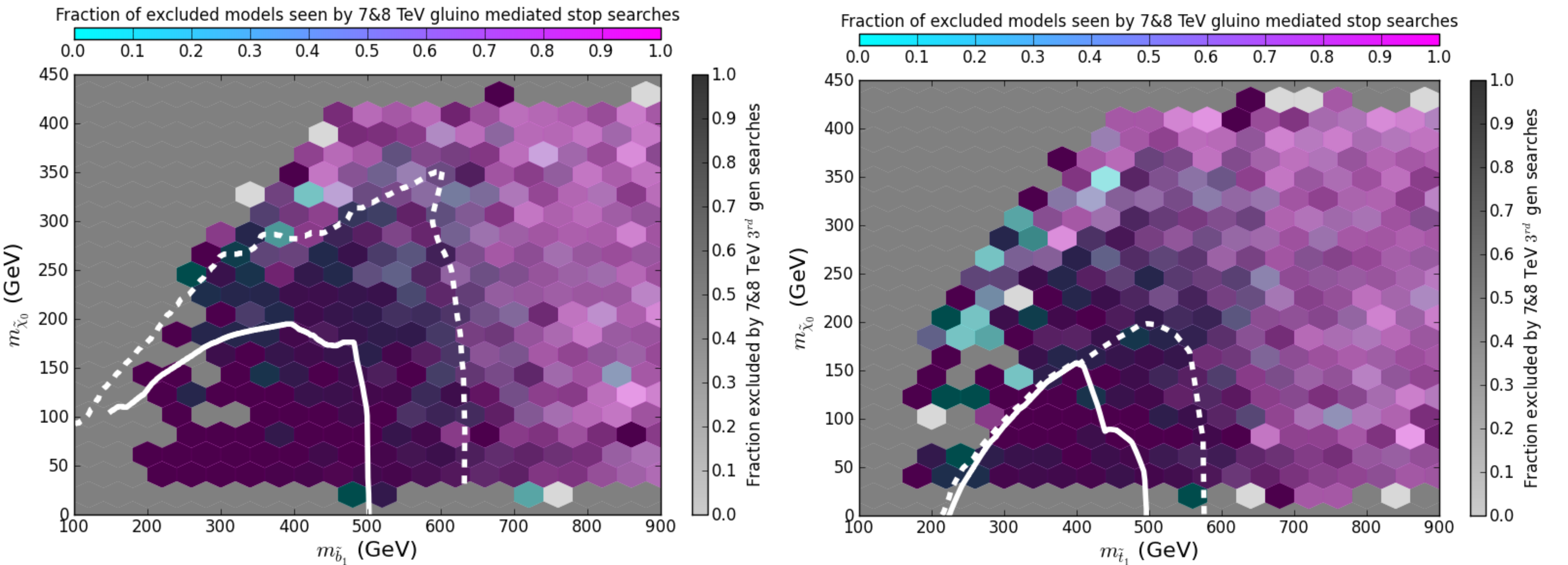




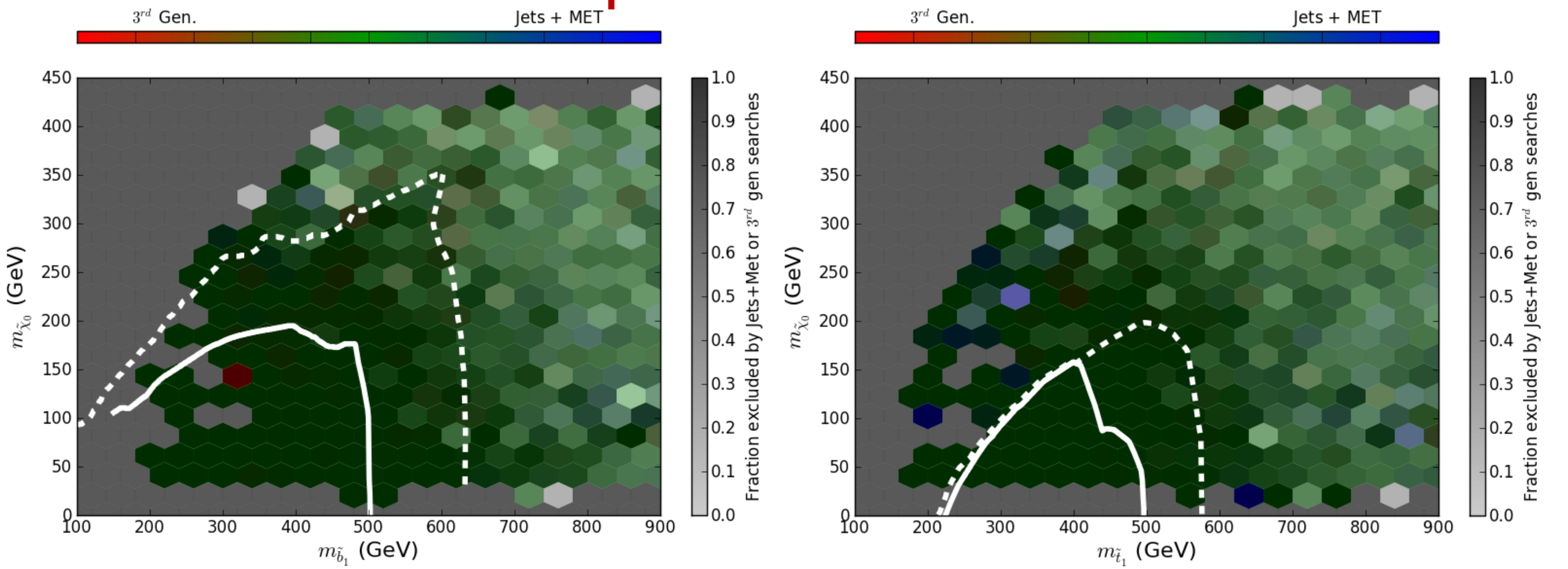


Search Comparisons: Neutralino LSP Set

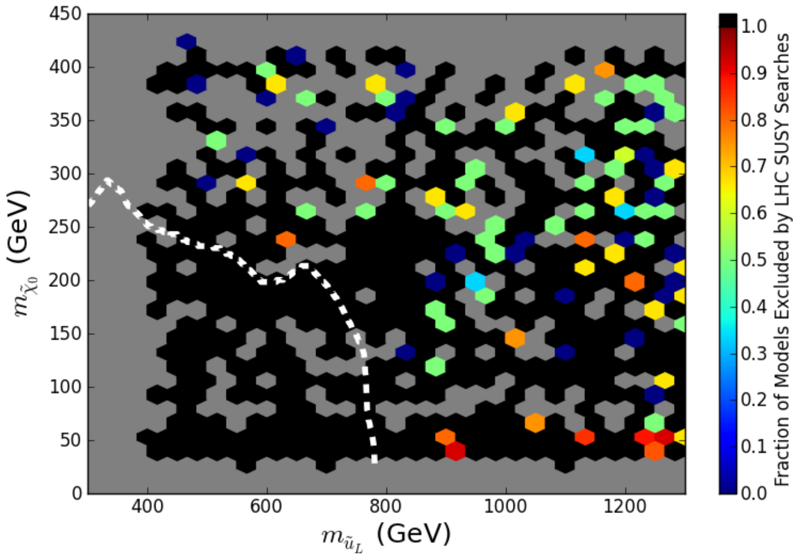


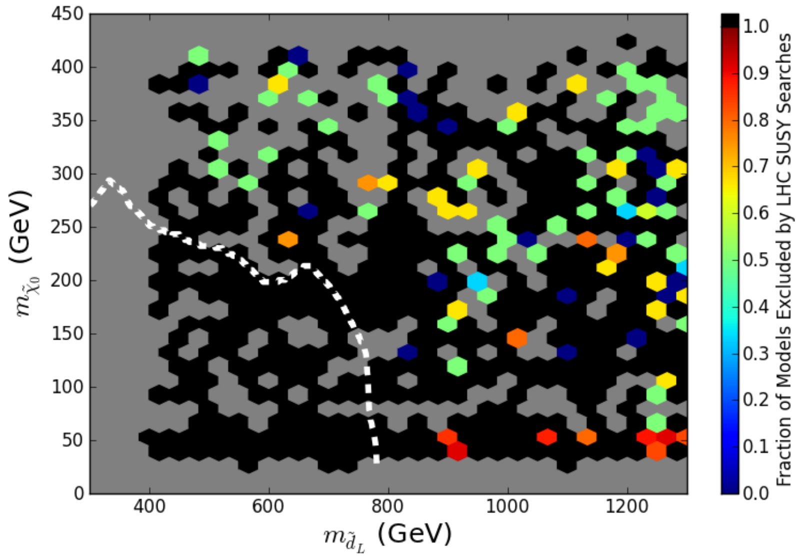


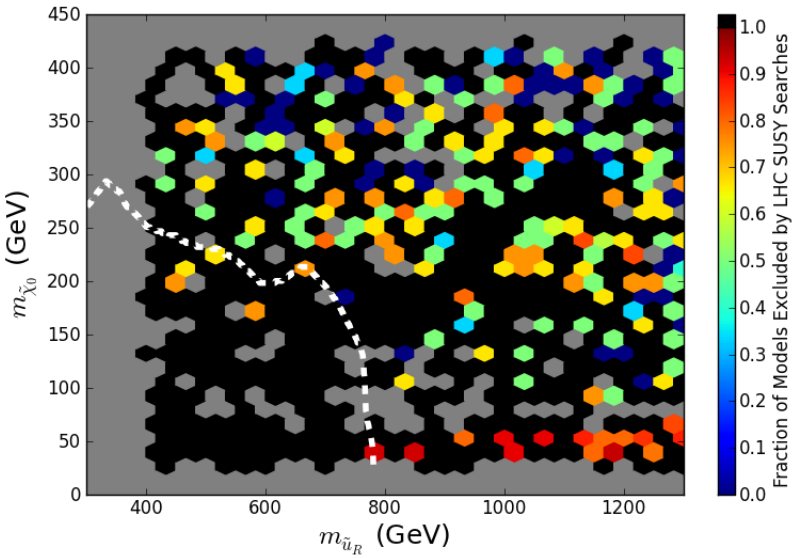
Search Comparisons: Low-FT Set

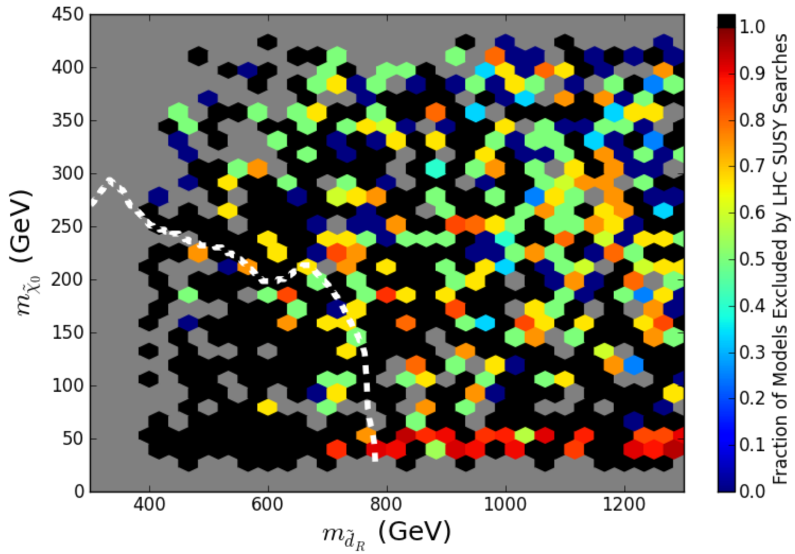


Low-FT Light Squark Results

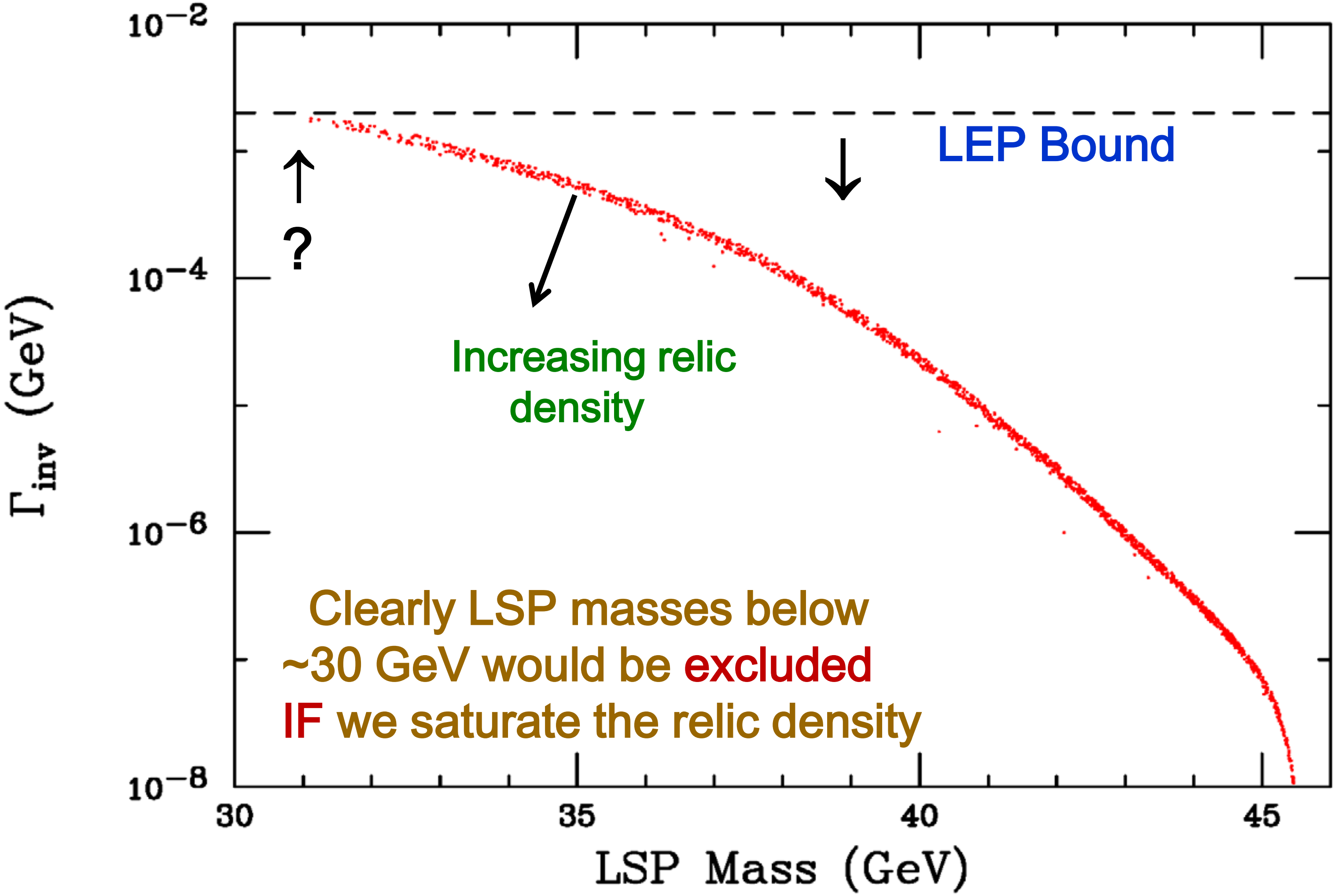






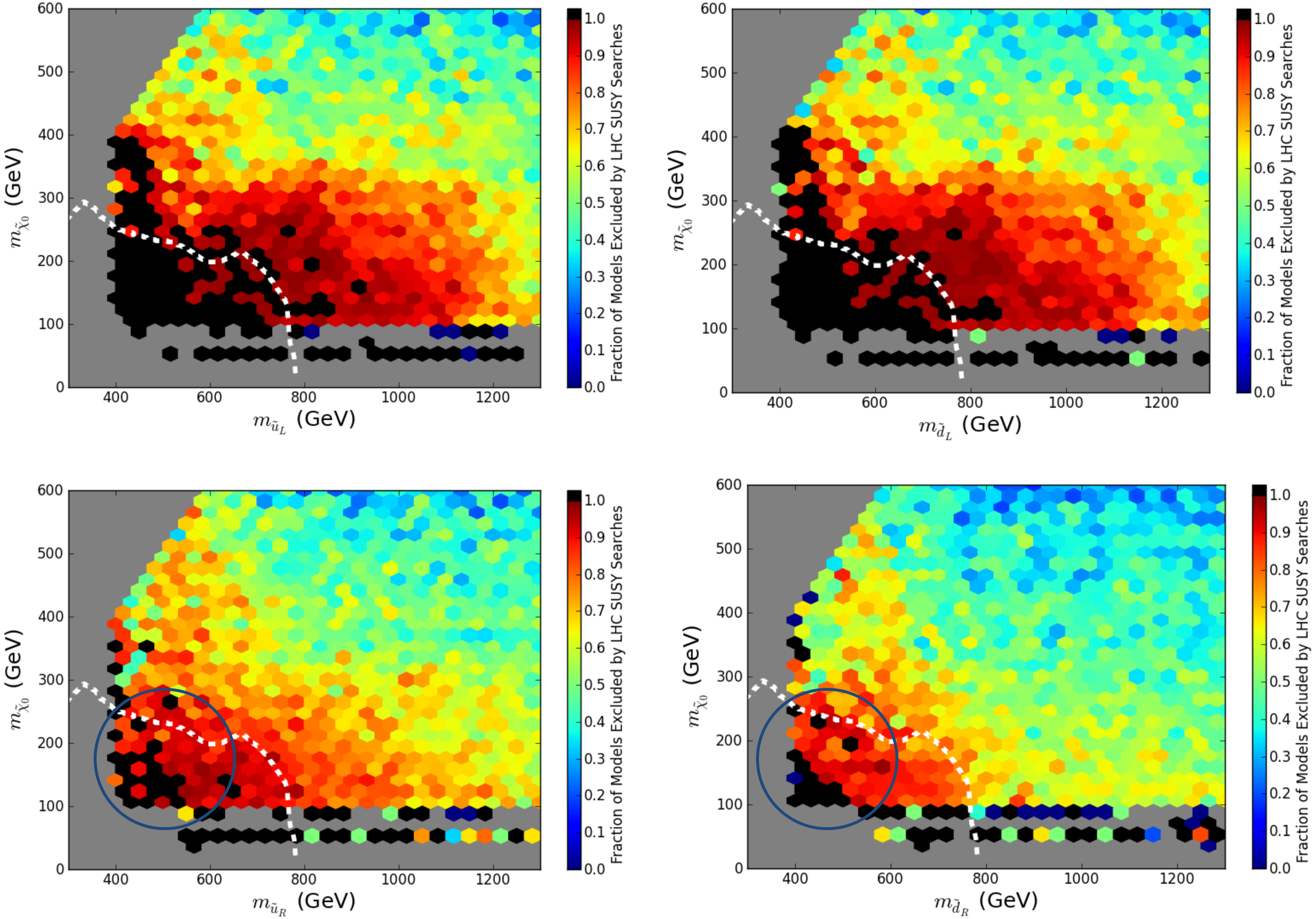


$\Gamma(Z \rightarrow \chi\chi) < 2$ MeV

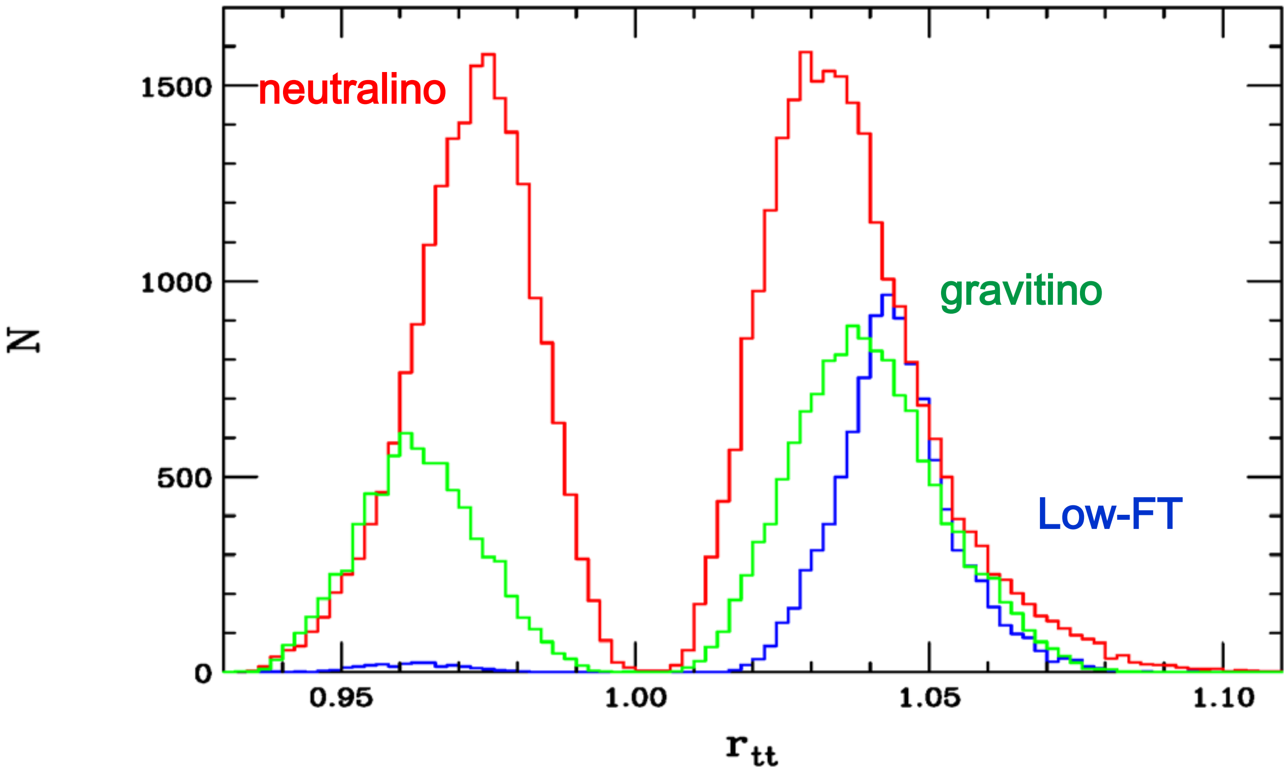


Low-FT models w/ relic density saturated

Neutralino Set Squark Results



For Higgs coupling to tops, we don't expect the 95% CL constraints to get to the region of interest as shown here at the LHC, HL-LHC or at ILC500 (but will at ILC1000) since the shifts from unity are always found to be below ~ 10%



Some Constraints

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

- 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