Implications of the pMSSM

SLAC NATIONAL ACCELERATOR LABORATORY

J. Hewett, Capri 2014

pMSSM Studies

C.F. Berger, J. Berger, Bloom, Cahill-Rowley, Conley, Cotta, Drlica-Wagner, Funk, Gainer, Ghosh, JLH, Hoeche, Howe, Ismail, Le, Murgia, Rizzo, Wood 0812.0980, 1007.5520, 1009.2539, 1103.1697, 1105.1199, 1111.2604, 1206.4321, 1206.5800, 1211.1981, 1211.7106, 1305.2419, 1305.6921, 1307.8444, 1308.0297, 1309.7653, 1405.asap, 1405.next, 1406.more, 1406.xtra

AbdusSalam, Allanach, Chourdhury, Quevedo, Feroz, Hobson 0909.2548, 1009.4308, 1106.2317, 1210.3331, 1211.0999

Arbey, Battaglia, Djouadi, Mahmoudi 1110.3726, 1112.3032, 1205.2557, 1207.1348, 1211.4004, 1308.2153, 1311.7641

Bechtle, Heinemeyer, Stal, Stefaniak, Weiglein, Zeune 1211.1955

Boehm, Dev, Mazumdar, Pukartas 1303.5386

Carena, Lykken, Sekmen, Shah, Wagner 1205.5903

Chakraborti, Chattopadhyay, Chourdhury, Datta, Poddar, 1404.4841

CMS, conference note

Sekmen, Kraml, Lykken, Moortgat, Padhi, Pape, Pierini, Prosper, Spiropulu 1109.5119

Strubig, Caron, Rammensee 1202.6244

The pMSSM Model Framework

- The phenomenological MSSM (pMSSM)
  - Most general CP-conserving MSSM with R-parity
  - Minimal Flavor Violation, First 2 sfermion generations are degenerate w/ negligible Yukawas
  - No GUT, SUSY-breaking, high-scale assumptions!
  - 19/20 real, weak-scale parameters (Neutralino/Gravitino LSP)

    scalars:

    $m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}$

    gauginos: M_1, M_2, M_3

    tri-linear couplings: A_b, A_t, A_τ

    Higgs/Higgsino: $\mu, M_A, \tan\beta$

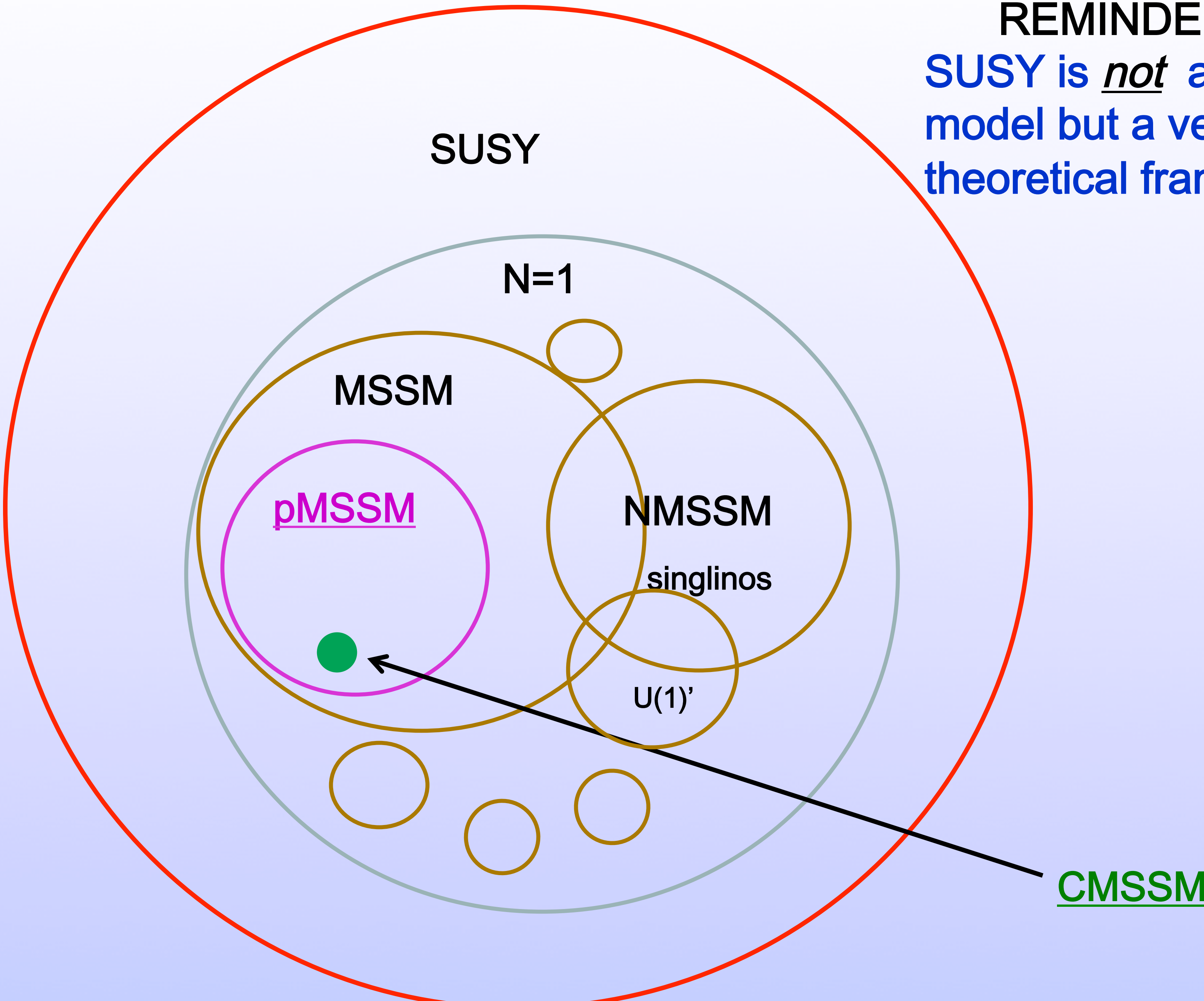
    (Gravitino: M_G)

Supersymmetry without Prejudice

Berger, Gainer, JLH, Rizzo 0812.0980

REMINDER:

SUSY is *not* a single model but a very large theoretical framework



Rizzo

Study of the pMSSM (Neutralino/Gravitino LSP)

Scan with Linear Priors

Perform large scan over Parameters

$100\ \text{GeV} \leq m_{sfermions} \leq 4\ \text{TeV}$

$50\ \text{GeV} \leq |M_1, M_2, \mu| \leq 4\ \text{TeV}$

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

$100\ \text{GeV} \leq M_A \leq 4\ \text{TeV}$

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

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

$(1\ \text{ev} \leq m_G \leq 1\ \text{TeV})$ (log prior)

Subject these points to Constraints from:

- Flavor physics
- EW precision measurements
- Collider searches
- Cosmology

~225,000 models survive constraints for each LSP type!

~10,000 low fine-tuning, Neutralino sample

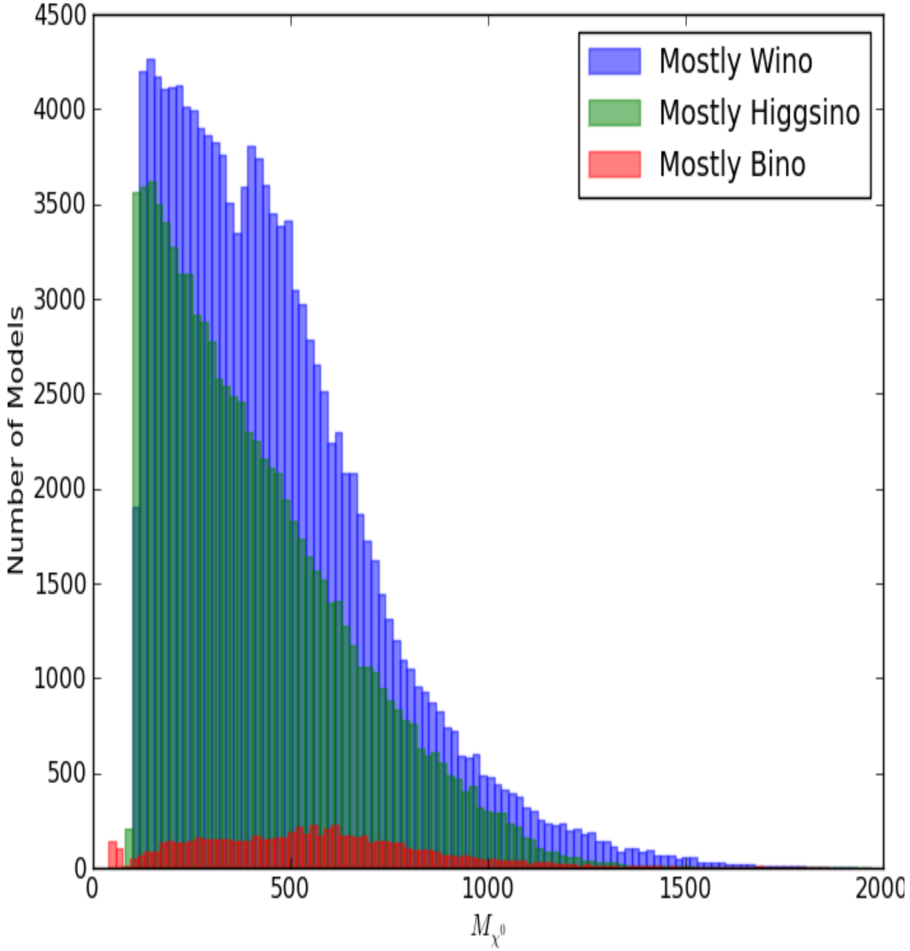
Cahill-Rowley etal 1206.4321

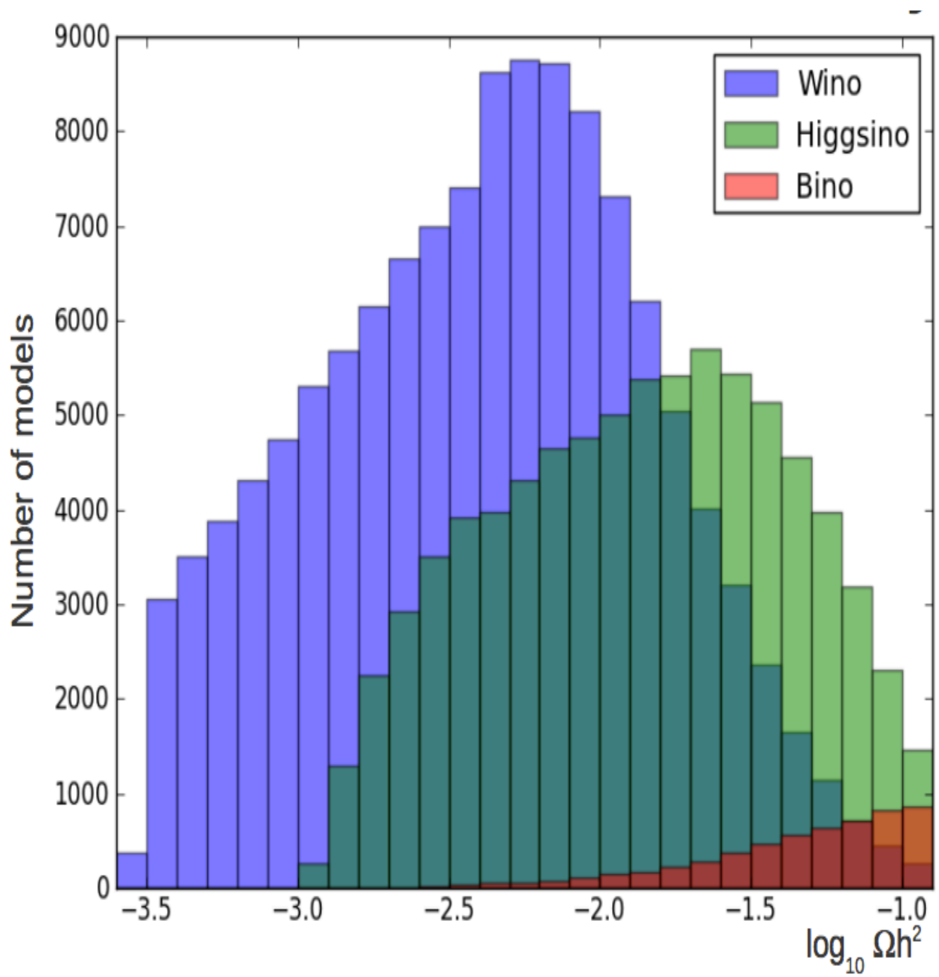
Full List of Model Constraints

- $\Delta\rho$ / W–mass
- $\Gamma(Z \to$ invisible)
- $\Delta(g-2)_\mu$
- $b \to s\,\gamma$
- 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
- BBN energy deposition for gravitinos
- Relic ν's & diffuse photon bounds
- LEP and Tevatron Direct Higgs & SUSY searches
- LHC stable sparticle searches
- No tachyons or color/charge breaking minima
- Stable vacua

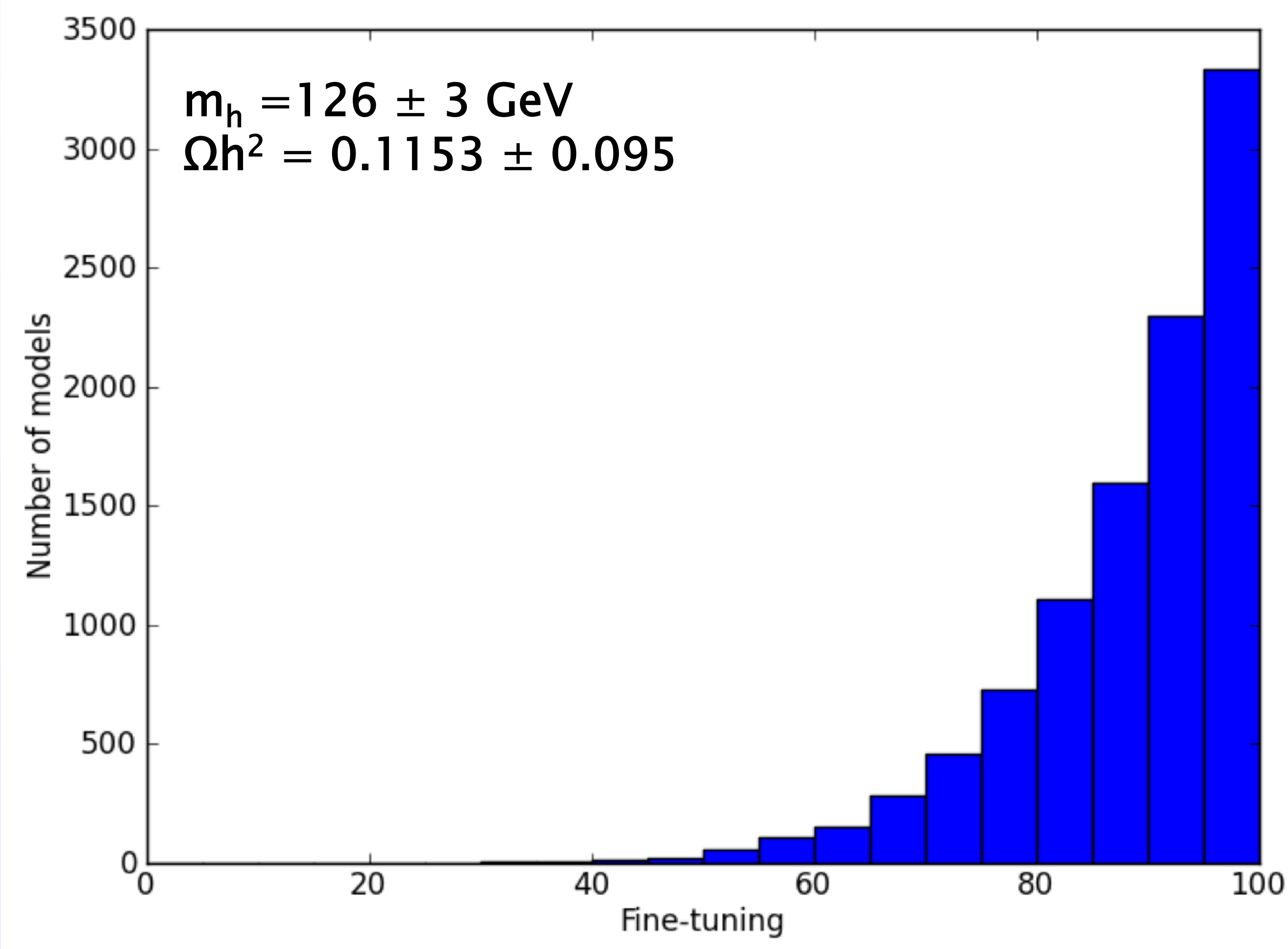
Neutralino Mass Distribution & Relic Density



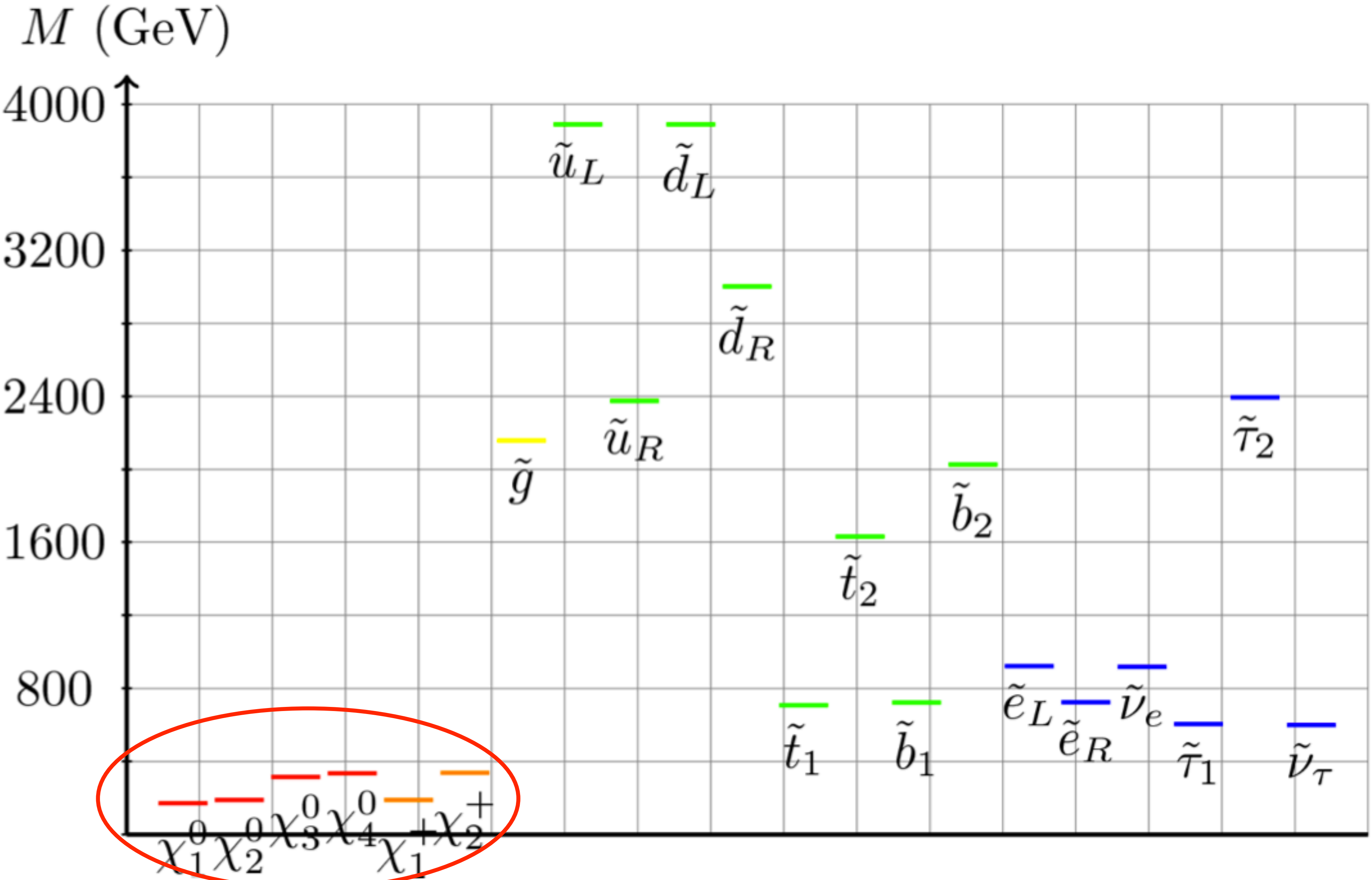


Low Fine-Tuned pMSSM Model Sample

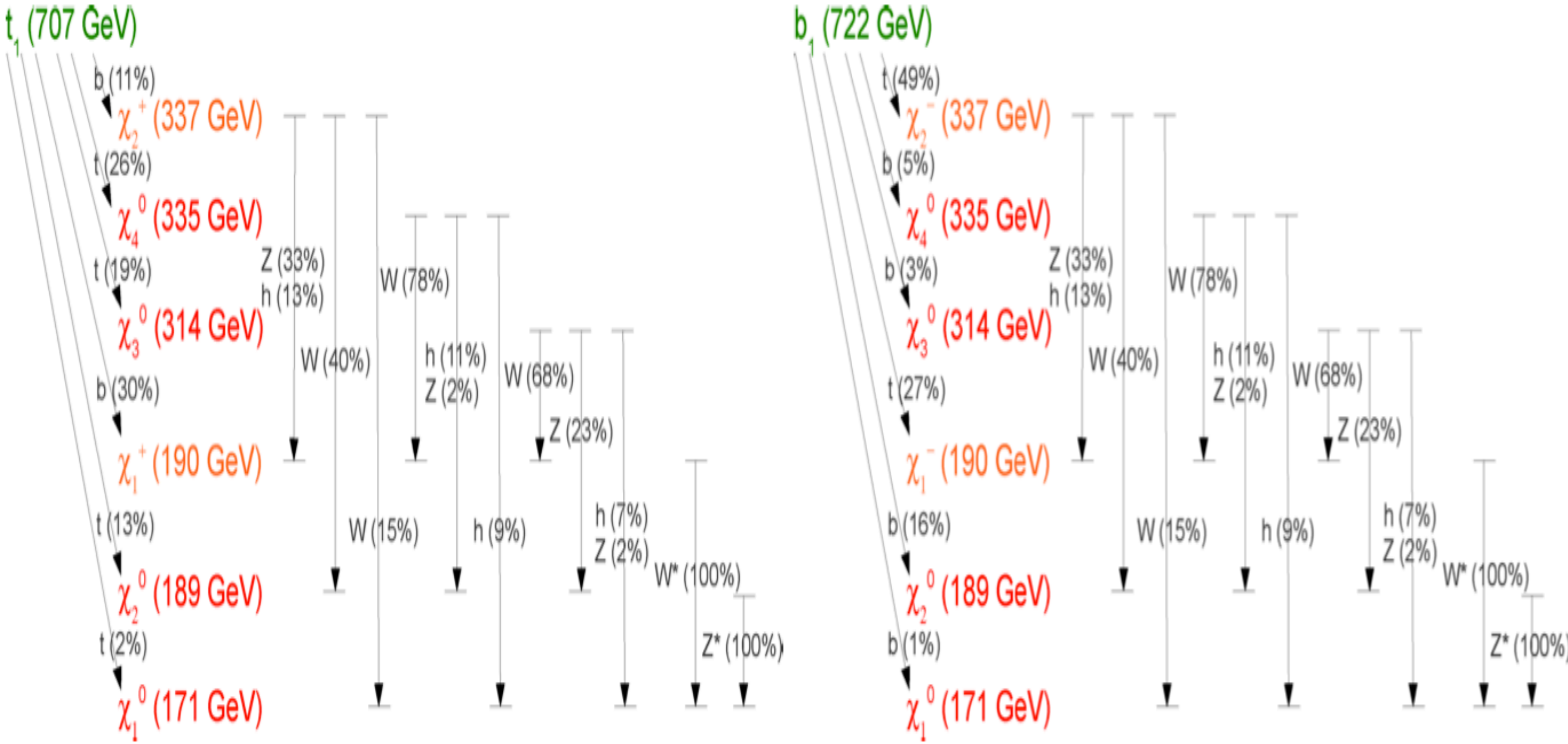
Barbieri-Giudice formulism



Low Fine-Tuning Sample Spectra



Low Fine-Tuning Sample Decay Patterns



ATLAS MET-based SUSY Analyses @ 7 & 8 TeV

- Apply the general LHC SUSY MET-based searches to our model sets
- We (almost) exclusively follow the ATLAS analysis suite as closely as possible with fast MC (modified versions of PGS, Pythia, SoftSUSY, SDECAY, HDECAY)
- Generate signal events for every model for all ~90 SUSY processes (~10^{13} events!) & scale to NLO with Prospino
- Validated our results with ATLAS benchmark models
- We combine the various analyses signal regions (as ATLAS does) into : nj0l, multi-j, nj1l, nj2l and we quote the coverage for each as well as the combined result..
- This approach is CPU intensive!!

Benchmark Validation

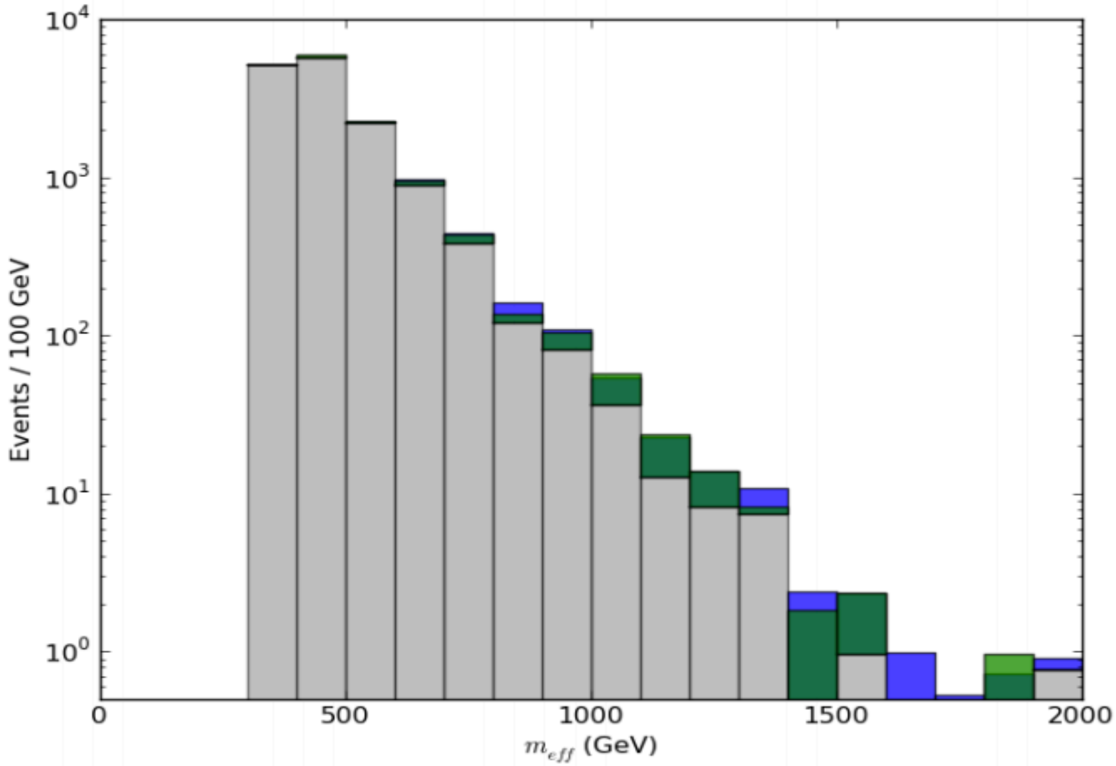


Figure 16: Effective mass distribution for events passing the cuts of the two jet signal region from the ATLAS jets plus MET search [48]. The SM background is shown in gray, with our signal prediction (blue) and the corresponding ATLAS signal prediction (green) on top, for the benchmark mSUGRA point $m_0 = 660\,\text{GeV}, m_{\frac{1}{2}} = 240\,\text{GeV}, A_0 = 0\,\text{GeV}, \tan\beta = 10, \mu > 0$. Imposing the effective mass cut of 1000 GeV leaves us with 42.2 events, which compares favorably with the ATLAS result of 38.9 events.

Employ all publically released ATLAS analyses since Moriond13 + 21 fb^{-1} jets+MET

2012 data (8 TeV)

Short Title of the CONF note	Date	√s (TeV)	L (fb^{-1})	Document	Plots
0 lepton + 2 b-jets + Etmiss [Medium / heavy stop] NEW	12/2012	8	12.8	ATLAS-CONF-2013-001	Link
2 leptons + Etmiss [Medium stop] NEW	12/2012	8	13.0	ATLAS-CONF-2012-167	Link
1 lepton + >=4 jets (>=1 b-jet) + Etmiss [Medium / heavy stop] NEW	12/2012	8	13.0	ATLAS-CONF-2012-166	Link
2 bjets + Etmiss [Direct sbottom] NEW	12/2012	8	12.8	ATLAS-CONF-2012-165	Link
3 leptons + Etmiss [Direct gauginos]	11/2012	8	13.0	ATLAS-CONF-2012-154	Link
4 leptons + Etmiss [RPV]	11/2012	8	13.0	ATLAS-CONF-2012-153	Link
0 lepton + >=3 b-jets + Etmiss [3rd gen. squarks]	11/2012	8	12.8	ATLAS-CONF-2012-145	Link
3 leptons + jets + Etmiss [3rd gen. squarks]	11/2012	8	13.0	ATLAS-CONF-2012-151	Link
Monojet + Etmiss [WIMP, gravitino prod.] X	11/2012	8	10.5	ATLAS-CONF-2012-147	Link
Z + jets + Etmiss [GGM, higgsino NLSP]	11/2012	8	5.8	ATLAS-CONF-2012-152	Link
0 leptons + >=2-6 jets + Etmiss	08/2012	8	5.8	ATLAS-CONF-2012-109	Link
0 leptons + >=6-9 jets + Etmiss	08/2012	8	5.8	ATLAS-CONF-2012-103	Link
1 lepton + >=4 jets + Etmiss	08/2012	8	5.8	ATLAS-CONF-2012-104	Link
2 same-sign leptons + >=4 jets + Etmiss	08/2012	8	5.8	ATLAS-CONF-2012-105	Link

✓

2011 data (7 TeV)

Short Title of the Paper	Date	√s (TeV)	L (fb^{-1})	Document	Plots+Aux. Material	Journal
0-2 leptons + 0-1 b-jets multichannel (razor) X	12/2012	7	4.7	1212.6149	Link	Submitted to EPJC
~~Heavy resonance to eμ, eτ, μτ [RPV-LFV] NEW~~	12/2012	7	4.6	1212.1272	Link	Submitted to PLB
Long-lived particles [R-hadrons, slepton] NEW CMS	11/2012	7	4.7	1211.1597	Link	Submitted to PLB
1 photon + >=1 b-jet + Etmiss [GGM, higgsino NLSP] NEW ✓	11/2012	7	4.7	1211.1167	Link (+ data)	Accepted by PLB

Muon + displaced vertex [RPV] ✓	10/2012	7	4.7	1210.7451	Link		Accepted by PLB
~~Pair of 2-jet resonance [N=1/2 scalar gluon]~~	10/2012	7	4.6	1210.4826	Link		Accepted by EPJC
~~Pair of 3-jet resonance [RPV]~~	10/2012	7	4.6	1210.4813	Link		JHEP 12 (2012) 086
>=4 leptons + Etmiss [RPV]	10/2012	7	4.7	1210.4457	Link (+ data)		JHEP 12 (2012) 124
Monojet + Etmiss [WIMP] X	10/2012	7	4.7	1210.4491	Link		Submitted to JHEP
Disappearing track + jets + Etmiss [Direct long-lived charginos - AMSB] ✓	10/2012	7	4.7	1210.2852	Link		JHEP 01 (2013) 131
~~1-2 taus + 0-1 leptons + jets + Etmiss [GMSB]~~	10/2012	7	4.7	1210.1314	Link		EPJC 72 (2012) 2215
Monophoton [ADD, WIMP] X	09/2012	7	4.7	1209.4625	Link		PRL 110 (2013) 011802
2 leptons + jets + Etmiss [Medium stop] ✓	09/2012	7	4.7	1209.4186	Link (+ data)		JHEP 11 (2012) 094
1-2 b-jets + 1-2 leptons + jets + Etmiss [Light Stop] ✓	09/2012	7	4.7	1209.2102	Link		Accepted by PLB
2 photons + Etmiss [GGM, bino NLSP] ✓	09/2012	7	4.7	1209.0753	Link (+ data)		PLB 718 (2012) 411
1-2 leptons + >=2-4 jets + Etmiss ✓	08/2012	7	4.7	1208.4688	Link		PRD 86 (2012) 092002
2 leptons + >=1 jet + Etmiss [Very light stop] ✓	08/2012	7	4.7	1208.4305	Link (+ data)		EPJC (2012) 72 2237
3 leptons + Etmiss [Direct gauginos] ✓	08/2012	7	4.7	1208.3144	Link (+ data)		PLB 718 (2013) 841
2 leptons + Etmiss [Direct gauginos/sleptons] ✓	08/2012	7	4.7	1208.2884	Link		PLB 718 (2013) 879
1 lepton + >=4 jets (>=1 b-jet) + Etmiss [Heavy stop] ✓	08/2012	7	4.7	1208.2590	Link (+ data)		PRL 109 (2012) 211803
0 lepton + 1-2 b-jet + 5-4 jets + Etmiss [Heavy stop] ✓	08/2012	7	4.7	1208.1447	Link (+ data)		PRL 109 (2012) 211802
0 lepton + >=2-6 jets + Etmiss ✓	08/2012	7	4.7	1208.0949	Link (+ data)		PRD 87 (2013) 012008
0 lepton + >=3 b-jets + >=(1-3) jets + Etmiss [Gluino med. stop/sb] ✓	07/2012	7	4.7	1207.4686	Link		EPJC 72 (2012) 2174
0 lepton + >=(6-9) jets + Etmiss ✓	06/2012	7	4.7	1206.1760	Link (+ data)		JHEP 1207 (2012) 167

Short Title of the Conf. note	Date	√s (TeV)	L (fb^{-1})	Document	Plots
✓ *1 photon + 1 lepton + Etmiss [GGM, wino NLSP]*	10/2012	7	4.8	*ATLAS-CONF-2012-144*	*Link*
✓ *1 lepton + >=7 jets + Etmiss*	10/2012	7	4.7	*ATLAS-CONF-2012-140*	*Link*
✓ *3 leptons + jets + Etmiss [3rd gen. squarks]*	08/2012	7	4.7	*ATLAS-CONF-2012-108*	*Link*
✓ *2 b-jets + Etmiss [Direct sbottom]*	08/2012	7	4.7	*ATLAS-CONF-2012-106*	*Link*
General new phenomena search	08/2012	7	4.7	*ATLAS-CONF-2012-107*	*Link*
Disappearing track + jets + Etmiss [AMSB Strong Prod.] In progress	03/2012	7	4.7	*ATLAS-CONF-2012-034*	*Link*

21 fb^{-1} jets+MET

LHC Search Results for the pMSSM: percentage of models excluded by data

7 TeV Searches

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	-	1.1%	-
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%	*

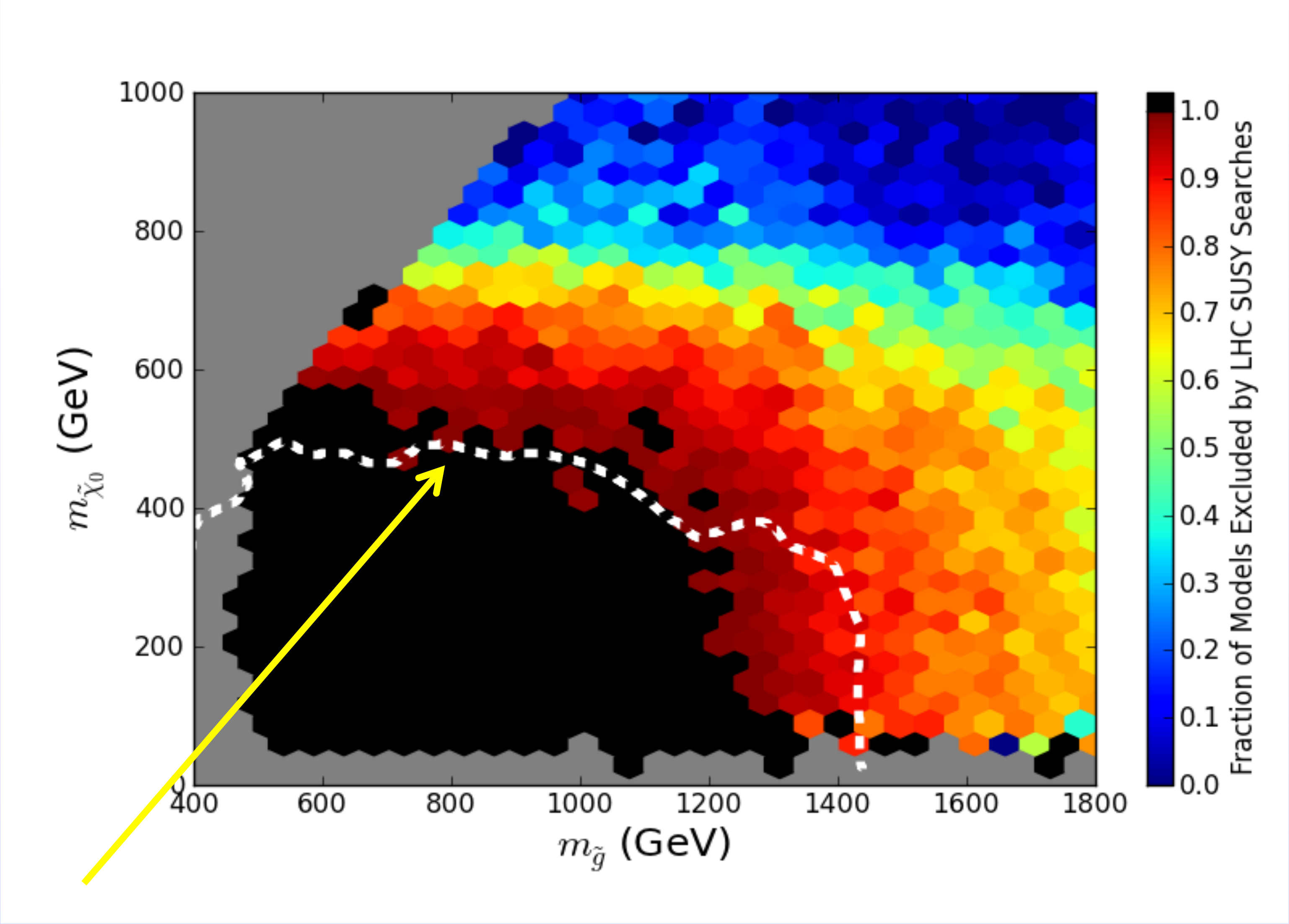
LHC Search Results for the pMSSM: percentage of models excluded by data

8 TeV Searches

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%
Total Excluded 7+8 TeV		**46%**	**61%**	**74%**

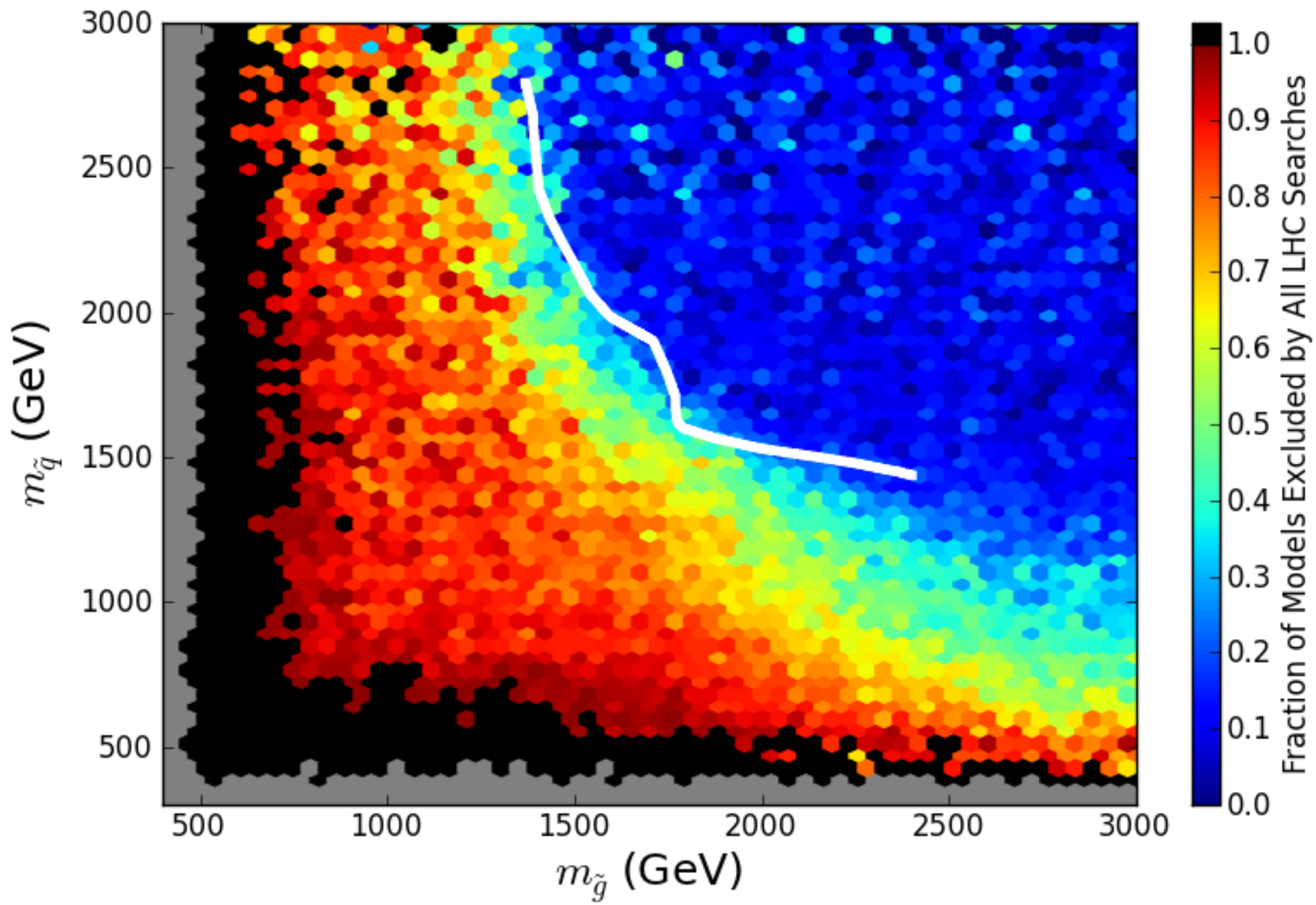
Cahill-Rowley etal, 1307.8444, 1405.asap

Effects of LHC Searches on Neutralino LSP Sample

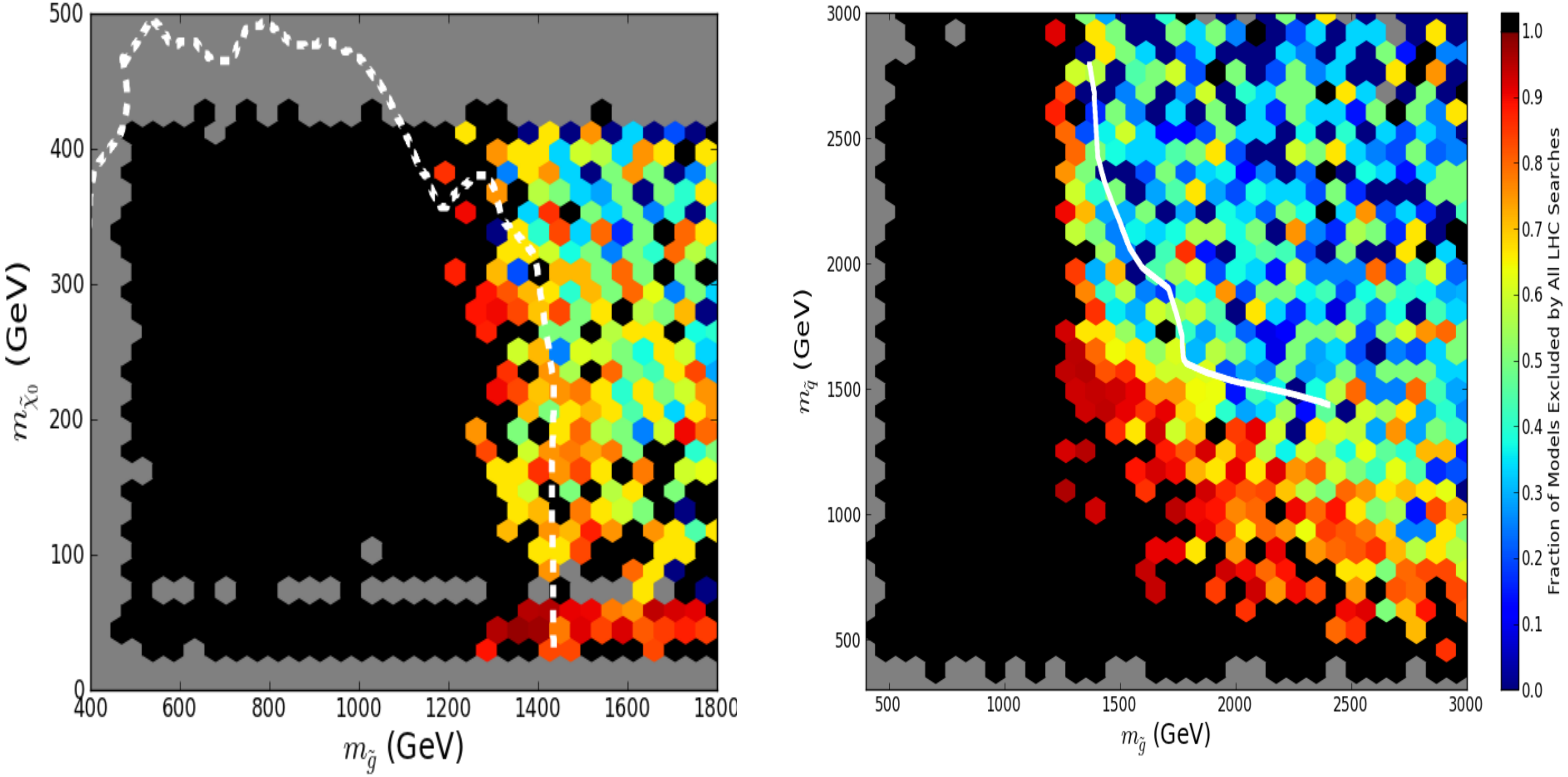


Simplified Model Limit (ATLAS)

Effects of LHC Searches on Neutralino LSP Sample



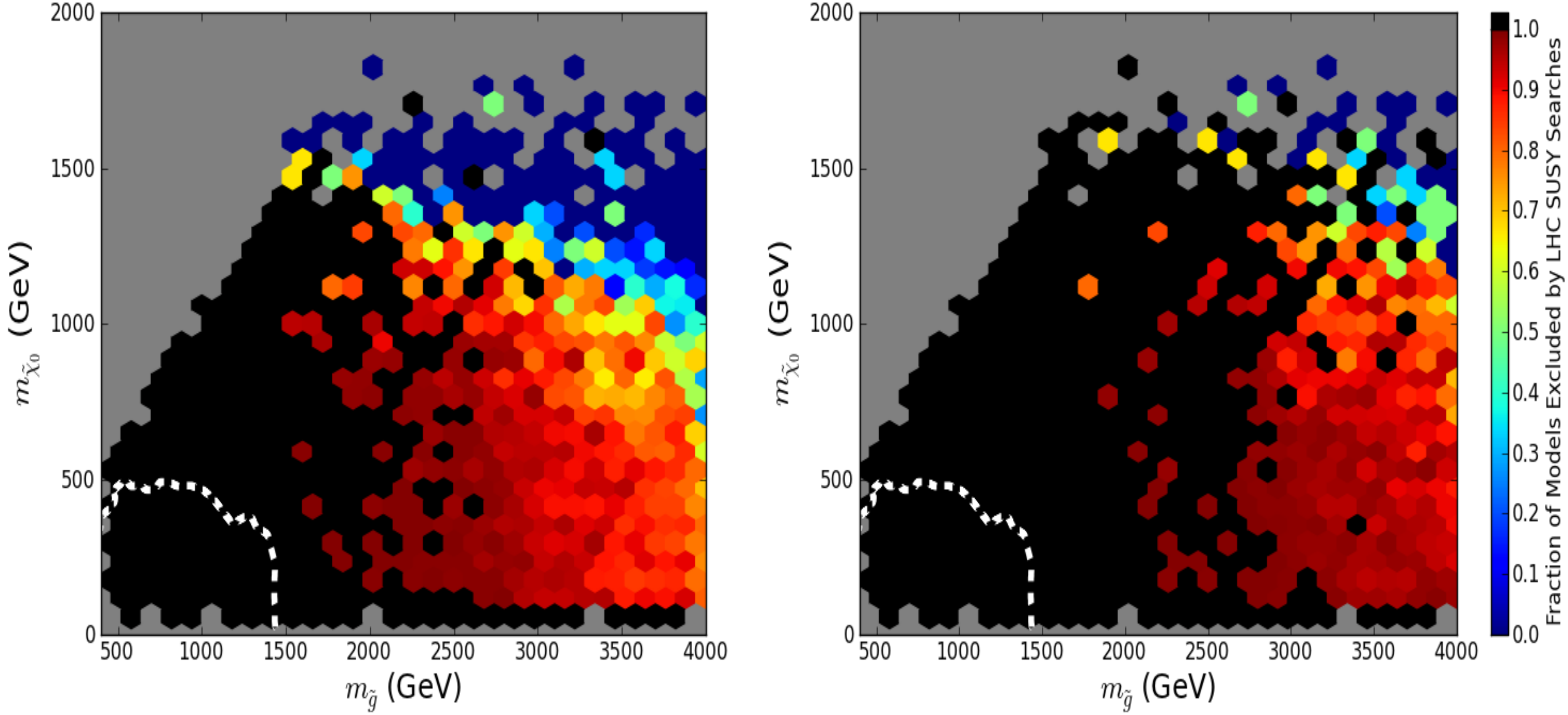
Effects of LHC Searches on Low Fine-Tuning, Neutralino LSP Sample



14 TeV LHC pMSSM Coverage for 0.3 & 3 ab^{-1}

Jets+MET Analysis only (ATLAS European Strategy Study)
Stop Search (ATLAS Snowmass Study)
Neutralino model set

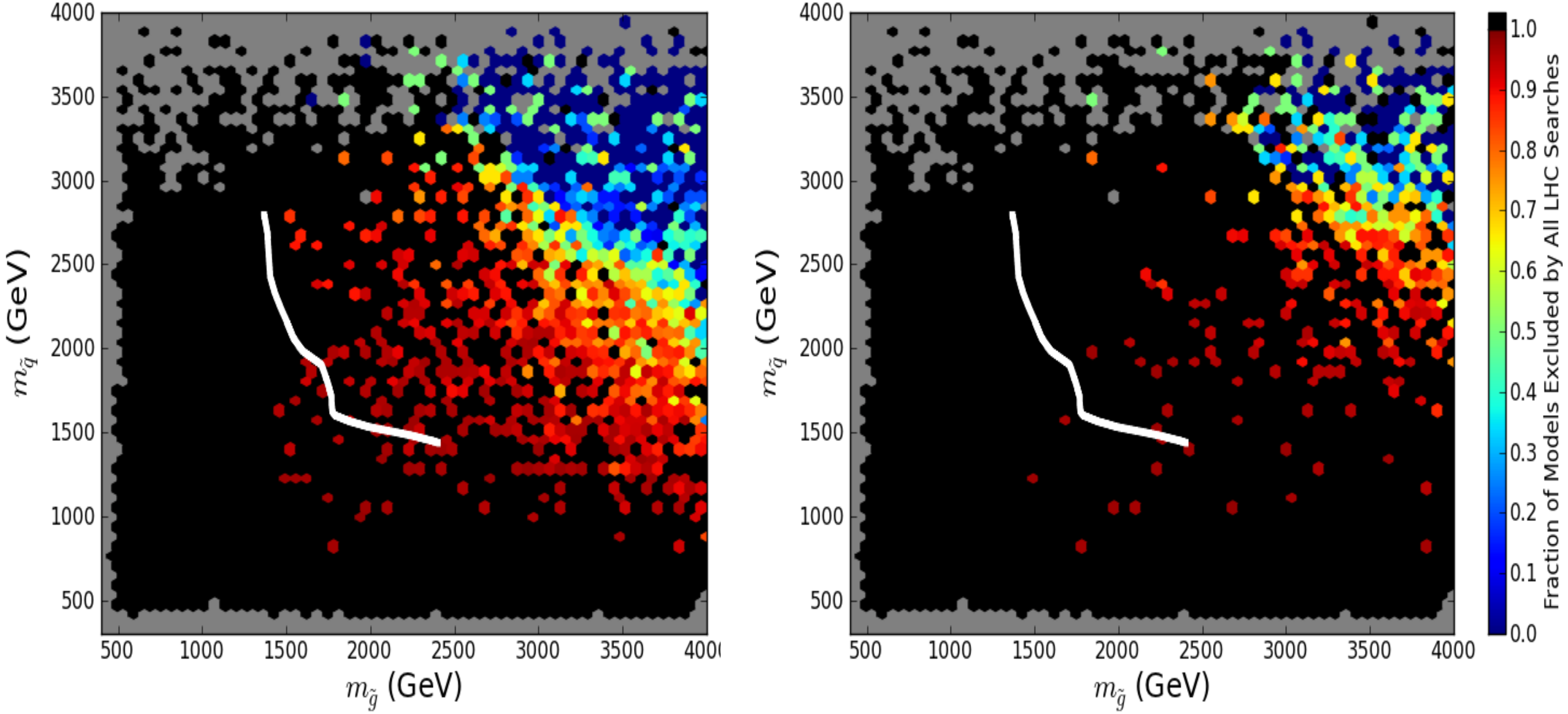
300 fb^{-1}: 90.8% of models excluded   3 ab^{-1}: 97.2% of models excluded



14 TeV LHC pMSSM Coverage for 0.3 & 3 ab^{-1}

Jets+MET Analysis only (ATLAS European Strategy Study)
Stop Search (ATLAS Snowmass Study)
Neutralino model set

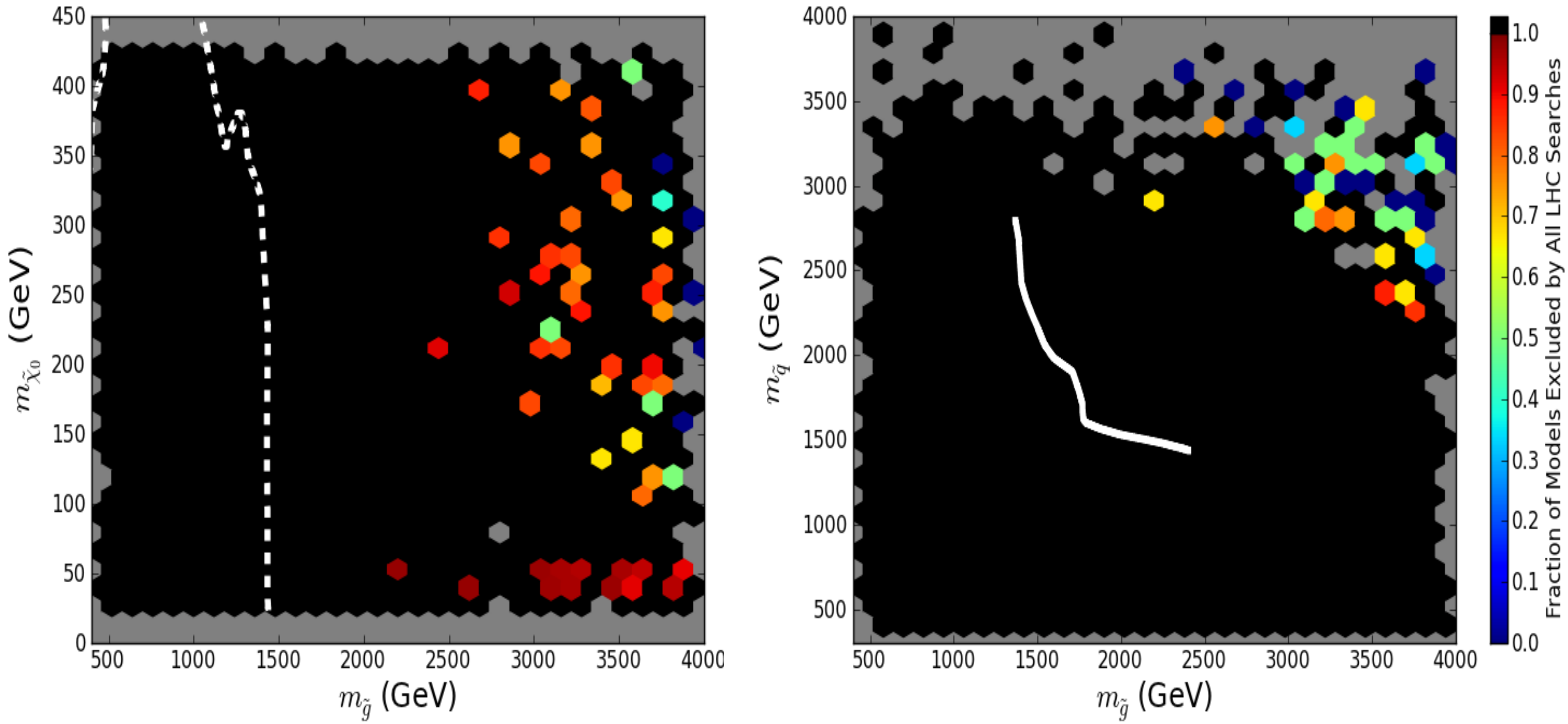
300 fb^{-1}: 90.8% of models excluded   3 ab^{-1}: 97.2% of models excluded



14 TeV LHC pMSSM Coverage for 0.3 & 3 ab^{-1}

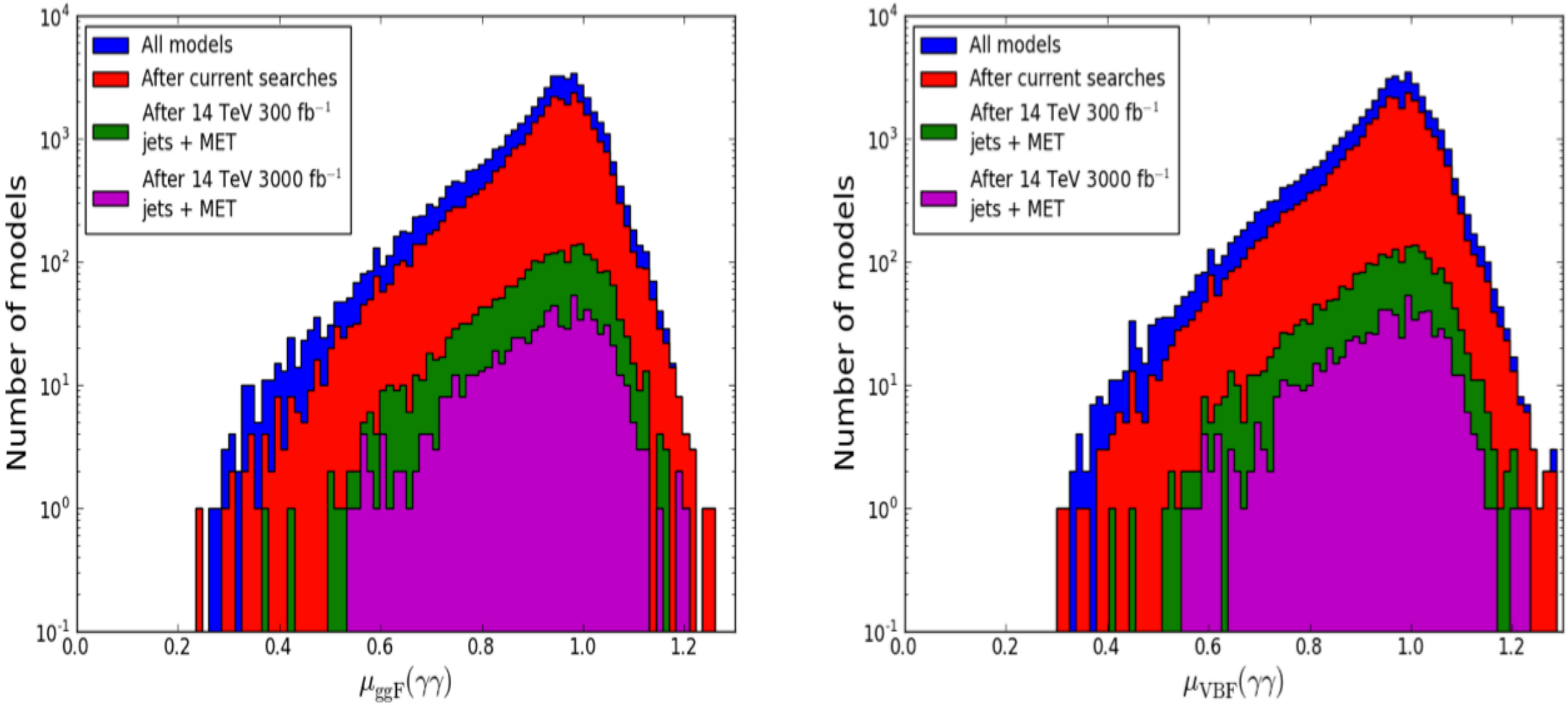
Jets+MET Analysis only (ATLAS European Strategy Study)
Stop Search (ATLAS Snowmass Study)
Low-FT model set: 3000 fb^{-1}: 100% of models excluded!

300 fb^{-1}: 97.4% of models excluded



Higgs Diphoton Signal Strength

$$\mu_{gg,VBF}(X) = \frac{\sigma(gg \to h)\ B(h \to X)}{SM}$$



Cahill-Rowley etal, 1308.0297, 1406.more

Precision Higgs Measurements

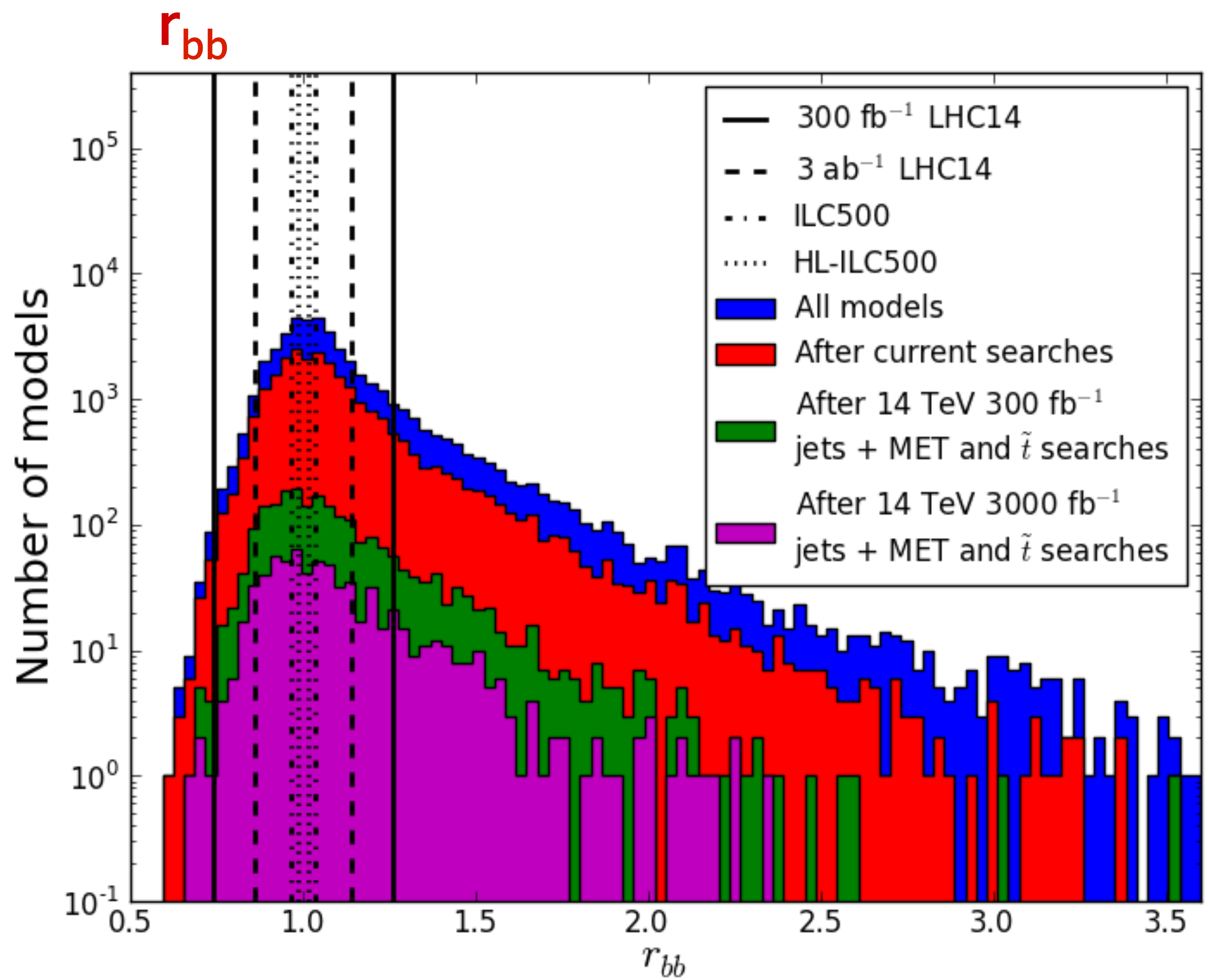
Snowmass Higgs Working Group Report: 1310.8361

CMS: current theory and sys errors: decrease by 2 and √N

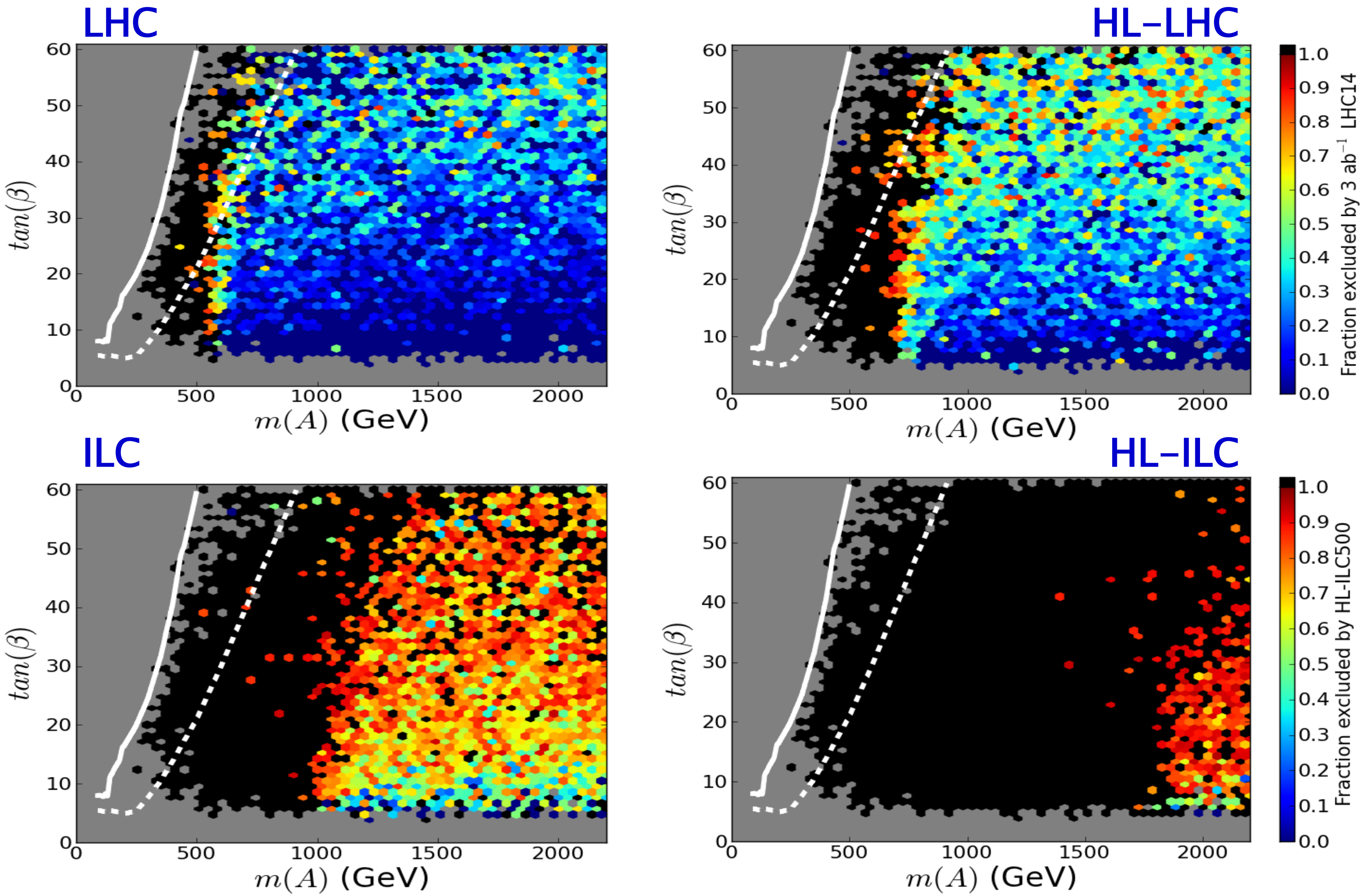
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

	ILC 250/500/1000 GeV		ILC LumiUp‡ 250/500/1000 GeV	
	ZH	$\nu\bar{\nu}H$	ZH	$\nu\bar{\nu}H$
Inclusive	2.6/3.0/−%	−	1.2/1.7/−%	−
$H \to \gamma\gamma$	29-38%	−/20-26/7-10%	16/19/−%	−/13/5.4%
$H \to gg$	7/11/−%	−/4.1/2.3%	3.3/6.0/−%	−/2.3/1.4%
$H \to ZZ^*$	19/25/−%	−/8.2/4.1%	8.8/14/−%	−/4.6/2.6%
$H \to WW^*$	6.4/9.2/−%	−/2.4/1.6%	3.0/5.1/−%	−/1.3/1.0%
$H \to \tau\tau$	4.2/5.4/−%	−/9.0/3.1%	2.0/3.0/−%	−/5.0/2.0%
$H \to b\bar{b}$	1.2/1.8/−%	11/0.66/0.30%	0.56/1.0/−%	4.9/0.37/0.30%
$H \to c\bar{c}$	8.3/13/−%	−/6.2/3.1%	3.9/7.2/−%	−/3.5/2.0%
$H \to \mu\mu$	−	−/−/31%	−	−/−/20%

Higgs partial widths in the pMSSM: $b\bar{b}$



Combined Effect of γγ,ττ, bb Channels



CP-Violating pMSSM

- Expand pMSSM to include CP-Violation
- Work in basis where M_3 and B_μ are real

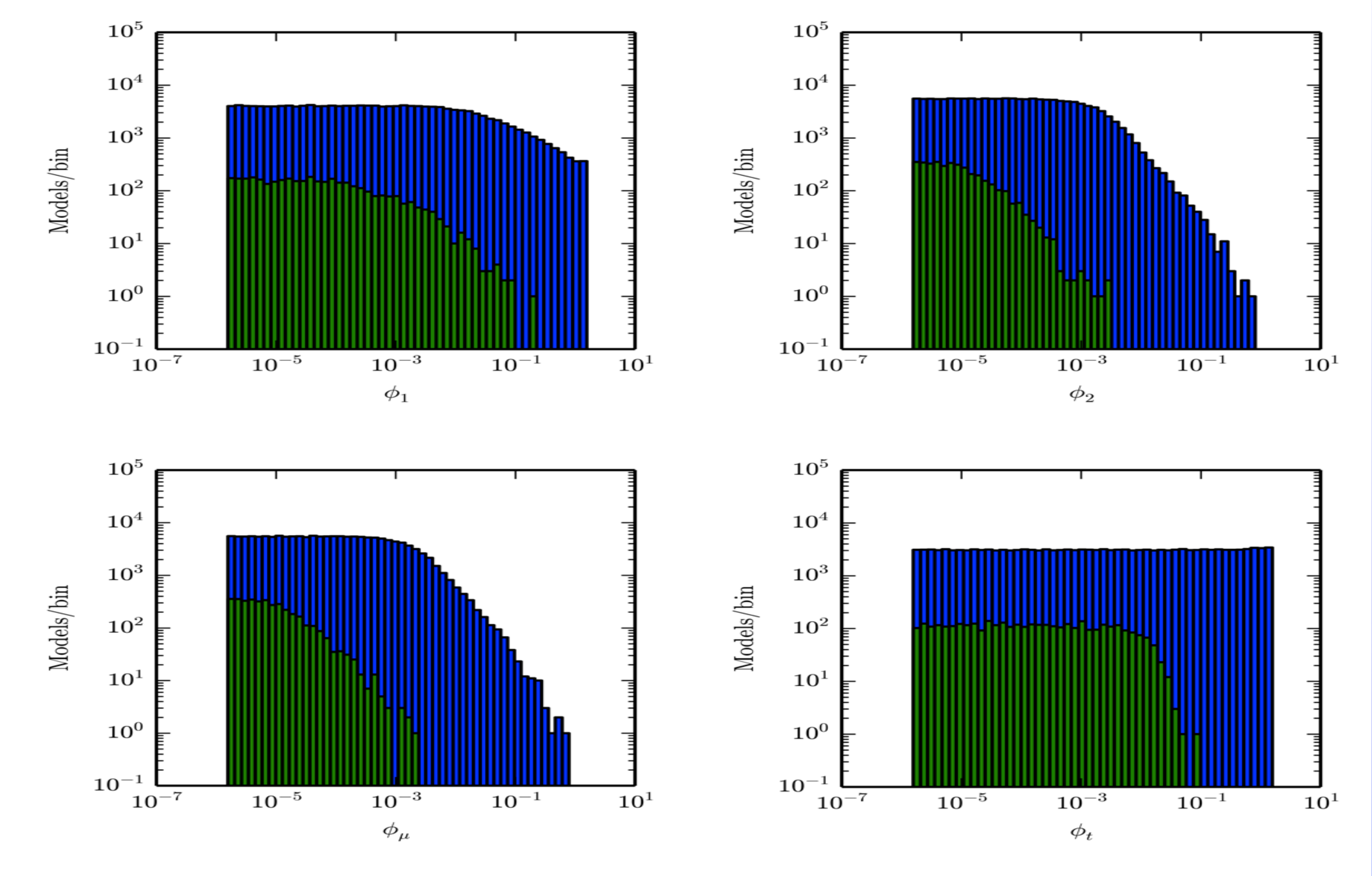
  ➔ Six independent phases allowed in the MSSM

  $\phi_1 = \mathrm{Arg}(M_1)$, $\phi_2 = \mathrm{Arg}(M_2)$, $\phi_\mu = \mathrm{Arg}(\mu)$

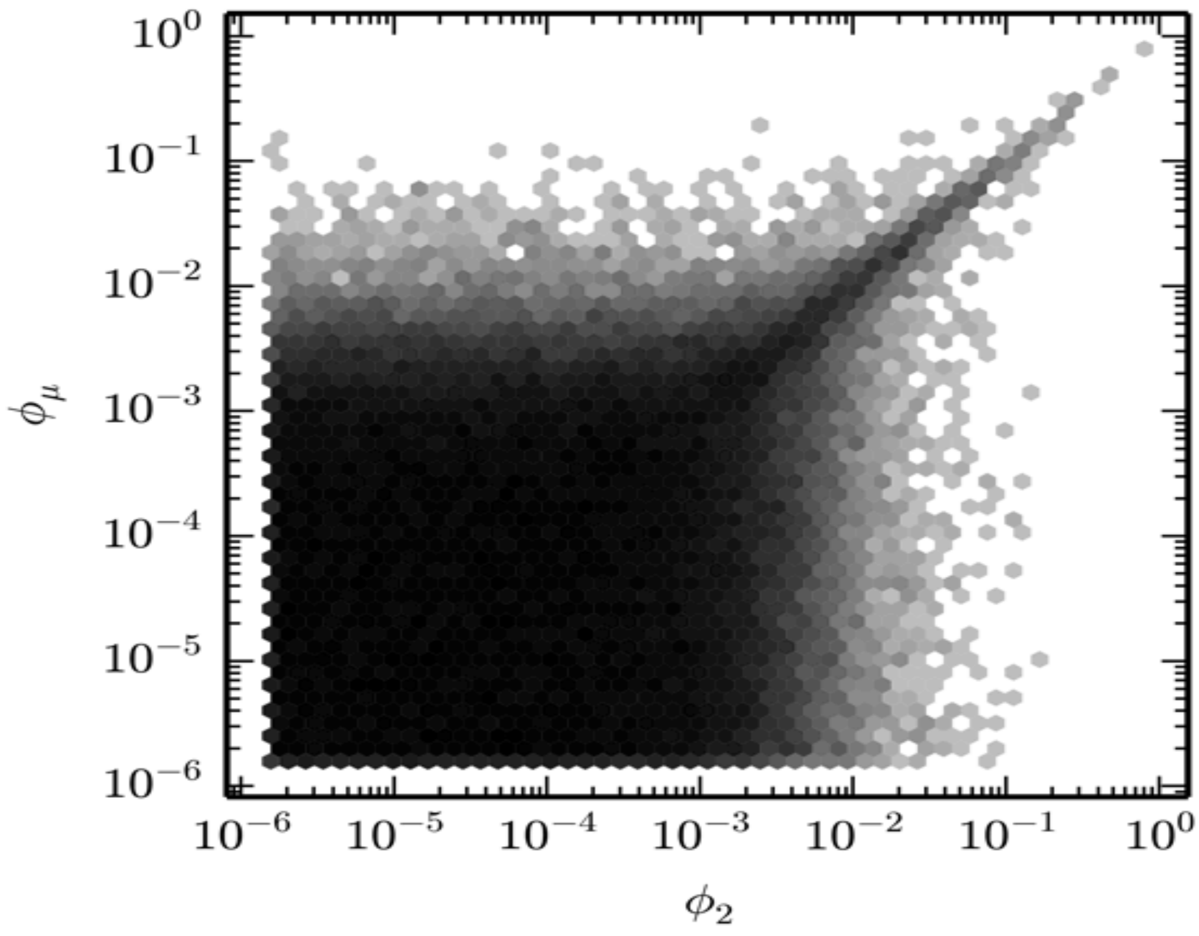
  $\phi_t = \mathrm{Arg}(A_t)$, $\phi_b = \mathrm{Arg}(A_b)$, $\phi_\tau = \mathrm{Arg}(A_\tau)$
- Take 1000 pMSSM models from previous scan
  - 500 observable @ LHC14 with 300 fb^{-1}
  - 500 not observable @ LHC14 with 3 ab^{-1}
- For each model, perform 10^3 scans over phases in the range $10^{-6}\,\pi/2 - \pi/2$ (log priors w/ random sign)
- Total 10^6 models with CPV
- Examine effects in CP-conserving and CP-violating flavor observables via SUSY_FLAVOR*
  - Little impact in LHC direct searches

Berger etal, 1406.xtra

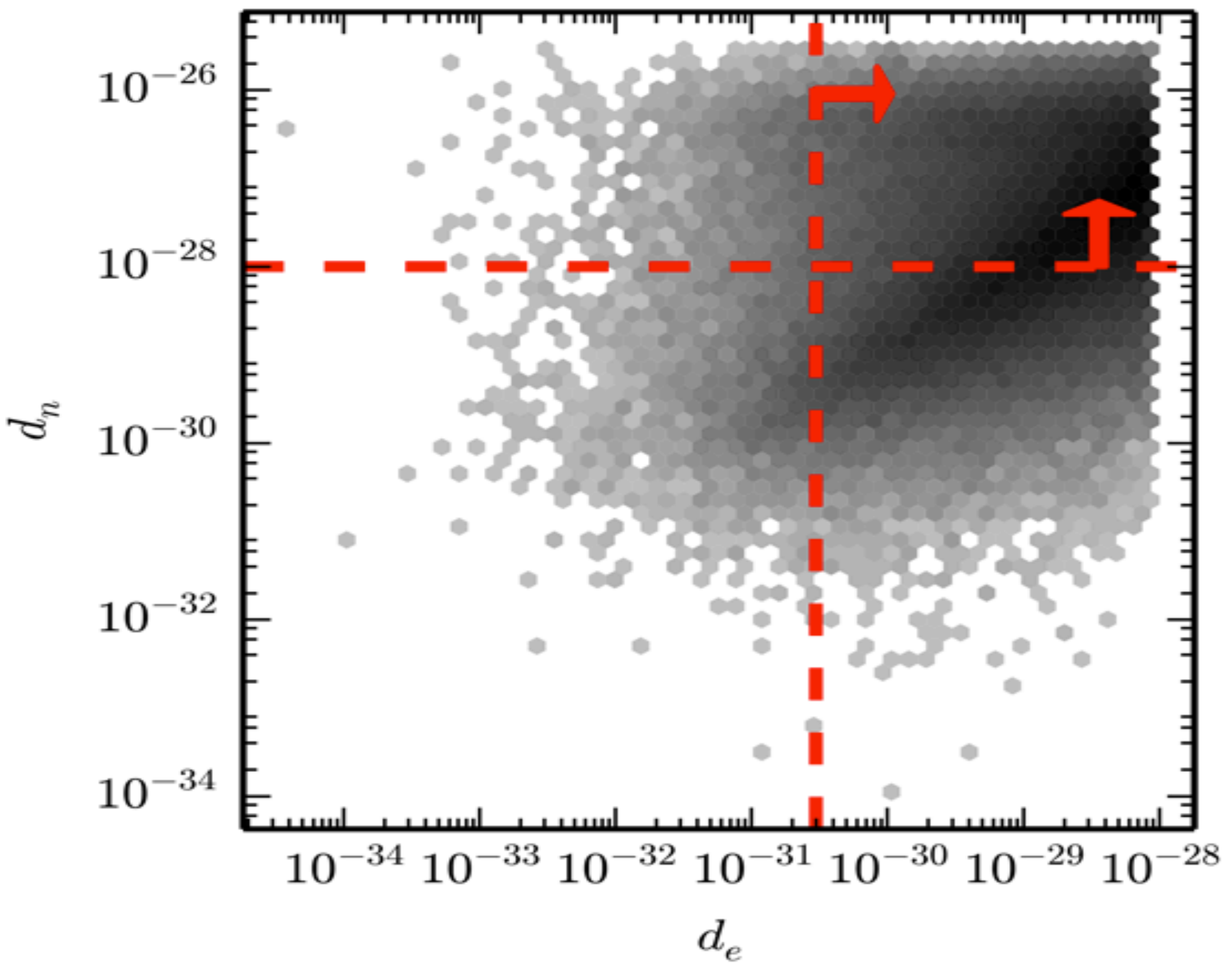
Allowed Ranges of Phases



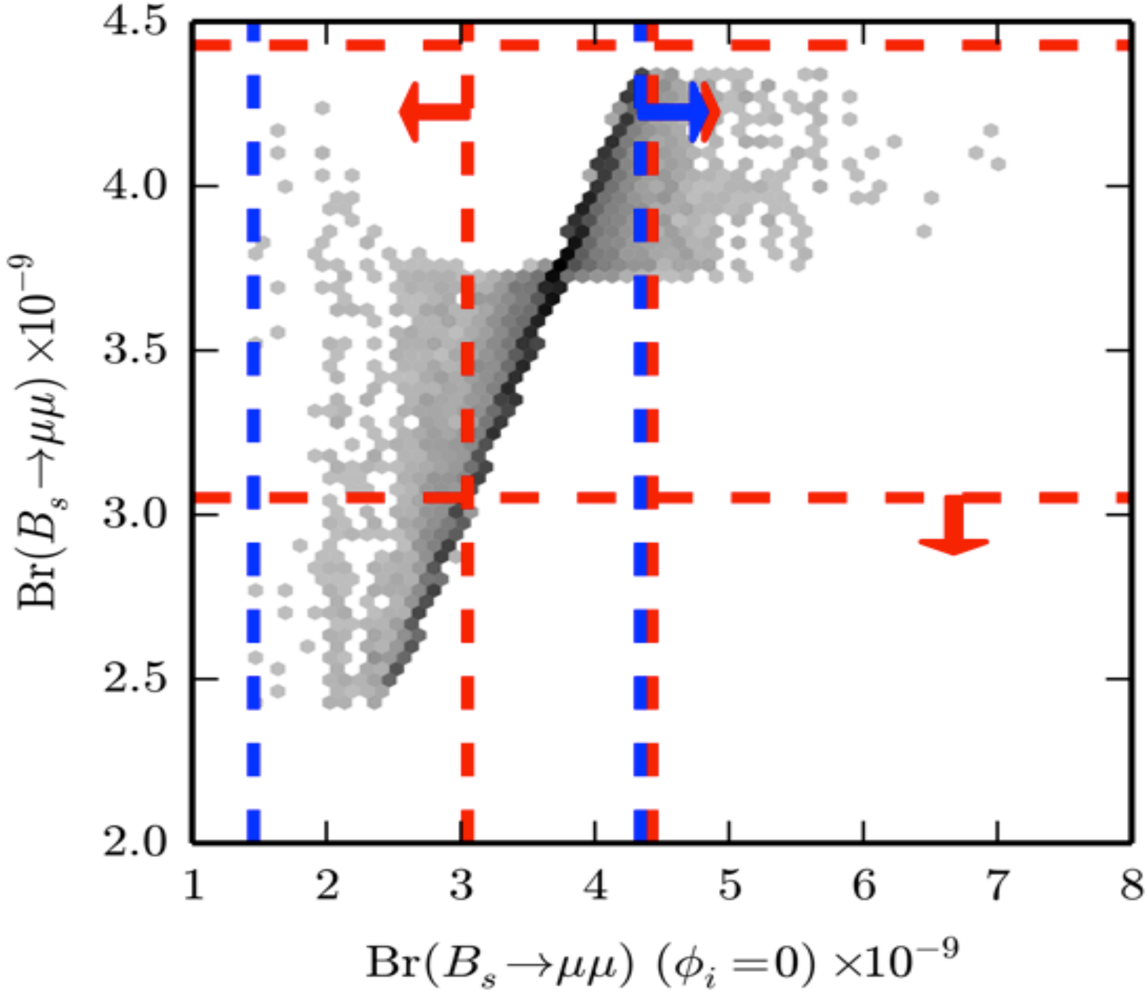
Allowed Ranges of Phases



Constraints from EDMs

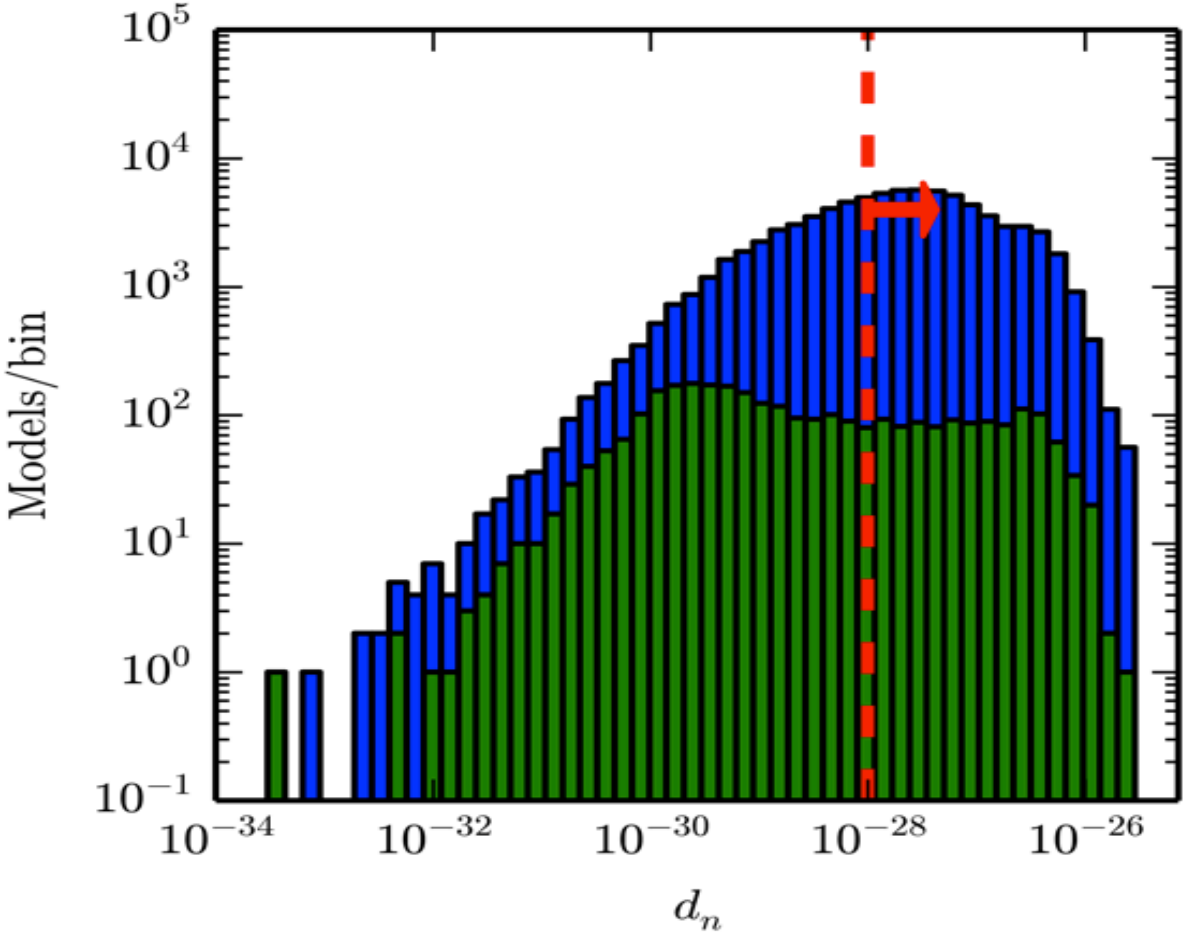


Effects of Phases in $B_s \rightarrow \mu\mu$



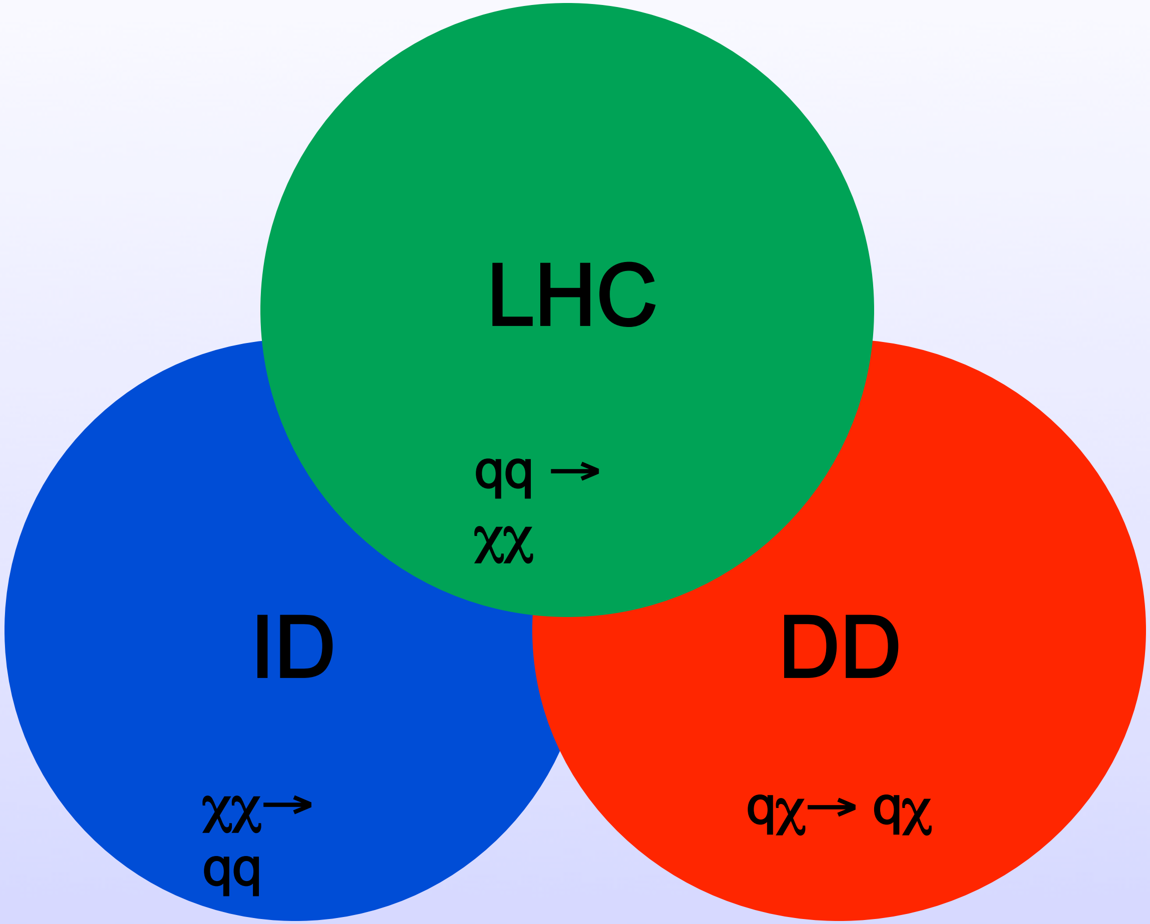
Phases can pull BR towards SM value

Flavor Observables vs LHC



Set of pMSSM models not observed at LHC14 with 3 ab^{-1}

Green: Models Remaining after future flavor measurments



Dark Matter Complementarity

Dark Matter Complementarity Study

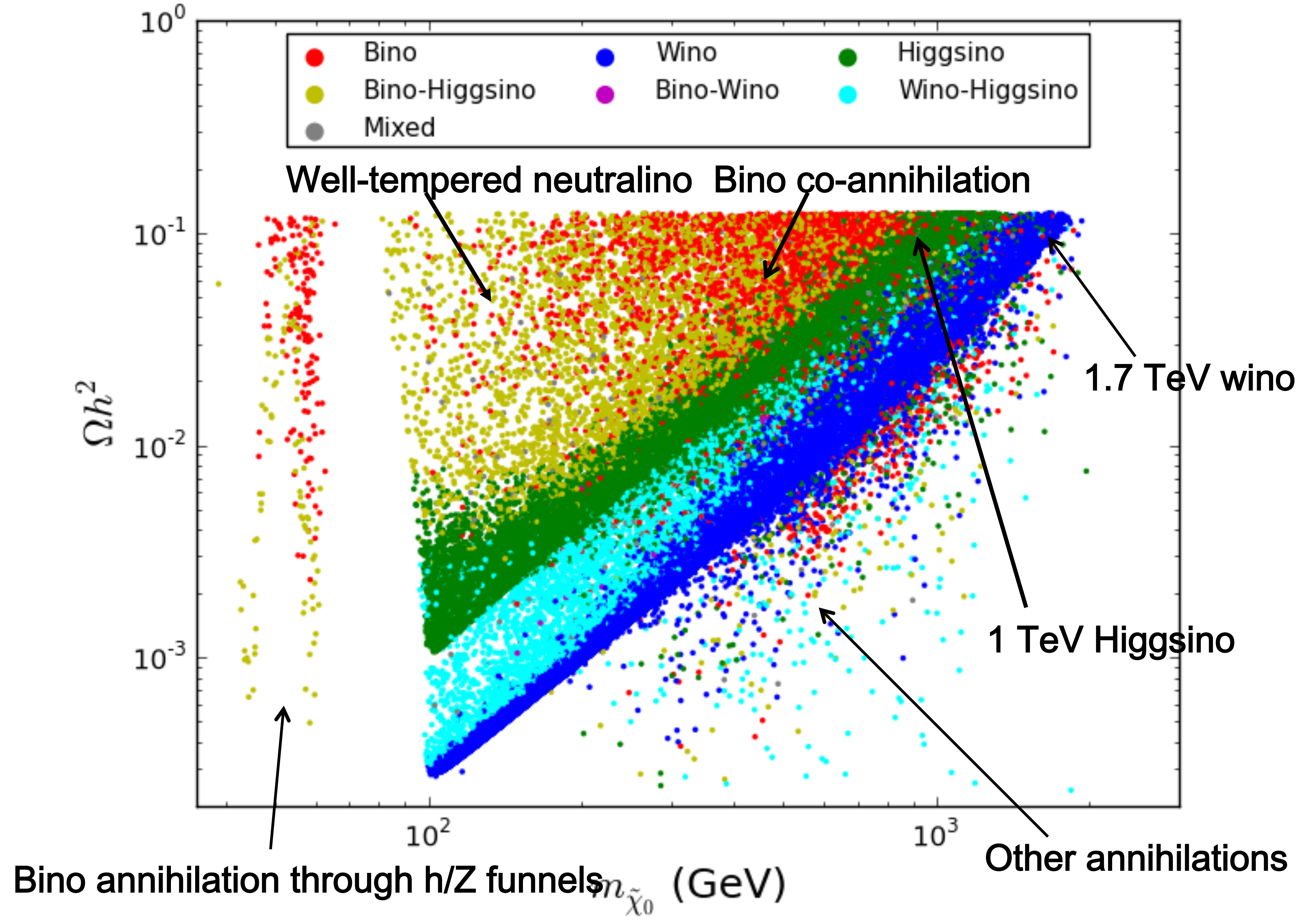
Ingredients

- 7 & 8 TeV LHC MET & non-MET → 14 TeV
- DD w/ Xenon/LUX & COUPP
- ID w/ FERMI & CTA
- ICE^3
- Complementarity

What do these different experiments say about the LSP & the pMSSM in general ?

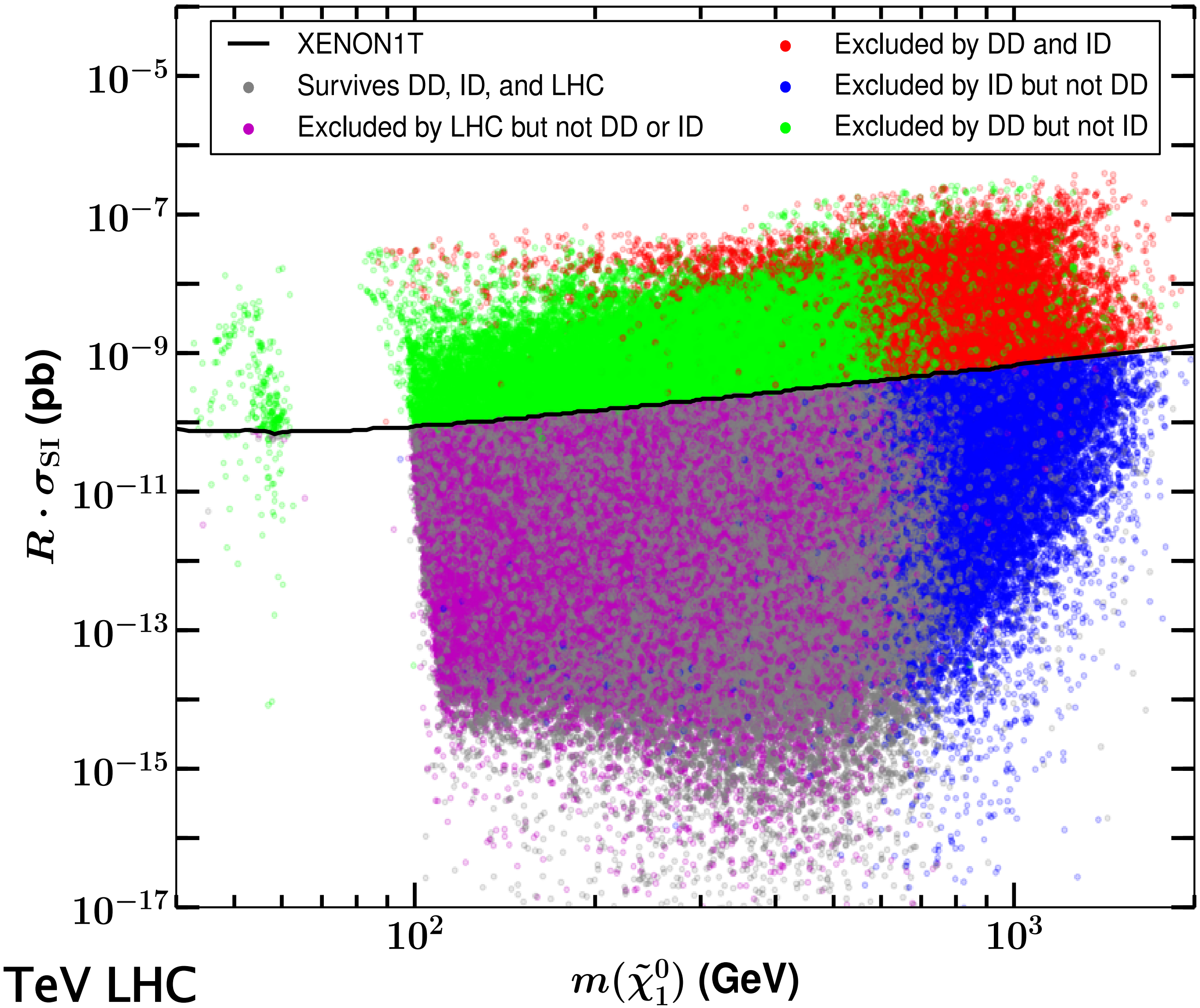
What happens when they are combined ?

Cahill-Rowley etal, 1305.6921, 1405.next



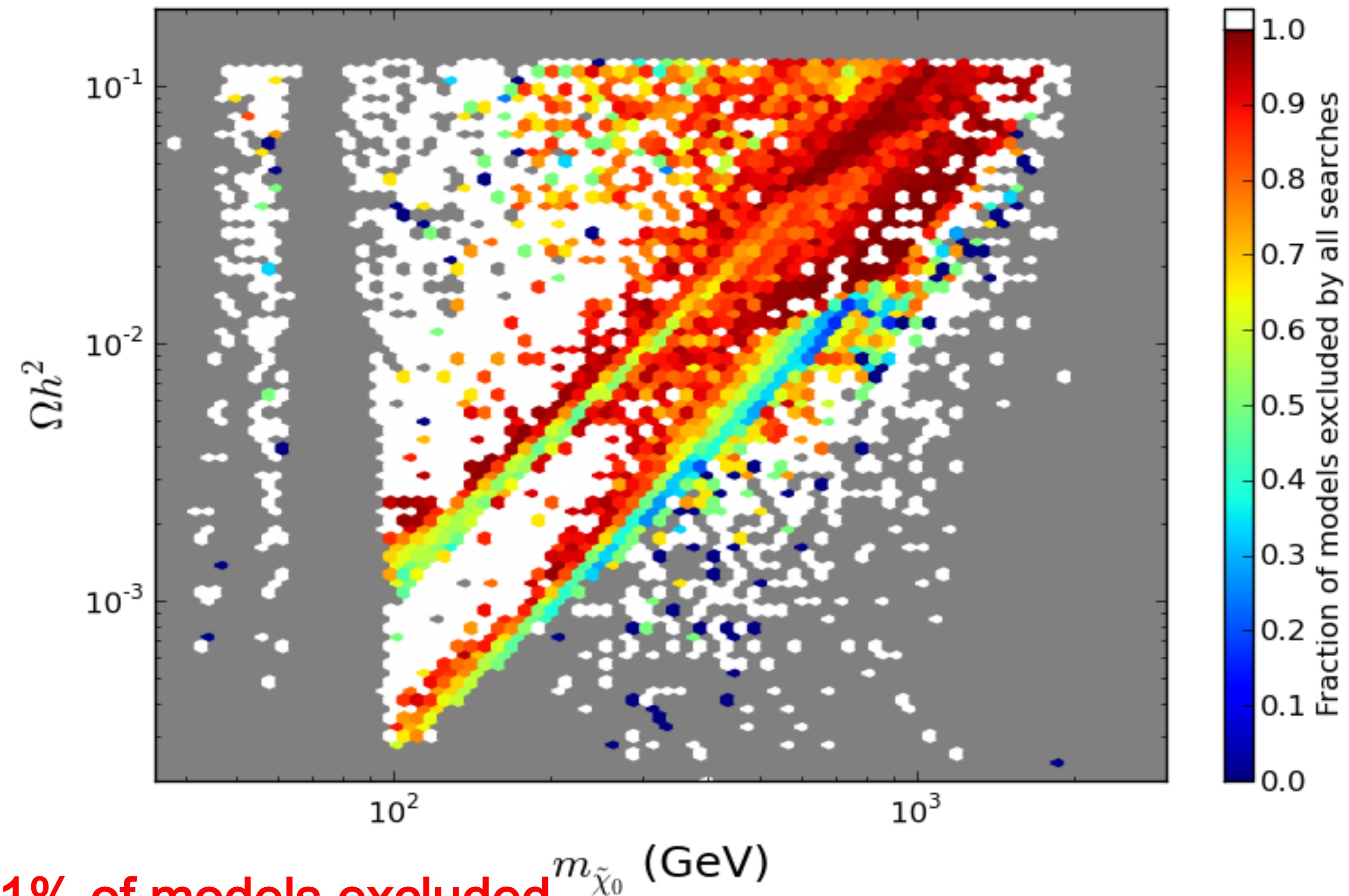
Bino
Wino
Higgsino
Bino-Higgsino
Bino-Wino
Wino-Higgsino
Mixed
Well-tempered neutralino
Bino co-annihilation
1.7 TeV wino
1 TeV Higgsino
Other annihilations
Bino annihilation through h/Z funnels
Ωh^2
$m_{\tilde{\chi}_0}$ (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^2
10^3

Complementarity of Searches



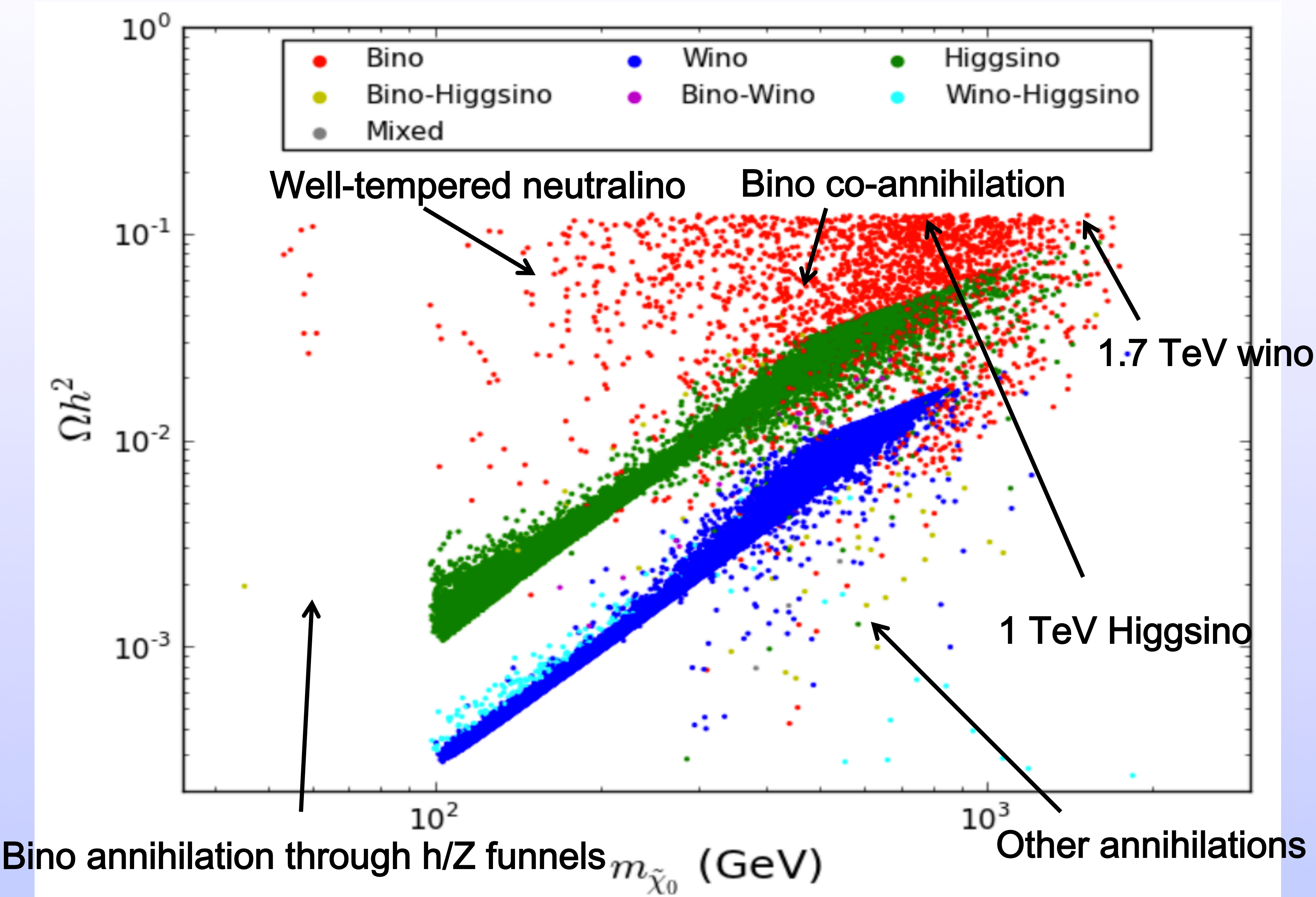
7-8 TeV LHC

OVERALL Combined Search Efficiency

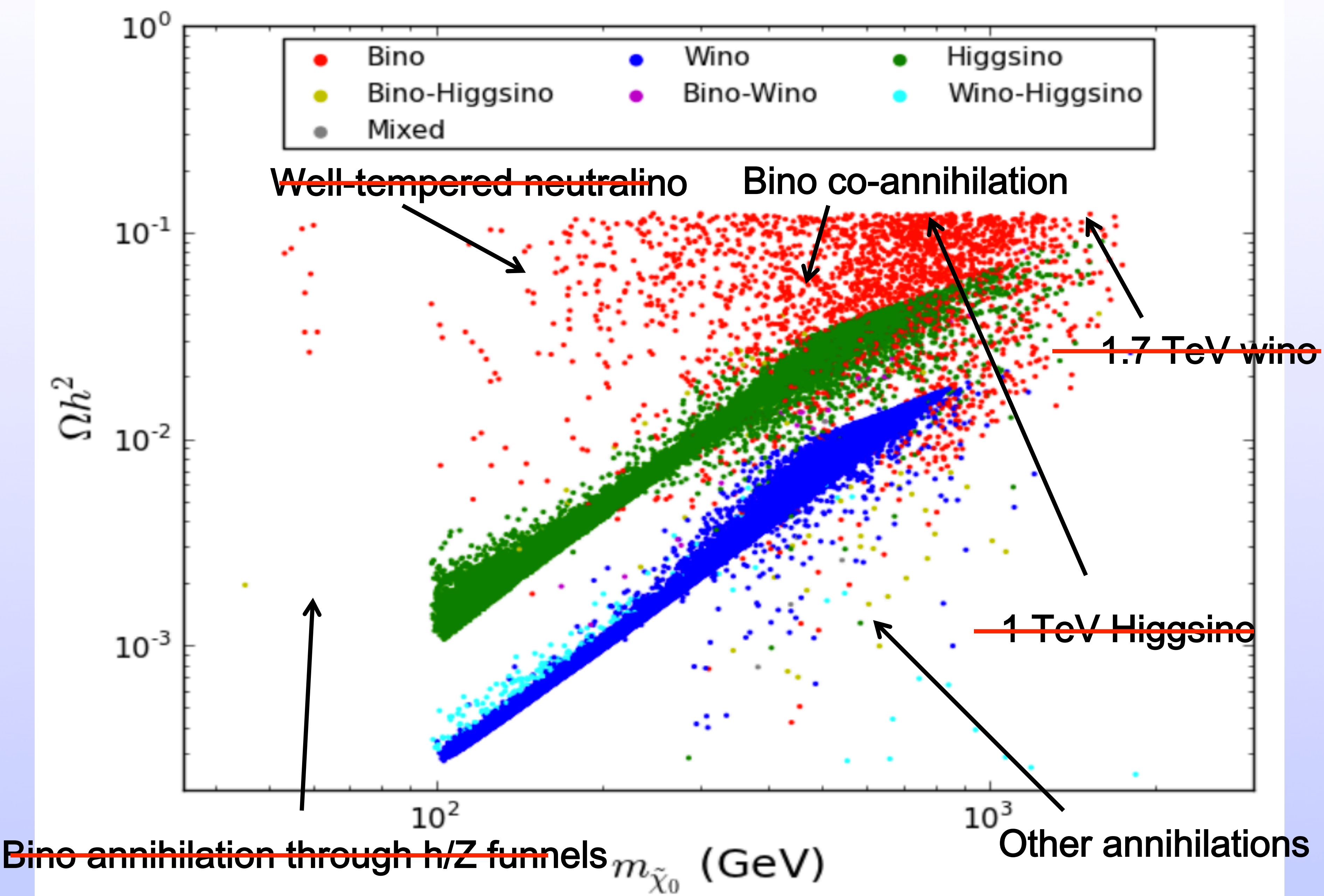


~61% of models excluded

Remaining Model Set



Remaining Model Set

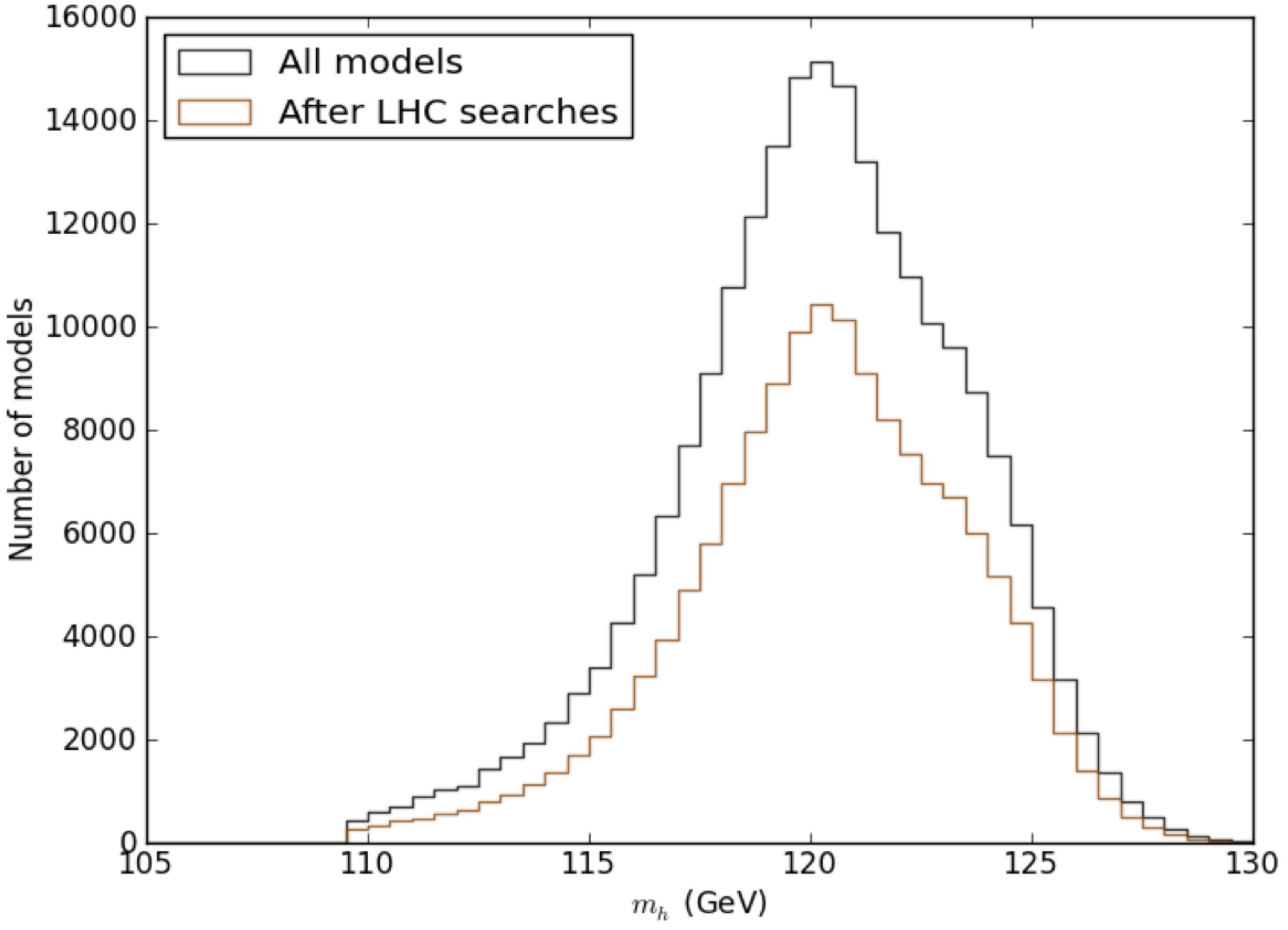


Conclusions

- pMSSM provides excellent playground to study SUSY
- Strong bounds from LHC (and Dark Matter) searches
  - Lighter squarks/gluinos still allowed
  - 14 TeV LHC will probe Natural SUSY @ ~95% level
- Precision Higgs Measurements are important
  - Can probe models missed by 14 TeV LHC
- Reasonable fine-tuning ~1% is possible
  - Selects region of parameter space
  - Light stop/sbottom
  - Very light and compressed EW-ino sector: good for ILC
- All approaches to Dark Matter searches are important for probing the parameter space
- Flavor Physics provides a valuable probe
  - Can probe models missed by 14 TeV LHC

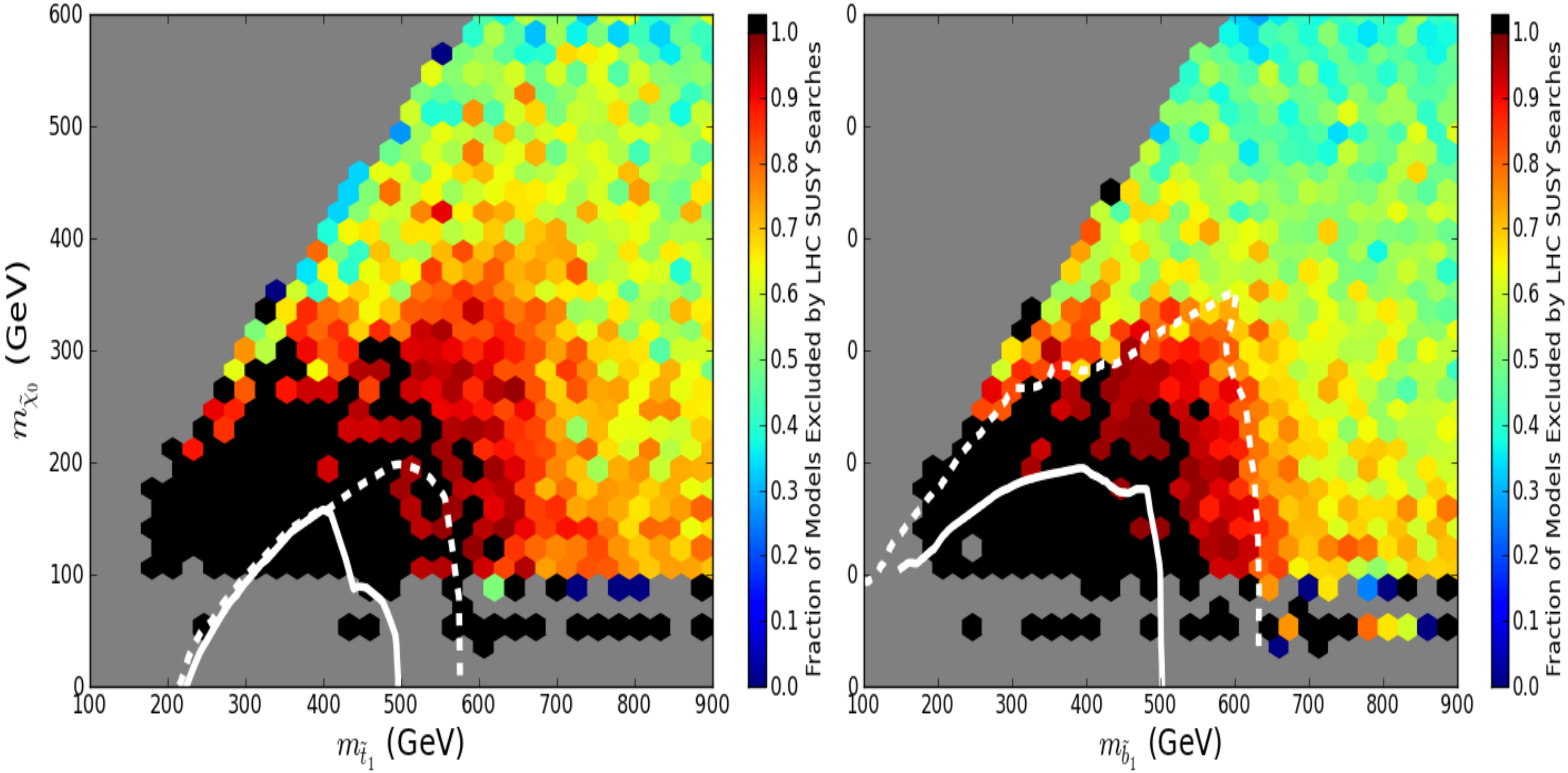
Backup

Higgs Mass Effect on LHC MET-based Searches

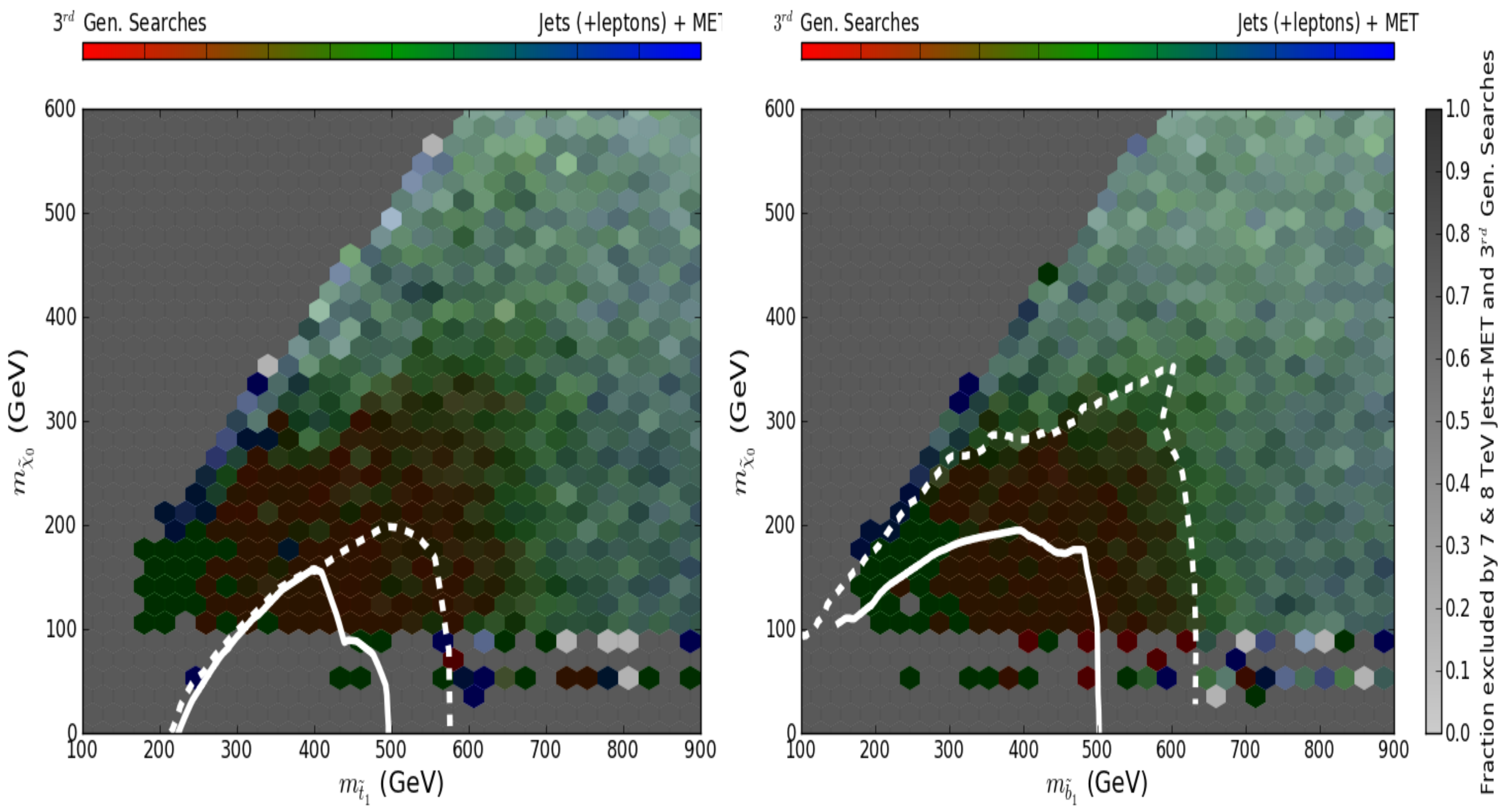


The MET-based searches are roughly independent of the of the Higgs mass: the predicted mass of the Higgs is roughly independent of the searches

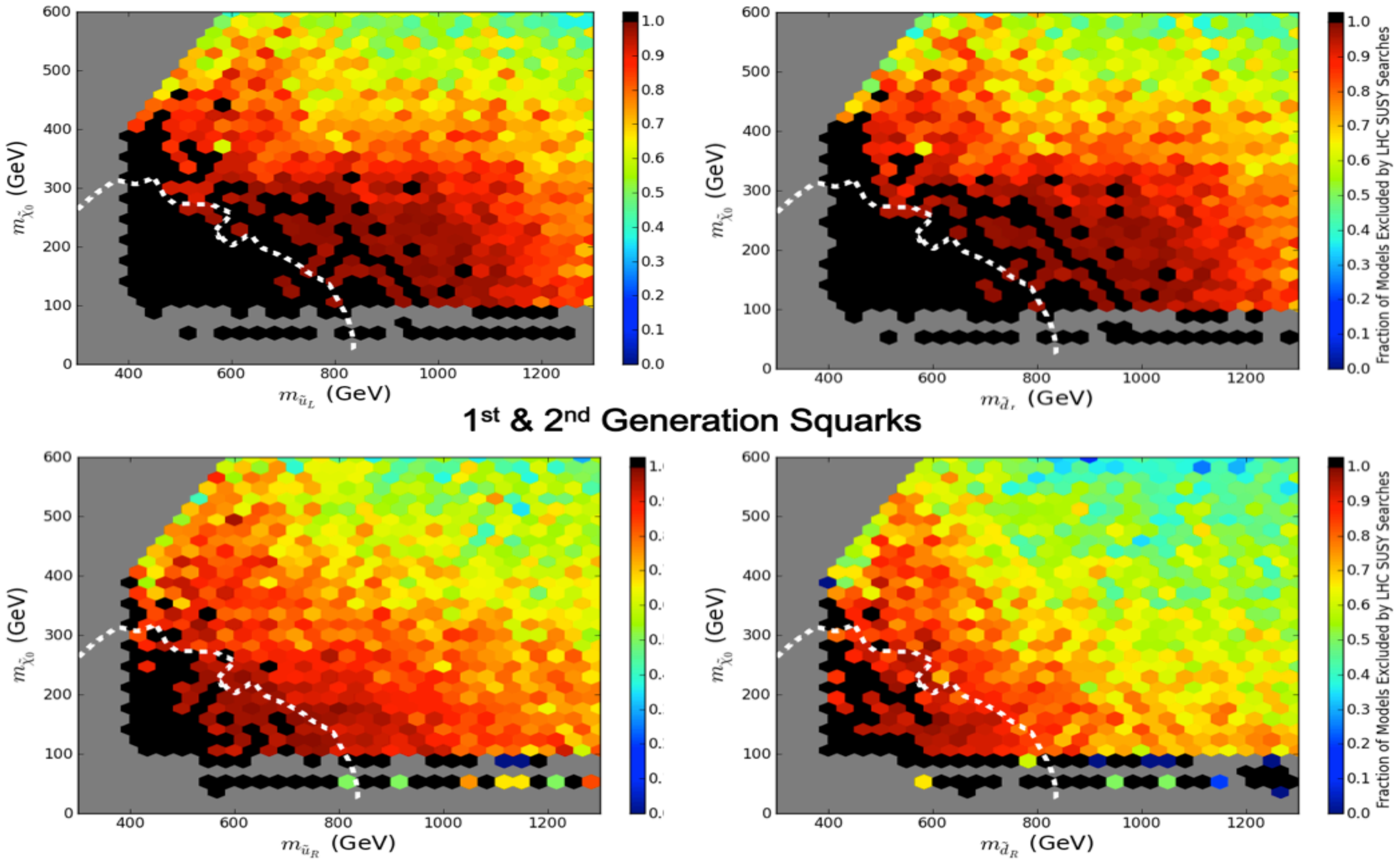
Effects of LHC Searches on Neutralino LSP Sample



Effects of LHC Searches on Neutralino LSP Sample

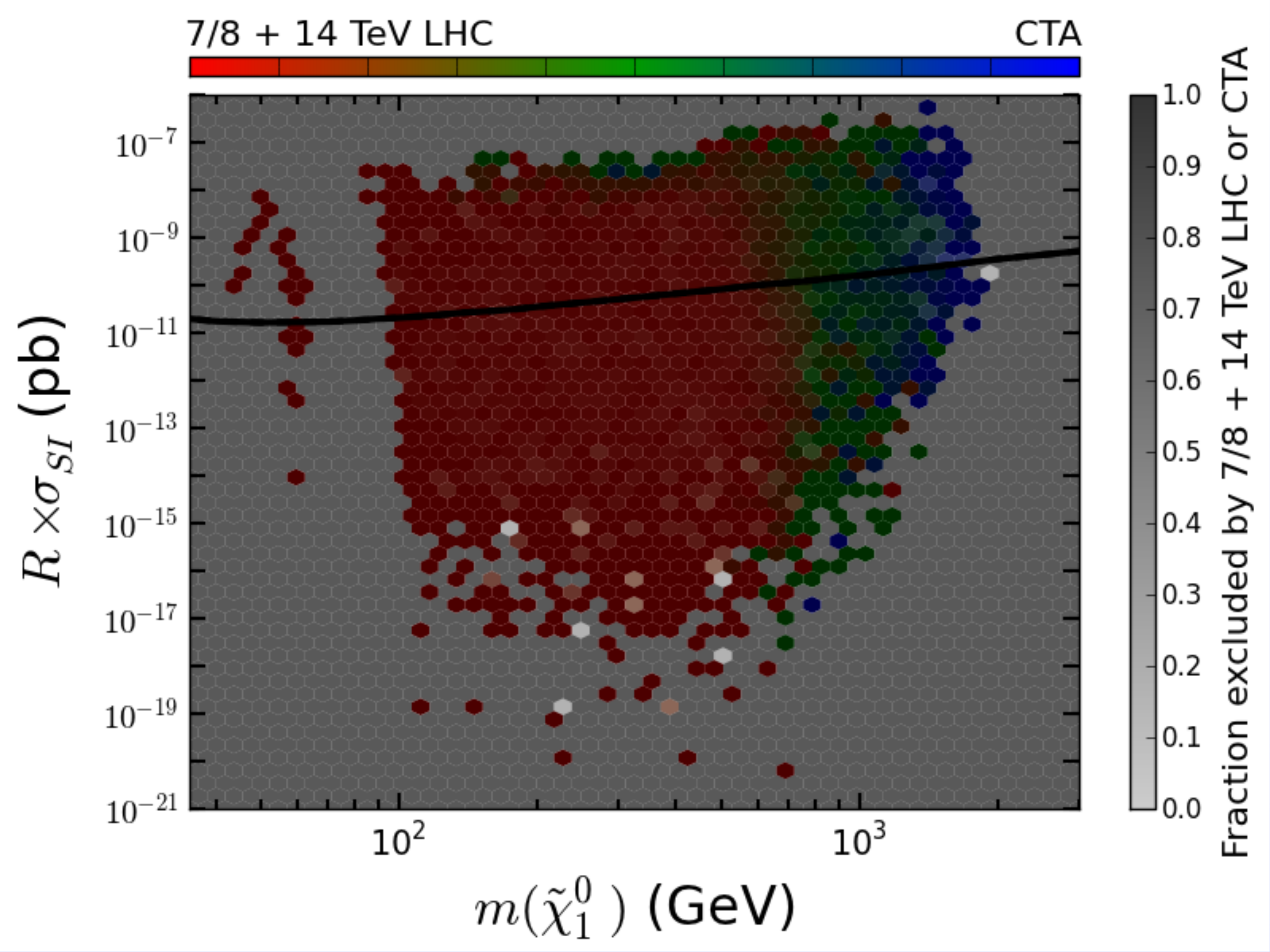


Effects of LHC Searches on Neutralino LSP Sample



1st & 2nd Generation Squarks

Complementarity of Searches



'All-But' Survivor Density Distributions