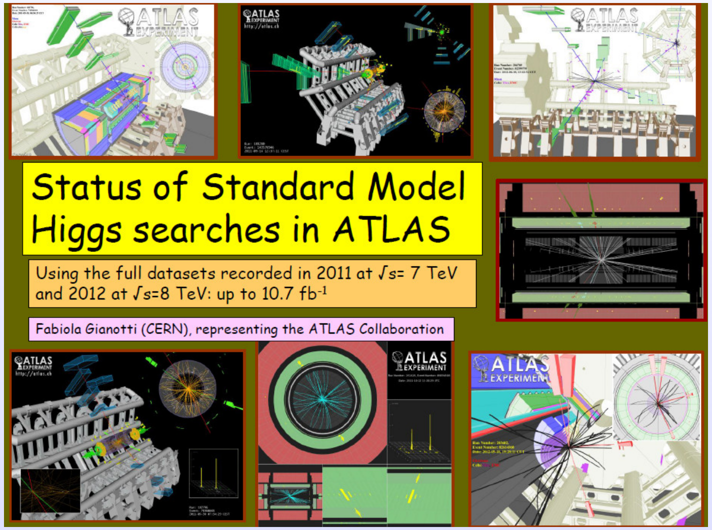
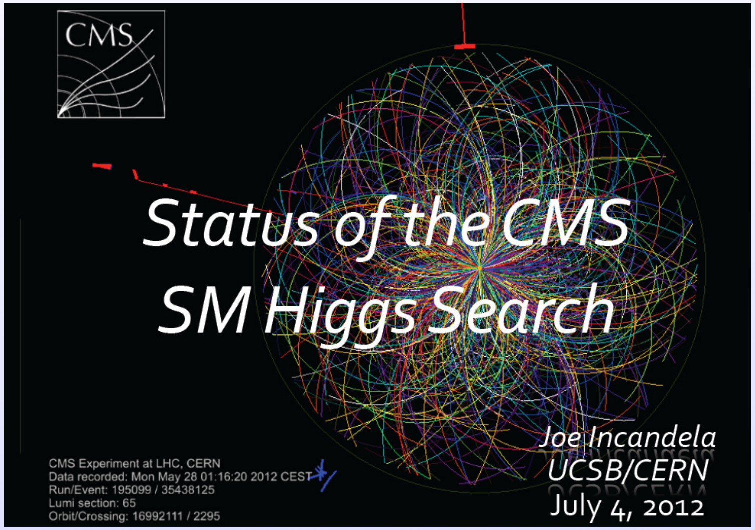
A Higgs, but no Sparticles yet: What it means for the pMSSM





Cahill-Rowley, JLH, Hoeche, Ismail, Rizzo 1206.4321, 1206.5800, 1211.1981, 1211.7106

pMSSM Studies

Berger, Cahill-Rowley, Conley, Cotta, Gainer, JLH, Hoeche, Howe, Ismail, Le, Rizzo 0812.0980, 1007.5520, 1009.2539, 1103.1697, 1105.1199, 1111.2604, 1206.4321, 1206.5800, 1211.1981, 1211.7106

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

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

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

Strubig, Caron, Rammensee 1202.6244

Carena, Lykken, Sekmen, Shah, Wagner 1205.5903

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

    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: μ, M_A, $\tan\beta$

    (Gravitino: M_G)

Berger, Gainer, JLH, Rizzo 0812.0980

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!

Model Constraints

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

- Direct Detection of Dark Matter (SI & SD)
- WMAP Dark Matter density upper bound
- LEP and Tevatron Direct Higgs & SUSY searches
- LHC stable sparticle searches
- BBN energy deposition for gravitinos
- Relic ν's & diffuse photon bounds
- No tachyons or color/charge breaking minima
- Stable vacua only

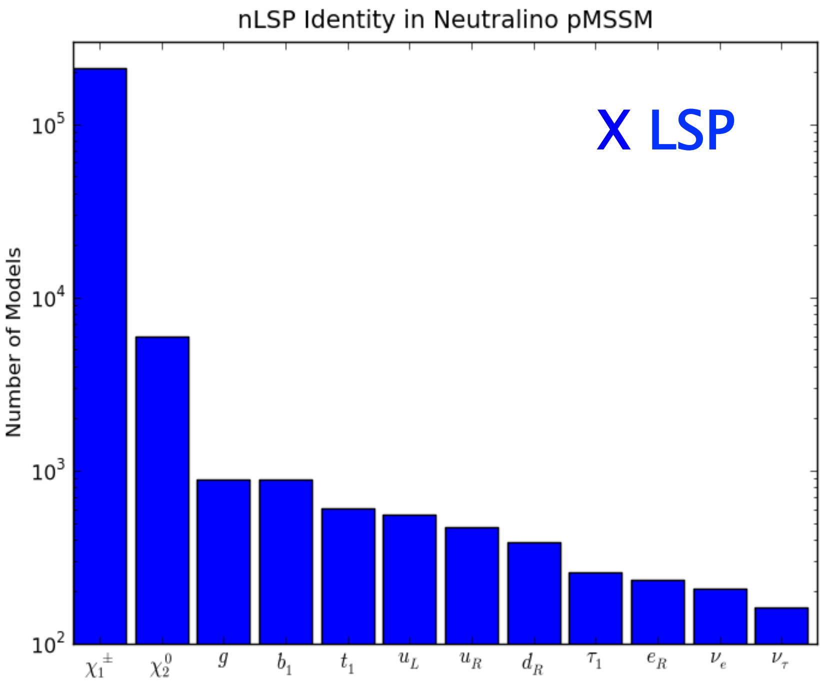
Electroweak Content of χ_1^0

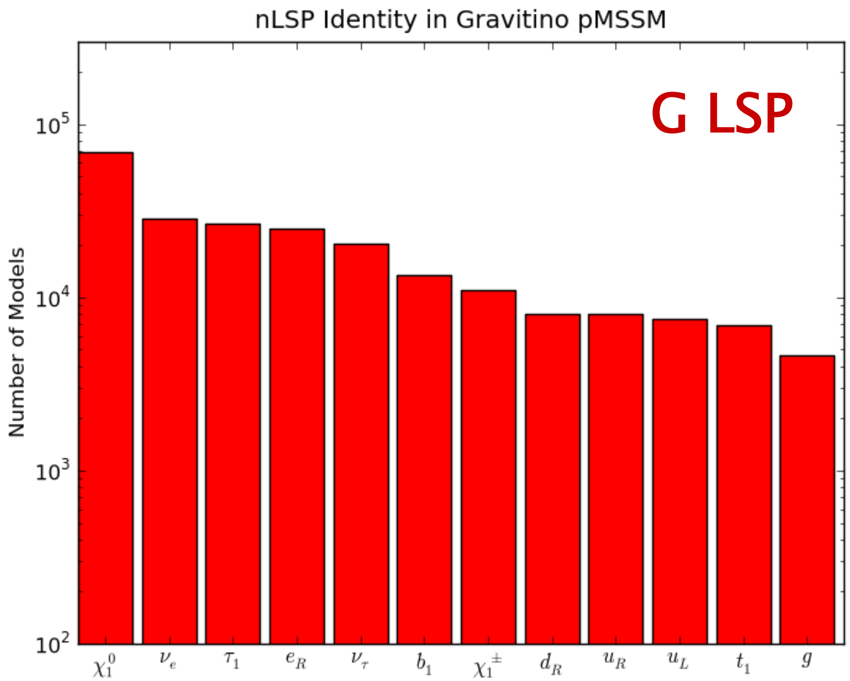
Lightest Neutralino	Definition	Neutralino LSP	Gravitino LSP
Bino	$\lvert N_{11}\rvert^2 > 0.95$	0.024	0.313
Mostly Bino	$0.80 < \lvert N_{11}\rvert^2 < 0.95$	0.002	0.012
Wino	$\lvert N_{12}\rvert^2 > 0.95$	0.546	0.296
Mostly Wino	$0.80 < \lvert N_{12}\rvert^2 < 0.95$	0.022	0.019
Higgsino	$\lvert N_{13}\rvert^2 + \lvert N_{14}\rvert^2 > 0.95$	0.340	0.296
Mostly Higgsino	$0.80 < \lvert N_{13}\rvert^2 + \lvert N_{14}\rvert^2 < 0.95$	0.029	0.029
All other models	$\lvert N_{11}\rvert^2, \lvert N_{12}\rvert^2, \lvert N_{13}\rvert^2 + \lvert N_{14}\rvert^2 < 0.80$	0.036	0.035

With most of the neutralino parameters ~ 1 TeV the mass & electroweak eigenstates are generally quite close !

Identity of the Next-to-LSP

- The frequency of various NLSP identities is very strongly dependent on the LSP choice
- This can have a potentially large influence on LHC SUSY searches (apart from, e.g., additional cascades)





ATLAS SUSY Analyses @ 7 & 8 TeV

- Apply the general LHC SUSY MET searches to our model sets
- We (almost) exclusively follow the ATLAS analysis suite as closely as possible with fast MC (modified PGS/Pythia)
- 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!!

2011 Data (7 TeV)

Short Title of the Paper	Mark	Date	√s (TeV)	L (fb^{-1})	Document	Plots+Aux. Material	Journal
1-2 leptons + >=2-4 jets + Etmiss NEW	✓	08/2012	7	4.7	1208.4688	Link	Submitted to PRD
2 leptons + >=1 jet + Etmiss [Very light stop] NEW	✓	08/2012	7	4.7	1208.4305	Link	Submitted to EPJC
3 leptons + Etmiss [Direct gauginos] NEW	✓	08/2012	7	4.7	1208.3144	Link	Submitted to PLB
2 leptons + Etmiss [Direct gauginos/sleptons] NEW	✓	08/2012	7	4.7	1208.2884	Link	Submitted to PLB
1 lepton + >=4 jets (>=1 b-jet) + Etmiss [Heavy stop] NEW	✓	08/2012	7	4.7	1208.2590	Link	Submitted to PRL
0 lepton + 1-2 b-jet + 5-4 jets + Etmiss [Heavy stop] NEW	✓	08/2012	7	4.7	1208.1447	Link	Submitted to PRL
~~0 lepton + >=2-6 jets + Etmiss NEW~~		08/2012	7	4.7	1208.0949	Link	Submitted to PRD
0 lepton + >=3 b-jets + >=(1-3) jets + Etmiss [Gluino med. stop/sb.]	✓	07/2012	7	4.7	1207.4686	Link	Submitted to EPJC
0 lepton + >=(6-9) jets + Etmiss		06/2012	7	4.7	1206.1760	Link	JHEP 1207 (2012) 167
Electron-muon continuum [RPV]	X	05/2012	7	2.05	1205.0725	Link (inc. HEPData)	EPJC 72 (2012) 2040
Z->ll + b-jet + jets + Etmiss [Direct stop in natural GMSB]	✓	04/2012	7	2.05	1204.6736	Link (inc. HEPData)	PLB 715 (2012) 44

Short Title of the Conf. note	Mark	Date	√s (TeV)	L (fb^{-1})	Document	Plots
1-2 taus + 0-1 leptons + jets + Etmiss NEW	X	08/2012	7	4.7	ATLAS-CONF-2012-112	Link
3 leptons + jets + Etmiss NEW	✓	08/2012	7	4.7	ATLAS-CONF-2012-108	Link
2 b-jets + Etmiss [Direct sbottom] NEW	✓	08/2012	7	4.7	ATLAS-CONF-2012-106	Link
muon + displaced vertex [RPV] NEW	✓	08/2012	7	4.7	ATLAS-CONF-2012-113	Link
Disappearing track + jets + Etmiss [Direct long-lived charginos - AMSB] NEW	✓✓	08/2012	7	4.7	ATLAS-CONF-2012-111	Link
~~*2 jet-pair resonances [N=1/2 scalar gluons]*~~ NEW		08/2012	7	4.7	ATLAS-CONF-2012-110	Link
General new phenomena search NEW		08/2012	7	4.7	ATLAS-CONF-2012-107	Link
Monophoton [ADD, WIMP]		07/2012	7			
Monojet [ADD, WIMP]		07/2012	7			
Long-Lived Particles [R-hadron, slepton]	✓	07/2012	7			
2 photons + Etmiss [GGM]	✓	07/2012	7			
2 leptons + jets + Etmiss [Medium stop]	✓	07/2012	7			
1-2 b-jets + 1-2 leptons + jets + Etmiss [Light Stop]	X	07/2012	7			

2012 Data (8 TeV)

Short Title of the CONF note	Date	√s (TeV)	L (fb^{-1})	Document	Plots
0 leptons + >=2-6 jets + Etmiss NEW	08/2012	8	5.8	ATLAS-CONF-2012-109	Link
0 leptons + >=6-9 jets + Etmiss NEW	08/2012	8	5.8	ATLAS-CONF-2012-103	Link
1 lepton + >=4 jets + Etmiss NEW	08/2012	8	5.8	ATLAS-CONF-2012-104	Link
2 same-sign leptons + >=4 jets + Etmiss NEW	08/2012	8	5.8	ATLAS-CONF-2012-105	Link

Benchmark Validation

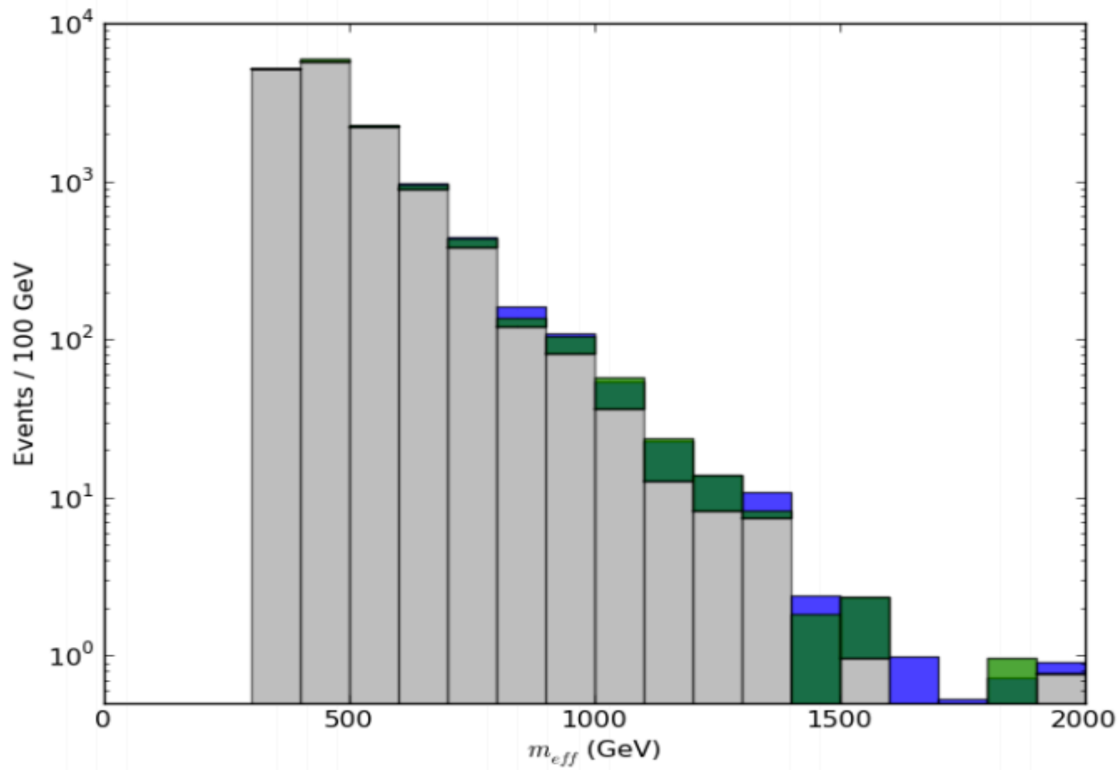


Figure 16: Effective mass distribution for events passing the cuts of the two jet signal region from the ATLAS jets plus MET search [48]. The SM background is shown in gray, with our signal prediction (blue) and the corresponding ATLAS signal prediction (green) on top, for the benchmark mSUGRA point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

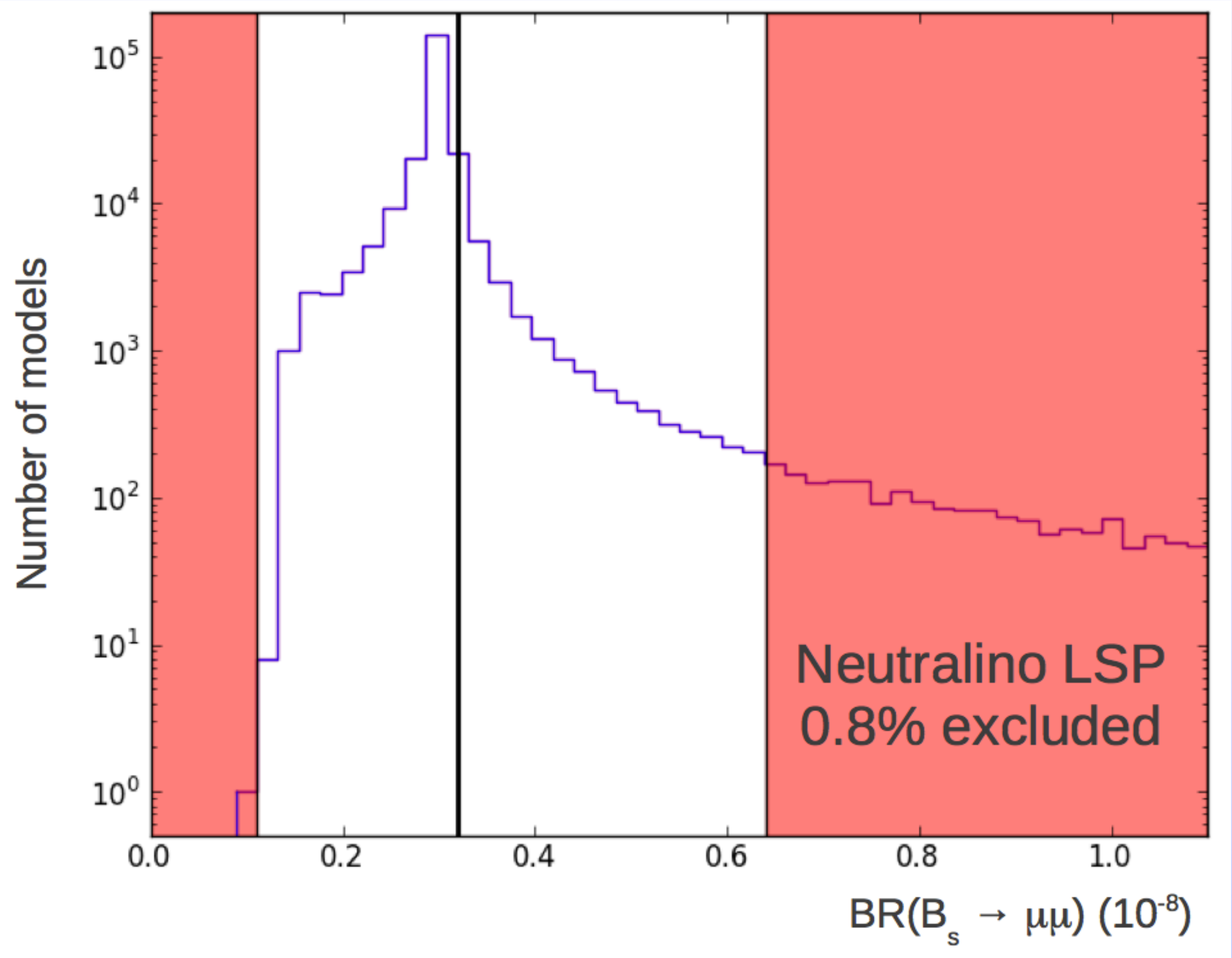
LHC Search Results on the pMSSM: percentage of models excluded by data

Analysis	7 TeV	8 TeV	*8 TeV 25 fb^{-1}*
Jets + MET	21.0%	26.5%	*25.3%*
Many jets + MET	1.6%	3.3%	*3.3%*
1 ℓ + jets + MET	3.2%	3.3%	*3.8%*
SSDL	—	4.9%	*7.5%*
Multi-leptons	4.3%	—	—
Stop/sbottom	7.3%	—	—
HSCP	4.0%	—	—
Disappearing tracks	2.6%	—	—
$B_s \to \mu\mu, \Phi \to \tau\tau$	2.2%		—
Remaining models	66.4%		*65.6%*

- ~1% of models killed by 7 TeV data, pass 8 TeV searches
- Fraction of models remaining not sensitive to Higgs mass cut

Non-MET Searches

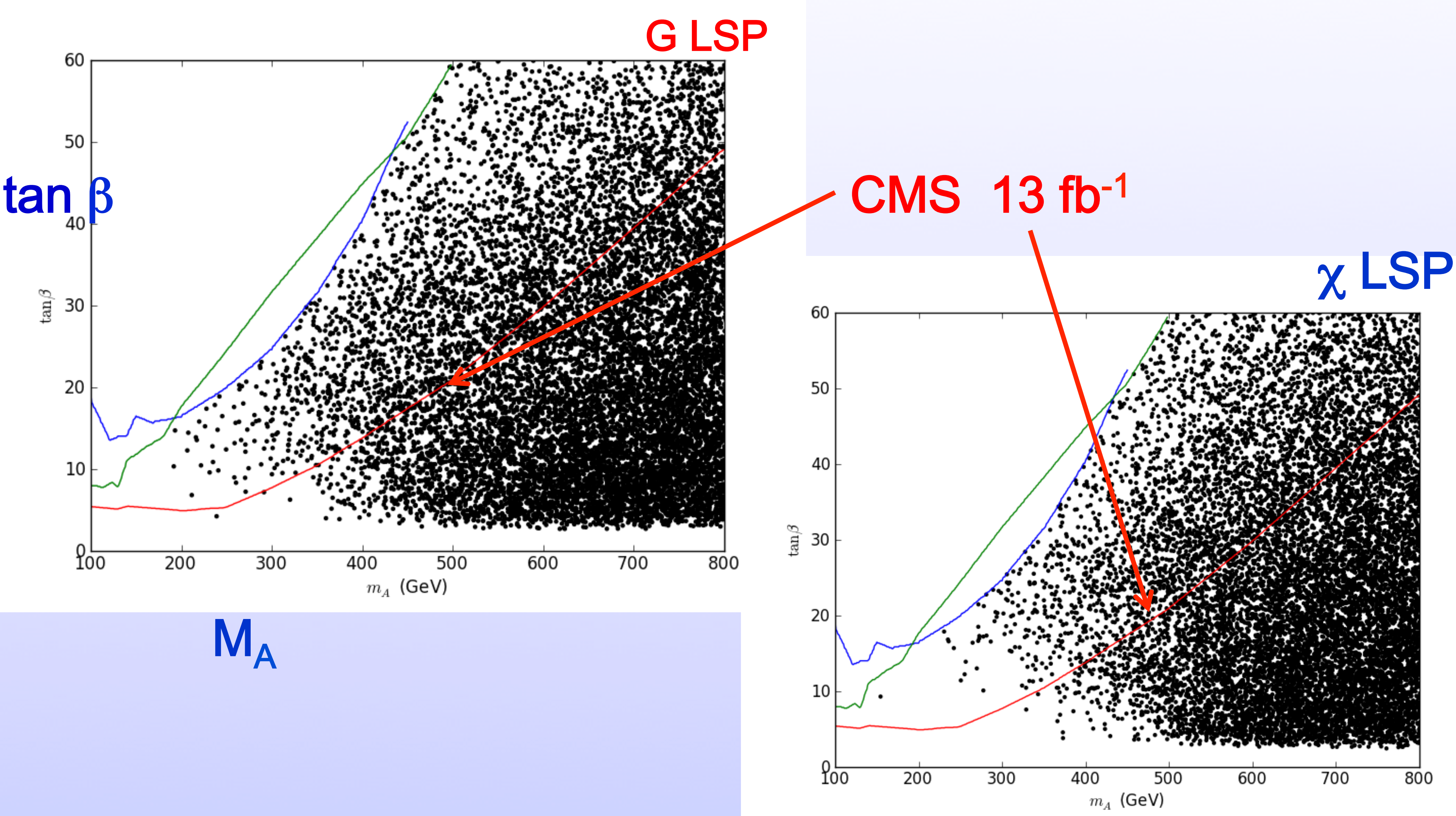
LHCb: $B(B_s \rightarrow \mu\mu) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$



95% CL interval:
$[1.1, 6.4] \times 10^{-9}$

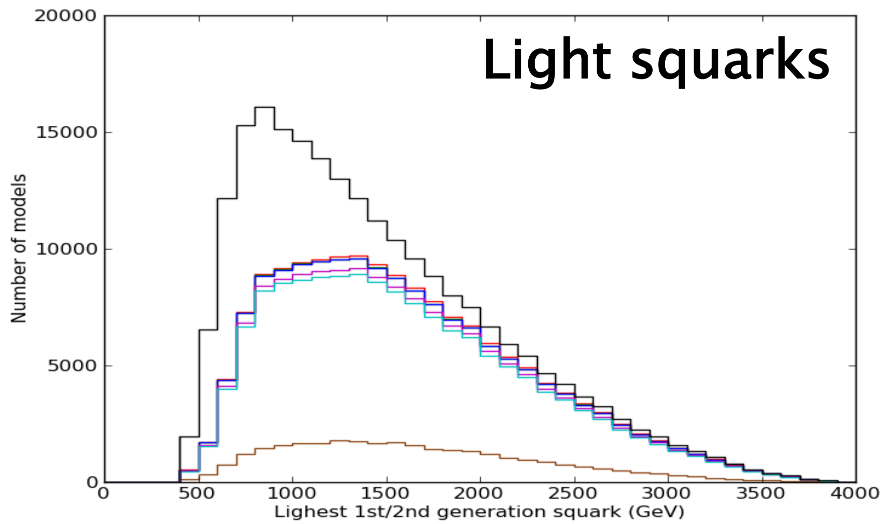
Excludes
1819 χ LSP models
2167 G LSP models

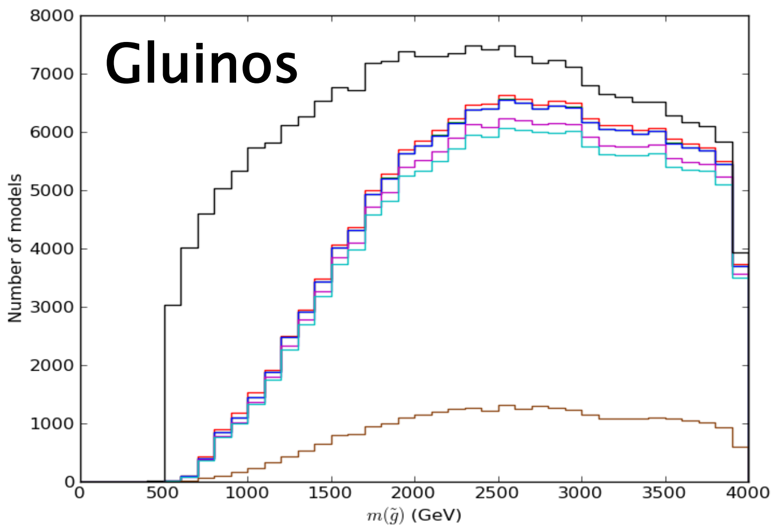
Impact of A,H $\rightarrow\tau\tau$ Searches

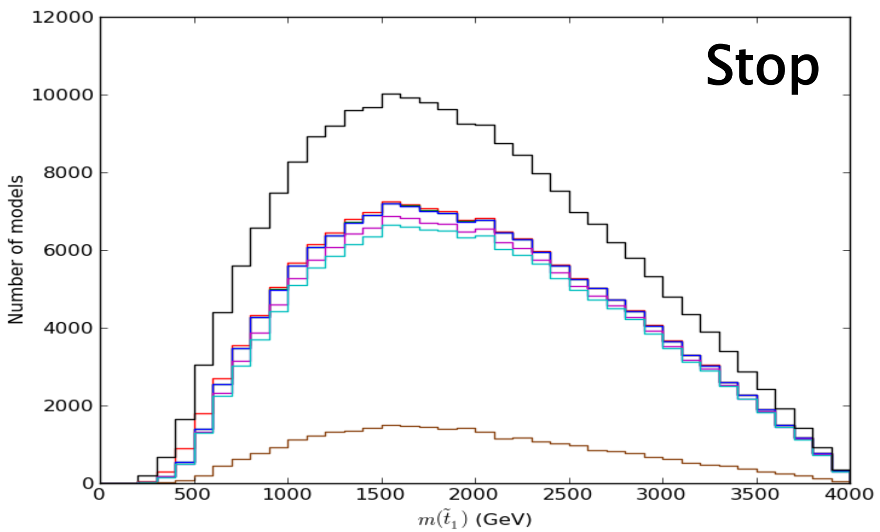


As in the case of $B_s \rightarrow\mu\mu$, improvement in non-MET searches impact the pMSSM analyses… 3671(3309) models removed from the χ (G) LSP set…

Results of LHC Searches on Neutralino LSP Sample



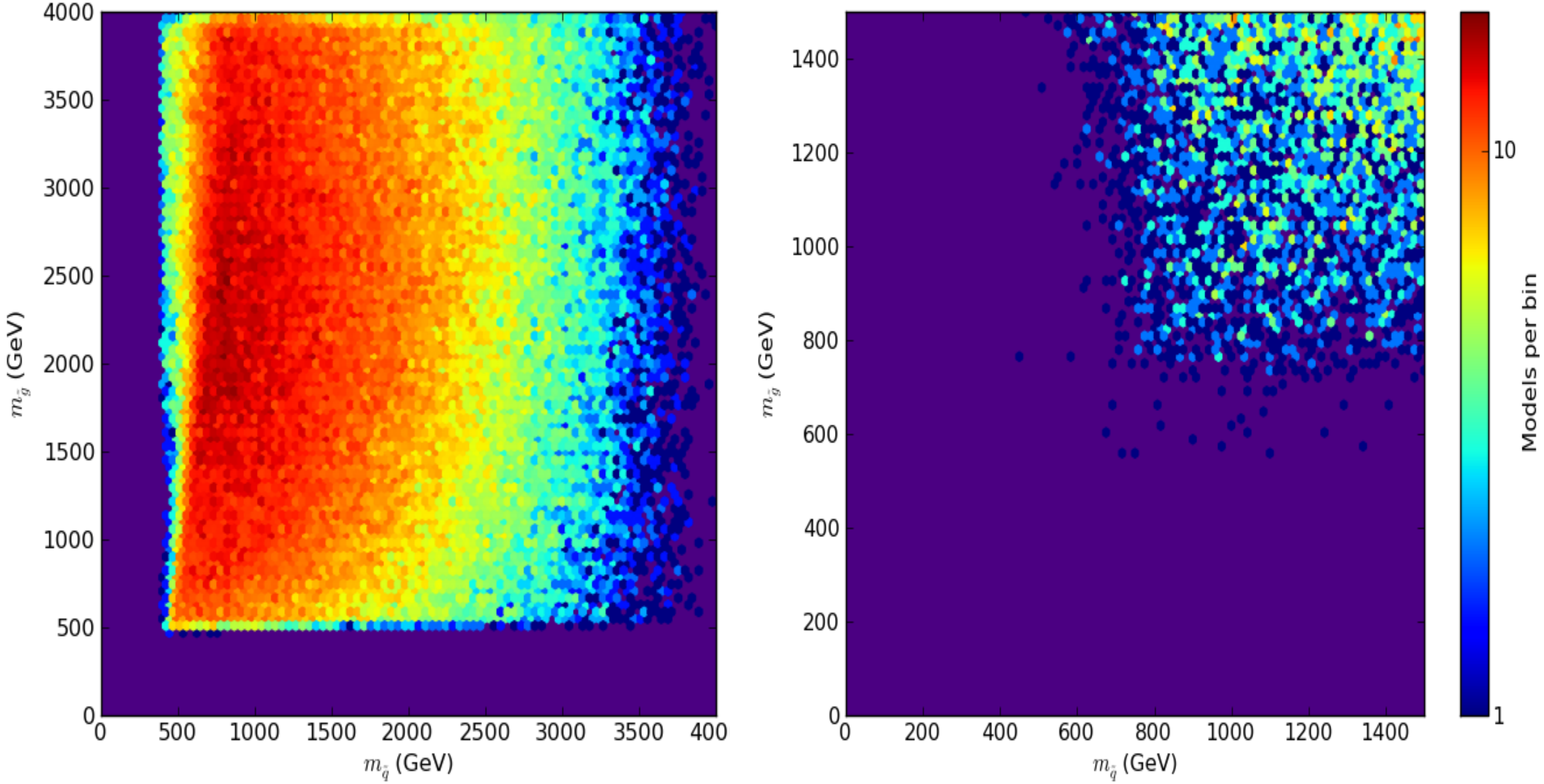




Sparticle distributions:
Before LHC
7/8 TeV Jets+MET
Heavy Flavor
Multileptons
HSCP & Disappearing tracks
Non-MET
126 +/- 3 GeV Higgs

Light Squarks/Gluinos are still allowed!

Full model set **After LHC Searches**



Some New Features for Gravitino LSP Set

- For non-G decays (e.g., for the NNLSP → NLSP) add all 3-body sparticle decays not in SUSY-Hit via CalcHEP
- Add relevant 4 & 5-body decays for gluinos, t_1 & $\chi_1^{\pm}$

→ RESULT: NNLSPs can also be detector stable

- For NLSP decays to G, add all 3- & 4-body modes w/ BBN relevant lifetimes (~10^{-4} to 10^{14} sec) via MadGraph
- Calculate NLSP density using Micromegas & rescale to the gravitino mass
- Use lifetime & BF info for NLSPs from modified SUSY-Hit & check the constraints on EM or hadronic energy deposition during BBN
- Apply constraints from the cosmo relic ν & diffuse photon fluxes

Gravitino Model Searches @ 7 TeV: percentage of models excluded by data

	7 TeV ~5 fb^{-1}	8 TeV ~6 fb^{-1}	w/ Higgs cut (8 TeV)
nj0l	17.76%	21.83%	20.82 %
multi-j	2.27%	4.13%	4.02%
nj1l	5.31%	5.38%	5.05%
SS dileptons		11.50%	11.14%
(sub)total	19.44%	28.69%	27.19%
HSCP	16.93%		
3^{rd} Gen	11.14%		
Multi-l	12.10%		
ϒϒ+MET	5.2%		

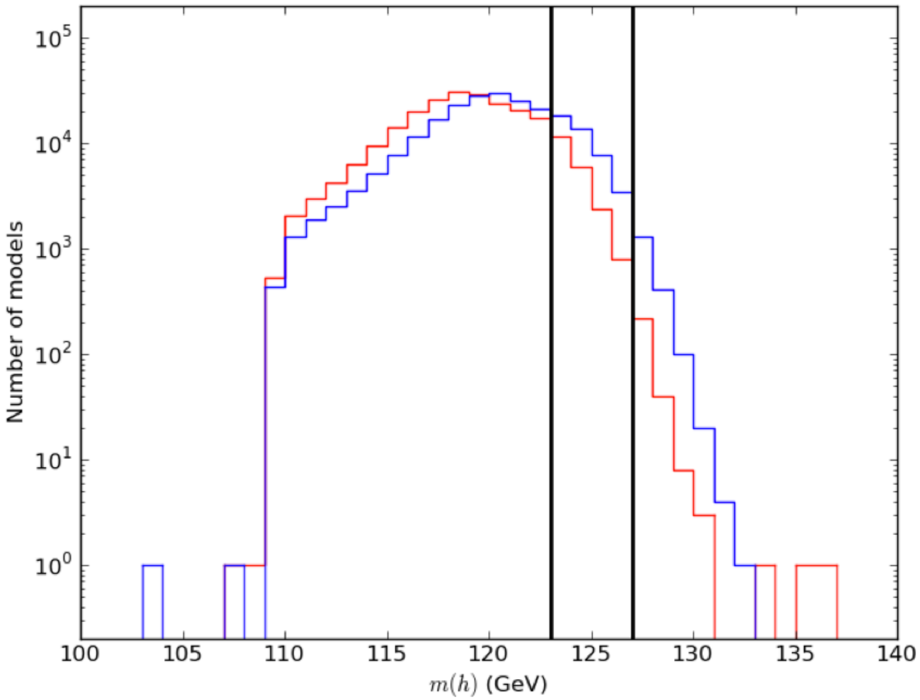
Total models remaining: 53.25%, 54.42% with Higgs mass cut

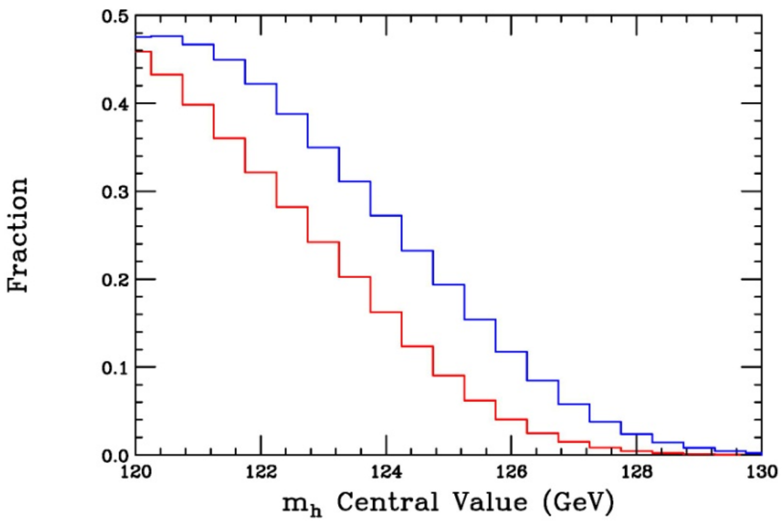

It is not higgs.
http://arXiv:physics/030201
(a meson, probably).
The Clifford pentads
DELEGATE
the electroweak theory and
ontological hypotheses.

Predictions for Lightest Higgs Mass in the pMSSM

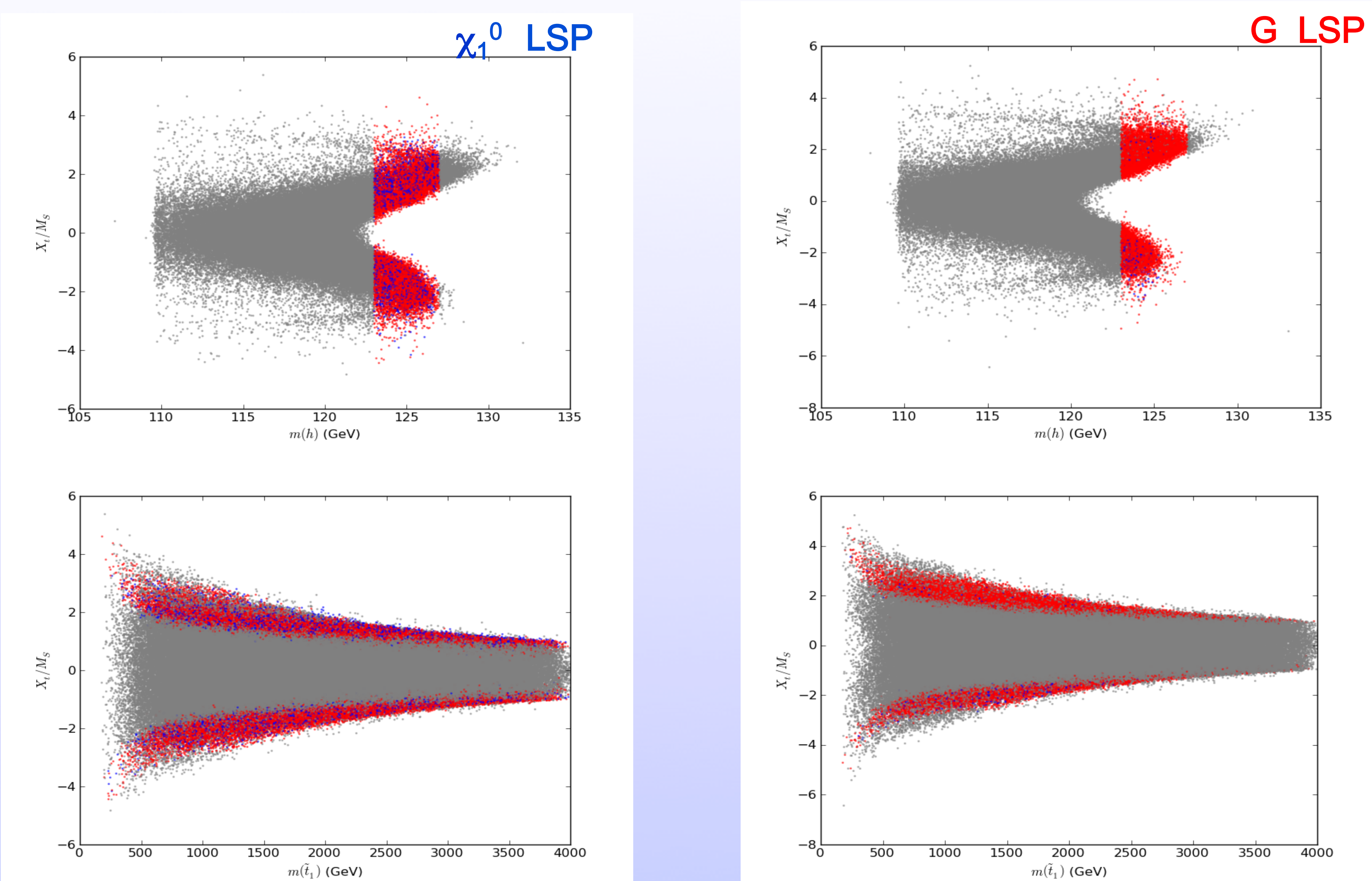
Models consistent with EW Precision, B Physics, Cosmology, and Collider data

Neutralino LSP
Gravitino LSP





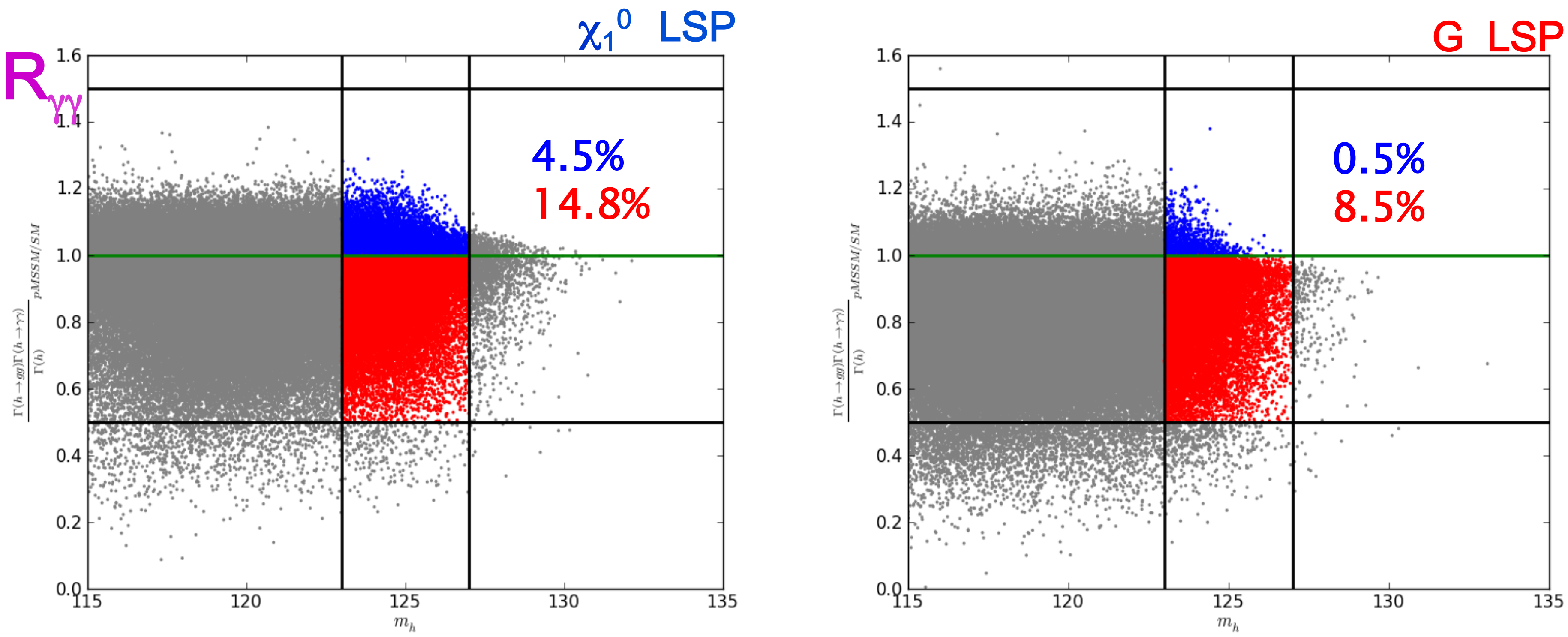
Special parameter regions needed for the126 GeV Higgs



Need large stop mixing: $X_t = A_t - \mu\cot\beta$

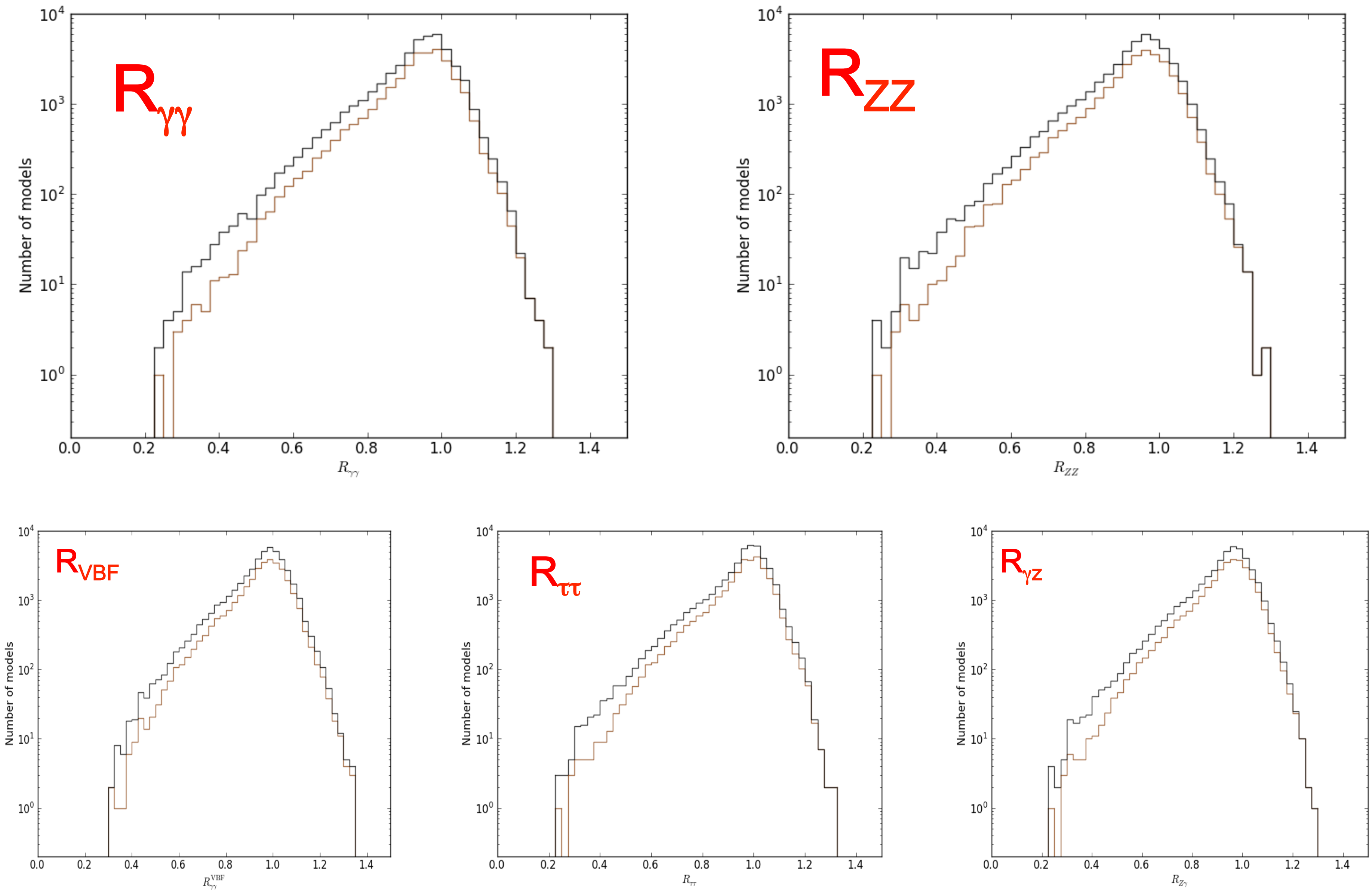
Higgs Properties

$R_{XX} = \sigma(gg\rightarrow h)\, B(h\rightarrow XX)|_{pMSSM/SM}$



The two different model sets lead to qualitatively similar yet quantitatively very different predictions…

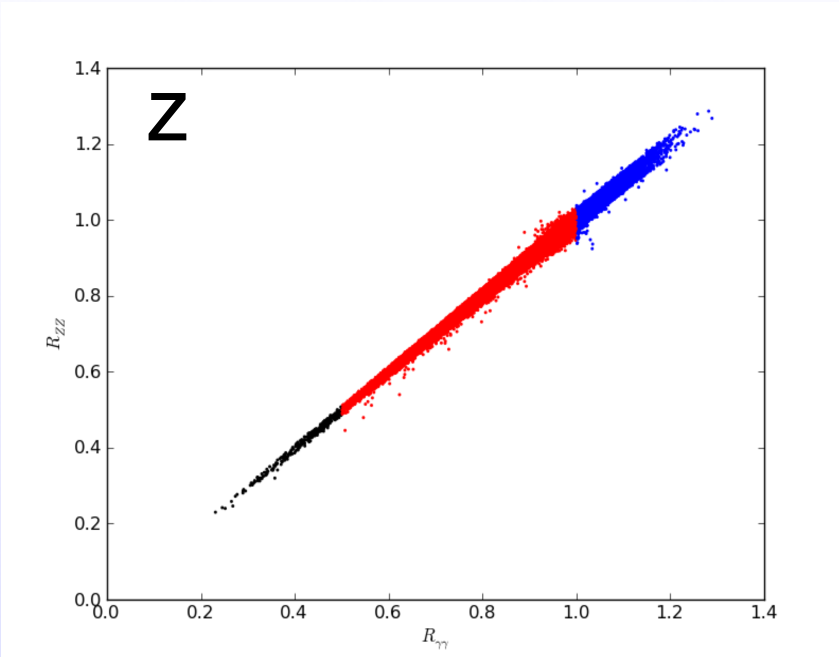
χ_1^0 LSP

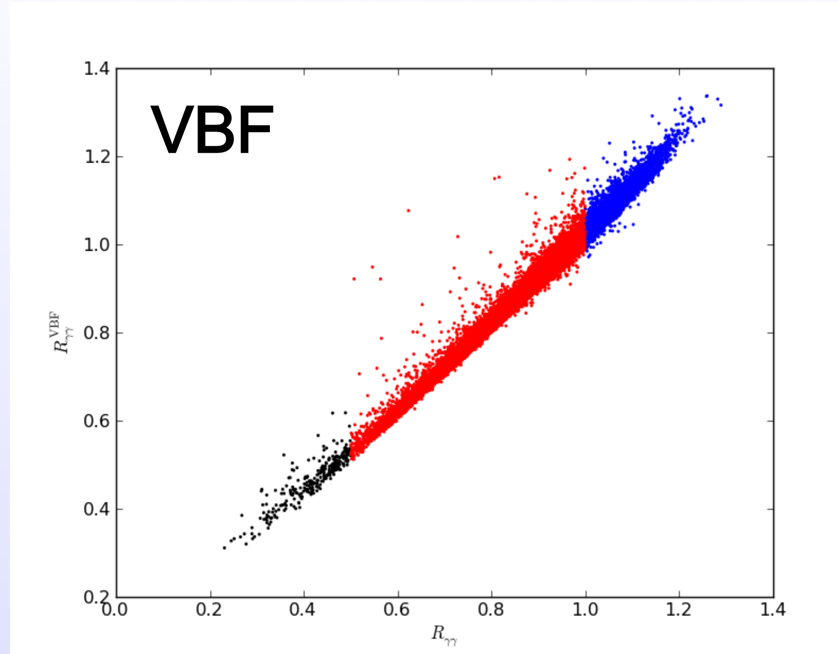


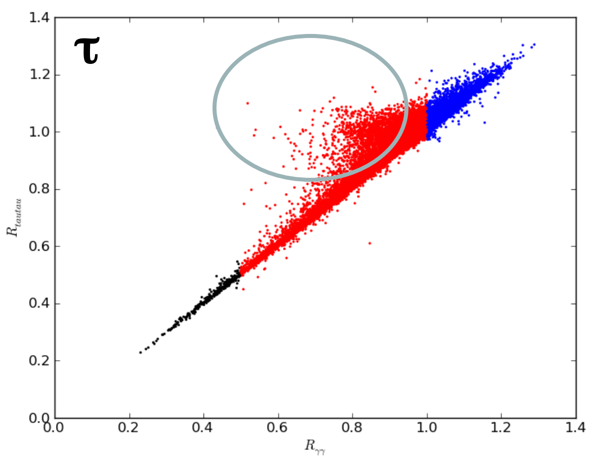
$R_{\gamma\gamma}$
Number of models
$R_{\gamma\gamma}$
R_{ZZ}
Number of models
R_{ZZ}
R_{VBF}
Number of models
$R_{\gamma\gamma}^{VBF}$
$R_{\tau\tau}$
Number of models
$R_{\tau\tau}$
$R_{\gamma Z}$
Number of models
$R_{Z\gamma}$

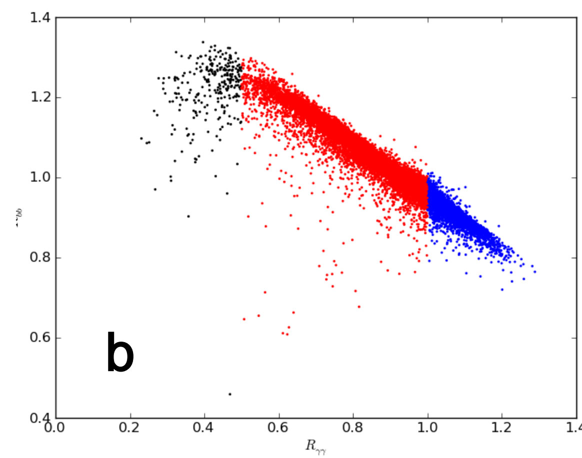
χ_1^0 LSP

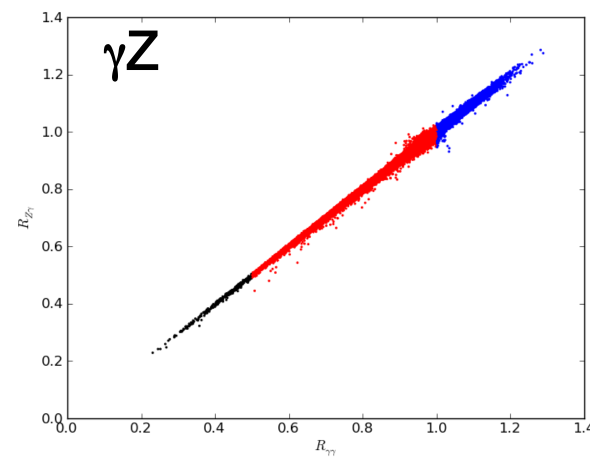
Very Highly Correlated !







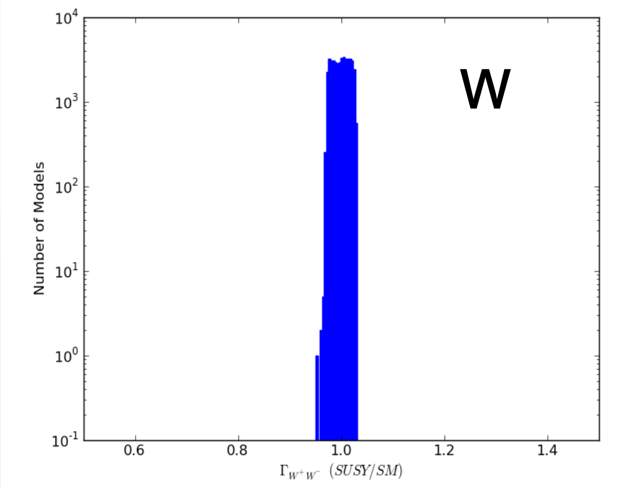


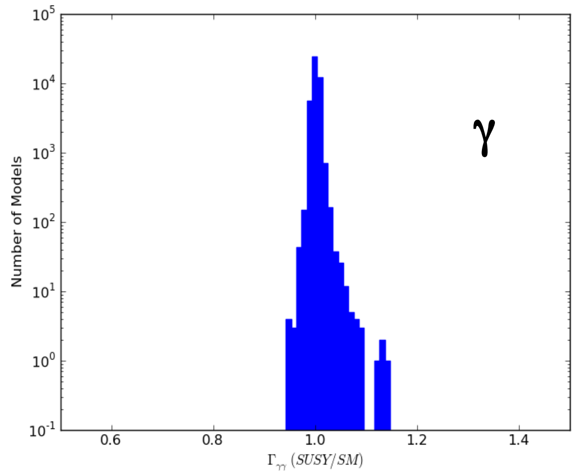


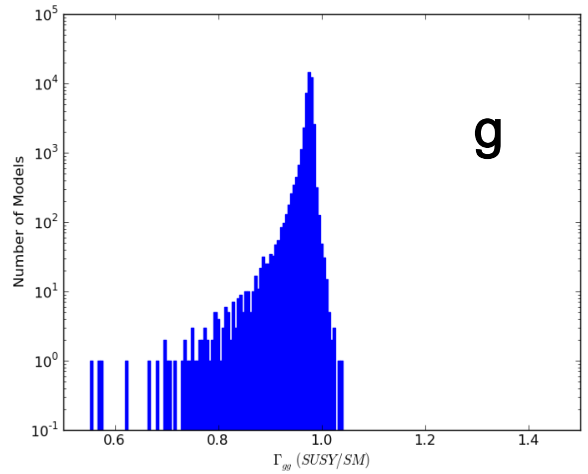
Examination of Partial Widths

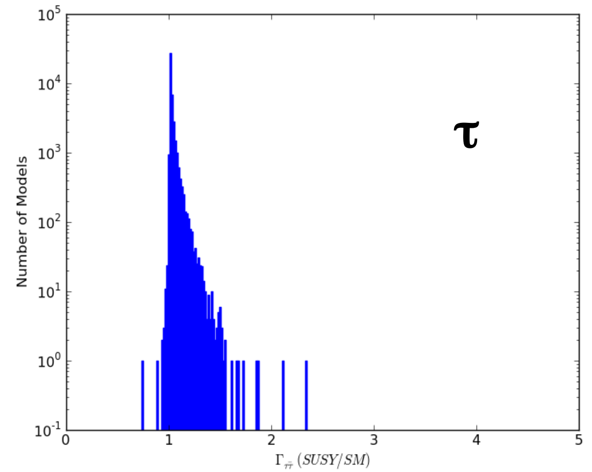
χ_1^0 LSP

- Most partial widths are close to their SM values due to decoupling
- for both LSP model sets we get highly peaked $r = \Gamma / \Gamma_{SM}$ distributions (here for the neutralino model set)
- Precision ILC measurements could Select pMSSM parameters



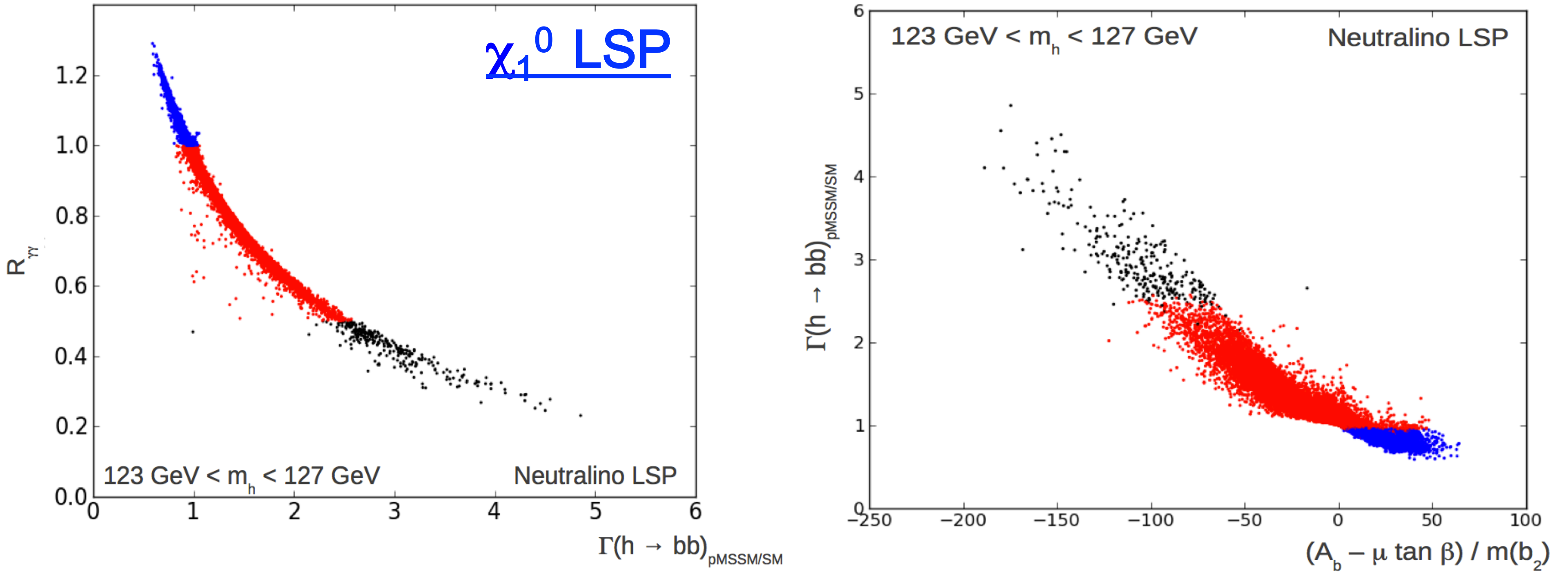




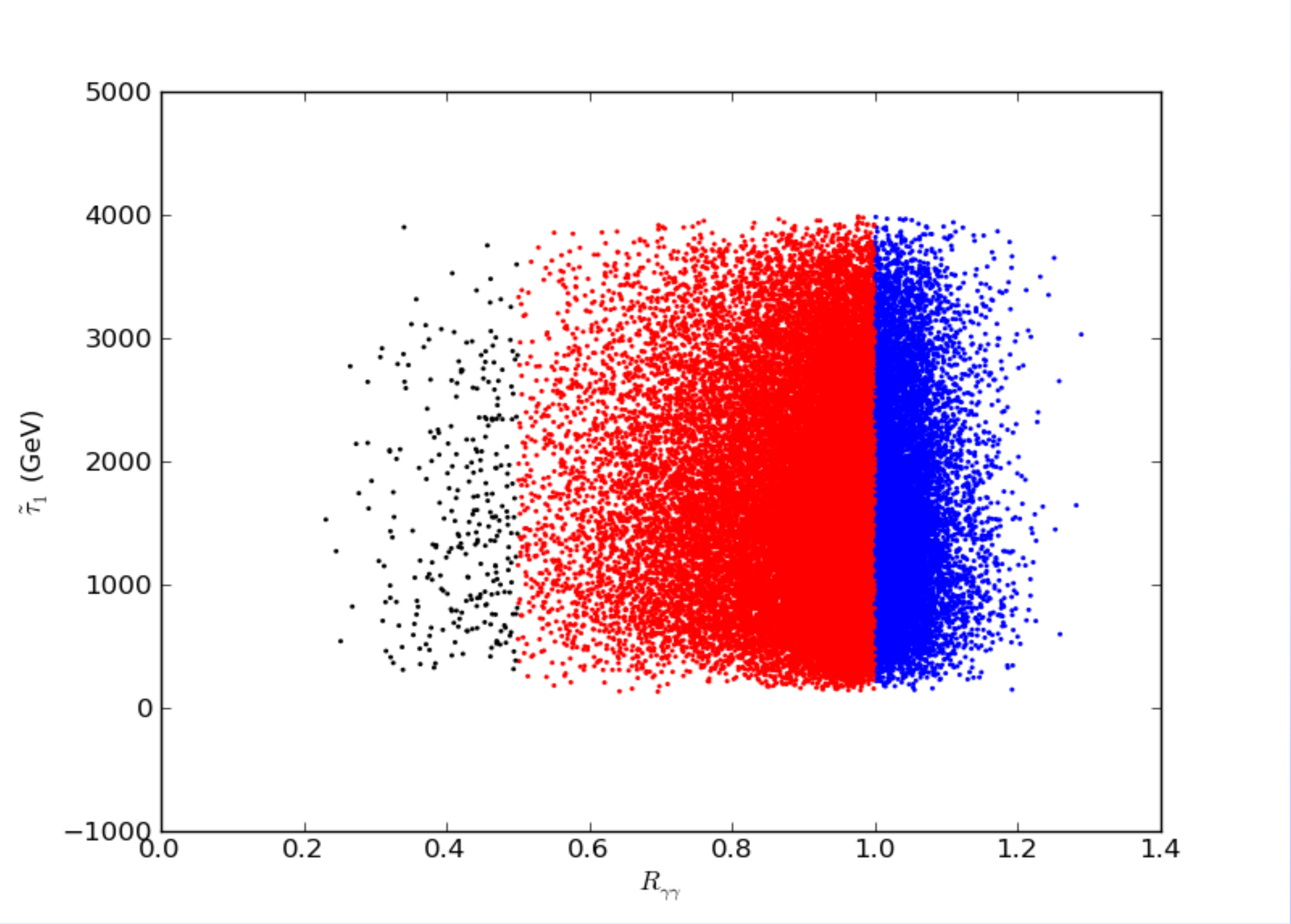


h→bb is quite different…

- Large hbb coupling loop corrections decouple very slowly especially if there is large sbottom mixing (Haber etal.)
- These lead to a significant Higgs width increase/decrease since it is the dominant decay mode



Rγγ Dependence on stau mass

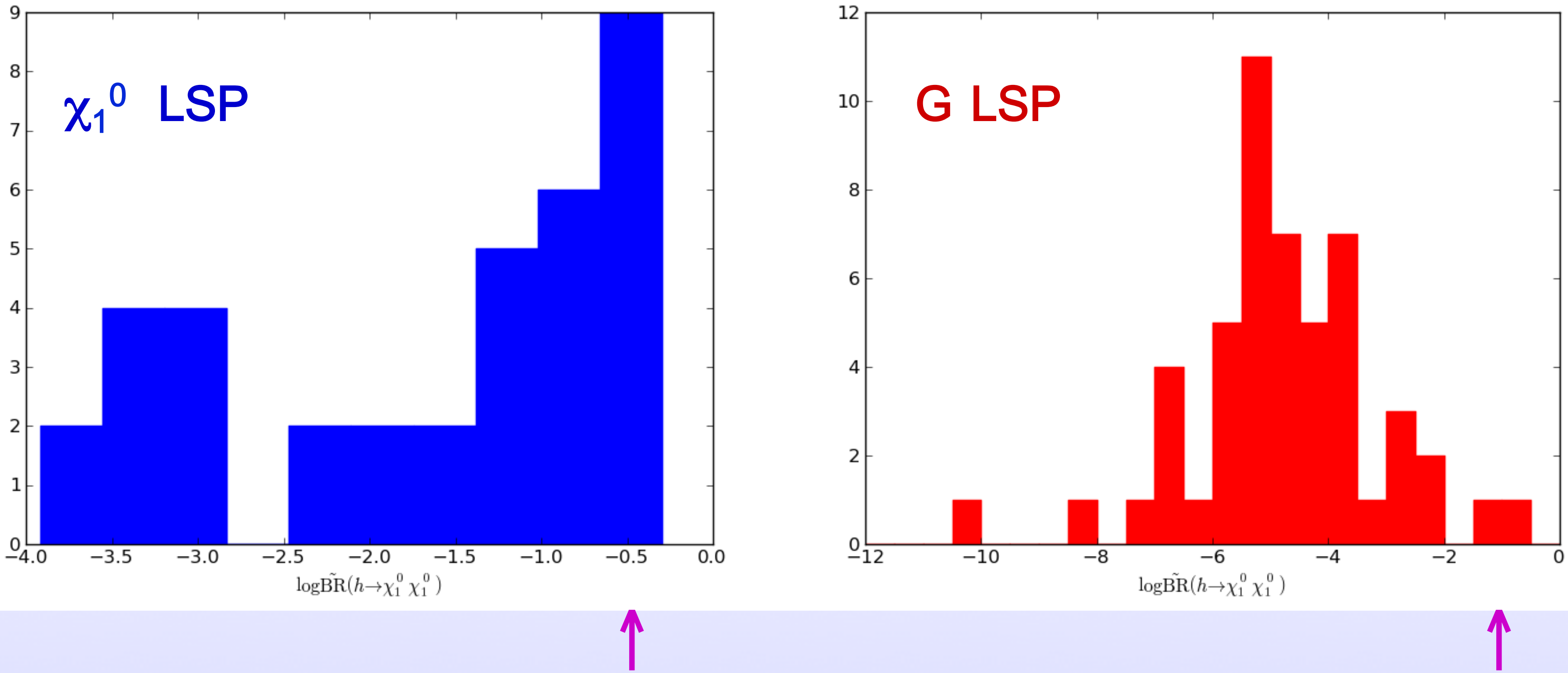


Invisible Higgs decays

- In the neutralino (gravitino) model set 36 (51) models have kinematically accessible h (=125 ±2 GeV) decays to pairs of neutralinos which are mostly bino w/ a small Higgsino admixture. (There are a higher fraction of bino χ_1^0 s in the gravitino set but there are fewer Higgs in this mass range.) The rate scales ~ as the product of the bino & Higgsino fractions.

- In the neutralino set this is the usual 'invisible Higgs decay'. 15/36 have $h \to$ invisible BF > 10% & in one case it's ≈ 50%

- In the gravitino set the NLSP neutralino will decay to γ +gravitino producing a $\gamma\gamma$ + (small ?) MET signature. The neutralinos in this set have high bino purity & thus we expect a lower BF in this mode. Only 1/51 models lead to a BF > 1% (19%).



As expected the BF for this mode is higher in the neutralino set due to the high bino purity of the neutralino NLSP in the gravitino set

It will be important to continue to search for unusual Higgs decay modes as further tests of new physics beyond just measuring couplings to the SM fields.

Naturalness Criterion

Standard prescription to compute fine-tuning:

- Take mass relation w/ radiative corrections

$$M_Z^2 = -2\mu^2 + 2\,\frac{m_{H_d}^2 - t_\beta^2\, m_{H_u}^2}{t_\beta^2 - 1}$$ + higher order

- Compute dependence on each SUSY parameter, p_i

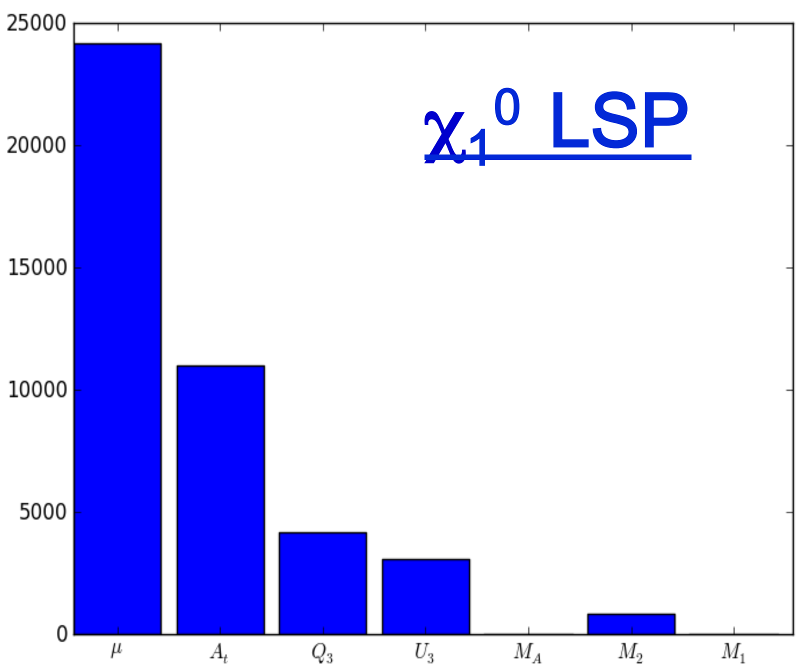
$$Z_i = \frac{\partial(\log M_Z^2)}{\partial(\log p_i)} = \frac{p_i}{M_Z^2}\,\frac{\partial M_Z^2}{\partial p_i}$$

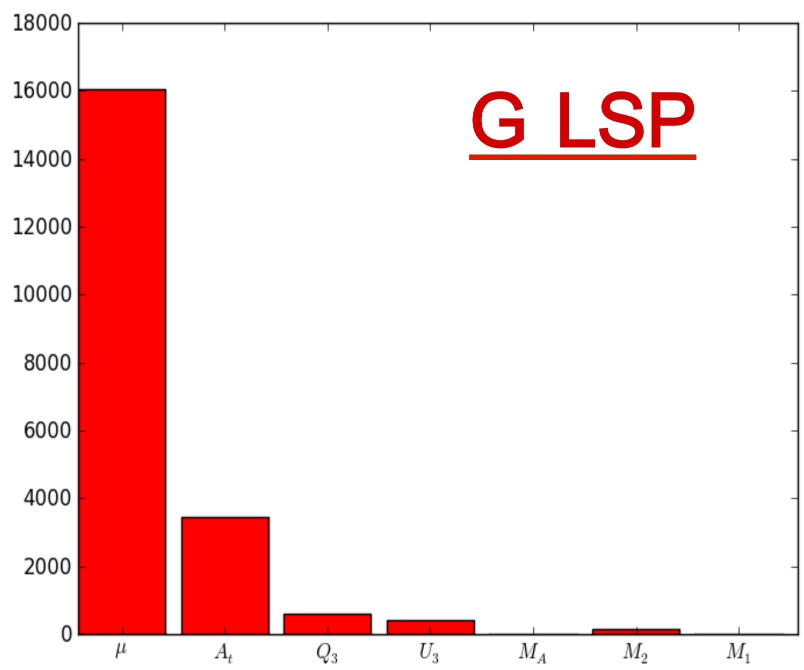
- Overall fine-tuning of model given by

  $\Delta = \max|Z_i|$

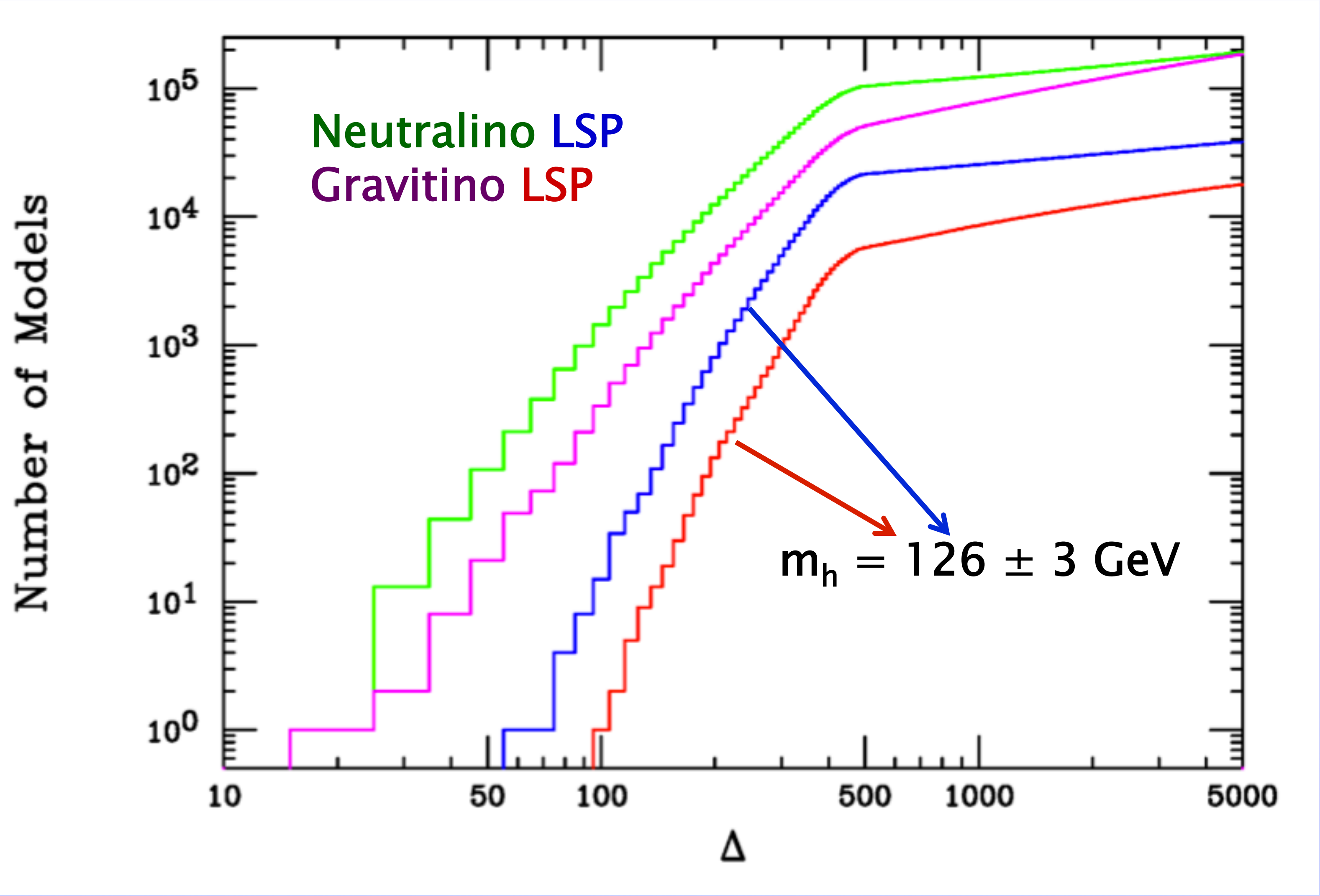
Barbieri, Giudice
Kasahara, Freese, Gondolo

Dominant FT Contributors

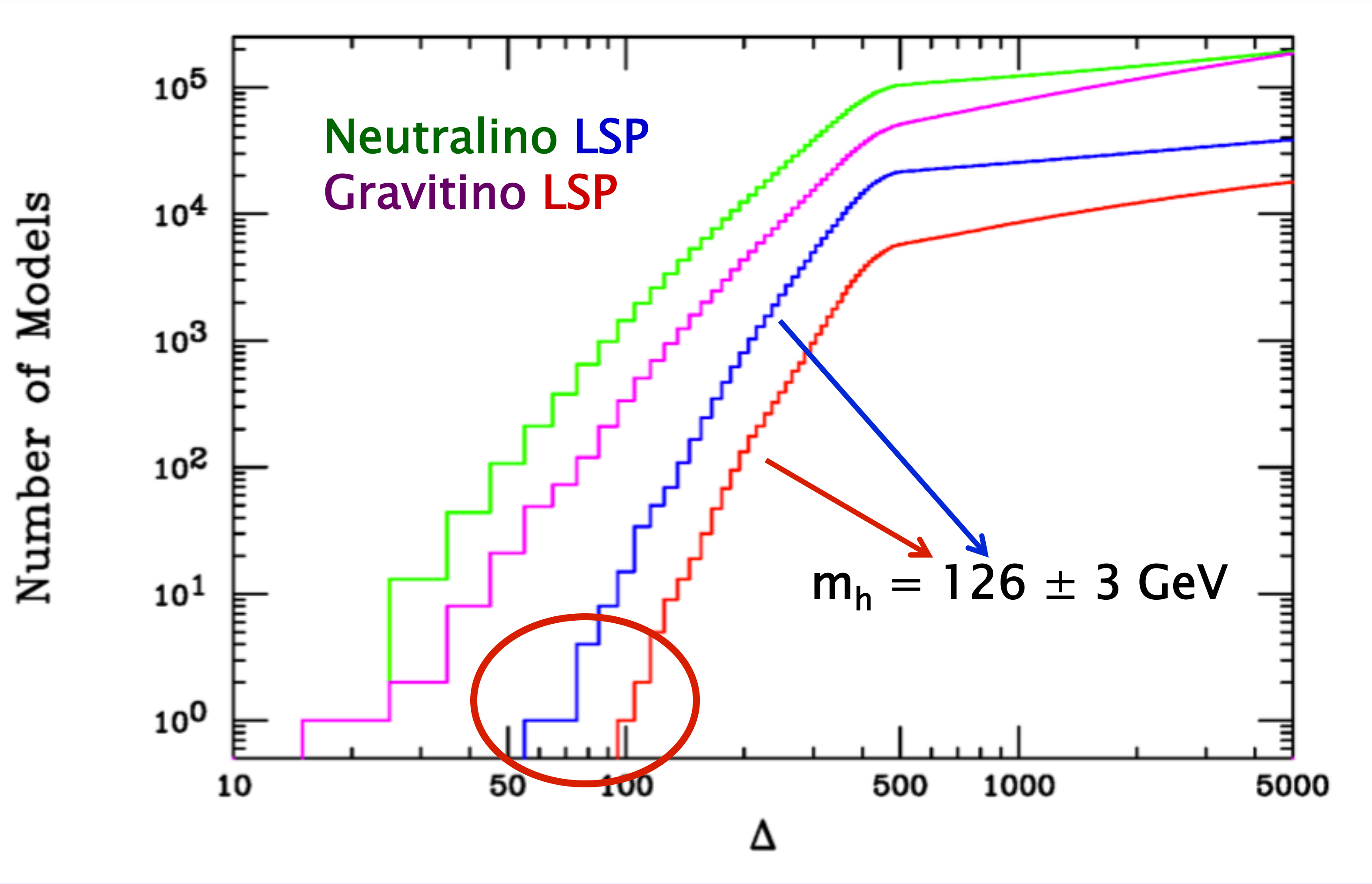




Fine-Tuning in the pMSSM

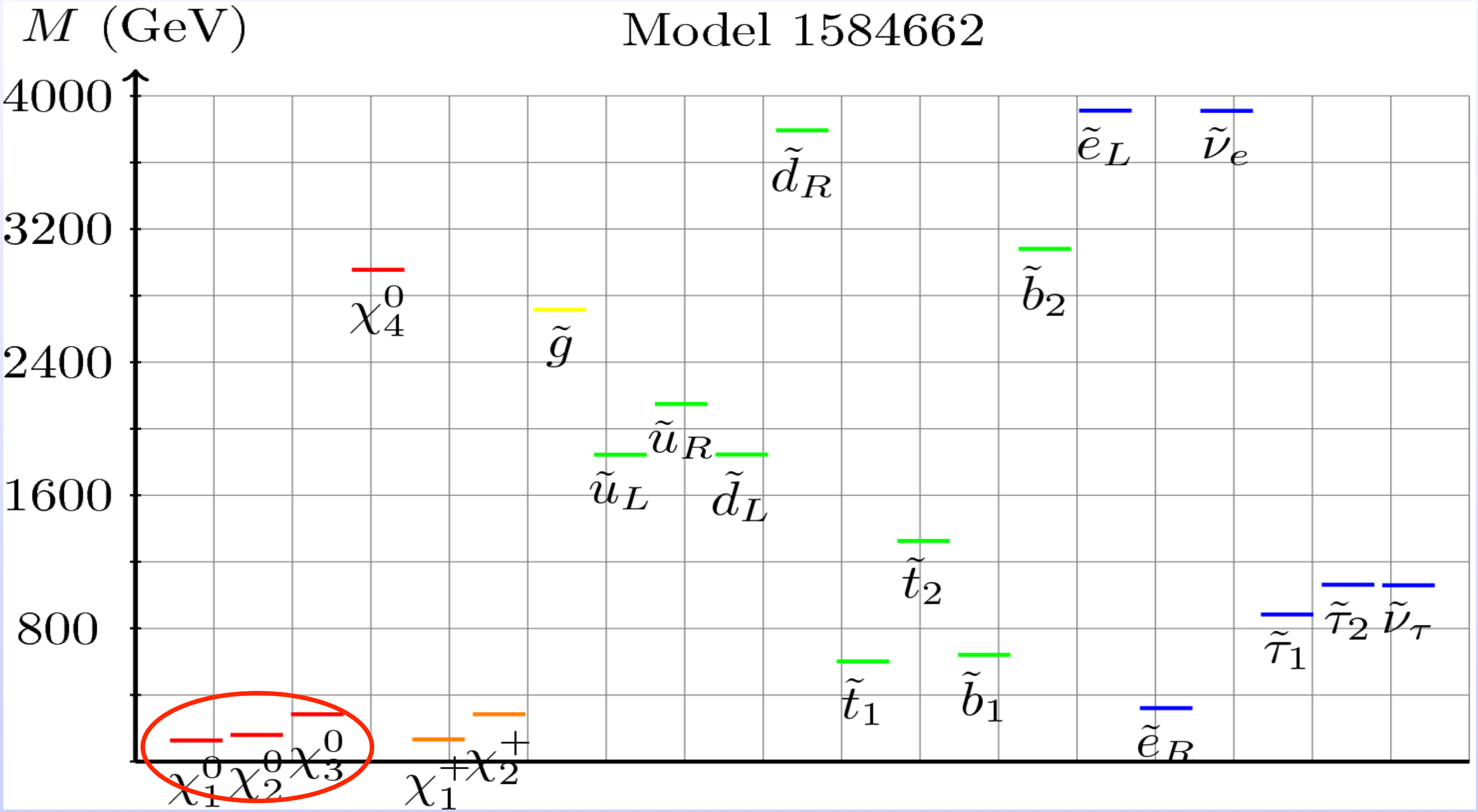


Fine-Tuning in the pMSSM

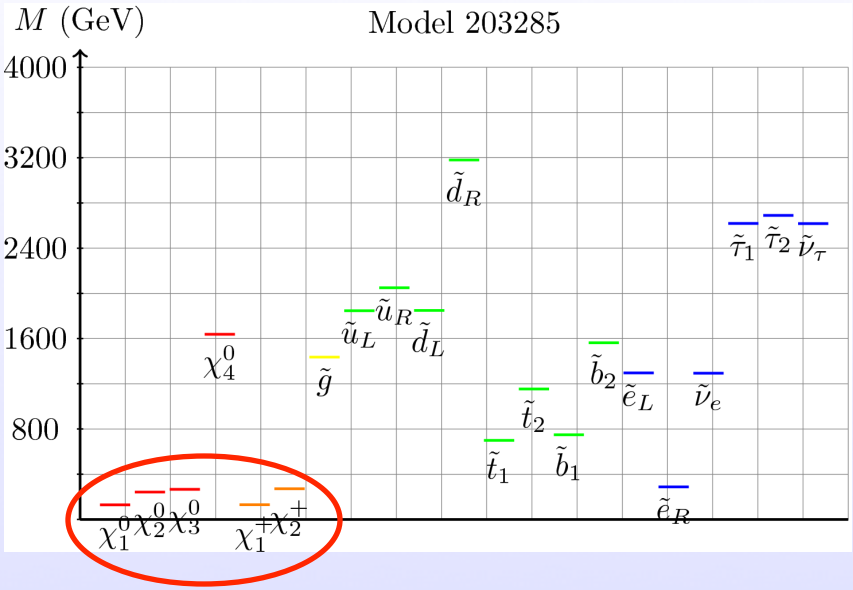


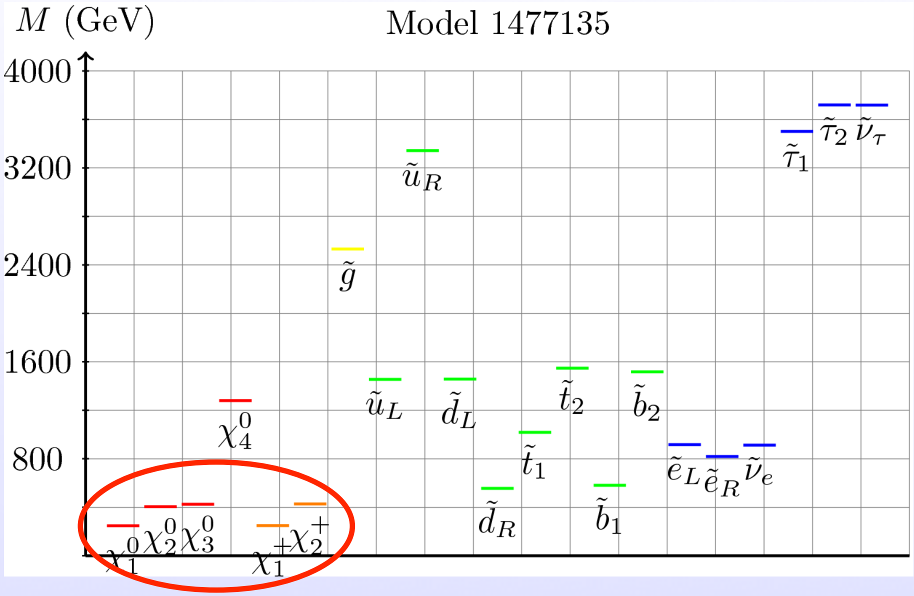
13 + 1 models with $\Delta < 100$,
4+1 of these are excluded by the LHC

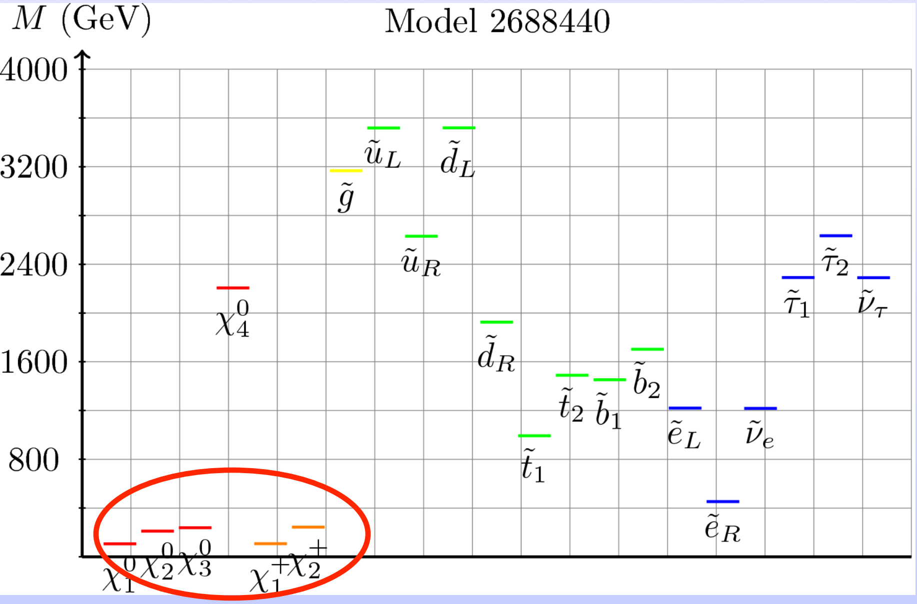
Low Fine-Tuning Model Spectra I

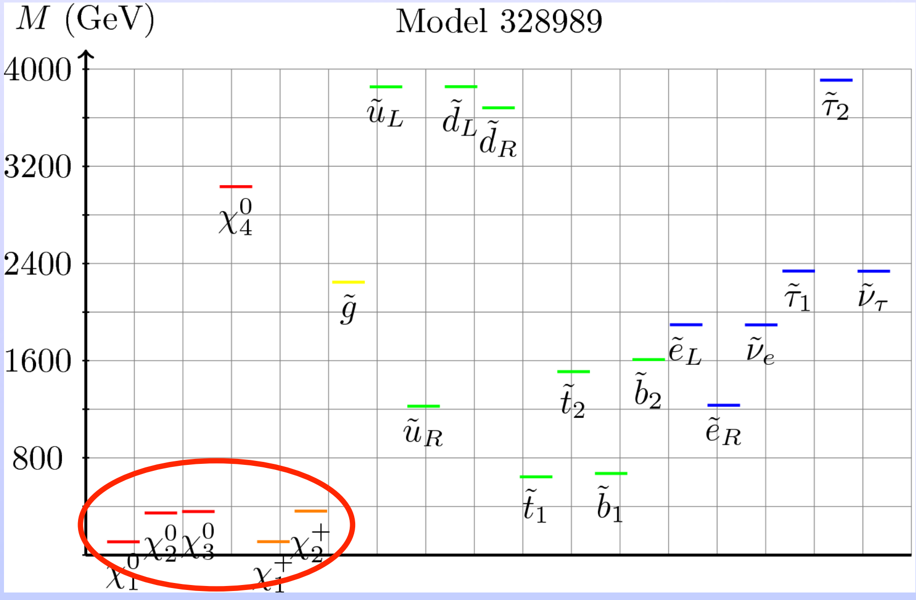


Low Fine-Tuning Model Spectra I

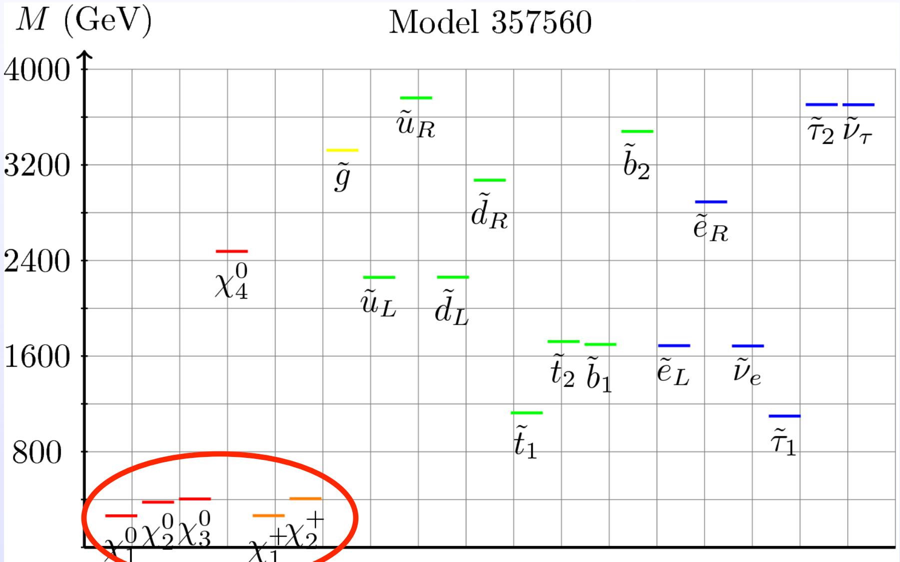


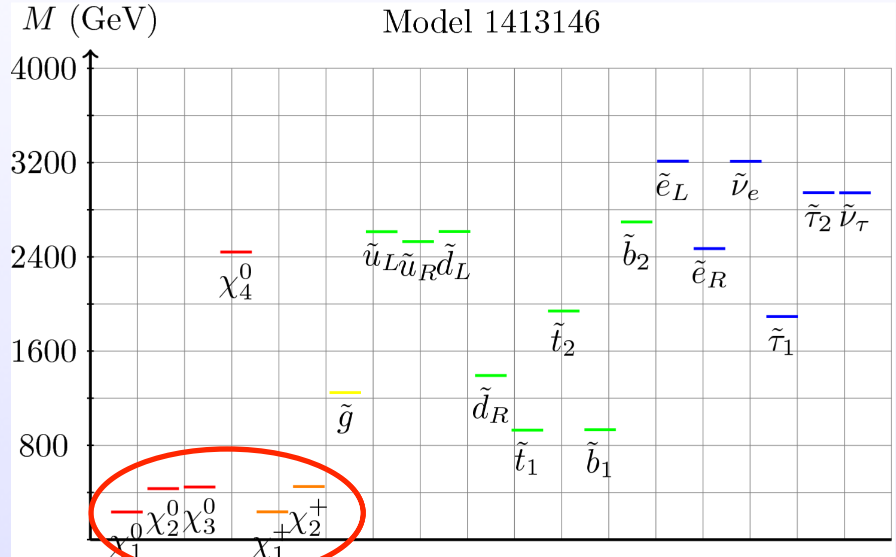


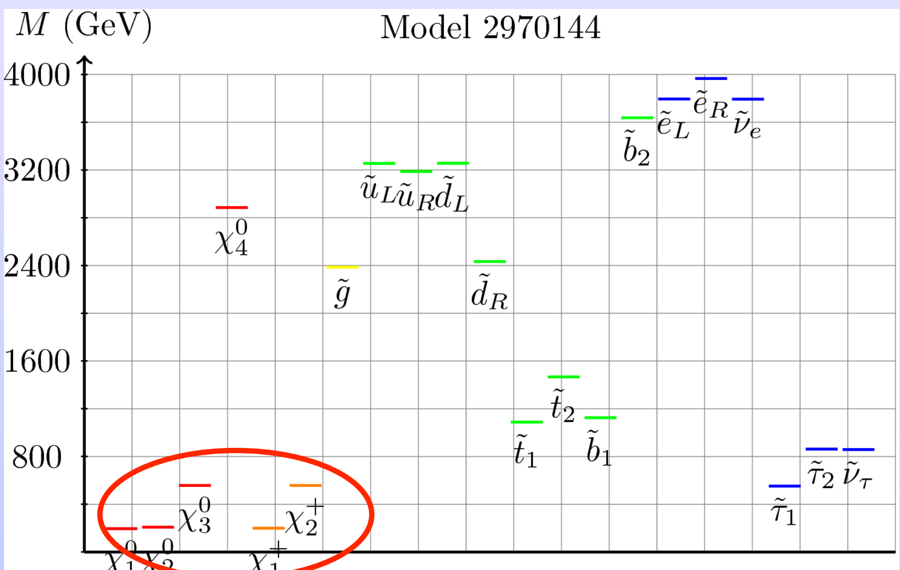


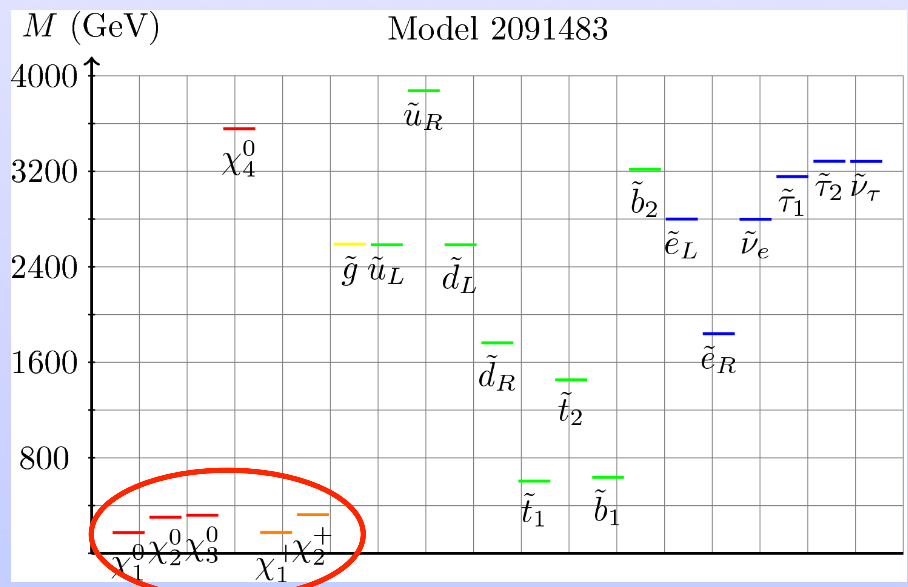


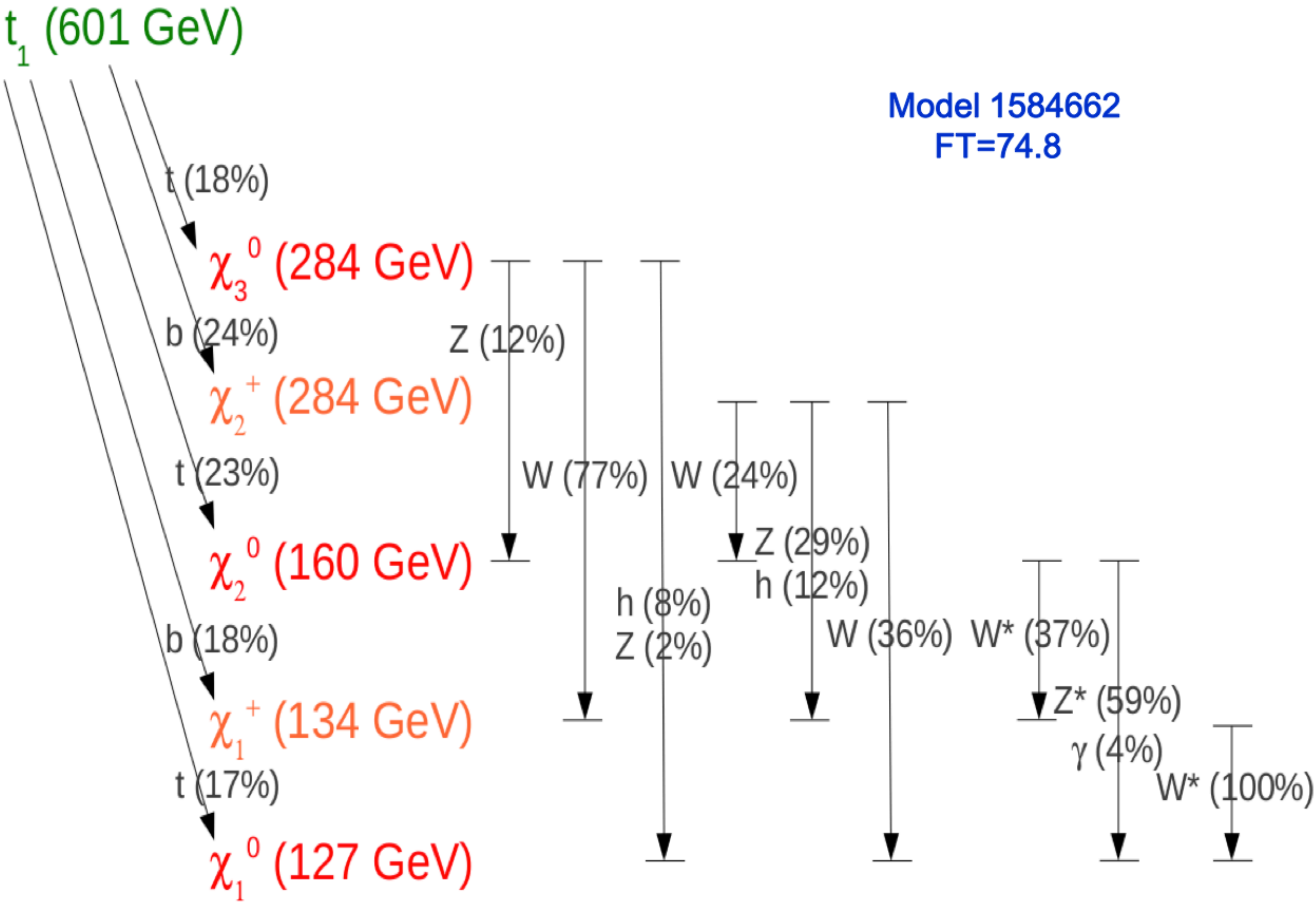
Low Fine-Tuning Model Spectra II



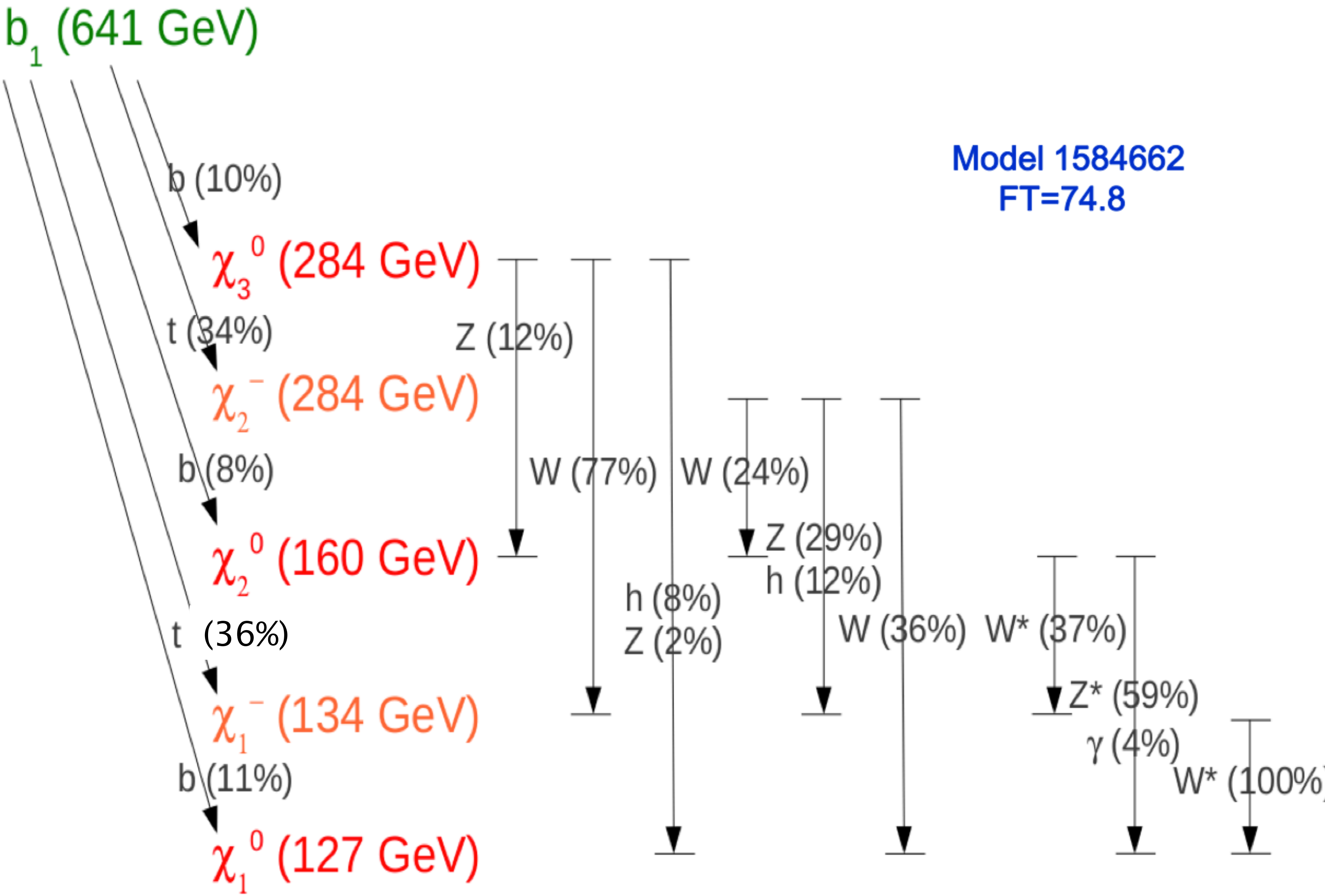






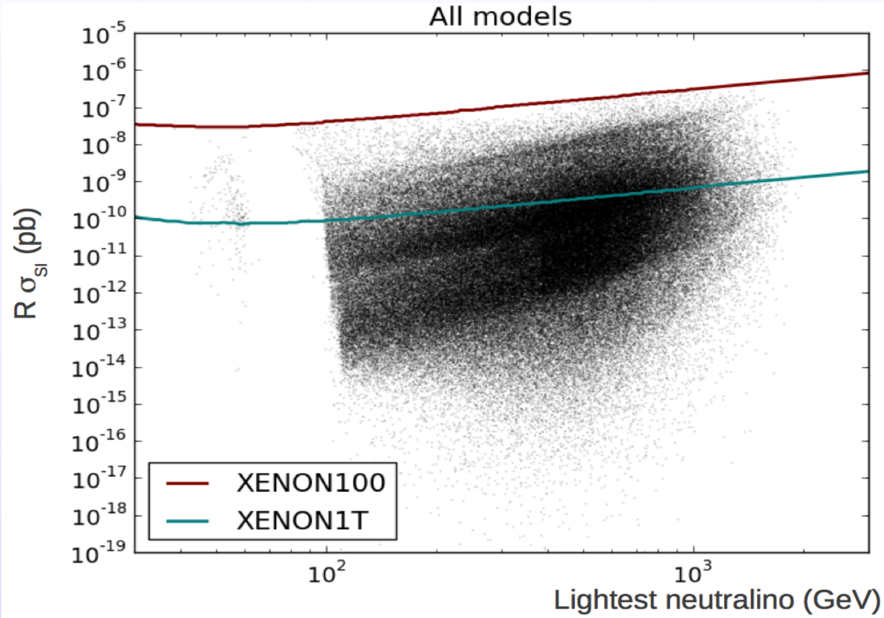


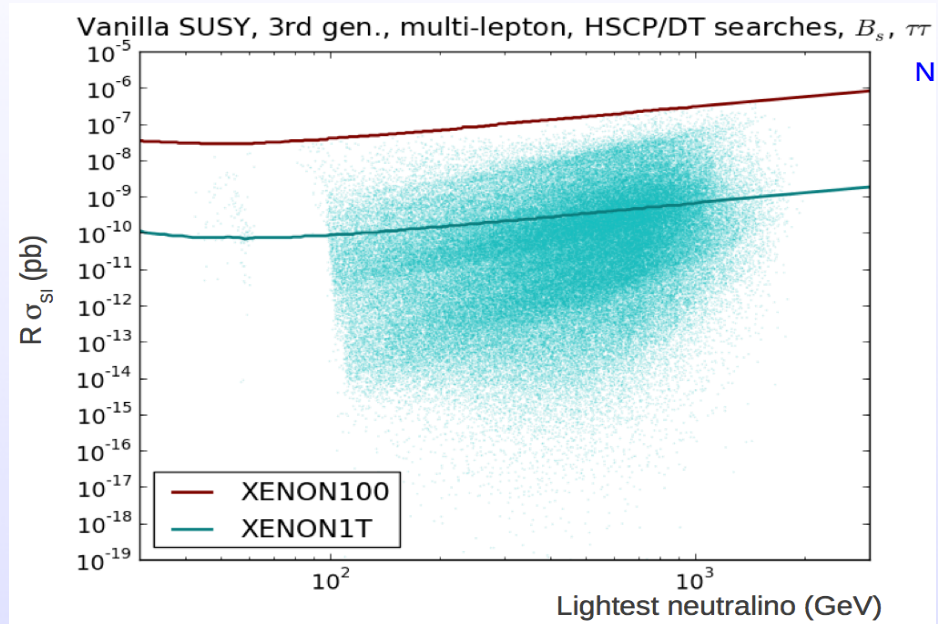
t1 (601 GeV)
Model 1584662
FT=74.8
t (18%)
χ3 0 (284 GeV)
b (24%)
Z (12%)
χ2 + (284 GeV)
t (23%)
W (77%)
W (24%)
Z (29%)
χ2 0 (160 GeV)
h (12%)
h (8%)
Z (2%)
b (18%)
W (36%)
W* (37%)
Z* (59%)
χ1 + (134 GeV)
γ (4%)
t (17%)
W* (100%)
χ1 0 (127 GeV)

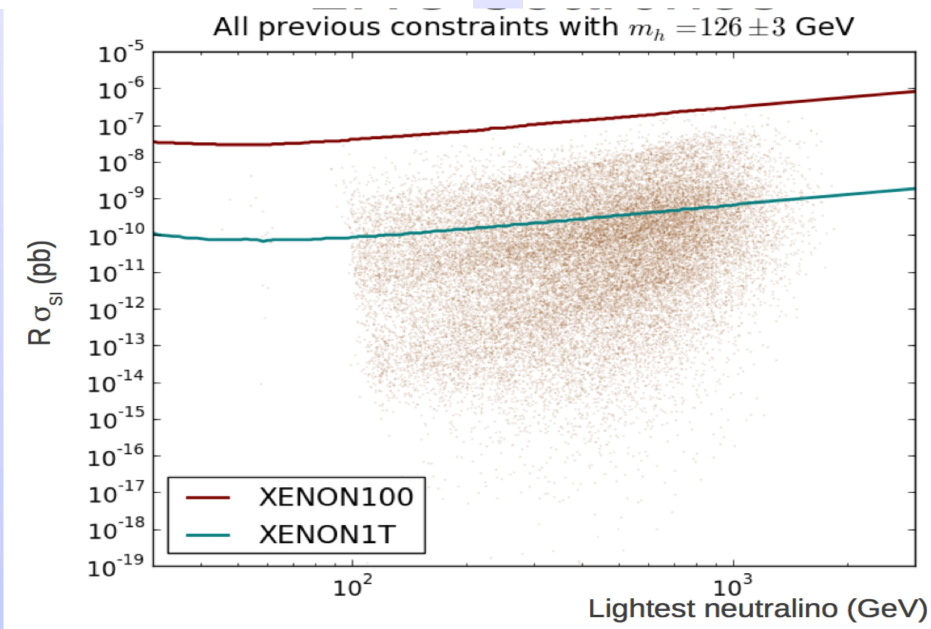


b1 (641 GeV)
Model 1584662
FT=74.8
b (10%)
χ3 0 (284 GeV)
t (34%)
Z (12%)
χ2 − (284 GeV)
b (8%)
W (77%)
W (24%)
Z (29%)
χ2 0 (160 GeV)
h (12%)
h (8%)
Z (2%)
t (36%)
W (36%)
W* (37%)
Z* (59%)
χ1 − (134 GeV)
γ (4%)
b (11%)
W* (100%)
χ1 0 (127 GeV)

Direct Detection of Dark Matter





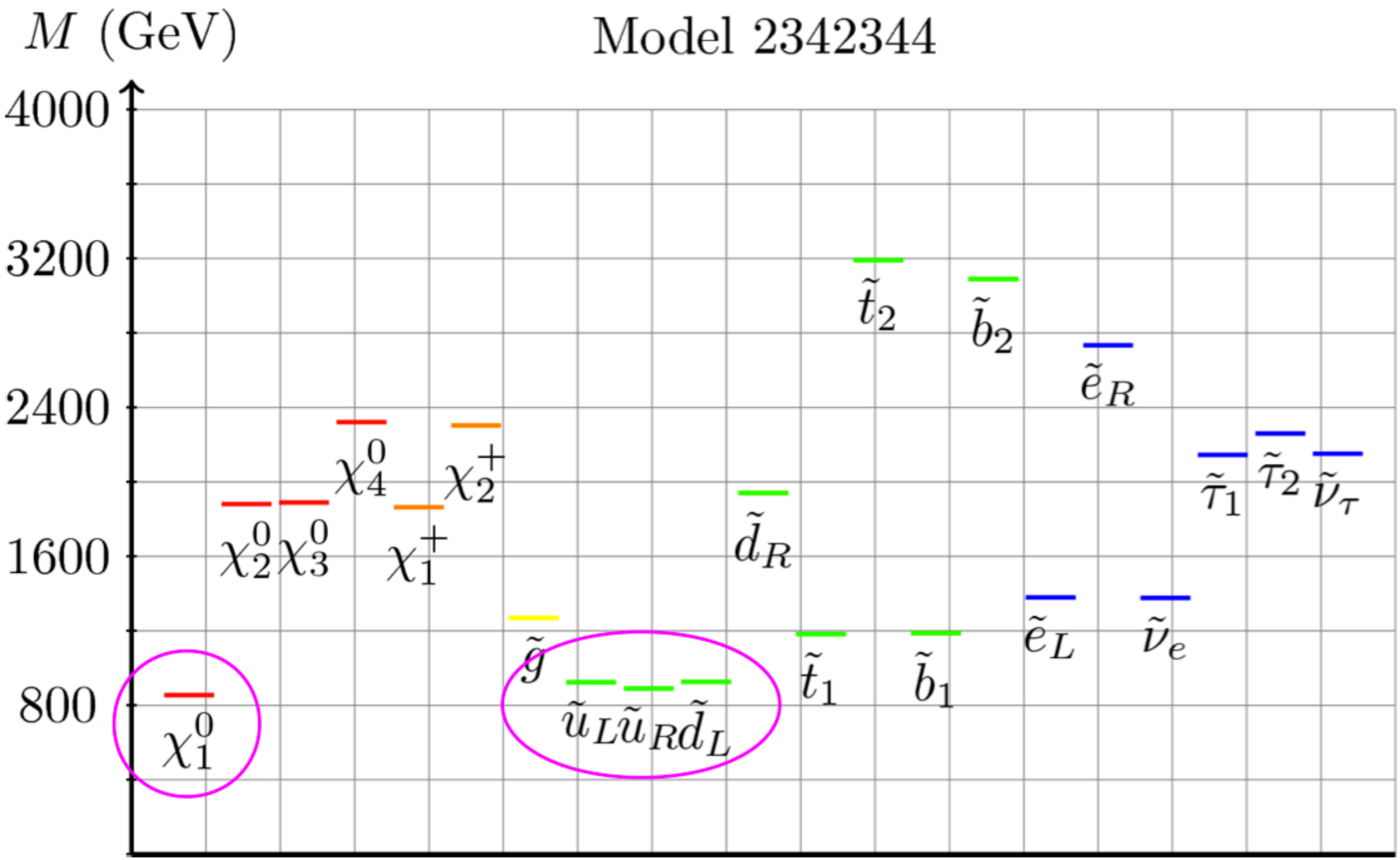


Conclusions

- Relatively easy to accommodate 125/6 Higgs in the pMSSM
  - Selects region of stop mixing
- Higgs branching fractions are correlated
  - Lower bb predicted
  - Lower ττ difficult
- Reasonable fine-tuning ~1% is possible
  - Selects region of parameter space
  - Light stop/sbottom
  - Very light and compressed EW-ino sector: Tailor-made for the ILC!
- Future Plans
  - Provide Snowmass benchmarks for EF and CF groups (24 models chosen)
  - New set of points focused on 126 GeV higgs + low fine-tuning

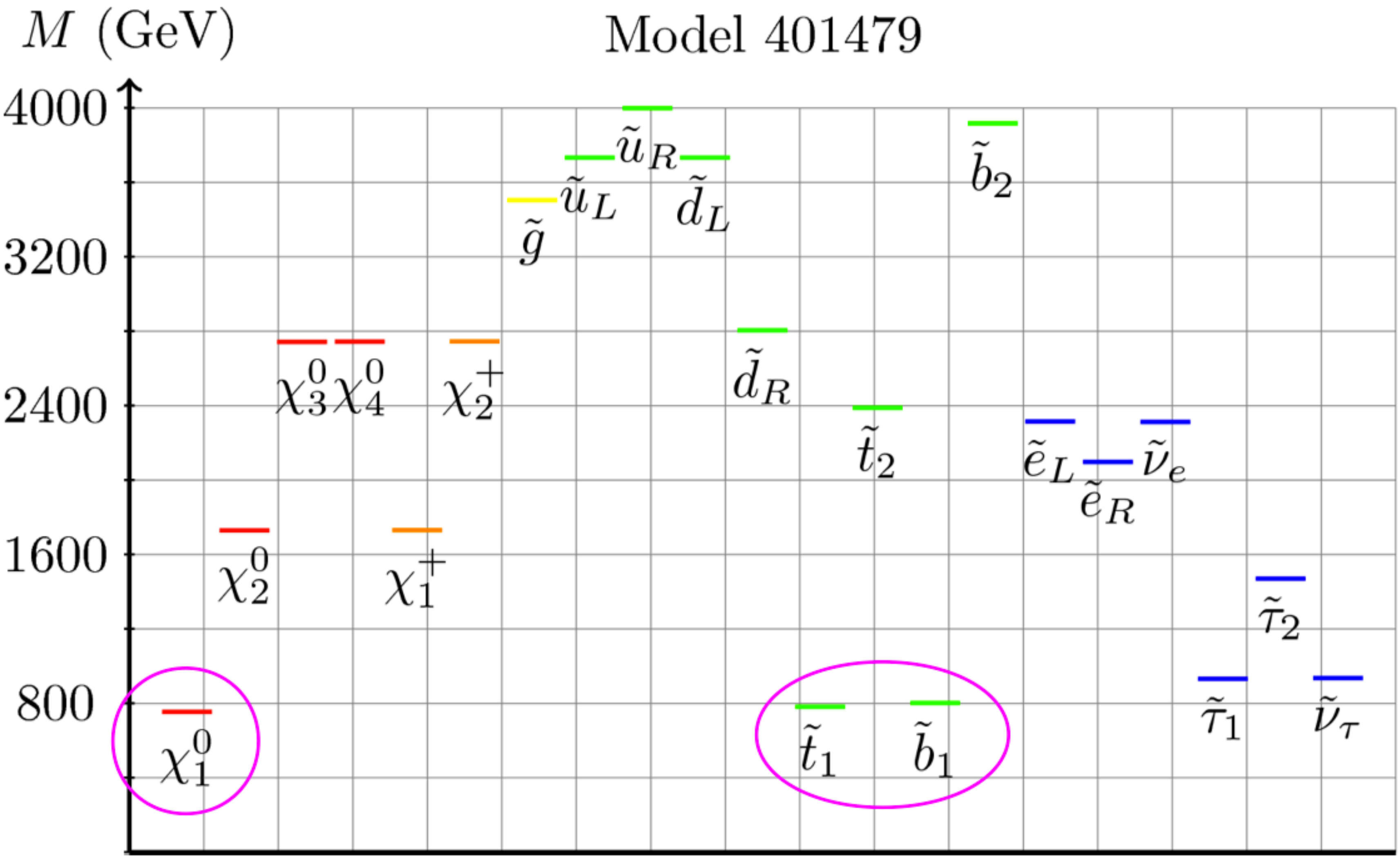
Backup

Bino-squark coannihilation



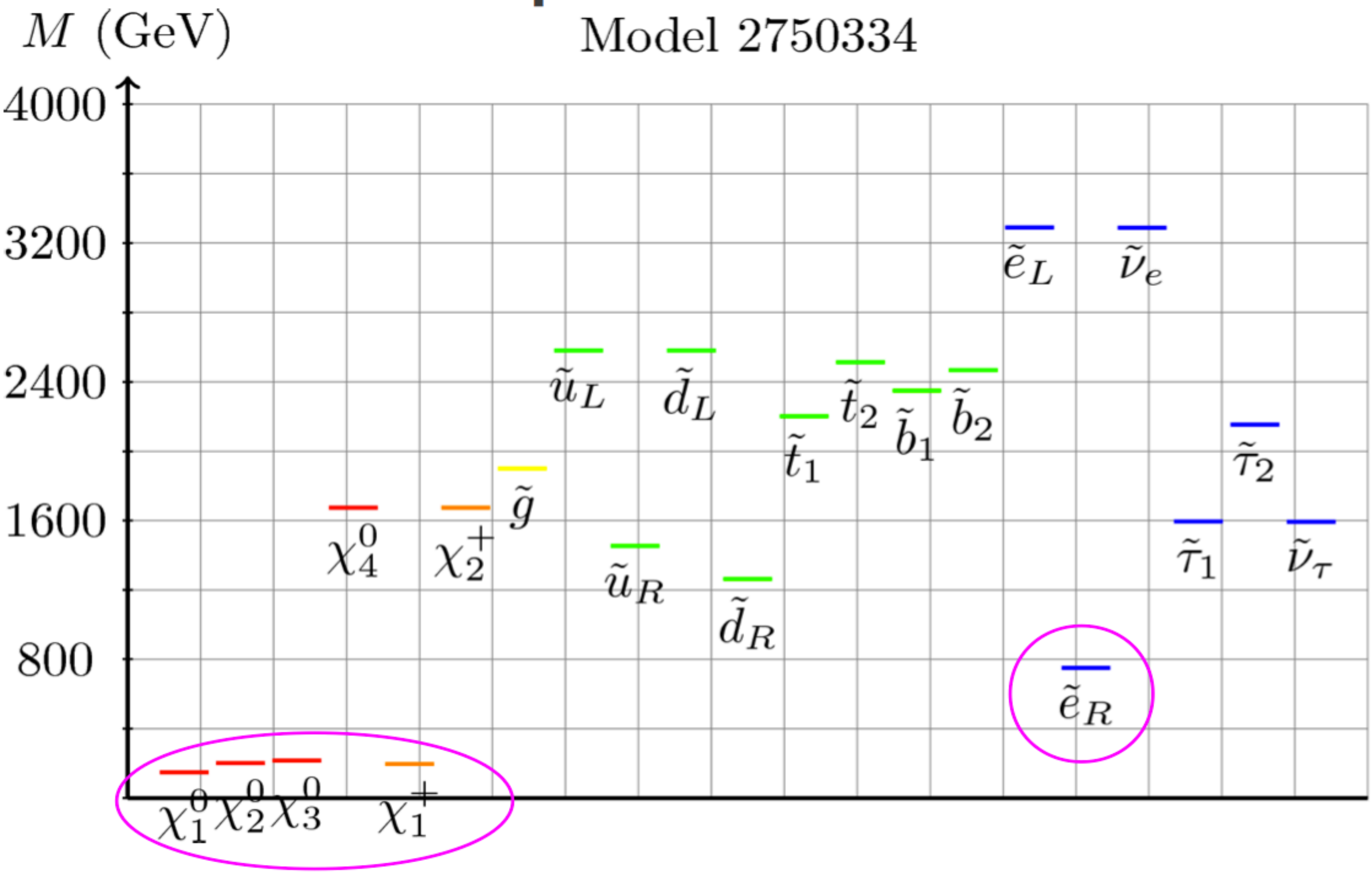
Compressed spectrum makes squarks difficult to see

Bino-stop coannihilation



Now, 1st/2nd generation squarks are decoupled
Very challenging to see stops and sbottoms

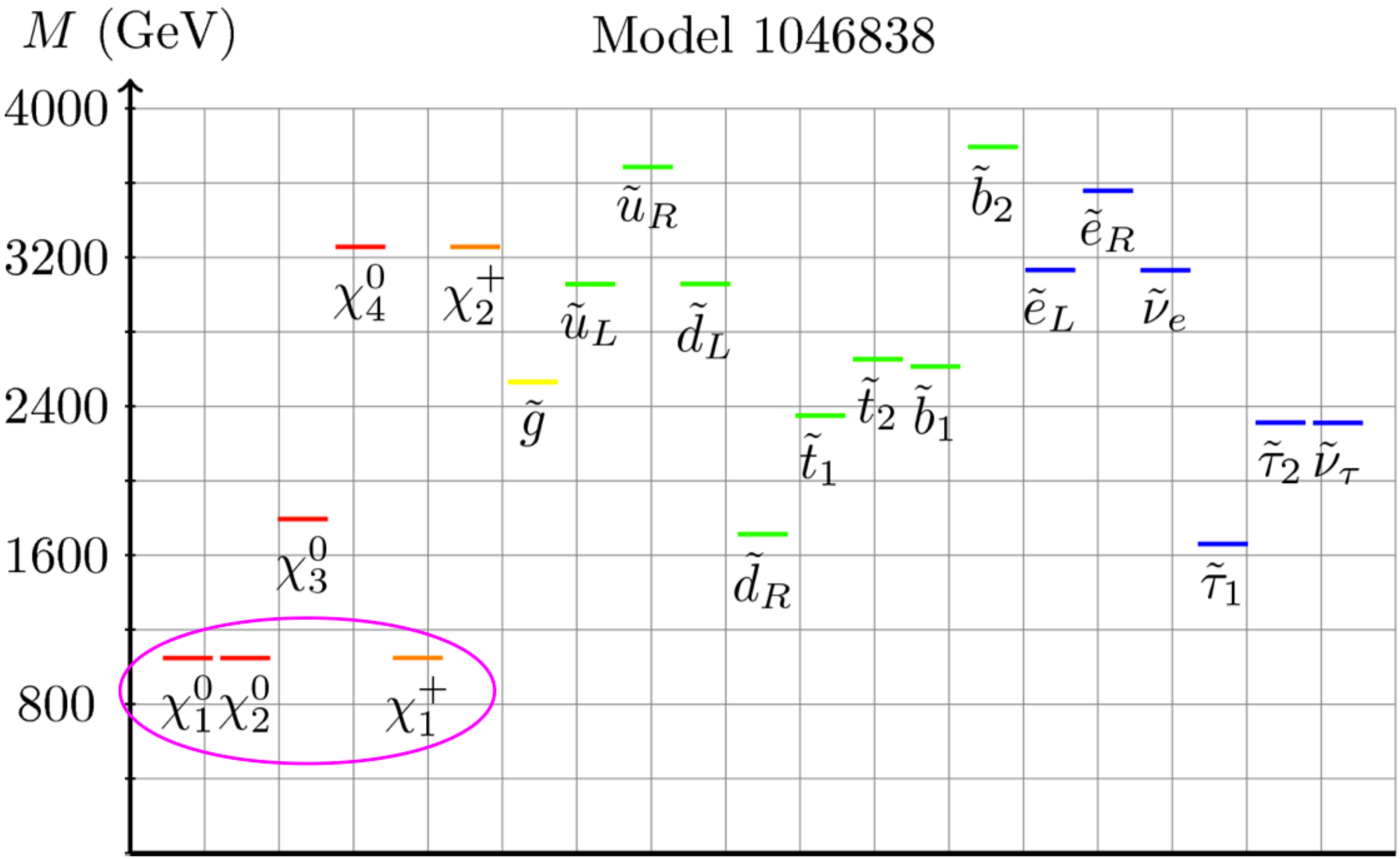
Well-tempered neutralino



All states below 1 TeV are uncolored

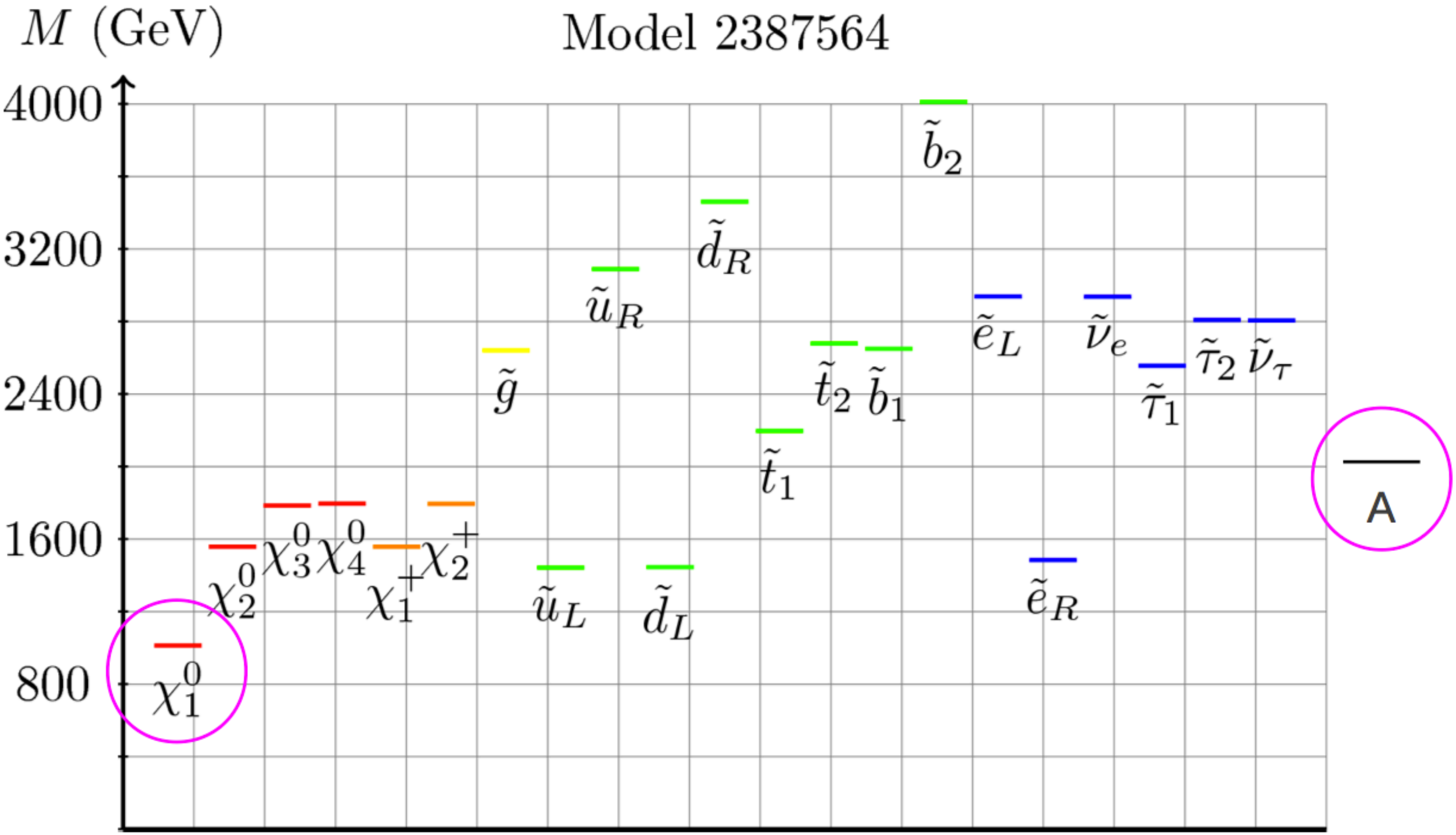
Consider studying with linear collider

"Goldilocks" Higgsino



Higgsino at 1 TeV gives right relic density
Heavier Higgsino LSPs typically require coannihilations

A funnel

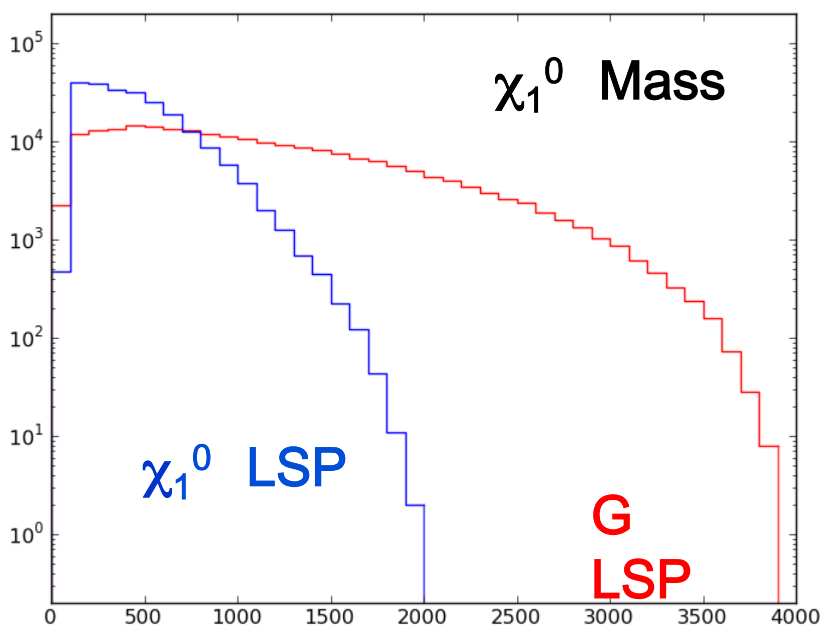


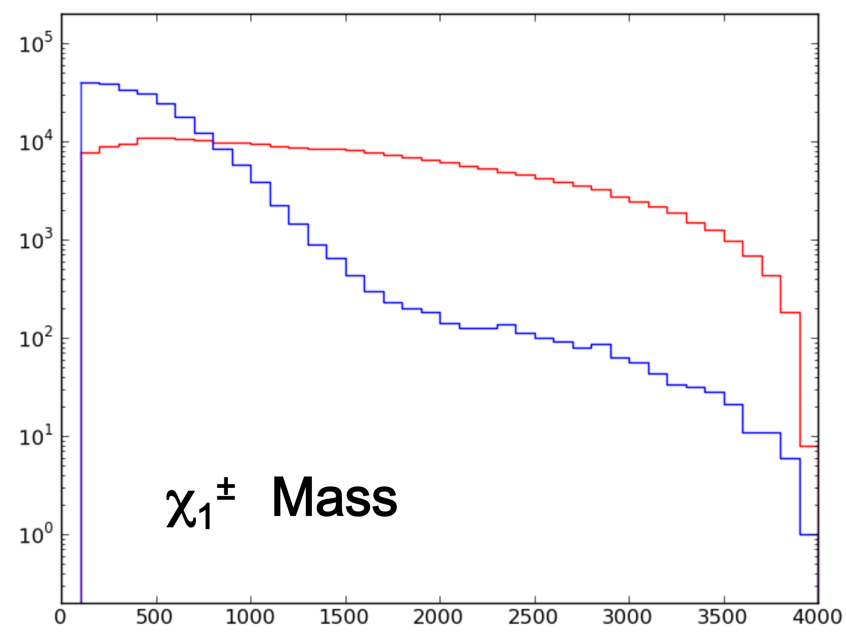
Bino at 1013 GeV, A at 2043 GeV → resonant annihilation

Gaugino Mass Spectra

- The mass spectra of the MSSM fields are (indirectly) influenced by the nature of the LSP

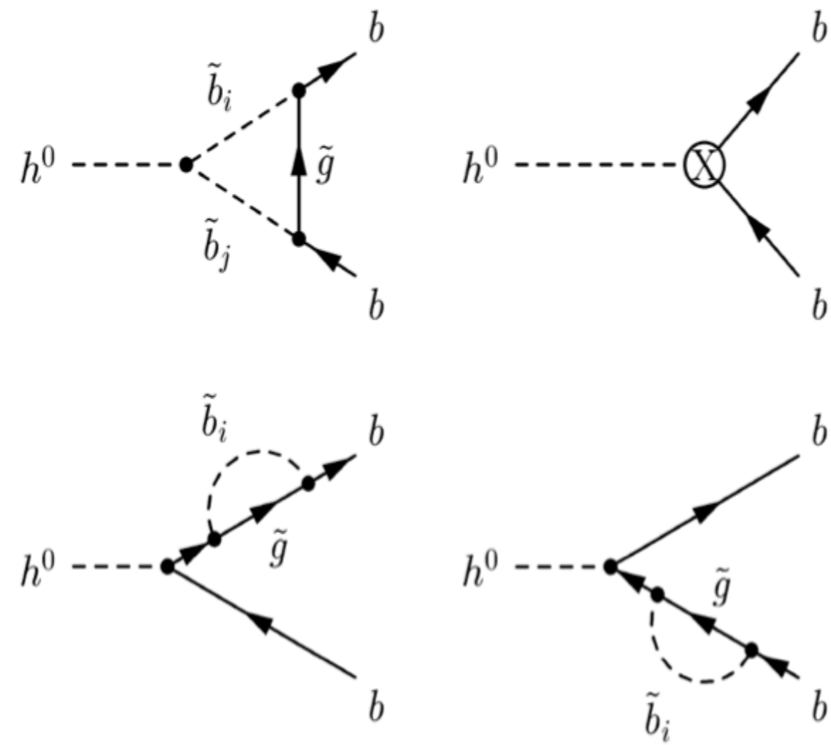
- Other sparticle masses are less influenced due to scan ranges



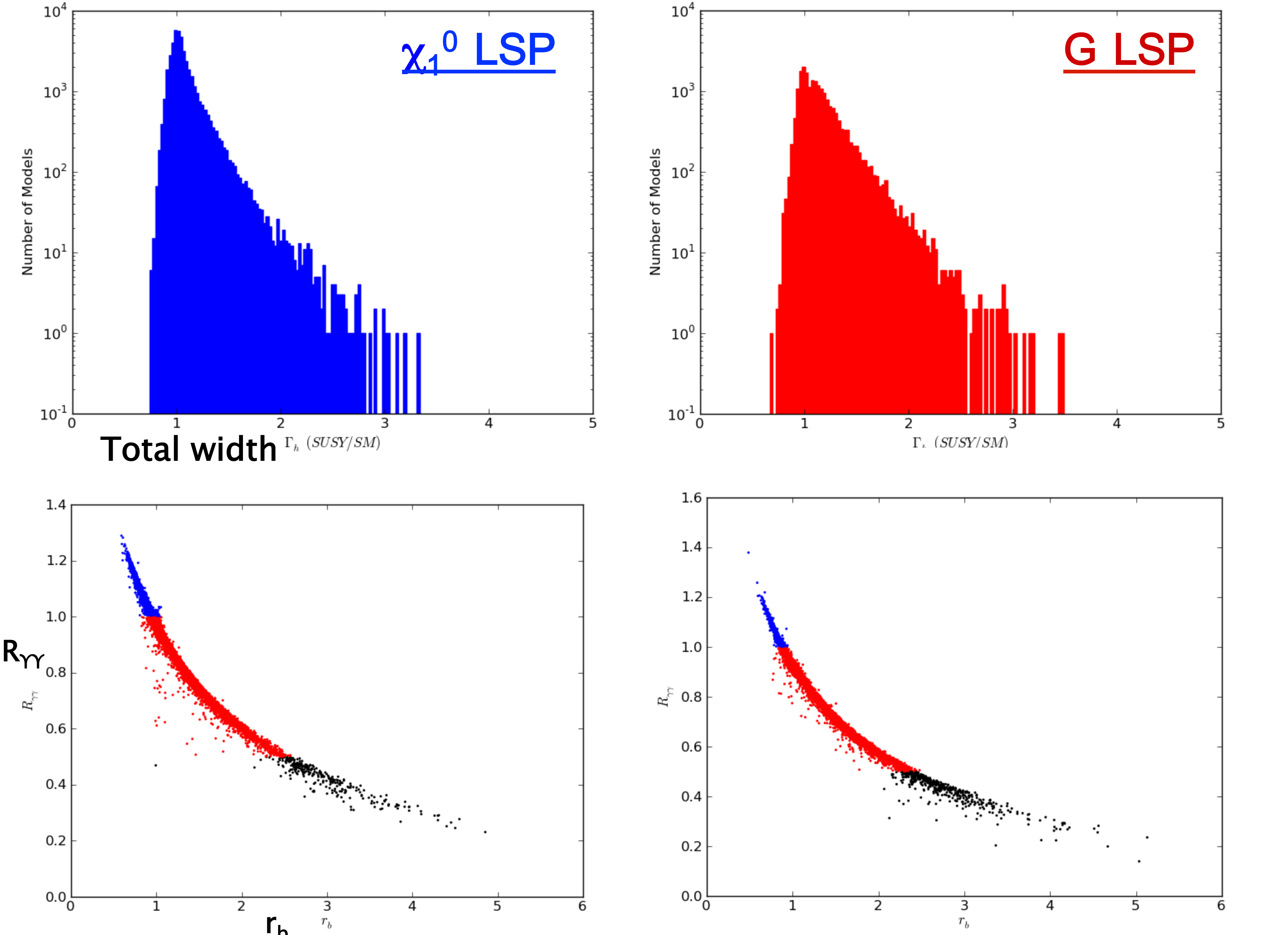


$h \to bb$ decoupling

- $\Gamma = \Gamma_0(1 + 2\,\delta g^{QCD}/ g + 2\,\delta g^{SQCD}/ g)$
- δg^{SQCD} receives contributions from vertex correction, b wave function renormalization, and hbb counterterm

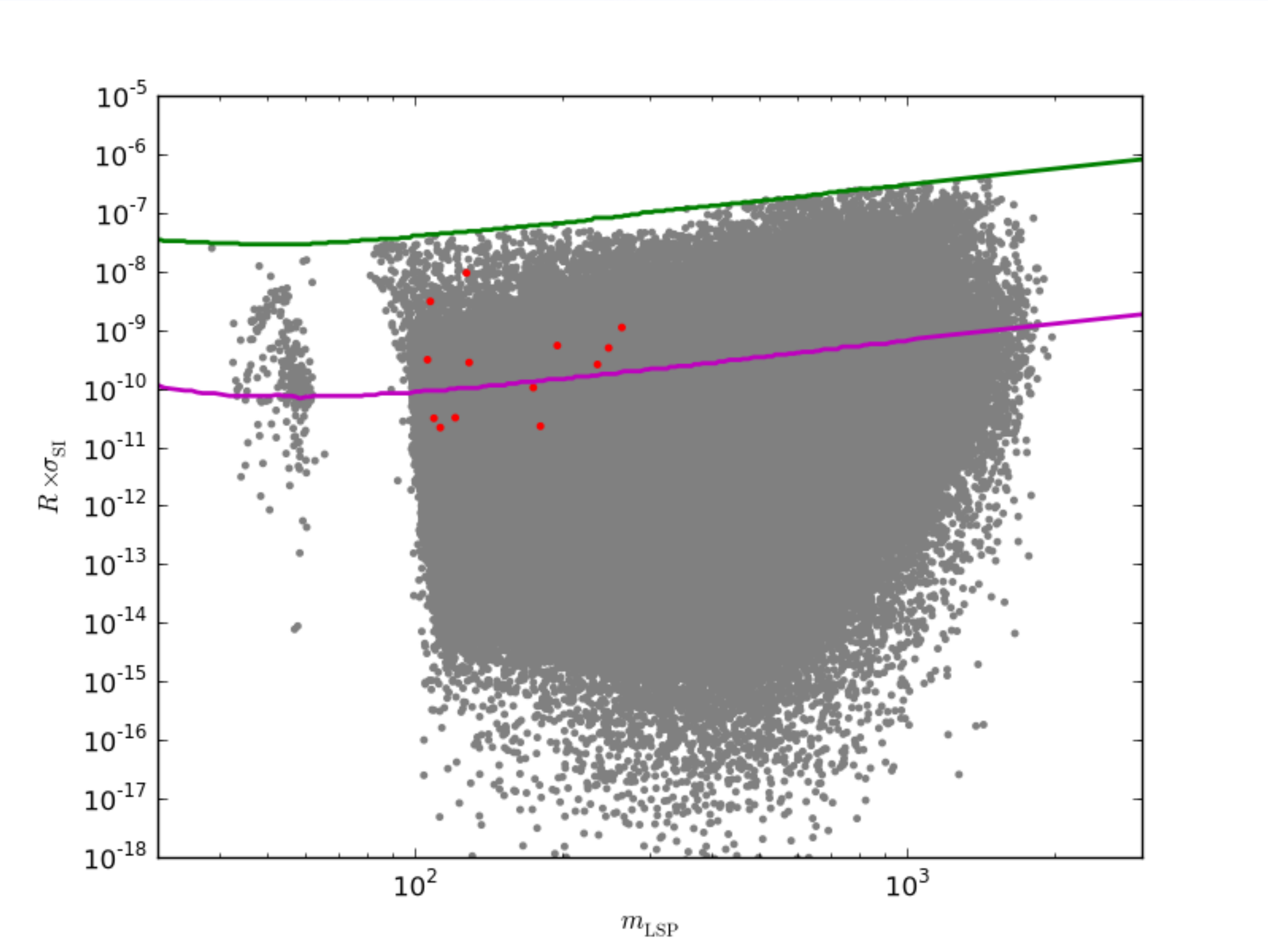


Haber et al., hep-ph/0007006



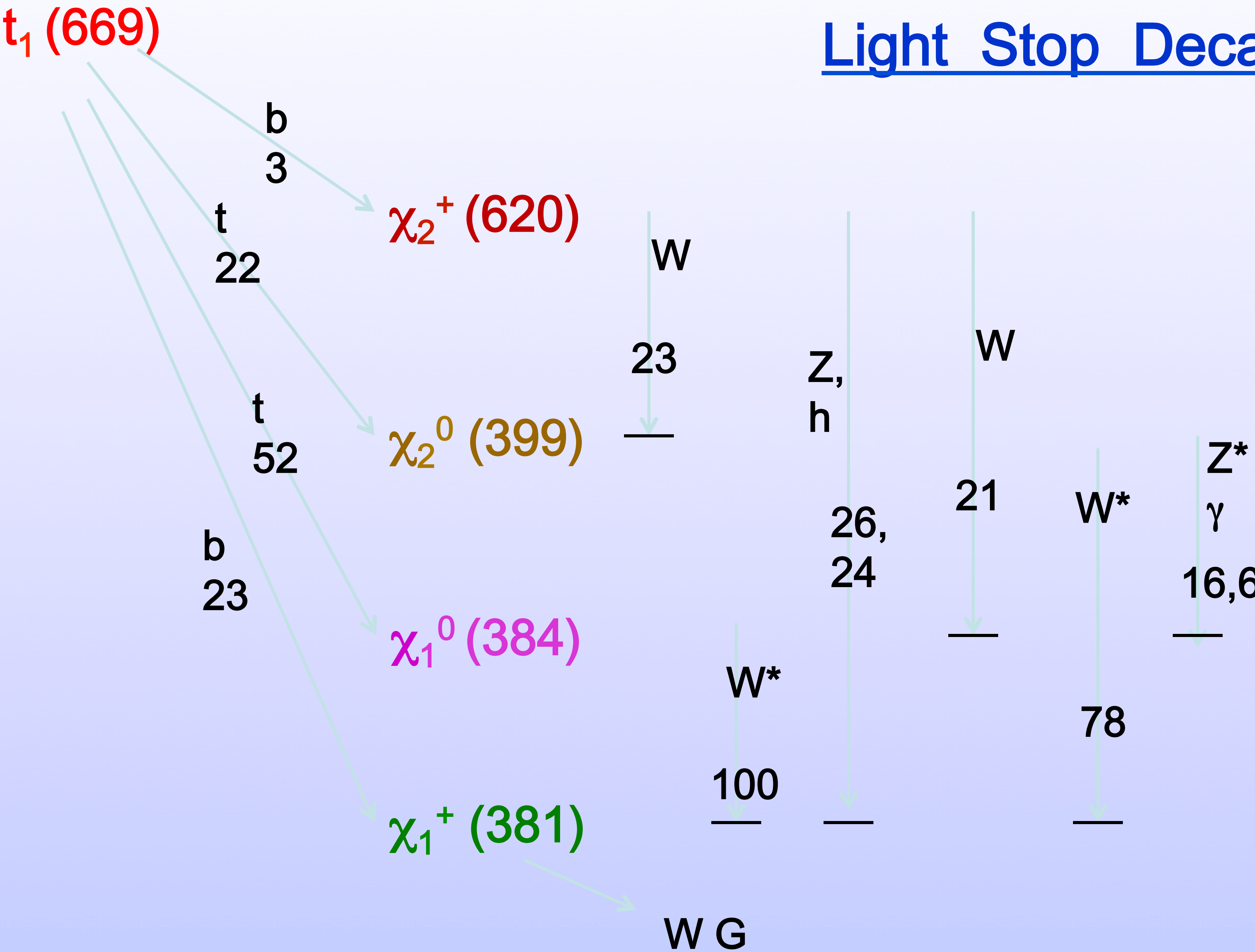
χ1 0 LSP
Number of Models
Total width
Γh (SUSY/SM)
G LSP
Number of Models
Γh (SUSY/SM)
Rγγ
rb
Rγγ
rb

Direct Detection of Dark Matter



An Example :
#146314G w/ FT=95.9

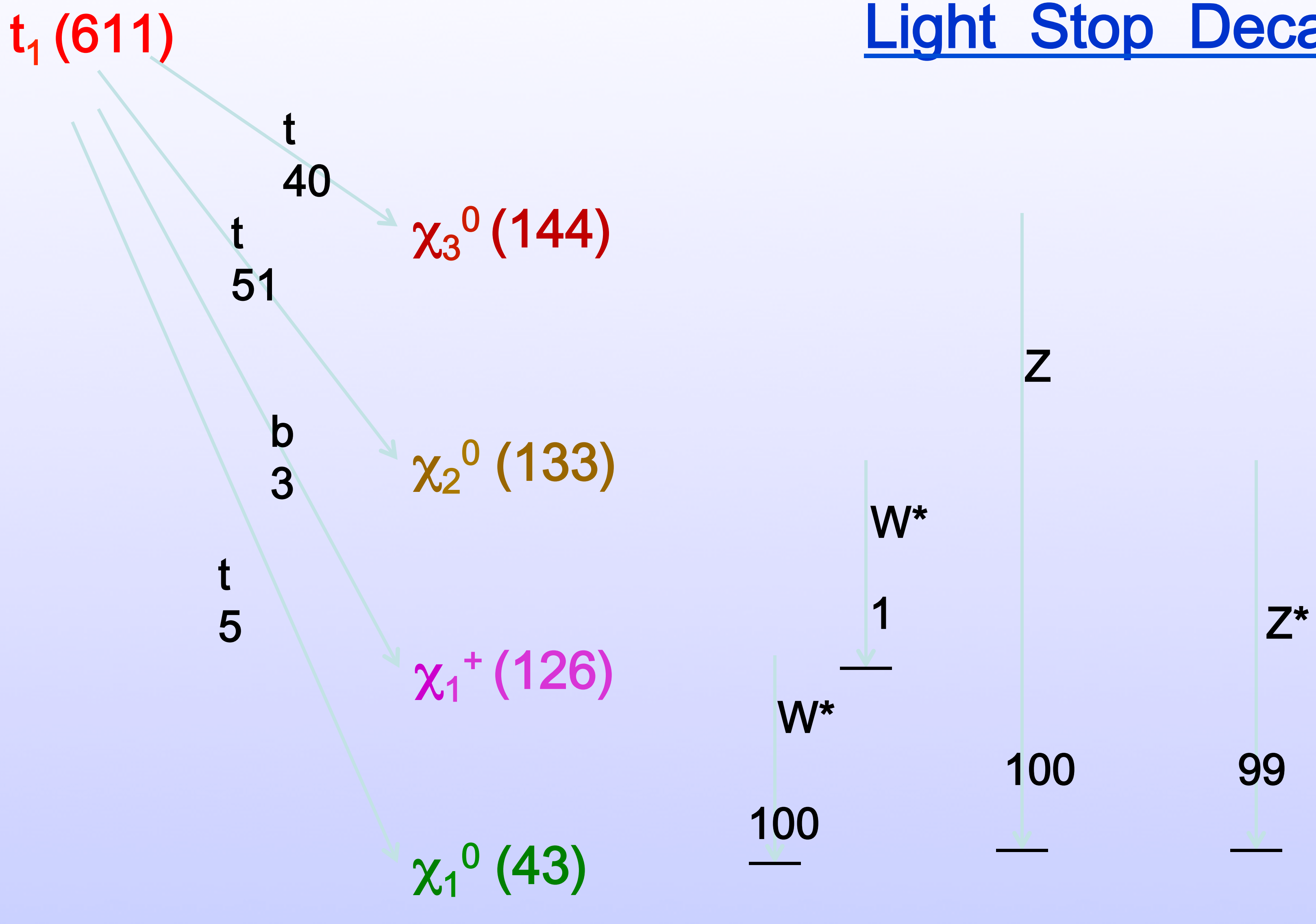
Light Stop Decays



An Example :

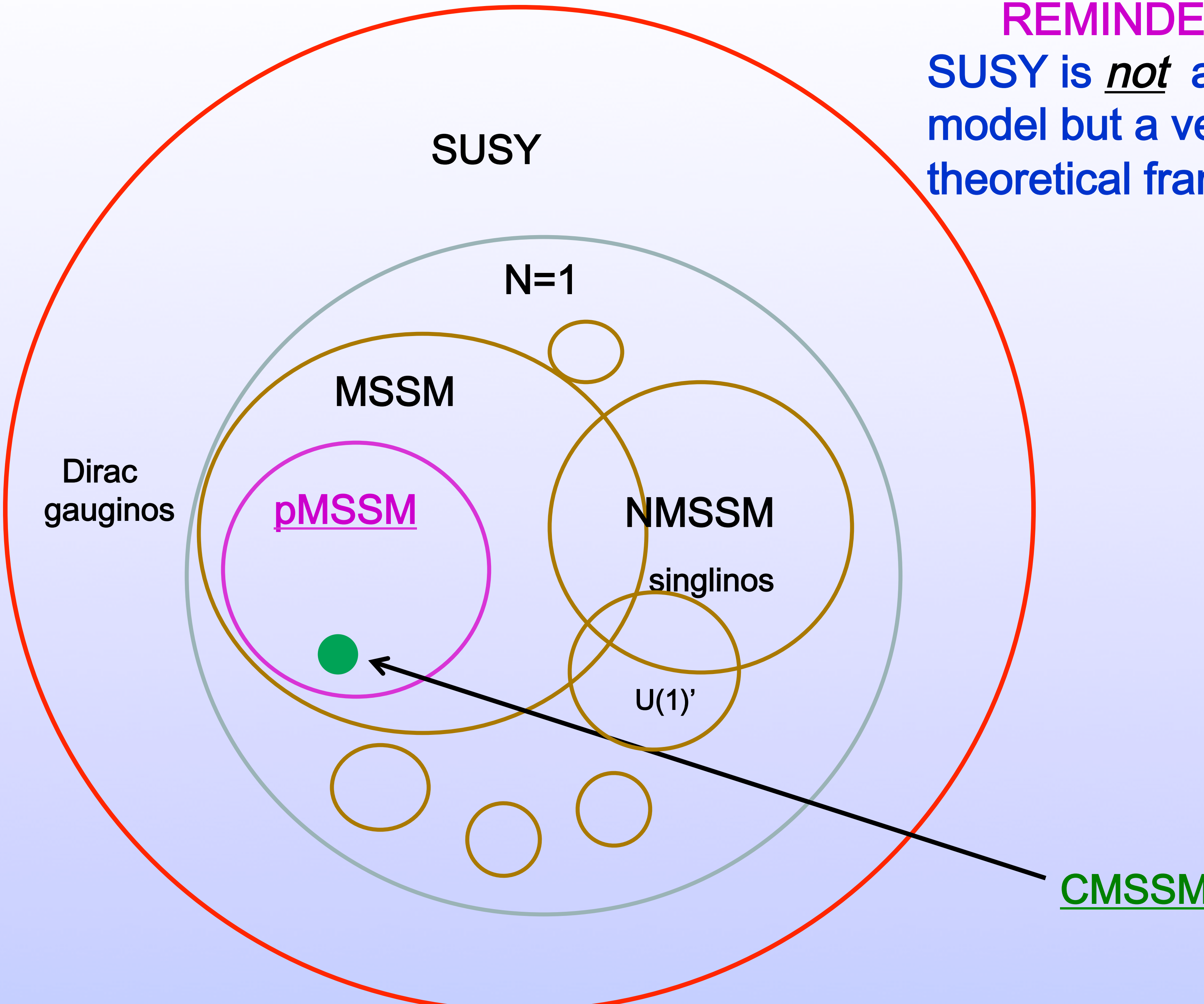
#2592398 w/ FT_{BBHMT} =6.6

Light Stop Decays



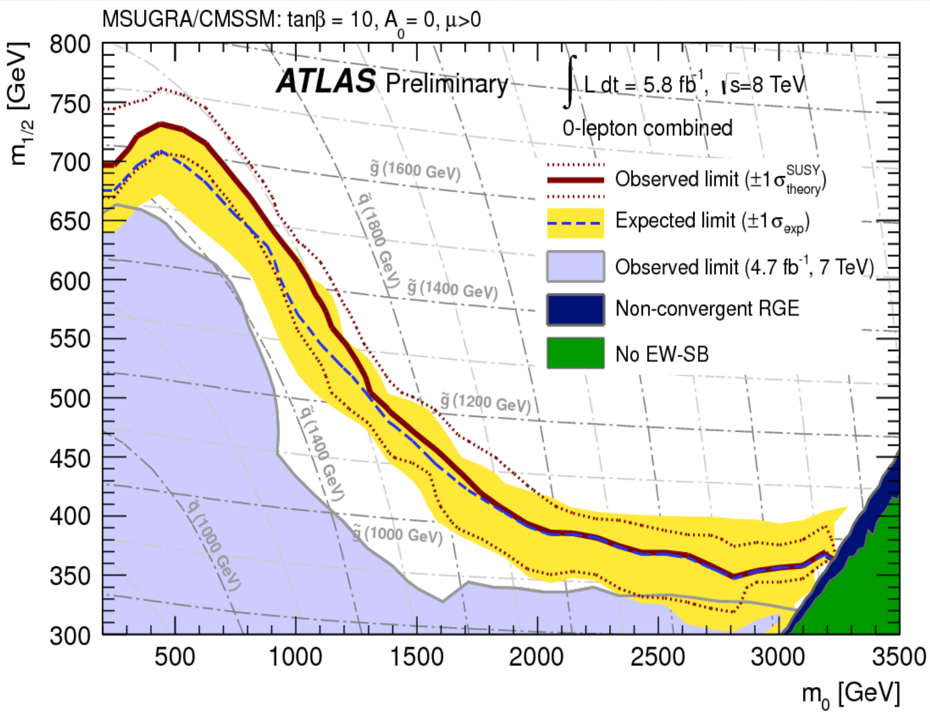
REMINDER:

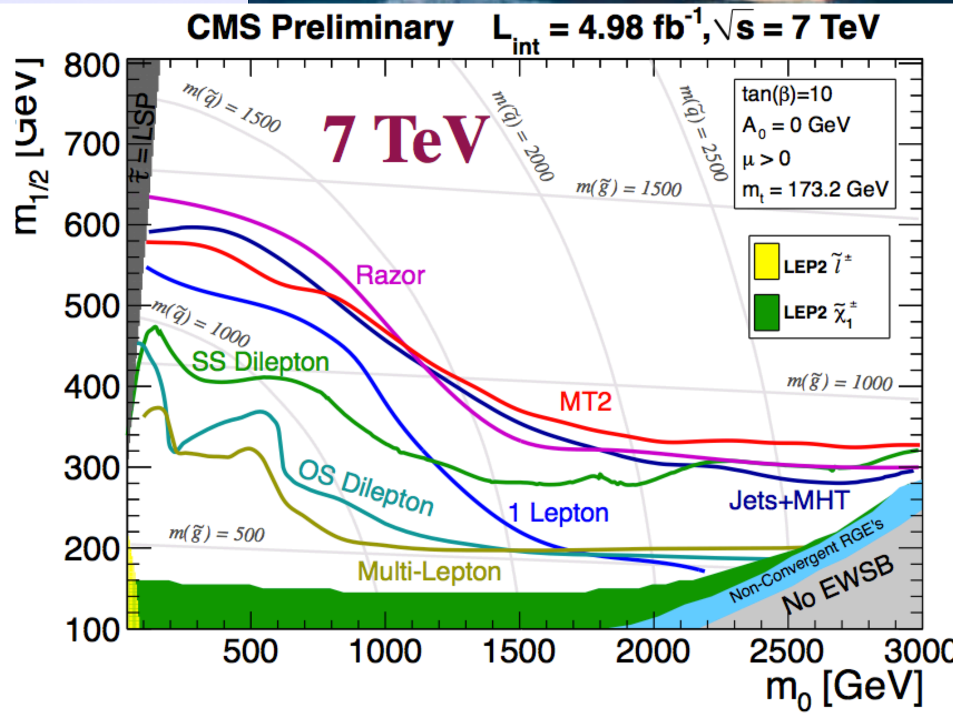
SUSY is *not* a single model but a very large theoretical framework

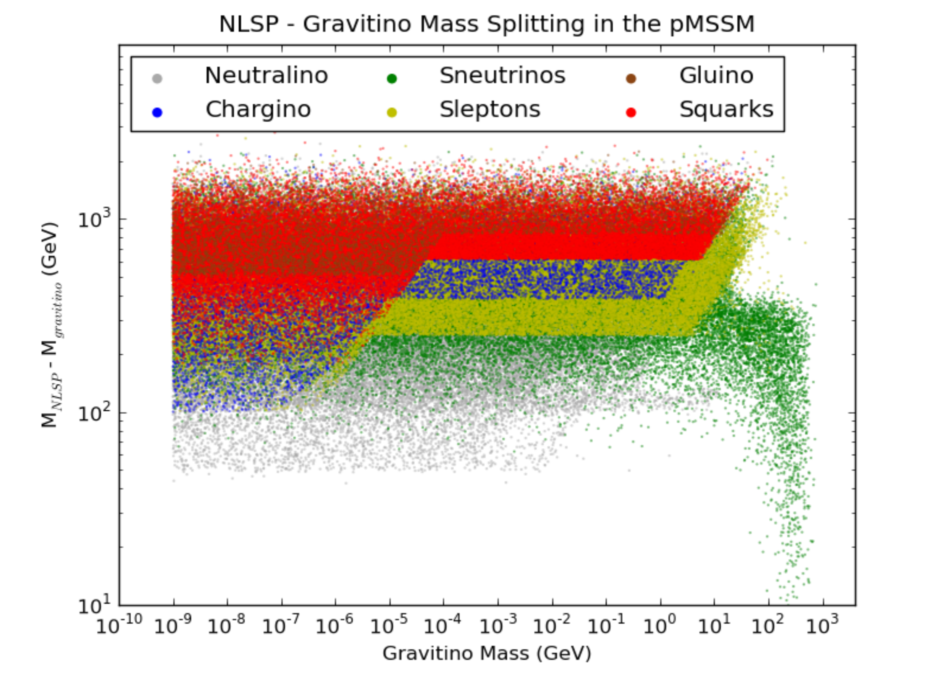


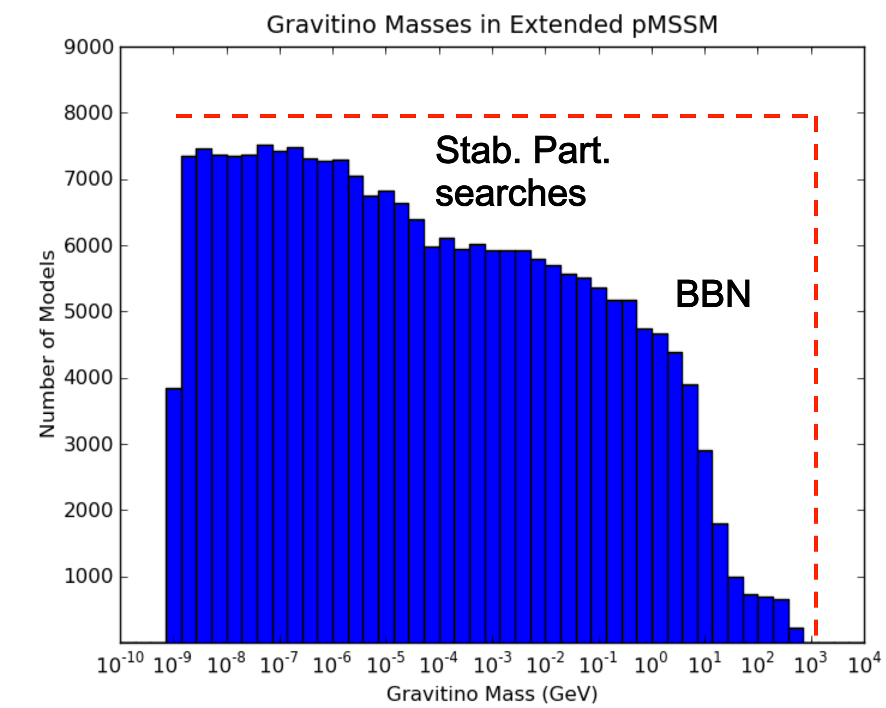
No Sign of SUSY (YET)

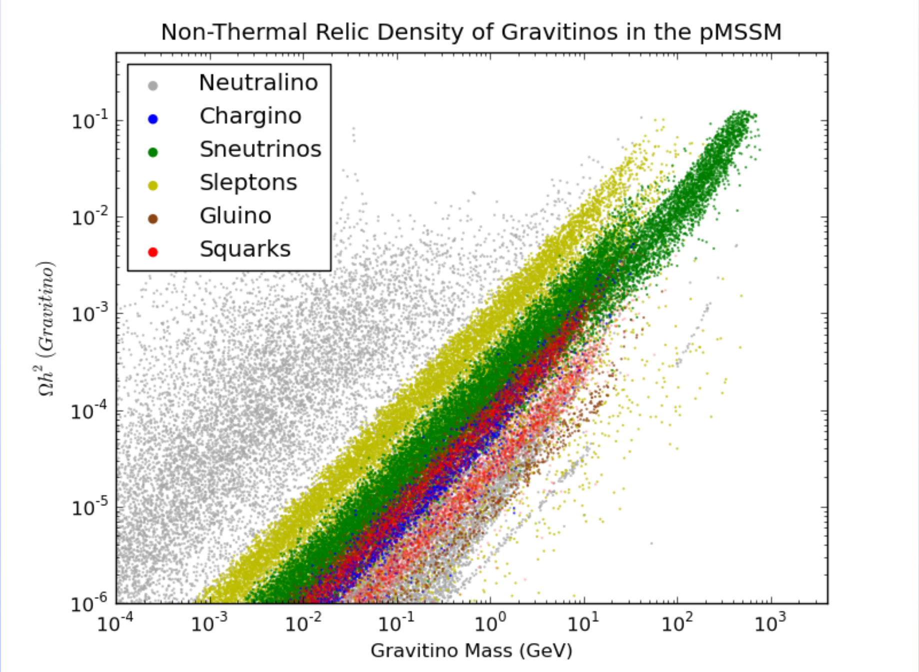
LHC Results in the CMSSM:
Looking difficult for the CMSSM











Some properties of the gravitino LSP models