Title: A Higgs but no sparticles yet: what it means for the (p)MSSM

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Abstract: The phenomenological Minimal Supersymmetric Standard Model (pMSSM) provides a broad perspective on supersymmetric phenomenology. We have generated two large sets of pMSSM models with neutralino and gravitino LSPs, with sparticle masses extending up to 4 TeV. In this talk, I will discuss the implications of searches for supersymmetry and the Higgs, with particular attention to naturalness. In particular, we find that while sparticle spectra with moderately light stops are still allowed, such stops are difficult to find experimentally because of a wide array of possible cascade decays.

A Higgs but no sparticles yet: what it means for the (p)MSSM

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October 2, 2012

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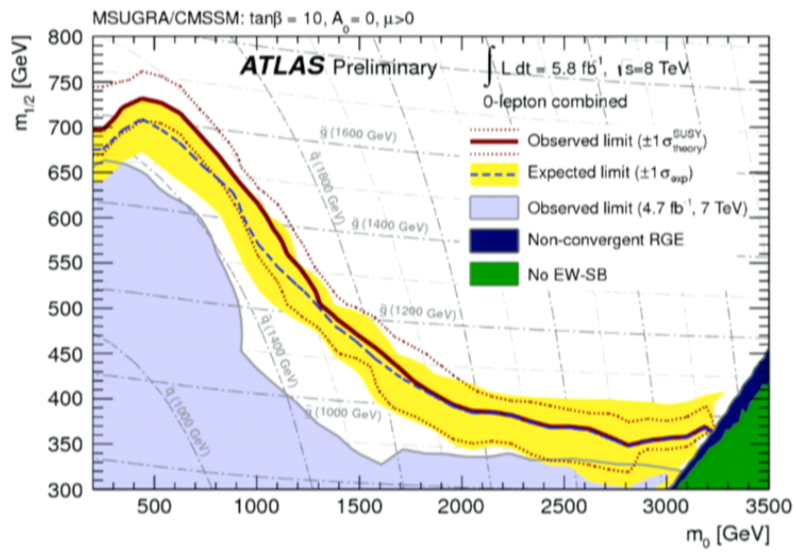
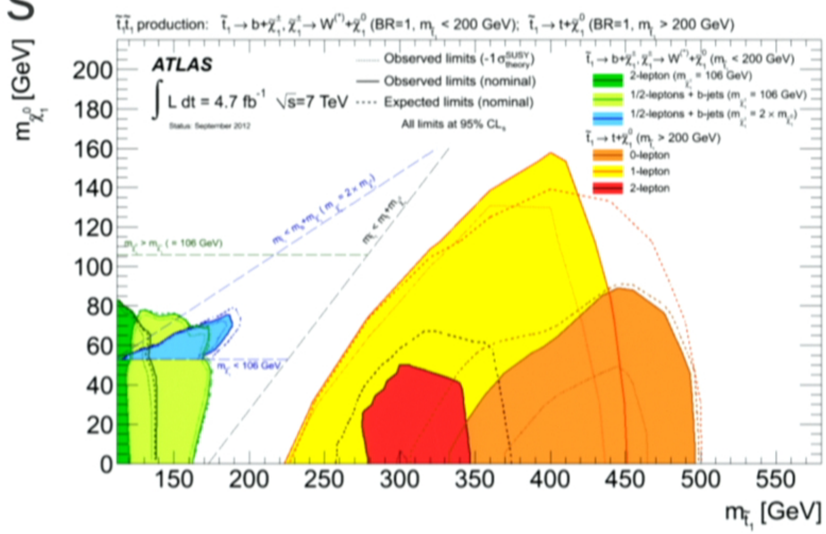
How well is SUSY being limited?

- LHC data continues to constrain new physics, including SUSY
- MSSM has many free parameters, so search limits are often presented in less general frameworks, e.g. mSUGRA



How well is SUSY being limited?

- Simplified models use more search-relevant parameters like new particle masses
- Assume rest of spectrum is decoupled



Another approach

- Instead: can scan over MSSM parameter space, searching for spectra that are consistent with existing experimental bounds (Berger et al., 0812.0980)
- Large number of parameters; sacrifice full coverage for more generality
- Results are not to be interpreted as hard limits on parameters, but examples of wide array of available MSSM phenomenology

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The phenomenological MSSM

- The full MSSM has 105 new free parameters, many of which are very strongly constrained by flavor data
- Minimal flavor violation decreases scan dimensionality without losing much generality
- Take sparticle mass matrices to be flavor diagonal, with first two generations degenerate
- No new sources of CP violation

The phenomenological MSSM

- Together, these assumptions leave us with the 19 free parameters of the *phenomenological MSSM*
- $M_1, M_2, M_3, \mu, \tan\beta, M_A, q_{1,3}, u_{1,3}, d_{1,3}, l_{1,3}, e_{1,3}, A_{t,b,\tau}$
- Can also add gravitino, with mass $m_{3/2}$
- Generate random points in this parameter space, and test vs. experimental constraints
- Investigate properties of resulting models

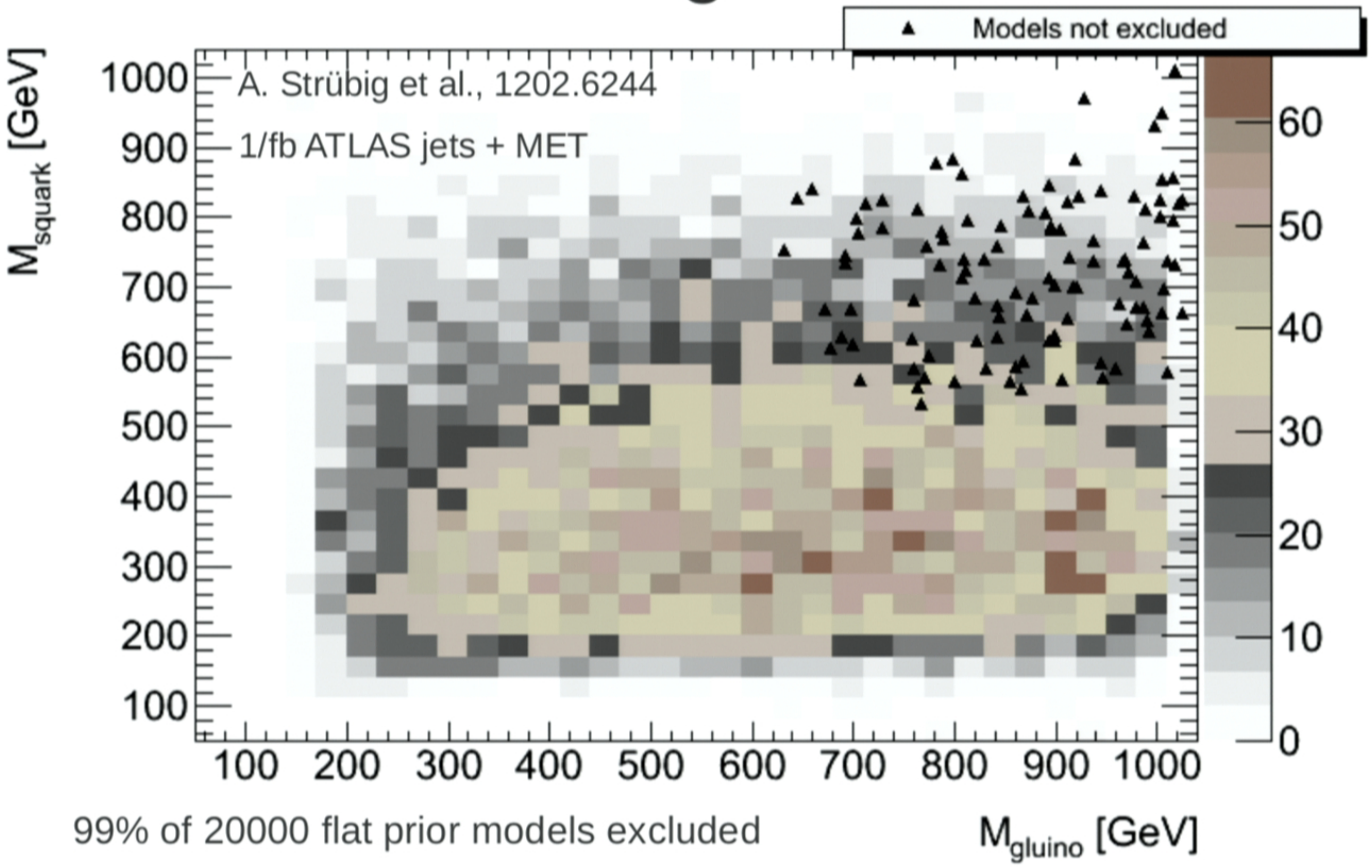
Parameter scan ranges

- 50 GeV ≤ $|M_1|$ ≤ 4 TeV
- 100 GeV ≤ $|M_2, \mu|$ ≤ 4 TeV
- 400 GeV ≤ M_3 ≤ 4 TeV
- 1 ≤ tan β ≤ 60
- 100 GeV ≤ M_A, l, e ≤ 4 TeV
- 400 GeV ≤ q_1, u_1, d_1 ≤ 4 TeV
- 200 GeV ≤ q_3, u_3, d_3 ≤ 4 TeV
- $|A_{t,b,t}|$ ≤ 4 TeV
- 1 eV ≤ $m_{3/2}$ ≤ 1 TeV (log prior)

Compare with Berger et al.

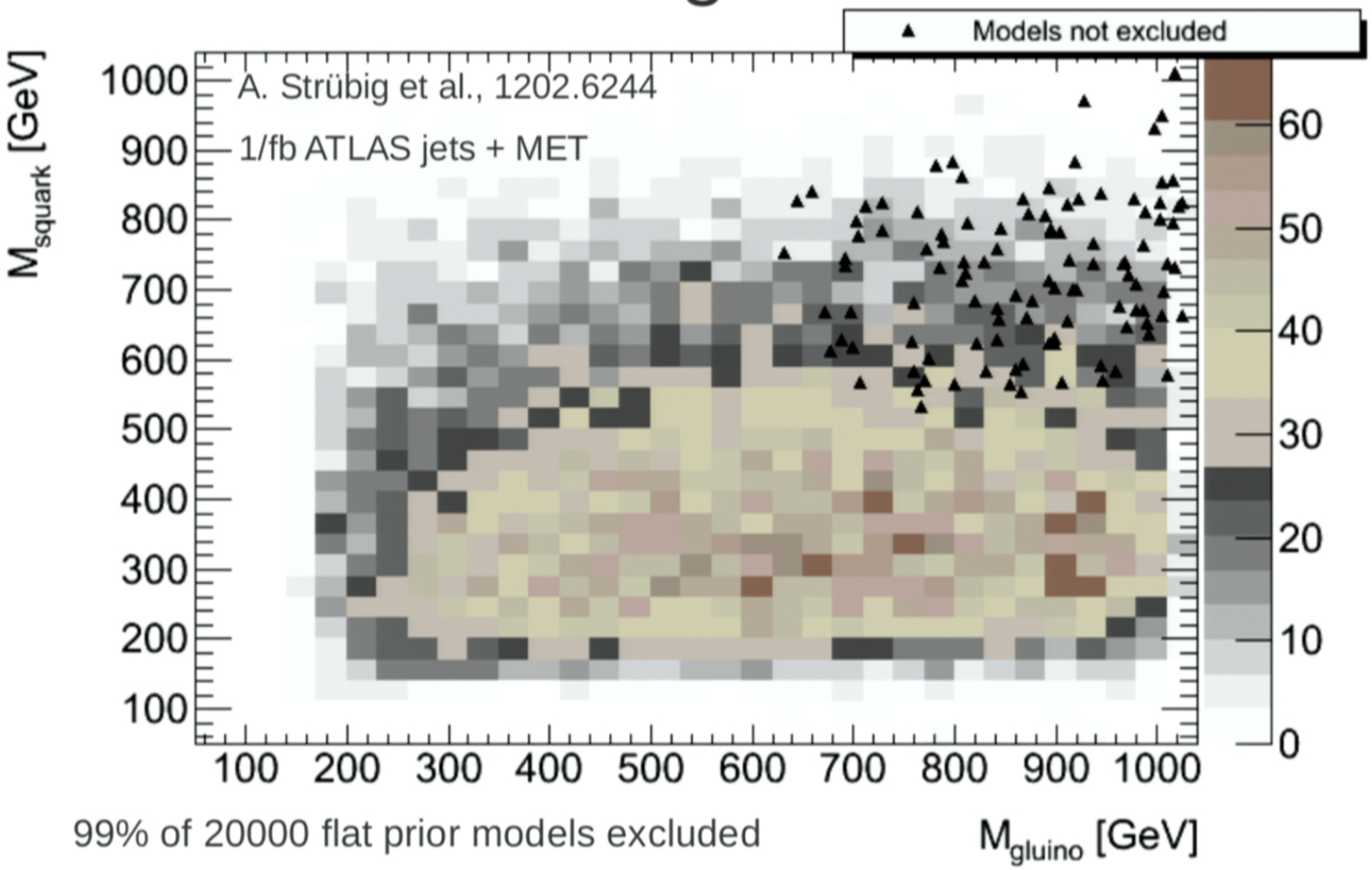
- 50 GeV ≤ $|M_{1,2}, \mu|$ ≤ 1 TeV
- 100 GeV ≤ M_3 ≤ 1 TeV
- 1 ≤ tan β ≤ 50
- 43.5 GeV ≤ M_A ≤ 1 TeV
- 100 GeV ≤ q, u, d, l, e ≤ 1 TeV
- $|A_{t,b,\tau}|$ ≤ 1 TeV

Model set generation



Most models from old scan now ruled out!

Model set generation



99% of 20000 flat prior models excluded

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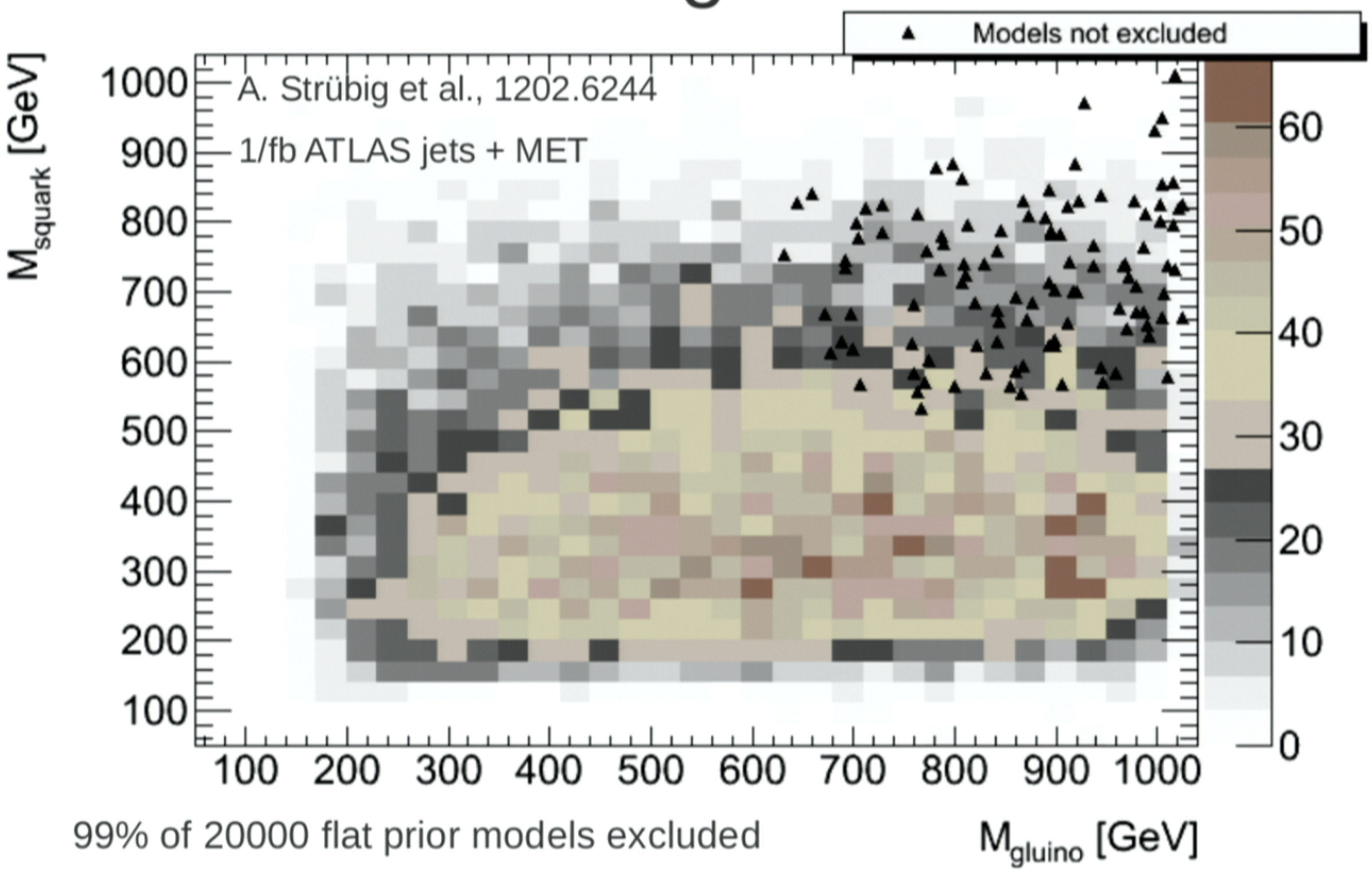

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Model set generation

- Two separate scans
- Neutralino LSP: generate spectra for $3 \cdot 10^6$ points in 19 dimensional parameter space, requiring lightest neutralino to be LSP
- Gravitino LSP: add gravitino mass and scan over 20 dimensional space using $7 \cdot 10^5$ points, with gravitino as LSP
- Spectra are generated with SOFTSUSY and SuSpect, and tossed if there are problems (tachyons, color/charge breaking minima, unbounded scalar potentials) or the generators disagree significantly
- Decay tables are calculated with modified versions of SDECAY, HDECAY, MadGraph, and CalcHEP

Model set generation

- Neutralino LSP set: impose WMAP as upper bound on thermal relic density of lightest neutralino, and check against DM direct detection constraints
- Gravitino LSP set: assume the NLSP is quasi-stable and reaches its relic density, decaying to the gravitino after freezeout; impose WMAP, cosmological constraints
- Precision EW constraints: g – 2, invisible width of Z, $\Delta\rho$
- Flavor constraints: $b \to s\gamma$, $B_s \to \mu\mu$, $B \to \tau\nu$
- Require all charged sparticles > 100 GeV
- Impose LHC stable particle, $\phi \to \tau\tau$ constraints as of 12/2011
- $2 \cdot 10^5$ models left in each set; computationally demanding!

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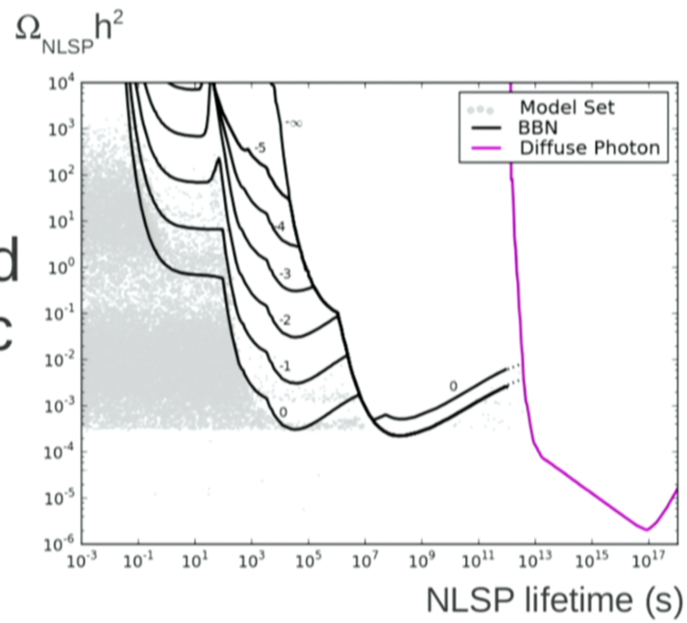
Gravitino LSP cosmology

- No assumptions about early universe gravitino cosmology, e.g. reheating temperature or entropy production
- NLSP freezes out later
- Assume NLSP reaches its thermal relic density, and consider out-of-equilibrium decays to gravitino
- Gravitino LSP has very weak couplings, so no dark matter detection constraints
- However, for a gravitino LSP, the NLSP can be very long-lived

Gravitino LSP cosmology

- NLSP lifetimes between 10^{-2} and 10^{5} s can affect BBN if decay products are hadronic
- For lifetimes from 10^{5} s to 10^{12} s, BBN is affected even for electromagnetic energy injection
- Diffuse photon constraints become applicable for longer lifetimes

Constraints on neutralino NLSPs

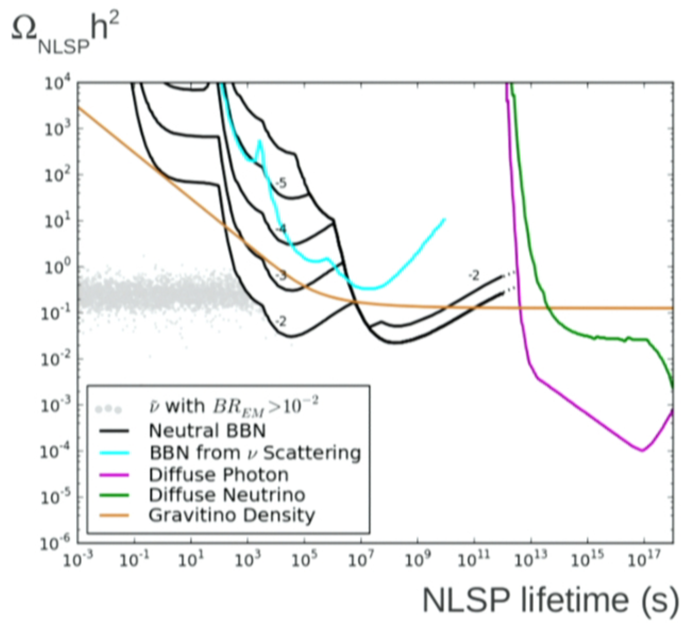


BBN limits from Jedamzik et al., hep-ph/0604251

Gravitino LSP cosmology

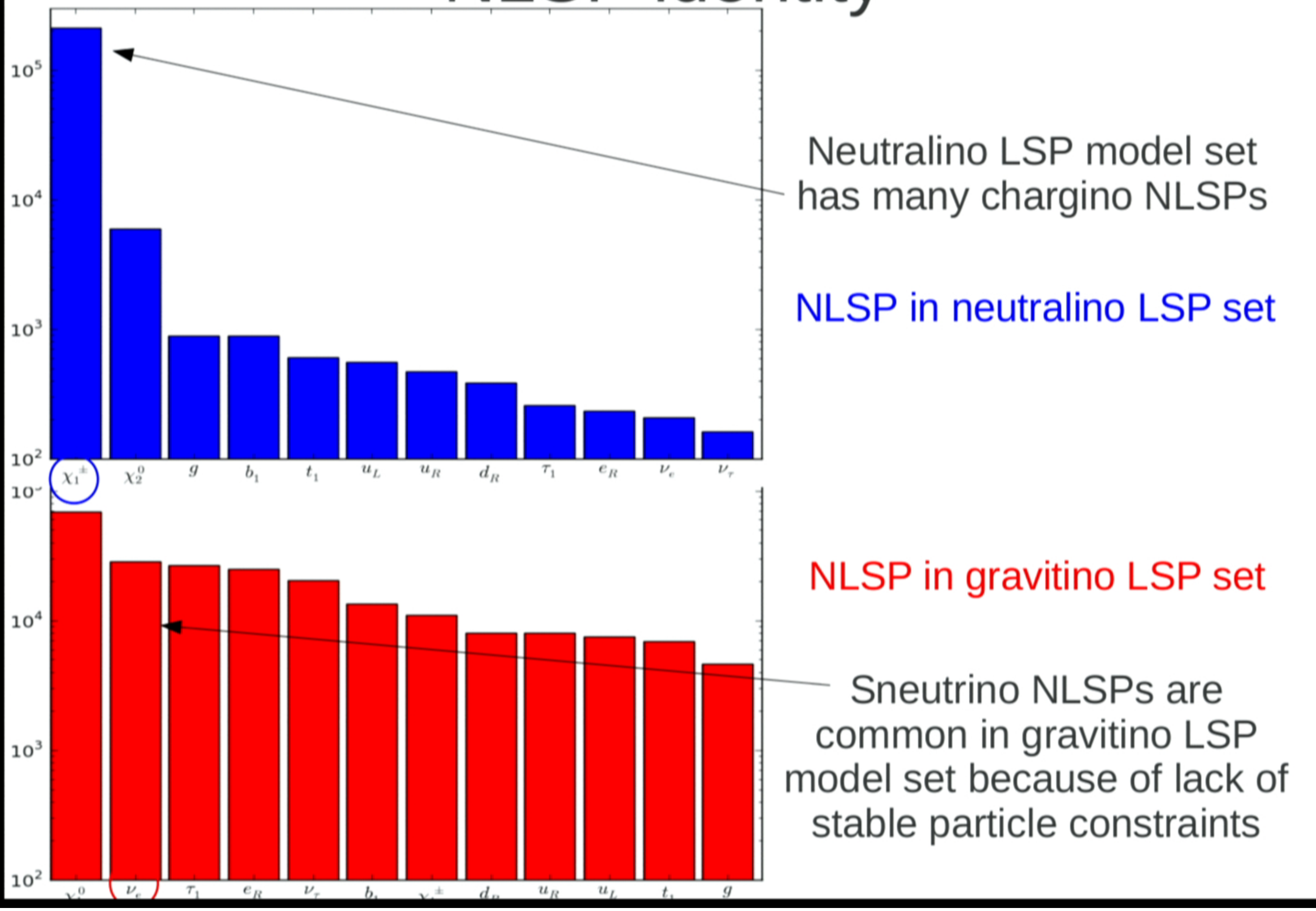
- Sneutrino NLSPs have small branching ratios for decays that produce visible SM particles
- Neutrinos resulting from sneutrino NLSP decays can also scatter off leptons, giving leptons/mesons that affect BBN
- Diffuse photon/neutrino flux for longer lifetimes

Constraints on sneutrino NLSPs



Neutrino scattering limits from Kanzaki et al., 0705.1200

NLSP identity

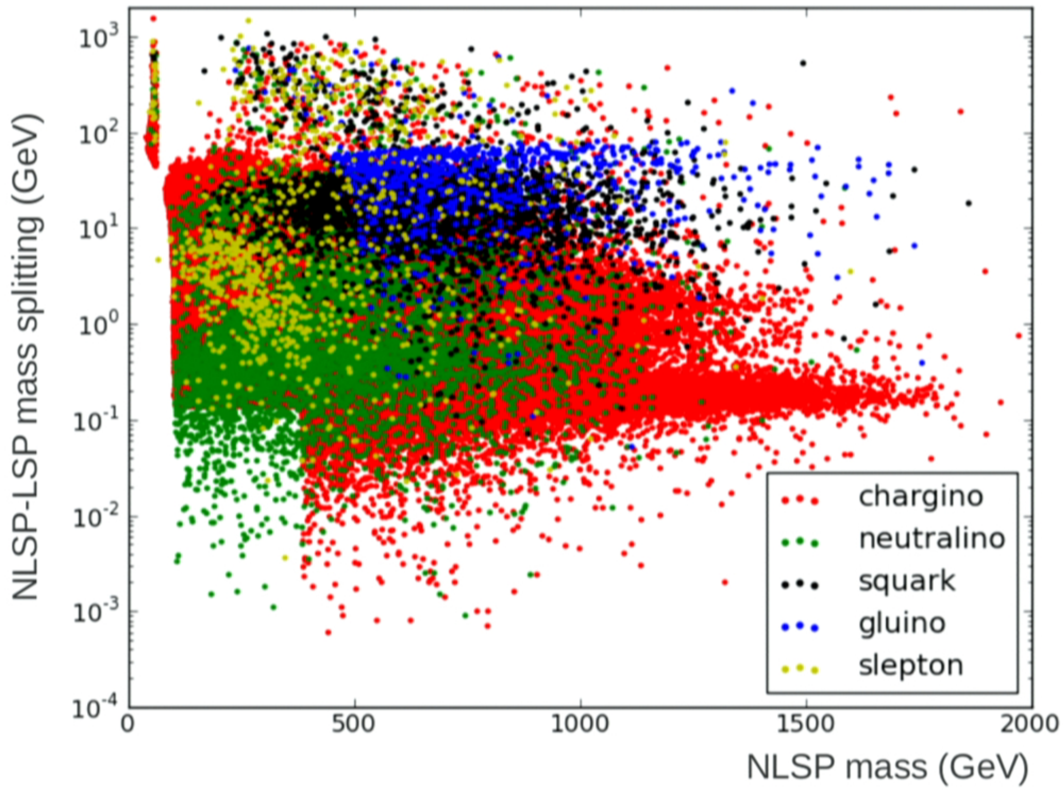


Lightest neutralino composition

Lightest Neutralino	Definition	$\tilde{\chi}_1^0$ LSP	$\tilde{G}$ 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

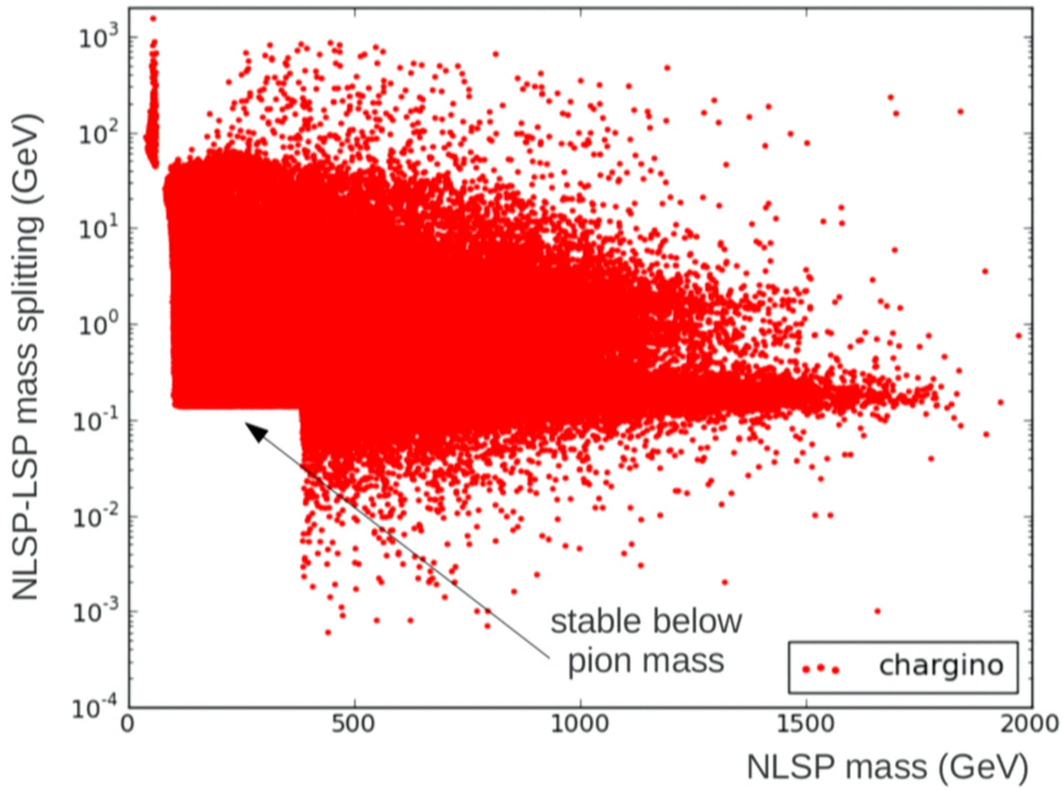
Bino LSPs tend to give high relic densities in neutralino LSP model set
In gravitino LSP model set, lightest neutralino does not make up DM

Stable particles



Neutralino LSP models can have
stable charginos if LSP is wino

Stable particles



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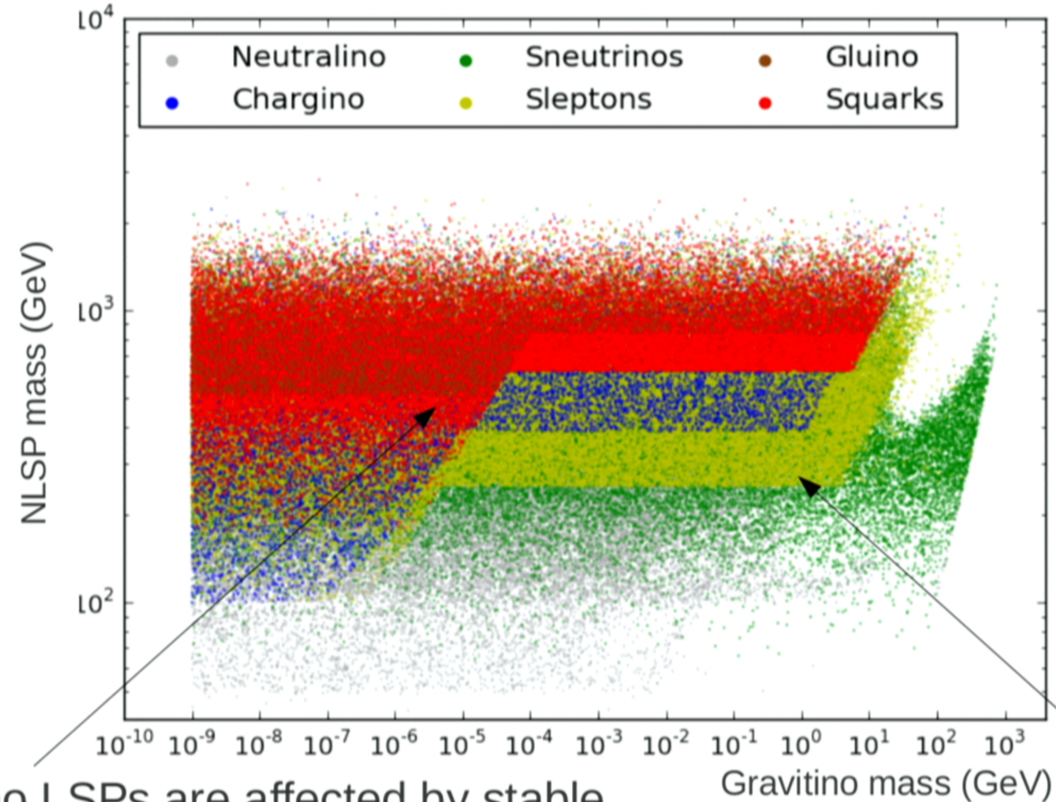
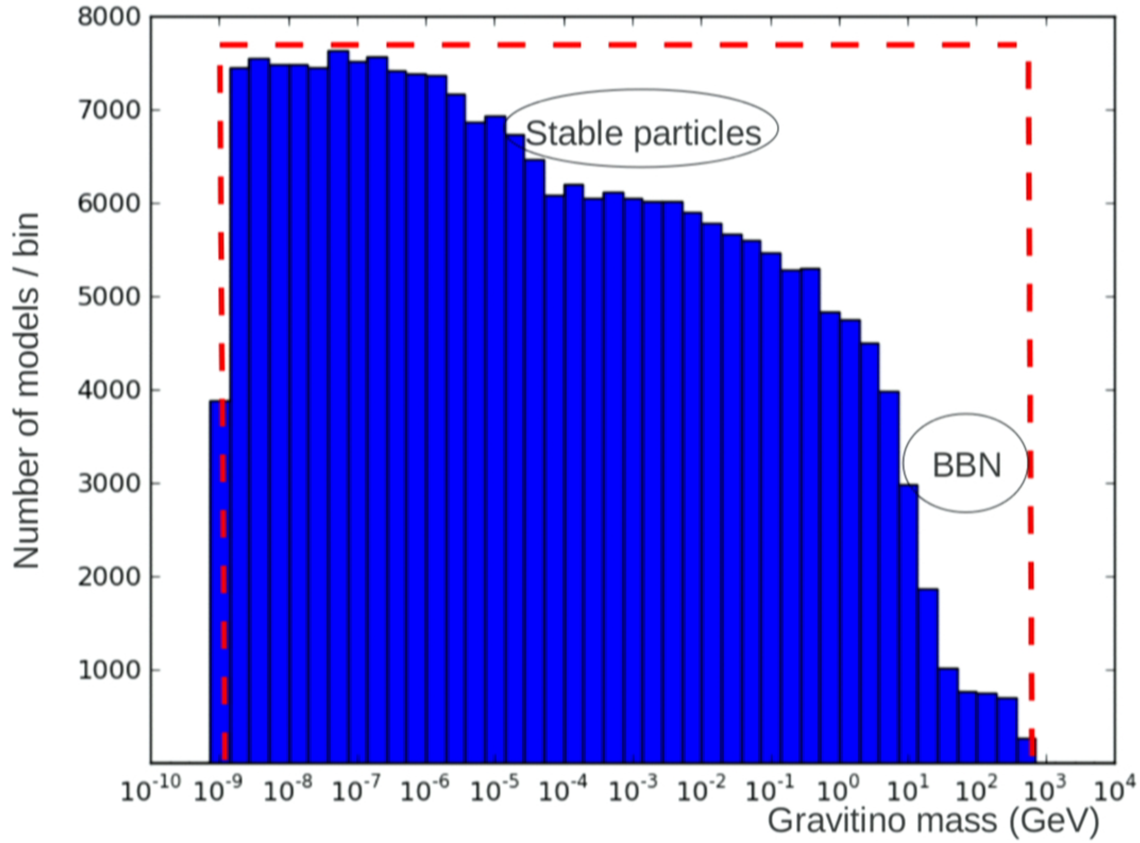


Gravitino LSPs are affected by stable charged particle searches too

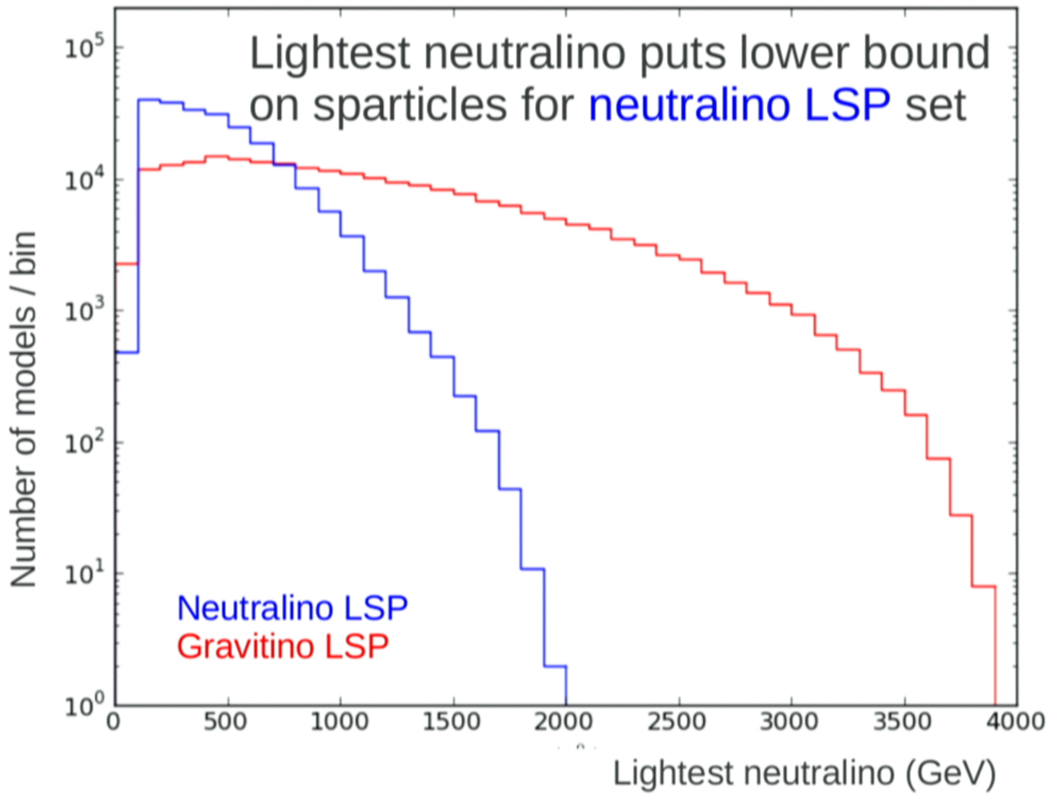
When the NLSP is very long-lived, cosmological constraints come in

Gravitino LSP mass distribution



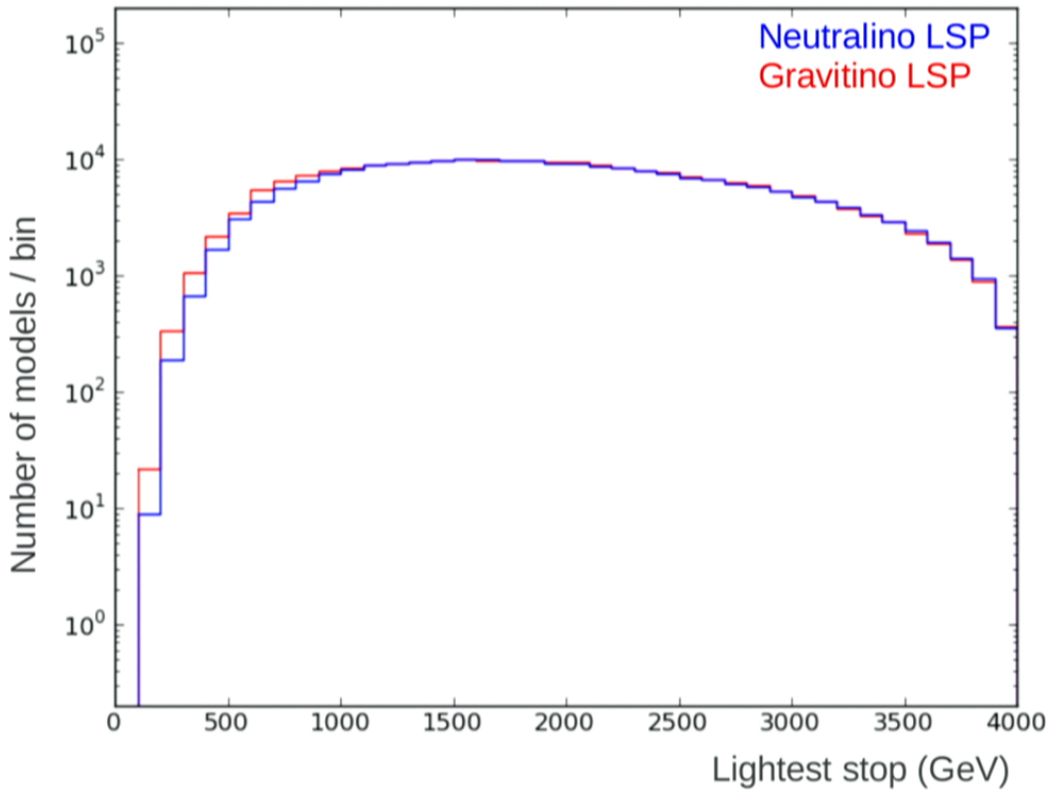
Resulting mass distribution is peaked towards lighter gravitinos

Model set comparison



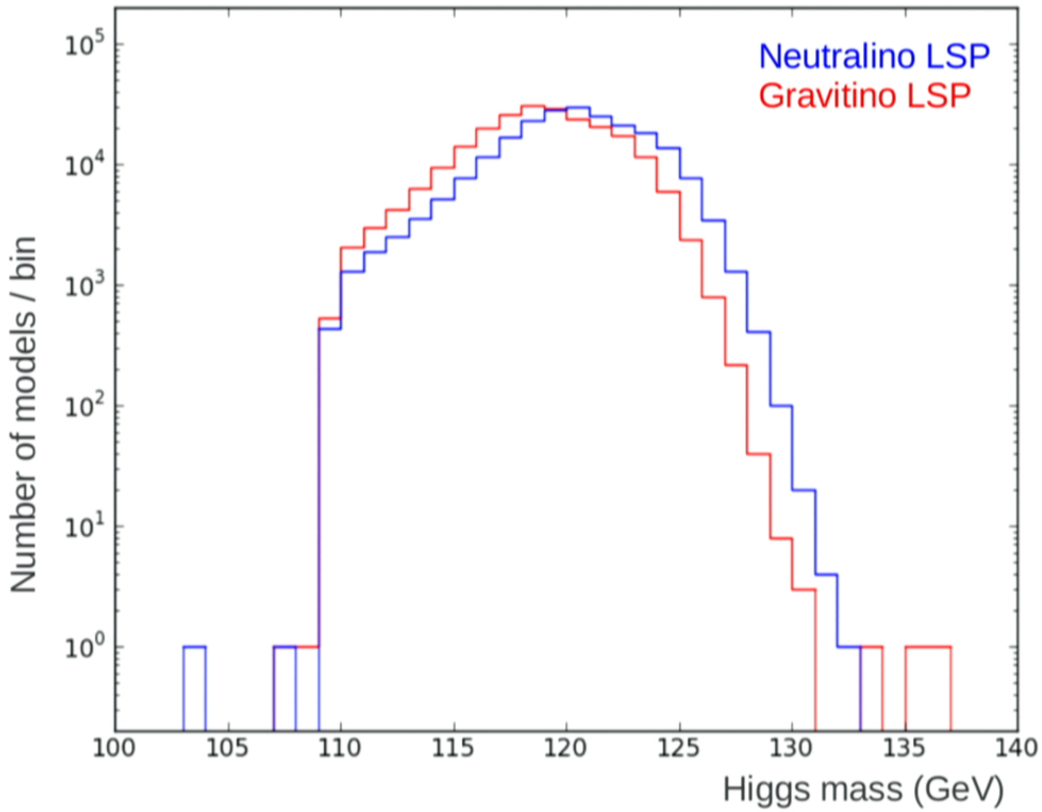
For gravitino LSP set, there is no such bound from the lightest neutralino mass, so sparticles end up lighter

Model set comparison



Stops are pushed up by this lower bound in the neutralino LSP set

Model set comparison

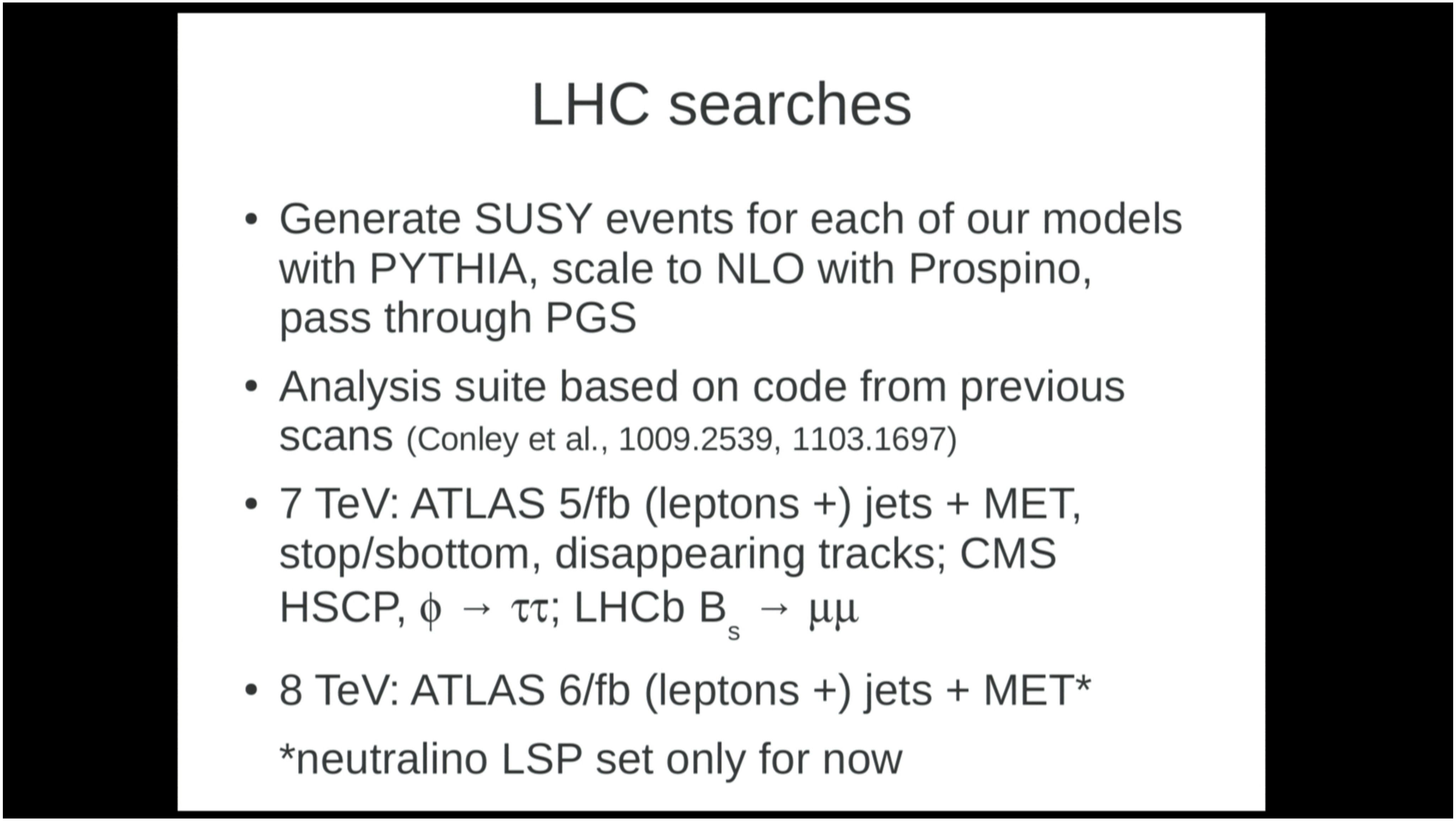


Neutralino LSP set gets heavier Higgses from heavier stops, on average

LHC searches

- Generate SUSY events for each of our models with PYTHIA, scale to NLO with Prospino, pass through PGS
- Analysis suite based on code from previous scans (Conley et al., 1009.2539, 1103.1697)
- 7 TeV: ATLAS 5/fb (leptons +) jets + MET, stop/sbottom, disappearing tracks; CMS HSCP, $\phi \to \tau\tau$; LHCb $B_s \to \mu\mu$
- 8 TeV: ATLAS 6/fb (leptons +) jets + MET*

*neutralino LSP set only for now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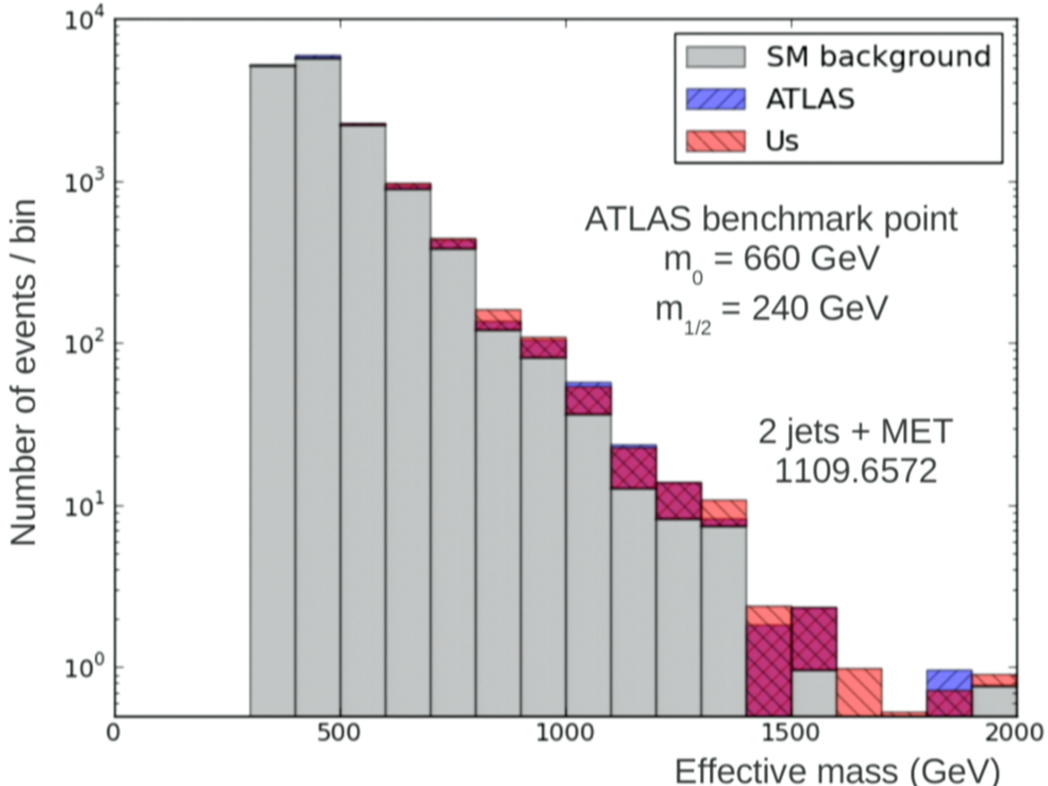
LHC searches

	Short Title of the CONF note	Date	√s (TeV)	L (fb^{-1})	Document	Plots
✓	*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
	Monophoton [ADD, WIMP] NEW	09/2012	7	4.7	1209.4625	Link	Submitted to PRL
✓	2 leptons + jets + Etmiss [Medium stop] NEW	09/2012	7	4.7	1209.4186	Link	Submitted to JHEP
	1-2 b-jets + 1-2 leptons + jets + Etmiss [Light Stop] NEW	09/2012	7	4.7	1209.2102	Link	Submitted to PLB
	2 photons + Etmiss [GGM] NEW	09/2012	7	4.7	1209.0753	Link	Submitted to PLB
✓	1-2 leptons + >=2-4 jets + Etmiss	08/2012	7	4.7	1208.4688	Link	Accepted by PRD
✓	2 leptons + >=1 jet + Etmiss [Very light stop]	08/2012	7	4.7	1208.4305	Link (inc. HEPData)	Submitted to EPJC
✓	3 leptons + Etmiss [Direct gauginos]	08/2012	7	4.7	1208.3144	Link (inc. HEPData)	Submitted to PLB
✓	2 leptons + Etmiss [Direct gauginos/sleptons]	08/2012	7	4.7	1208.2884	Link	Submitted to PLB
✓	1 lepton + >=4 jets (>=1 b-jet) + Etmiss [Heavy stop]	08/2012	7	4.7	1208.2590	Link	Accepted by PRL
✓	0 lepton + 1-2 b-jet + 5-4 jets + Etmiss [Heavy stop]	08/2012	7	4.7	1208.1447	Link	Accepted by PRL
✓	0 lepton + >=2-6 jets + Etmiss	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	Accepted by EPJC
✓	0 lepton + >=(6-9) jets + Etmiss	06/2012	7	4.7	1206.1760	Link	JHEP 1207 (2012) 167
	Electron-muon continuum [RPV]	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
	=3 leptons + Etmiss [Direct gauginos]	04/2012	7	2.05	1204.5638	Link (inc. HEPData)	PRL 108 (2012) 261804
	>=1 tau + jets + Etmiss [GMSB]	04/2012	7	2.05	1204.3852	Link (inc. HEPData)	PLB 714 (2012) 197

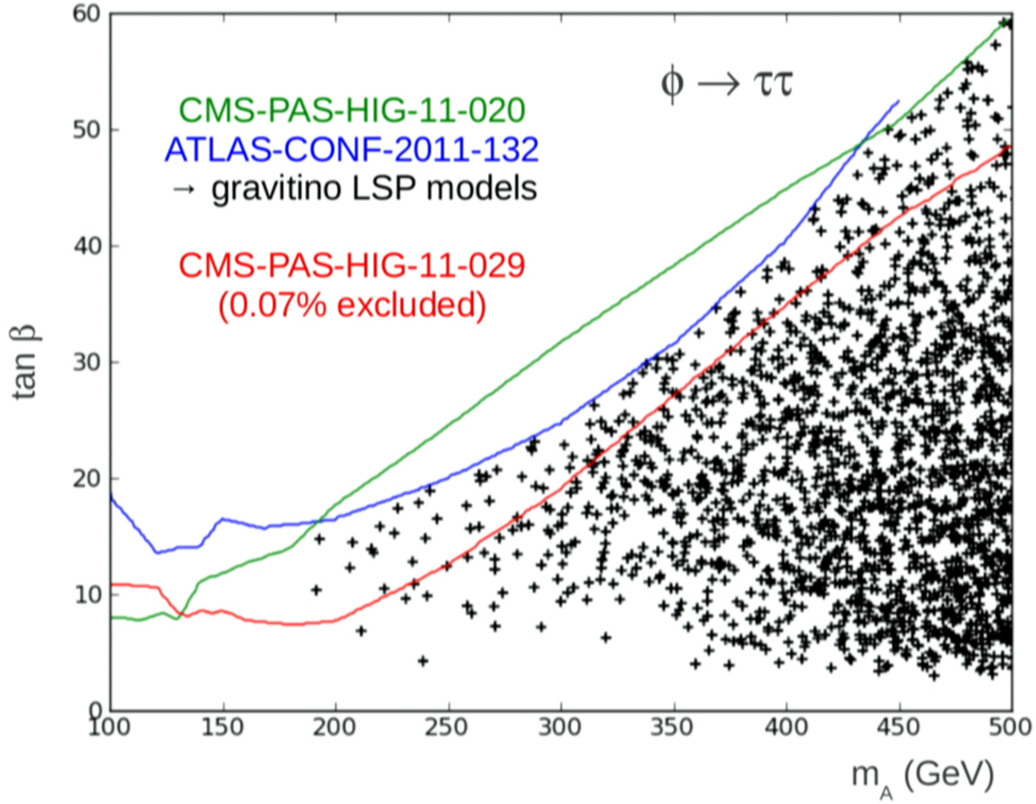
LHC searches



Shape reproduced well

Normalization good given ~35% uncertainty quoted by ATLAS

LHC searches



LHC searches

Neutralino LSP

Analysis	7 TeV 4.7 fb^{-1}	8 TeV 5.8 fb^{-1}	*8 TeV 25 fb^{-1}*
Jets + MET	21.8%	26.3%	*25.2%*
Many jets + MET	1.7%	3.3%	*3.6%*
1 ℓ + jets + MET	3.3%	3.3%	*3.8%*
SSDL	—	4.8%	*7.4%*
Multi-leptons	4.2%	—	—
Stop/sbottom	7.2%	—	—
HSCP	3.7%	—	—
Disappearing tracks	2.1%	—	—
$B_s \to \mu\mu, \phi \to \tau\tau$	4.2%	—	—
Remaining models	66.3%		*65.4%*

- 1.0% of the model set is excluded by the 7 TeV vanilla SUSY searches but *not* by the corresponding 8 TeV analyses (tighter cuts)
- Going to 25/fb at 8 TeV doesn't gain much!

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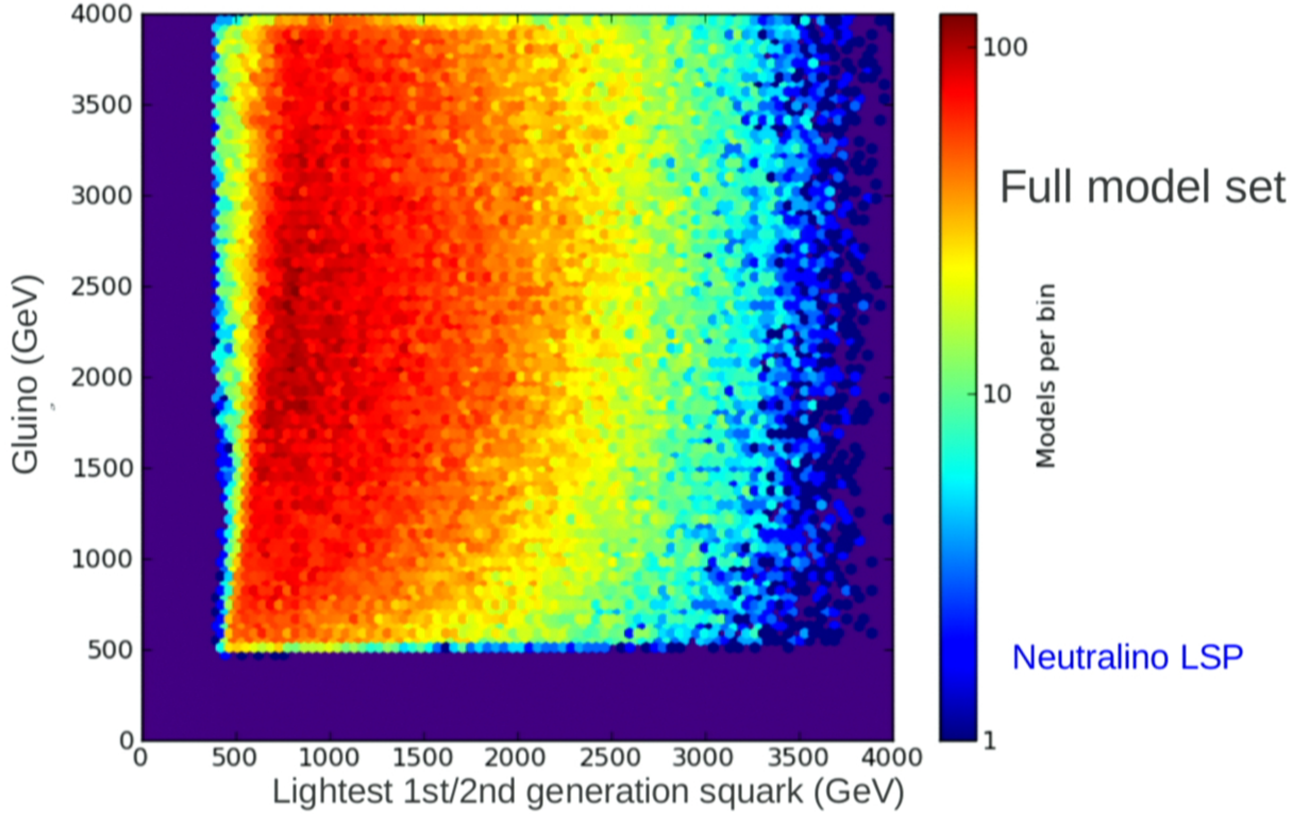
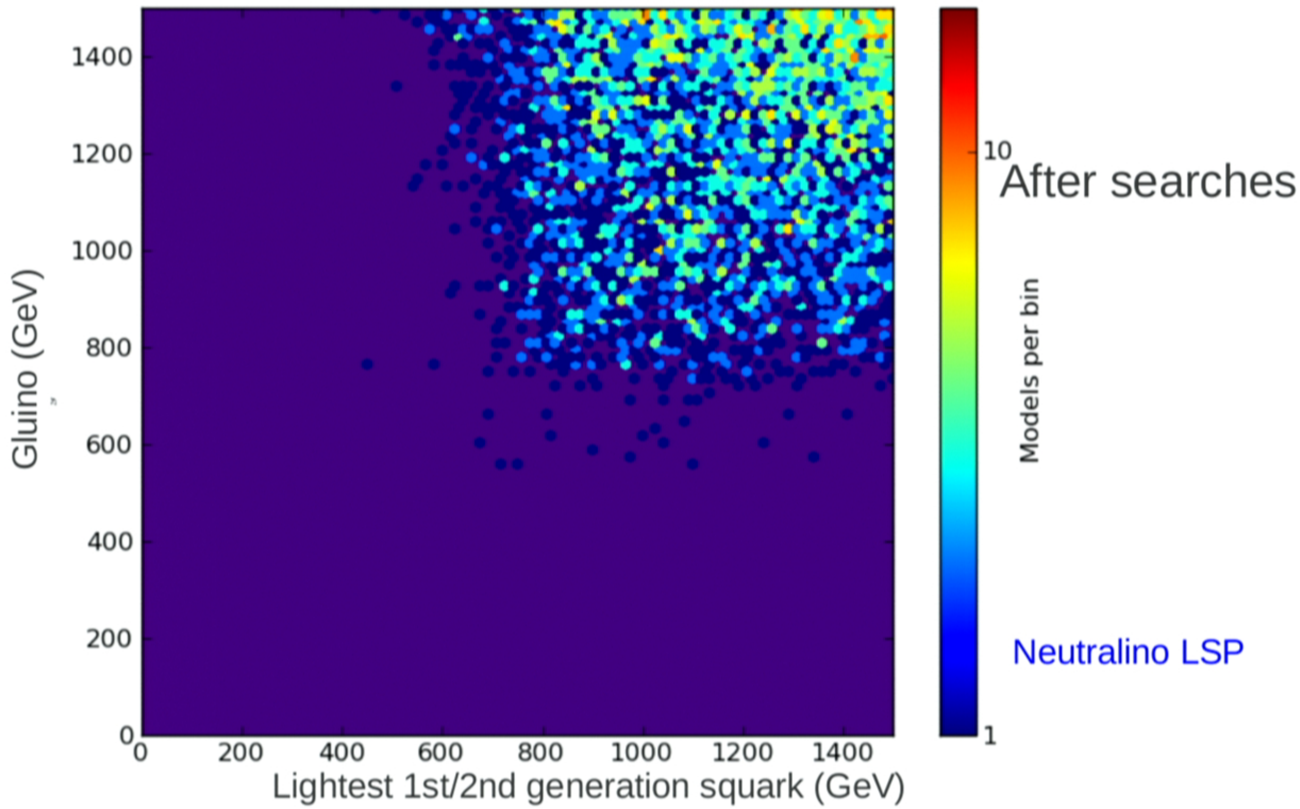


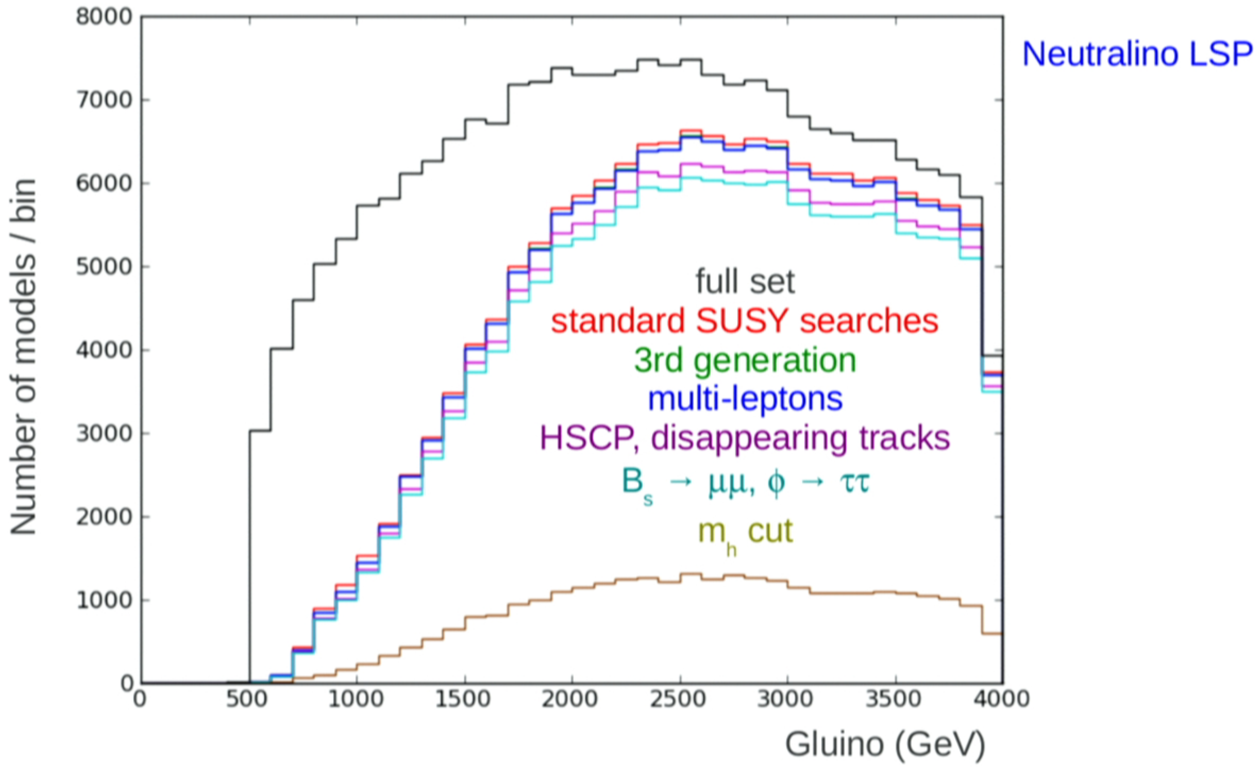
Most SUSY searches designed to exclude models on bottom/left of density plot

LHC searches



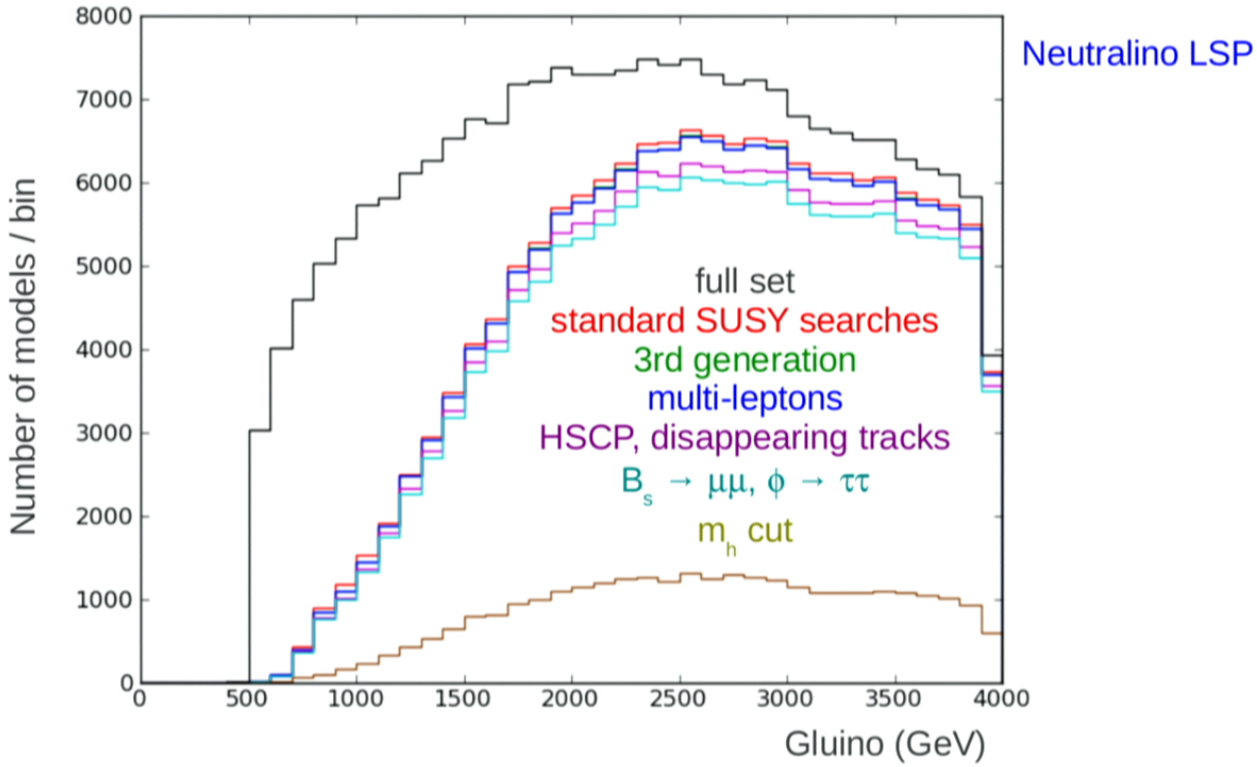
Models with light squarks and gluinos are constrained, but can survive with, e.g., compressed spectra

LHC searches



Non-MET searches are orthogonal to MET searches
Cutting on Higgs mass affects gluino distribution

LHC searches



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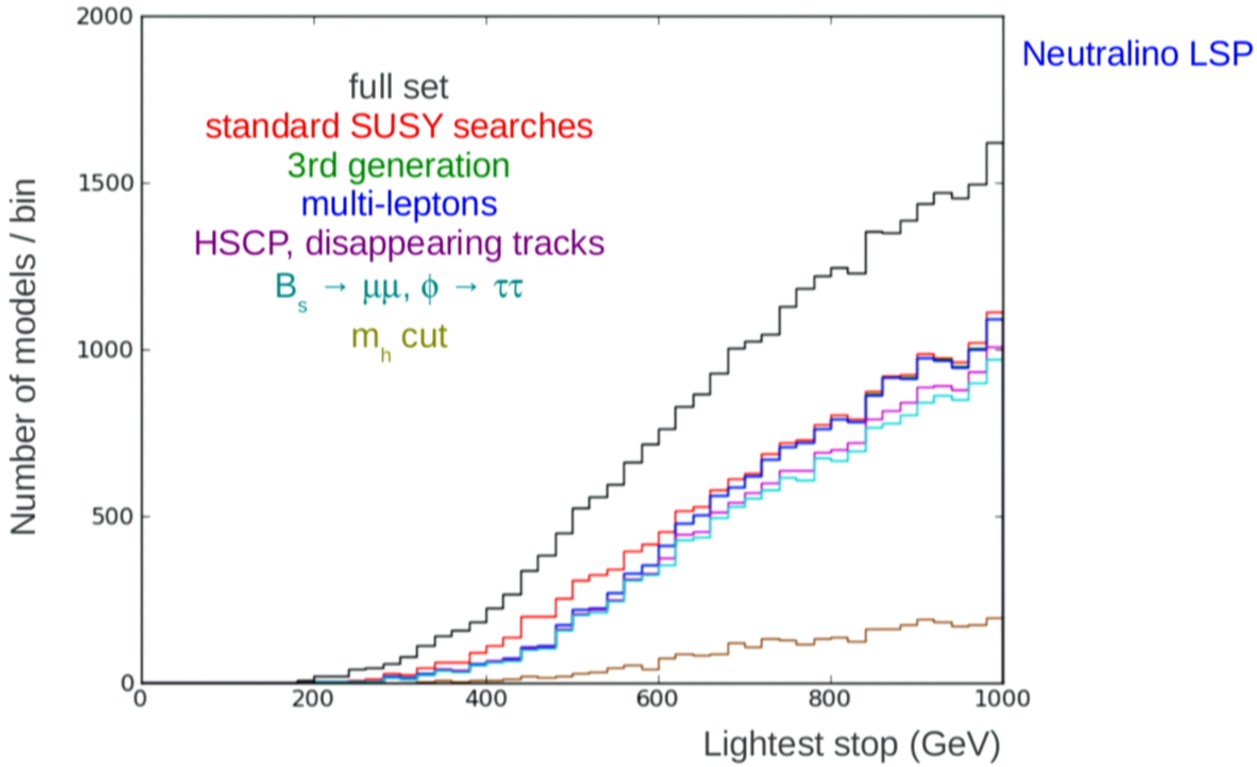
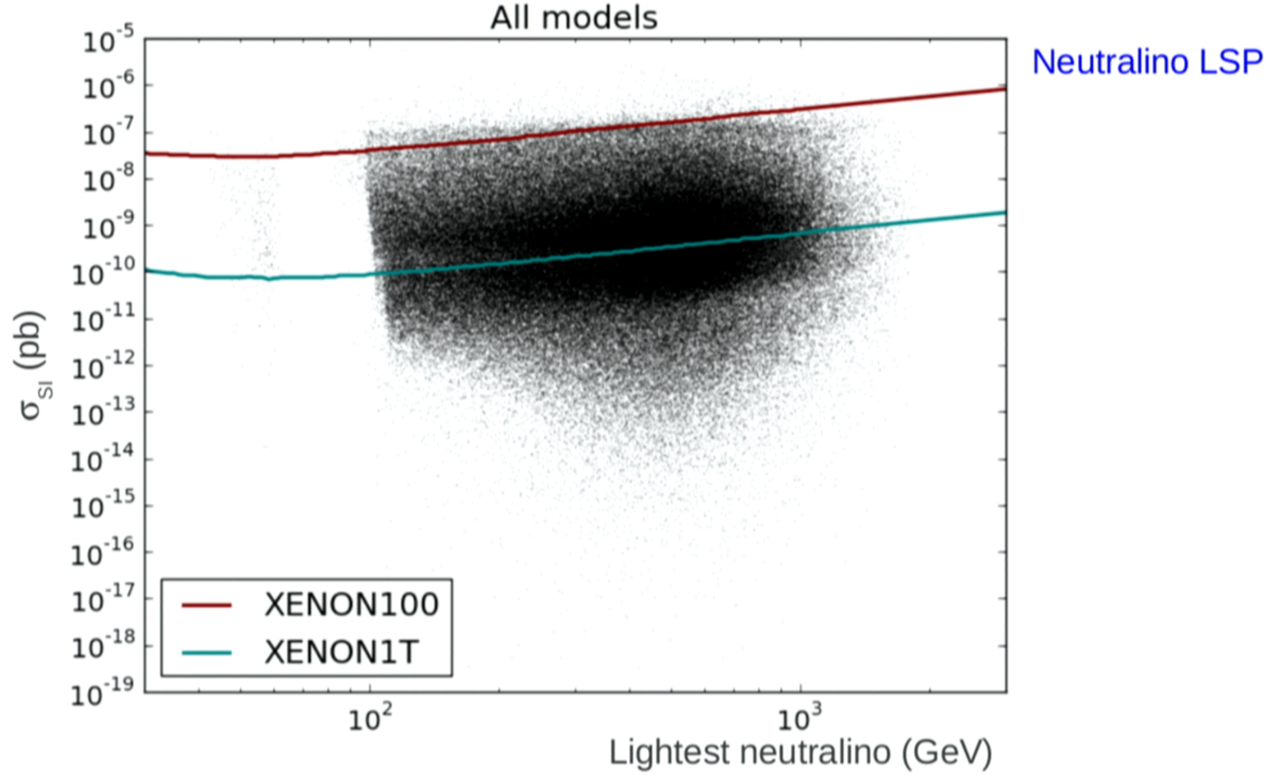


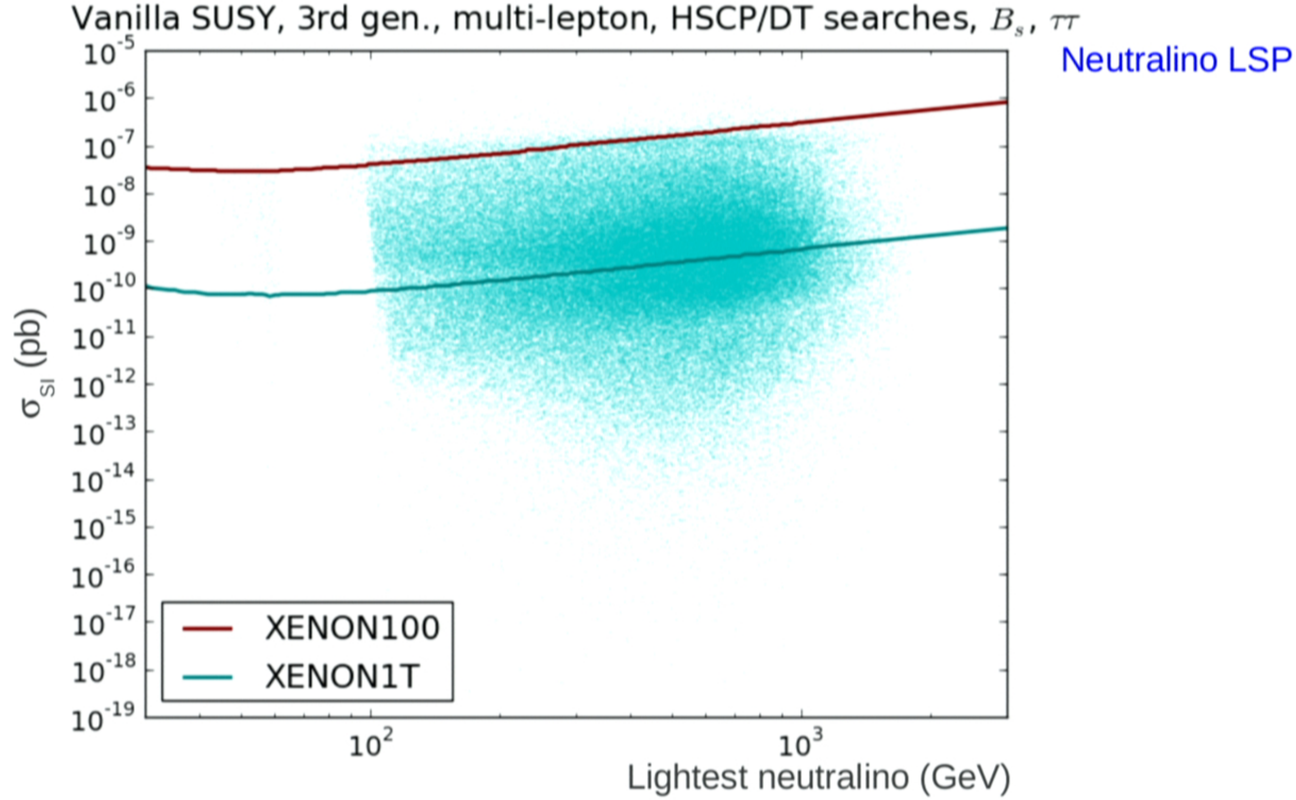
Searches for stop/sbottoms work to some extent, but some models have tricky cascade decays

LHC searches



Dark matter and LHC searches for SUSY complement each other

LHC searches



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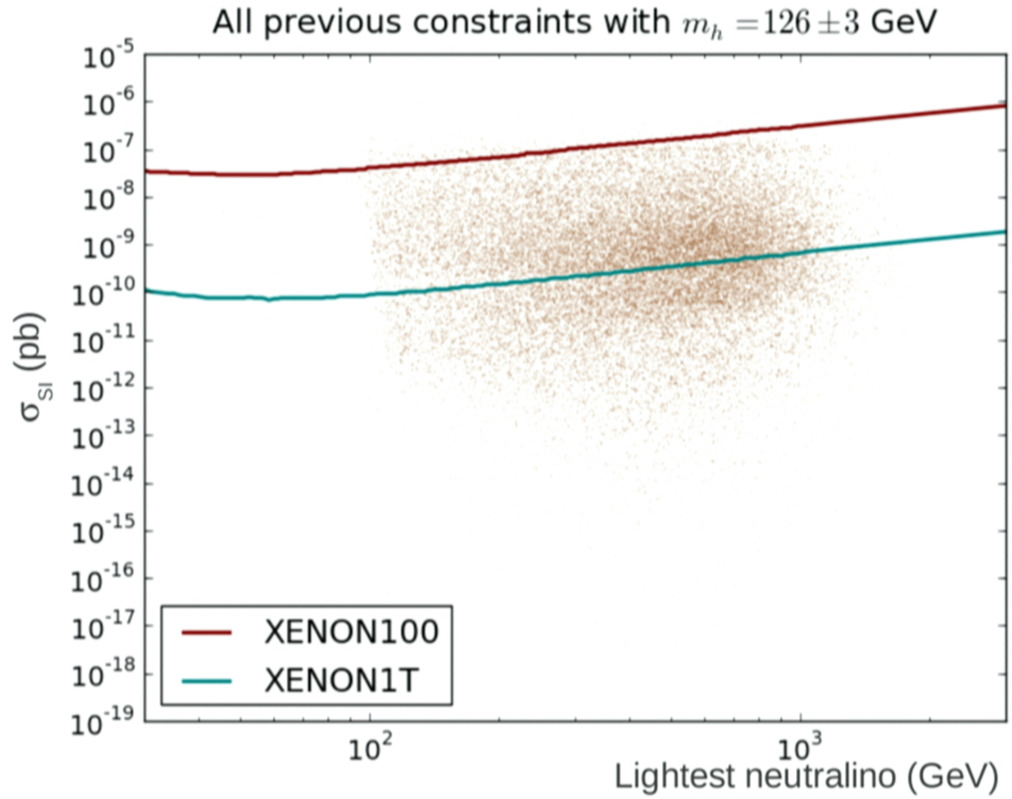
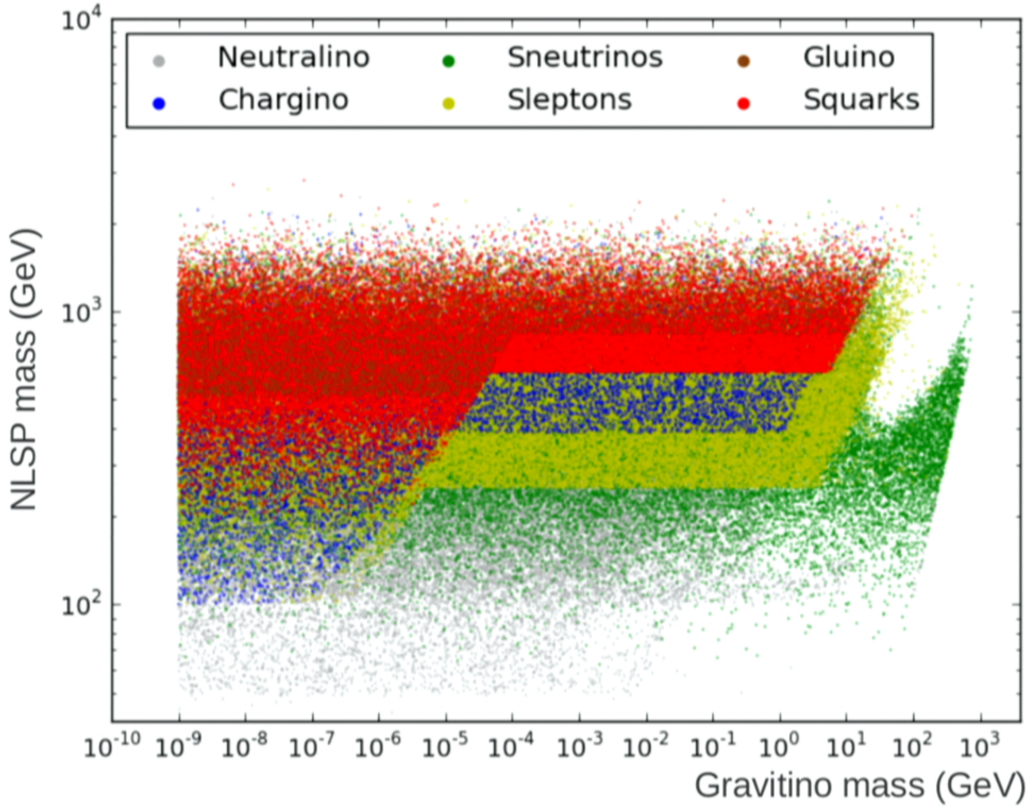


Neutralino LSP

Higgs mass cut Is approximately independent of LHC and DM searches

LHC searches

Full model set

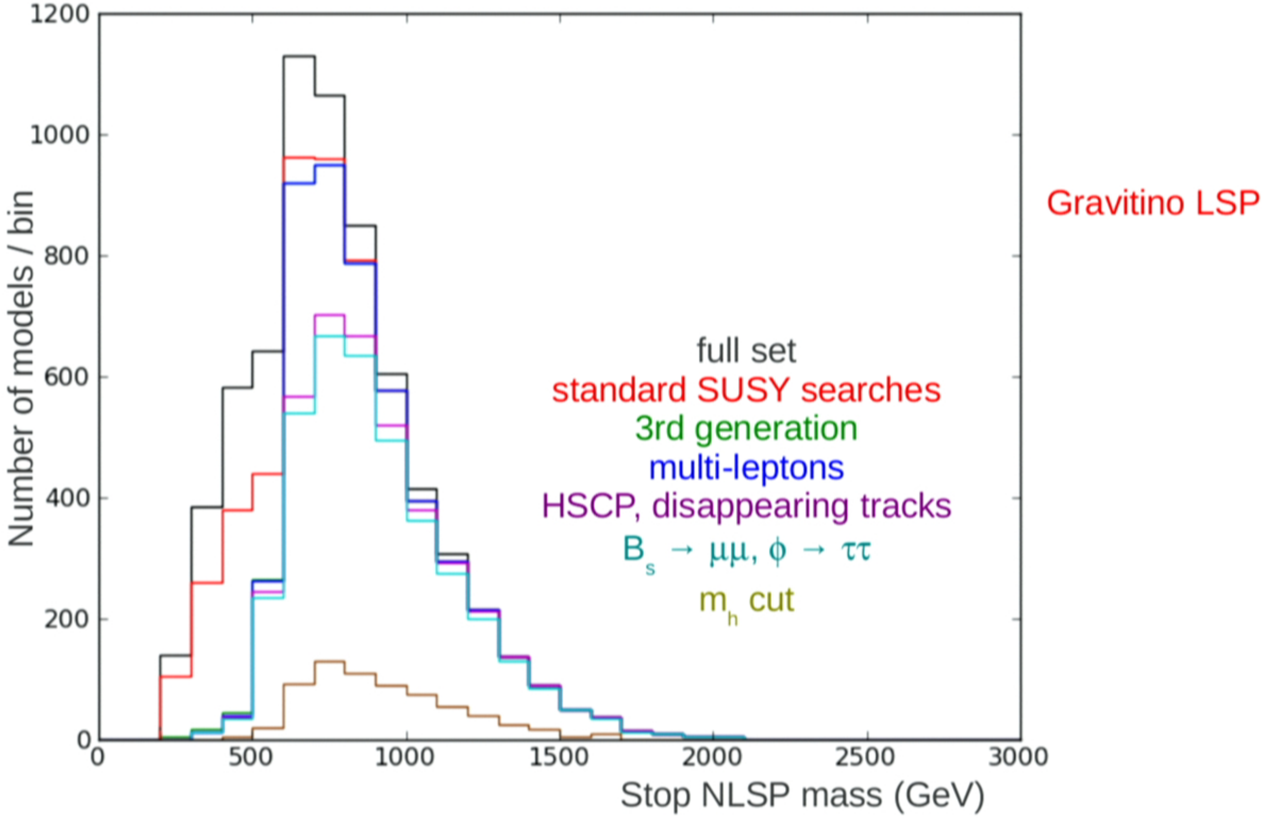


Gravitino LSP

Stable particles in gravitino LSP set are constrained by HSCP searches

LHC searches

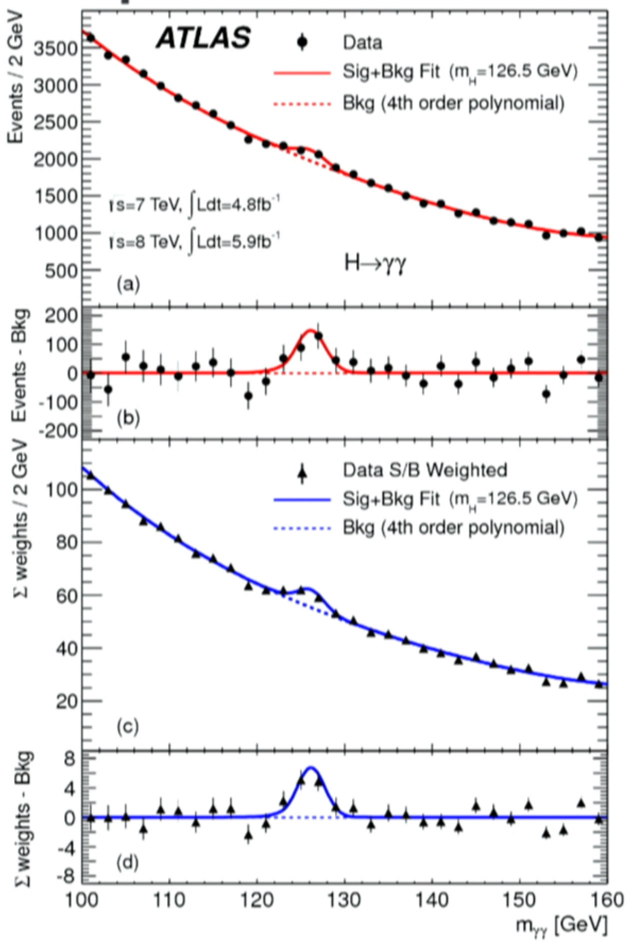
After searches



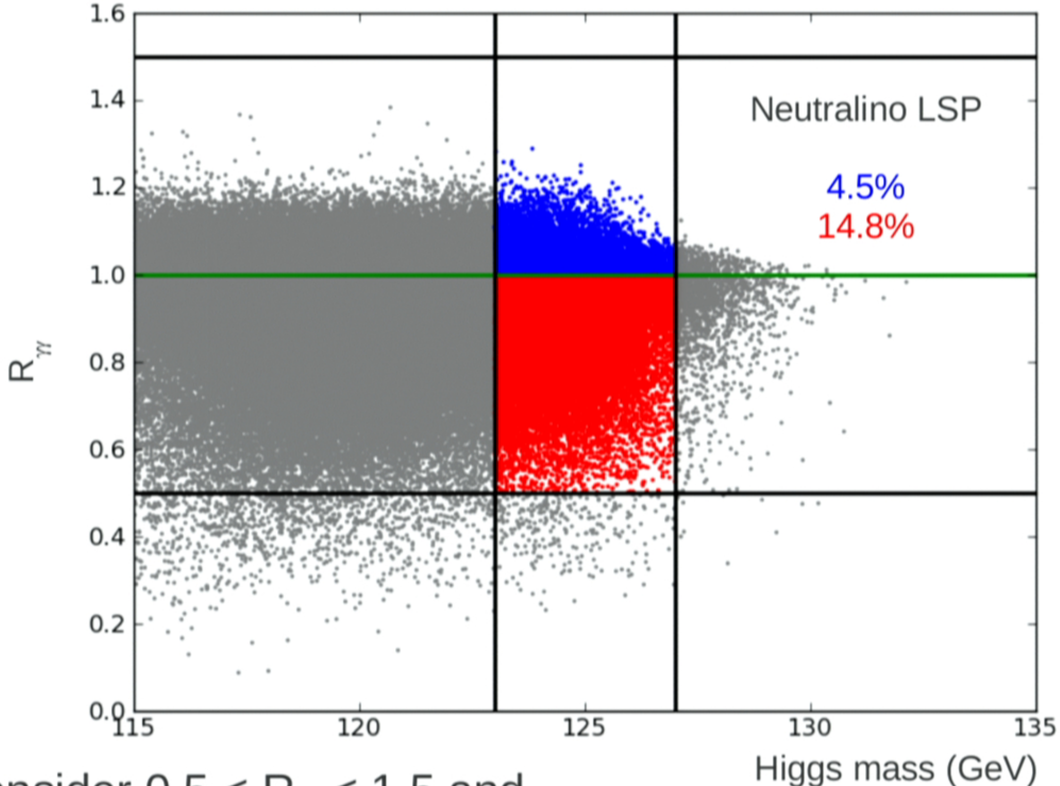
Light stops are very likely to be excluded if stop is NLSP

Higgs discovery implications

- Excess events in both ATLAS and CMS Higgs searches near 126 GeV
- Greatest significance obtained from diphoton channel
- Can we easily obtain such a Higgs in the pMSSM?



$h \to \gamma\gamma$ in the pMSSM



We consider $0.5 < R_{\gamma\gamma} < 1.5$ and

$123 \text{ GeV} < m_h < 127 \text{ GeV}$

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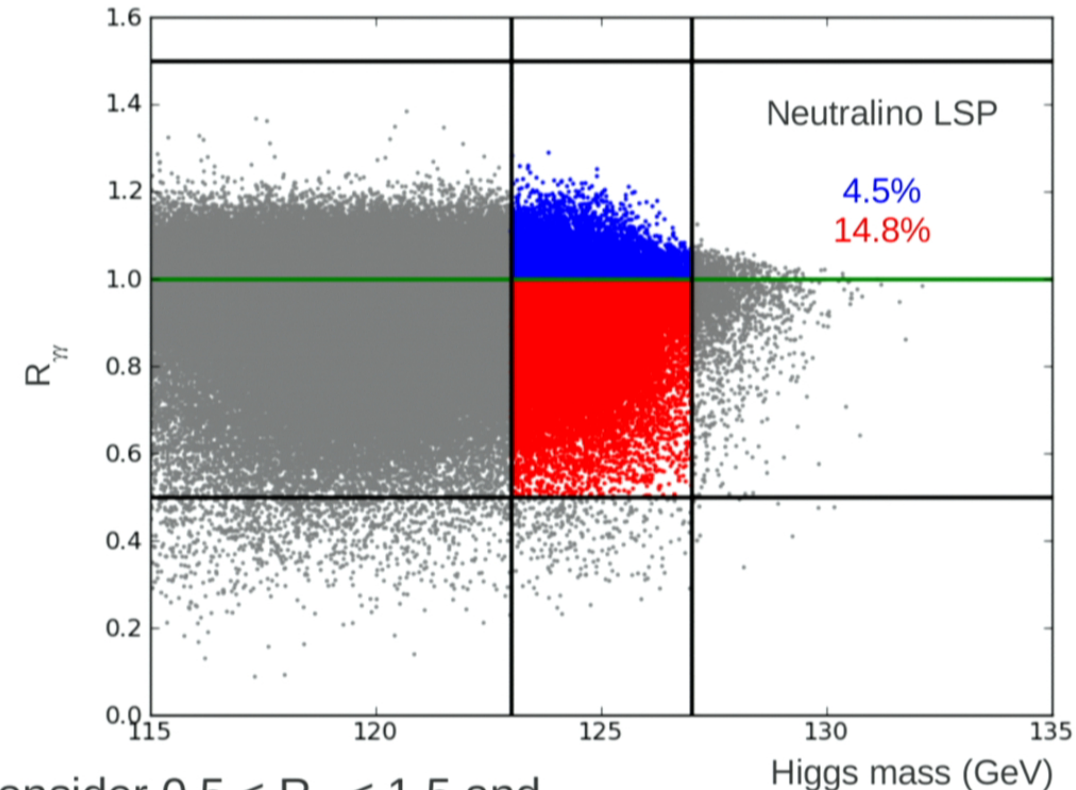

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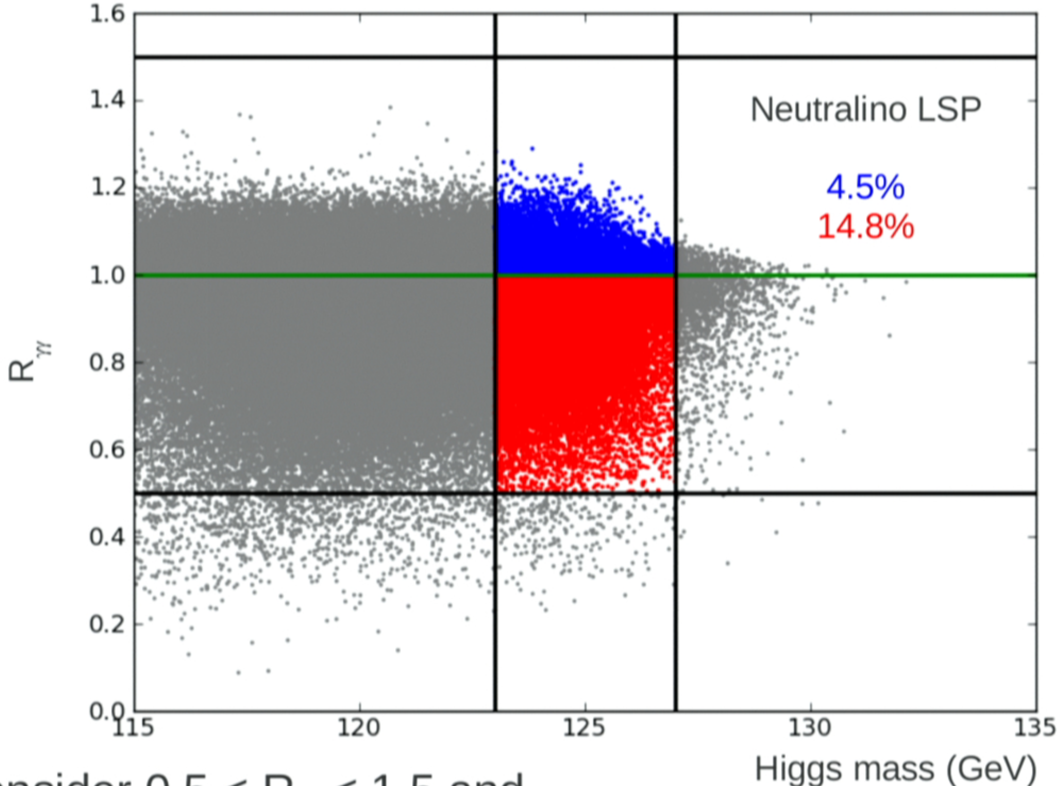

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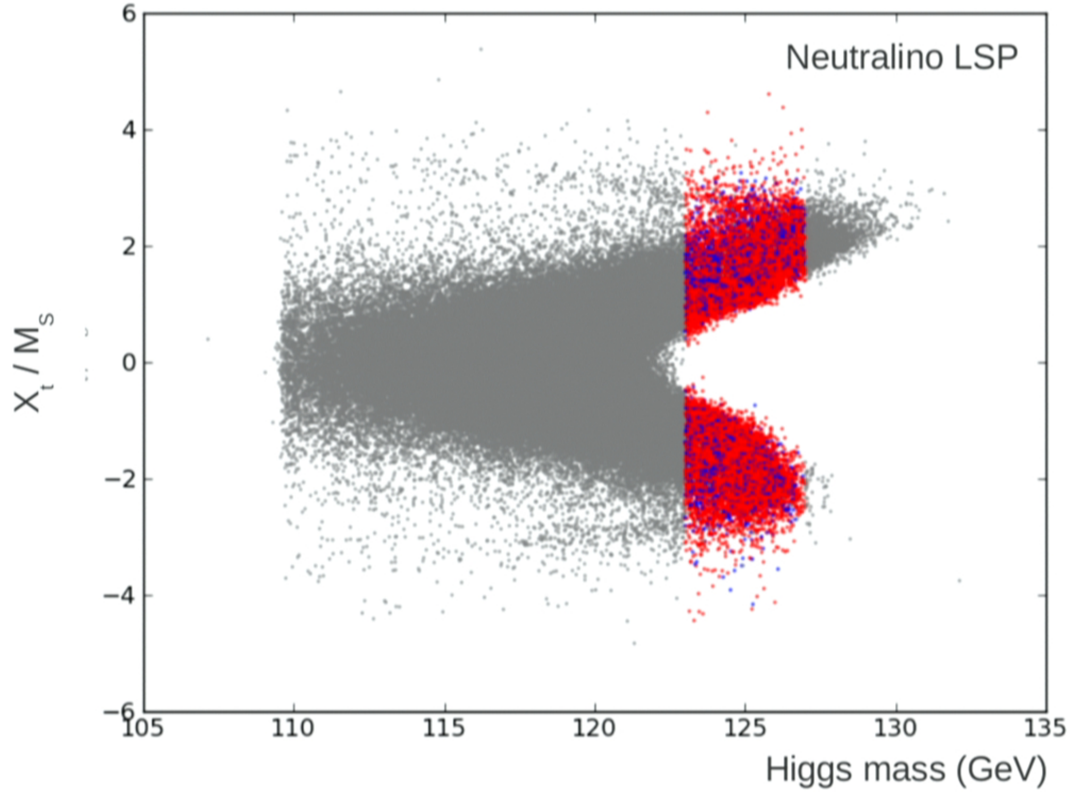
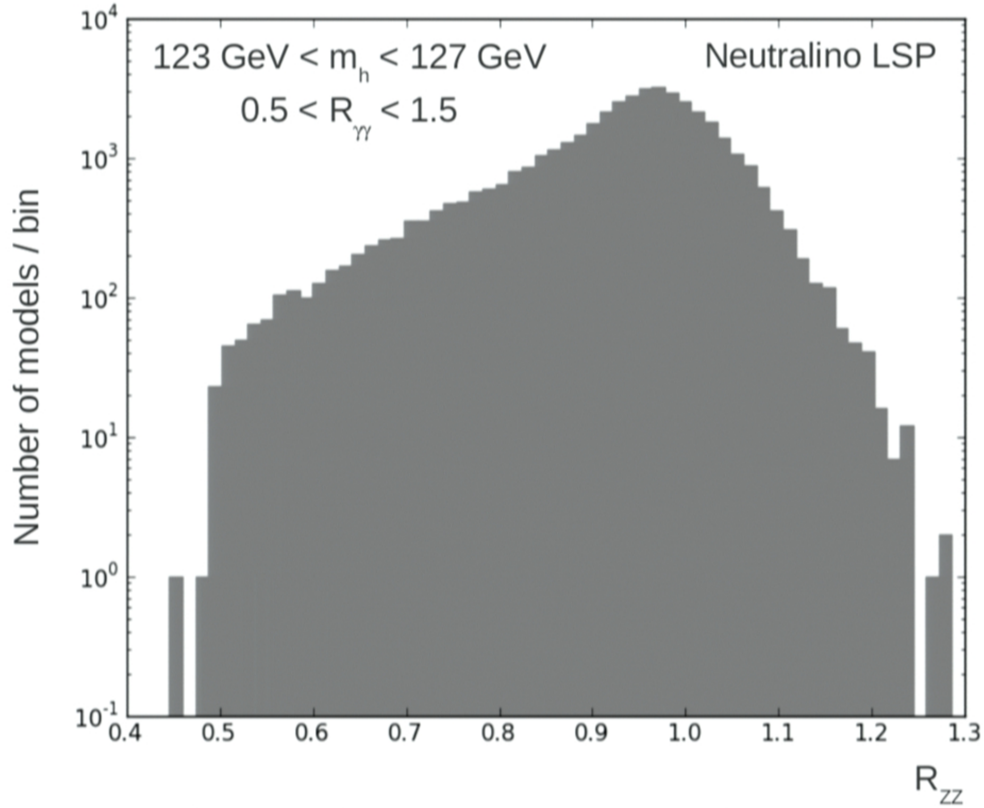
Getting a heavy Higgs



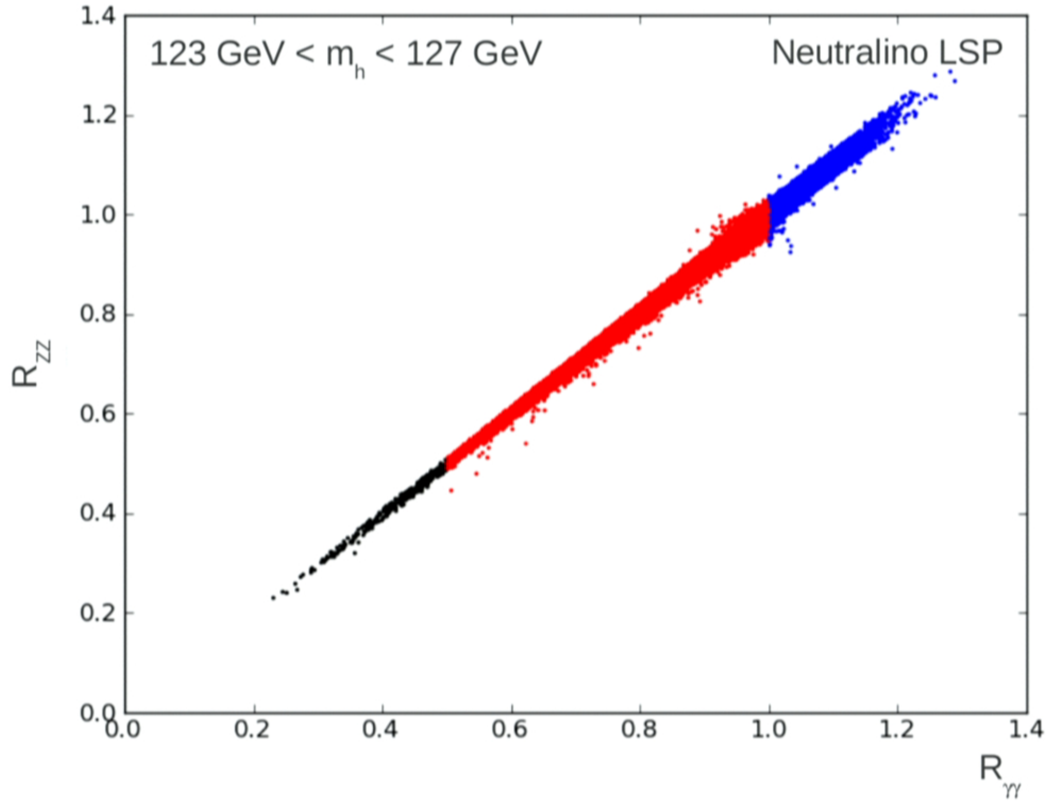
To get heavy Higgs, need large stop mixing $X_t = A_t - \mu \cot \beta$

Higgs LHC phenomenology



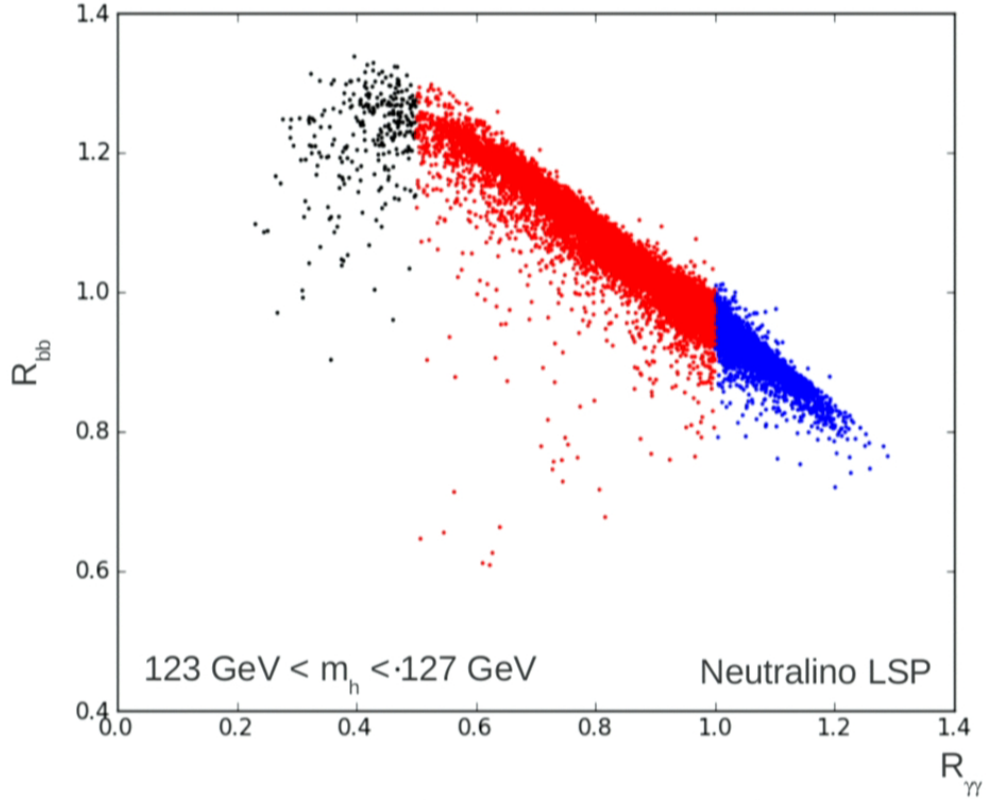
Wide spread of gg → h → ZZ cross section....

Higgs LHC phenomenology



...but strongly correlated with number of h → γγ events!
happens because all models are ~decoupled

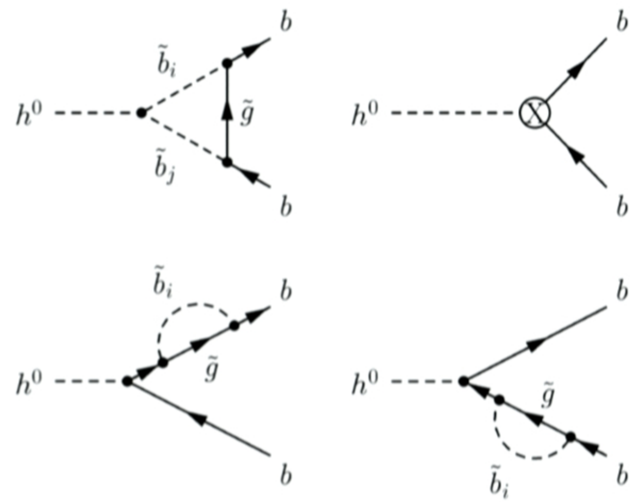
Higgs LHC phenomenology



bb production is anti-correlated with other decay modes

$h \to bb$ 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

Outline

- The phenomenological MSSM
- LHC search results
- Higgs discovery implications
- Fine-tuning
- Outlook

Fine-tuning

- Measure sensitivity of electroweak symmetry breaking scale to each pMSSM parameter p_i

  Barbieri and Giudice, Nucl.Phys. B306 (1988) 63

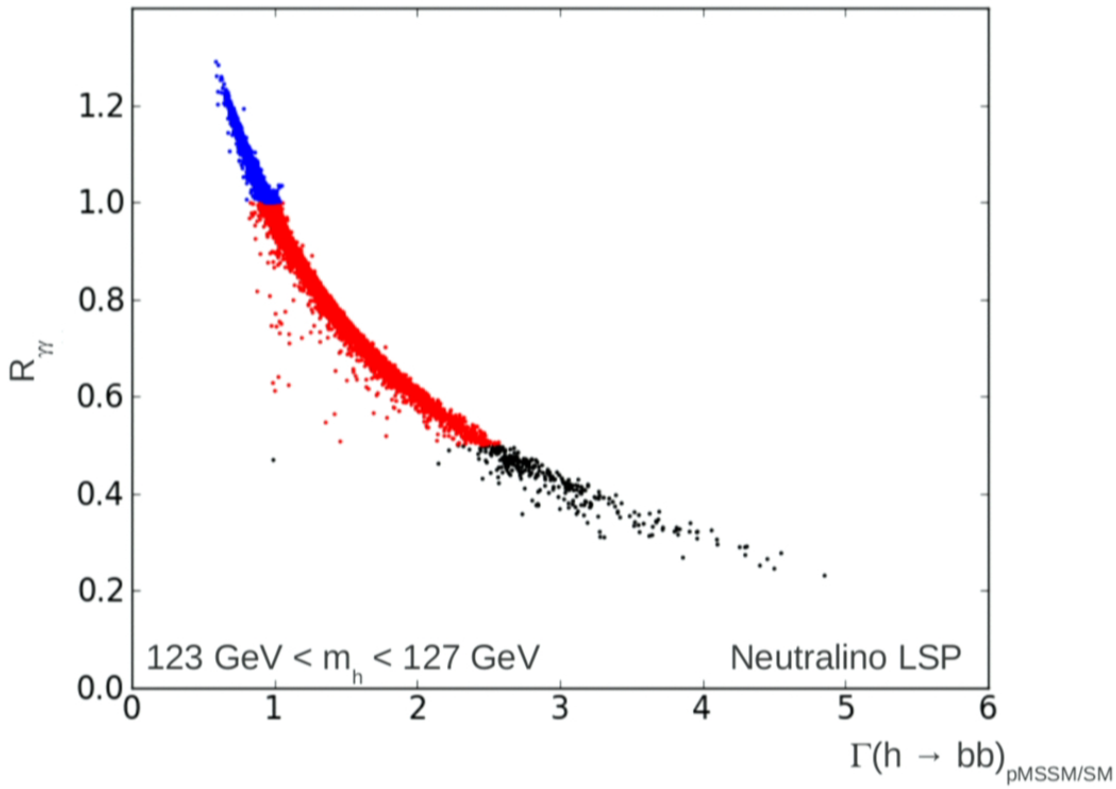
- $A_i = \partial(\log M_Z^2) / \partial(\log p_i)$, $1 \leq i \leq 19$

- Most sensitive to μ and stop mass parameters, but gluino mass enters at higher order

$$\frac{2\alpha_s X^2}{(3\pi^3)(t_\beta^2 - 1)} \frac{M_3}{M_Z^2} \left[- y_b^2(2M_3 - A_b) + t_\beta^2 y_t^2 (2M_3 - A_t) \right]$$

- Take maximum of all A_i to get fine-tuning Δ

Higgs LHC phenomenology



SUSY corrections to bb width reduce other branching ratios!

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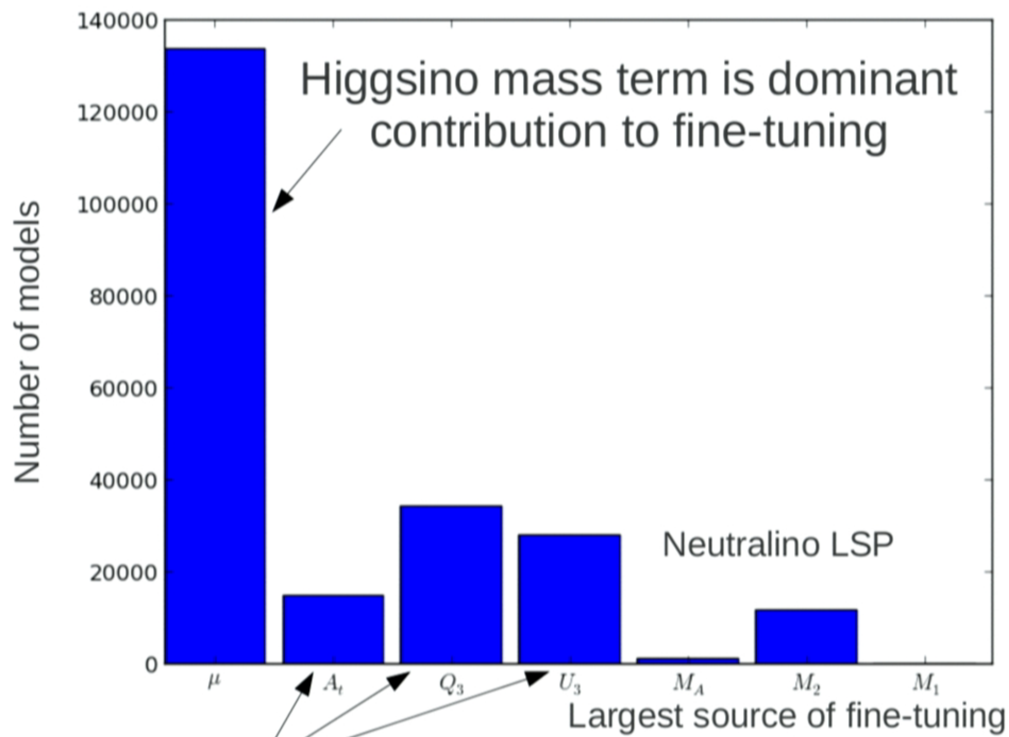
Sources of fine-tuning



Stop mass terms also important, but even with strong coupling, loop-induced gluino contribution is less than wino FT

Features of models with low FT

- Look at models with $\Delta < 100$, Higgs near 125 GeV, and passing all existing constraints
- 9 (0) such models in neutralino (gravitino) LSP model set
- Light higgsinos, usually light winos
- Moderately light 3rd generation squarks, heavy 1st/2nd generation squarks
- Gluino is not really constrained at this level of fine-tuning

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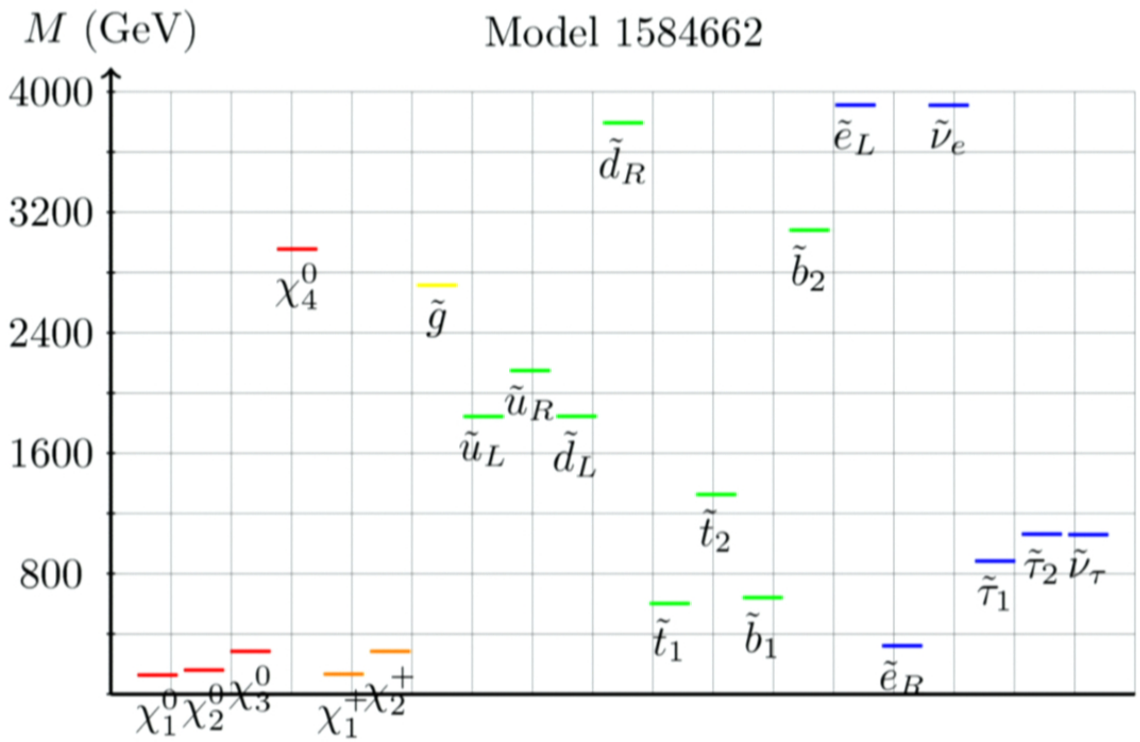
Sample spectrum



Many possible cascades for light stops and sbottoms

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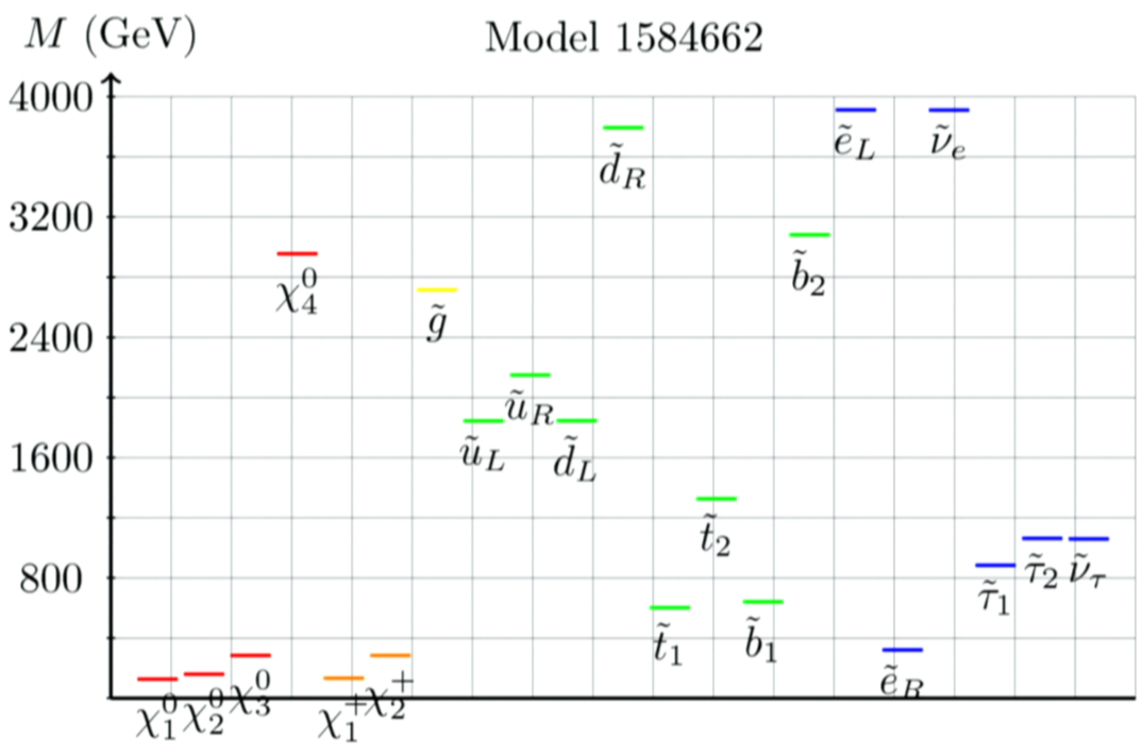
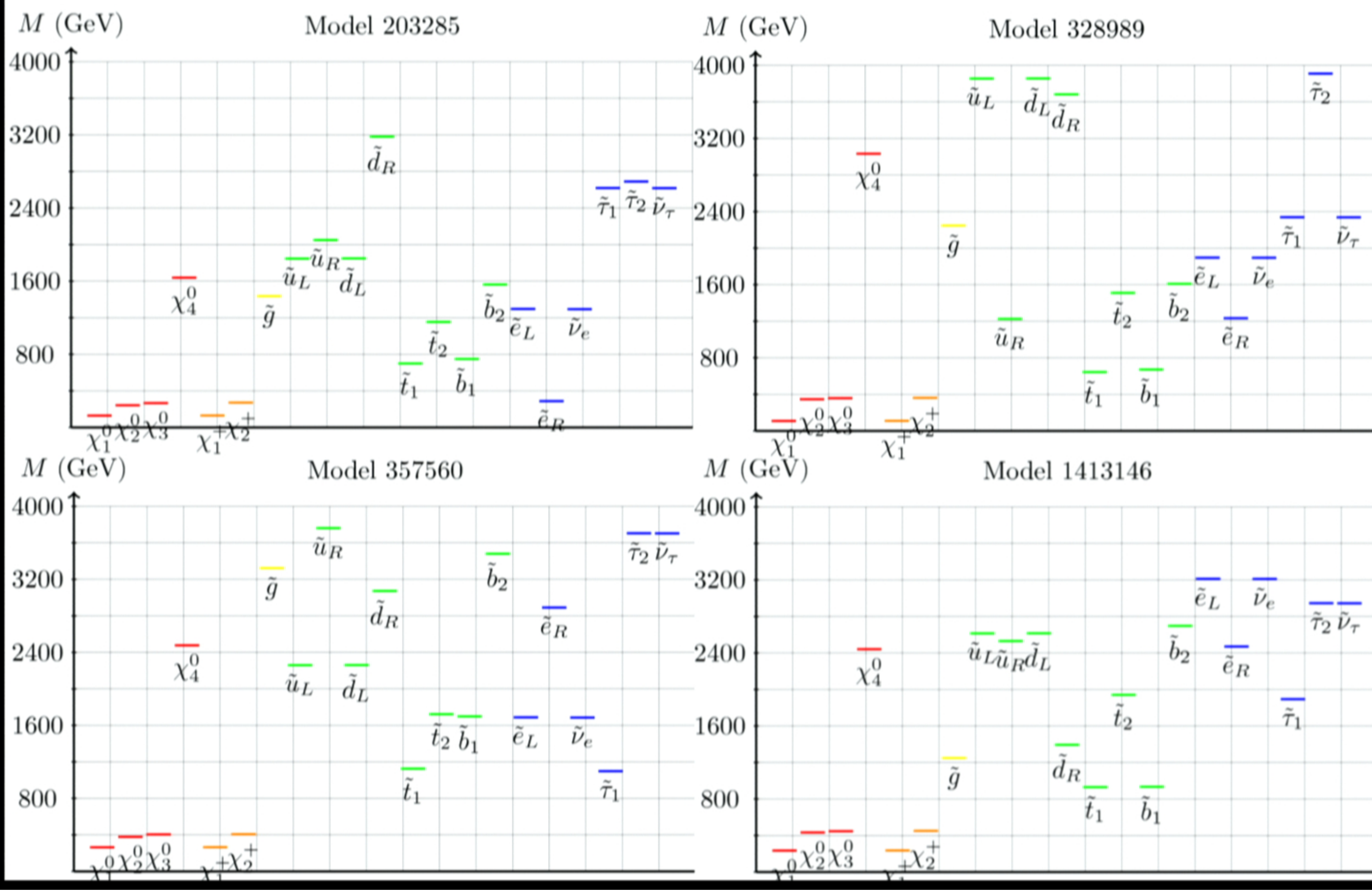


Many possible cascades for light stops and sbottoms

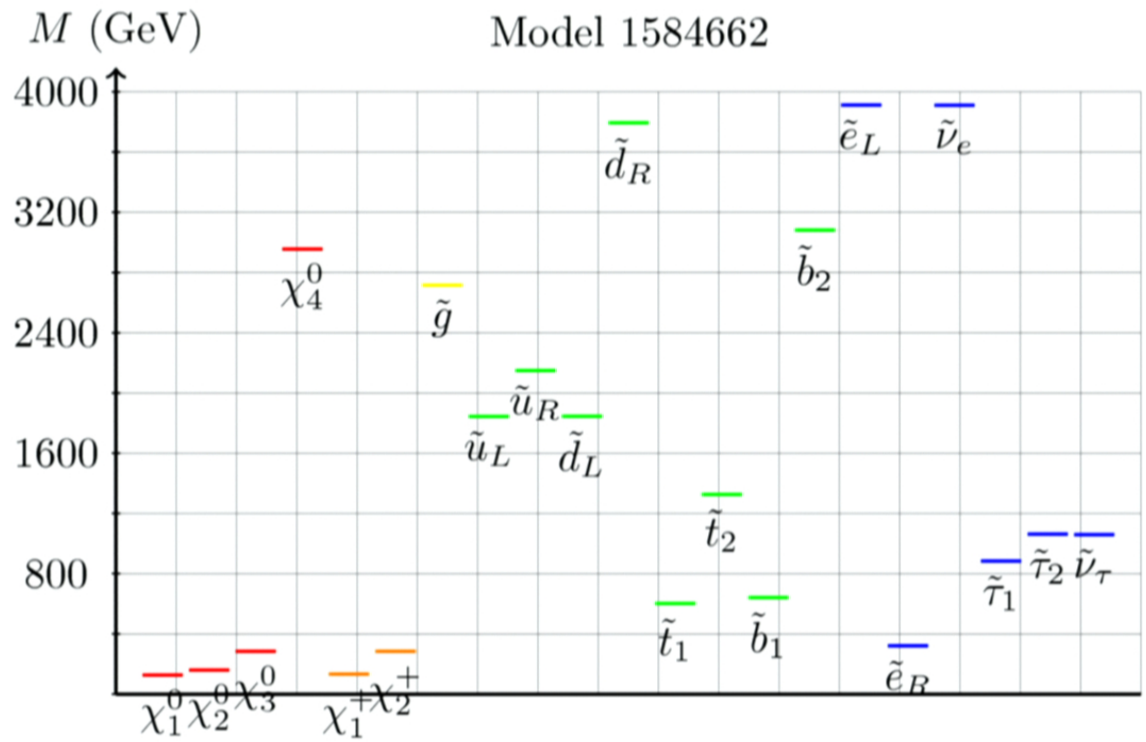
More sample spectra



Outlook

- The pMSSM allows us to investigate complete, realistic supersymmetric spectra at the LHC and beyond
- Phenomenology different between neutralino and gravitino LSP model sets, though both have collider-stable particles
- LHC is already excluding models in our sets, through both MET and non-MET searches
- 8 TeV searches improve coverage overall, but tighter cuts means models can get missed

Sample spectrum



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