Using PGS to study the phenomenological MSSM

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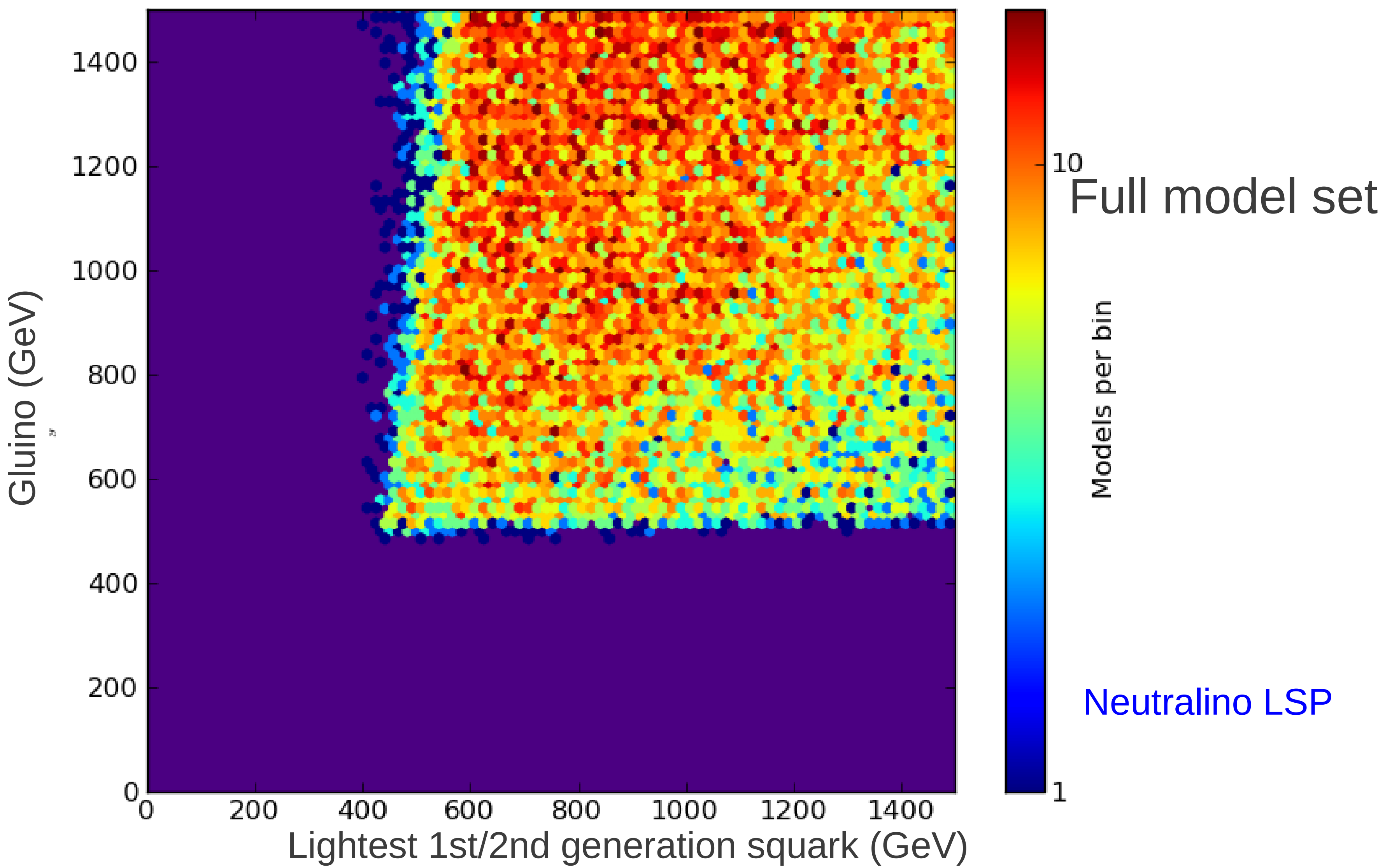
1206.4321, 1206.5800, 1211.1981, 1211.7106

The pMSSM

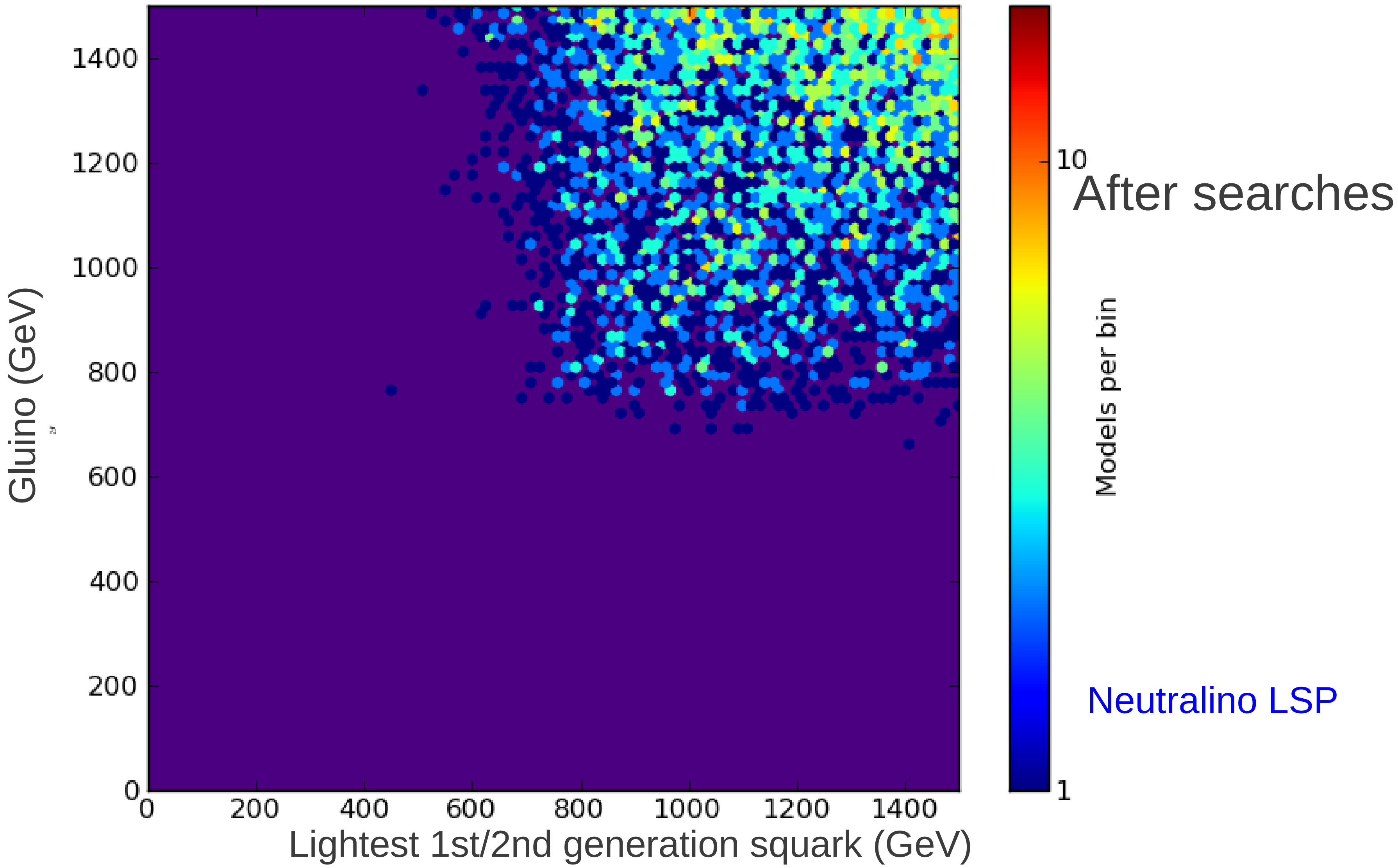
- A *framework* for investigating the MSSM, imposing only experimentally motivated constraints on the full parameter space
- Start from random points in ~19-dimensional pMSSM space with R-parity and CP conservation, taking Minimal Flavor Violation
- Select points which correspond to spectra surviving existing experimental constraints
- See if corners are left unexplored
- Explore complementarity of different analyses

LHC searches



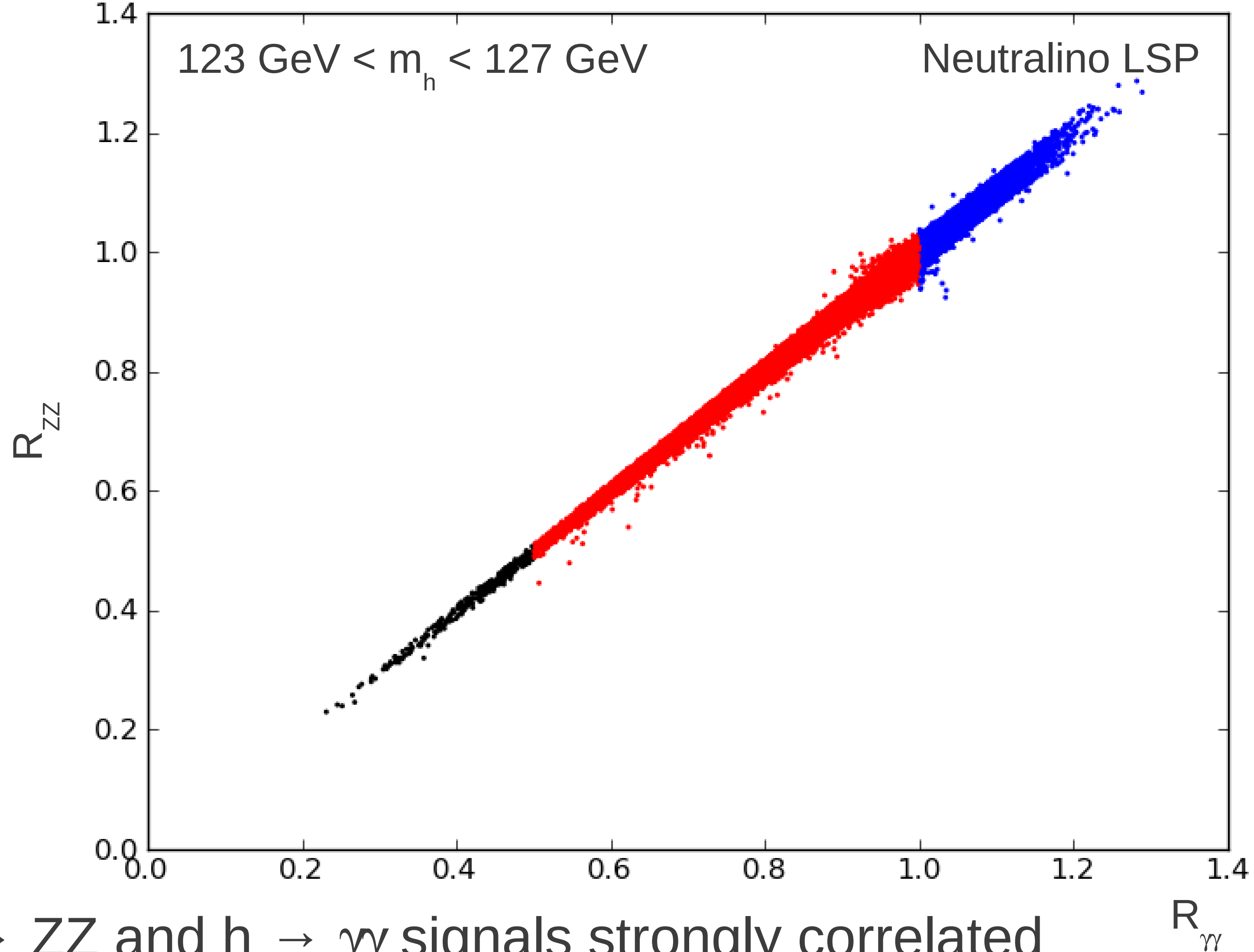
Which of these models are excluded by the LHC?
Simulate SUSY events, reproduce analyses

LHC searches



Light squarks and gluinos in compressed spectra often survive; detector simulation clearly important

Higgs LHC phenomenology



$h \rightarrow ZZ$ and $h \rightarrow \gamma\gamma$ signals strongly correlated

Why? Most deviations in Higgs BR come from slowly decoupling corrections to $h \rightarrow bb$

Event simulation

- How well can existing LHC searches probe the pMSSM? Need to go *beyond* mSUGRA, simplified model limits
- Generate events with PYTHIA, scale to NLO with Prospino
- An experimentally-approved public fast simulator would be great, but for now theorists use independent tools such as PGS and Delphes to obtain a reasonable approximation
- Today: our experience with PGS

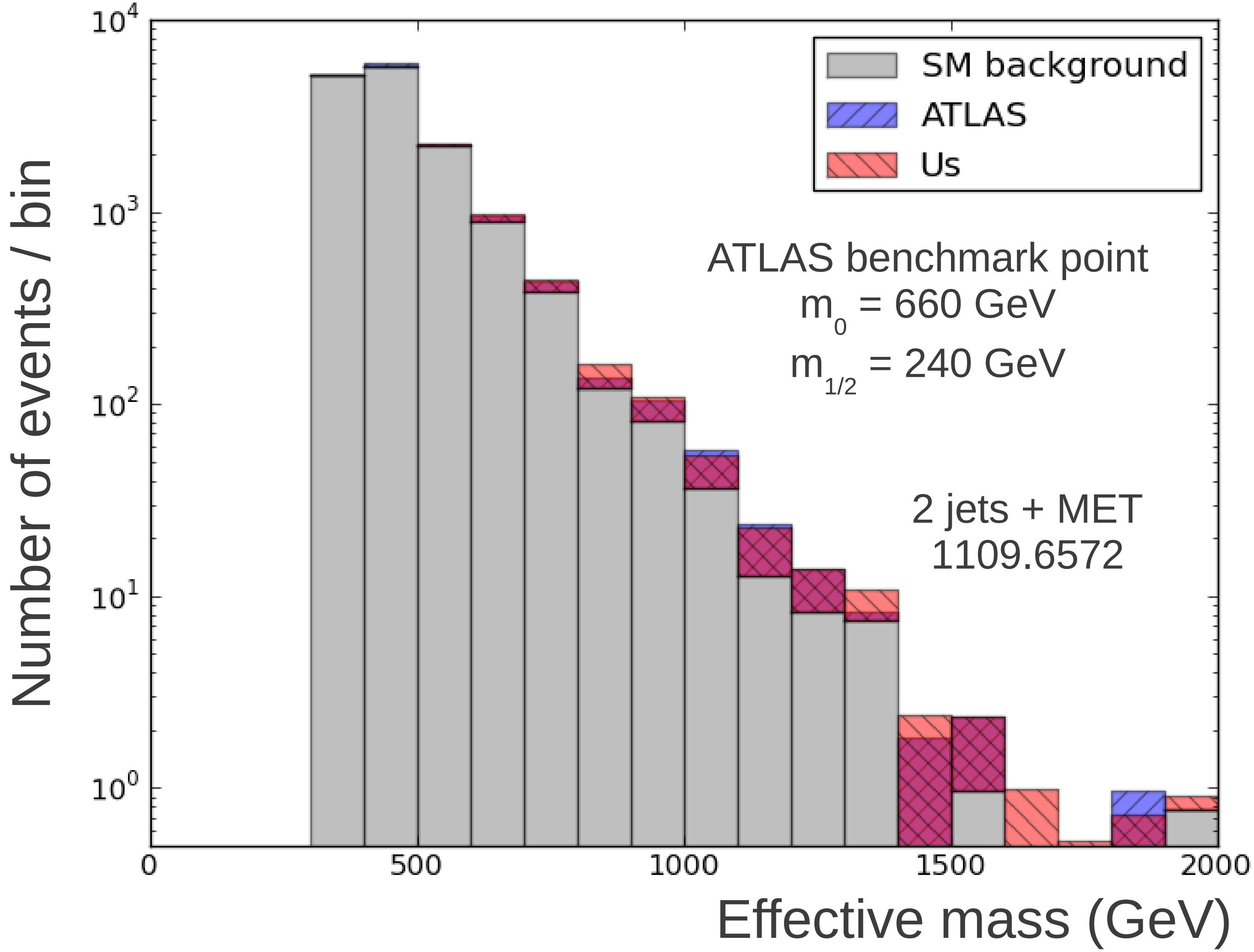
PGS

- Evolved out of CDF/D0 simulation SHW for Snowmass 2001, due to John Conway and others
- Can call PYTHIA, HERWIG, ISAJET, ALPGEN
- Or run on existing events (LHE *or* STDHEP)
- Package exists for MadGraph to take parton level events, pass them through Pythia, and implement detector simulation with PGS
- Default PGS output is in LHC Olympics format, suitable for implementing analysis

PGS

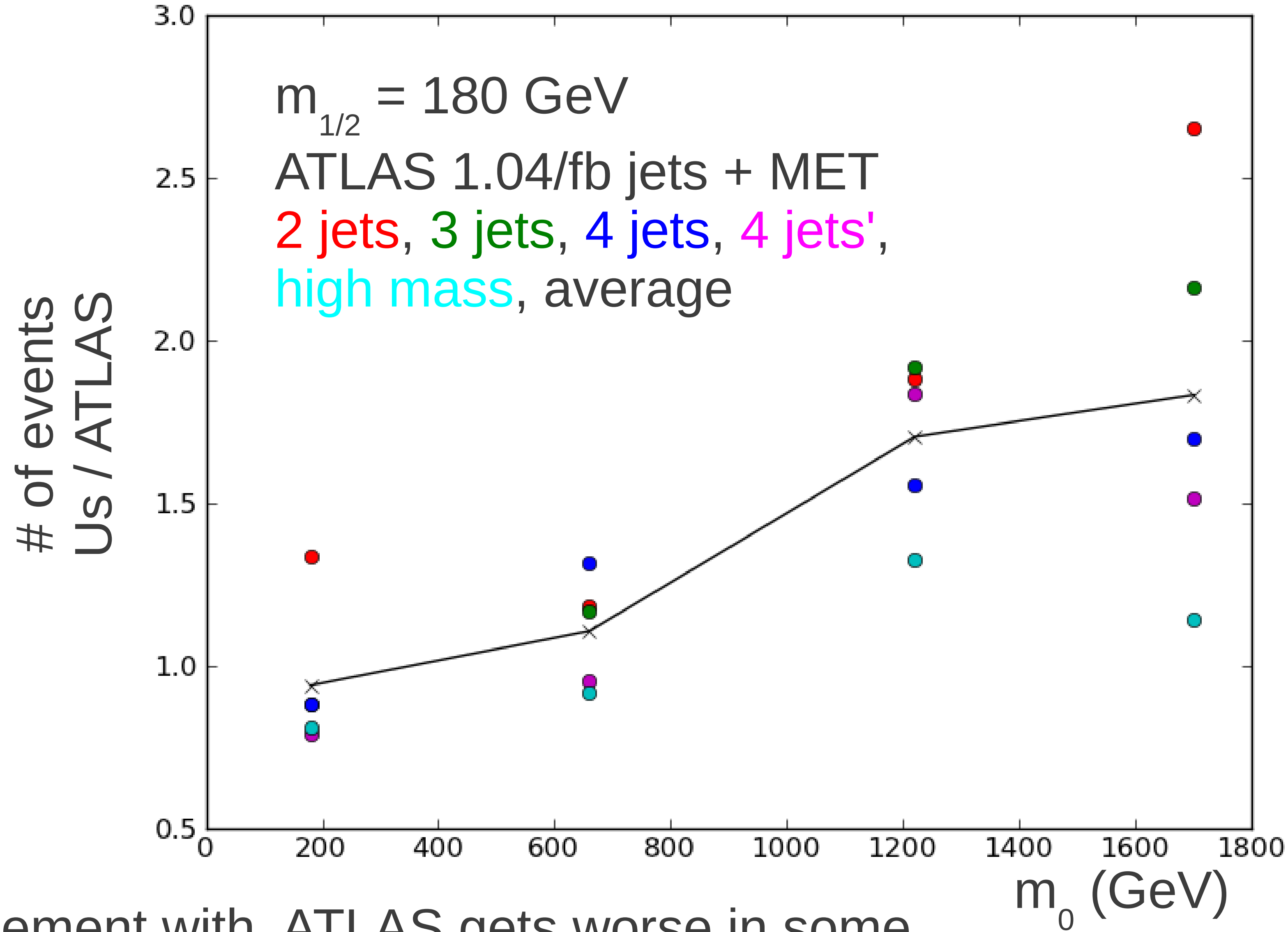
- Generate tracks
- Simulate energy deposition in ECAL and HCAL
- Object reconstruction
  - Choice of jet algorithms including anti-k_T
  - EM fraction discriminates between e/γ and jets
  - Isolation requirements
- Many parameters can be easily changed with input detector card, e.g. calorimeter energy resolution, tracker magnetic field

Validation



Shape, normalization reproduced reasonably well

Validation

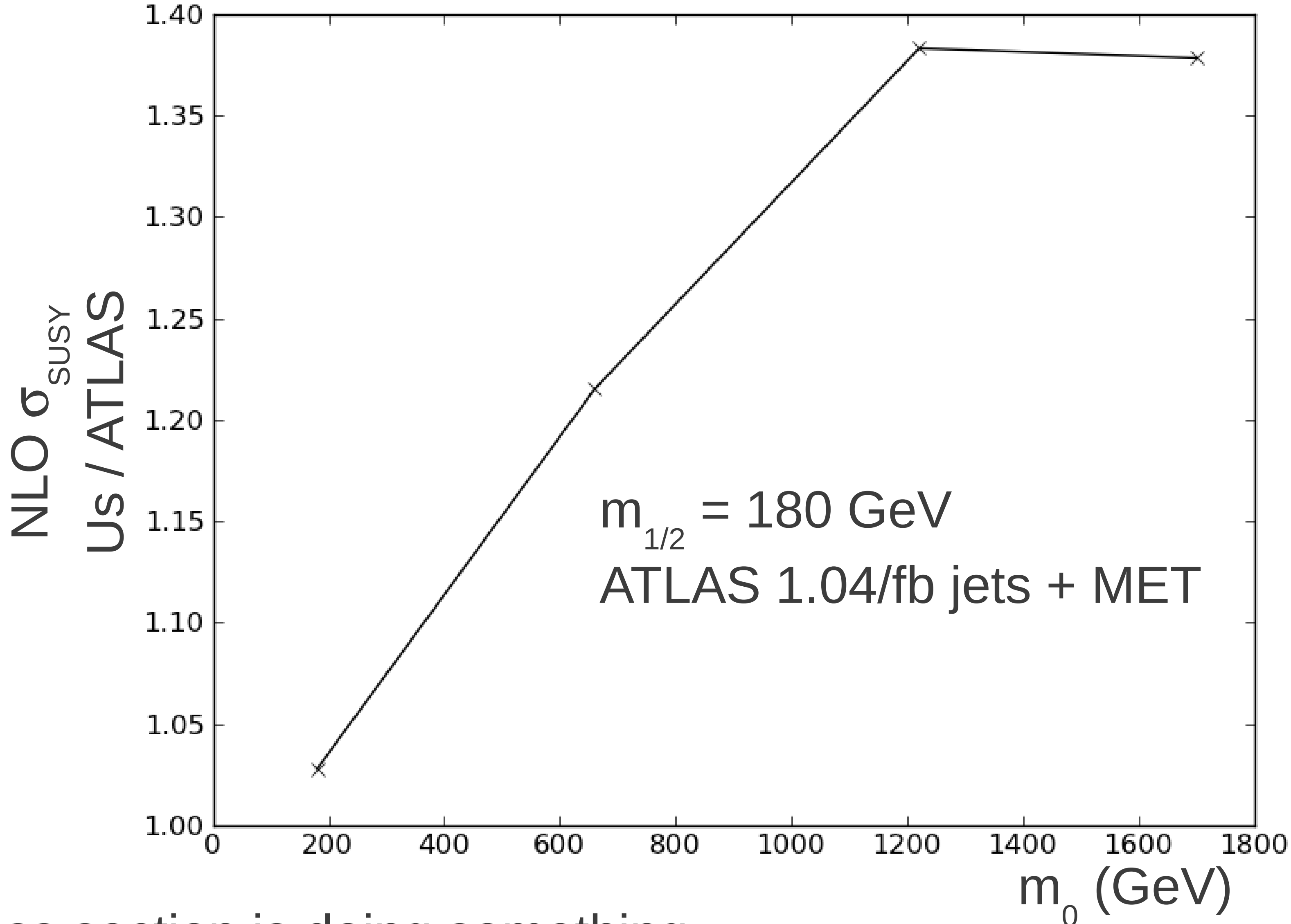


Agreement with ATLAS gets worse in some situations, e.g. 2 jets + MET with heavy squarks

Validation

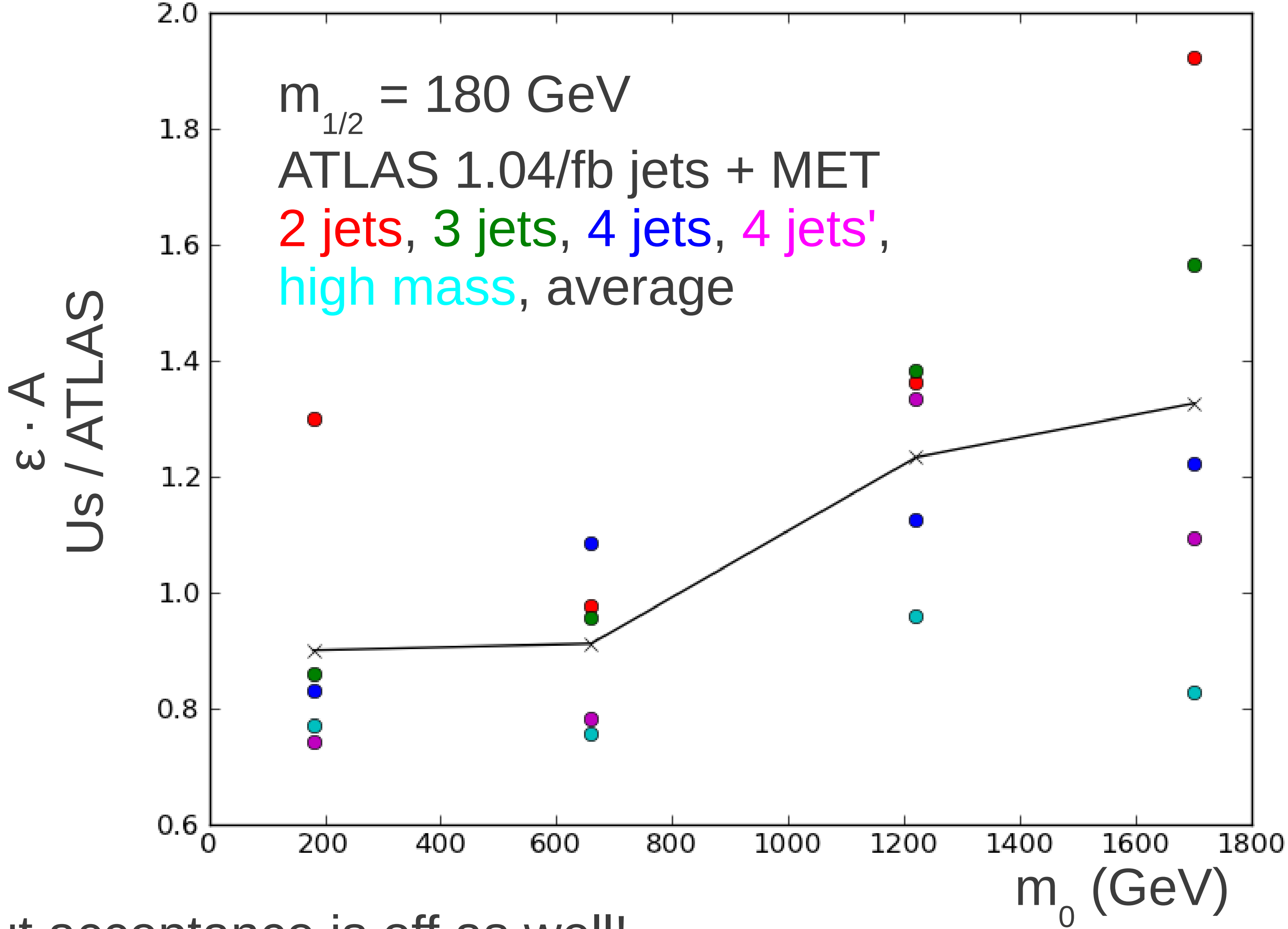
- Total number of events = cross section × acceptance × efficiency × luminosity
- Can separate out effects of cross section calculation versus detector simulation using quoted ATLAS cross section values for benchmark models in HepData
- We use Pythia + Prospino + PGS, while ATLAS uses Herwig++ + Prospino + Geant4
- Efficiency comparison indicates how PGS performs relative to full ATLAS simulation

Validation



Cross section is doing something....

Validation



...but acceptance is off as well!

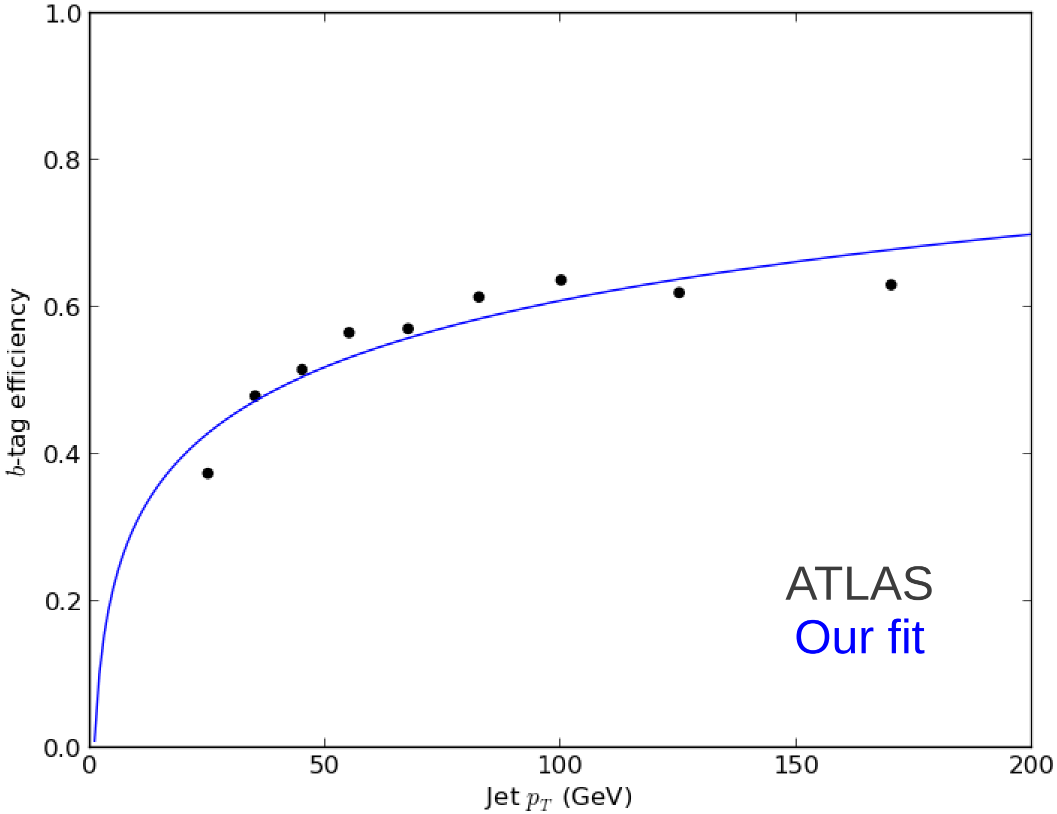
b-tagging

- Much interest in 2012 in searches requiring final state *b*-jets, driven by considerations of naturalness and lack of signals of new physics
- We implemented all relevant ATLAS searches involving third generation squarks to investigate the capability of the LHC to discover the most natural pMSSM spectra
- Important to reliably reproduce various *b*-tagging algorithms at different operating efficiencies, particularly for signal regions involving multiple *b*-jets

b-tagging

- PGS: truth tagger looks for type of hardest parton near jet, followed by applying efficiencies and rejection factors that are based on CDF
- We put in our own functions from fits to ATLAS results

→ 400 GeV stops



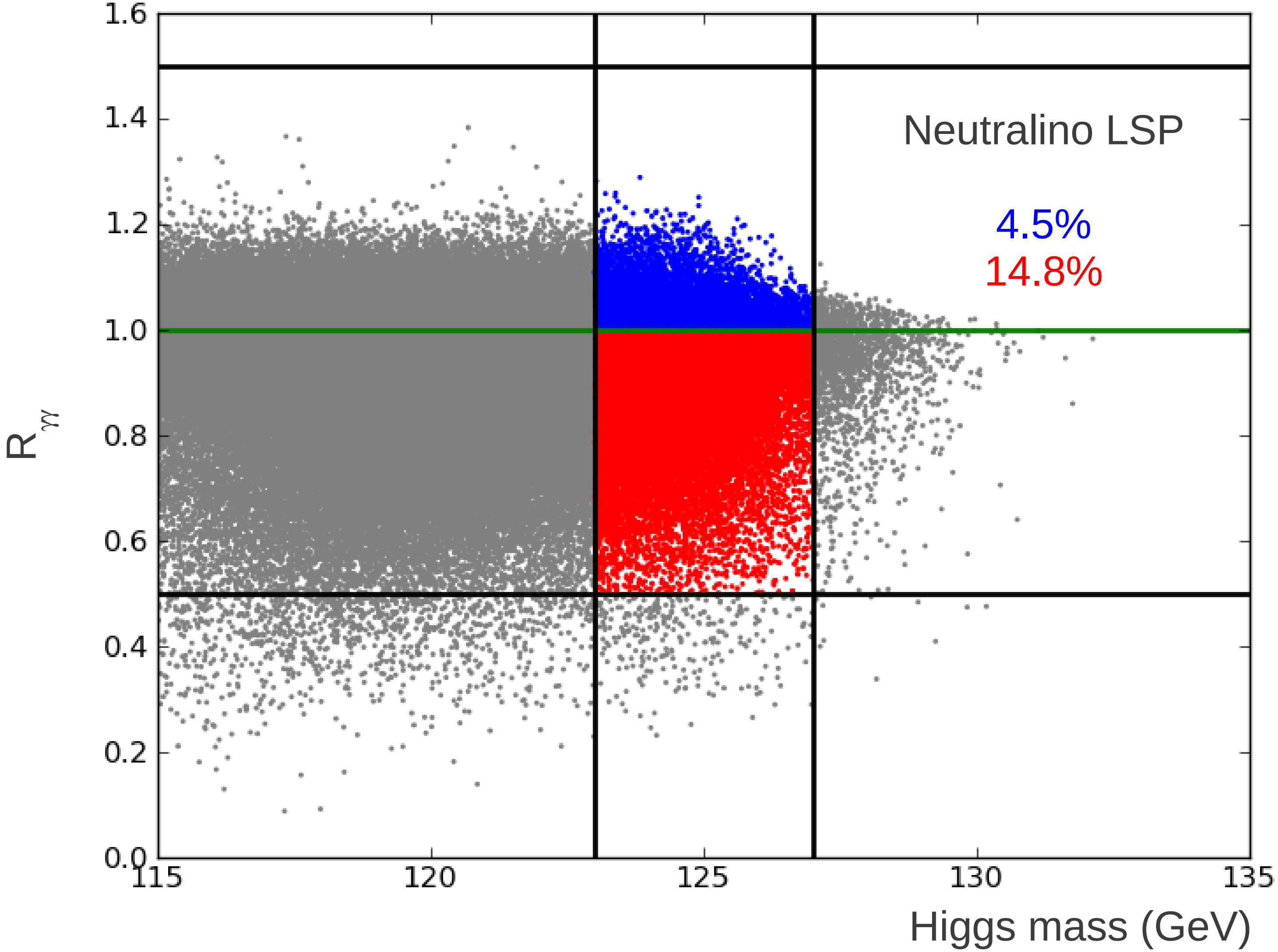
MV1 algorithm, 60% efficiency

Summary

- Studying the pMSSM requires a large amount of detector simulation, given the enormous parameter space and the importance of different experimental searches
- PGS generally approximates detectors well, though agreement with experiment gets worse in some tricky regions
- Some steps need updating for realistic simulation, such as *b*-tagging

Backup

h → γγ in the pMSSM



Can study observables such as signals in various Higgs channels from SUSY

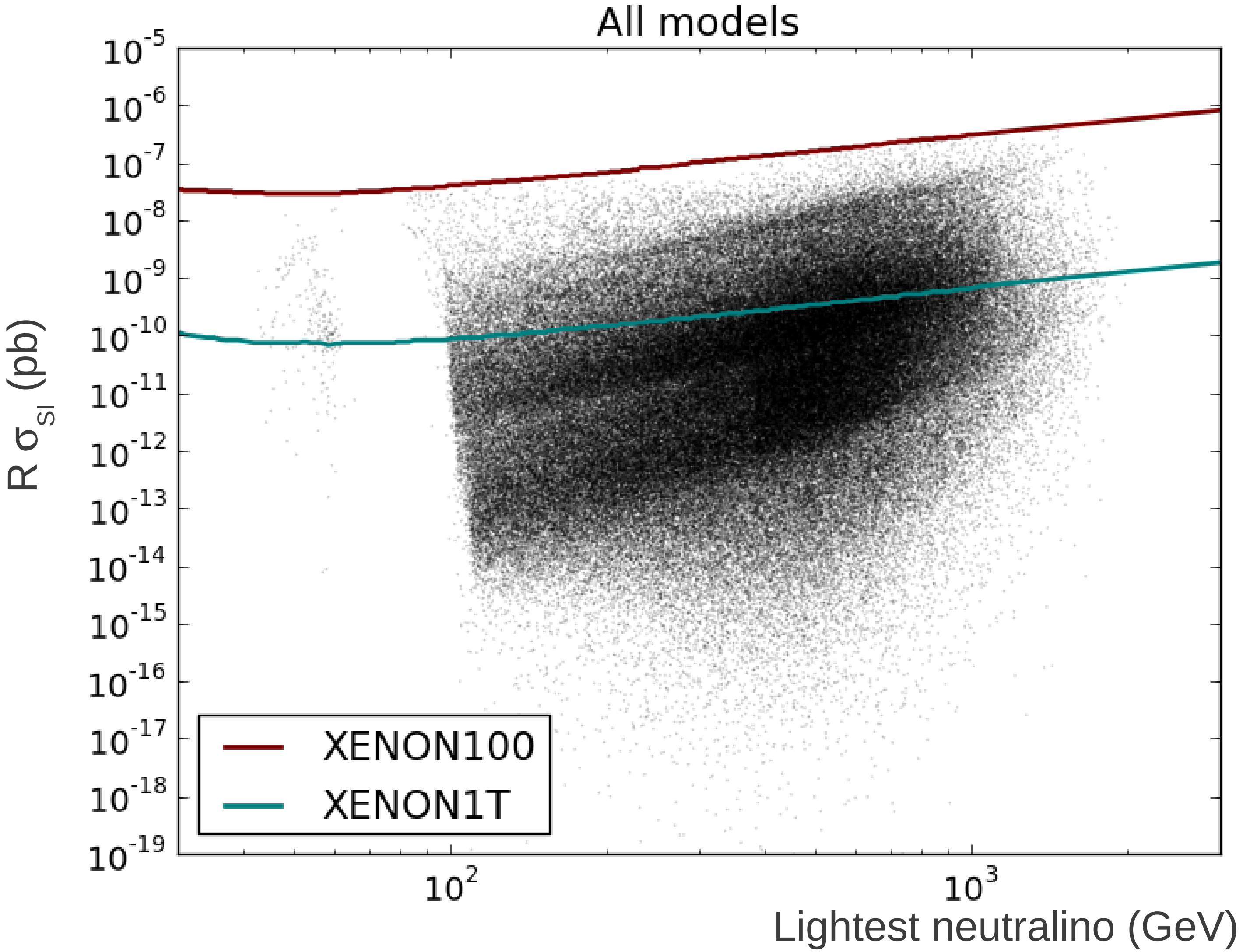
LHC searches

Neutralino LSP

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%*

- 0.7% 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!
- Fractions of models killed are ~independent of Higgs mass cut

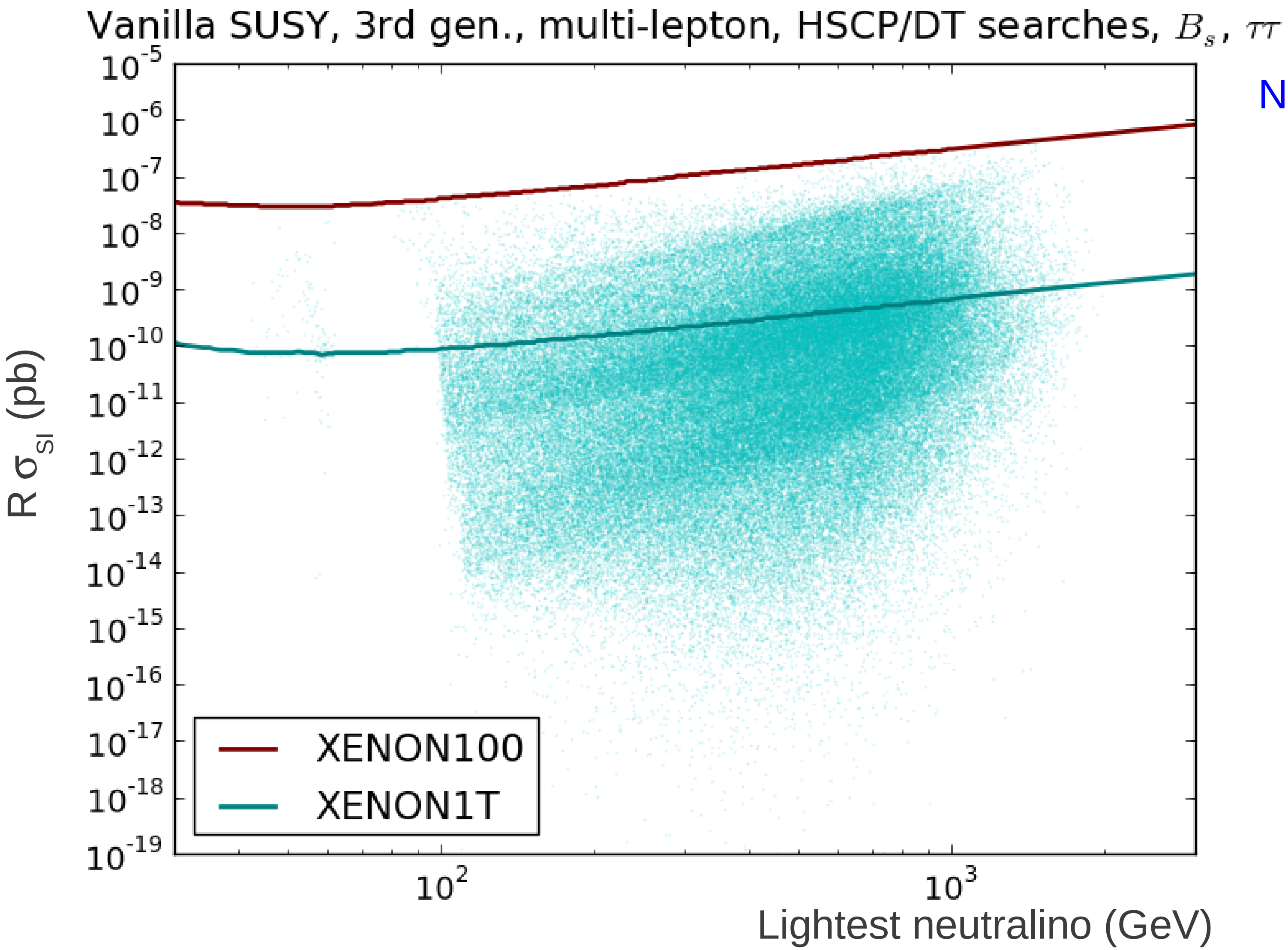
LHC searches



Neutralino LSP

Dark matter and LHC searches for SUSY
complement each other

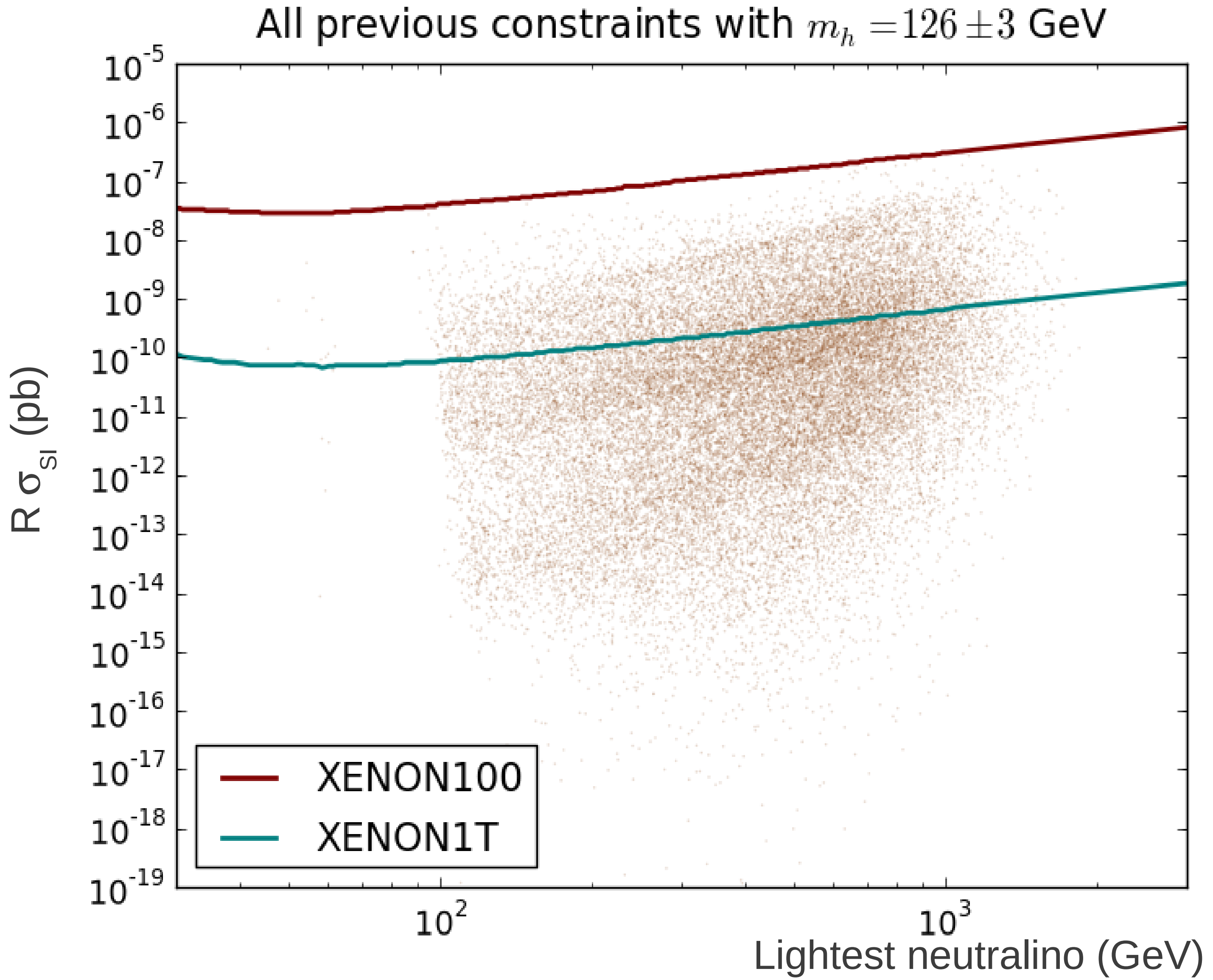
LHC searches



Neutralino LSP

Dark matter and LHC searches for SUSY complement each other

LHC searches



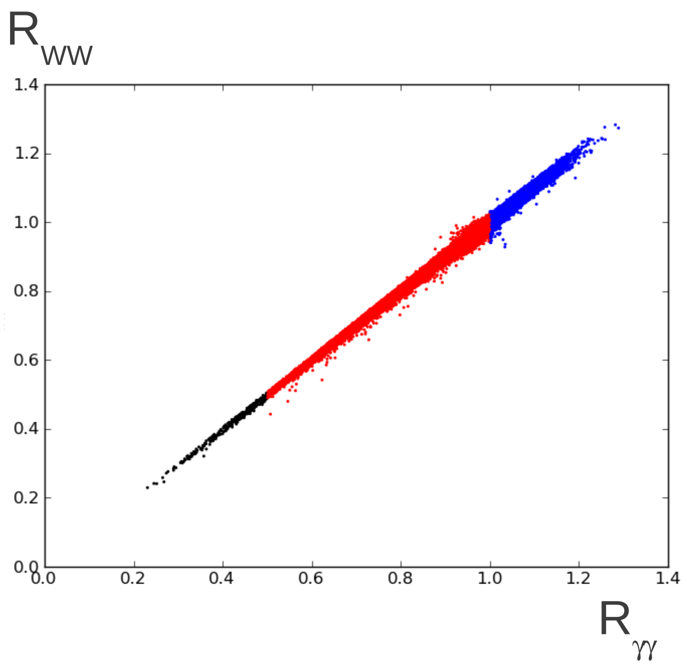
Neutralino LSP

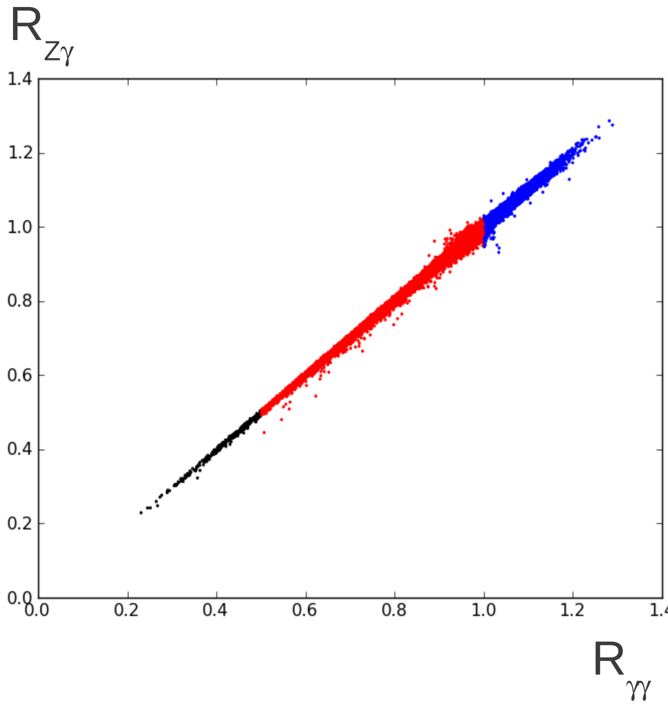
Higgs mass cut Is approximately independent of LHC and DM searches

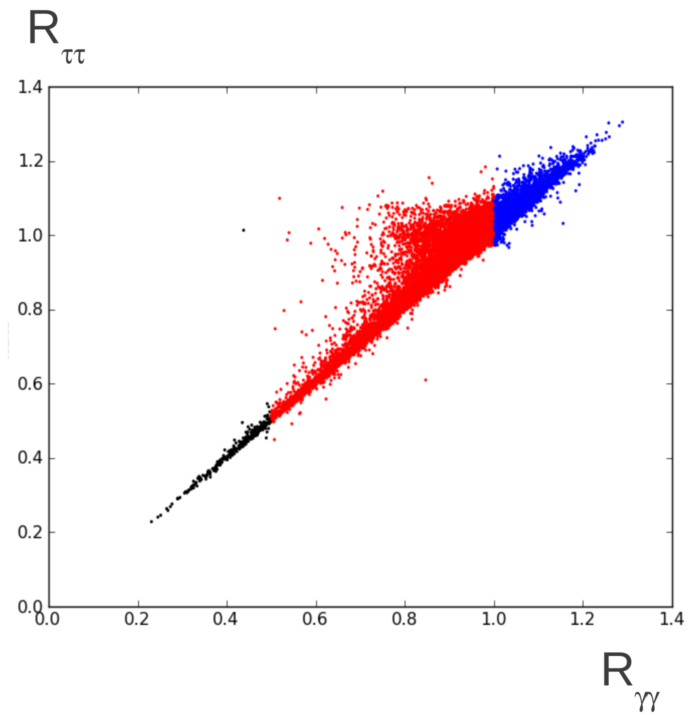
Higgs LHC phenomenology

Neutralino LSP

123 GeV < m_h < 127 GeV

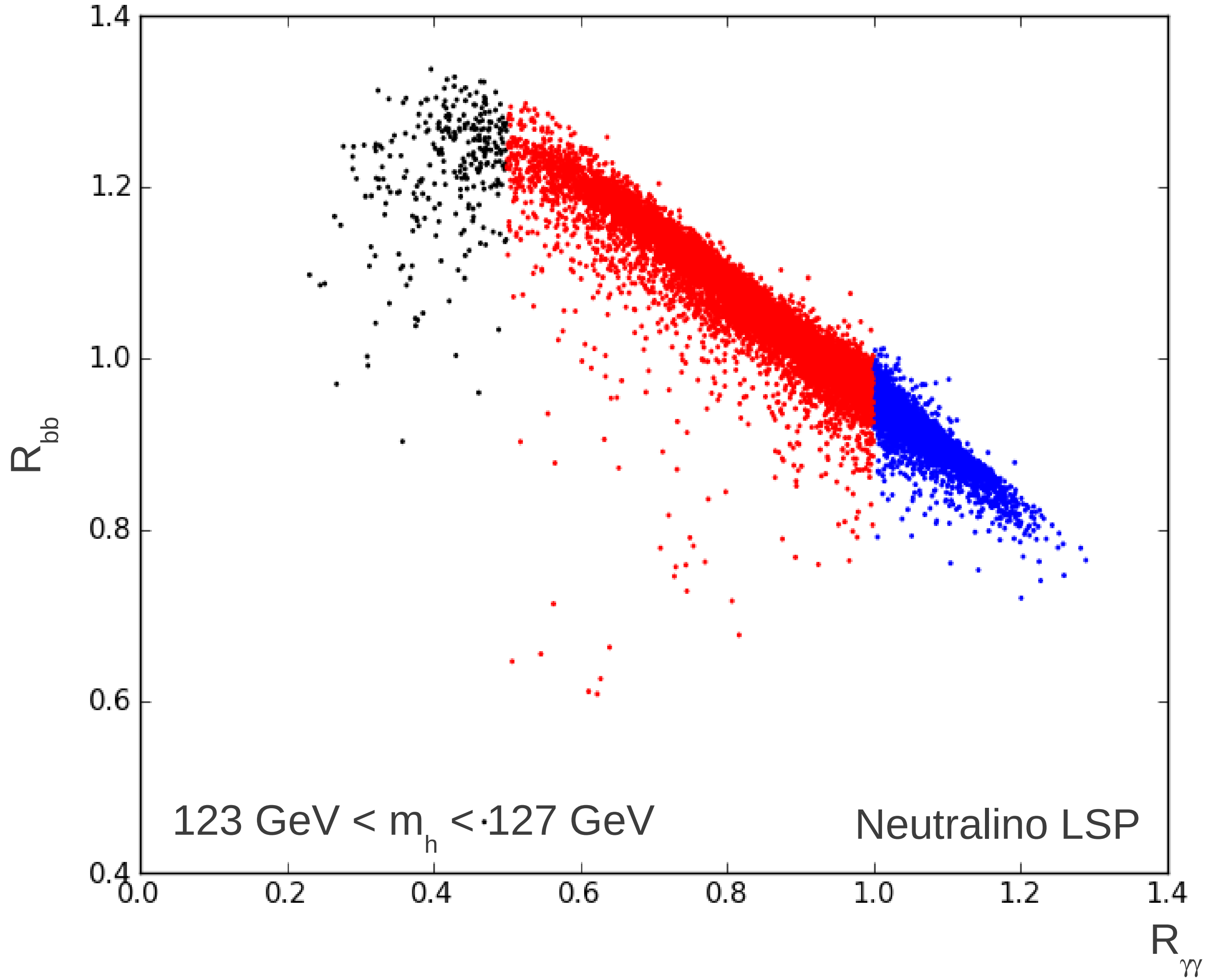






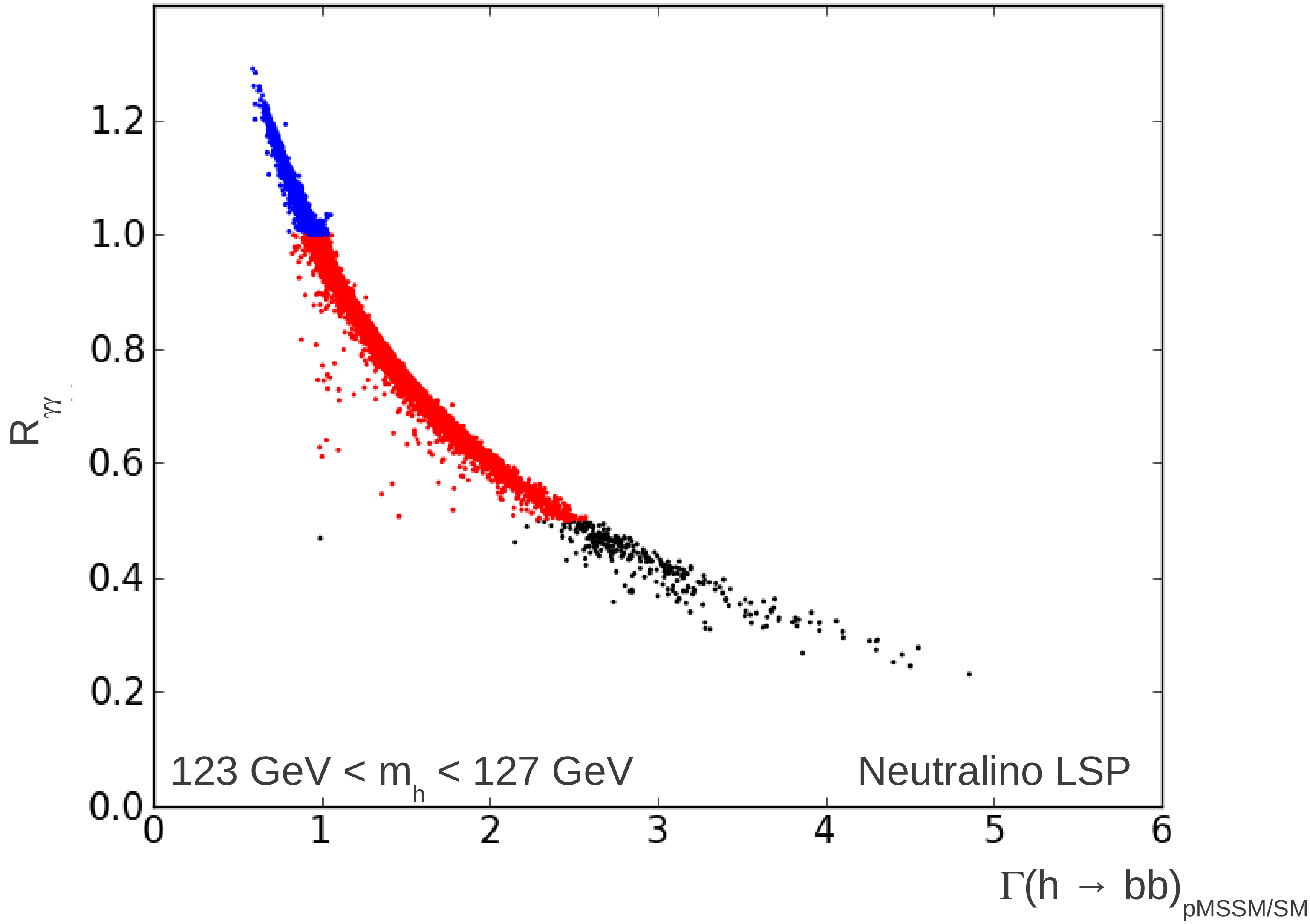
Other modes behave the same way because of decoupling

Higgs LHC phenomenology



bb production is anti-correlated with other decay modes

Higgs LHC phenomenology

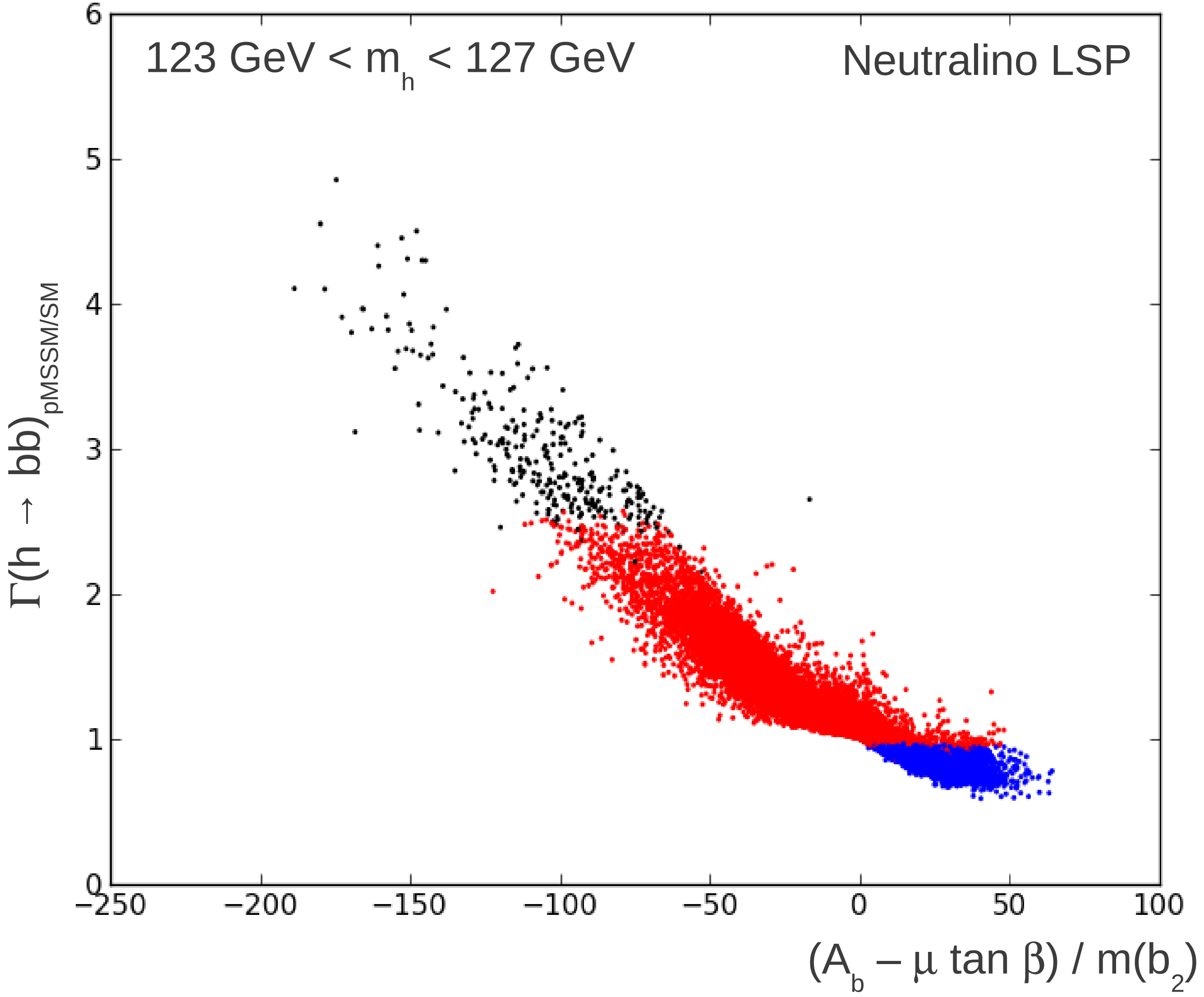


SUSY corrections to bb width reduce other branching ratios!

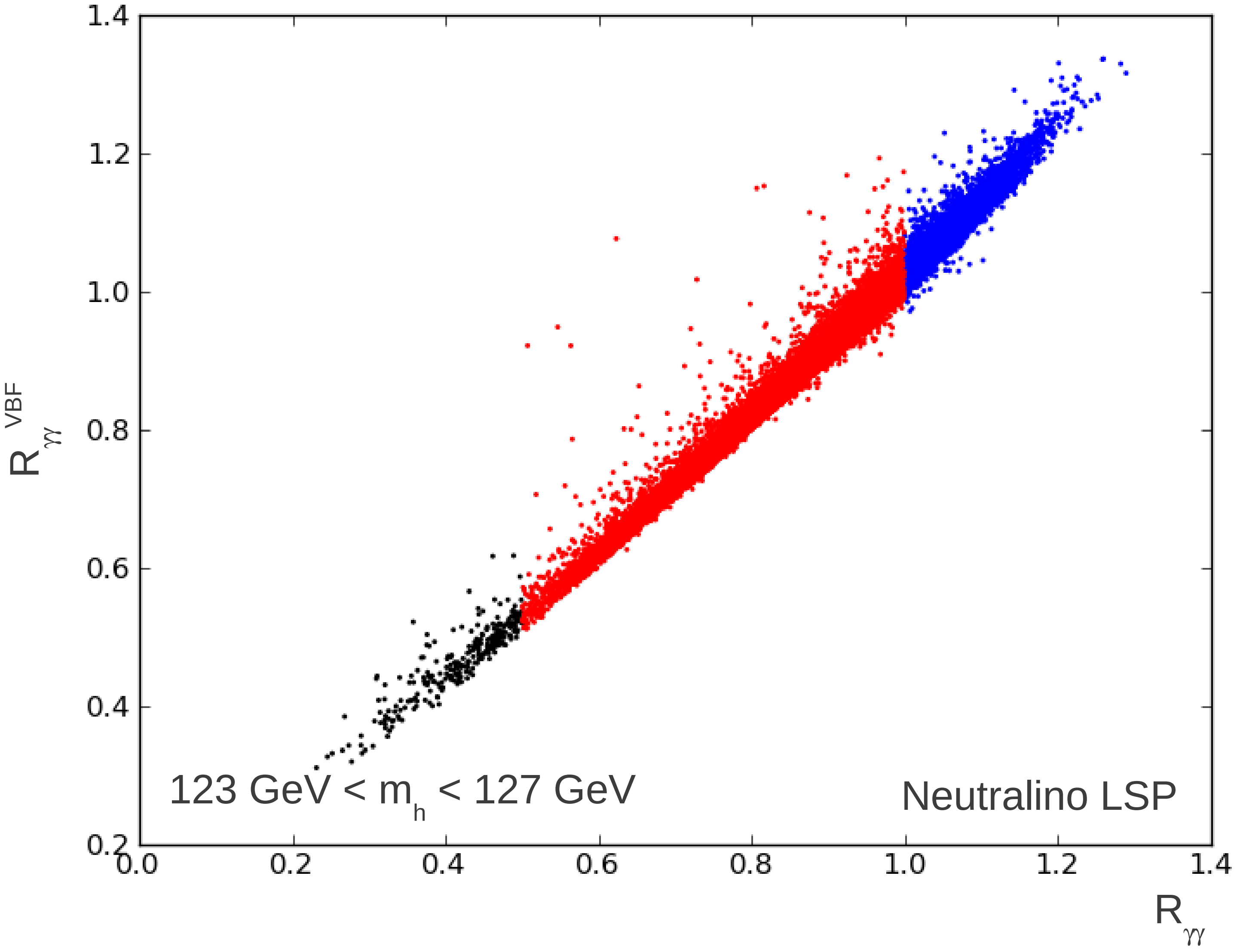
h → bb decoupling

- As sparticles get heavier, SUSY corrections to h → bb width usually decouple quickly
- However, in certain limits, e.g. near-maximal sbottom mixing with large tan β, the decoupling happens very slowly, and corrections can be large
- Large resulting corrections push up bb width, decreasing all other branching ratios accordingly

h → bb decoupling



Higgs LHC phenomenology



Can also look at vector boson fusion production WW → h → γγ

Fine-tuning

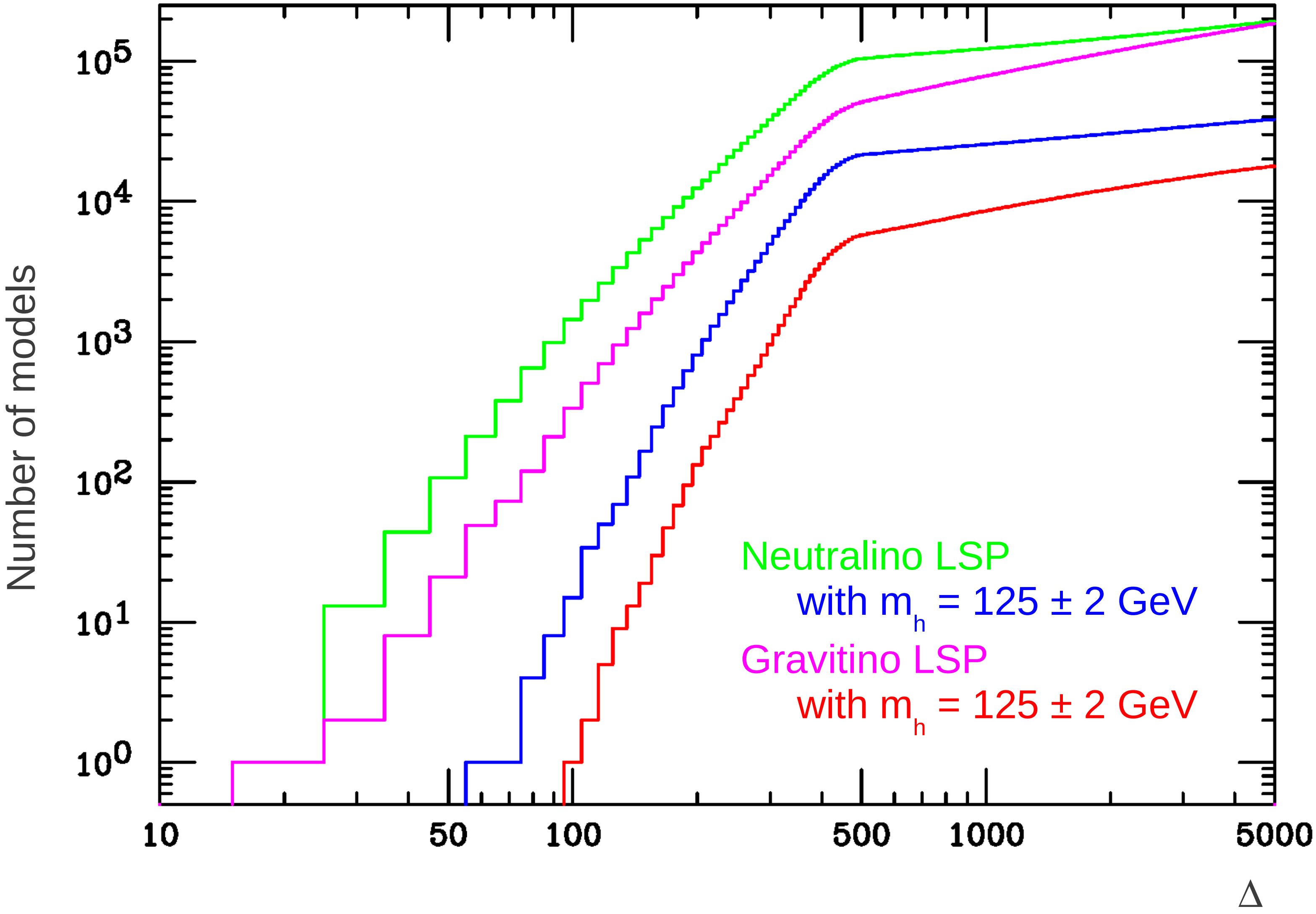
- Measure sensitivity of electroweak symmetry breaking scale to each pMSSM parameter p_i

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

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

- $A_i = \partial(\log M_Z^2) / \partial(\log p_i),\ 1 \leq i \leq 19$
- Most sensitive to μ and stop mass parameters, but gluino mass enters at higher order
- Take maximum of all A_i to get fine-tuning Δ

Fine-tuning

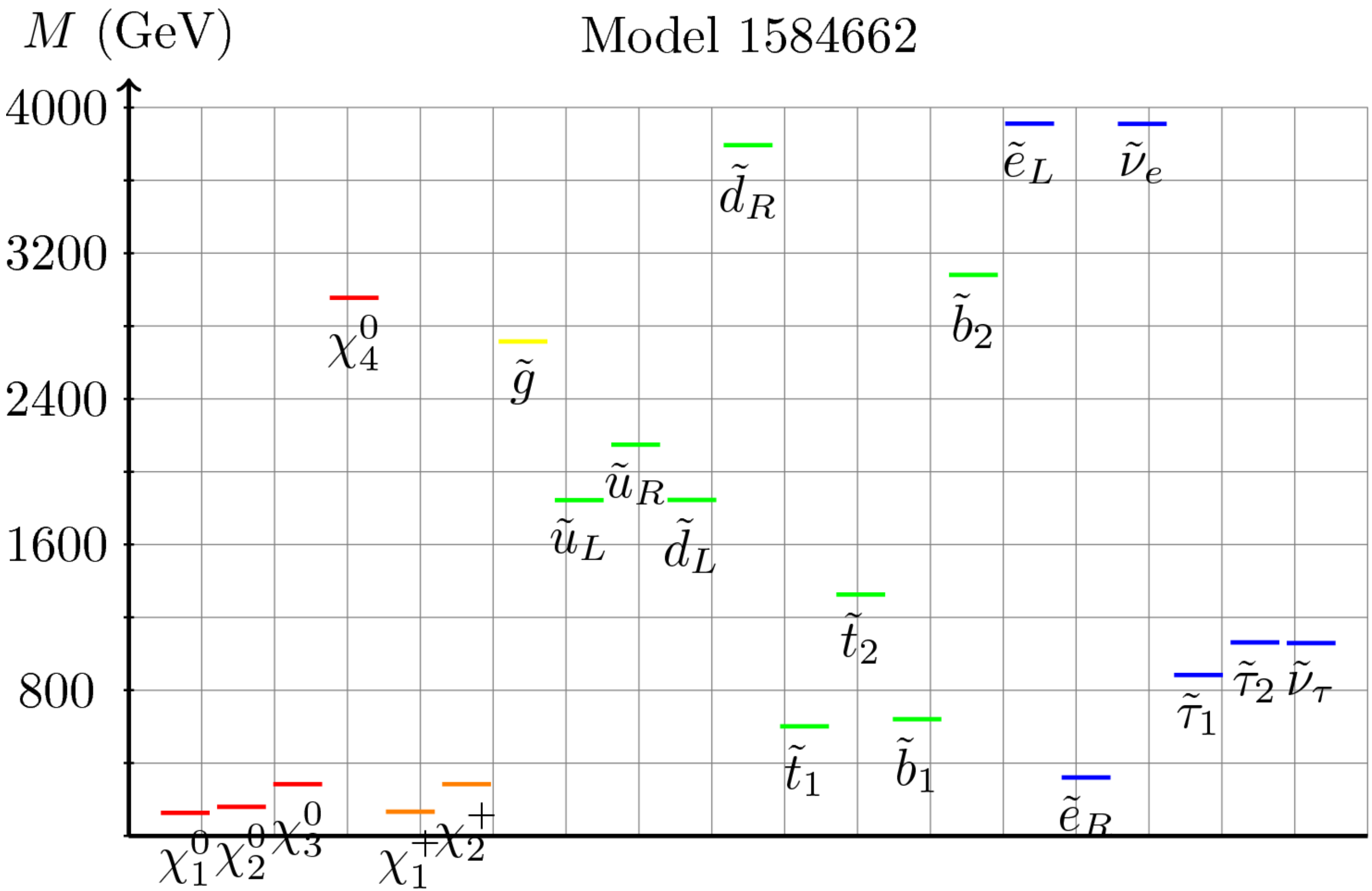


models with Higgs near 125 GeV
are more fine-tuned

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 constrained by LHC searches, but not naturalness at this level of fine-tuning

Sample spectrum

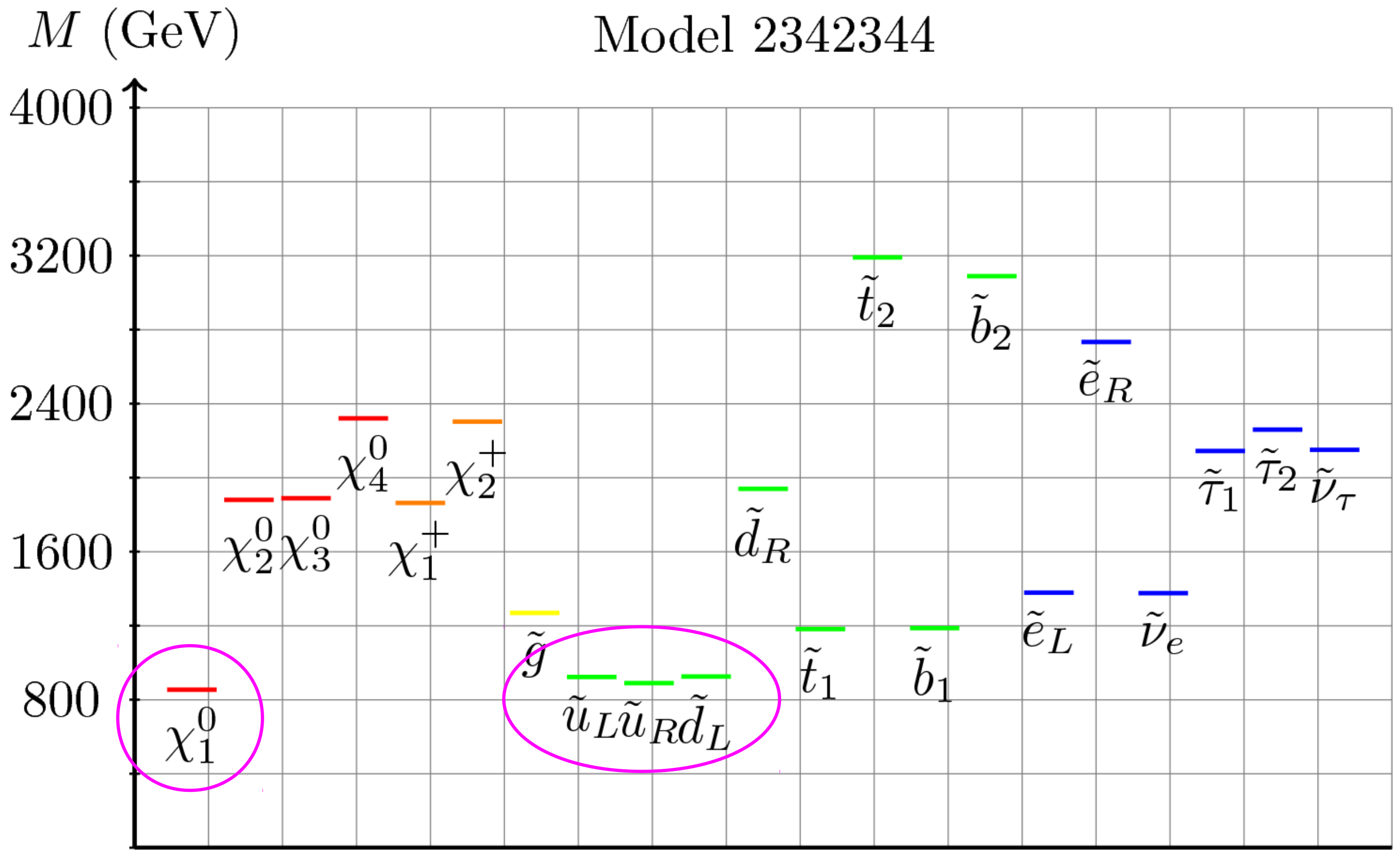


Many possible cascades for light stops and sbottoms

What happens if the LSP makes up all the dark matter?

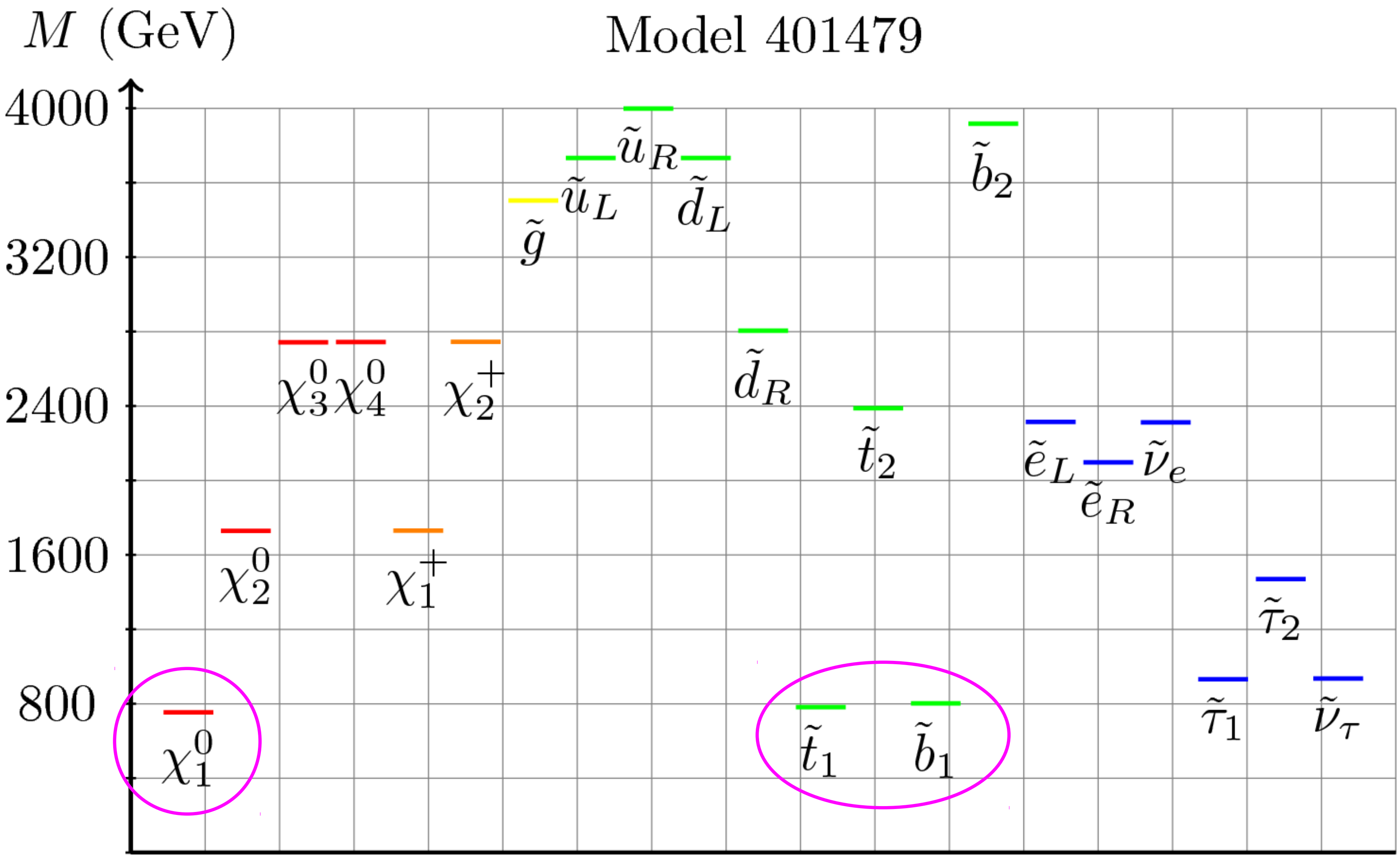
- Goal: get small set of benchmark models with right Higgs mass and relic density
- Require $m_h = 126 \pm 1$ GeV, neutralino LSP relic density within 1σ of WMAP, LHC constraints satisfied
- 24 models, representing many collider and DM scenarios (thanks to Michael Peskin)
- Sfermion coannihilation, well-tempered neutralino, resonant annihilation all represented; compressed spectra common

Bino-squark coannihilation



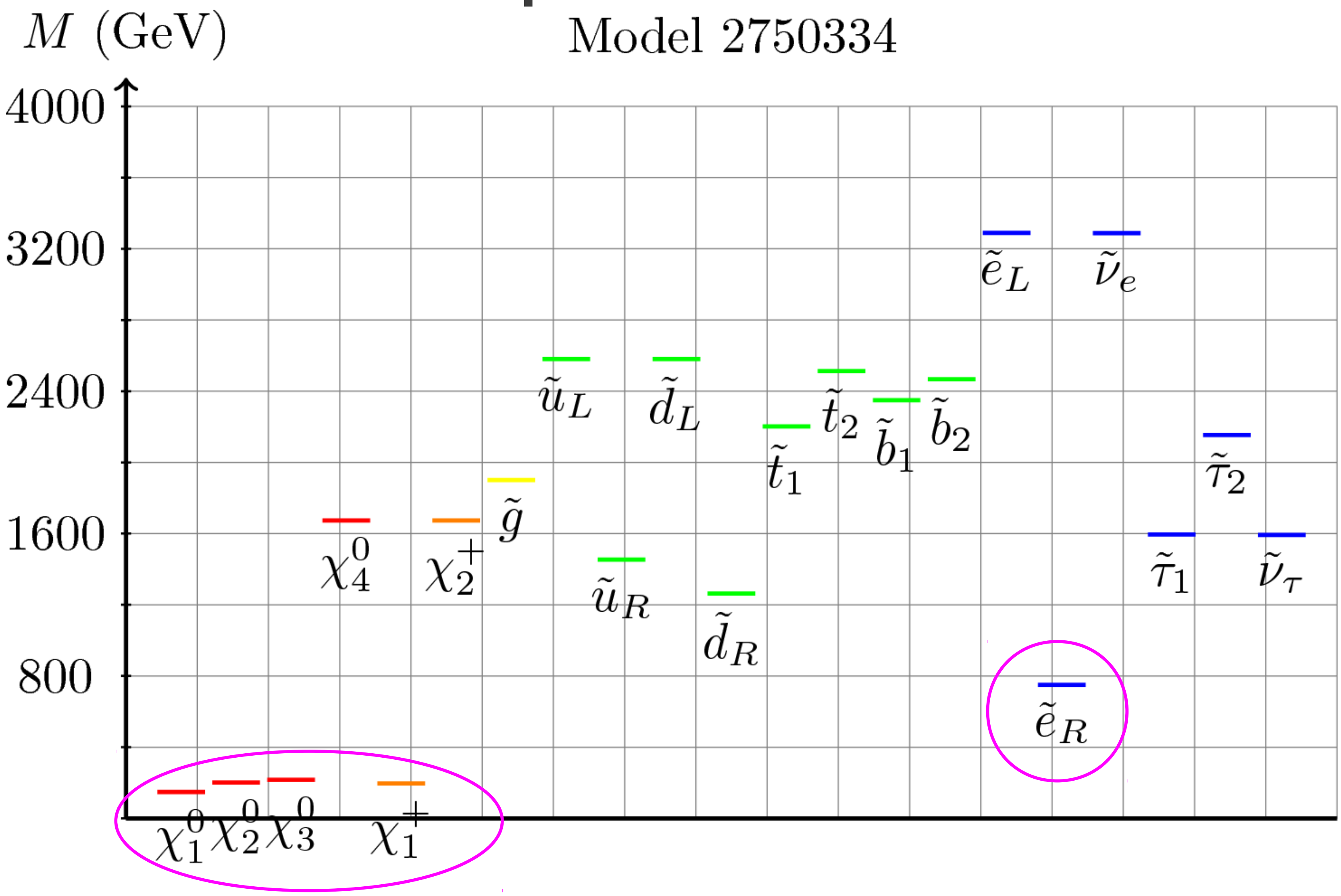
Compressed spectrum makes squarks difficult to see

Bino-stop coannihilation



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

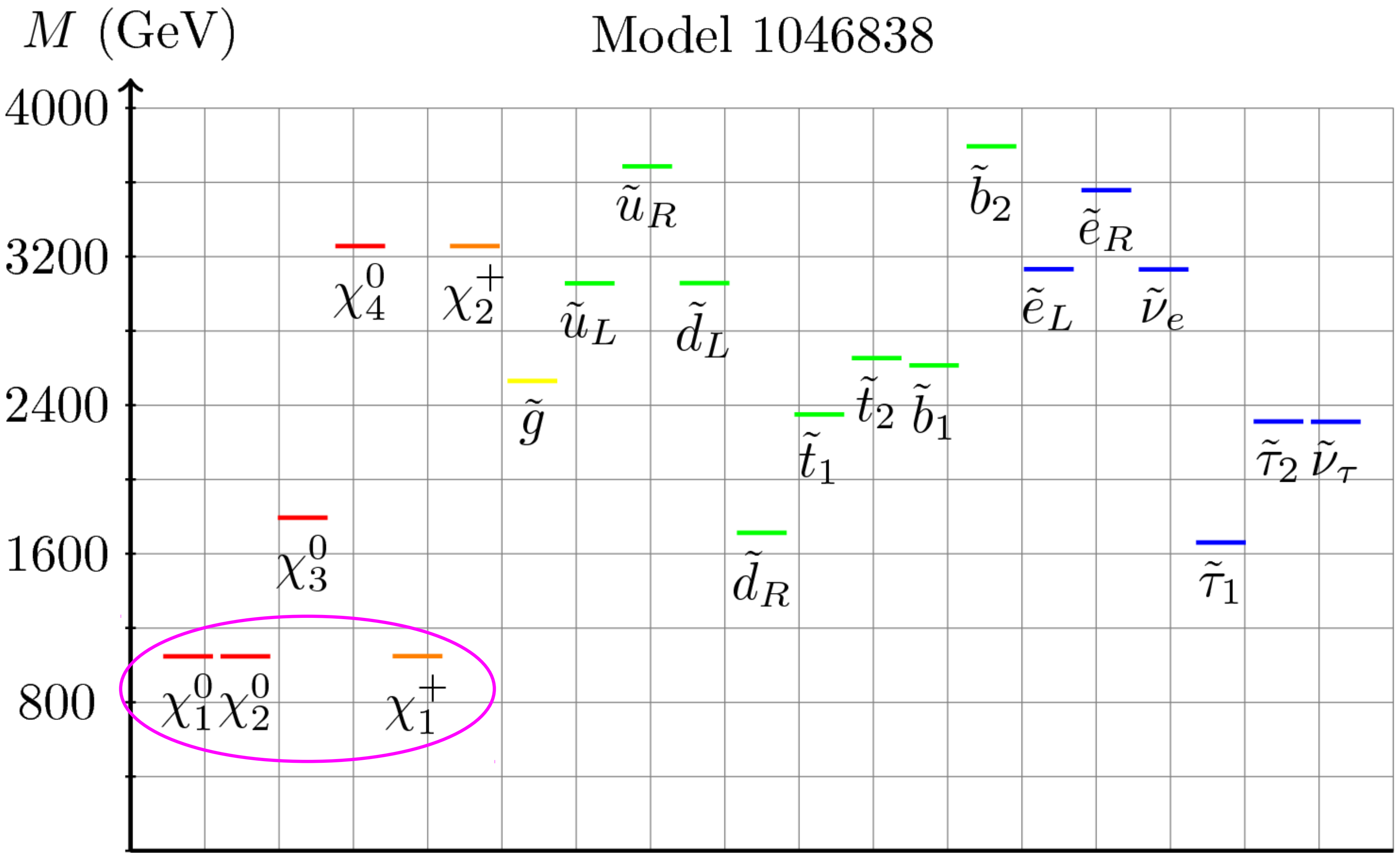
Well-tempered neutralino



All states below 1 TeV are uncolored

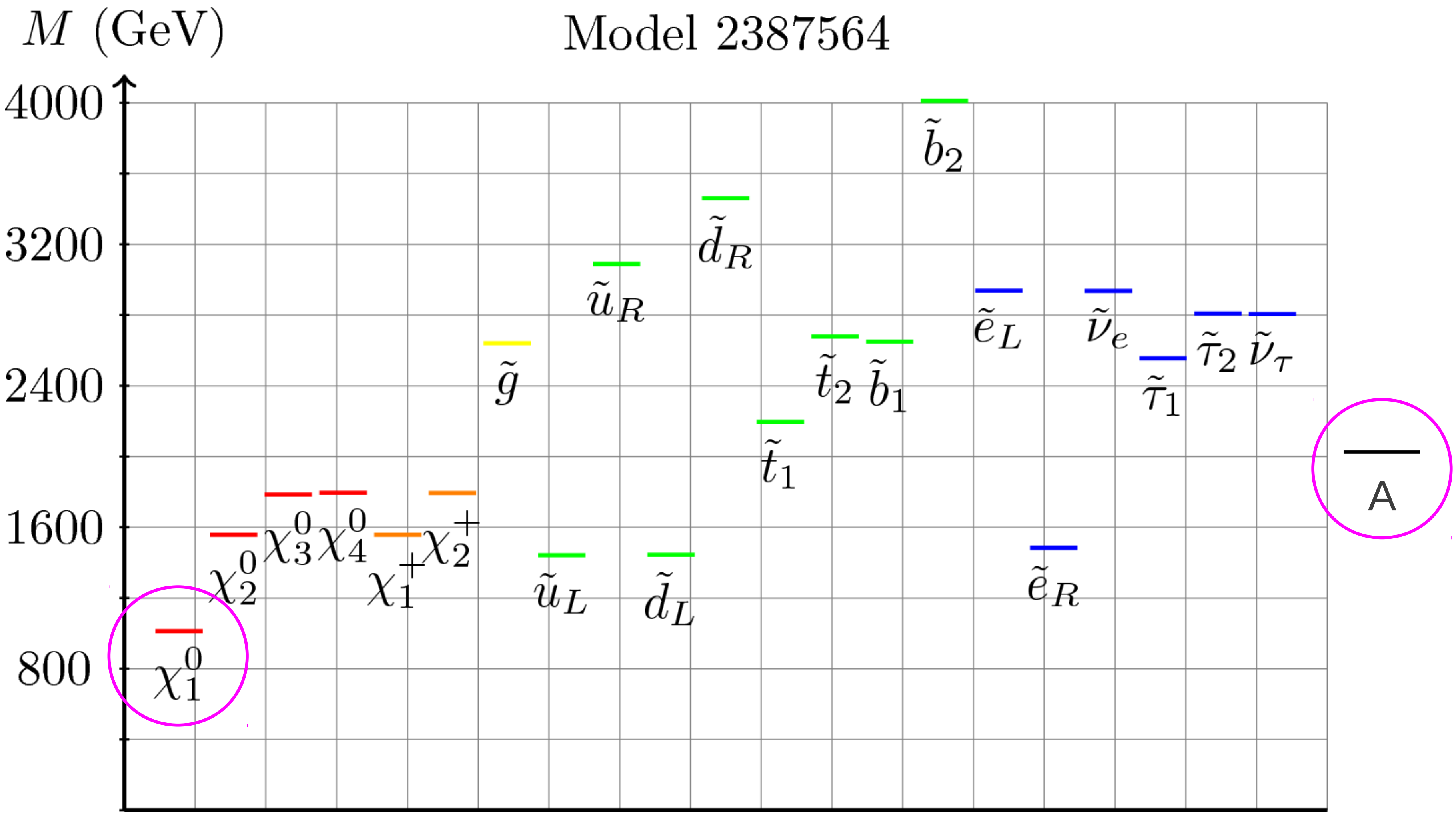
Consider studying with linear collider

“Goldilocks” Higgsino



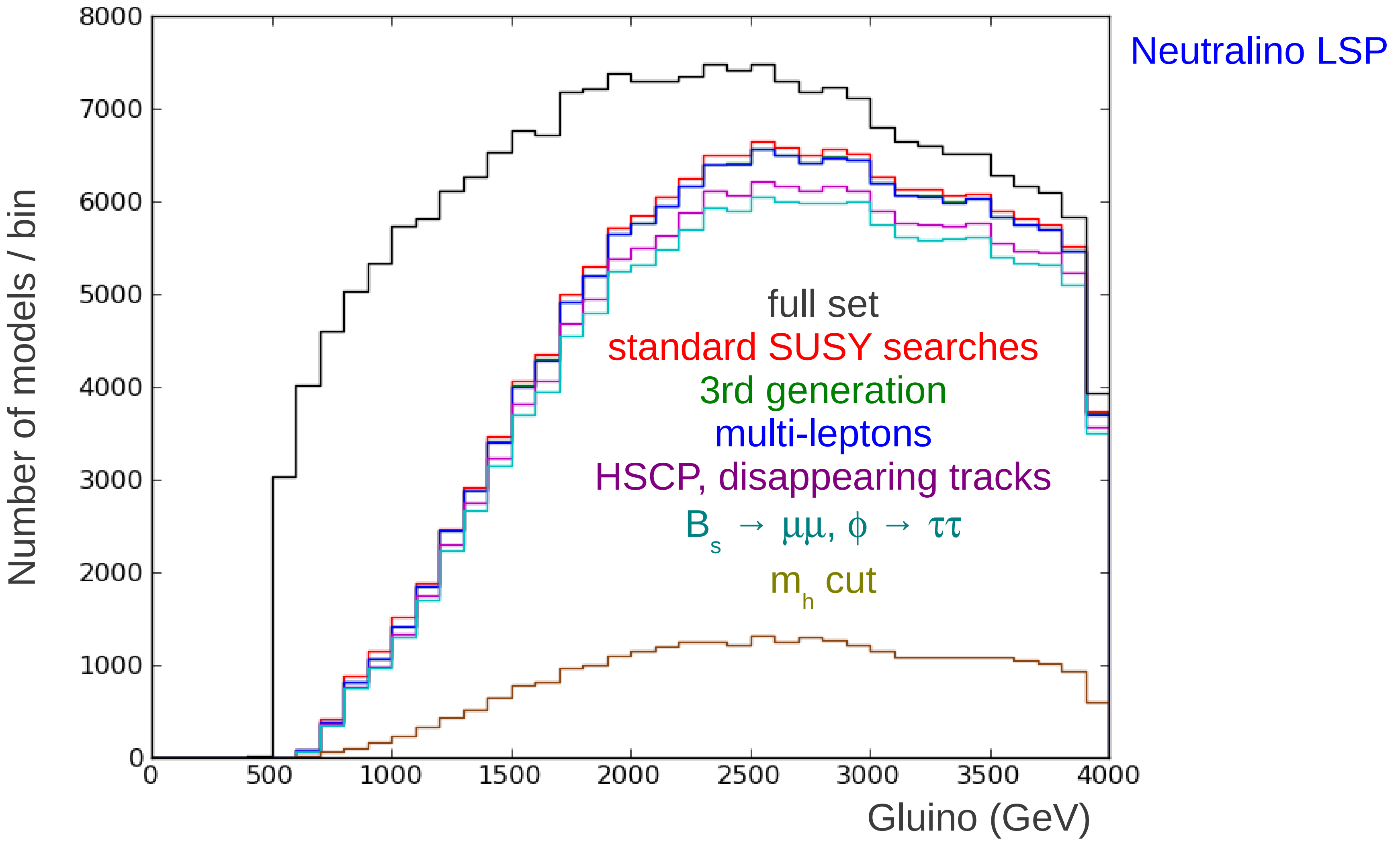
Higgsino at 1 TeV gives right relic density
Heavier Higgsino LSPs typically require coannihilations

A funnel



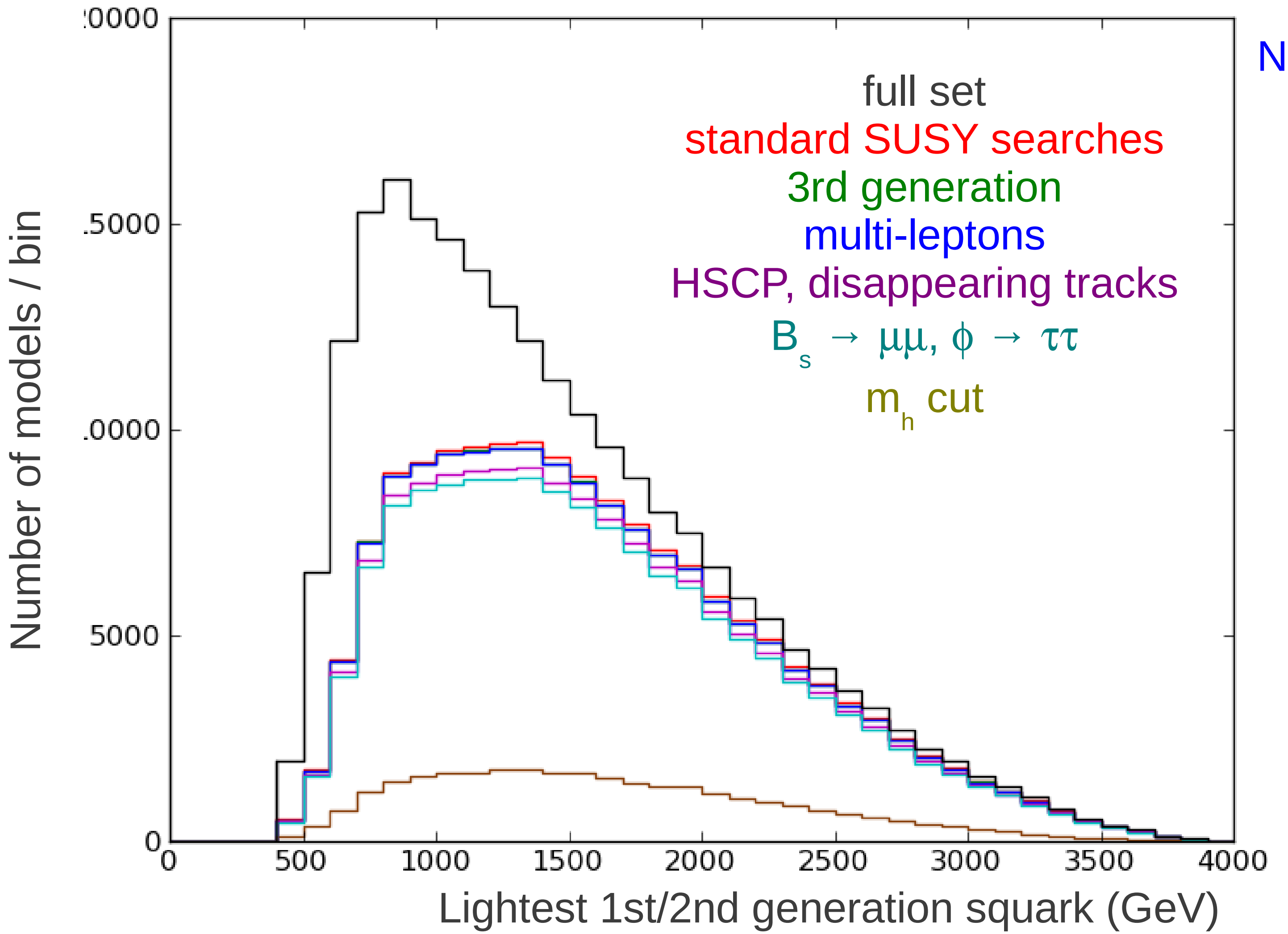
Bino at 1013 GeV, A at 2043 GeV → resonant annihilation

LHC searches



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

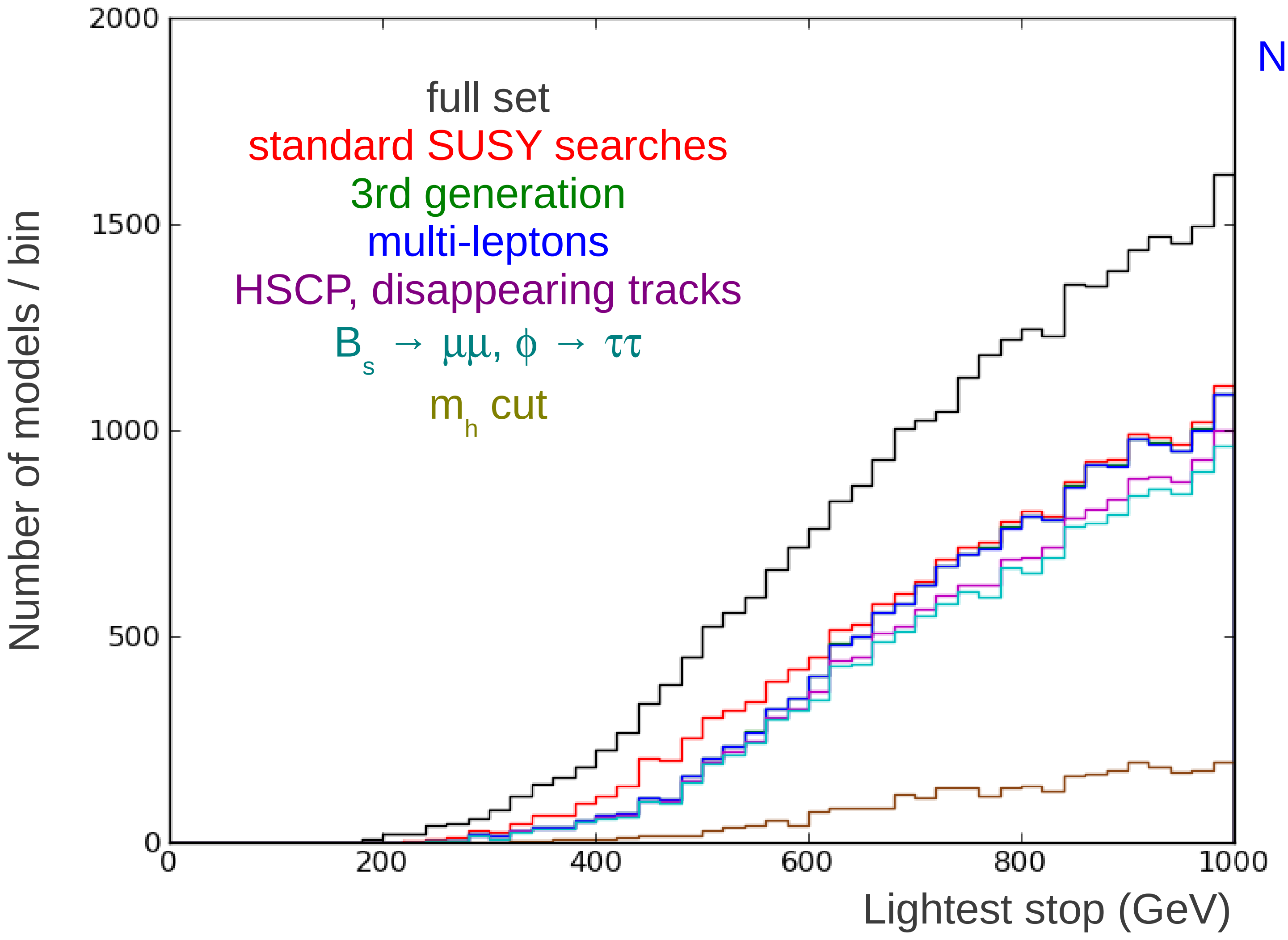
LHC searches



Neutralino LSP

“Vanilla” SUSY searches do well at seeing light squarks, more specific searches are less successful

LHC searches



Neutralino LSP

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