The phenomenological MSSM and natural SUSY

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SUSY at the Near Energy Frontier
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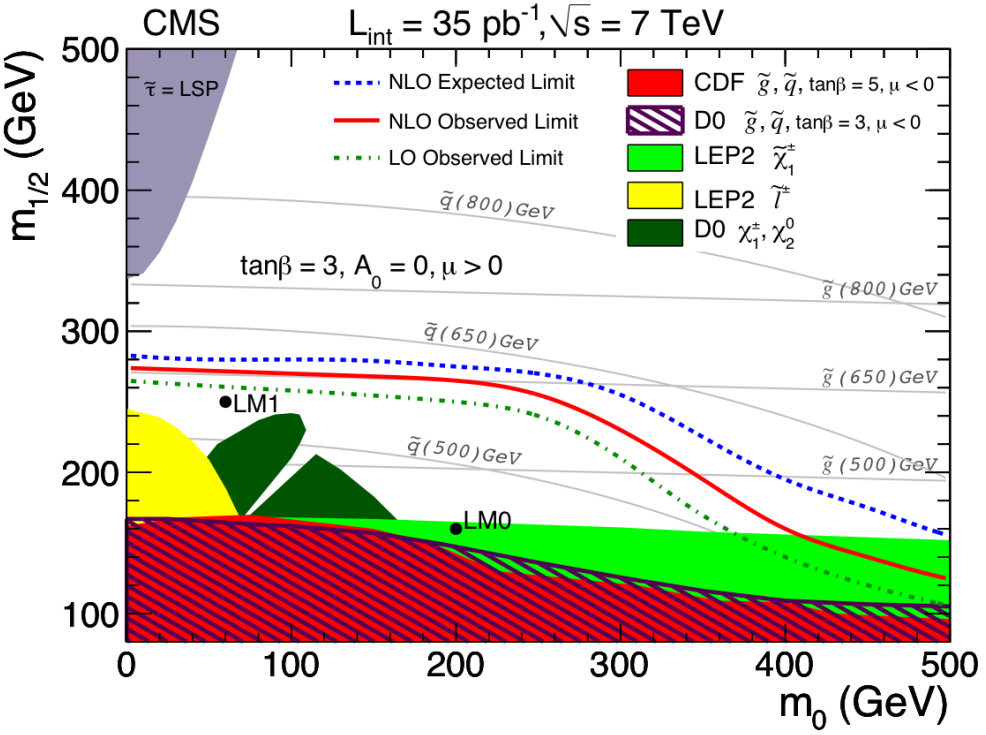
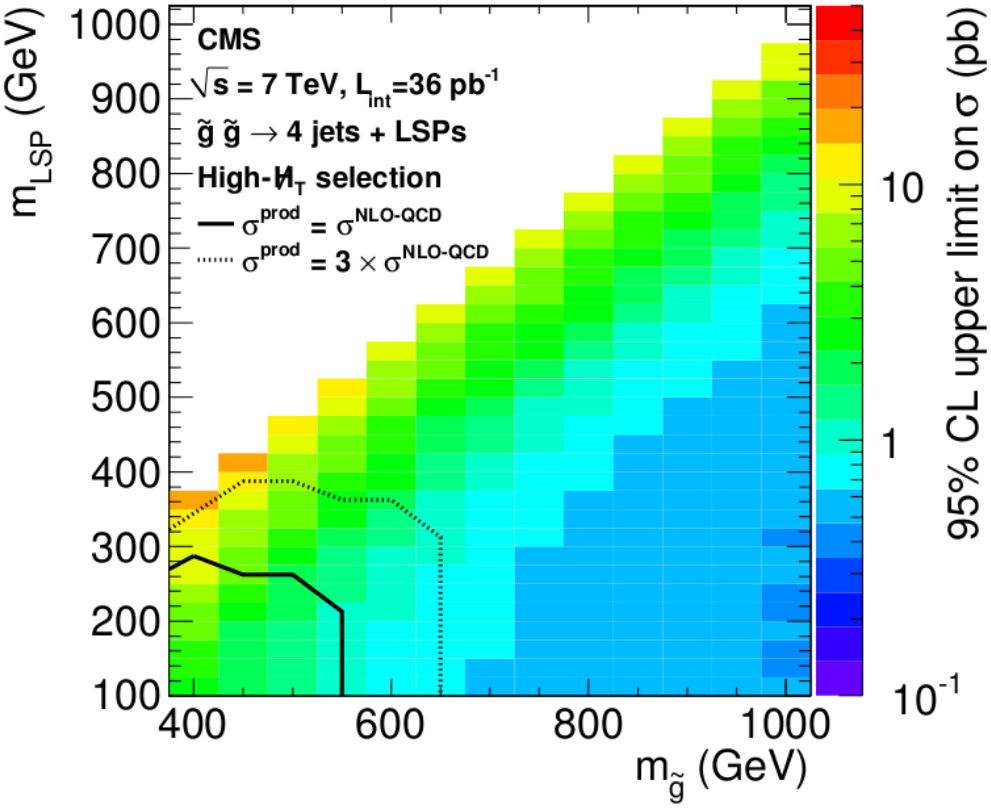
with Matthew Cahill-Rowley, JoAnne Hewett, and Tom Rizzo

The old days....



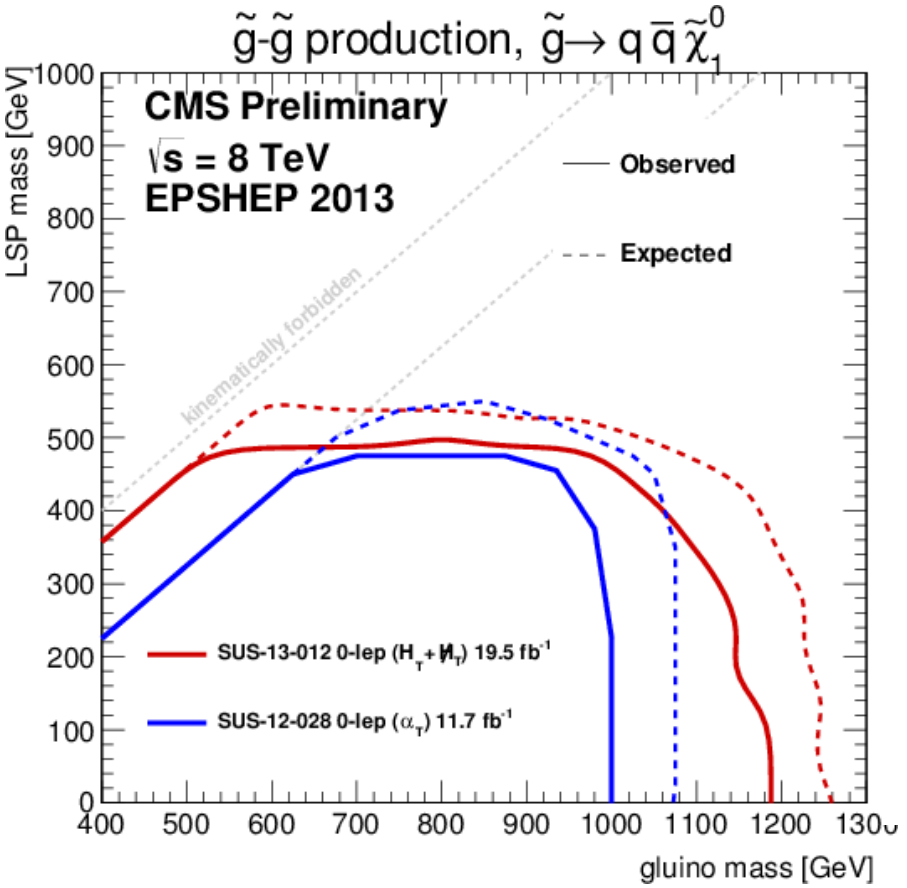
First CMS jets + MET, 1101.1628

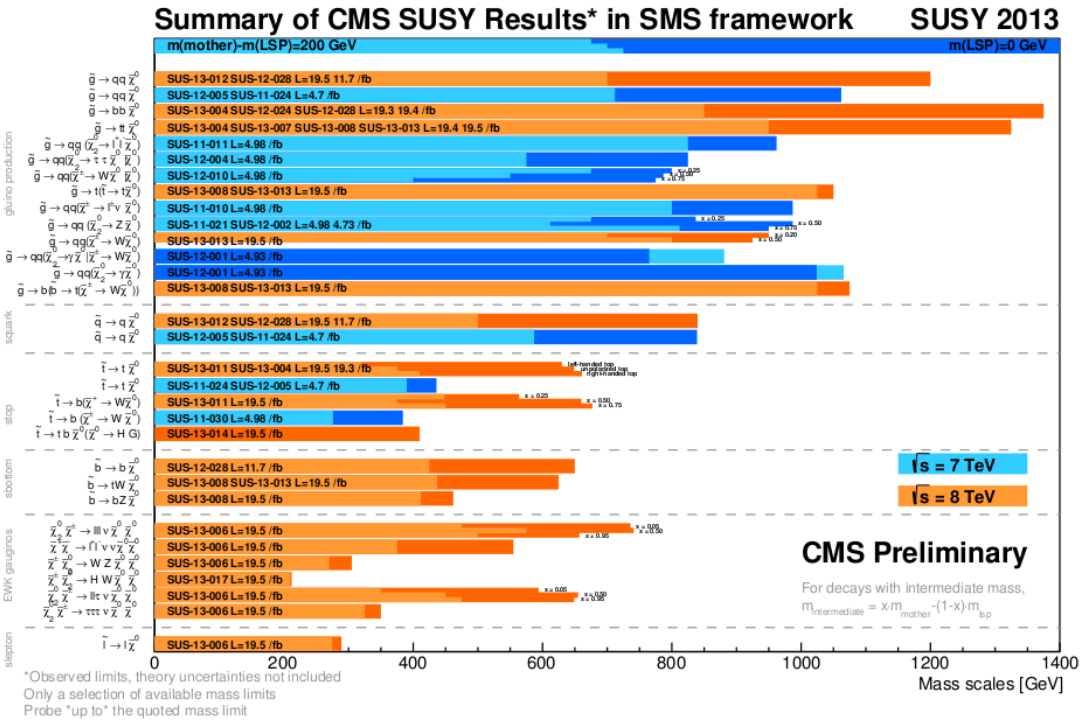


More CMS jets + MET, 1106.4503

Results of early searches were sometimes presented only in mSUGRA plane; simplified models provided an approach which is much less model-dependent

But we still haven't found anything!





CMS summary plots for simplified models

Investigate possibilities remaining below these limits using more complete spectra → pMSSM

The phenomenological MSSM

- Scan over larger SUSY parameter space
- The full MSSM has 105 new free parameters, many of which are very strongly constrained by flavor data, electric dipole moments, etc.
- Minimal flavor violation decreases scan dimensionality without losing much generality; CKM matrix controls SUSY flavor physics
- Take sparticle mass matrices to be flavor diagonal, with first two generations degenerate
- No new sources of CP violation

The phenomenological MSSM

- 19 free parameters of the phenomenological MSSM
- M_1, M_2, M_3, μ, $\tan\beta$, M_A, $q_{1,3}$, $u_{1,3}$, $d_{1,3}$, $l_{1,3}$, $e_{1,3}$, $A_{t,b,\tau}$
- Generate random points in this parameter space, and test vs. experimental constraints
- Surviving points go into model set, which is then tested against incoming data

Model set generation

- $50\ \text{GeV} \leq |M_1| \leq 4\ \text{TeV}$
- $100\ \text{GeV} \leq |M_2, \mu| \leq 4\ \text{TeV}$
- $400\ \text{GeV} \leq M_3 \leq 4\ \text{TeV}$
- $1 \leq \tan\beta \leq 60$
- $100\ \text{GeV} \leq M_A, l, e \leq 4\ \text{TeV}$
- $400\ \text{GeV} \leq q_1, u_1, d_1 \leq 4\ \text{TeV}$
- $200\ \text{GeV} \leq q_3, u_3, d_3 \leq 4\ \text{TeV}$
- $|A_{t,b,\tau}| \leq 4\ \text{TeV}$

- Generate spectra for 3×10^6 points in 19 dimensional parameter space, requiring lightest neutralino to be 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

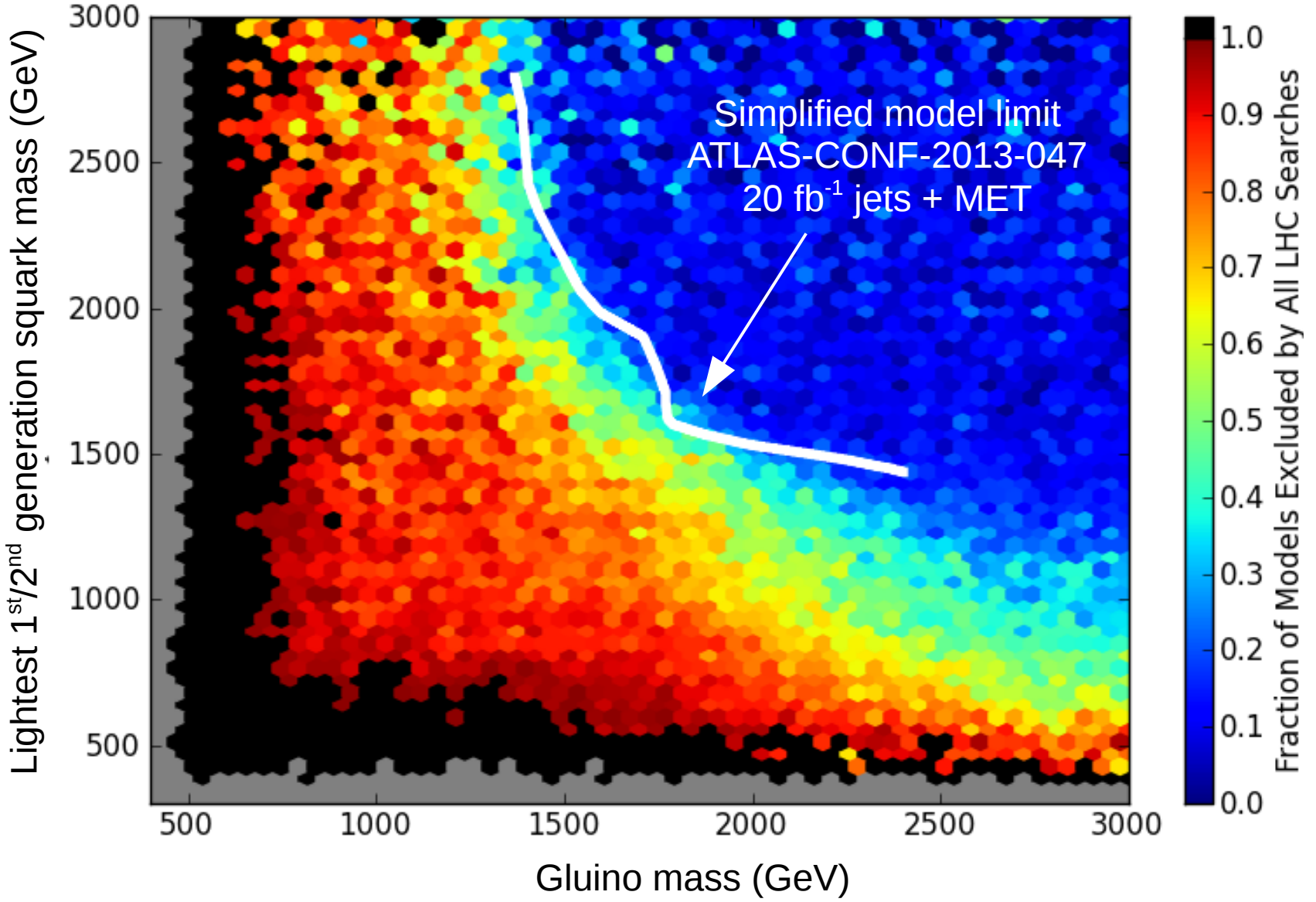
Model set generation

- Precision EW constraints: g – 2, invisible width of Z, $\Delta\rho$
- Flavor constraints: $b \rightarrow s\gamma$, $B_s \rightarrow \mu\mu$, $B \rightarrow \tau\nu$
- Impose WMAP7 as upper bound on thermal relic density of lightest neutralino, and check against DM direct detection constraints
- Require all charged sparticles > 100 GeV
- Apply LHC stable particle, $\Phi \rightarrow \tau\tau$ constraints as of 12/2011
- 2×10^5 models left; computationally demanding!

LHC searches

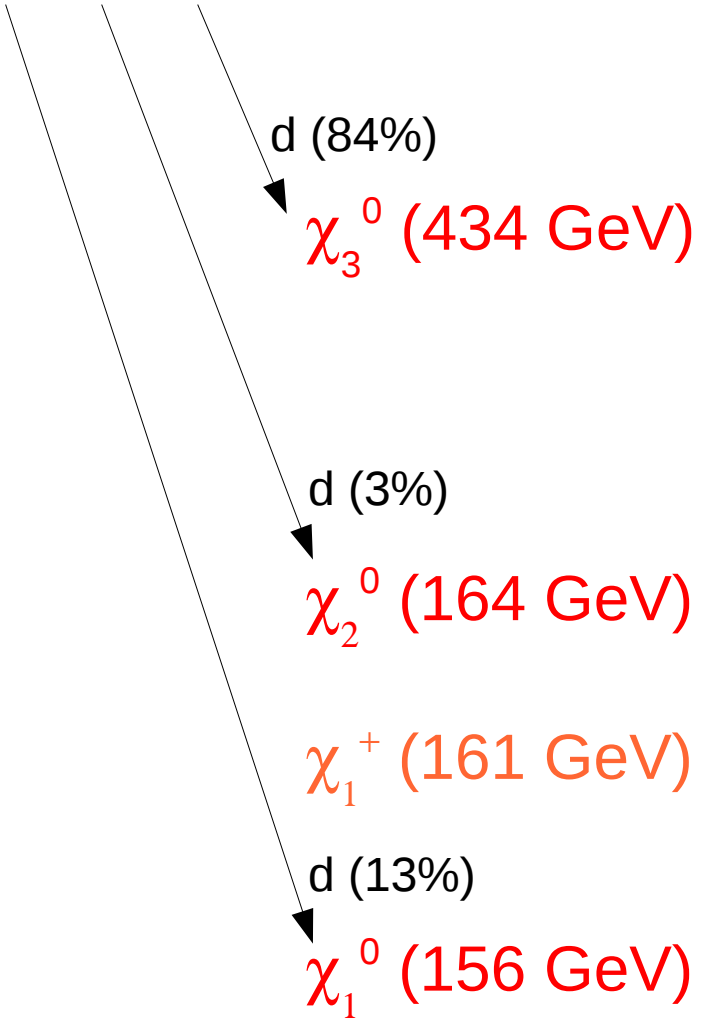
- Goal: reproduce relevant SUSY searches
- Generate SUSY events for each model with PYTHIA/Prospino/PGS; codes modified!
- Input MET-based SUSY searches up to March 2013, generally following ATLAS
  + 20 fb^{-1} jets + MET
- Non-MET searches also included, e.g. searches for heavy stable charged particles, SUSY Higgs $\rightarrow \tau\tau$ (CMS), $B_s \rightarrow \mu\mu$ (LHCb)

LHC searches



Models survive due to non-degenerate squarks, massive LSPs

Light squark pathology



Bino

Higgsinos

t_1 at 999 GeV, all other colored sparticles above 1.8 TeV

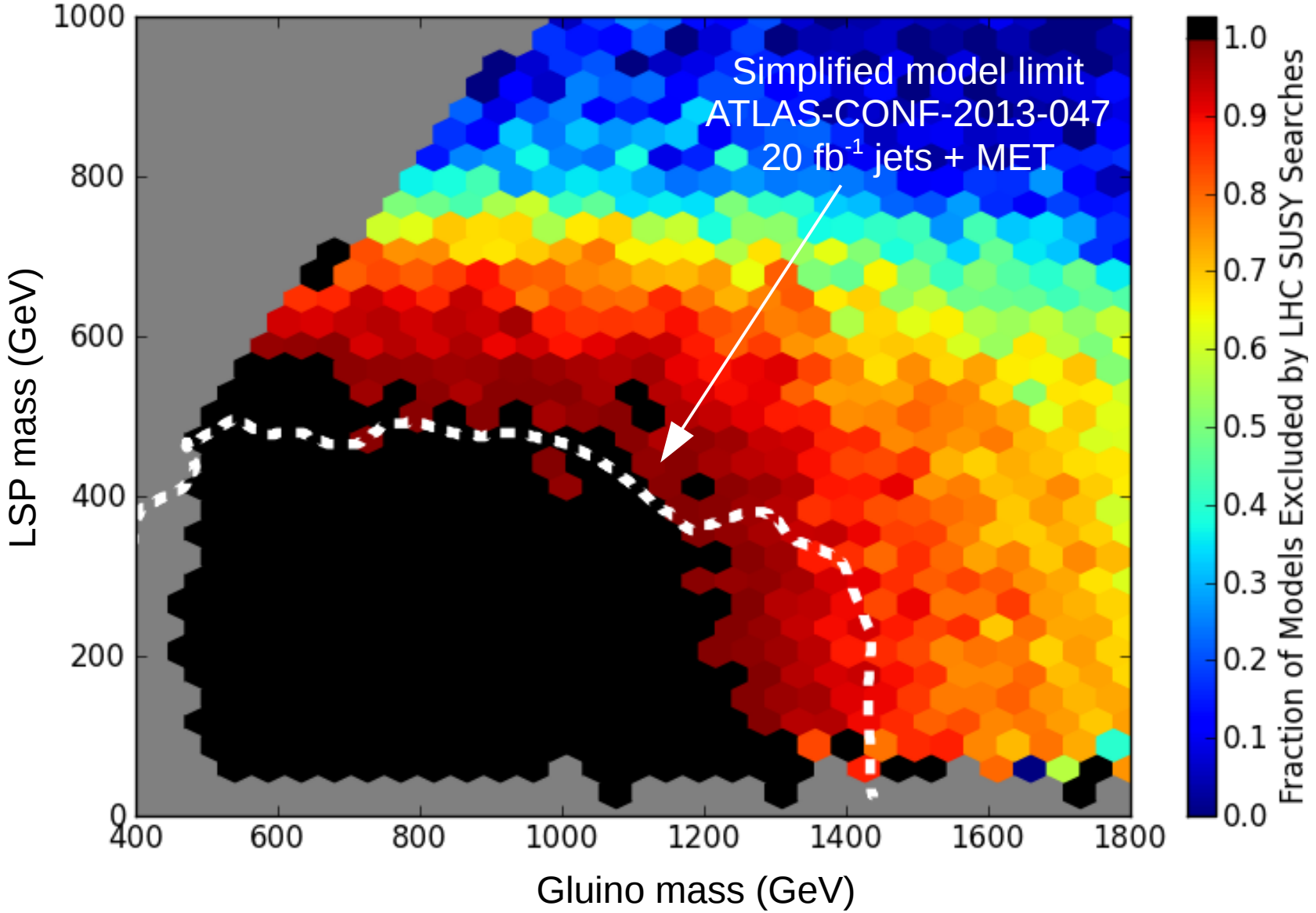
Production cross section lower than with 8 degenerate squarks

Squark prefers compressed decay due to gaugino composition!

Bino decays to Higgsinos through W (29%), Z (14%), h (12%), stau (22%), stau neutrino (23%)

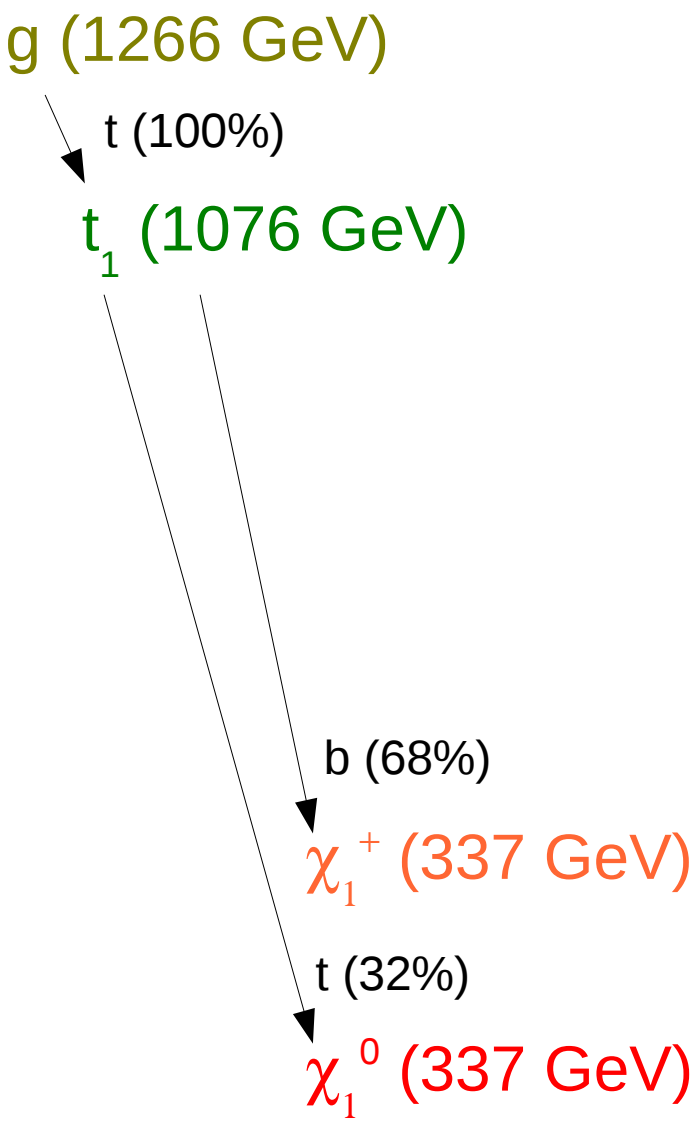
Model 2762364

LHC searches



Models can survive below limit if gluino does not decay to 2j + MET

Gluino decay through on-shell stop



All other colored sparticles above 1.8 TeV

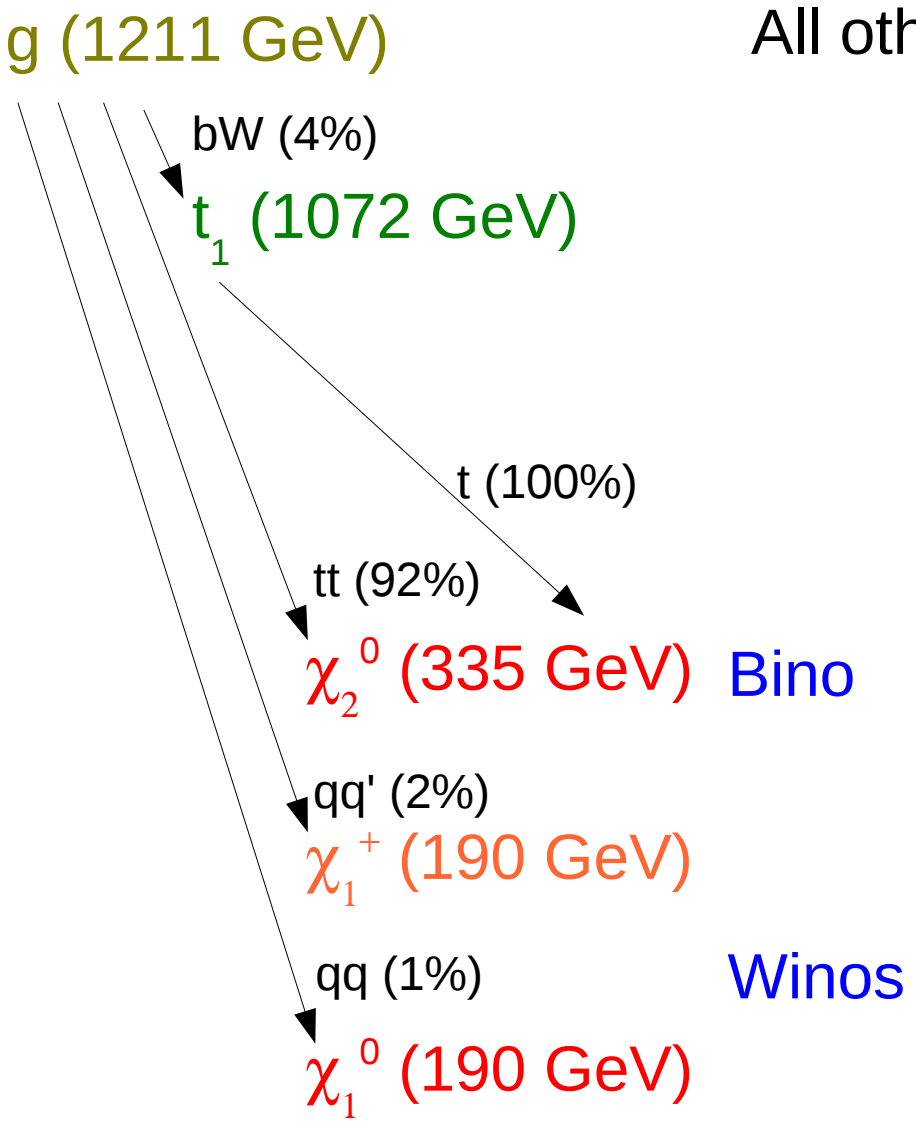
Most common gluino decays for this spectrum are not covered by models T1tttt/T1bbbb (CMS) or Gtb (ATLAS)

Features:
gluino decays to on-shell stop
stop prefers b + chargino decay
chargino is invisible

Winos

Model 1574462

Gluino decay through off-shell stop



All other colored sparticles above 2.2 TeV

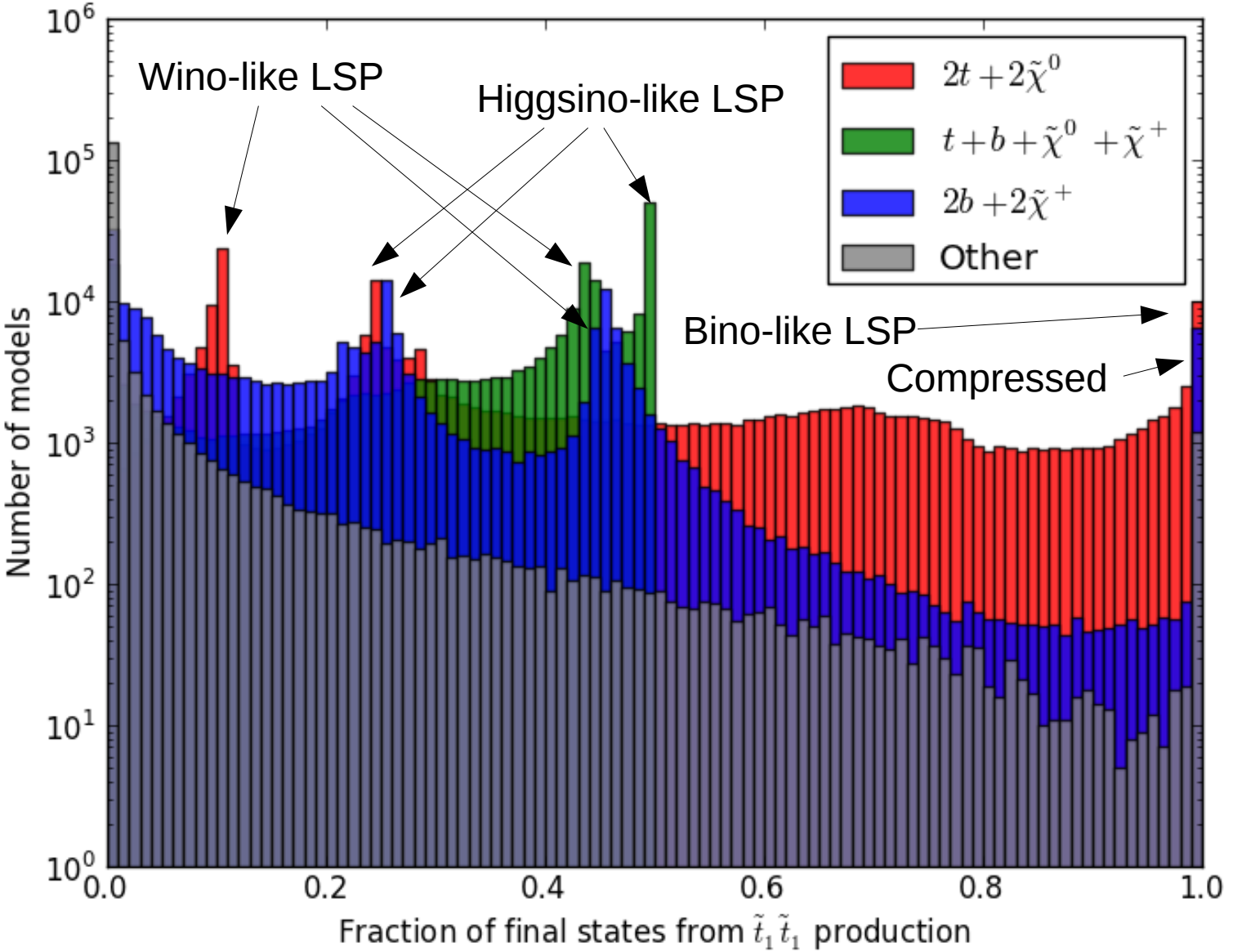
Lighter stop is right-handed but LSP is wino

Gluino prefers to decay through off-shell stop to *second* neutralino

Similar to three-body gluino to tt + LSP decays in T1tttt (CMS) or Gtt (ATLAS), but with χ_2^0, not χ_1^0!

Model 1000268

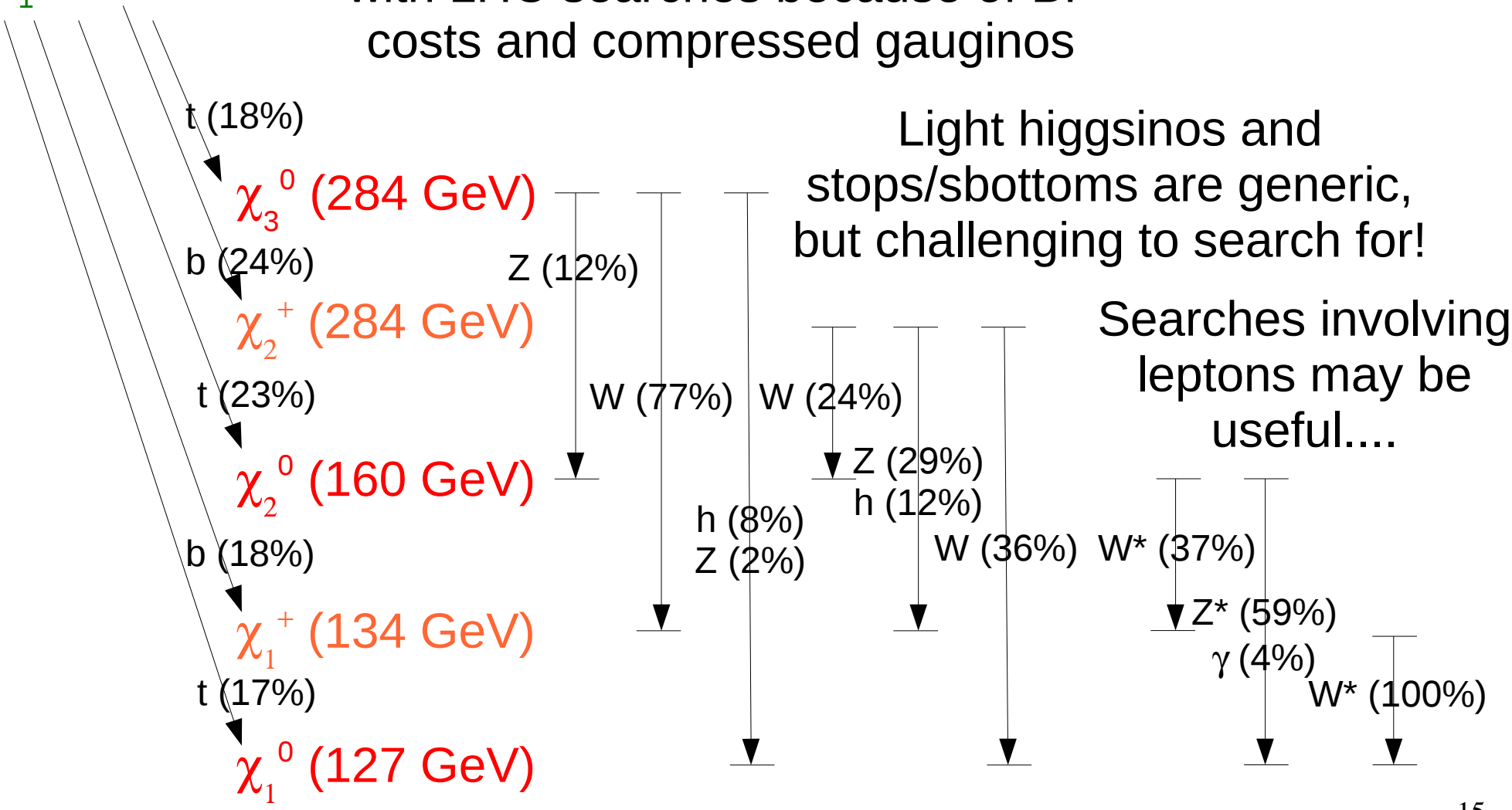
Stops in the pMSSM



Mixed decays can be important!

Searches for natural SUSY

Natural models are difficult to see with LHC searches because of BF costs and compressed gauginos



Light higgsinos and stops/sbottoms are generic, but challenging to search for!

Searches involving leptons may be useful....

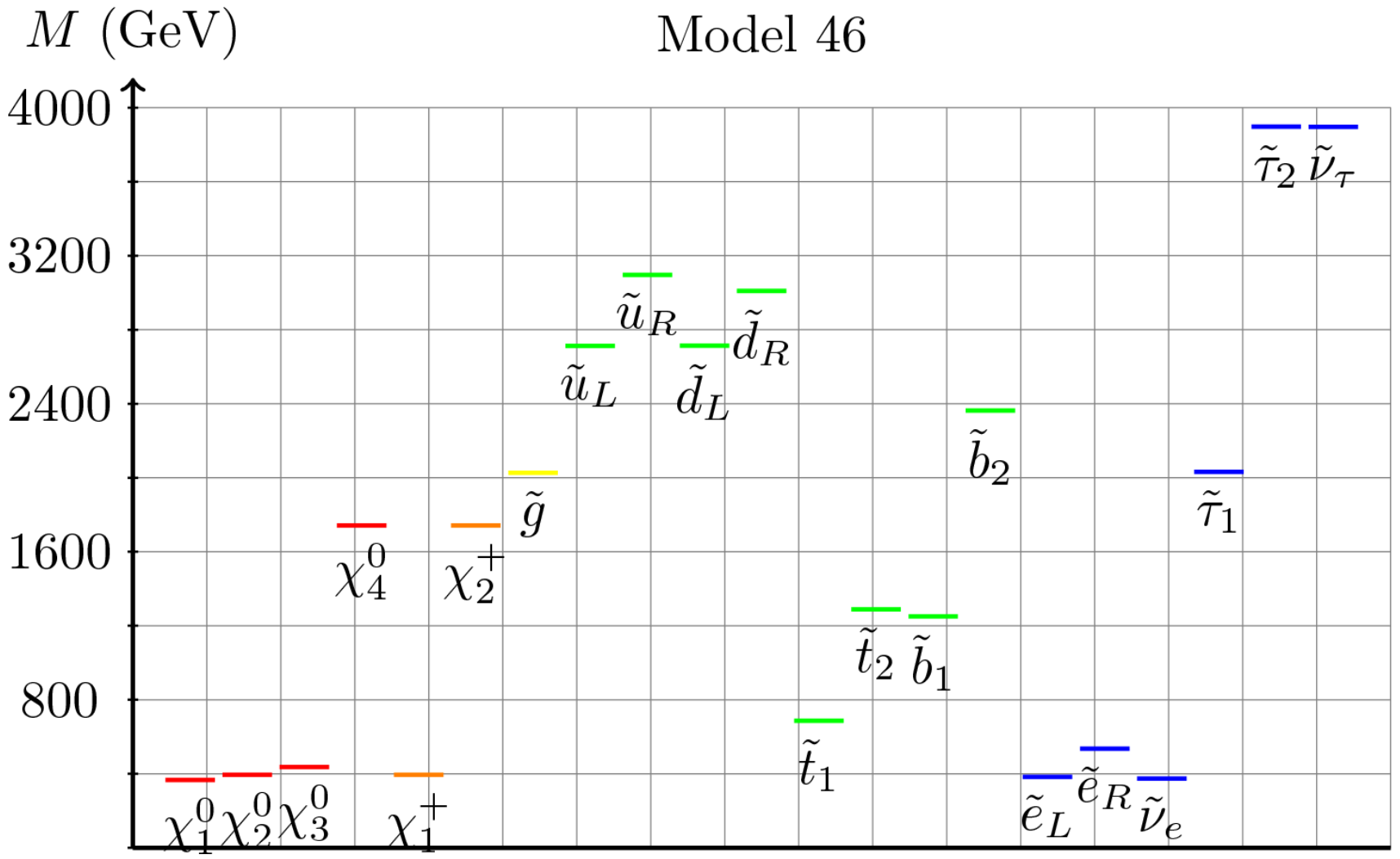
A new pMSSM scan

- Generate new set of neutralino LSP models
- Only scan over points with less than 1% tuning; start with 3.3×10^8 points
- Require Higgs mass of 126 ± 3 GeV
- No constraints imposed on Higgs branching ratios for now
- Additionally, now saturate dark matter by requiring neutralino LSP relic density to be within 5σ of WMAP9 measurement
- Have ~ 10^4 points left

A new pMSSM scan

- Higgsinos must now be below ~ 460 GeV for naturalness
- Stops are constrained by both naturalness and Higgs mass constraints, with large stop mixing becoming absolutely necessary
- Well-tempered bino-Higgsino mixtures, Z/h funnels, bino coannihilation are still viable mechanisms of producing the right amount of dark matter
- No pure Higgsino or wino LSP models

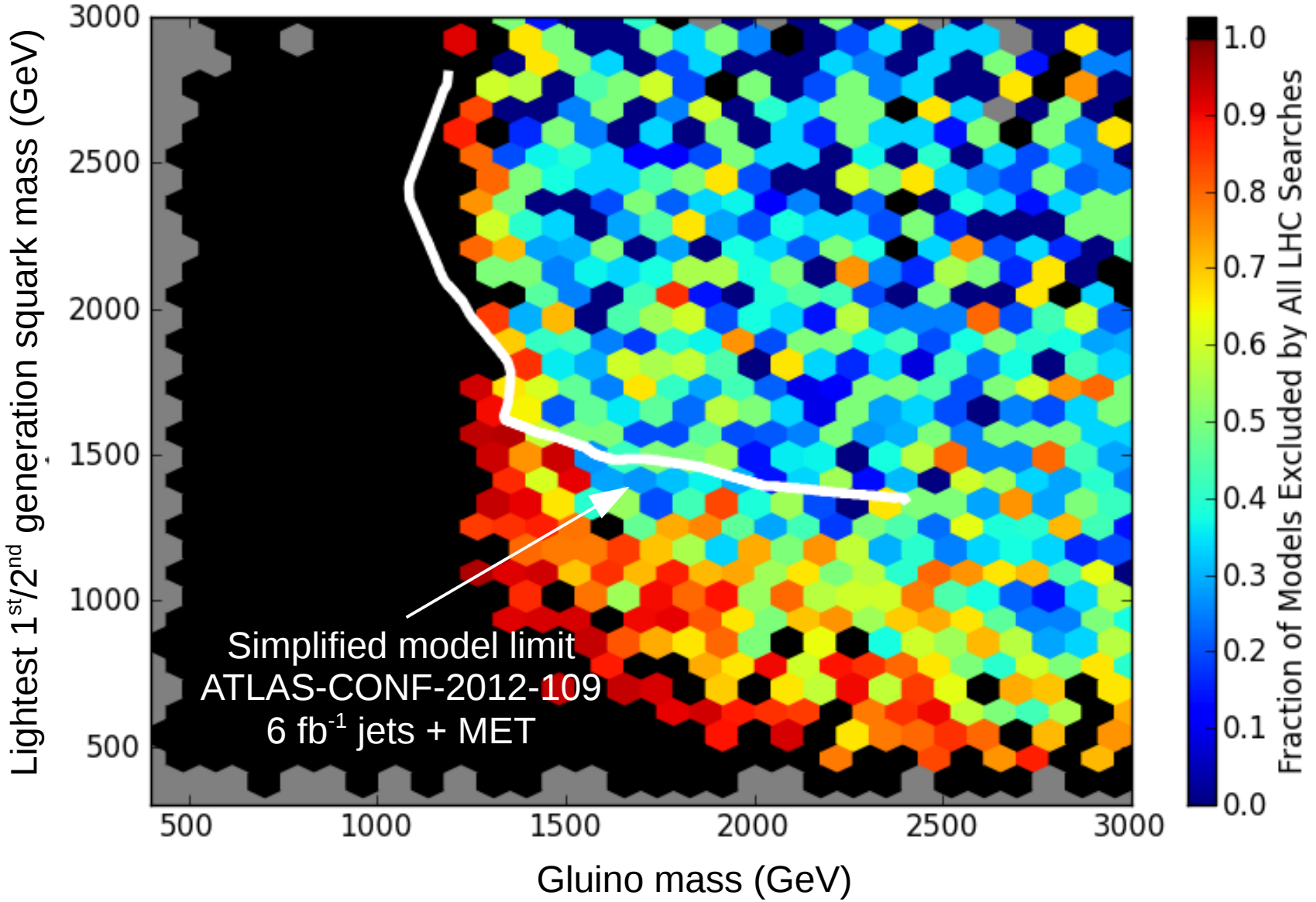
A sample model



Well-tempered LSP is 41% bino, 59% higgsino at 367 GeV

Large (but not maximal!) stop mixing: $(A_t - \mu \cot \beta) / M_s = 2.0$

LHC searches – natural SUSY

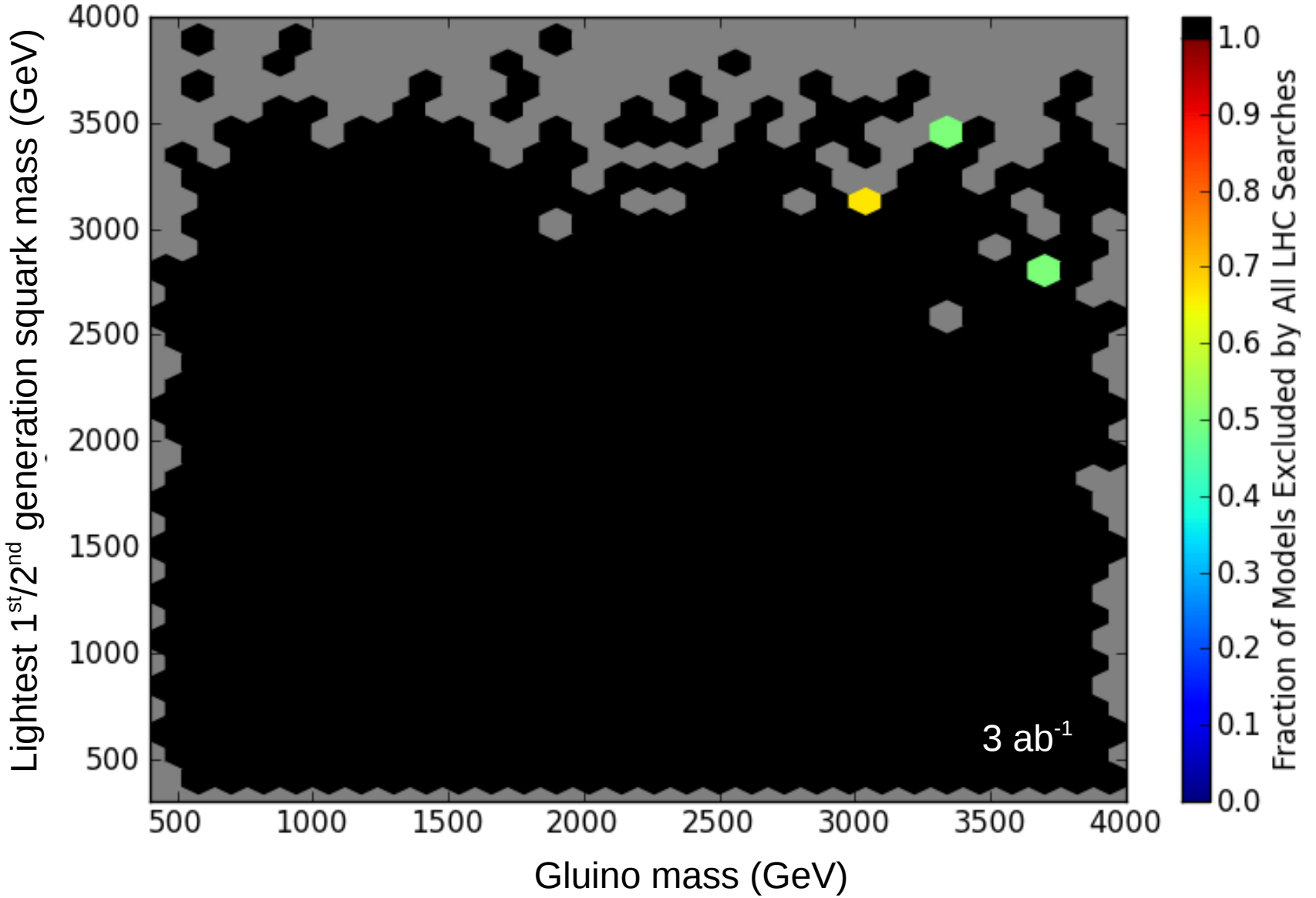


Four lepton search is sensitive to nearly half the low FT models

A look ahead

- Estimate 14 TeV reach by reproducing the analyses proposed in ATLAS European Strategy contribution
- Jets + MET and 0/1 lepton stop searches are implemented, at both 300 fb^{-1} and 3 ab^{-1}
- A caveat: only statistical errors are considered, not systematics
- Particularly useful to see how well these searches do on the set of natural models

Natural SUSY – 14 TeV jets + MET



Remaining models can be excluded by 14 TeV stop searches

Where to search next?

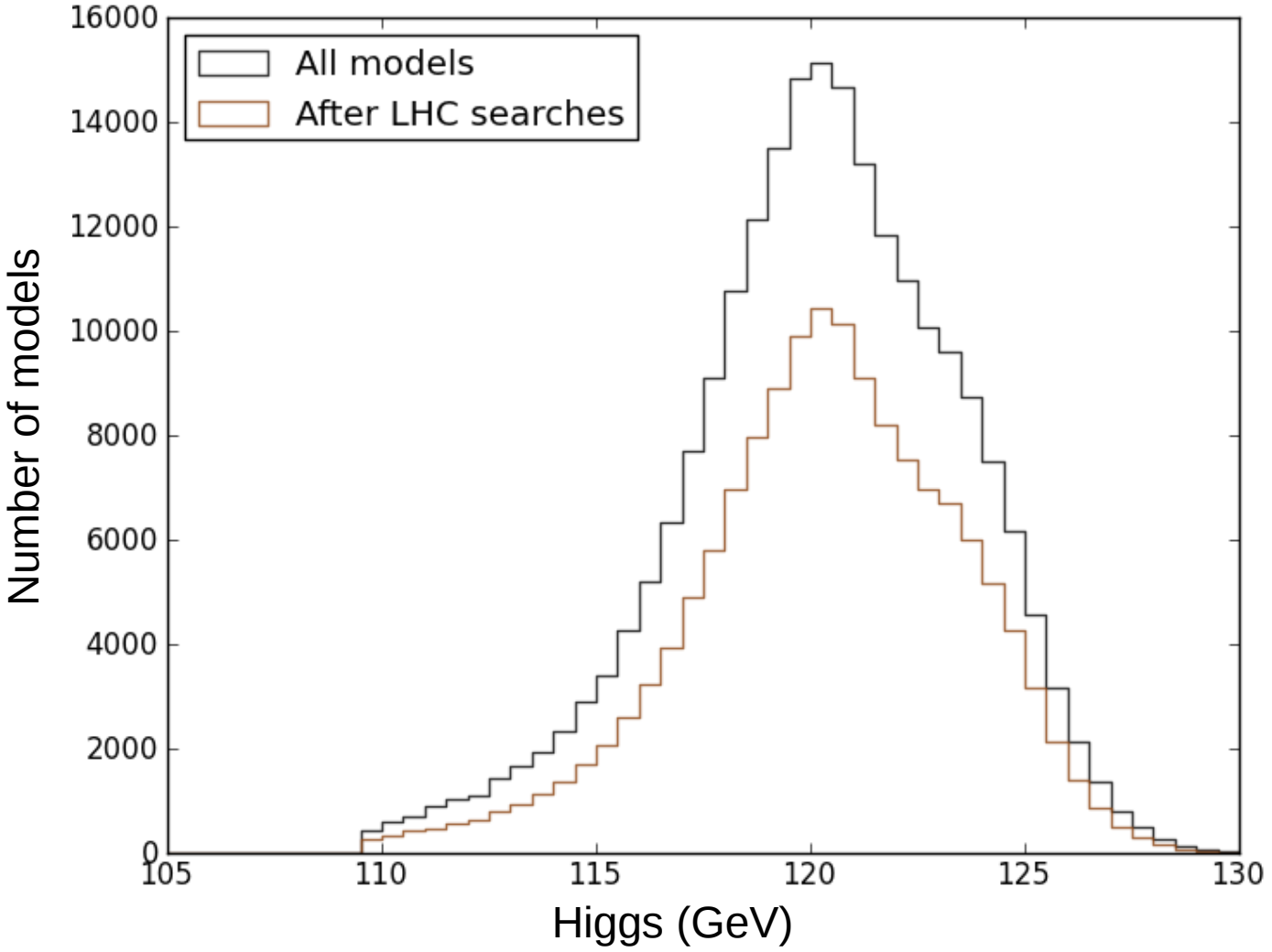
- The number of different topologies considered in analyzing the 2012 data is impressive
- Some scenarios may be interesting to investigate further, such as non-degenerate squarks and mixed stop decays
- Natural SUSY is being well-probed by current searches, and 14 TeV should provide a final determination of whether it's realized

Backup

An aside: the Higgs mass

- This model set was generated *before* the Higgs discovery
- 20% of our models have the lighter CP-even Higgs weighing 126 ± 3 GeV (1206.5800)
- Generally, an MSSM Higgs this heavy requires either heavy stops or large stop mixing
- The LHC results for the subset of our models with a Higgs near 126 GeV are very similar to those for the full model set (1211.1981)

LHC searches



Overall LHC search efficiency nearly completely independent of Higgs mass!

Naturalness in the pMSSM

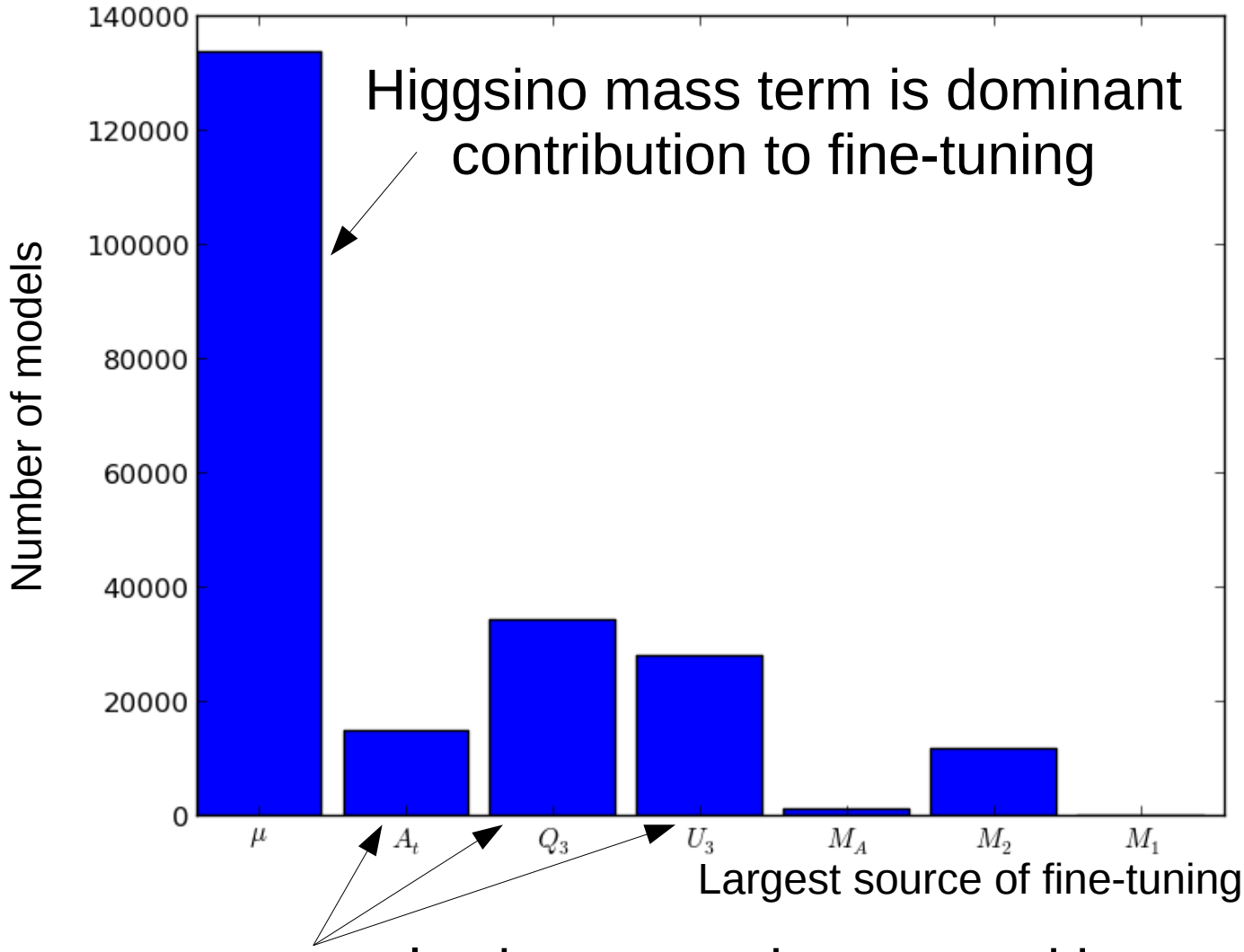
- Measure sensitivity of electroweak symmetry breaking scale to each pMSSM parameter p_i

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

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

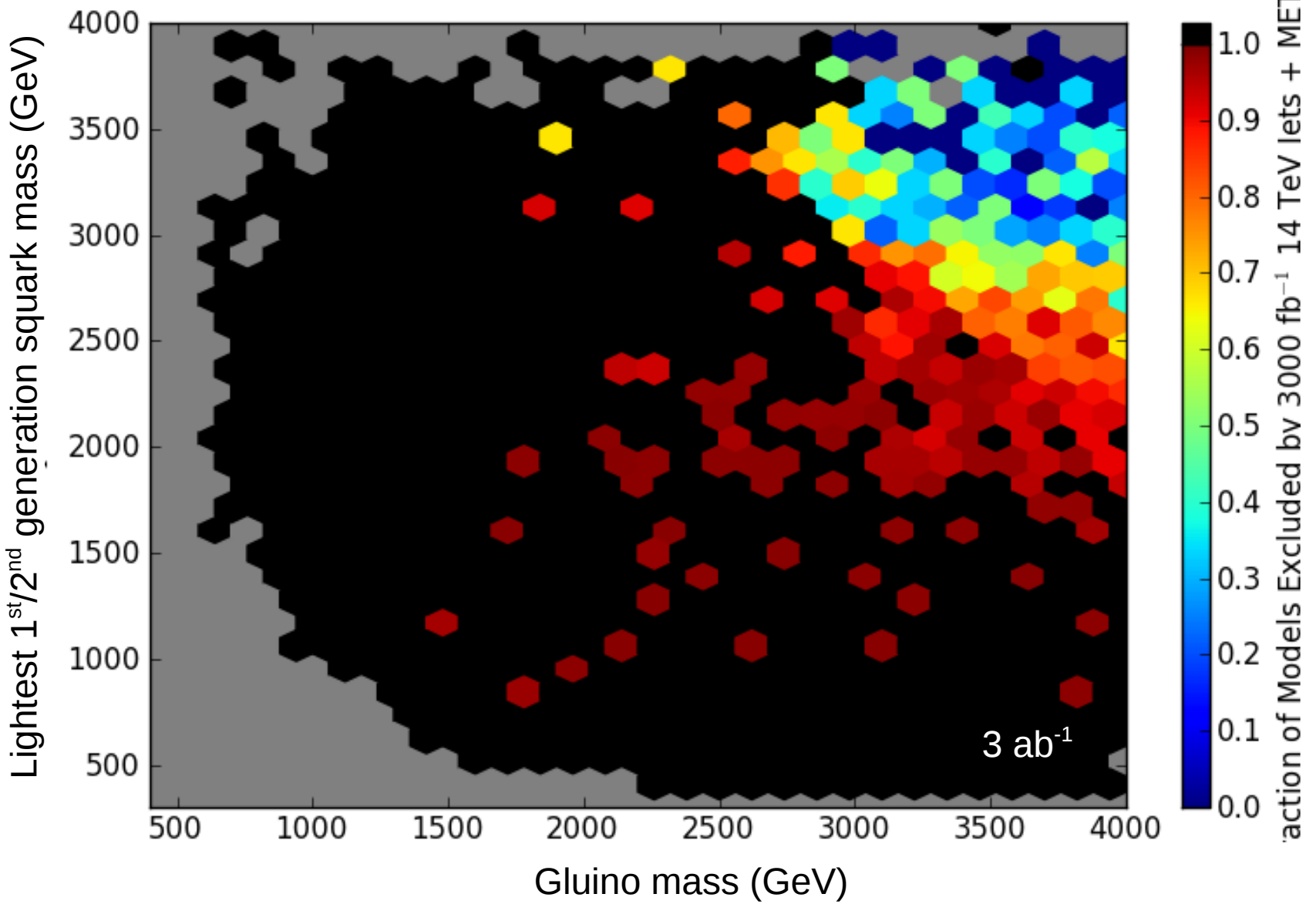
- $\Delta = \max(\partial(\log M_z^2) \,/\, \partial(\log p_i)),\ 1 \le i \le 19$
- Lower Δ = less tuned since the EW scale is insensitive to small changes in the parameters
- Most sensitive to μ and stop mass parameters, but gluino mass enters at two loops

Sources of fine-tuning



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

Neutralino LSP – 14 TeV jets + MET



Many models surviving due to leptons are probed by stop searches