The LHC confronts the pMSSM

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1206.4321, 1211.1981, 1307.8444, To Appear

The p(henomenological) MSSM

- 19/20 parameter subspace of the MSSM (Neutralino/Gravitino LSP).
- Created by applying experimentally-motivated assumptions to the full MSSM lagrangian.
- “Unprejudiced” by assumptions about physics at high scales.

Our Methodology

General MSSM Lagrangian +

Minimal Flavor Violation
No new CP phases
Flavor-Diagonal Sparticle Mass Matrices
1st and 2nd generations degenerate
R-parity Conservation

= **19/20 weak scale parameters**

$(M_1, M_2, M_3, \mu, \tan\beta, M_A, q_{1,3}, u_{1,3}, d_{1,3}, l_{1,3}, e_{1,3}, A_{t,b,\tau} + \boldsymbol{m_{3/2}})$

- Randomly sample the 19/20-dimensional parameter space.
- Discard points excluded by non-LHC constraints (precision EW, heavy flavor, LEP limits, Direct Detection, $\Omega_{LSP} \leq \Omega_{DM}$)
- Examine the LHC's ability to discover or exclude viable points.

Model Set Generation

Scan Ranges:

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

$100\ \text{GeV} \leq |M_2, \mu| \leq 4\ \text{TeV}$

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

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

$100\ \text{GeV} \leq M_A, l, e \leq 4\ \text{TeV}$

$400\ \text{GeV} \leq q_1, u_1, d_1 \leq 4\ \text{TeV}$

$200\ \text{GeV} \leq q_3, u_3, d_3 \leq 4\ \text{TeV}$

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

$1\ \text{eV} \leq m_{3/2} \leq 1\ \text{TeV}$ (log prior)

Calculations:

- Generate spectra with SOFTSUSY, cross-check with SuSpect.
- Calculate sparticle decays with modified SUSY-HIT, supplemented with CalcHEP and MadGraph (multi-body decays).
- Calculate thermal relic density of LSP (if LSP is a neutralino) or NLSP (if LSP is a gravitino) with micrOMEGAs.
- **Two model sets**, divided by LSP type:
  - **~2.2×10^5** points with a neutralino LSP (**45k** models have $m_h = 126 \pm 3$ GeV).
  - **~2.3×10^5** points with a gravitino LSP (**21k** models have $m_h = 126 \pm 3$ GeV).

Simulating the LHC Searches

- For each point, we generate events with PYTHIA, scale to NLO with Prospino, and pass through PGS for detector simulation.
- PYTHIA and PGS modified extensively to deal with long-lived sparticles:
  - Added object beta and production location to PGS output
  - Included hadronization for metastable squarks/gluinos
  - Altered momentum resolution and MET calculation to treat HSCPs correctly
- Analysis code applies the published cuts and compares the results for each channel with limits calculated using the CLs procedure.
- Analysis code validated for each search region by comparing with published benchmarks.
- 34 ATLAS + 3 CMS searches simulated! (MET-based, HSCP and Displaced Vertices)

A Gravitino LSP

- NLSP decays to gravitino with planck-suppressed width:

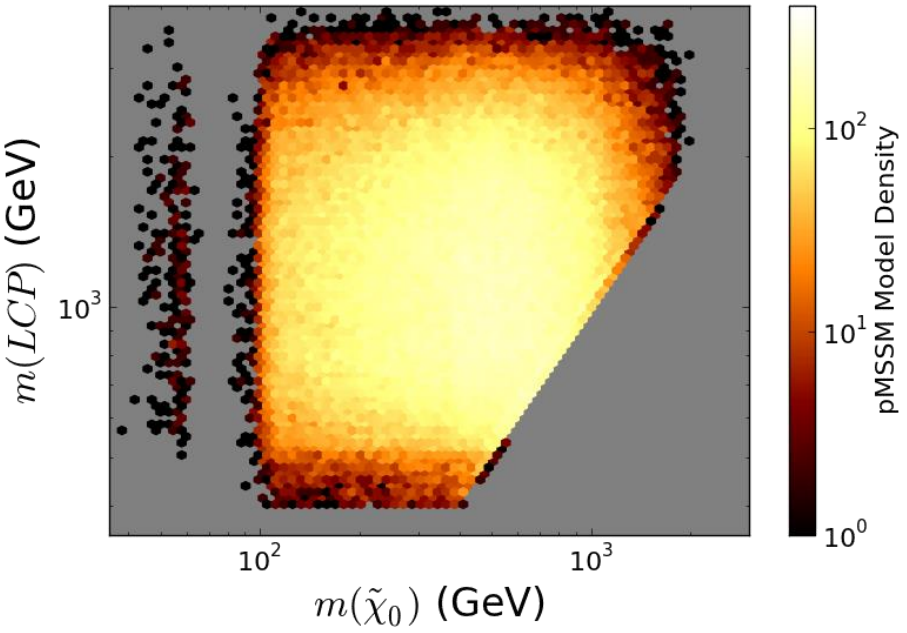
$$\Gamma_{NLSP} \approx \frac{1}{48\pi M_{planck}^2} \frac{m_{NLSP}^5}{m_{Gravitino}^2}$$

- Gravitino masses between 1 eV and 1 TeV give $c\tau_{NLSP}$ between 4×10^{-12} m and 8×10^{28} m.

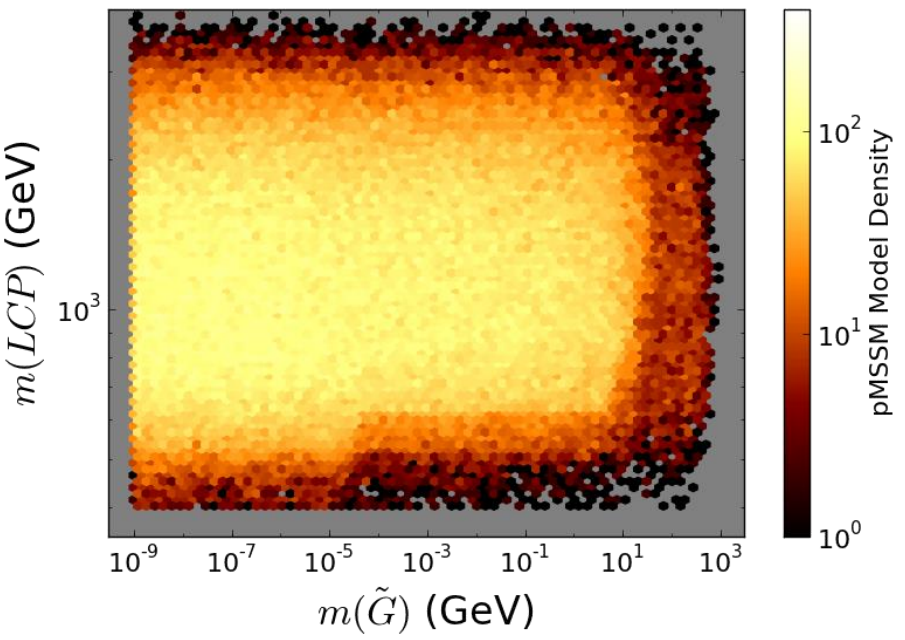
- NLSP is almost always produced in cascade decays.

Resulting Model Sets

Neutralino LSP
(223256 models)



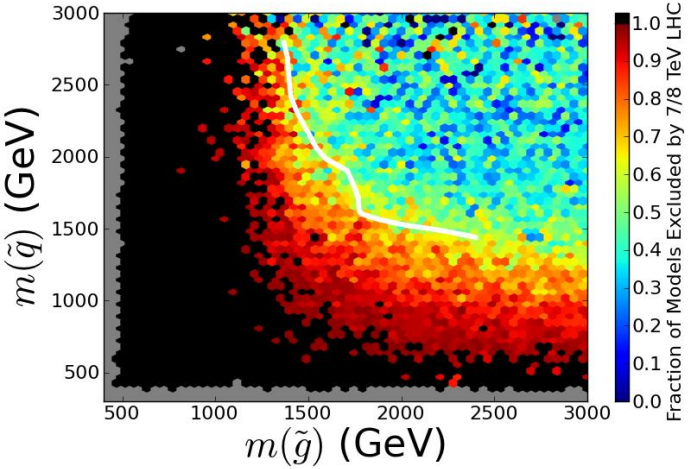
Gravitino LSP
(229303 models)



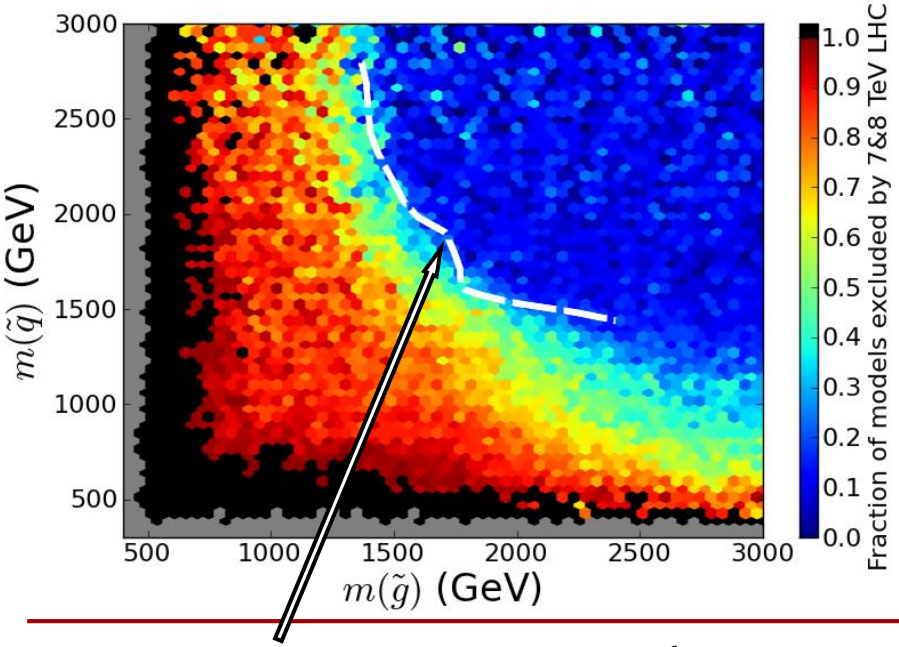
Colored Sparticle Exclusions

- Weakest limits on models with compressed spectra
- Invisible NLSPs are sneutrinos and detector-stable neutralinos
- Displaced NLSP decays can be rejected by quality cuts

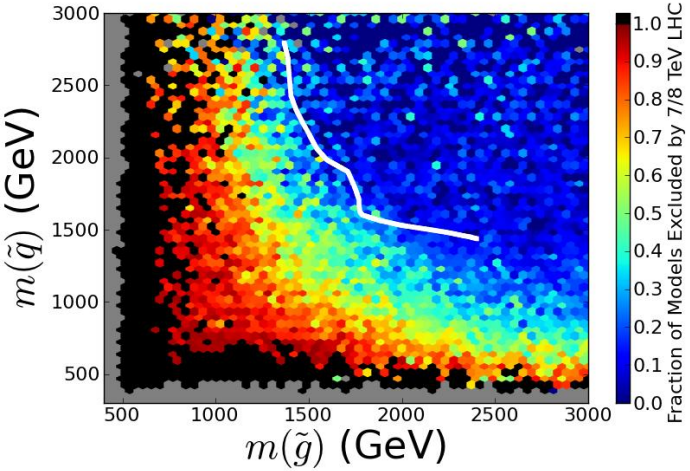
Gravitino LSP, Visible NLSP



Neutralino LSP



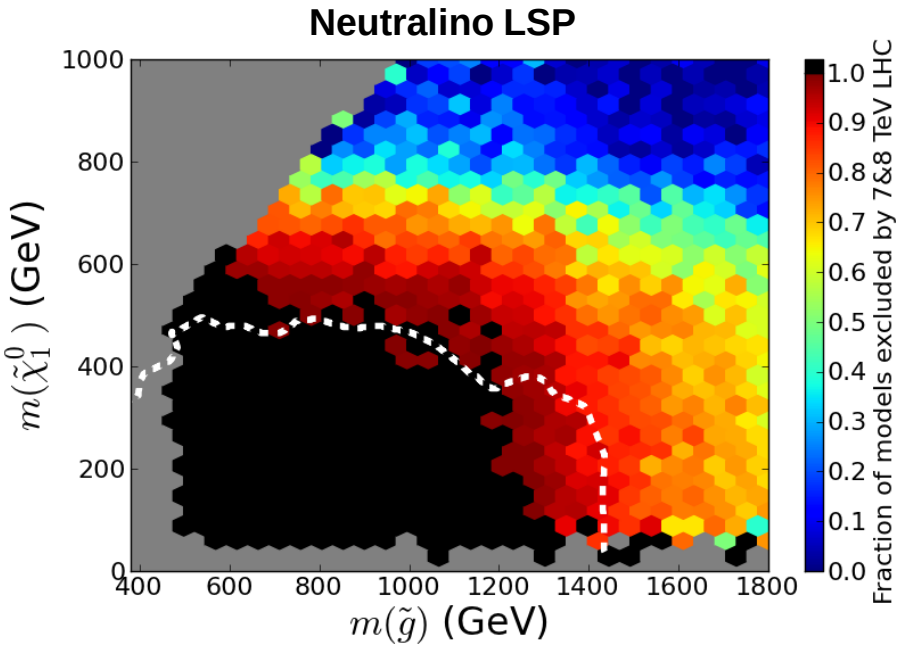
Gravitino LSP, Invisible NLSP

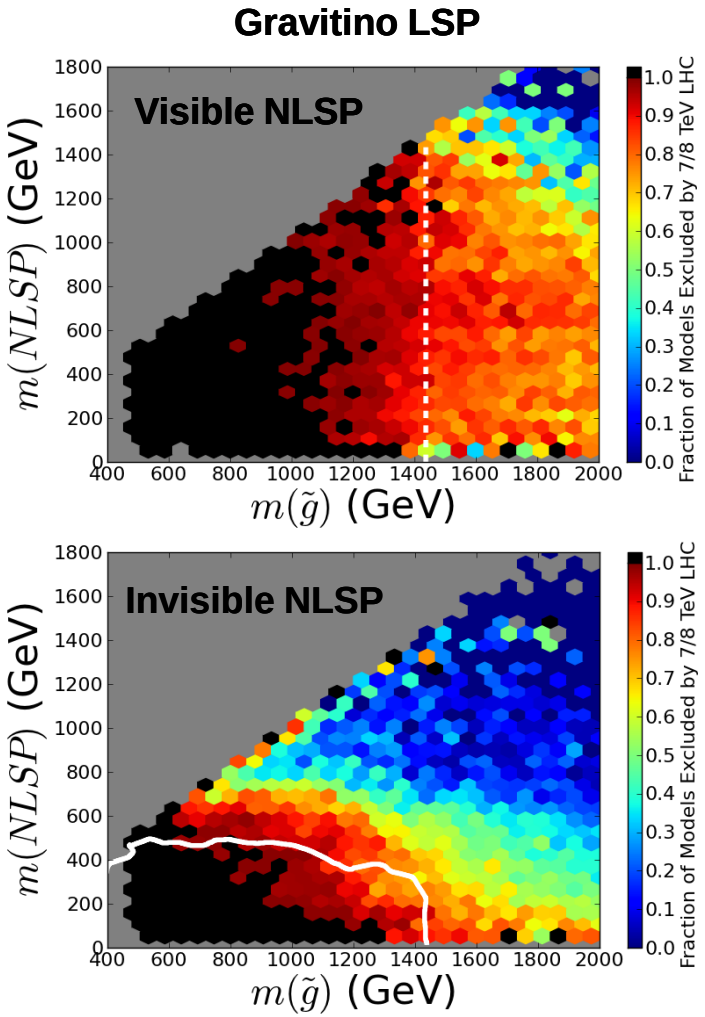


Simplified limit from 8 TeV 20 fb^{-1} Jets+MET
(Assumes degenerate squarks and massless LSP)

Sparticle Exclusions: Gluino

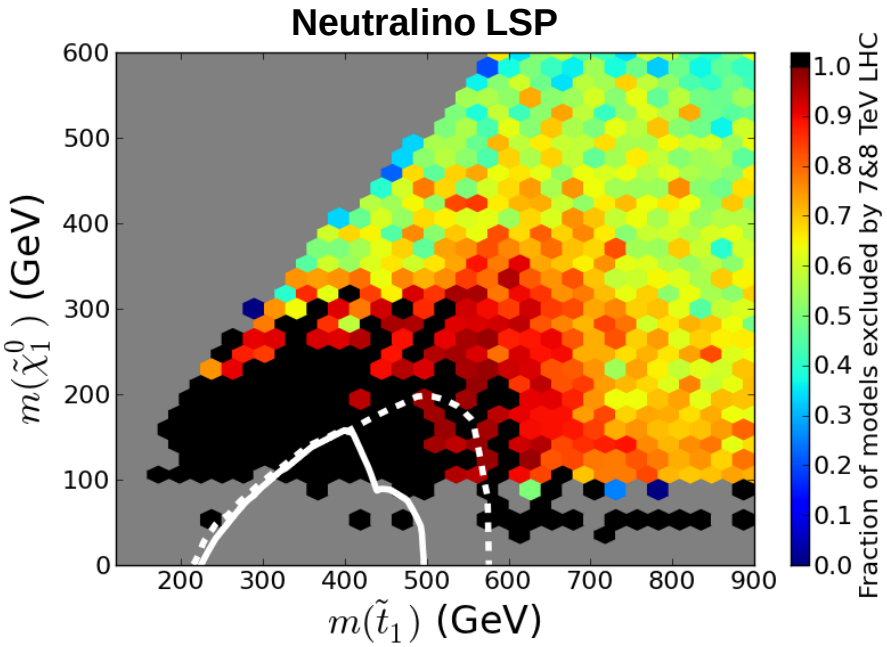
- Simplified model ≈ excluded region for Neutralino LSP
- Sneutrino and stau NLSPs account for most of surviving gravitino LSP models with light gluinos

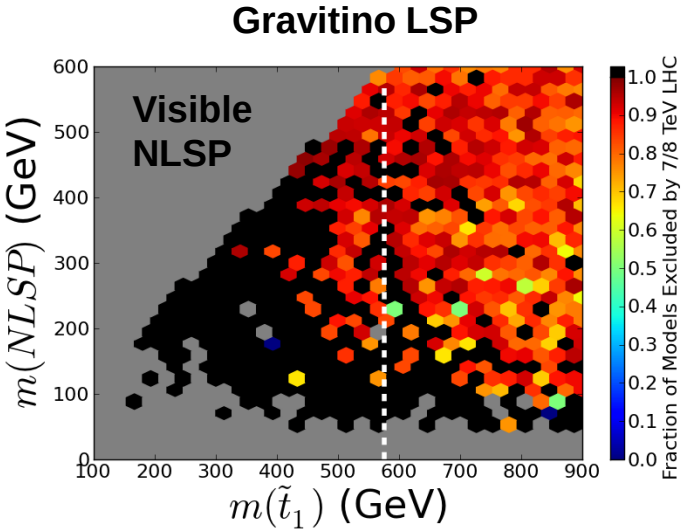


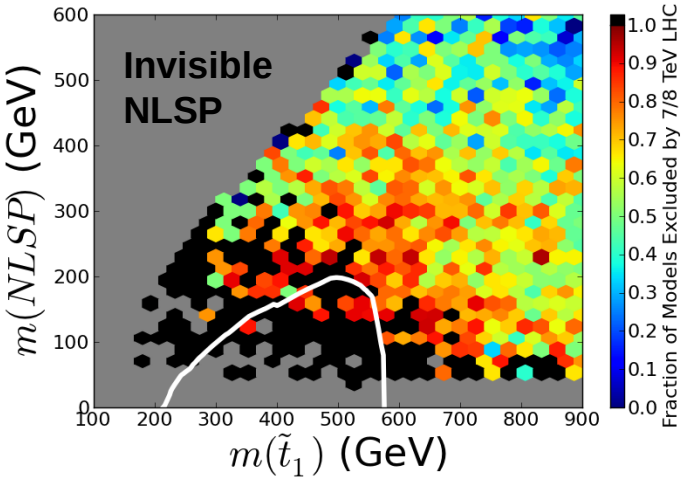


Sparticle Exclusions: Stop

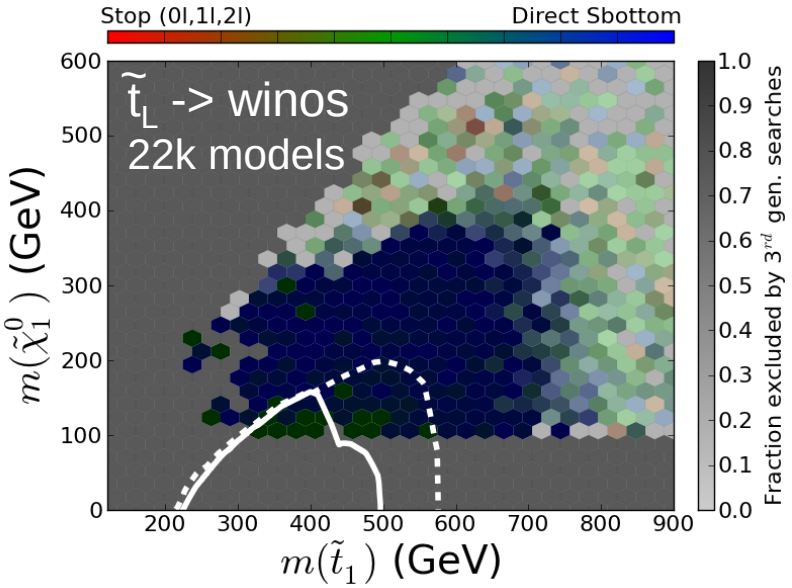
- Simplified model ≠ pMSSM exclusion!
- Stau, sneutrino NLSPs once again most weakly constrained for $\tilde{G}$ LSP

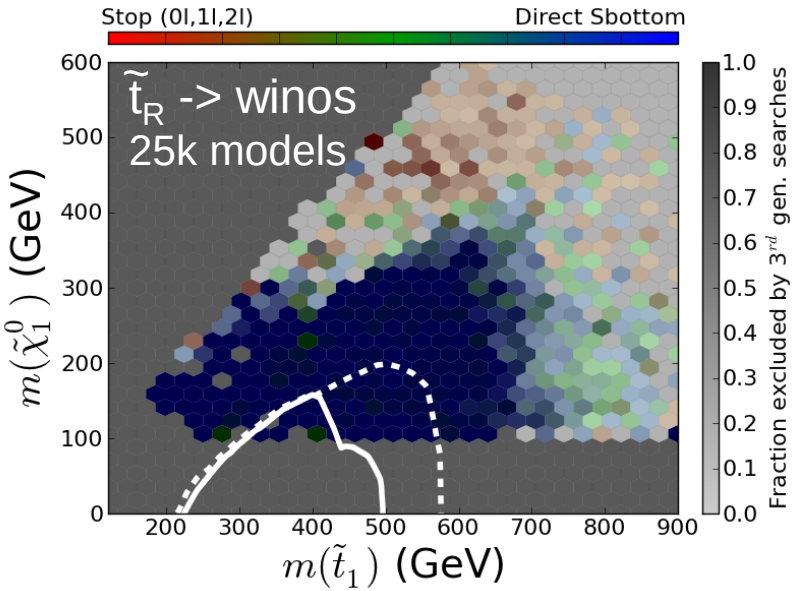


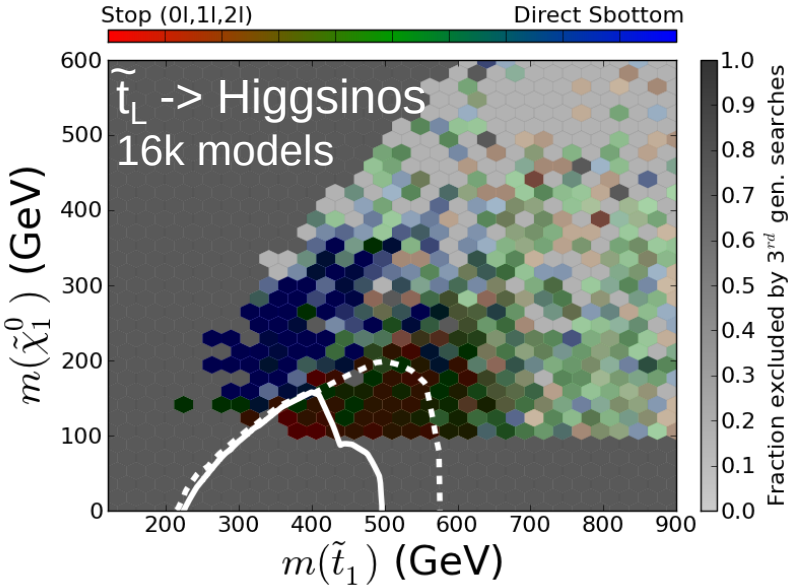


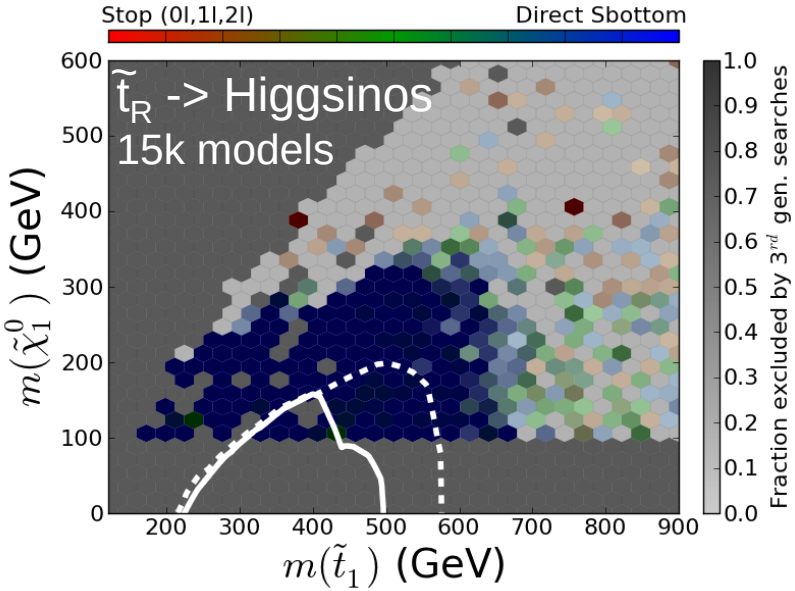


More about Stops (Neutralino LSP)



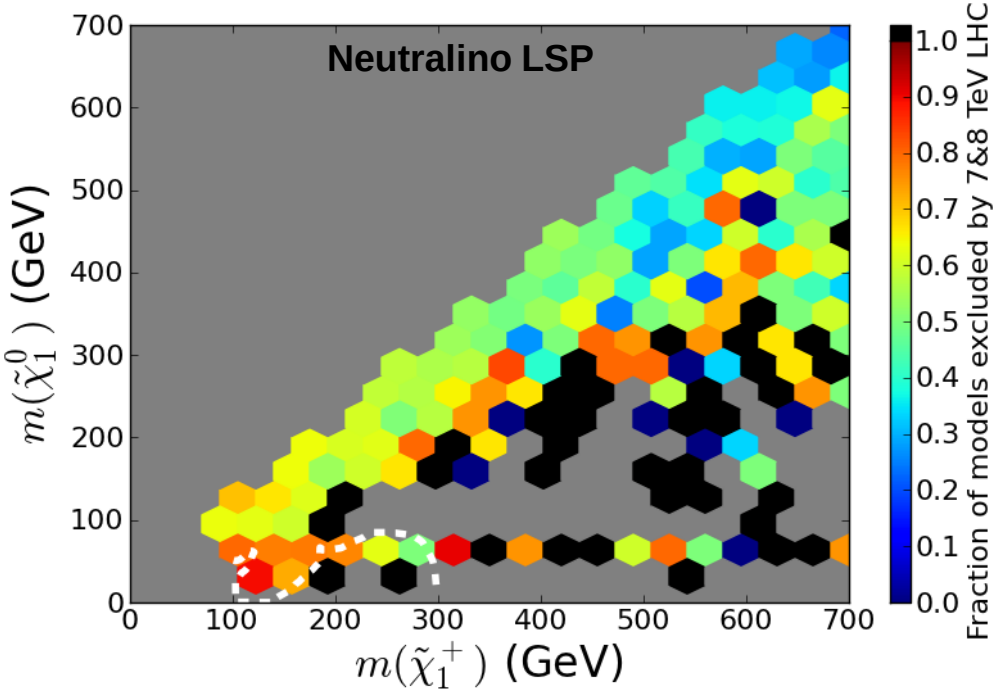


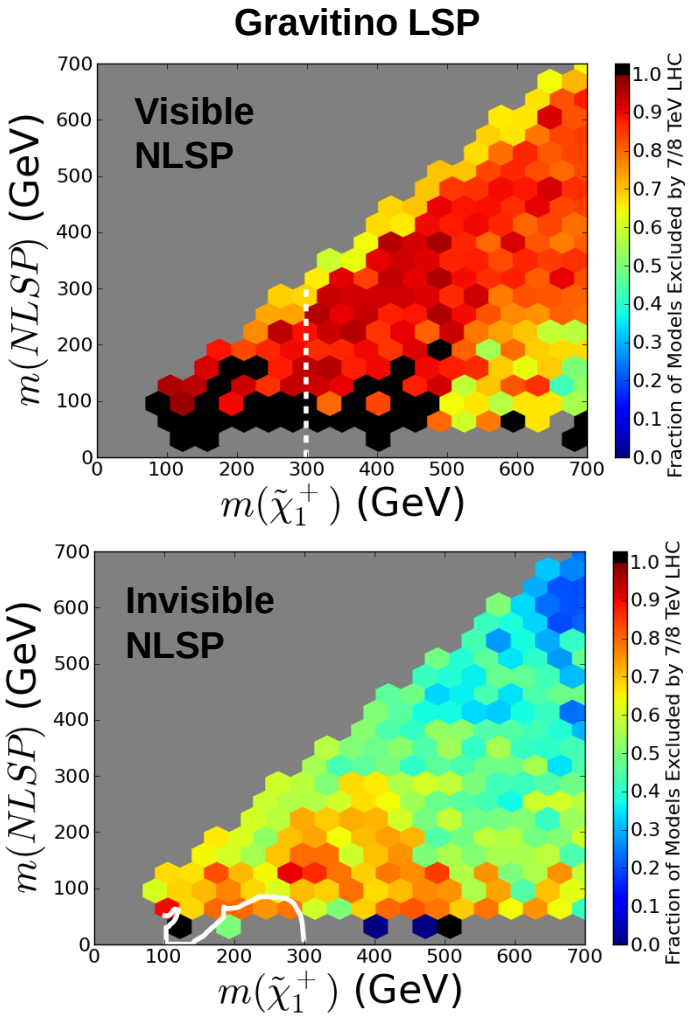




Sparticle Exclusions: Chargino

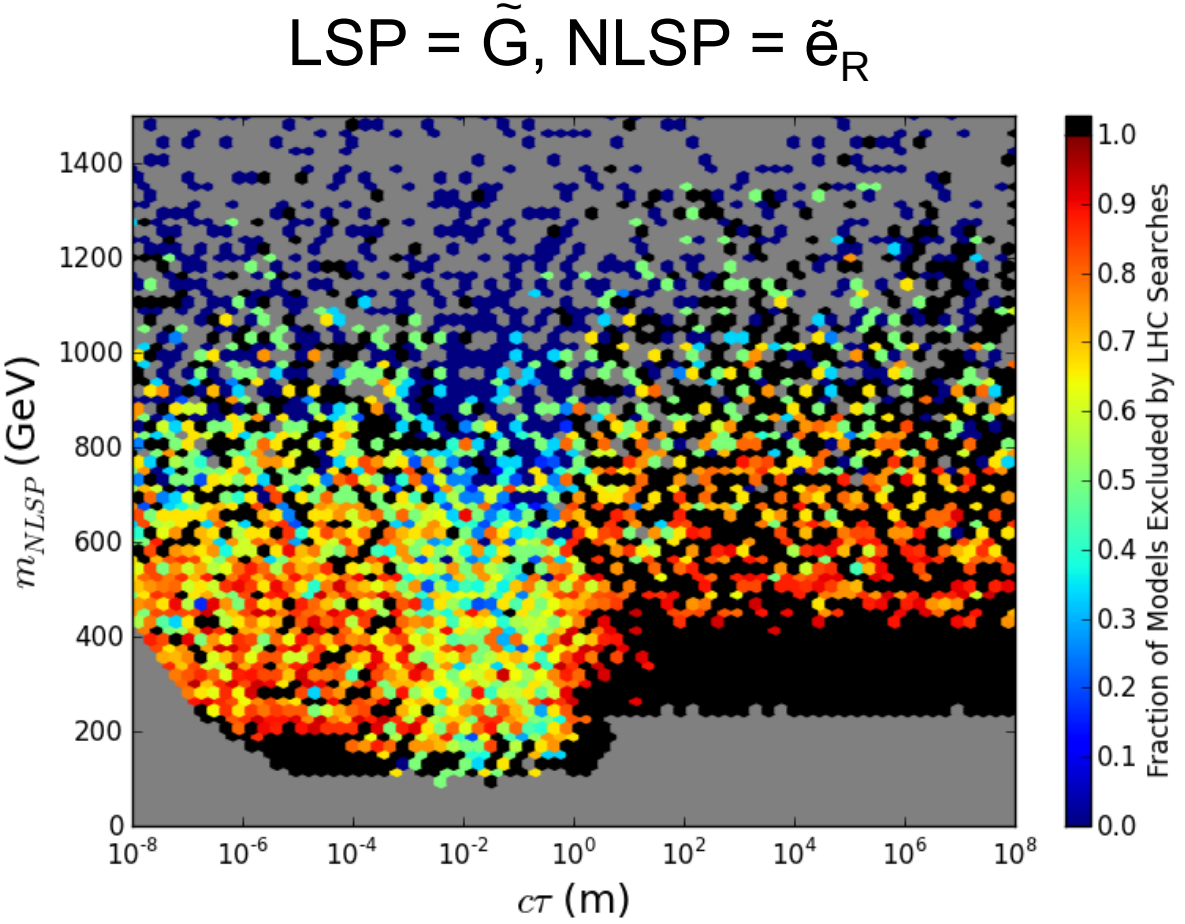
- Small exclusion reach for models without light sleptons.
- Key target for searches at 14 TeV!





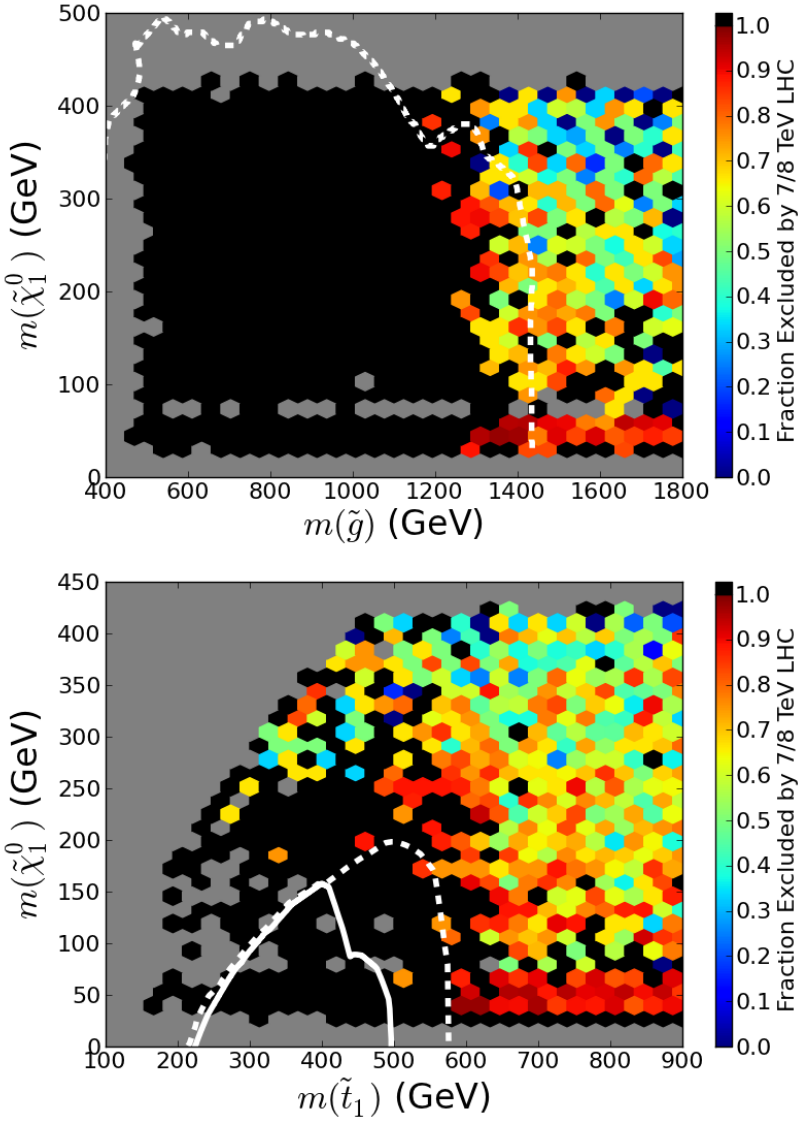
Displaced Decays

- If NLSP is metastable, nearly all events contain displaced objects!
- Displaced leptons/jets typically removed/rejected by quality cuts.
- Some displaced decays can be targeted by exotics searches, but coverage remains incomplete.



Low Fine-Tuning

- Generated smaller model set (~10k models) with FT < 100 (Barbieri-Giudice) + $\Omega_{LSP} = \Omega_{DM.}$
- Characteristics:
  - Stop below ~1.7 TeV
  - Higgsino mass below 450 GeV
  - Bino-like LSP (to saturate relic density)
- Simulated 14 TeV Jets+MET and Stop searches exclude **all** of these models!



Summary

- The pMSSM is a powerful tool for analyzing the performance of the LHC, and looking for particularly challenging regions.
- LHC searches have robust sensitivity to models with neutralino and gravitino LSPs.
- Weakest sensitivity to compressed spectra and gravitino LSP models with slepton/sneutrino NLSPs and/or displaced NLSP decays.
- LHC Run II will be a powerful test of natural SUSY!

Backup Slides

Model Set Generation (Constraints)

- Precision EW constraints: g – 2, invisible width of Z, $\Delta\rho$
- Flavor constraints: $b \rightarrow s\gamma$, $B_s \rightarrow \mu\mu$, $B \rightarrow \tau\nu$
- Require all charged sparticles > 100 GeV
- Impose LHC stable particle, $\Phi \rightarrow \tau\tau$ constraints
- $m_h \approx 126$ GeV **not** required during model generation (SUSY searches generally independent of Higgs mass)
- Cosmology: LSP-dependent
  - Neutralino: Check direct detection constraints, impose WMAP as **upper bound** on thermal relic density
  - Gravitino: No direct detection limits, No limit on thermal relic density. Upper bound on nonthermal relic density (from NLSP decay) and limits from BBN

Standard (MET-based) SUSY searches

7 TeV searches

Search	Reference
2-6 jets	ATLAS-CONF-2012-033
multijets	ATLAS-CONF-2012-037
1 lepton	ATLAS-CONF-2012-041
3rd Gen. Squarks (3b)	1207.4686
Very Light Stop	ATLAS-CONF-2012-059
Medium Stop	ATLAS-CONF-2012-071
Heavy Stop (0ℓ)	1208.1447
Heavy Stop (1ℓ)	1208.2590
GMSB Direct Stop	1204.6736
Direct Sbottom	ATLAS-CONF-2012-106
3 leptons	ATLAS-CONF-2012-108
1-2 leptons	1208.4688
Slepton/gaugino (2ℓ)	1208.2884
Gaugino (3ℓ)	1208.3144
4 leptons	1210.4457
1 lepton + many jets	ATLAS-CONF-2012-140
1 lepton + γ	ATLAS-CONF-2012-144
γ + b	1211.1167
$\gamma\gamma$ + MET	1209.0753

8 TeV searches

Search	Reference
2-6 jets	ATLAS-CONF-2012-109
multijets	ATLAS-CONF-2012-103
1 lepton	ATLAS-CONF-2012-104
SS dileptons	ATLAS-CONF-2012-105
2-6 jets	ATLAS-CONF-2013-047
Medium Stop (2ℓ)	ATLAS-CONF-2012-167
Med./Heavy Stop (1ℓ)	ATLAS-CONF-2012-166
Direct Sbottom (2b)	ATLAS-CONF-2012-165
3rd Gen. Squarks (3b)	ATLAS-CONF-2012-145
3rd Gen. Squarks (3ℓ)	ATLAS-CONF-2012-151
3 leptons	ATLAS-CONF-2012-154
4 leptons	ATLAS-CONF-2012-153
Z + jets + MET	ATLAS-CONF-2012-152

Total: 32 ATLAS searches

Standard (MET-based) SUSY searches

Displaced Searches

Search	% Excluded
Disappearing Tracks (CONF-2012-111)	4.55 %
Displaced μ+Jet (1210.7451)	2.75 %
Displaced Dilepton (CMS, 1211.2472)	3.75 %
Displaced Dijet (CMS-PAS-EXO-12-038)	12.02 %
Combination	**15.30 %**

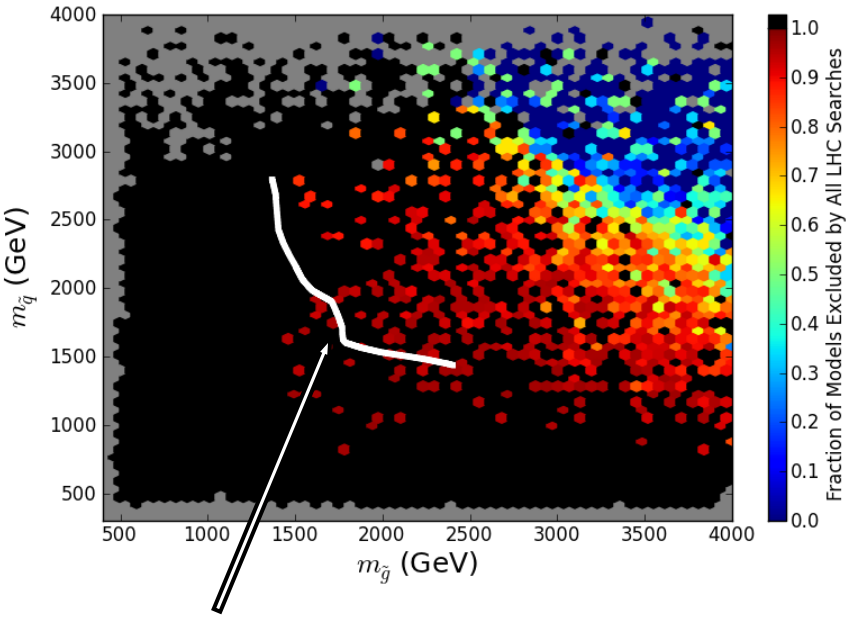
HSCP Searches

Search	% Excluded
7 TeV HSCP (CMS, 1205.0272)	**68.83 %**
8 TeV HSCP (CMS, 1305.0491)	**90.20 %**
Combination	**90.20 %**

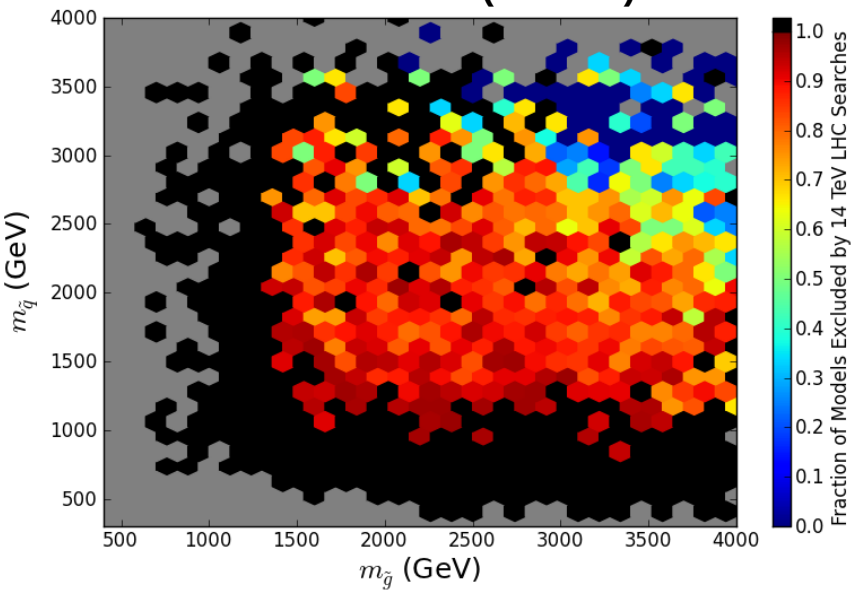
Colored Sparticle Exclusions (14 Tev)

- Simulated 14 TeV Jets+MET and stop searches (0-lepton and 1-lepton)
- Luminosity scaling to extrapolate limits between 300 fb-1 and 3 ab-1
- Only simulated models with correct Higgs mass due to CPU limitations

Neutralino LSP (300 fb^{-1})



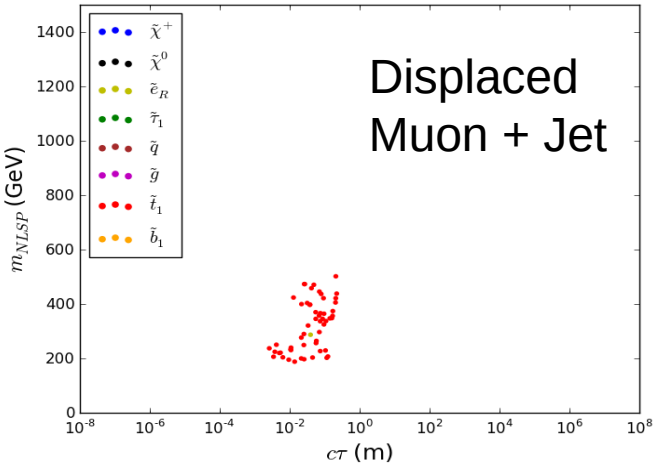
Gravitino LSP (300 fb^{-1})

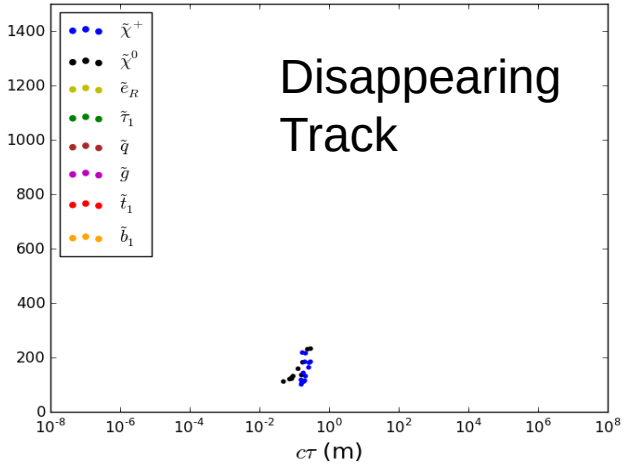


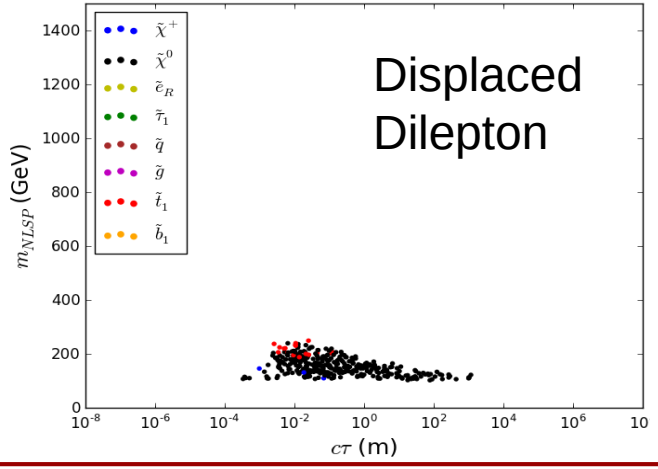
Simplified limit from 8 TeV 20 fb^{-1} Jets+MET
(Assumes degenerate squarks and massless LSP)

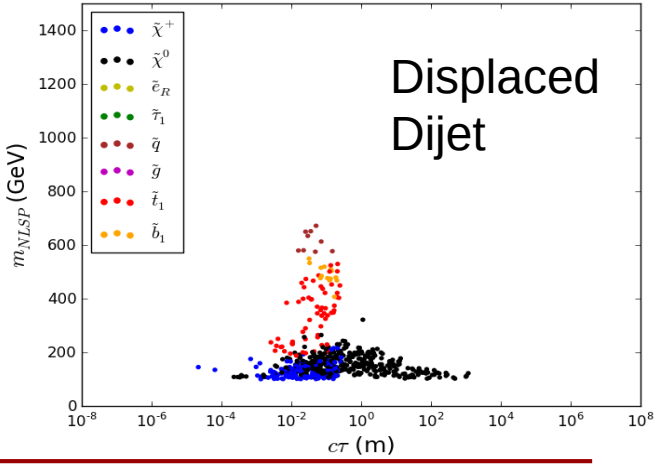
Displaced Object Searches

- Sensitive to NLSPs which produce multiple visible decay products (Neutralinos, Charginos, Stops)
- Dilepton and dijet searches require the displaced vertex and dijet/dilepton momentum to be collinear
- More careful simulation required to verify that the muon+jet search is sensitive to displaced stop decays



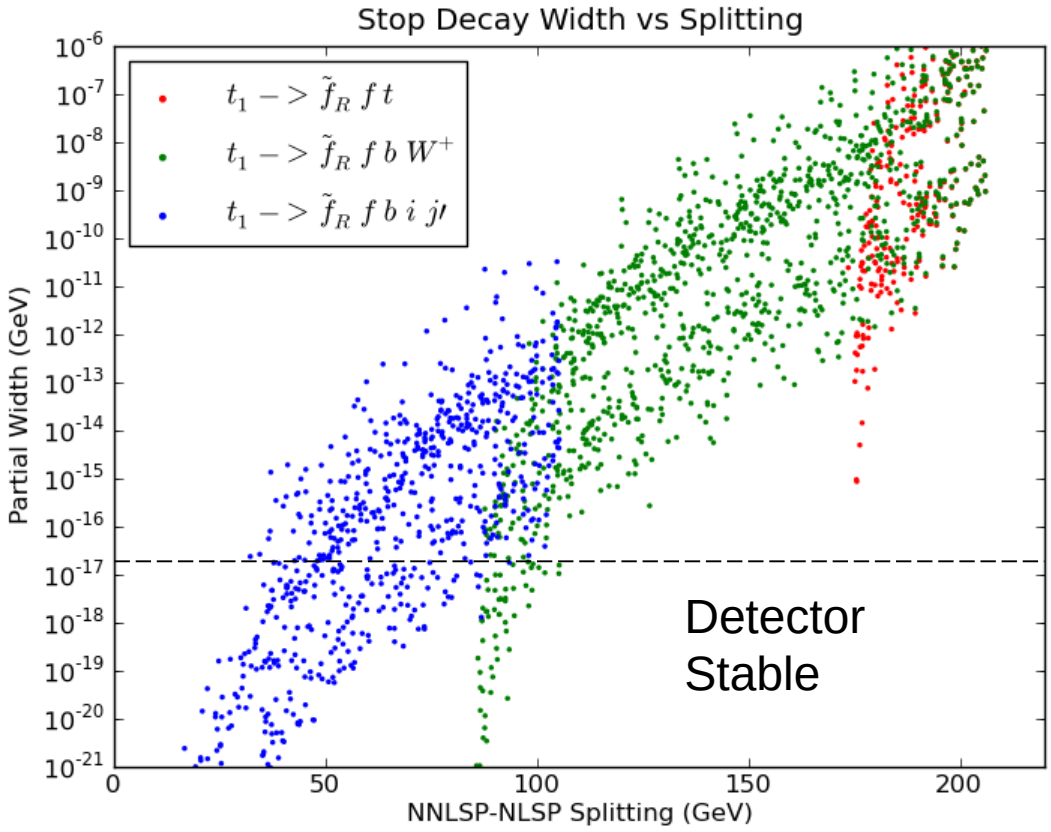






Multi-body Decays

- Direct decays to the gravitino are suppressed, so 3-, 4-, and even 5-body decays can be dominant (calculated in CalcHEP)
- Important for decays involving stops, charginos, or gluinos and right-handed sfermions



Gravitino Cosmology: Big Bang Nucleosynthesis

- Heavy gravitinos interact extremely weakly →

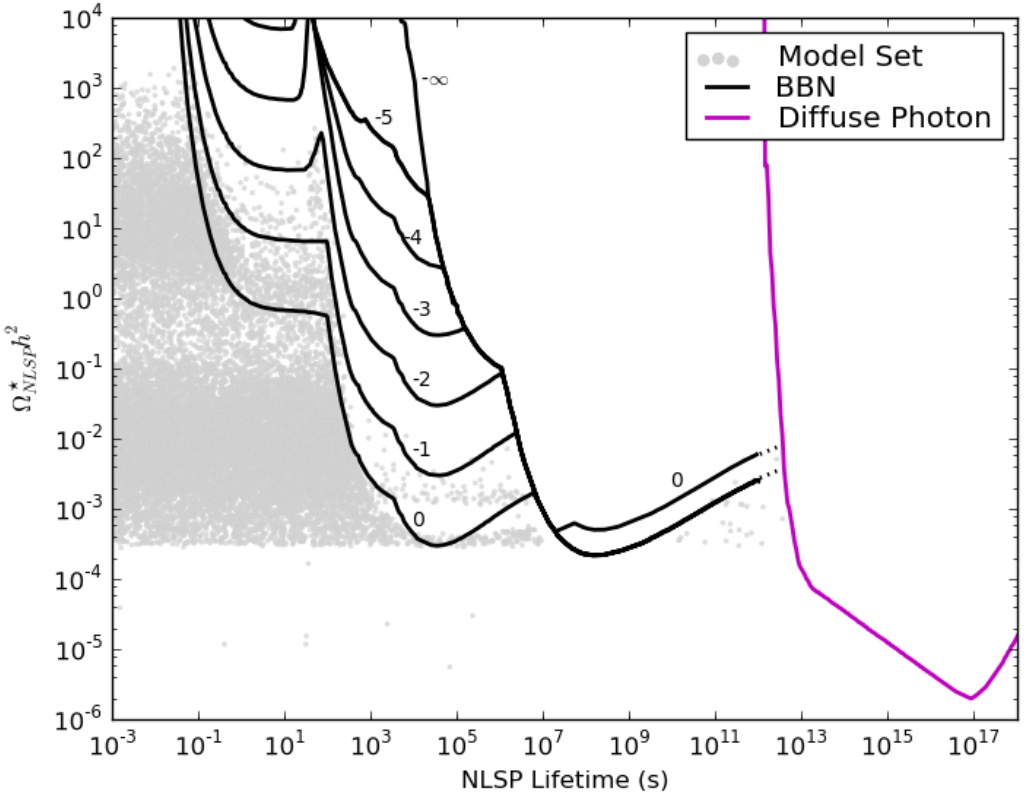
  NLSP can be very long-lived

- Decays after .01 s can affect BBN

- Constraints determined by decay product composition (hadronic, electromagnetic or invisible) and NLSP lifetime

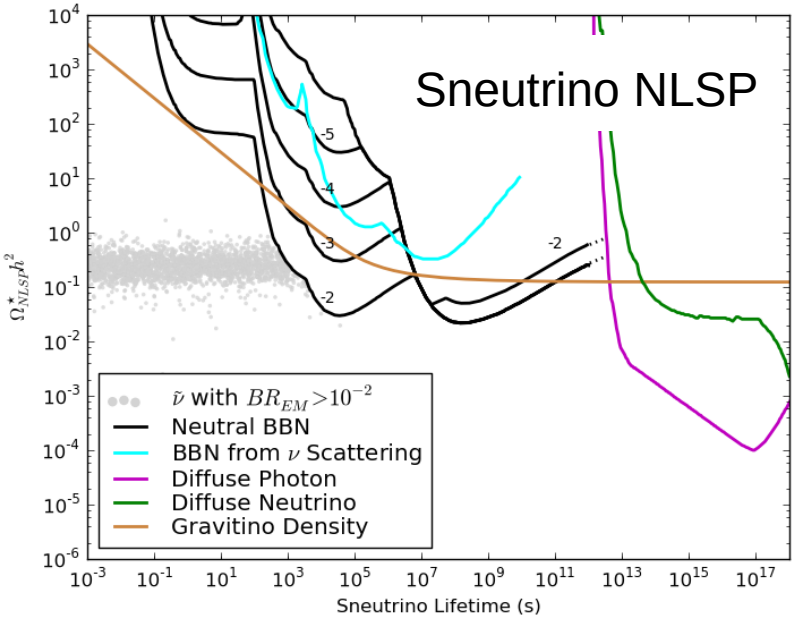
- Extremely long-lived particles can produce detectable photon or neutrino backgrounds

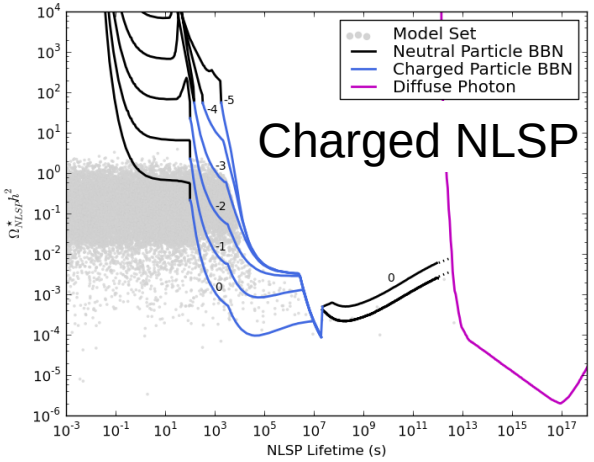
BBN Constraints on a neutralino NLSP

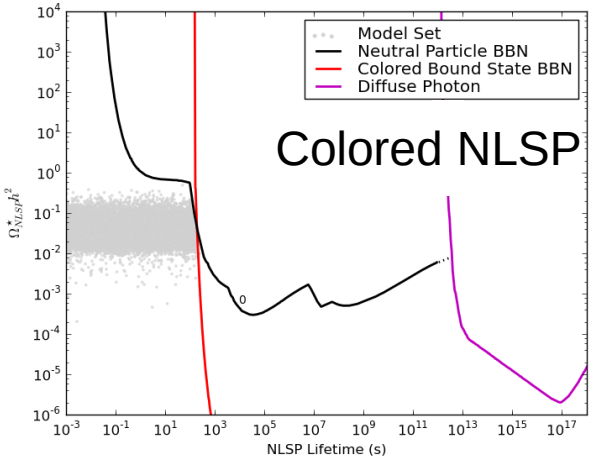


Gravitino Cosmology: Big Bang Nucleosynthesis

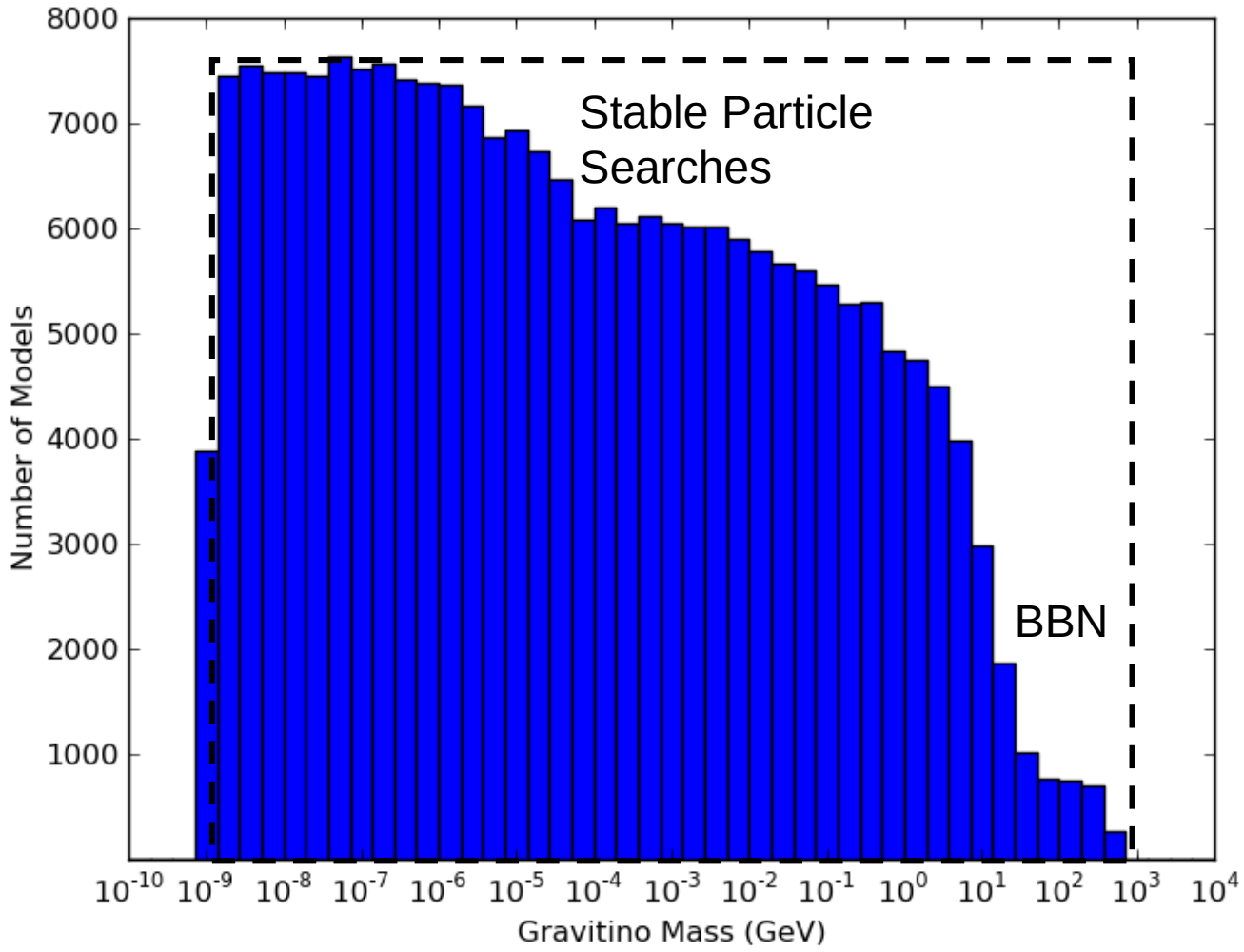
- Heavy charged/colored particles can catalyze reactions directly
- Neutrinos can scatter off thermal bath, producing pions and leptons which affect BBN



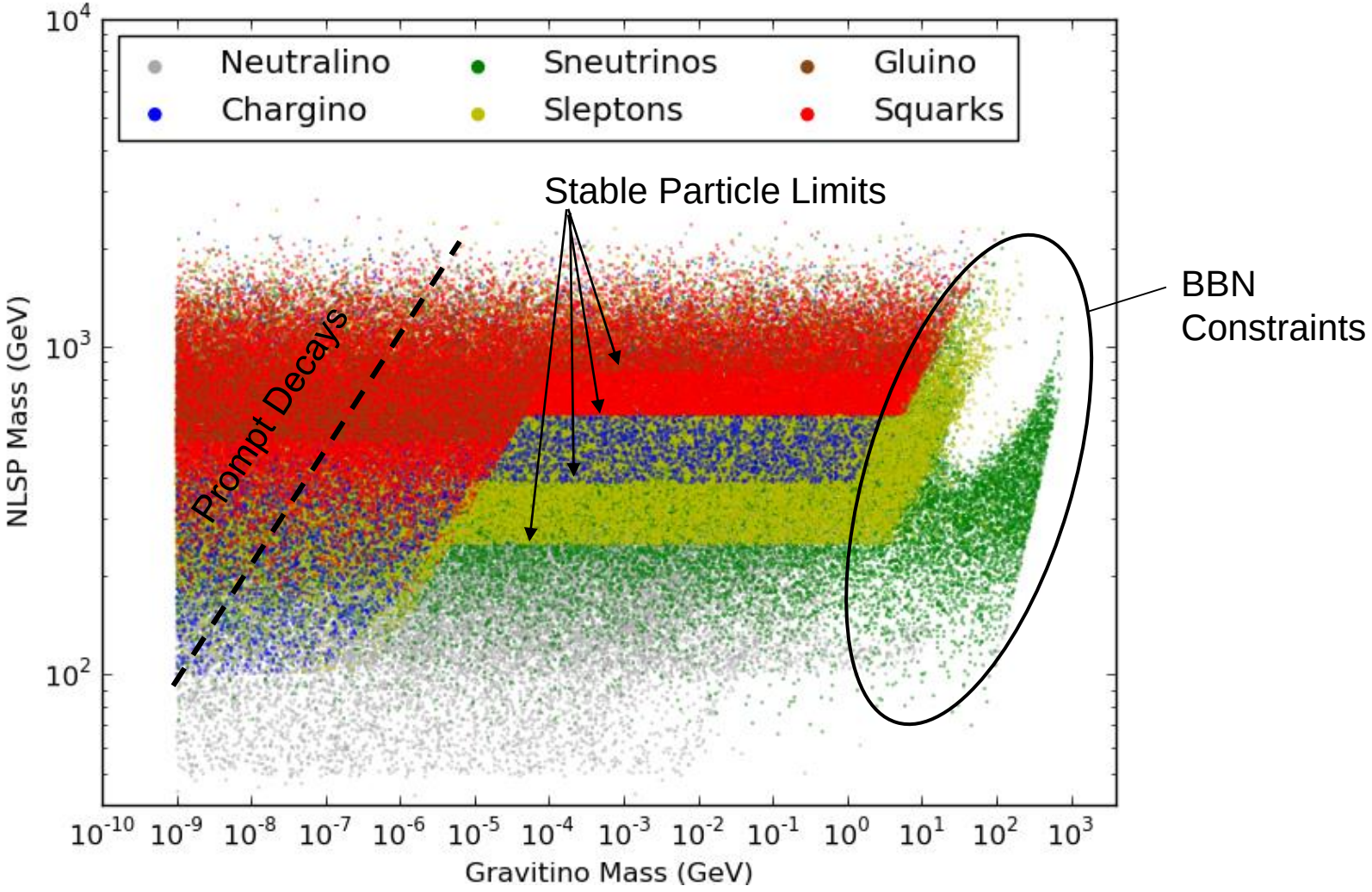




Gravitino Mass Histogram

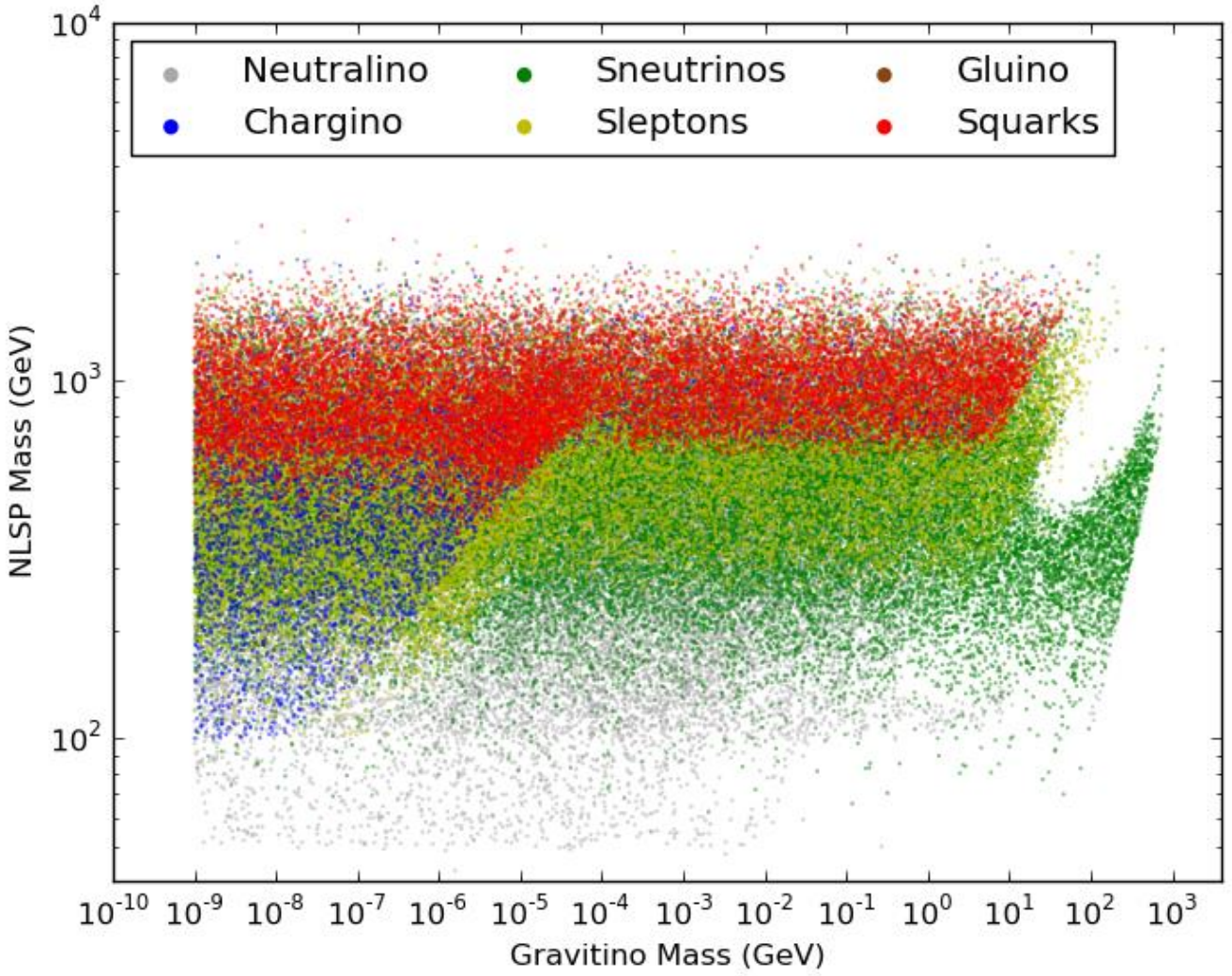


Resulting Model Set



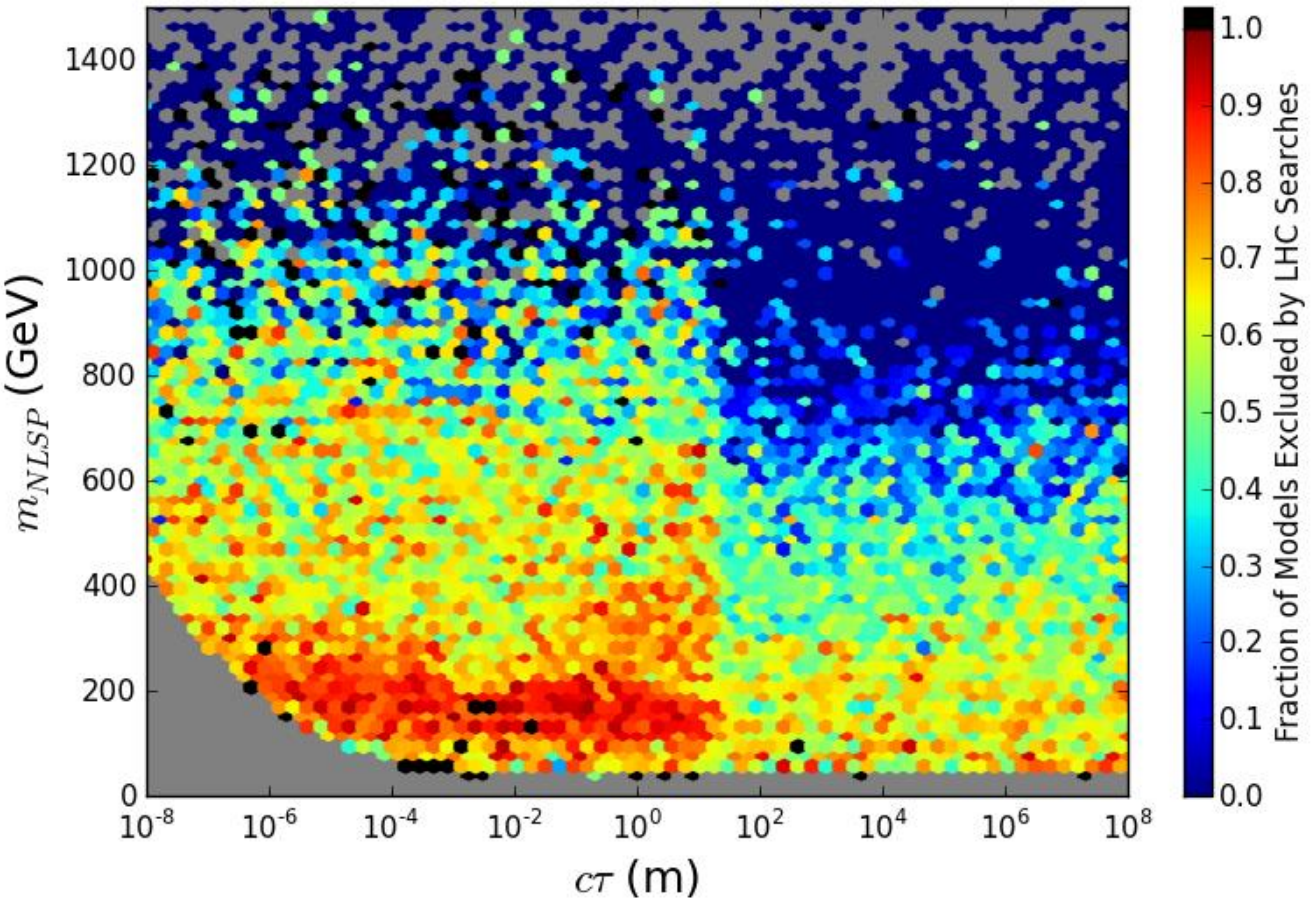
HSCP Searches

Models surviving LHC SUSY Searches



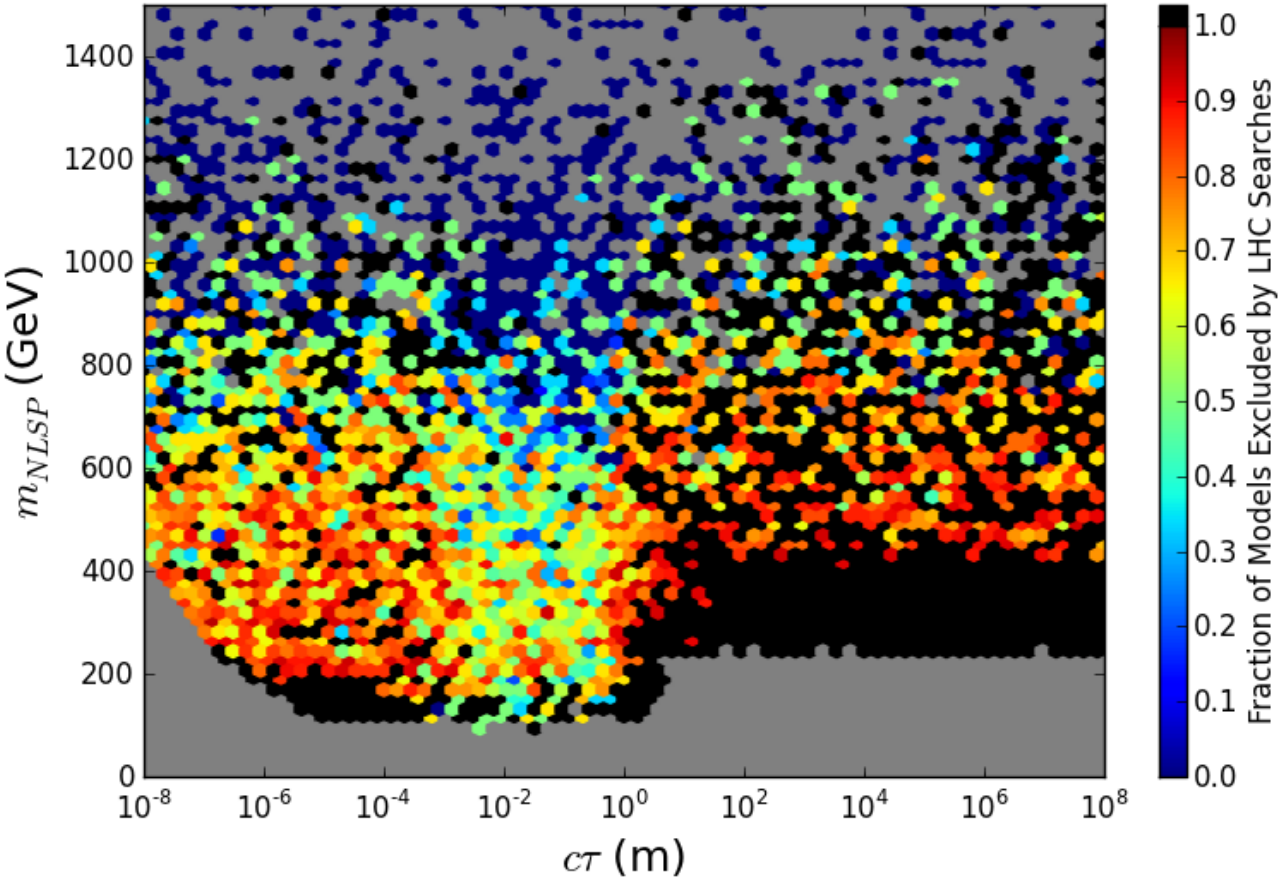
Neutralino NLSP

- Searches less effective for detector-stable neutralinos
- Minimal change (slight increase?) in exclusion fraction for neutralinos with macroscopic decay lengths



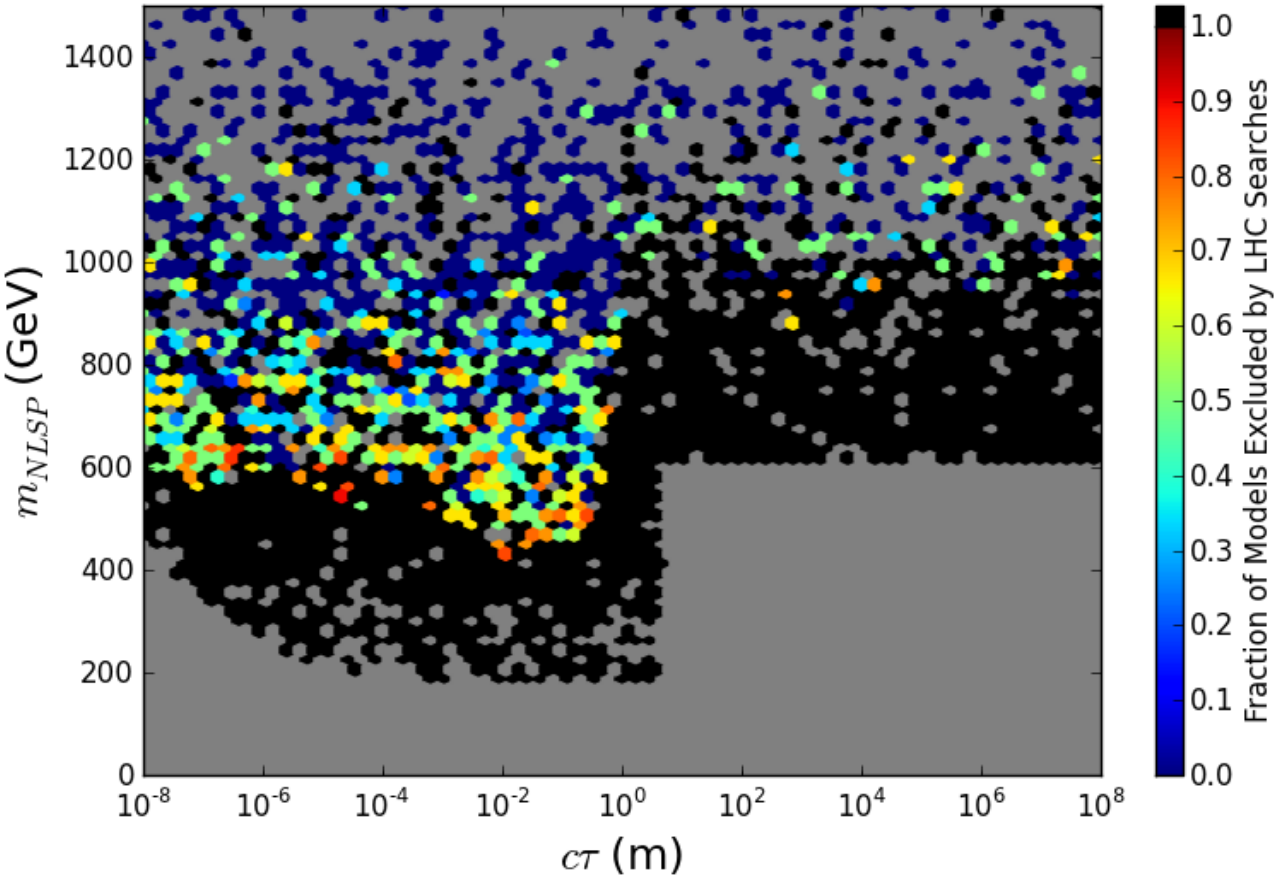
$\tilde{e}_R$ NLSP

- Strong limits on promptly decaying $\tilde{e}_R$ from multilepton searches
- Limits on direct production and cascade production degraded for macroscopic cτ
- Relatively weak limit on stable $\tilde{e}_R$ due to low production cross-section



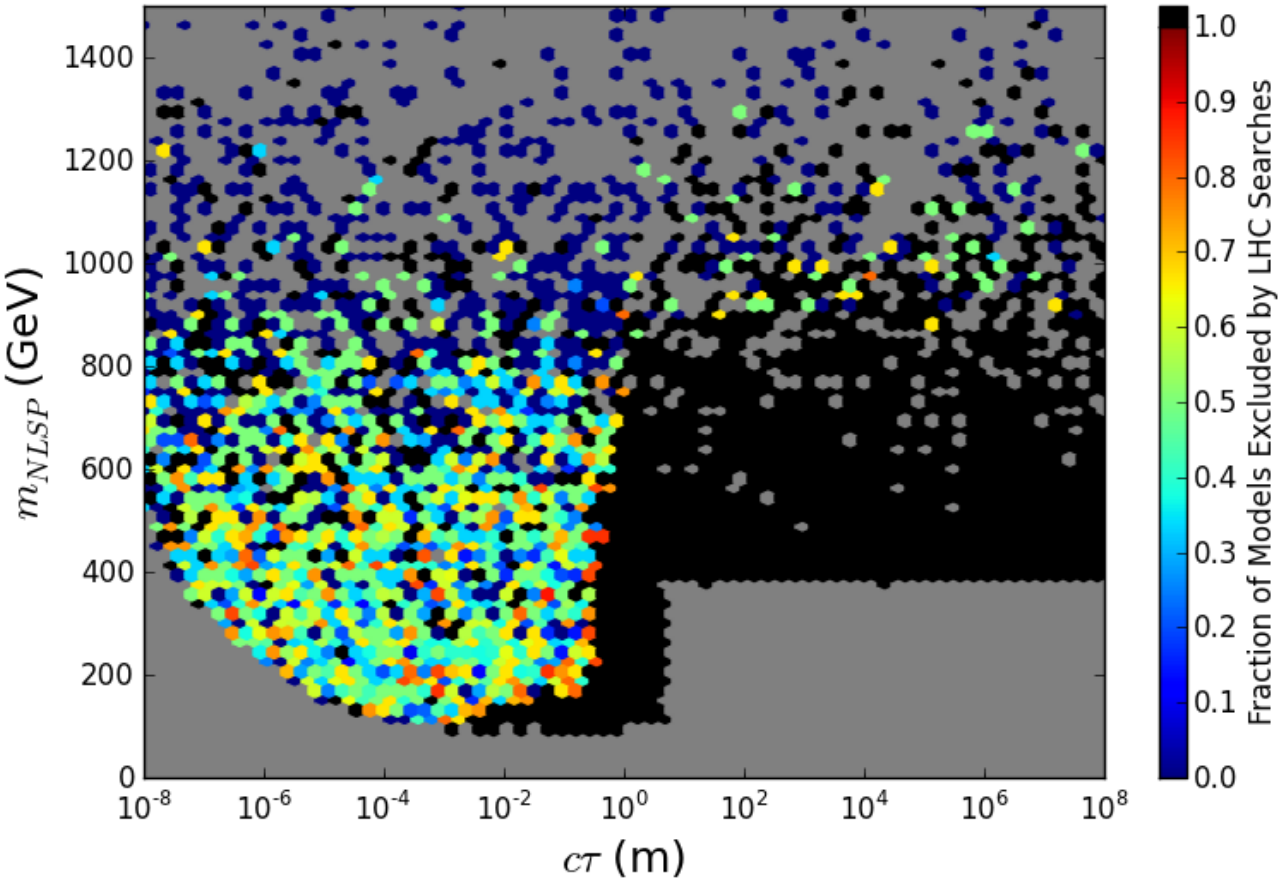
Stop NLSP

- Limit degraded for macroscopic stop decay lengths
- Muon+displaced vertex search provides important constraint on displaced stop decays
- Strong limit on stable stops (large production cross-section)



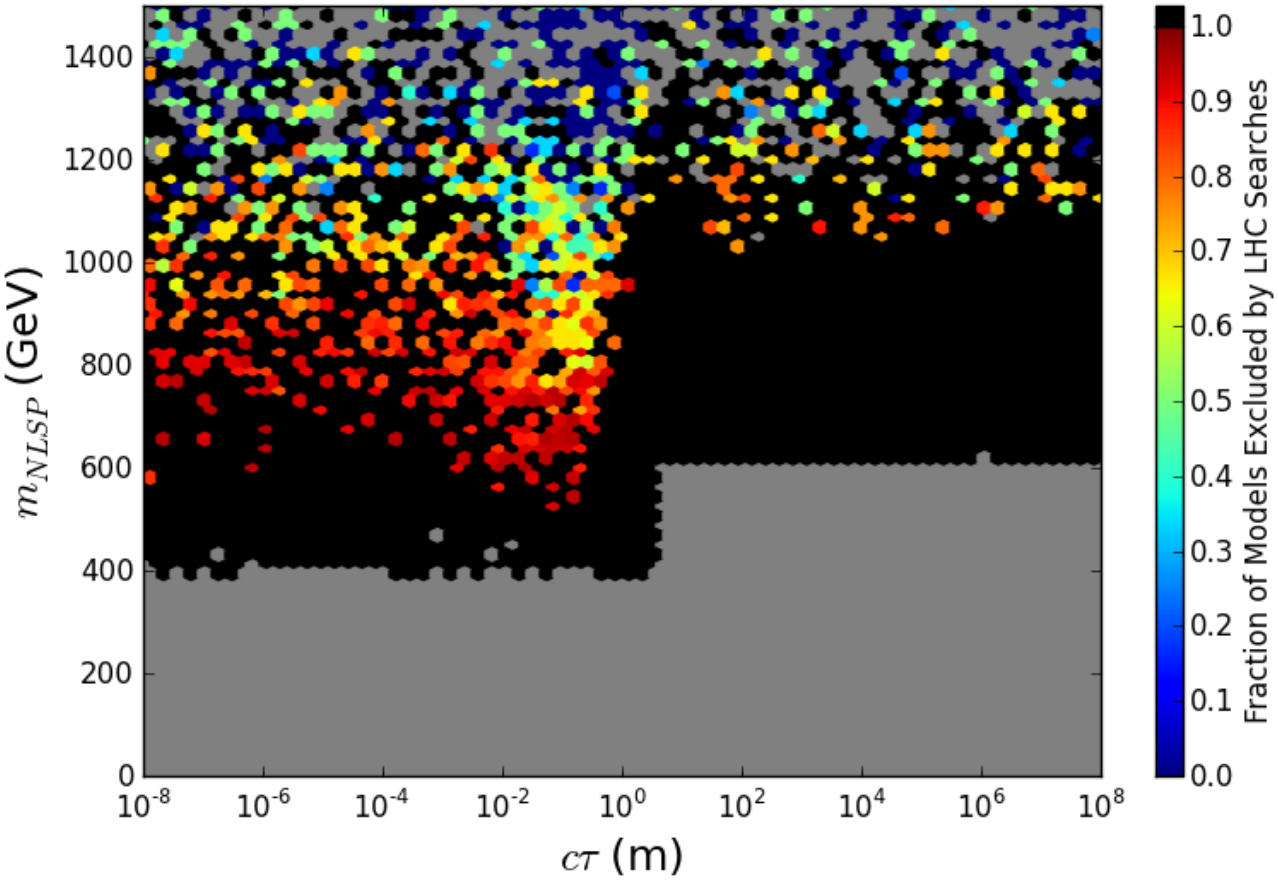
Chargino NLSP

- HSCP searches highly effective
- No direct limit on promptly decaying chargino NLSPs (WW+ MET has large backgrounds)



Squark/Gluino NLSP

- Limit degraded for macroscopic decay lengths (hardest jet frequently results from NLSP decay)
- Extremely strong limit on stable squarks/gluinos



Higgs Mass Histogram (Searches)

- SUSY searches are essentially independent of m_h
- Individual search exclusions also uncorrelated with m_h