Long-Lived Sparticles in the Gravitino pMSSM

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The p(henomenological) MSSM

- Subset of the MSSM described by 19/20 parameters (Neutralino/Gravitino LSP)

- Created by applying experimentally-motivated assumptions to the full MSSM lagrangian

- "Unprejudiced" by assumptions about physics at high scales.

A Gravitino LSP

- New pMSSM region (previously only considered neutralino LSPs)

- Huge range of gravitino masses to consider (1 eV < $m_{3/2}$ < 1 TeV)

- Gravitino LSP has Planck-suppressed couplings, so the NLSP has a small width:

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

- NLSP can have prompt or displaced decays, or can be detector-stable.

- NLSP is almost always the endpoint of cascade decays

- In this talk, mostly consider NLSPs with macroscopic decay lengths and visible decay products

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

= **20 weak scale parameters**

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

- Randomly sample the 20 dimensional parameter space

- Discard points excluded by non-LHC constraints

- Examine the LHC's ability to discover or exclude viable points

Parameter Scan Ranges

- Upper limit on mass parameters is 4 TeV

- Linear priors for all parameters except gravitino mass

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

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

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

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

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

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

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

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

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

Model Set Generation

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 NLSP with micrOMEGAs

Constraints:

Electroweak	$(g-2)_\mu$, Γ_{inv}, $\Delta\rho$
Flavor	$b \to s\gamma$, $B_s \to \mu\mu$, $B \to \tau\nu$
Collider Limits	Charged sparticles above 100 GeV (LEP), Model-independent LHC bounds on HSCPs
Cosmology	BBN constraints on NLSP mass and lifetime, $\Omega_{gravitino}$ from NLSP decay less than Ω_{DM}
Higgs Sector	$\Phi \to \tau\tau$ constraints on H, A; only LEP limit on m_h*

*Susy Searches Largely Independent of m_h

Simulating the LHC Searches

- **~2.2×10⁵** points survive the constraints applied in model generation (**21k** models have m_h = **126 ± 3 GeV**)

- 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 ATLAS benchmarks

Standard (MET-based) SUSY Searches

- **Advantages:**
  - Sensitive to variety of models and NLSP types

- **Disadvantages:**
  - Rely on MET, which is suppressed for charged, detector stable NLSPs
  - Quality requirements on jets+leptons reduce sensitivity to long-lived sparticles

- **Simulation Challenges:**
  - Quality requirements can be difficult to find and simulate

8 TeV 20 fb^{-1} Jets+MET requirements:	
Jets	Leading jet (pT > 100 GeV) has charged track fraction $f_{ch} > 0.02$
Electrons	Electron veto applies to electrons with $d_o < 5$ mm
Muons	Muon veto applies to muons of any impact parameter (prompt muons outside signal region; displaced muons subject to cosmic ray veto)

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 SUSY searches

- **141k** models have NLSPs that produce visible decay products or leave a charged track in the detector (remaining 87k have sneutrino or detector-stable neutralino NLSPs)

- Of these 141k models, **46k** have $c\tau_{NLSP} < 0.2$ mm (prompt NLSP category), **43k** have $c\tau_{NLSP}$ between 0.2 mm and 2 m (displaced NLSP category), and **52k** have $c\tau_{NLSP} > 2$ m (stable NLSP category)

Search Category	% of Models Excluded		
	Prompt NLSP (46k models)	**Displaced NLSP (43k models)**	**Stable NLSP (52k models)**
"vanilla" Searches	57.83%	51.67%	20.35%
3rd Gen. Squarks	28.36%	23.50%	27.06%
Multilepton	22.68%	13.73%	29.38%
Photon+X	10.66%	16.50%	0.31%
Combination	**66.67%**	**59.68%**	**40.89%**

"vanilla" searches: Jets + MET, Multijets, Jets + Lepton + MET

Standard SUSY searches - Exclusions

- Bounds are weakened significantly when the NLSP decay products are visible and observably displaced from the primary vertex

Prompt NLSP (46k models)

Displaced NLSP (43k models)
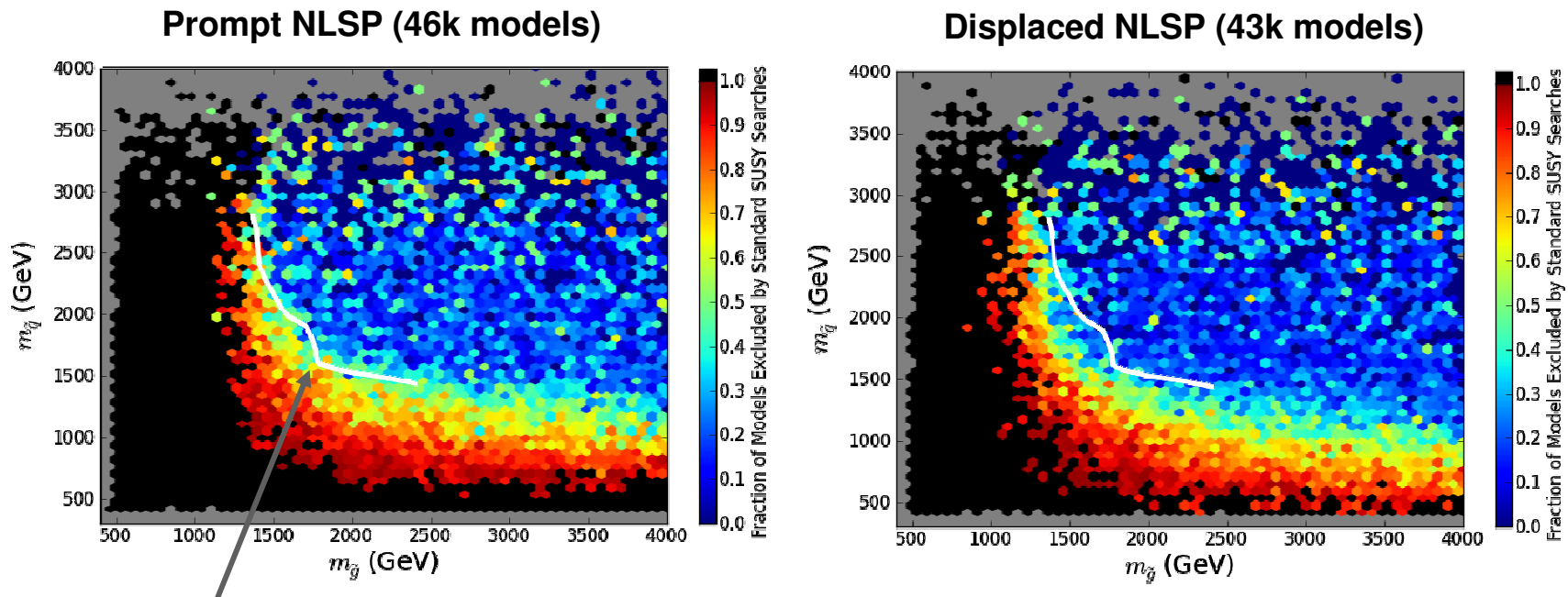
**Simplified limit from 8 TeV 20 fb^{-1} Jets+MET
(Assumes degenerate squarks and massless LSP)**

Displaced Object Searches

- Advantages:
  - No SM backgrounds

- Disadvantages:
  - Usually target RPV SUSY or exotic scenarios (low acceptances for gravitino models)
  - Only sensitive to specific NLSP types

- Simulation challenges:
  - Can't reproduce vertexing algorithms in theorist-level simulations – rely on approximations (Detailed cut flows and parameterized efficiencies essential).

Displaced NLSP (43k models):

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 %**

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
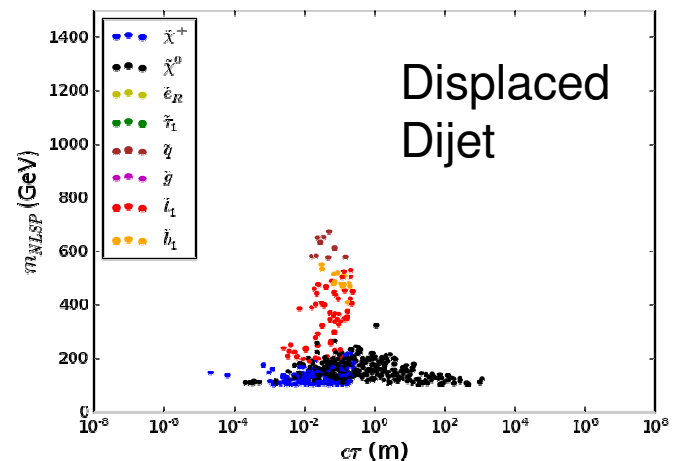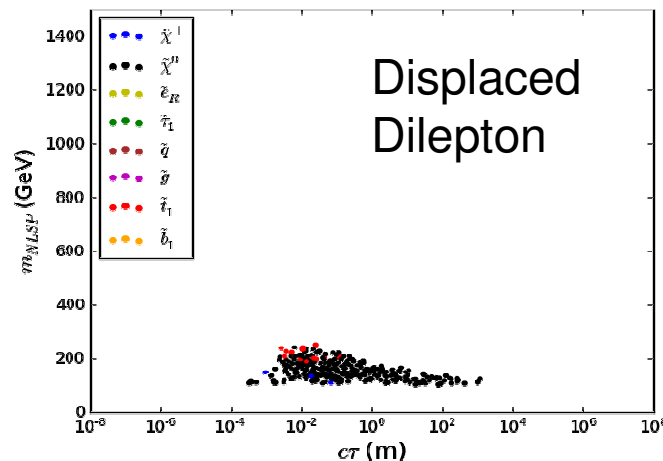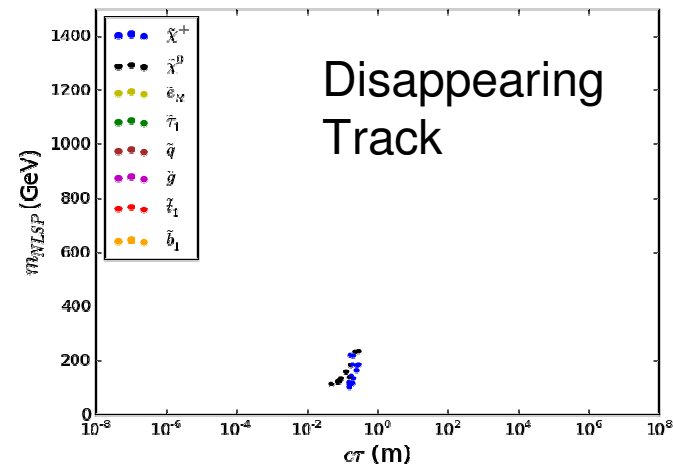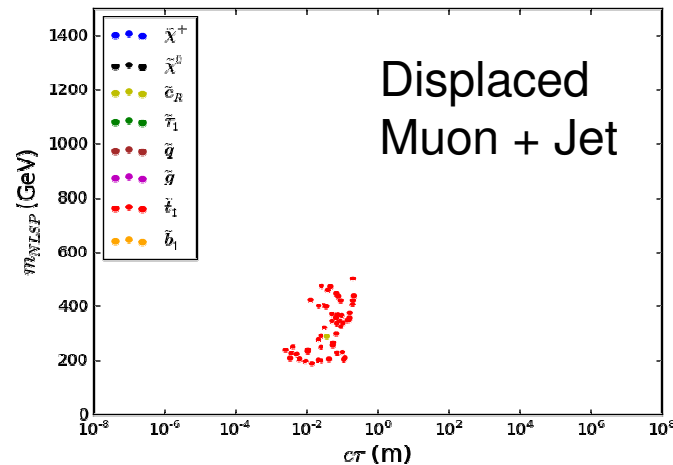
HSCP Searches

- Advantages:
  - Sensitive to all models with detector-stable charged/colored NLSPs
  - Sensitive to very small cross-sections

- Disadvantages:
  - Acceptance falls dramatically for NLSPs with $c\tau < 1$ m

- Simulation Challenges:
  - Energy deposition discriminants challenging to simulate
  - Requires numerous signal benchmarks with cut flows for accurate validation

Stable NLSP (52k models):

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

HSCP Searches

Stable NLSP (52k models):

- High fraction of models excluded even for very heavy squarks and gluinos

- A few models survive with light squarks and gluinos by having other long-lived sparticles.
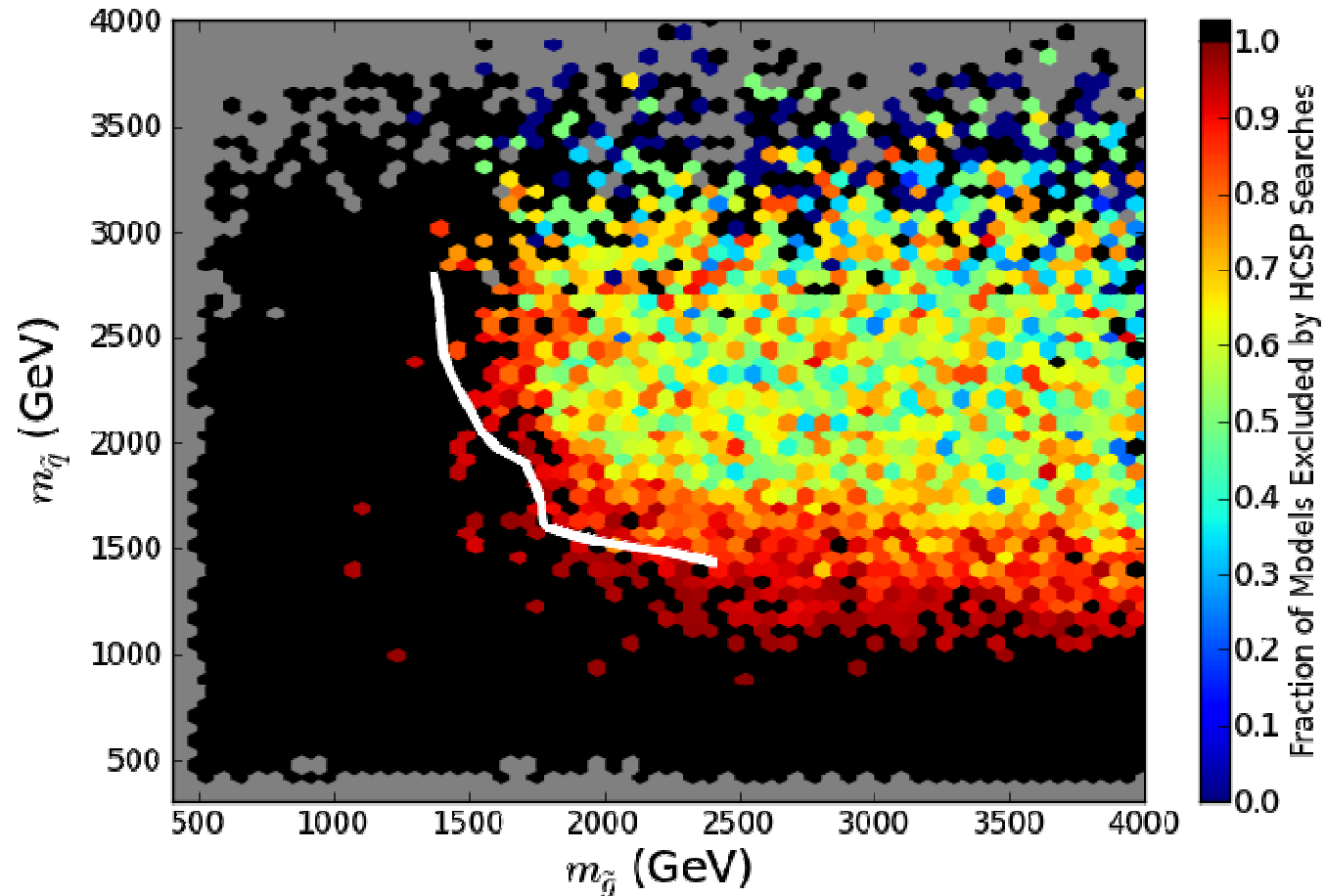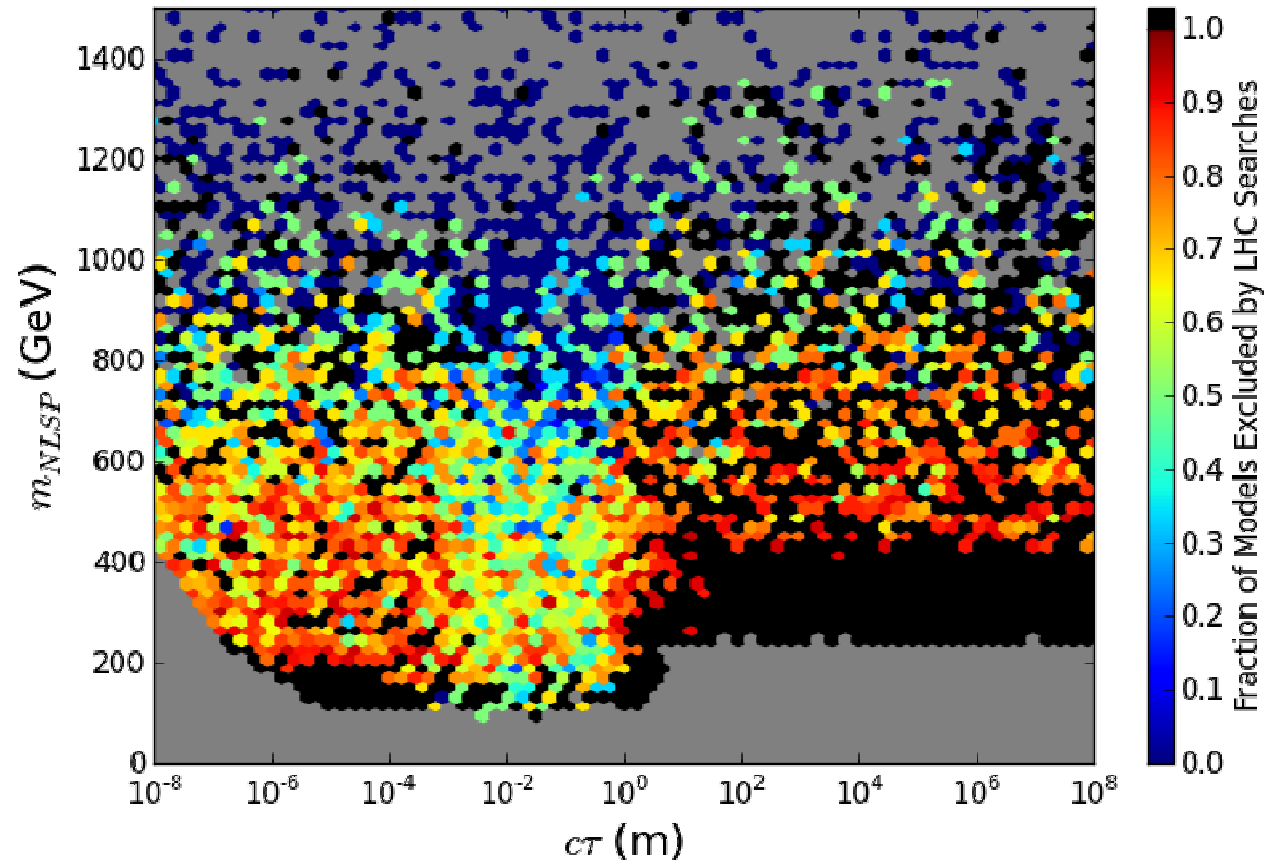
NLSP Constraints
(All searches)

Neutralino NLSP

- Searches less effective for detector-stable neutralinos

- Minimal change (slight increase?) in exclusion fraction for neutralinos with macroscopic decay lengths
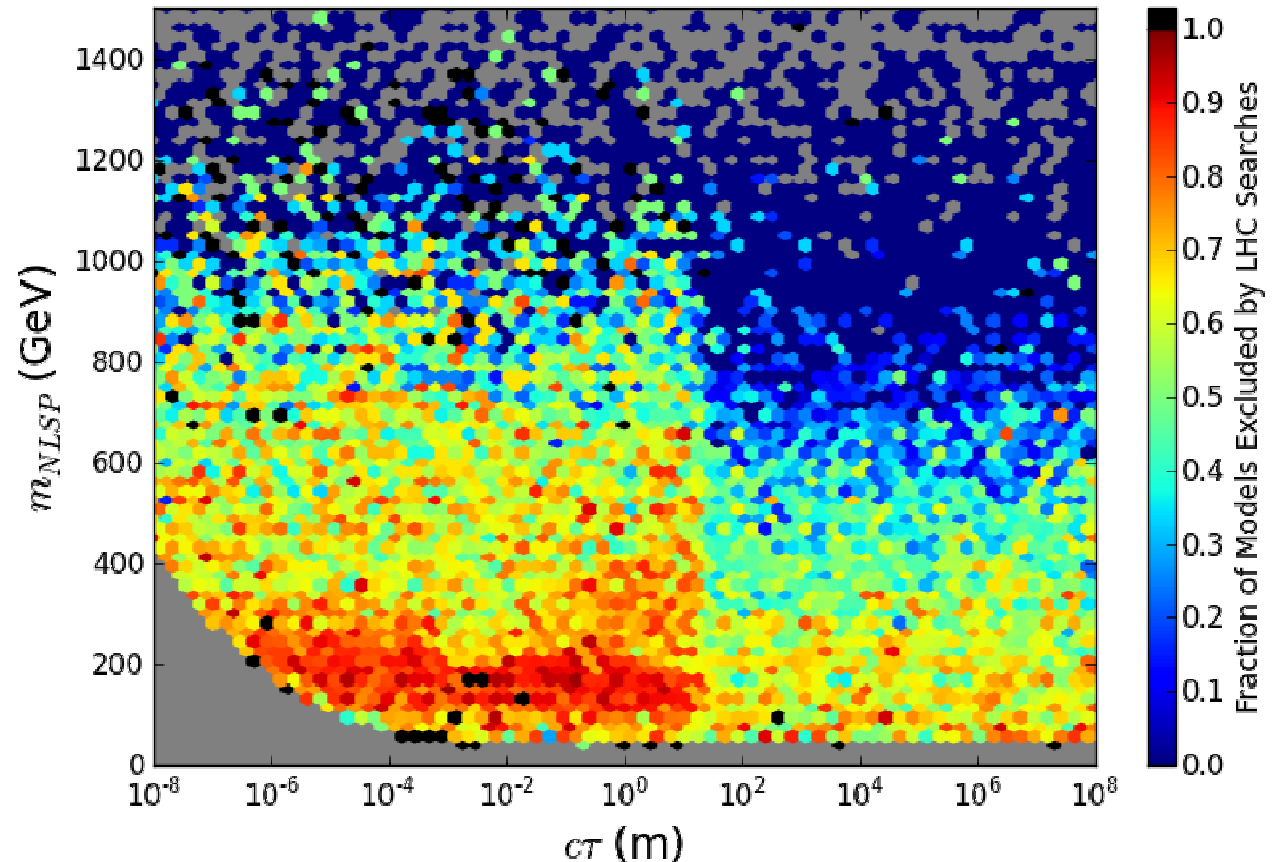
$\tilde{e}_R$ NLSP

- 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

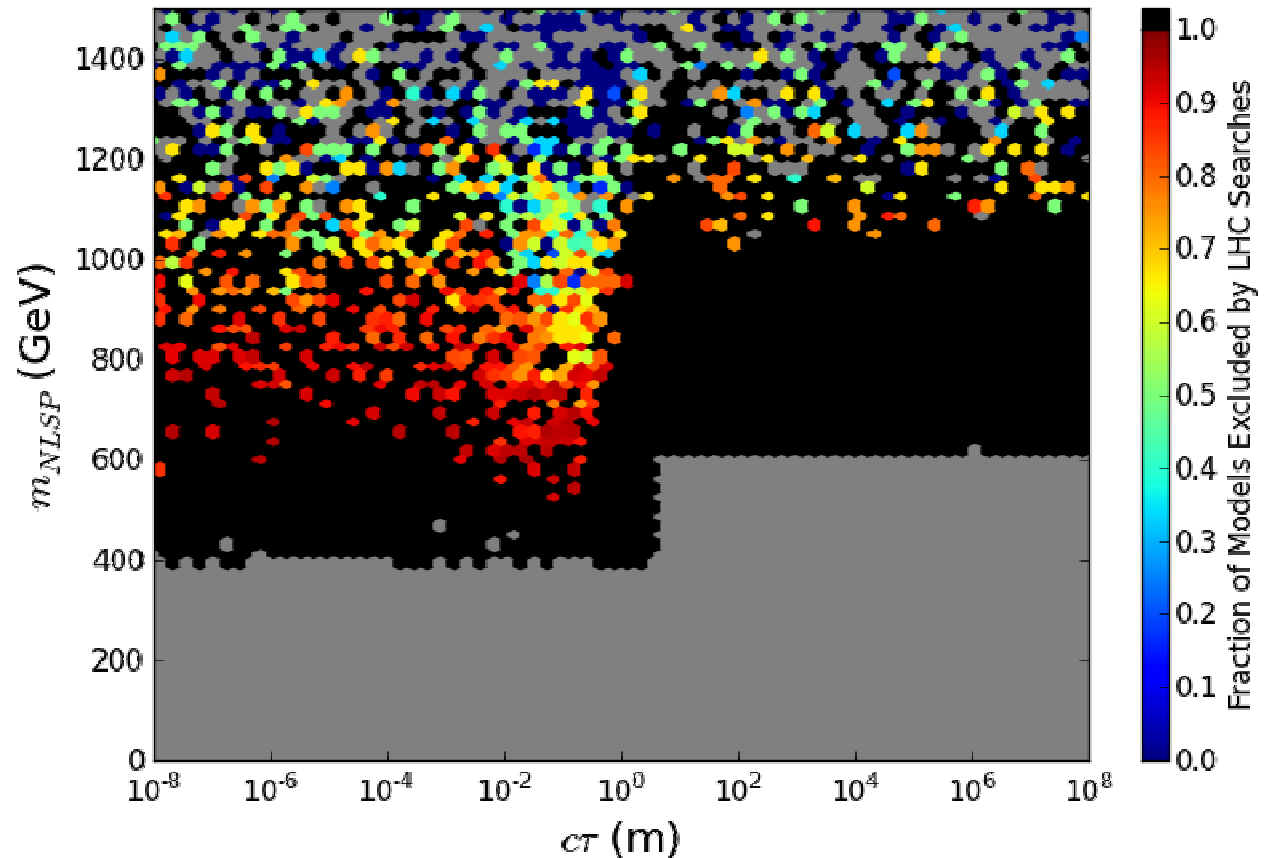- Strong limit on stable stops (large production cross-section)
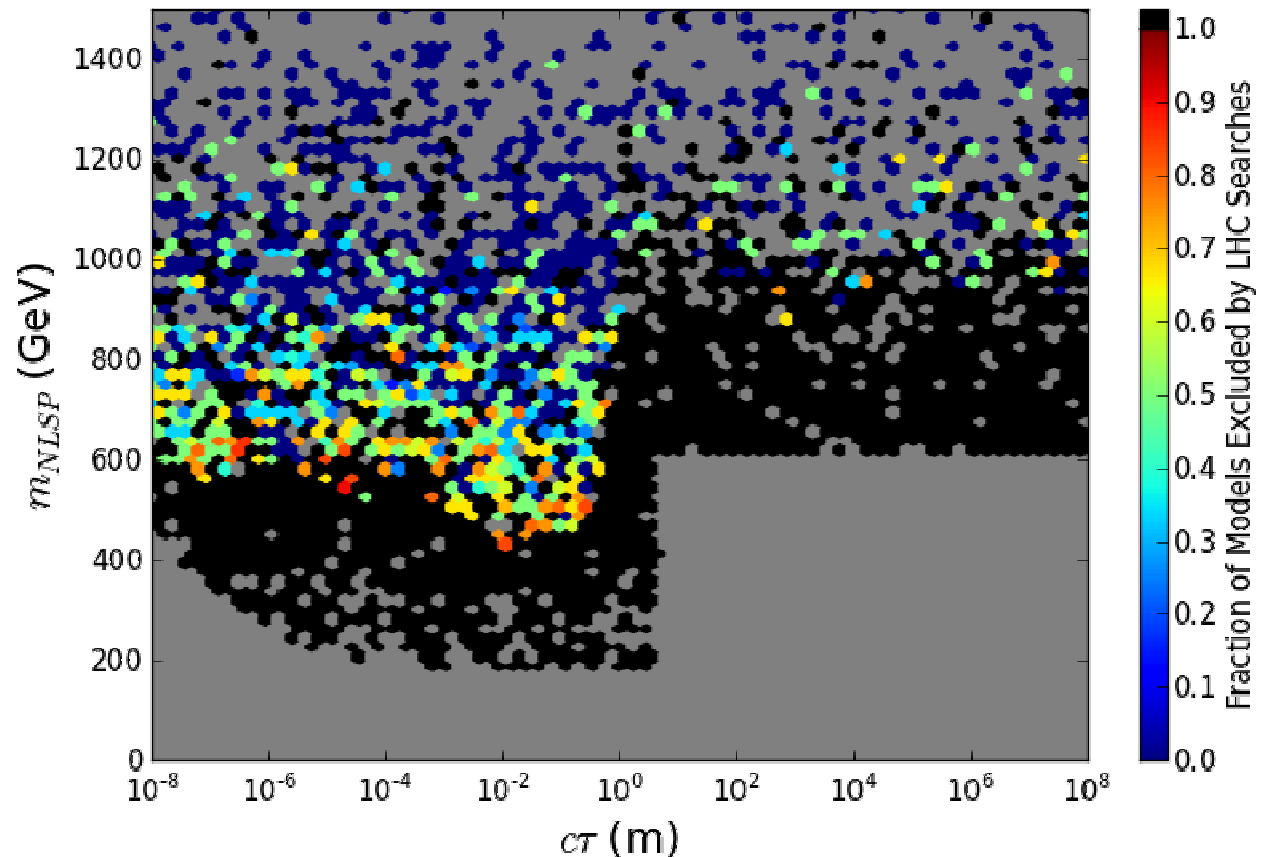
Chargino NLSP

- HSCP searches highly effective

- No direct limit on promptly decaying chargino NLSPs (WW+ MET has large backgrounds)
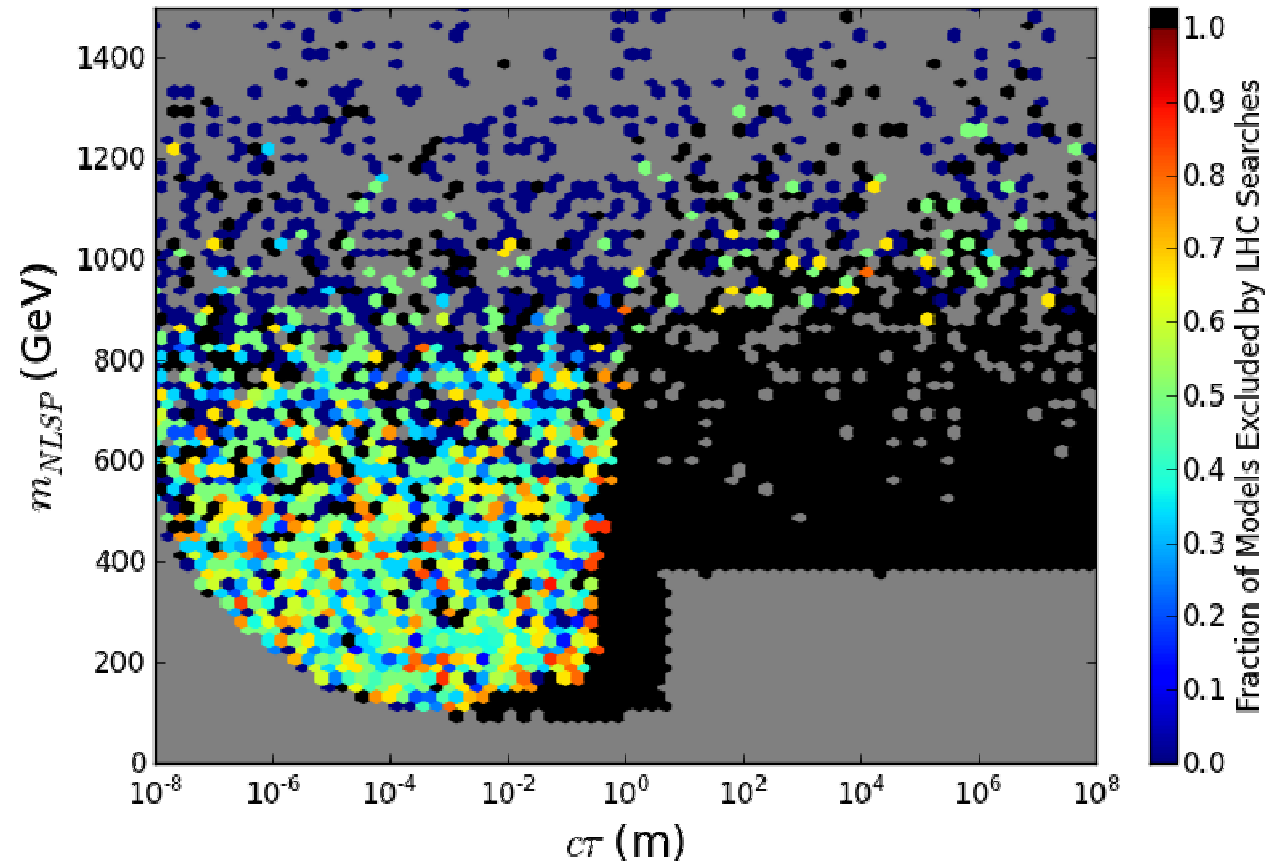
Squark/Gluino NLSP

- Limit degraded for macroscopic decay lengths (hardest jet frequently results from NLSP decay)

- Extremely strong limit on stable squarks/gluinos

Targeted Search Opportunities

- Optimize displaced dijet and displaced dilepton analyses by removing colinearity requirement between dijet/dilepton momentum and displaced vertex

- Target displaced objects from cascades by combining traditional requirements on Jets and/or MET with displaced object requirements

- Targeted searches for $\tilde{e}_R$ NLSPs – select high-pT displaced lepton + MET? (Cosmic ray veto critical)

Summary

- The pMSSM is a powerful tool for analyzing the performance of the LHC, and looking for particularly challenging regions.

- Standard SUSY searches place important constraints on models with long-lived NLSPs

- HSCP searches place extremely strong limits on the total SUSY production cross-section of models with HSCPs

- Current searches targeting displaced objects are ill-adapted for most NLSP types

- New searches targeting displaced NLSPs may be able to substantially improve current limits
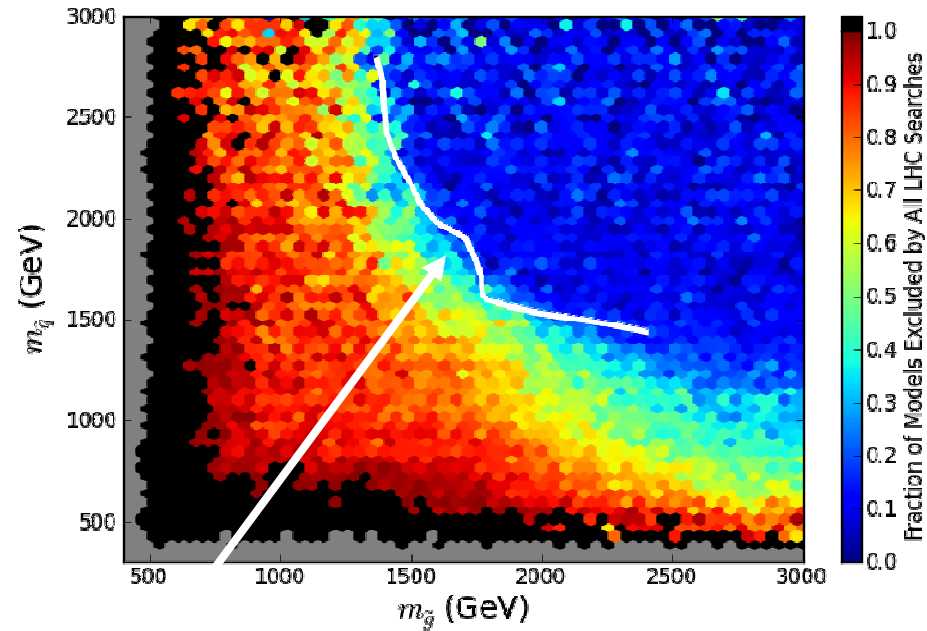
Backup Slides

Colored Sparticles

Gravitino LSP
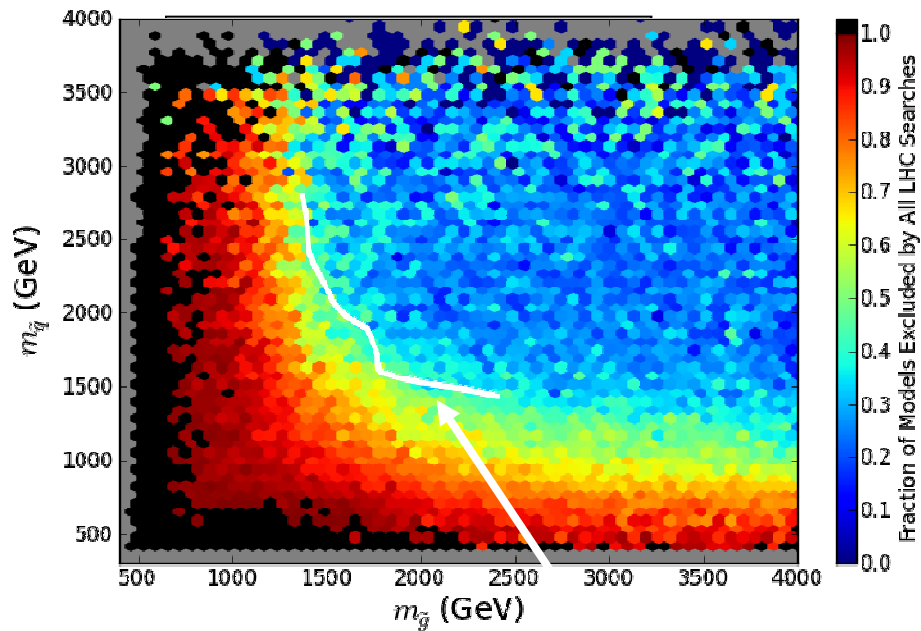
Neutralino LSP

Simplified limit from ATLAS-CONF-2012-109
(Assumes degenerate squarks and massless LSP)

Displaced Muon + Jet Analysis

- Used parameterized efficiency for reconstructing displaced vertices as a function of the decay radius, given for "MH" sample. This efficiency may not apply universally because of several factors (listed in the 8 TeV CONF note):
  - Boosted objects will have more tracks failing the $d_0 > 2mm$ requirement
  - Heavier vertex invariant mass and more tracks lead to higher reconstruction efficiency
  - Dependence on DV location (This should be captured by using the parametrized efficiency)

  Given vertex reconstruction efficiency is for full event; have to rely on simulation to separate out cuts on e.g. muon pT from the vertex reconstruction.

- The vertex reconstruction efficiency shown is the efficiency for the vertex to pass all cuts; we simulate the MH sample and deconvolute the factors that we can simulate (e.g. pT requirements on the muon).
  - Ideally would have track-finding efficiency as a function of track parameters, and then the efficiency for reconstructing a vertex given reconstructed tracks.

- Vertices combined and refitted if separated by less than 1 mm (8 tev analysis) – this suggests that b-jets should still be associated to the muon from displaced top decays, however a detailed simulation of this would be very helpful.

Displaced Dileptons

- Used efficiency for reconstructing displaced tracks, parametrized as function of d_0 and $z_{0;}$ assume that vertex is reconstructed if tracks are.

- Dilepton momentum is required to be collinear with displaced vertex vector (< .8 rad (electrons) and < .2 rad (muons))

- Require displaced vertex location to be > .1 mm from PV

- Minimum requirements on dilepton invariant mass to ensure that they can be resolved separately.

Displaced Dijets

- Dijet invariant mass > 4 GeV, require dijets to be separated by R > 0.5

- Displaced vertex between 0.5 mm and 60 cm

- Require jet momenta intersections with the dijet momentum to occur at a radius which differs from the decay length by less than 15%

HSCP Searches – Tracker Only

- Search for tracks with large dE/dX, identitified using Ias discriminant:

$$I_{as} = \frac{3}{J} \times \frac{1}{12J} + \sum_{i=1}^{J} [P_i \times (P_i - \frac{2i-1}{2J})^2],$$

- J = # hits in tracker, P_i = probability for a minimum-ionizing particle to produce the observed energy deposition

- Assume typical value of 16 hits

- Average value of energy deposition for HSCP:

$$\left(\frac{dE}{dx}\right)_{mp} = K\frac{m^2}{p^2} + C,$$

- Pick individual values of energy deposition from a gaussian around the average value (width from MIP distribution, 1007.1988)

- For each hit, calculate probability of MIP giving the chosen dE/dX value (using dE/dX distribution from minimum-bias events)

HSCP Searches (Cont.)

- Tracker + Time of Flight includes Ias cuts, additionally requires a muon track with low β.

- Parametrize muon reconstruction efficiency as a function of β by: (CMS-PAS-EXO-10-004)

$$f_{acc} = \begin{cases} 0 & \text{for} & \beta < 0.3, \\ 2.5\beta - 0.75 & \text{for} & 0.3 < \beta \leq 0.7, \\ 1 & \text{for} & \beta > 0.7, \end{cases}$$
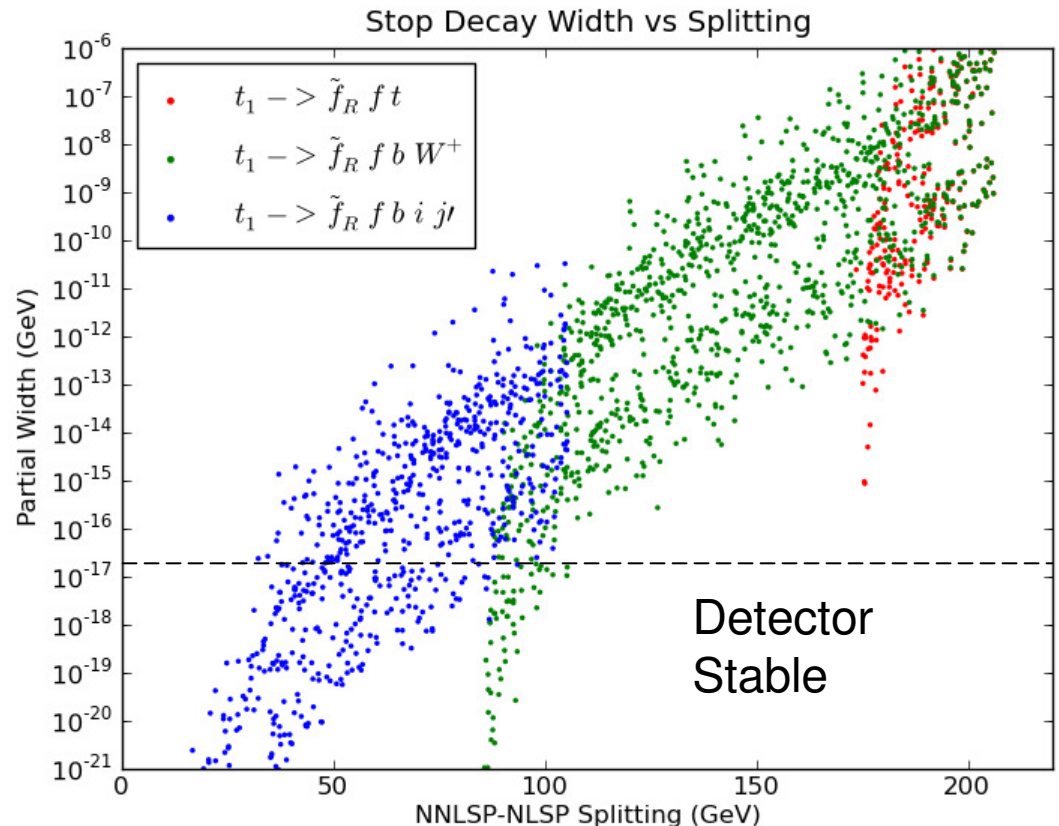
- Apply a gaussian smearing to β^{-1}, with width 0.06 (1205.0272)

HSCP Searches (Cont.)

- Only the ATLAS HSCP CONF note was available when implementing the HSCP analyses. This note did not provide limits in specific mass regions, but rather showed figures with the observed mass distributions and errors; extracting limits from these plots would have been difficult. Additionally, a mass cut was applied to the candidates, which was " different for different GMSB models, determined
by the expected significance of the signal" – these cuts were not specified for specific reagons. By contrast the CMS paper had specific mass regions with tabulated limits and efficiencies for benchmark models.

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

Stop Decay Width vs Splitting

Legend:
- $t_1 -> \tilde{f}_R\, f\, t$
- $t_1 -> \tilde{f}_R\, f\, b\, W^+$
- $t_1 -> \tilde{f}_R\, f\, b\, i\, j\prime$

Partial Width (GeV) axis: 10^{-6} to 10^{-21}

NNLSP-NLSP Splitting (GeV)

Detector Stable

# 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

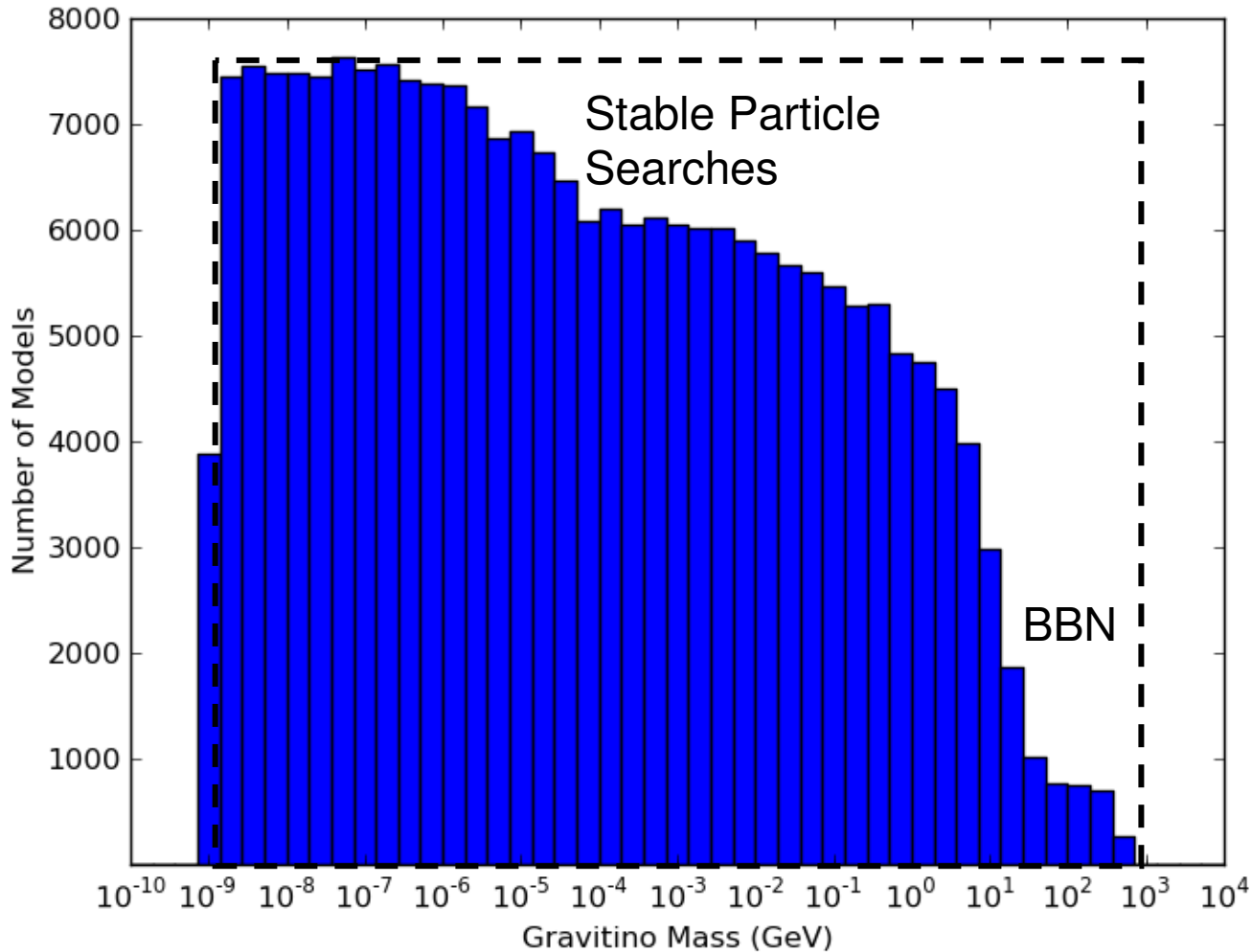### BBN Constraints on a neutralino NLSP
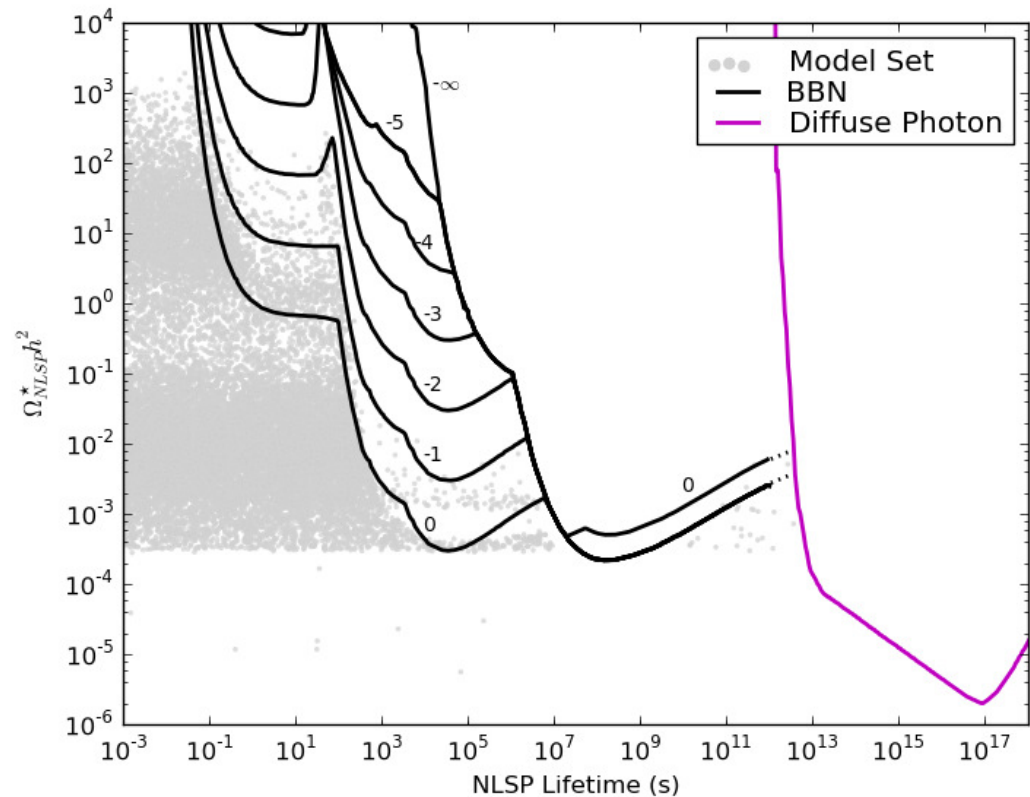
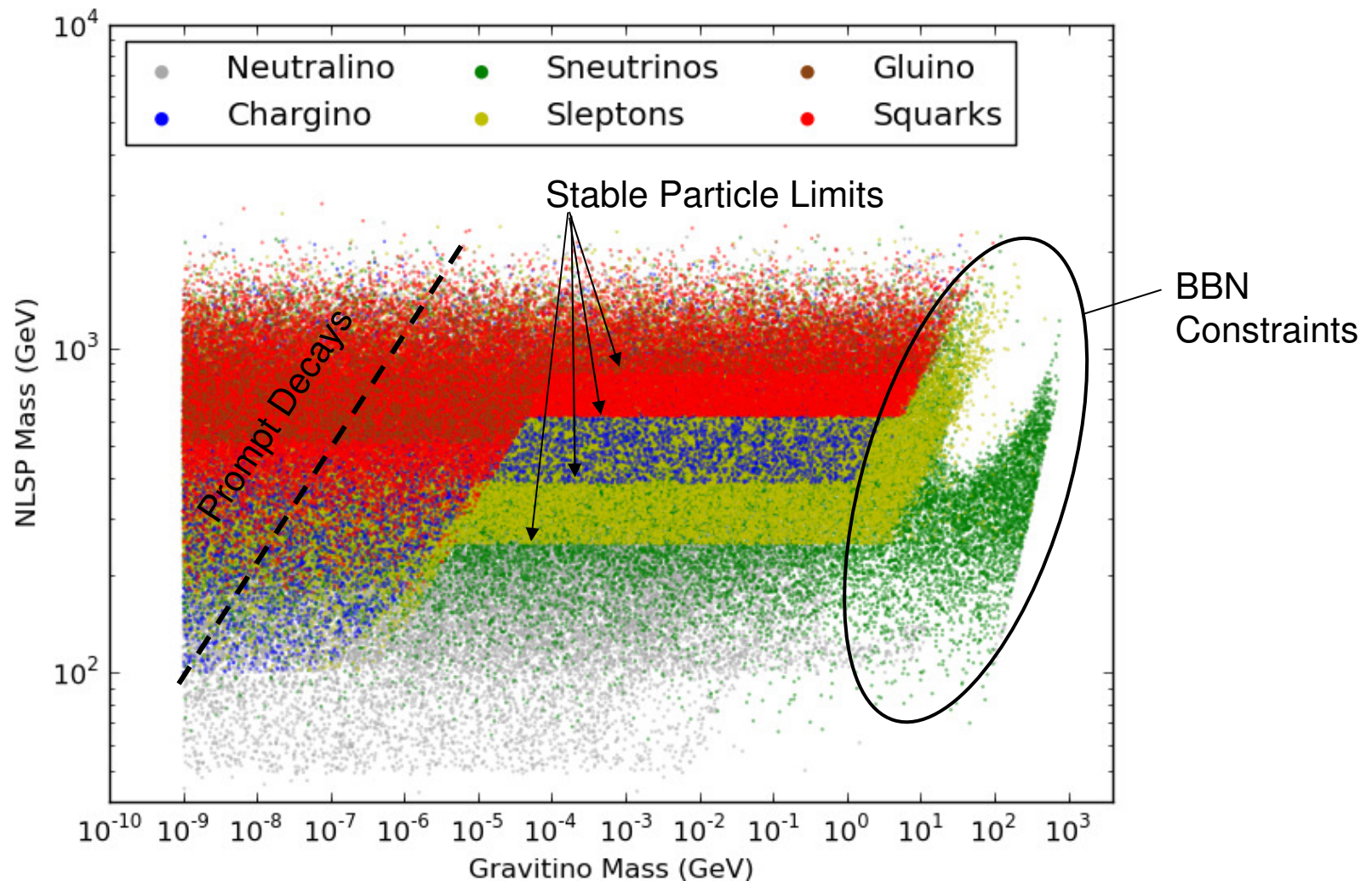# Gravitino Cosmology: Big Bang Nucleosynthesis

- Heavy charged/colored particles can catalyze reactions directly

- Neutrinos can scatter off thermal bath, producing pions and leptons which affect BBN
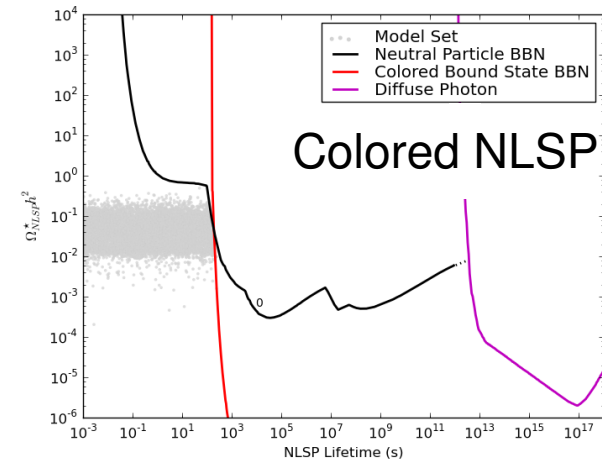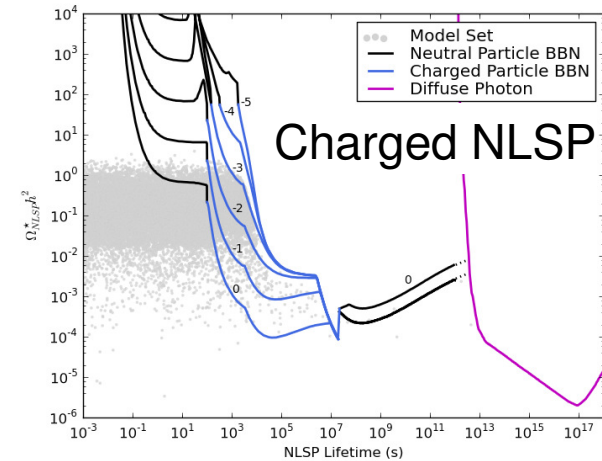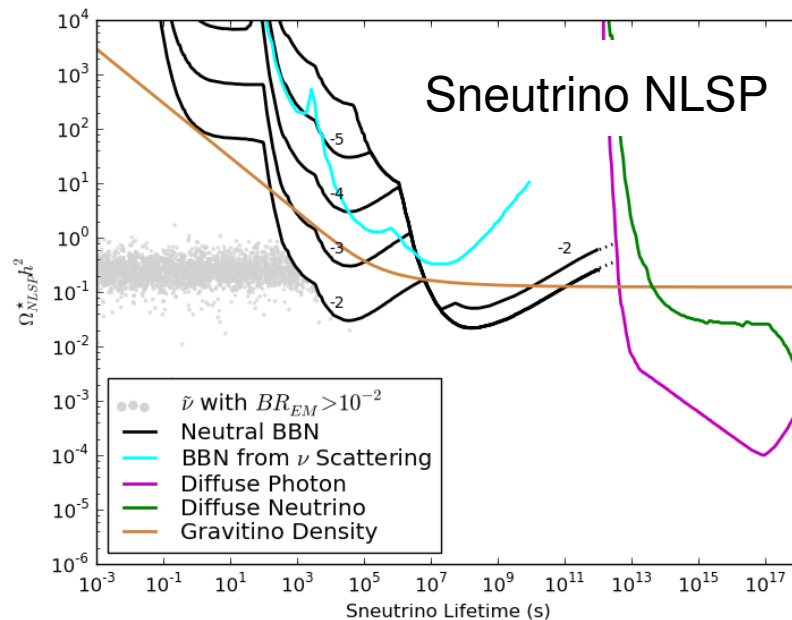
Gravitino Mass Histogram

Resulting Model Set

HSCP Searches