Interpreting LHC Searches for New Physics with Simplified Models

Ursula Laa
LPSC & LAPTh
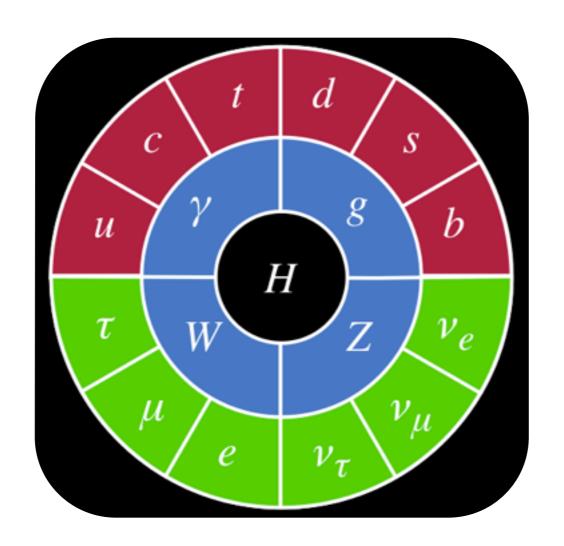
Introduction

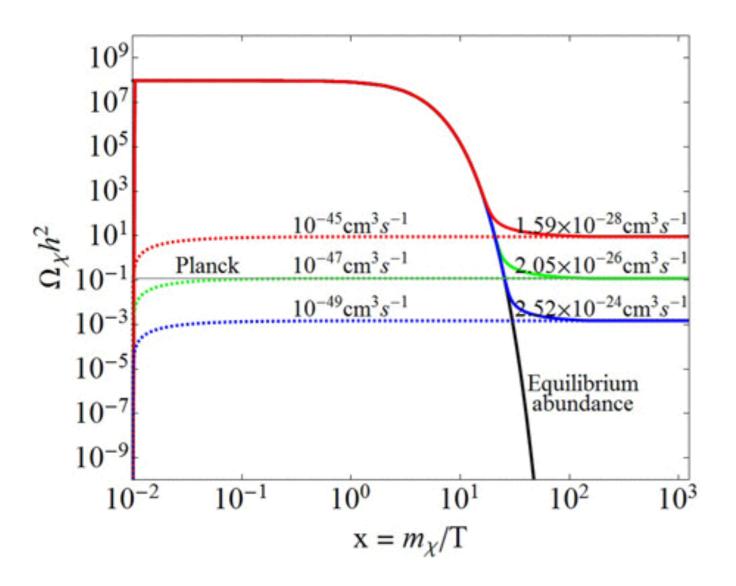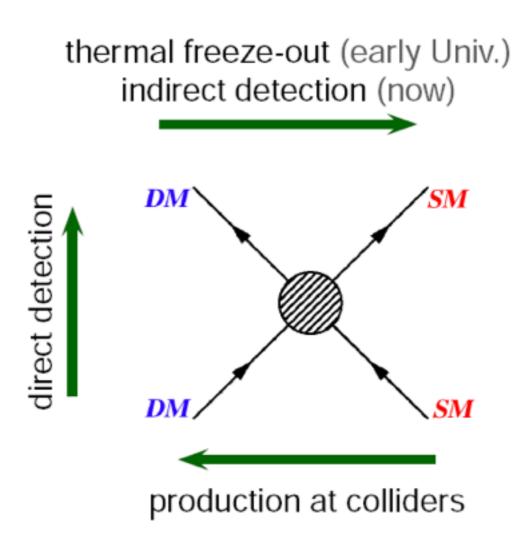# The Standard Model of Particle Physics

Open Questions:

- Particle description of dark matter ?
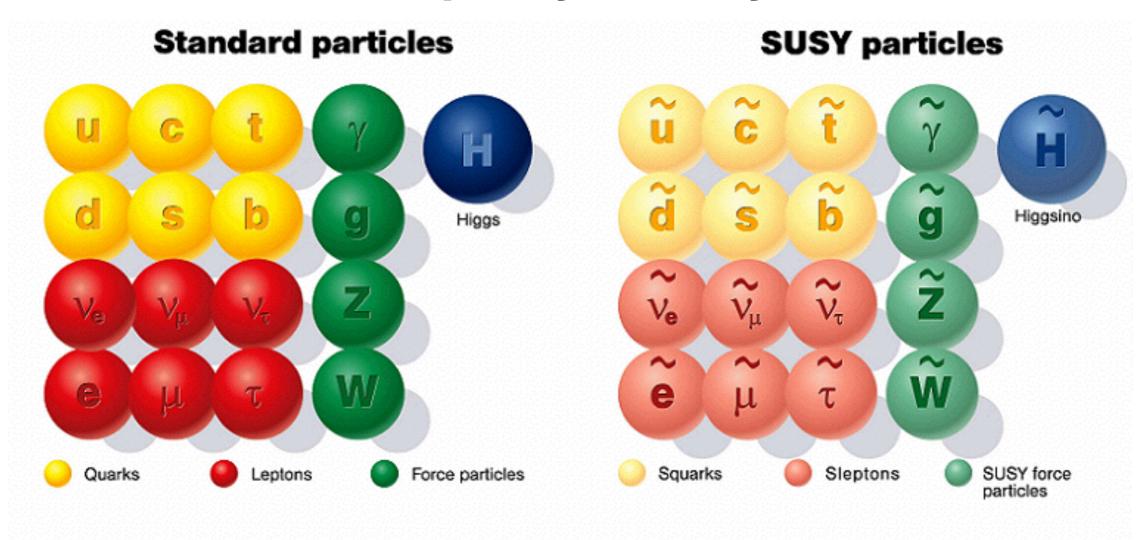- How do neutrinos obtain a mass ?

Dark Matter

- Precision cosmology → measurement of relic abundance
- Planck 2015: $\Omega h^2 = 0.1188 \pm 0.0010$
- Naturally obtained for WIMPS ("WIMP miracle")
- WIMPS are predicted in many theories Beyond the Standard Model, e.g. in supersymmetric models

Supersymmetry

Standard particles

u c t γ H

d s b g Higgs

ν_e ν_μ ν_τ Z

e μ τ W

Quarks   Leptons   Force particles

SUSY particles

$\tilde{u}$ $\tilde{c}$ $\tilde{t}$ $\tilde{\gamma}$ $\tilde{H}$

$\tilde{d}$ $\tilde{s}$ $\tilde{b}$ $\tilde{g}$ Higgsino

$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$ $\tilde{Z}$

$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$ $\tilde{W}$

Squarks   Sleptons   SUSY force particles

- Relating fermions and bosons
- New "superpartner" for all SM particles (same charges, spin differing by 1/2)
- R-parity → lightest partner (LSP) is stable
- SUSY broken → superpartners are heavy !
- Minimal (but general) model MSSM > 100 free parameters

Supersymmetric Dark Matter

Requirements

- Stable
- Invisible
- Reproduce observed relic density
- Consistent with bounds from direct and indirect detection experiments

Candidates

- Scalar neutrino (sneutrino) ✗
- cannot reproduce observed relic density
- excluded by direct detection experiments
- Partners of neutral electroweak gauge bosons and Higgs ✔
- physical states are mixed
- label them as neutralinos $\tilde{\chi}^0$, with $\tilde{\chi}^0_1$ the lightest physical state
- good dark matter candidate, details depend on the mixing !

$\Big($ The corresponding charged superpartners also mix, we call them charginos. Depending on the nature of the LSP the lighter chargino can be almost mass degenerate with the LSP. $\Big)$

What about neutrino masses ?

- Neutrino masses are not included in the MSSM
- Simplest implementation is Dirac mass term
- Requires right-handed (sterile) neutrinos
- Supersymmetric version: MSSM+RN

[Borzumati & Nomura, hep-ph/0007018]
[Arkani-Hamed et al., hep-ph/0006312]

We can describe the sneutrino mixing as

$$\begin{pmatrix} \tilde{\nu}_{k_1} \\ \tilde{\nu}_{k_2} \end{pmatrix} = \begin{pmatrix} -\sin\theta_{\tilde{\nu}}^k & \cos\theta_{\tilde{\nu}}^k \\ \cos\theta_{\tilde{\nu}}^k & \sin\theta_{\tilde{\nu}}^k \end{pmatrix} \begin{pmatrix} \tilde{\nu}_L^k \\ \tilde{N}^k \end{pmatrix}$$

where the mixing angle is a free parameter

example mass spectrum

other squarks

$\tilde{g}, \tilde{t}, \tilde{b}, \tilde{l}, \tilde{\chi}^0, \tilde{\chi}^\pm$

$\tilde{\nu}_{e_1,\mu_1}$
$\tilde{\nu}_{\tau_1}$

Mixed, mostly right-handed sneutrino LSP is a good dark matter candidate !

LHC Searches
&
Interpretation

Searching for Supersymmetry at the LHC (ATLAS & CMS)
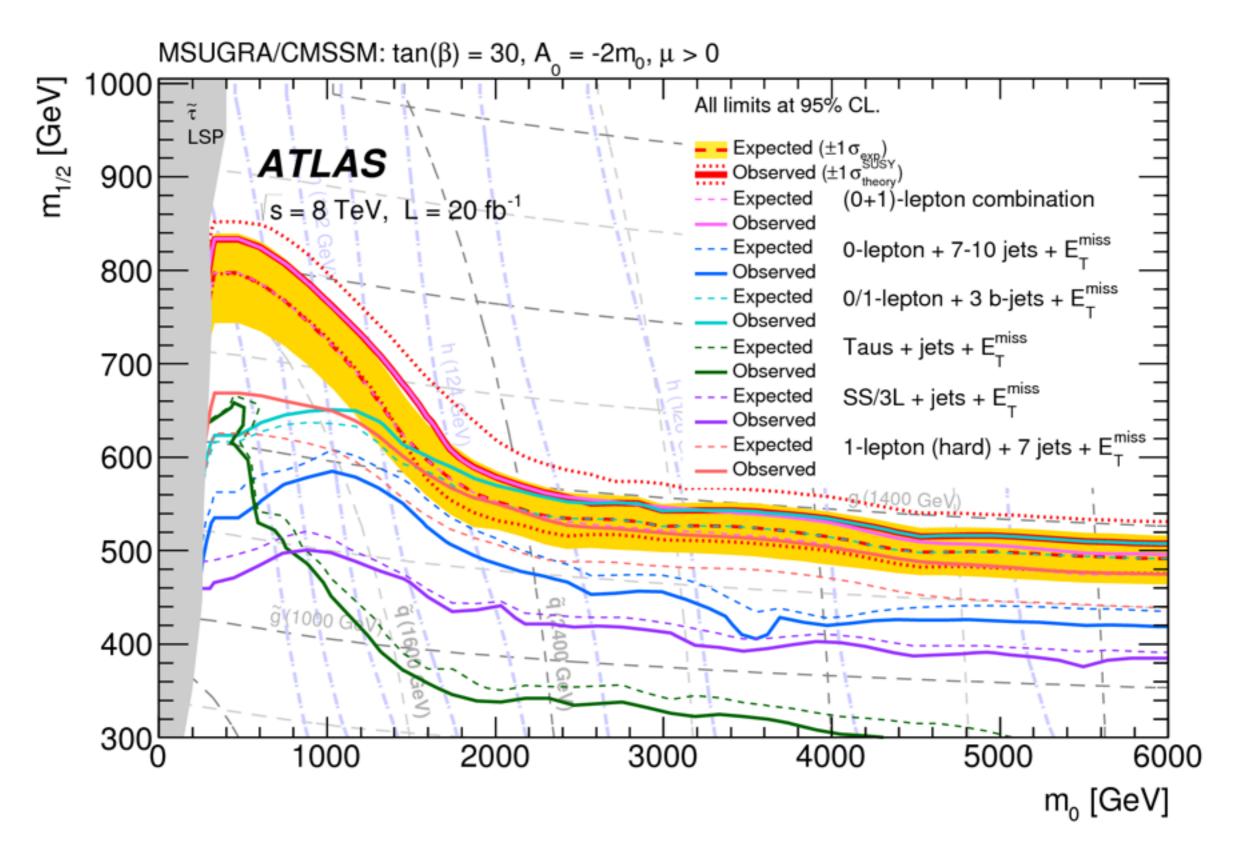
Searching for SUSY

- LSP is invisible → "Missing energy" (MET) in signal events
- Concrete signatures depend on the scenario → many different analyses, targeting different types of scenarios
- For example "cut and count": define cuts that select signal events, reject SM background, compare observation to SM expectation
- LHC Run 1 - All observations compatible with the SM
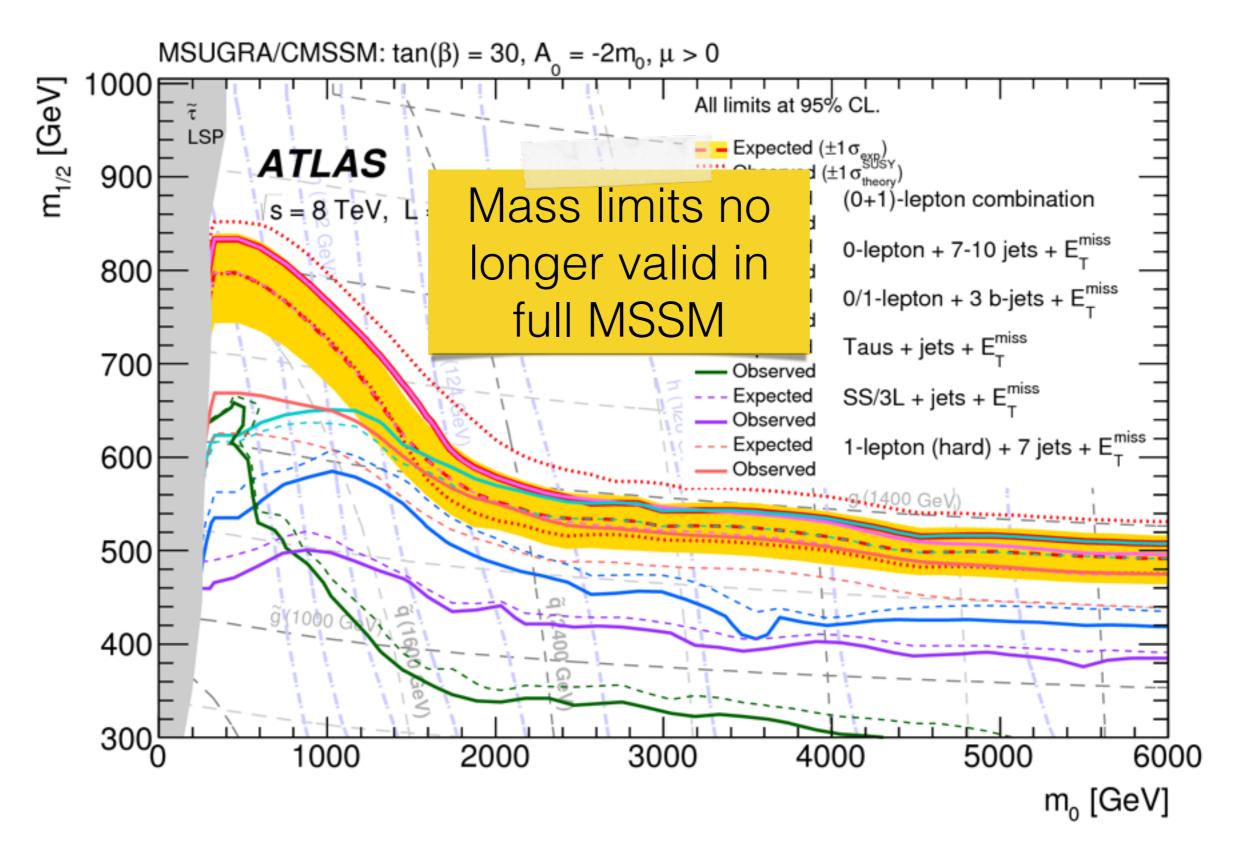- Non-observation puts strong constraints on parameter space of supersymmetric models

Interpretation (Top Down)

- Consider "cut and count" type search
- Choose model and parameters
- Evaluate signal selection efficiency, predict number of signal events
- Compare to expected number of background events and the observation
- How can we interpret the results if even the minimal model has more than 100 free parameters ?

Interpretation of LHC searches in constrained models

Interpretation of LHC searches in constrained models
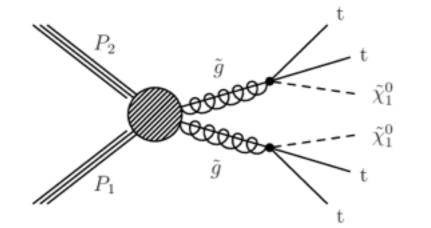
Alternative: Bottom Up Approach

- Can we interpret LHC results in a "model independent" way ?
- Instead of considering a full model, consider Simplified Models

Simplified Model Spectra (SMS)
- Effective approach: only specific superpartners are light and considered for the interpretation
- Other superpartners are too heavy to be produced at the LHC
- Decay branching ratios are fixed
- Free parameters: physical mass and production cross section
- This captures the main features relevant for LHC phenomenology, results can be interpreted in mass planes, giving upper limits on the cross section
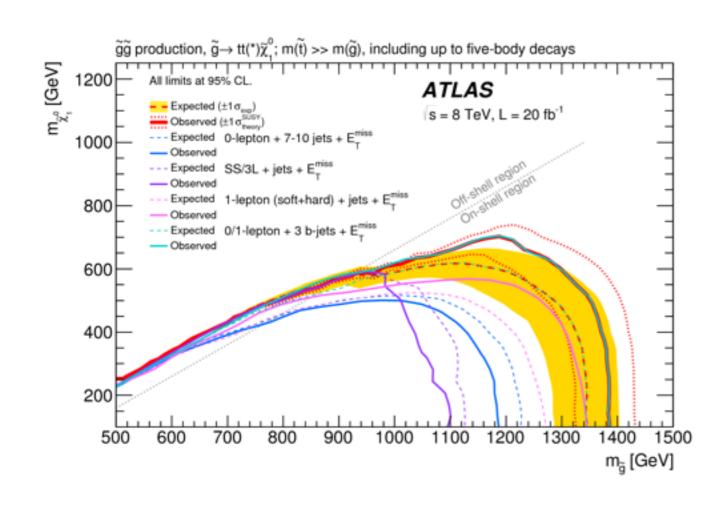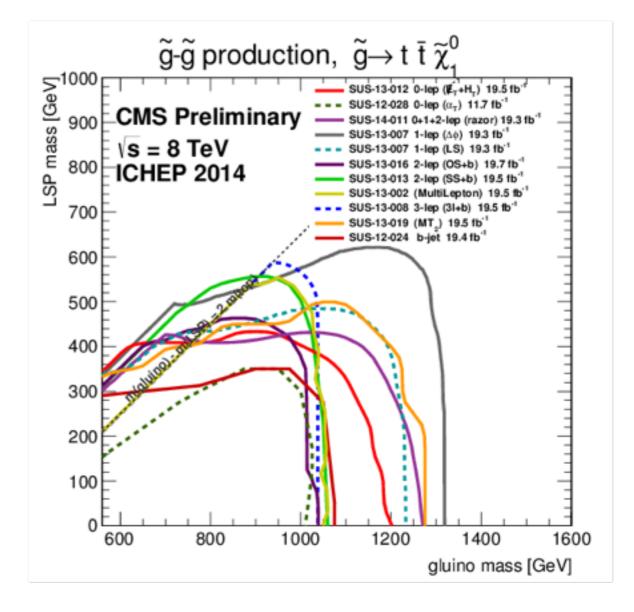
Example: Gluino Simplified Model

Production of gluino pair
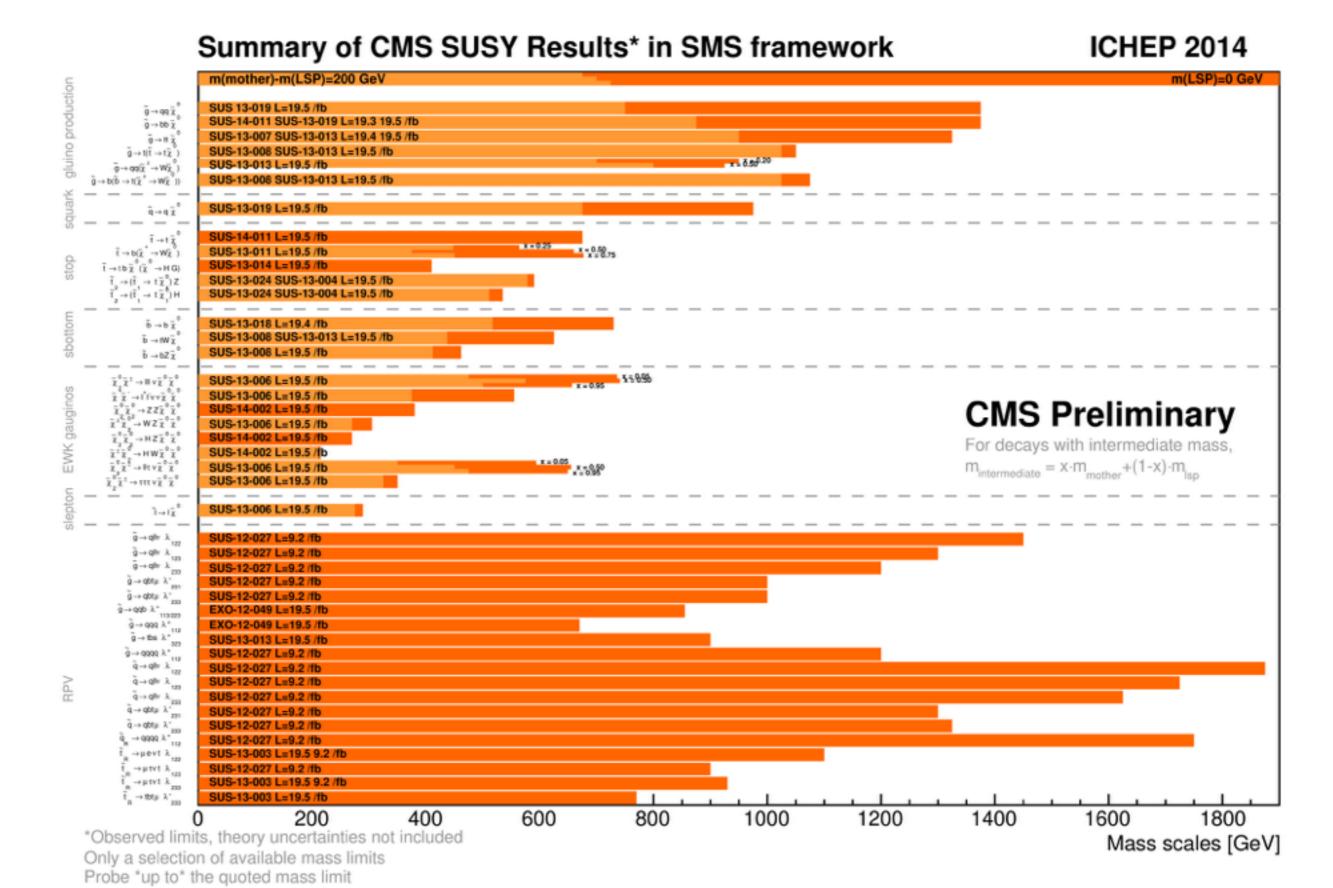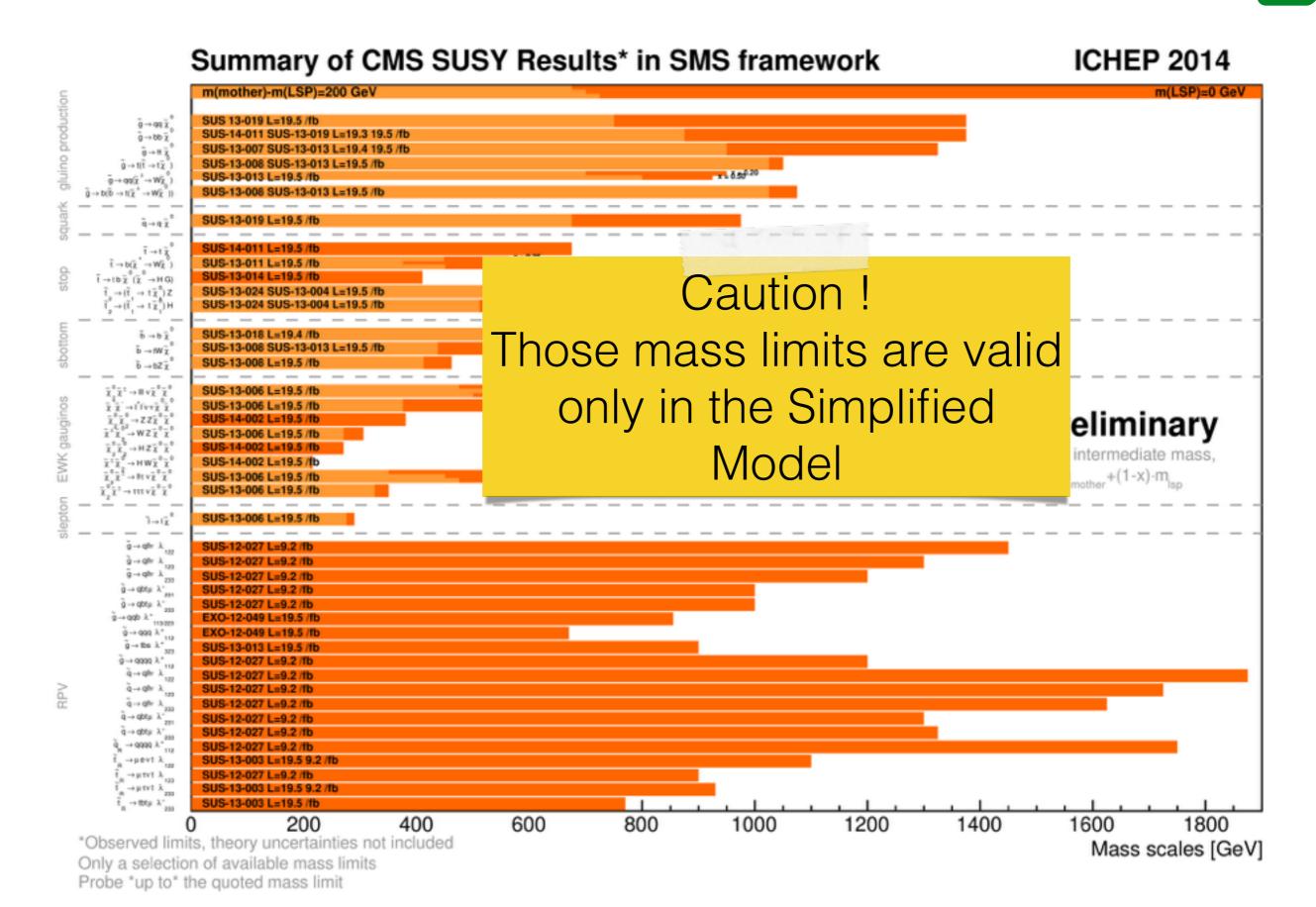
Gluino decays 100 % as

$$\tilde{g} \to tt\tilde{\chi}_1^0$$

Summary of CMS SUSY Results* in SMS framework — ICHEP 2014

CMS Preliminary

For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} + (1-x) \cdot m_{lsp}$

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe "up to" the quoted mass limit

Summary of CMS SUSY Results* in SMS framework

ICHEP 2014

Caution !
Those mass limits are valid only in the Simplified Model

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Mass scales [GeV]
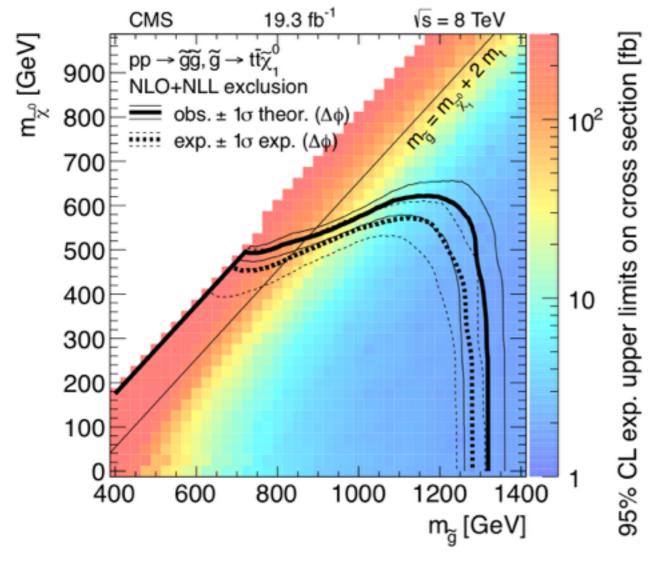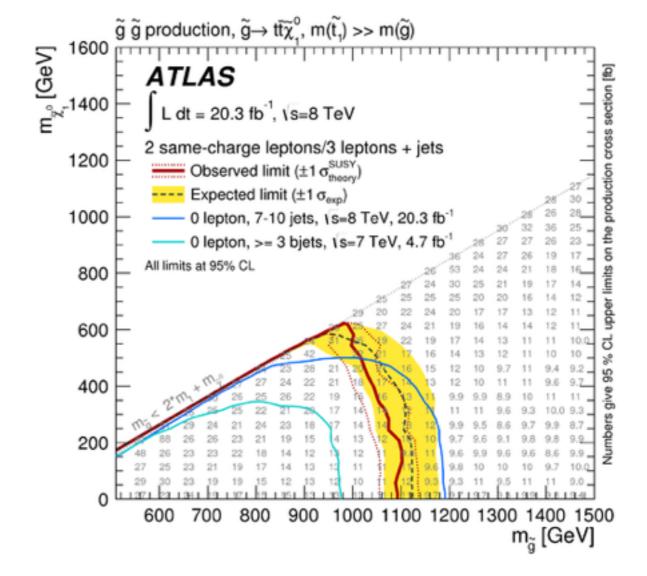
A closer look at the results

- The experiments evaluate an upper limit on the cross sections (for each mass bin)
- Those numbers still apply if the BR < 100 %
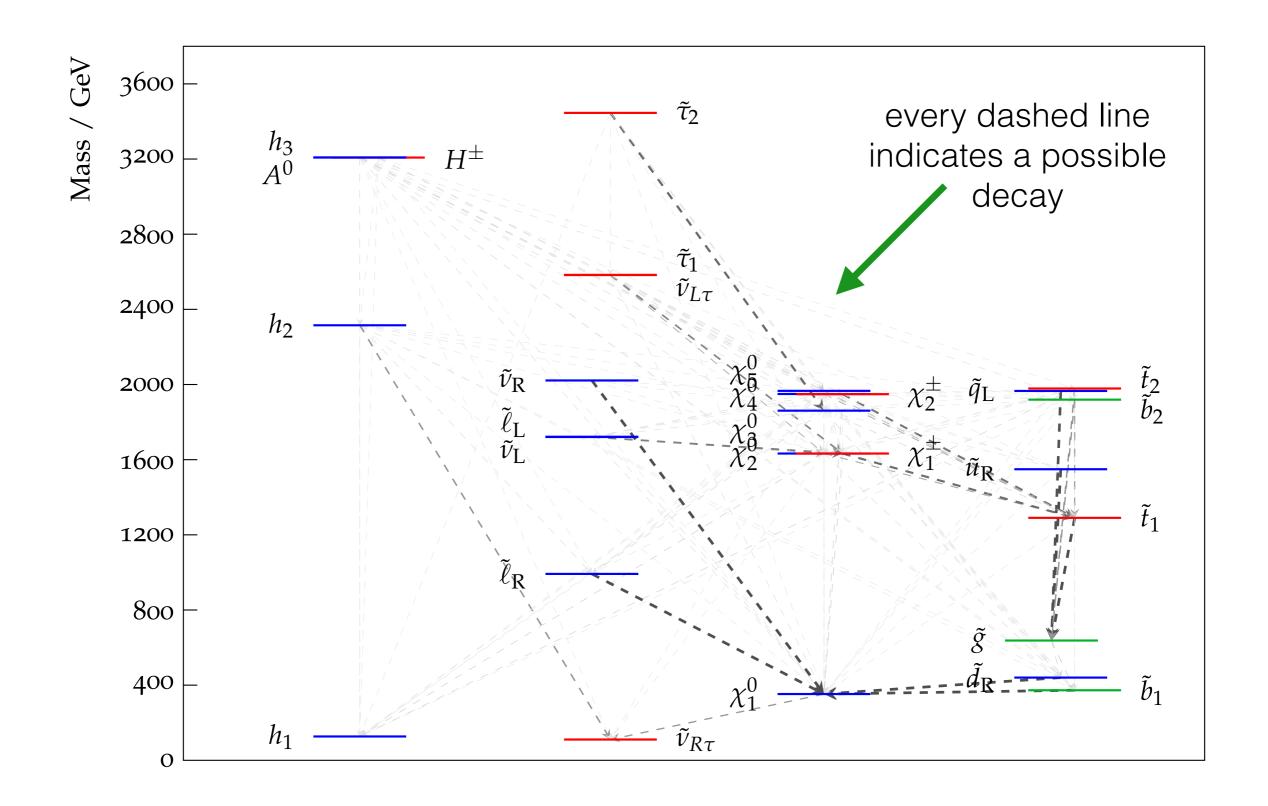- We can compare the upper limits directly to $\sigma * BR$
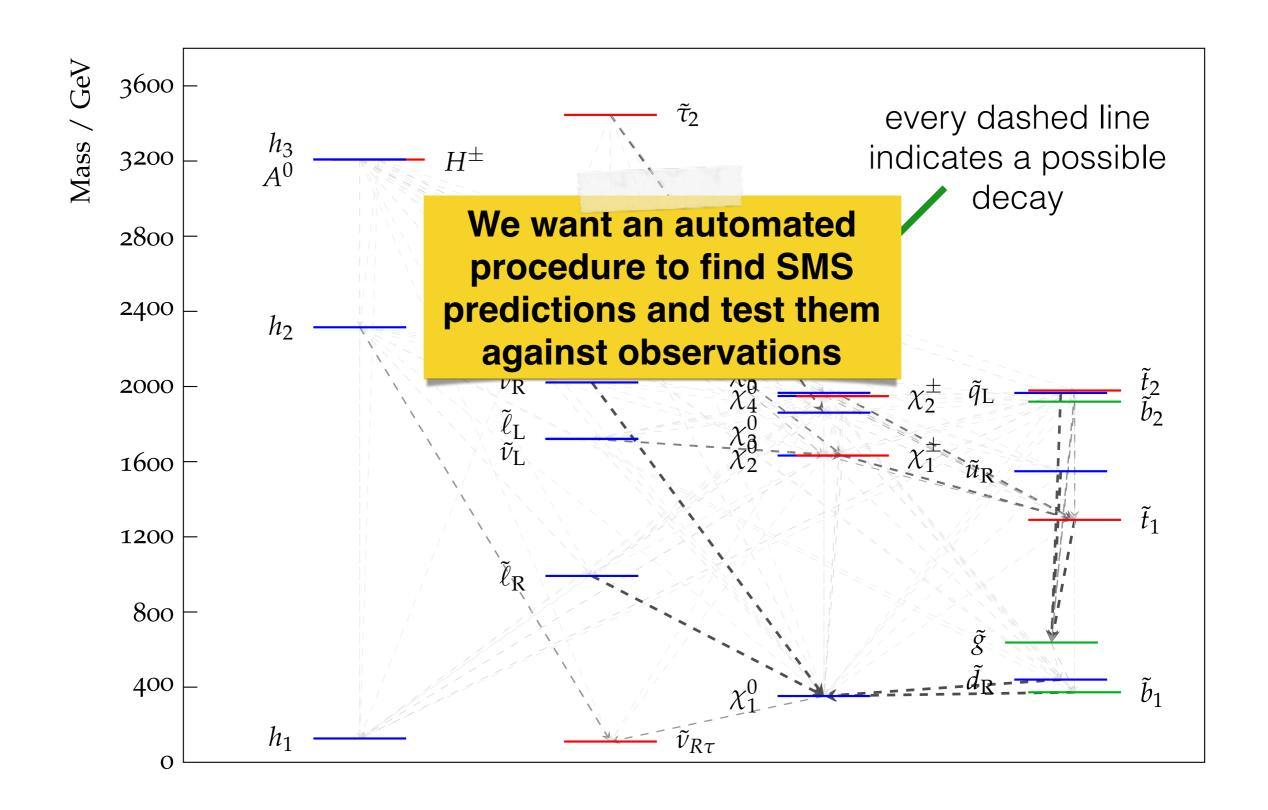
[CMS-SUS-13-007]
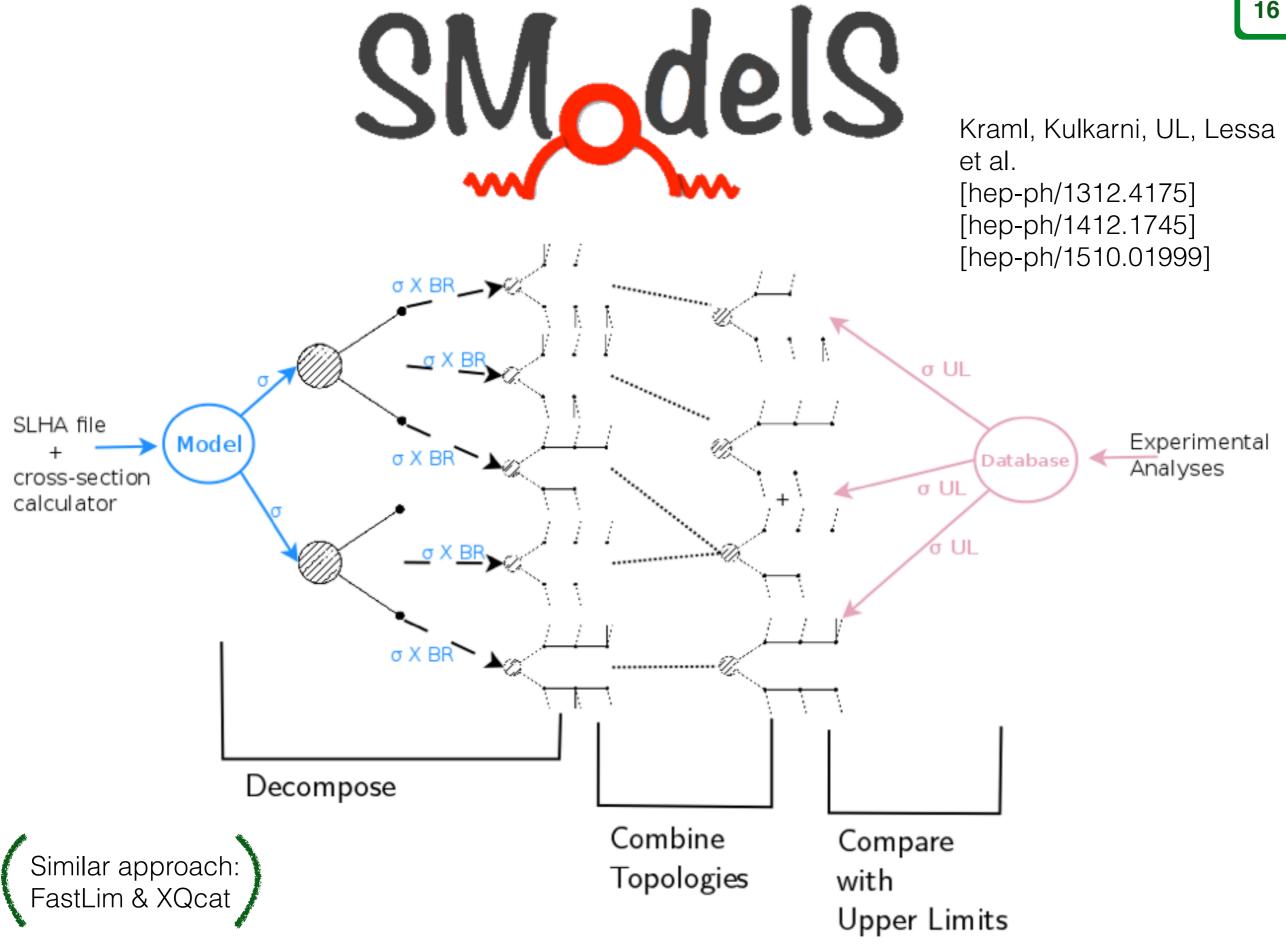
[ATLAS-SUSY-2013-09]

But full models are complicated !

every dashed line indicates a possible decay

But full models are complicated !

We want an automated procedure to find SMS predictions and test them against observations

every dashed line indicates a possible decay

Kraml, Kulkarni, UL, Lessa et al.
[hep-ph/1312.4175]
[hep-ph/1412.1745]
[hep-ph/1510.01999]

SLHA file
+
cross-section
calculator

Model

σ

σ

σ X BR

σ X BR

σ X BR

σ X BR

σ X BR

σ X BR

+

Database

σ UL

σ UL

σ UL

Experimental
Analyses

Decompose

Combine
Topologies

Compare
with
Upper Limits

Similar approach:
FastLim & XQcat

SModelS

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large database with more than 60 Simplified Model results

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works for every model with a Z2 symmetry

large database with more than 60 Simplified Model results

SLHA file
+
cross-section calculator

Model

σ X BR

σ UL

Database

Experimental Analyses

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Combine Topologies

Compare with Upper Limits

Similar approach:
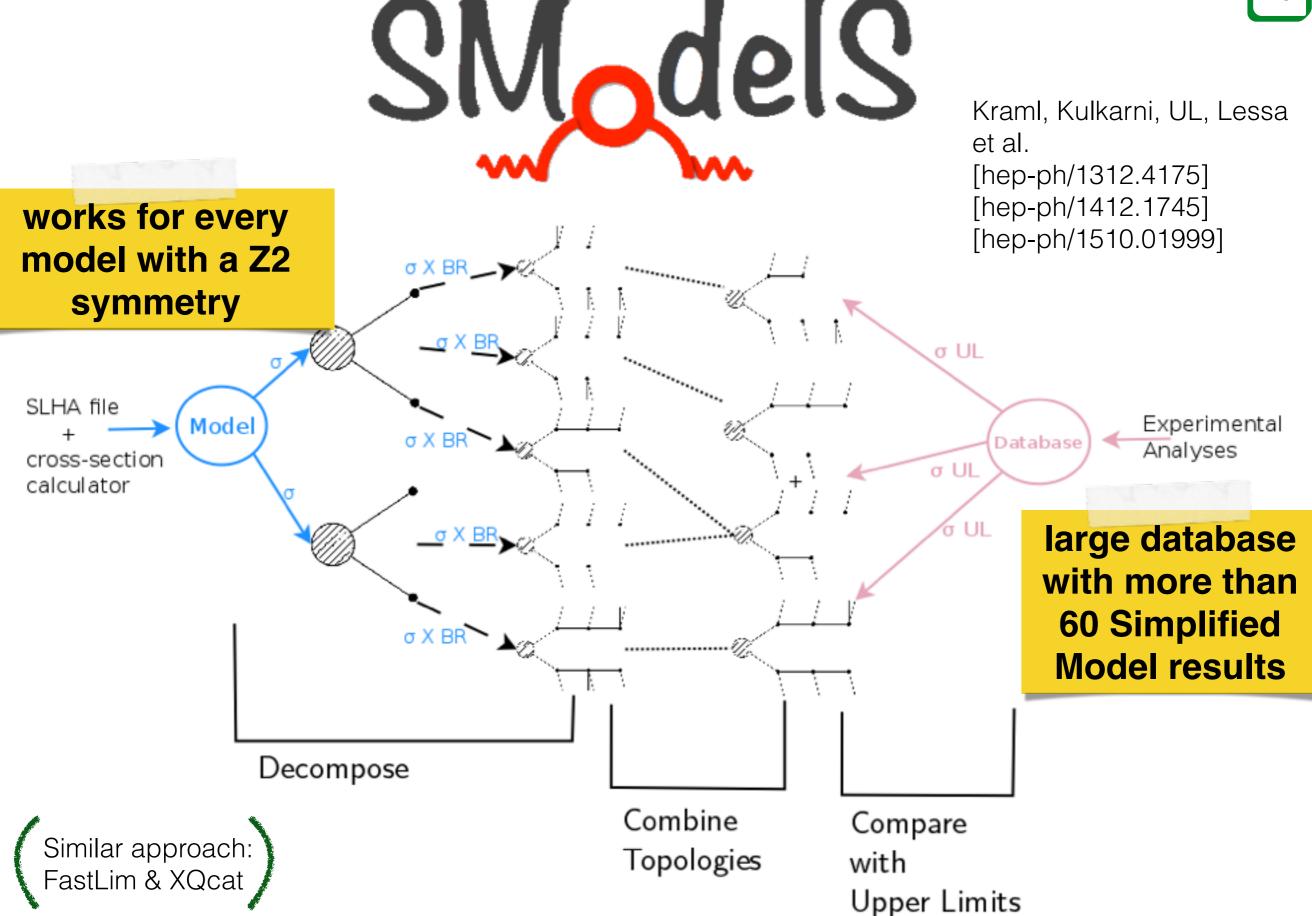FastLim & XQcat

New Features - made in Grenoble

■ "Missing Topologies"
SModelS identifies Simplified Model topologies with large cross section, not covered by the results in the database
This information can be used to improve coverage of BSM searches and SMS interpretations

■ Input Checks
Consistency checks for input models specified in SLHA format, in particular do not apply Simplified Model results in scenarios with long-lived particles

LHC signatures of long-lived particles can also be treated within the SMS framework - and included in SModelS
[Heisig, Lessa, Quertenmont, arXiv:1509.00473]

Application
The MSSM+RN model

[Arina, Cabrera Catalan, Kraml,
Kulkarni, UL, arXiv:1503.02960]

Sneutrino Dark Matter

- All points consistent with measured relic abundance and limits from direct detection

Collider Constraints
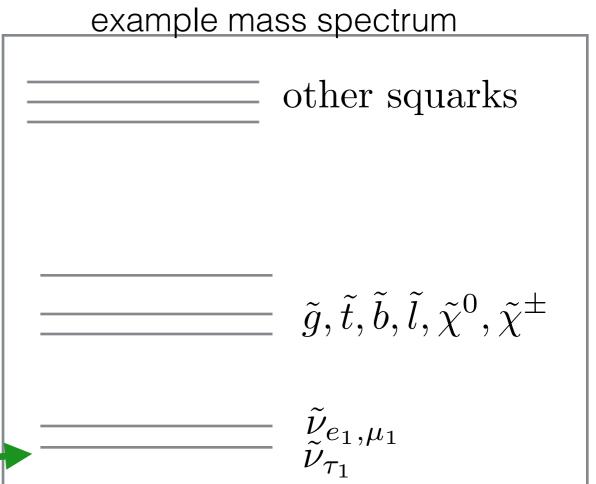
- Use SModelS to study SMS constraints
- Sort out points with long-lived particles
- Study for example scenarios where chargino is light

example mass spectrum

We can describe the sneutrino mixing as

$$\begin{pmatrix} \tilde{\nu}_{k_1} \\ \tilde{\nu}_{k_2} \end{pmatrix} = \begin{pmatrix} -\sin\theta_{\tilde{\nu}}^k & \cos\theta_{\tilde{\nu}}^k \\ \cos\theta_{\tilde{\nu}}^k & \sin\theta_{\tilde{\nu}}^k \end{pmatrix} \begin{pmatrix} \tilde{\nu}_L^k \\ \tilde{N}^k \end{pmatrix}$$

where the mixing angle is a free parameter

sneutrino LSP

other squarks

$\tilde{g}, \tilde{t}, \tilde{b}, \tilde{l}, \tilde{\chi}^0, \tilde{\chi}^\pm$

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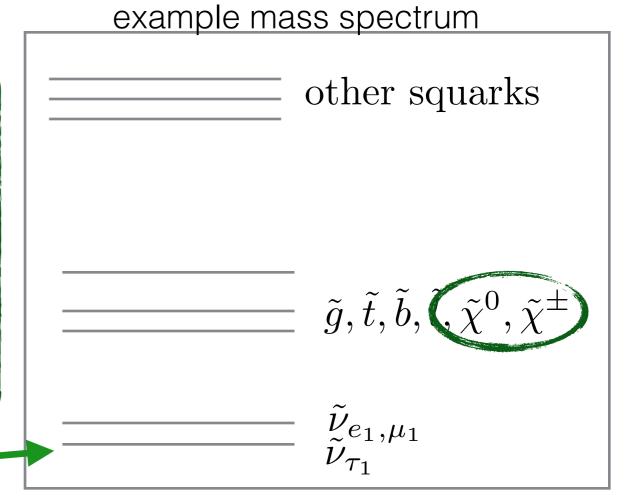
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other squarks

$\tilde{g}, \tilde{t}, \tilde{b}, \ldots, \tilde{\chi}^0, \tilde{\chi}^{\pm}$

$\tilde{\nu}_{e_1,\mu_1}$
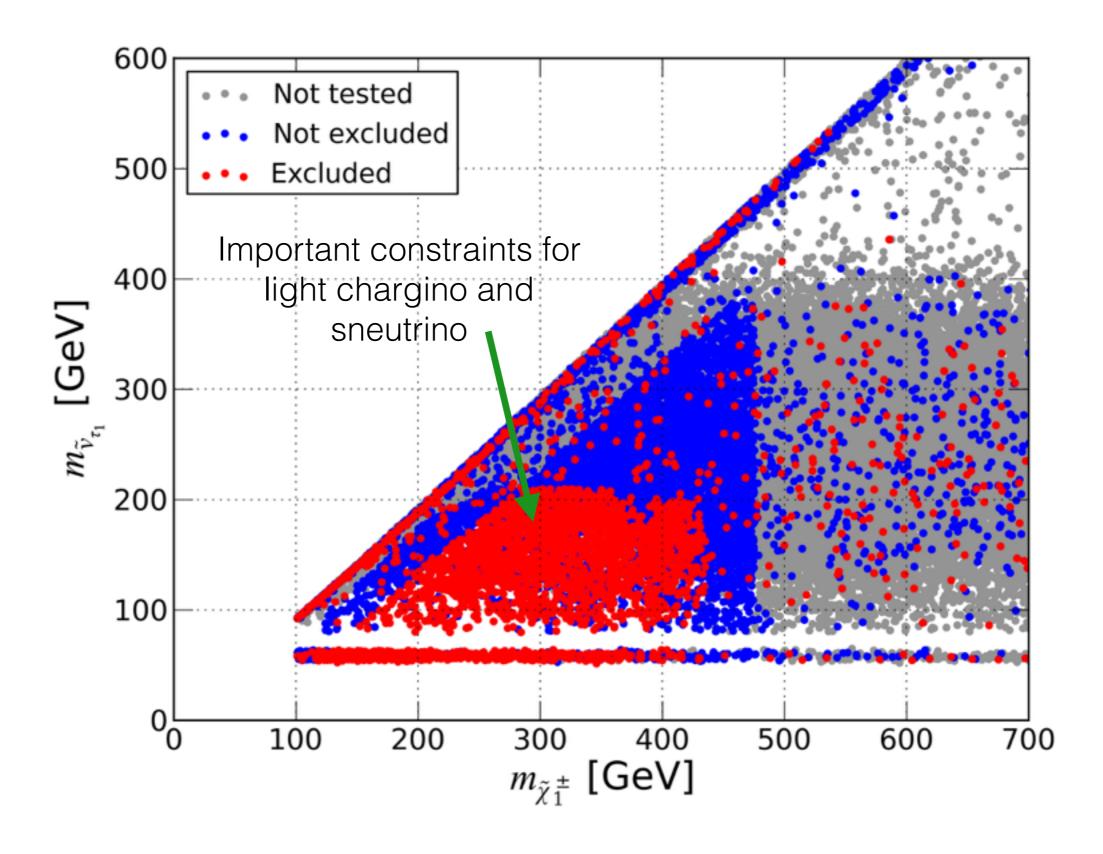$\tilde{\nu}_{\tau_1}$

sneutrino LSP

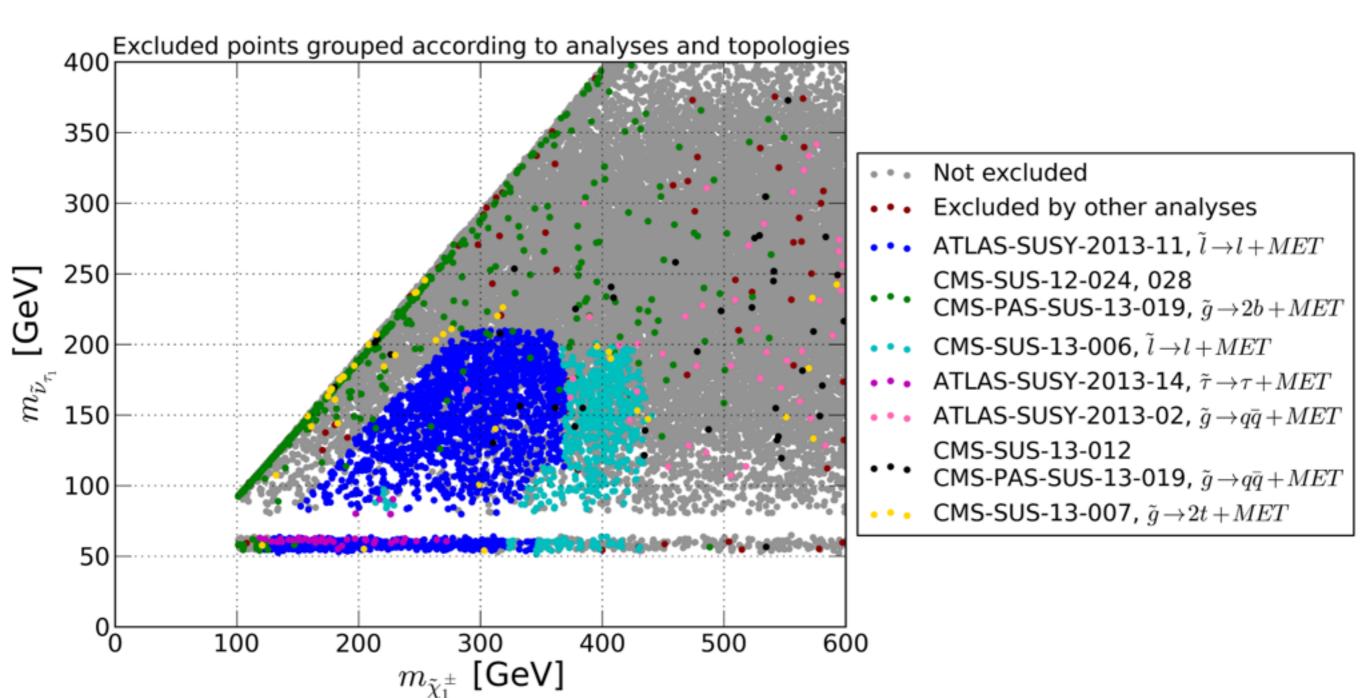# Scenarios with Light Chargino (and Neutralino)

Are sneutrino LSP scenarios constrained by results from LHC Run 1 ?
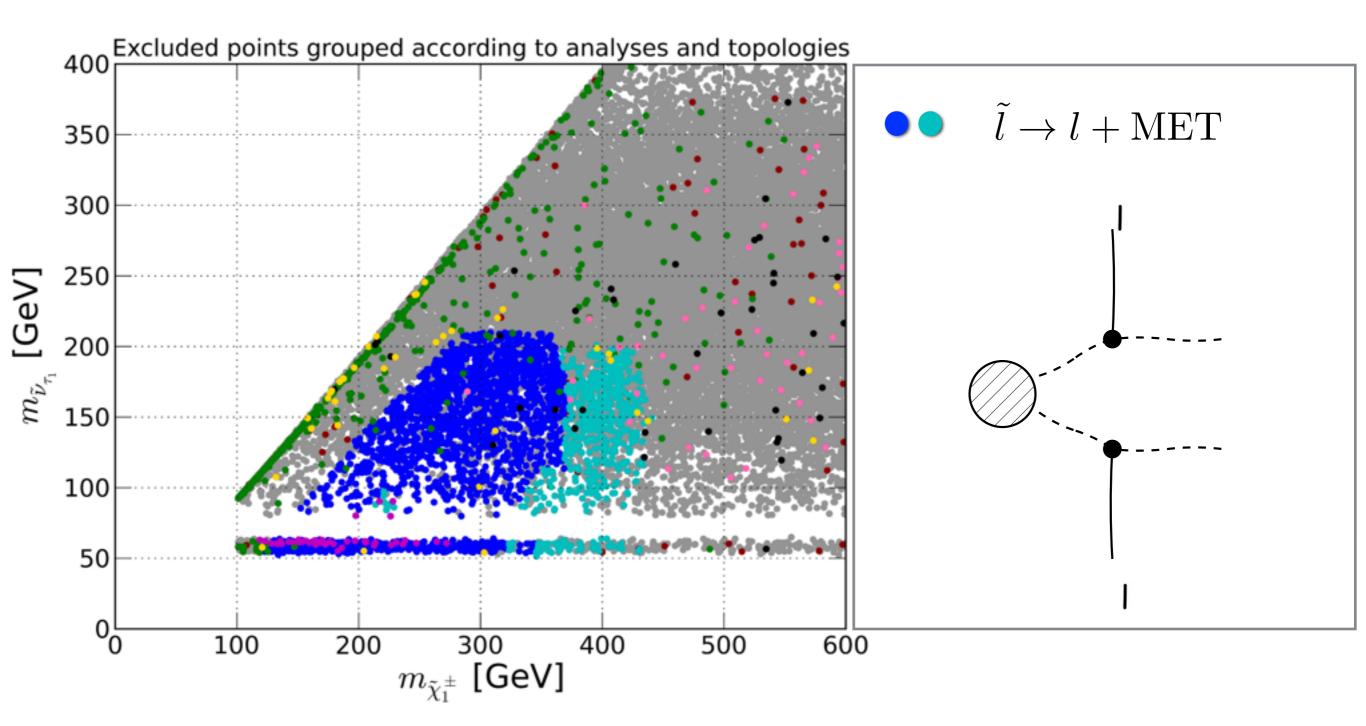
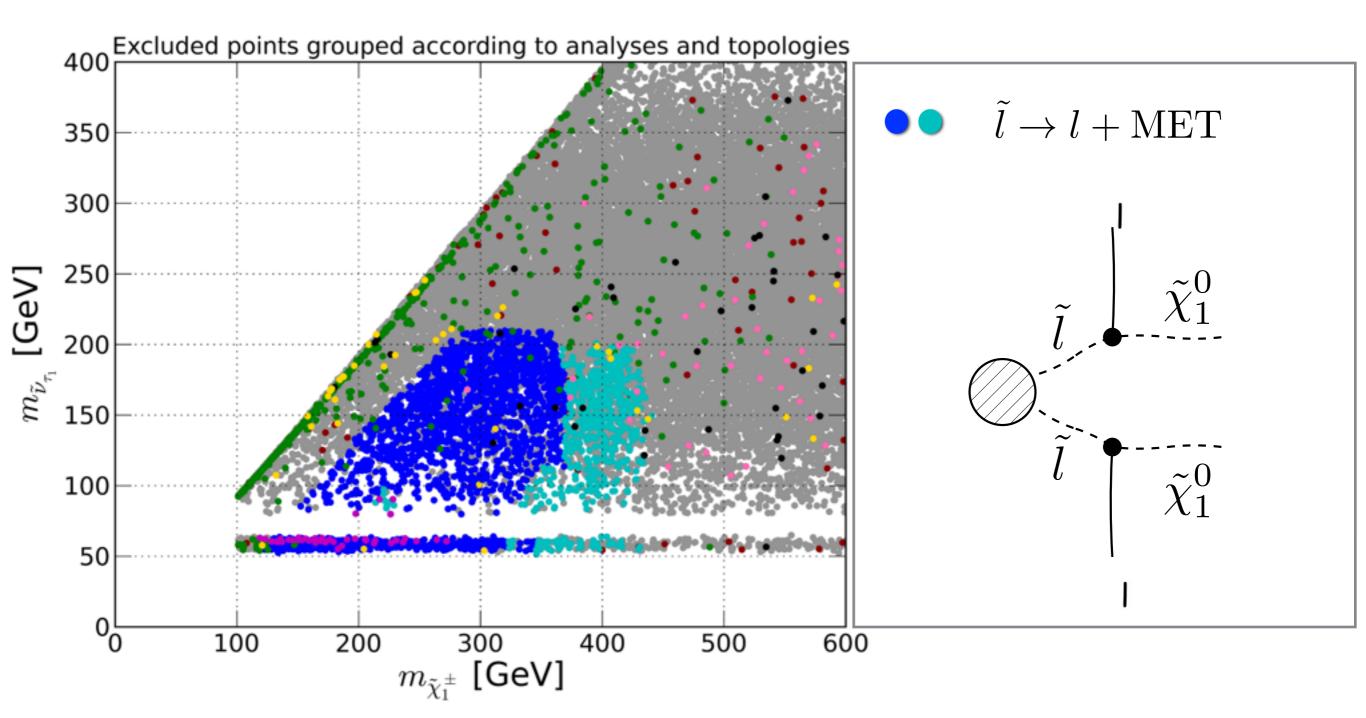Which searches give the most important constraints ?

Which Simplified Models are not yet considered but would improve the constraints ?

Results — Overview

Where do the Constraints come from ?

Excluded points grouped according to analyses and topologies

Legend:
- Not excluded
- Excluded by other analyses
- ATLAS-SUSY-2013-11, $\tilde{l} \rightarrow l + MET$
- CMS-SUS-12-024, 028 CMS-PAS-SUS-13-019, $\tilde{g} \rightarrow 2b + MET$
- CMS-SUS-13-006, $\tilde{l} \rightarrow l + MET$
- ATLAS-SUSY-2013-14, $\tilde{\tau} \rightarrow \tau + MET$
- ATLAS-SUSY-2013-02, $\tilde{g} \rightarrow q\bar{q} + MET$
- CMS-SUS-13-012 CMS-PAS-SUS-13-019, $\tilde{g} \rightarrow q\bar{q} + MET$
- CMS-SUS-13-007, $\tilde{g} \rightarrow 2t + MET$

Axes: $m_{\tilde{\chi}_1^{\pm}}$ [GeV], $m_{\tilde{\nu}_{\tau_1}}$ [GeV]

Where do the Constraints come from ?

Excluded points grouped according to analyses and topologies

$\tilde{l} \to l + \mathrm{MET}$

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Where do the Constraints come from ?

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Where do the Constraints come from ?

Excluded points grouped according to analyses and topologies

$\tilde{\tau} \rightarrow \tau + \mathrm{MET}$

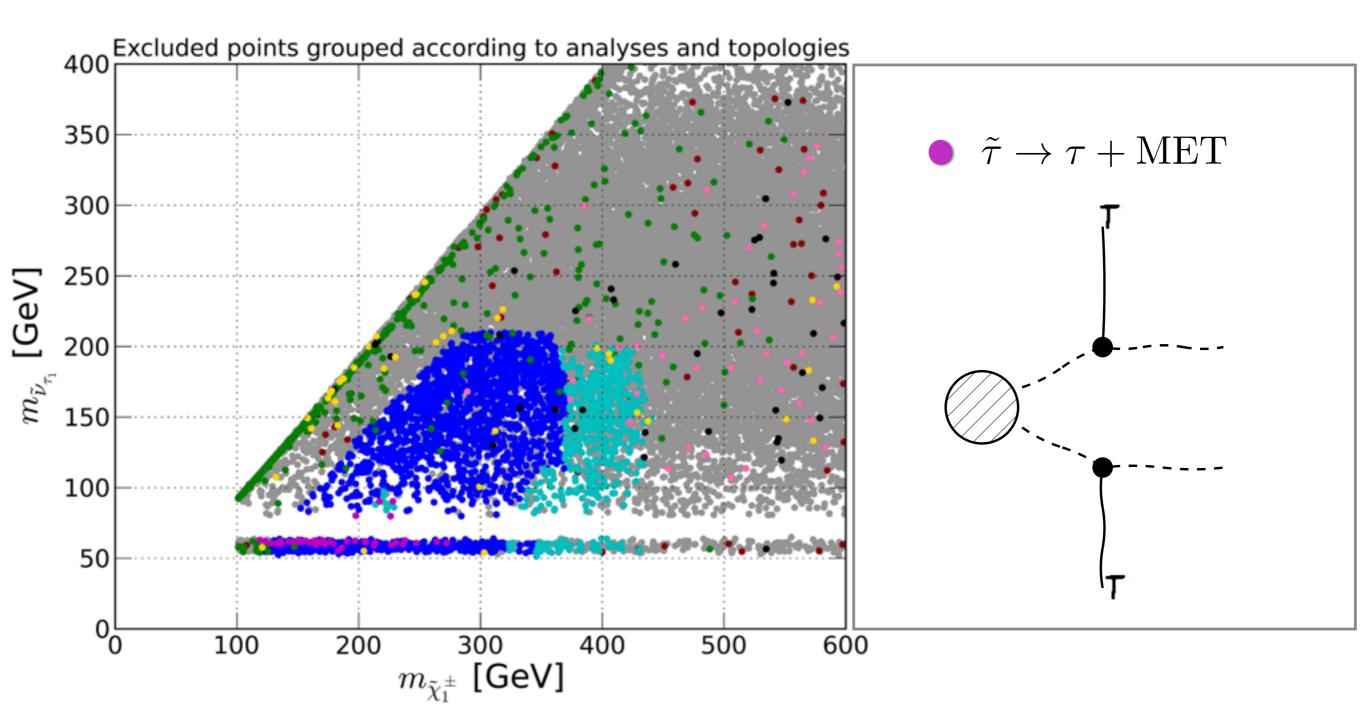# Where do the Constraints come from ?
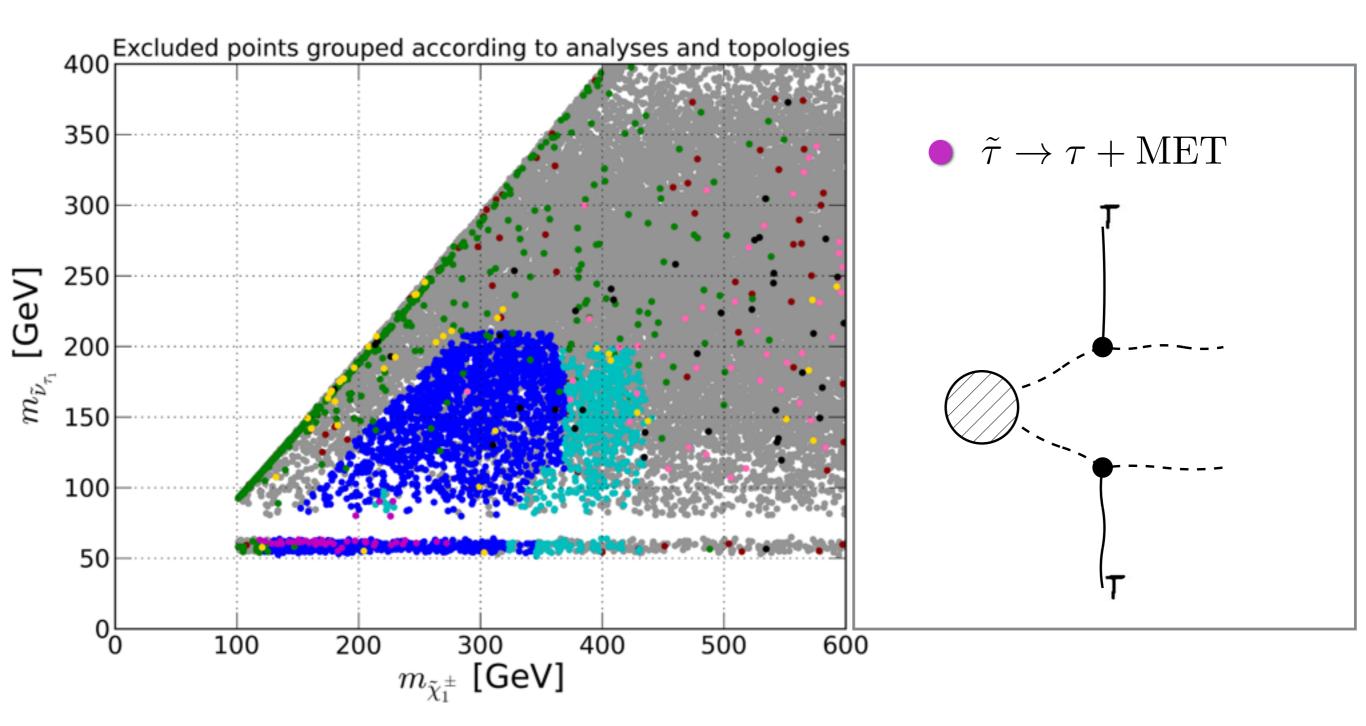

Excluded points grouped according to analyses and topologies
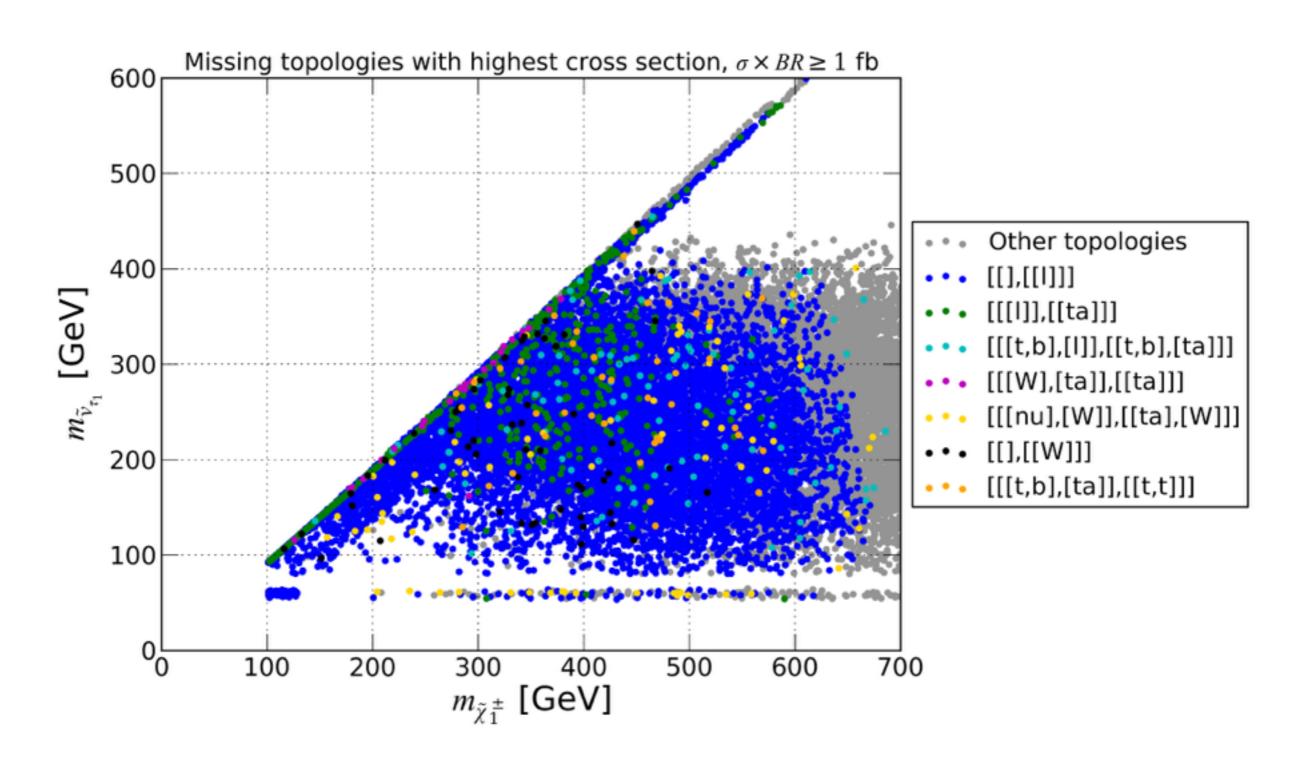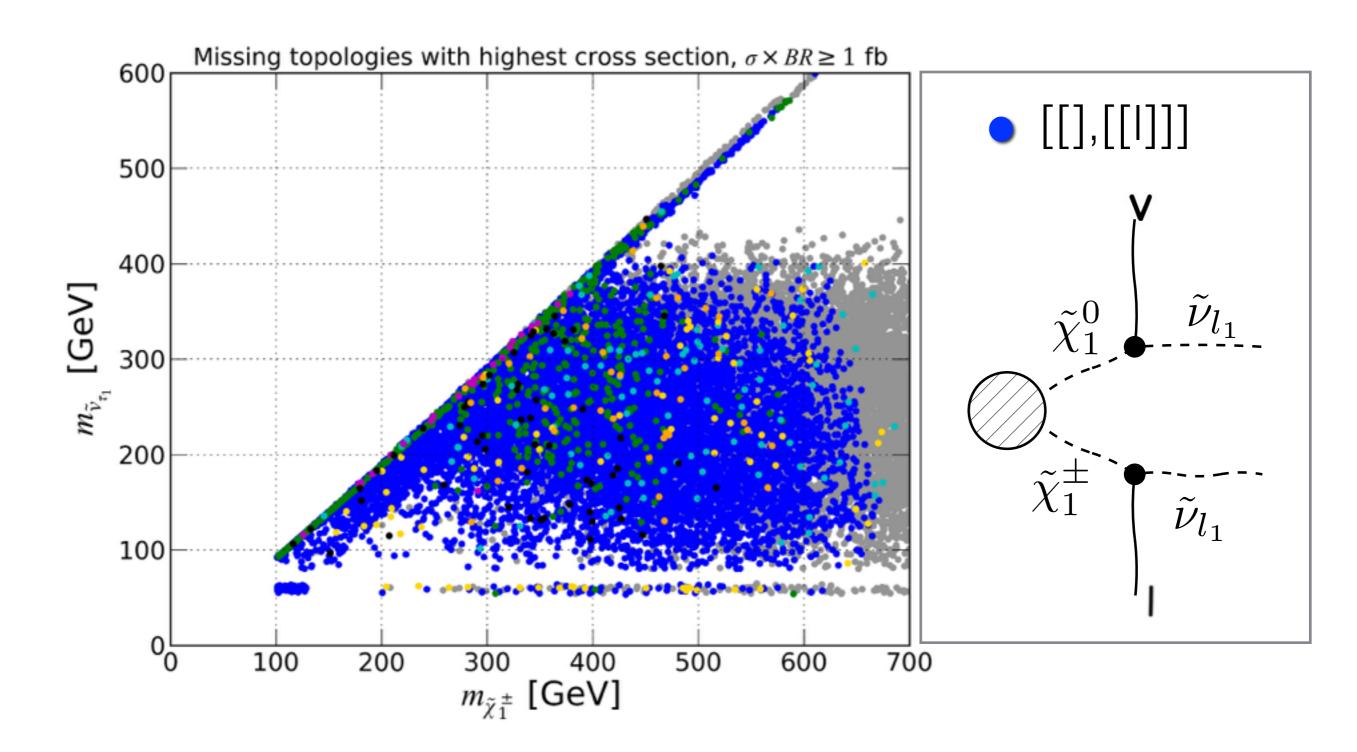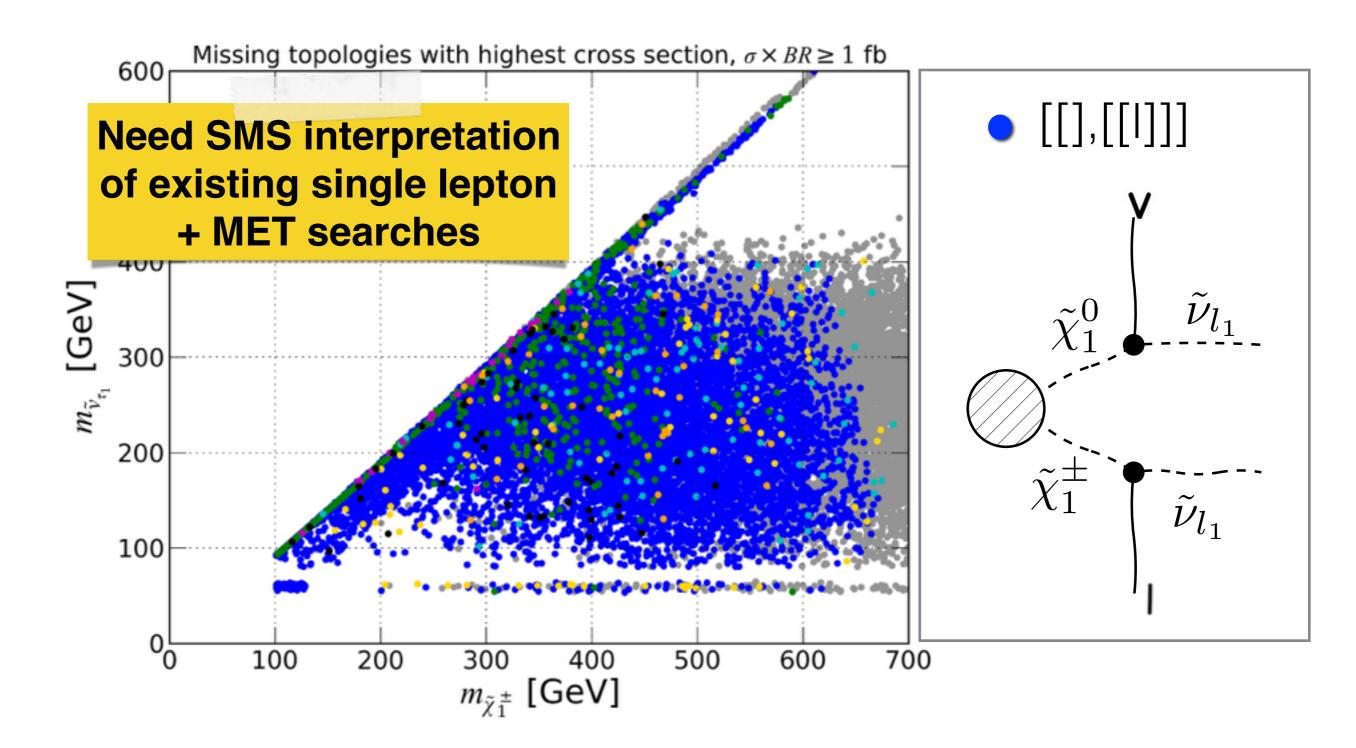
→ Slepton search results constrain chargino production

Single lepton + MET is important topology in non-excluded points

Missing topologies with highest cross section, $\sigma \times BR \geq 1$ fb

Legend:
- Other topologies
- [[ ],[[l]]]
- [[[l]],[[ta]]]
- [[[t,b],[l]],[[t,b],[ta]]]
- [[[W],[ta]],[[ta]]]
- [[[nu],[W]],[[ta],[W]]]
- [[ ],[[W]]]
- [[[t,b],[ta]],[[t,t]]]

Axes: $m_{\tilde{\chi}_1^\pm}$ [GeV] (horizontal), $m_{\tilde{\nu}_{\tau_1}}$ [GeV] (vertical)

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Single lepton + MET is important topology in non-excluded points

Missing topologies with highest cross section, $\sigma \times BR \geq 1$ fb

Need SMS interpretation of existing single lepton + MET searches

$[[],[[l]]]$

Application
The U(1)-extended MSSM

[Belanger, Da Silva, UL, Pukhov, arXiv:1505.06243]
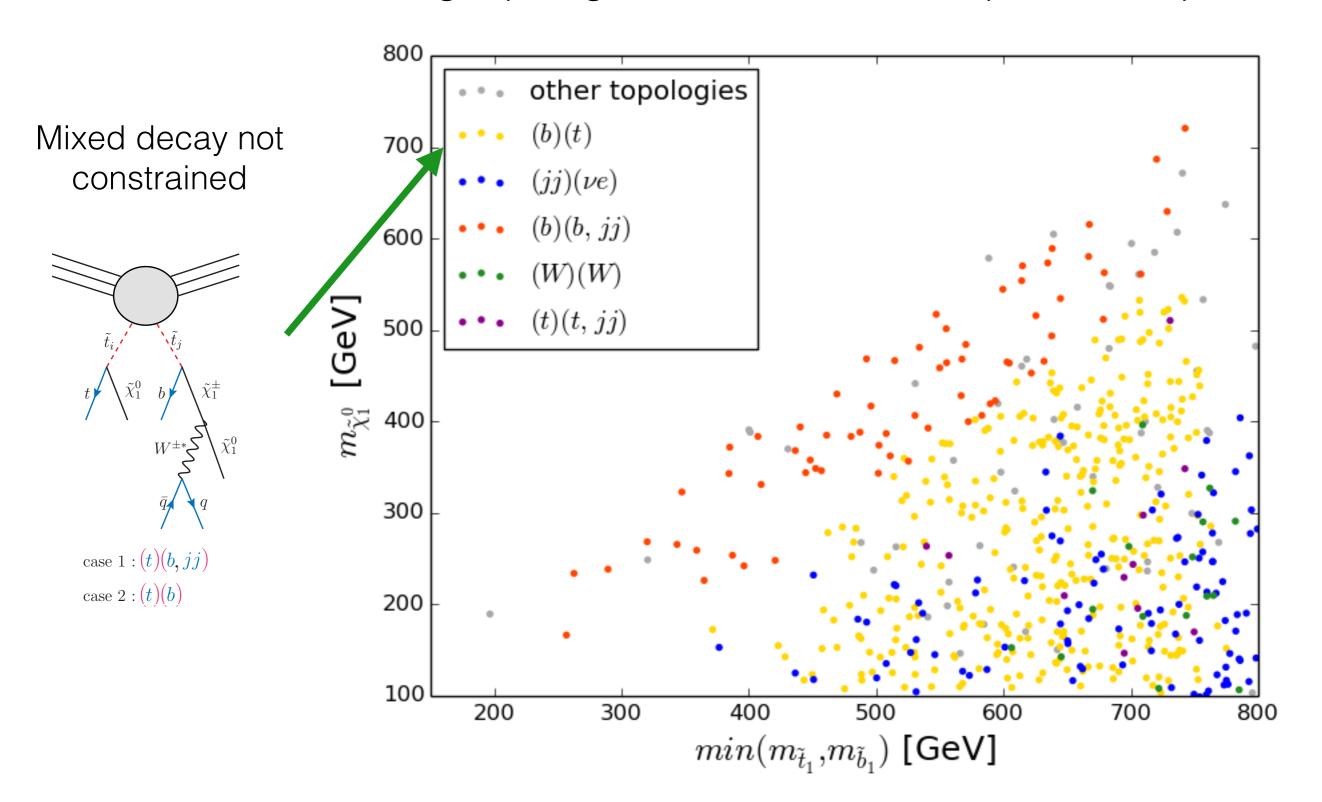
- Study of MSSM extension with extra U(1) gauge group
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U'(1)$$

- Extended particle contend, including in particular a Z'
- Constraints from SUSY searches included in terms of Simplified Model constraints
- Here: scenarios with "Higgs-like" LSP (higgsino, also possible in the MSSM) and light stop
- This differs from most Simplified Model assumptions because the lightest chargino is only slightly heavier than the LSP
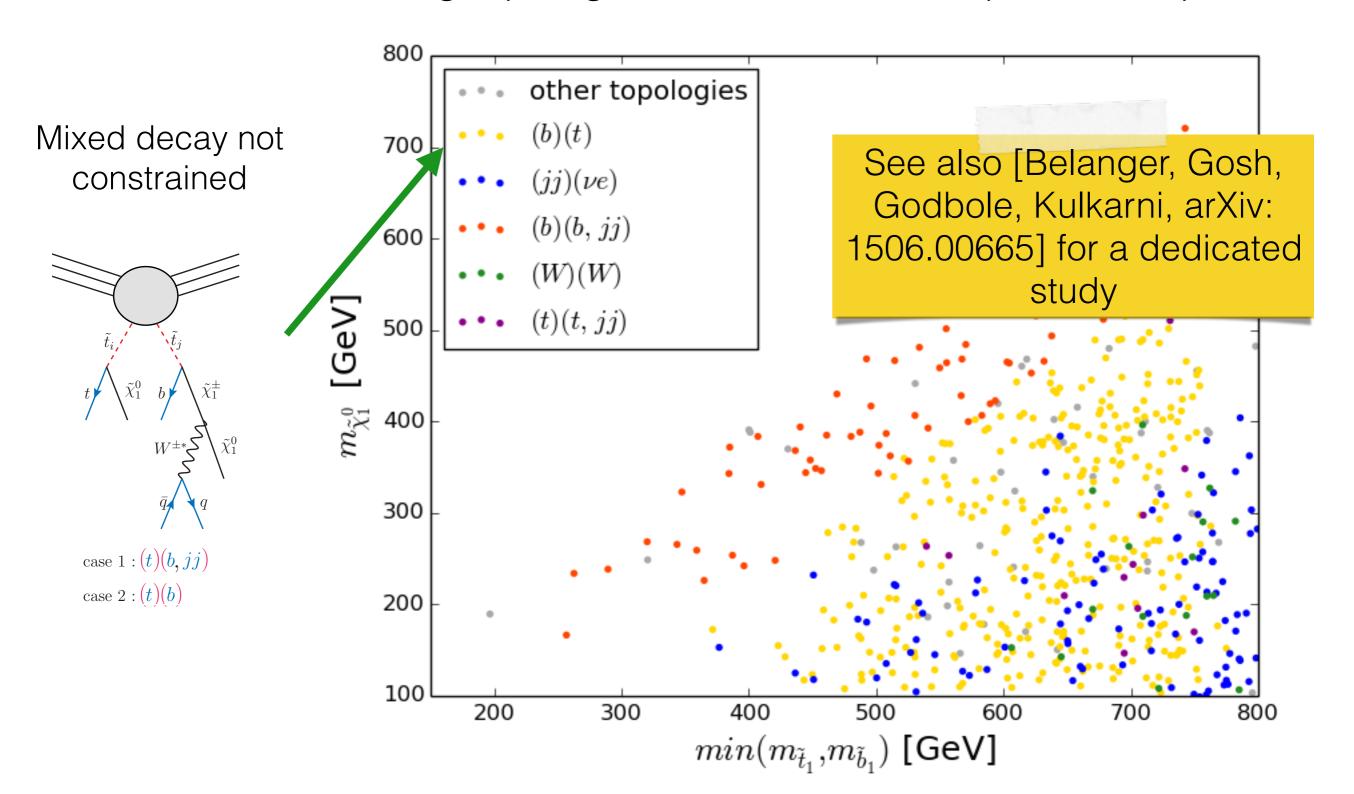
Many points with light stops are still allowed

→ Check the missing topologies for non-excluded parameter points

Mixed decay not constrained

case 1 : $(t)(b, jj)$

case 2 : $(t)(b)$

Legend:
- other topologies
- $(b)(t)$
- $(jj)(\nu e)$
- $(b)(b, jj)$
- $(W)(W)$
- $(t)(t, jj)$

Axes: $m_{\tilde{\chi}_1^0}$ [GeV] vs $min(m_{\tilde{t}_1}, m_{\tilde{b}_1})$ [GeV]

Many points with light stops are still allowed

→ Check the missing topologies for non-excluded parameter points

Mixed decay not constrained

case 1 : $(t)(b, jj)$

case 2 : $(t)(b)$

See also [Belanger, Gosh, Godbole, Kulkarni, arXiv: 1506.00665] for a dedicated study
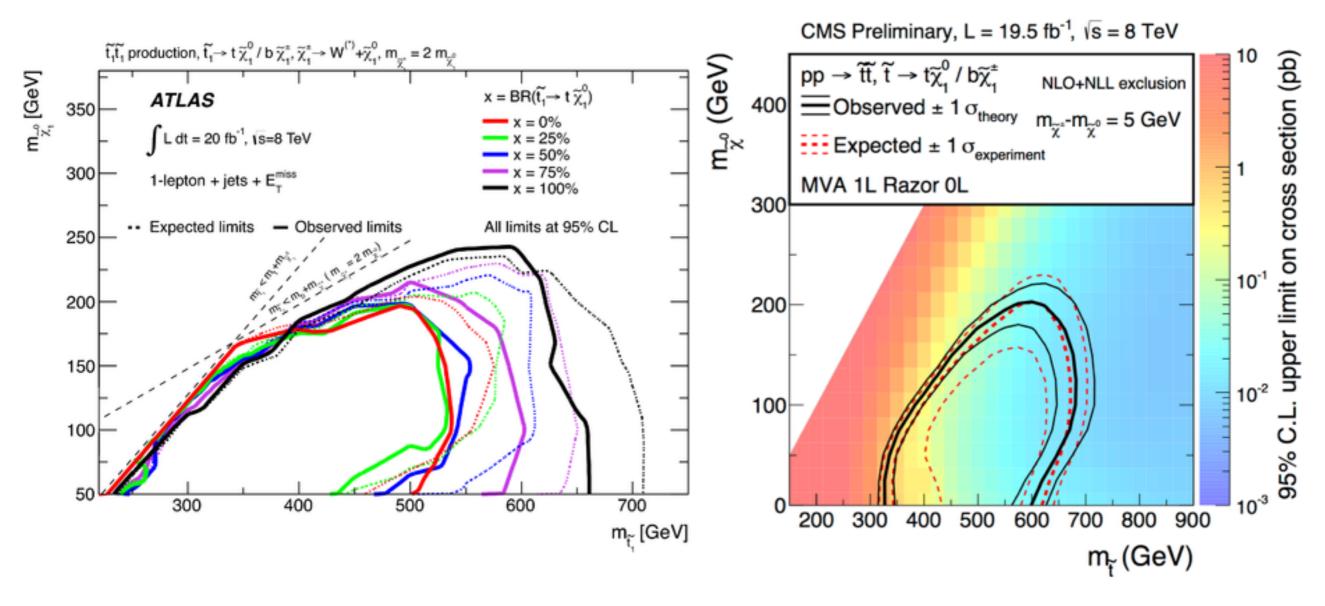
Presentation of Experimental Results

ATLAS-SUSY-2013-15

CMS-SUS-14-011

Parametrised in terms of BR → this cannot be used to study alternative models

Conservative limit valid for any BR → could be included in SModelS

Conclusion

■ Simplified Models
- useful tool for quick test of BSM models against constraints from LHC searches
- survey large parameter spaces

■ SModelS
- automated decomposition procedure
- identify constraints, missing topologies, long-lived particles

■ Sneutrino dark matter + light chargino
- main constraint from dilepton+MET searches
- important single lepton+MET Simplified Model not yet considered

■ Higgsino LSP + light stop
- SMS constraints weak
- mixed topologies not fully considered

Work in Progress

- SModelS
- new verision, using also efficiency map type constraints, in preparation
- database can be extended using recasting tools, generating efficiency maps for SMS not considered by the experiments
- interface SModelS - micrOMEGAs

- Testing the SModelS assumptions
- applicability of stop SMS results to fermionic top partners

- Beyond SMS
- use recasting tools to test LHC constraints on model with compressed spectra and/or long cascade decays

Backup

Reinterpretation of the Results

- To interpret the result of a search in an alternative model we need to determine the signal selection efficiency to predict an expected number of signal events
- This can be done using recasting frameworks, e.g. MadAnalysis5, CheckMate

Reinterpretation

Event simulation - MadGraph, Pythia, …

↓ *Parton Level events*

(fast) Detector simulation - Delphes

↓ *Reconstructed objects*

Application of signal selection cuts

Selection efficiency →

Cross section prediction - e.g. NLLfast

↓

Point excluded / compatible with observation

Number of expected and observed events ↙

Reinterpretation of the Results

- ◼ To interpret the result of a search in an alternative model we need to determine the signal selection efficiency to predict an expected number of signal events
- ◼ This can be done using recasting frameworks, e.g. MadAnalysis5, CheckMate

Reinterpretation

Event simulation - MadGr

Slow → not well suited to survey large parameter space

ss section
ction - e.g.
NLLfast

Parton Level events

(fast) Detector simulation - Delphes

Reconstructed objects

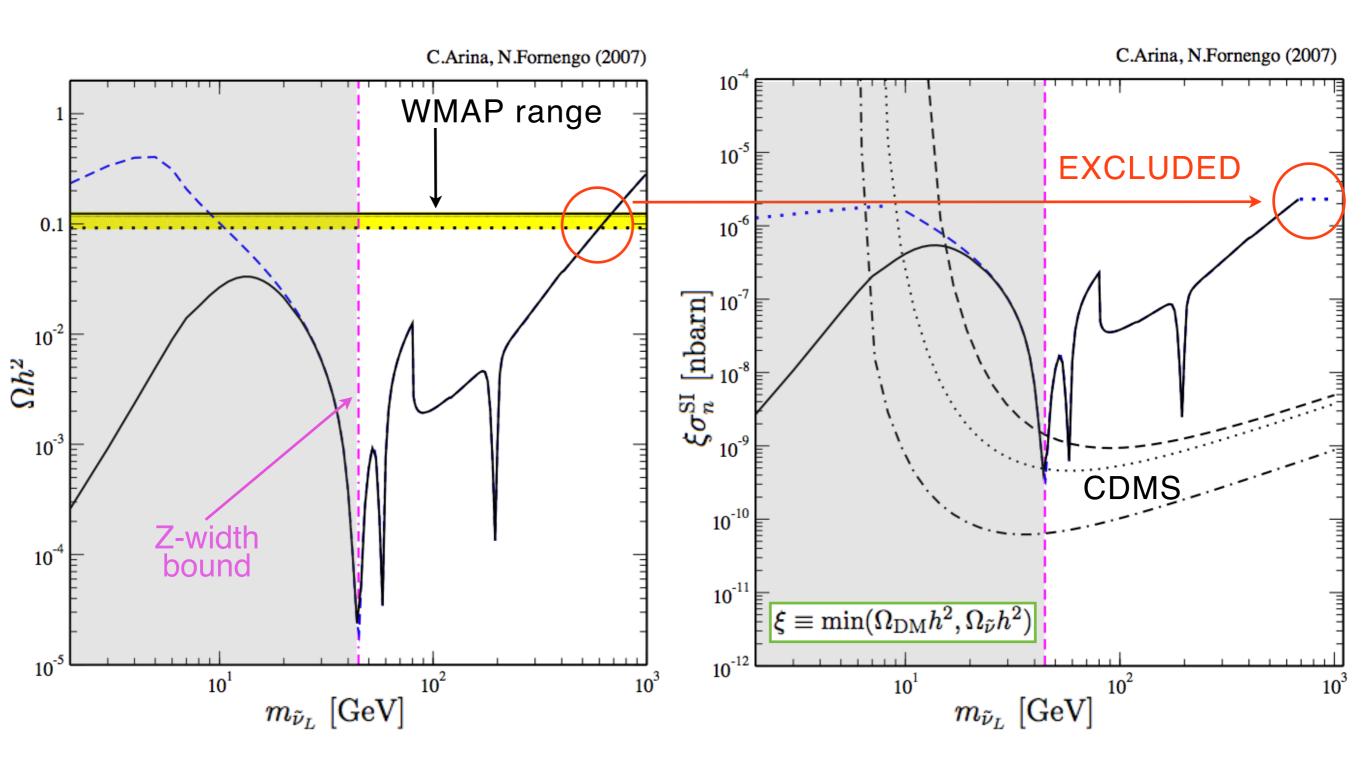Application of signal selection cuts

Selection efficiency

Point excluded / compatible with observation

Number of expected and observed events

LH Sneutrino Dark Matter ?

C.Arina, N.Fornengo (2007)

WMAP range

Z-width bound

C.Arina, N.Fornengo (2007)

EXCLUDED

CDMS

$\xi \equiv \min(\Omega_{\mathrm{DM}} h^2, \Omega_{\tilde{\nu}} h^2)$

The MSSM+RN Model

▷ superpotential for Dirac RH neutrino superfield

$$W = \epsilon_{ij}(\mu \hat{H}_i^u \hat{H}_j^d - Y_l^{IJ} \hat{H}_i^d \hat{L}_j^I \hat{R}^J + Y_\nu^{IJ} \hat{H}_i^u \hat{L}_j^I \hat{N}^J)$$

▷ additional terms in the soft-breaking potential

$$V_{\text{soft}} = (M_L^2)^{IJ} \tilde{L}_i^{I*} \tilde{L}_i^J + (M_N^2)^{IJ} \tilde{N}^{I*} \tilde{N}^J$$

$$-[\epsilon_{ij}(\Lambda_l^{IJ} H_i^d \tilde{L}_j^I \tilde{R}^J + \Lambda_\nu^{IJ} H_i^u \tilde{L}_j^I \tilde{N}^J) + \text{h.c.}]$$

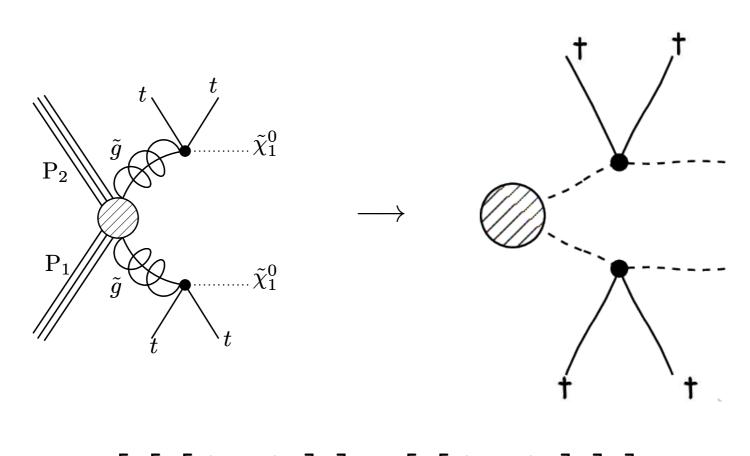▷ the sneutrino mass eigenstates are then given by

$$\begin{pmatrix} \tilde{\nu}_{k_1} \\ \tilde{\nu}_{k_2} \end{pmatrix} = \begin{pmatrix} -\sin\theta_{\tilde{\nu}}^k & \cos\theta_{\tilde{\nu}}^k \\ \cos\theta_{\tilde{\nu}}^k & \sin\theta_{\tilde{\nu}}^k \end{pmatrix} \begin{pmatrix} \tilde{\nu}_L^k \\ \tilde{N}^k \end{pmatrix}$$

with $\sin 2\theta_{\tilde{\nu}}^k = \sqrt{2} \dfrac{A_{\tilde{\nu}}^k v \sin\beta}{(m_{\tilde{\nu}_{k2}}^2 - m_{\tilde{\nu}_{k1}}^2)}$

SModelS description

Additional assumption Simplified Model results depend mainly on the mass spectrum of the new particles, not on specifics of the model (spin structure, production process, …)
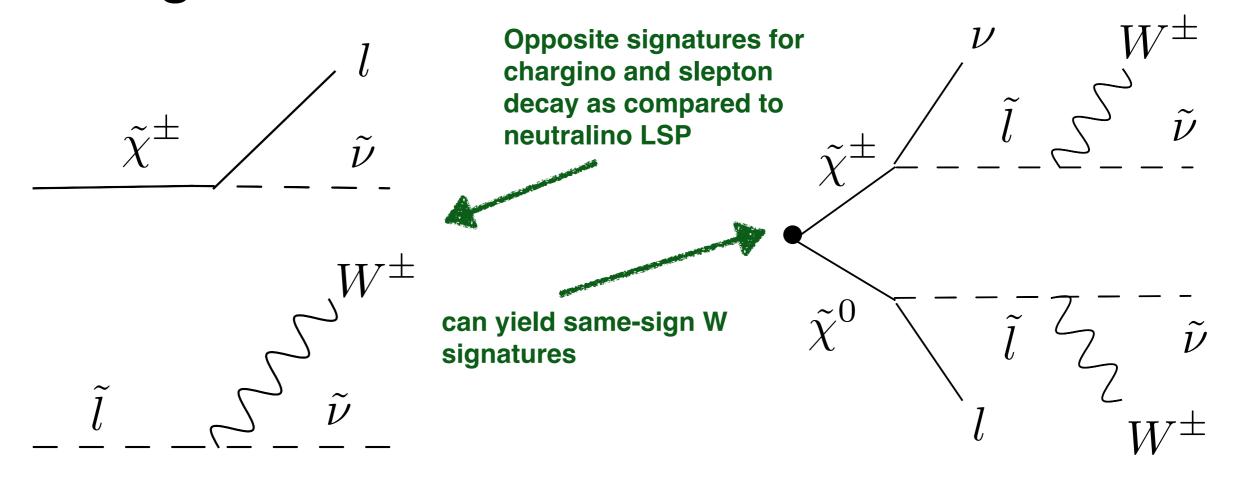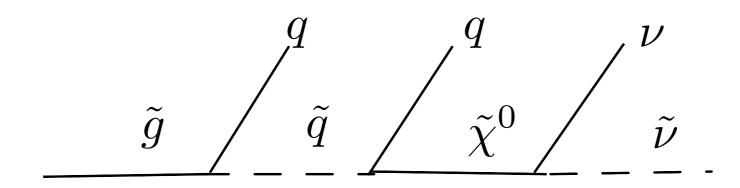
➡ describe topology by vertex structure and outgoing SM particles in each vertex

$$[[[t,t]],[[t,t]]]$$

Signatures in Sneutrino LSP scenarios

Opposite signatures for chargino and slepton decay as compared to neutralino LSP

can yield same-sign W signatures

$\tilde{\chi}^{\pm}$ l $\tilde{\nu}$

$\tilde{l}$ $W^{\pm}$ $\tilde{\nu}$

ν $W^{\pm}$ $\tilde{\chi}^{\pm}$ $\tilde{l}$ $\tilde{\nu}$

$\tilde{\chi}^{0}$ $\tilde{l}$ $\tilde{\nu}$ l $W^{\pm}$

q q ν

$\tilde{g}$ $\tilde{q}$ $\tilde{\chi}^{0}$ $\tilde{\nu}$

gluino decay indistinguishable from neutralino LSP scenario

MSSM+RN Parameters sampled using Multinest

GUT scale Parameters	Prior range
M_1, M_2	(-4000, 4000) GeV
$log_{10}(M_3/\mathrm{GeV})$	(-4, 4)
$log_{10}(m_Q/\mathrm{GeV})$	(2, 5)
m_L, m_R	(1, 2000) GeV
m_N	(1, 2000) GeV
$log_{10}(A_Q/\mathrm{GeV})$	(-5, 5)
A_L	(-4000, 4000) GeV
$A_{\tilde{\nu}}$	(-1000, 1000) GeV
$log_{10}(m_H/\mathrm{GeV})$	(1, 5)
$\tan\beta$	(3, 50)

MSSM + RN Selection Details

Observable	Value / constraint
m_h	125.85 ± 0.4 (exp) ± 4 (theo) GeV
$\mathrm{BR}(B \to X_s \gamma) \times 10^4$	3.55 ± 0.24 ± 0.09 (exp)
$\mathrm{BR}(B \to \mu^+ \mu^-) \times 10^9$	3.2 (+1.4 -1.2) (stat) (+0.5 -0.3) (sys)
$\Omega_{\mathrm{DM}} h^2$	0.1186 ± 0.0031 (exp) ± 20% (theo)
$\Delta\Gamma_Z^{\mathrm{invisible}}$	< 2 MeV (95% CL)
$\mathrm{BR}(h \to \mathrm{invisible})$	< 20% (95% CL)
$m_{\tilde{\tau}_1^-}$	> 85 GeV (95% CL)
$m_{\tilde{\chi}_1^+}, m_{\tilde{e}, \tilde{\mu}}$	>101 GeV (95% CL)
$m_{\tilde{g}}$	> 308 GeV (95% CL)
σ_n^{SI}	< $\sigma_{\mathrm{LUX}}^{SI}$ (90% CL)

Measurements

Limits

Application of Slepton Limits to Chargino Production

test this for ATLAS-SUSY-2013-11, using the MadAnalysis 5 implementation
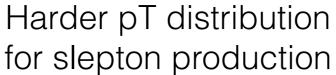(B. Dumont, INSPIRE-1326686)

Compare the corresponding efficiencies in a benchmark scenario with
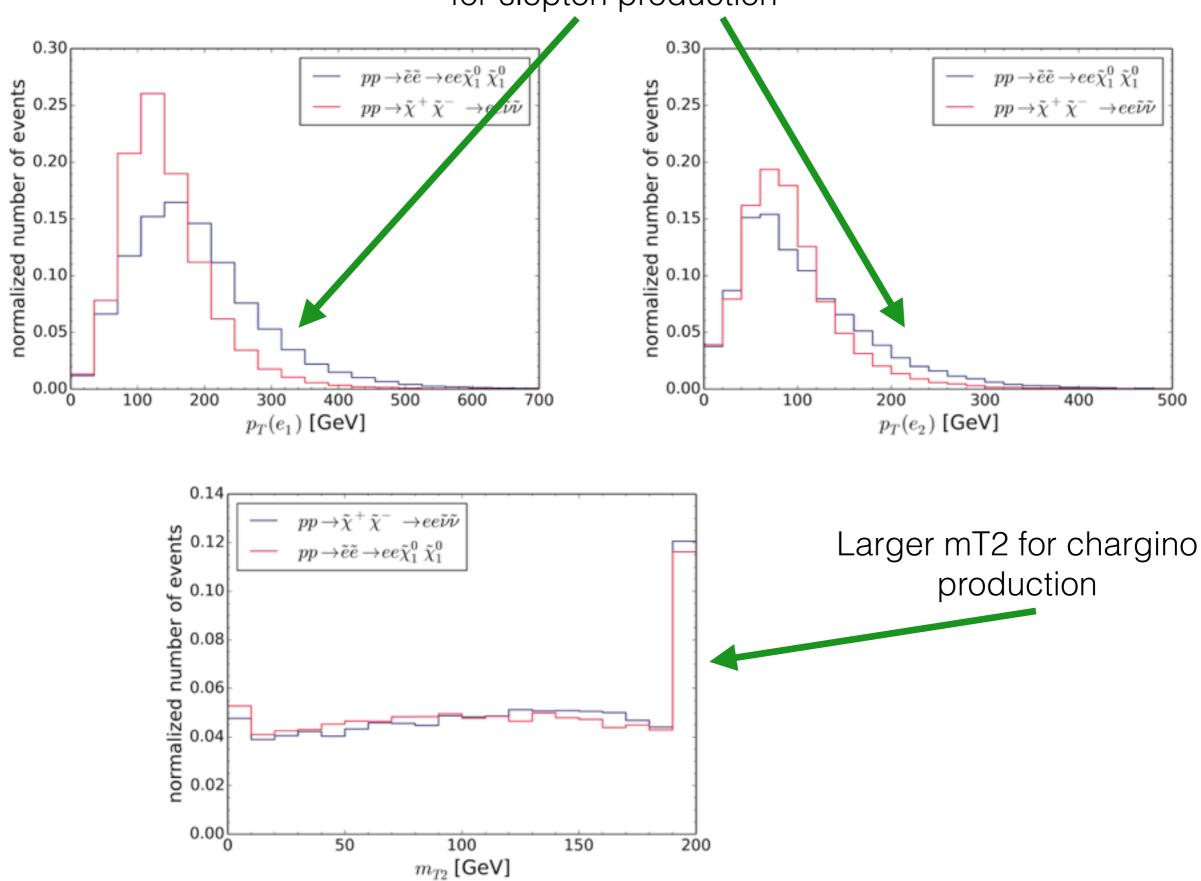
$$m_{mother} = 270 \text{ GeV}, m_{LSP} = 100 \text{ GeV}$$

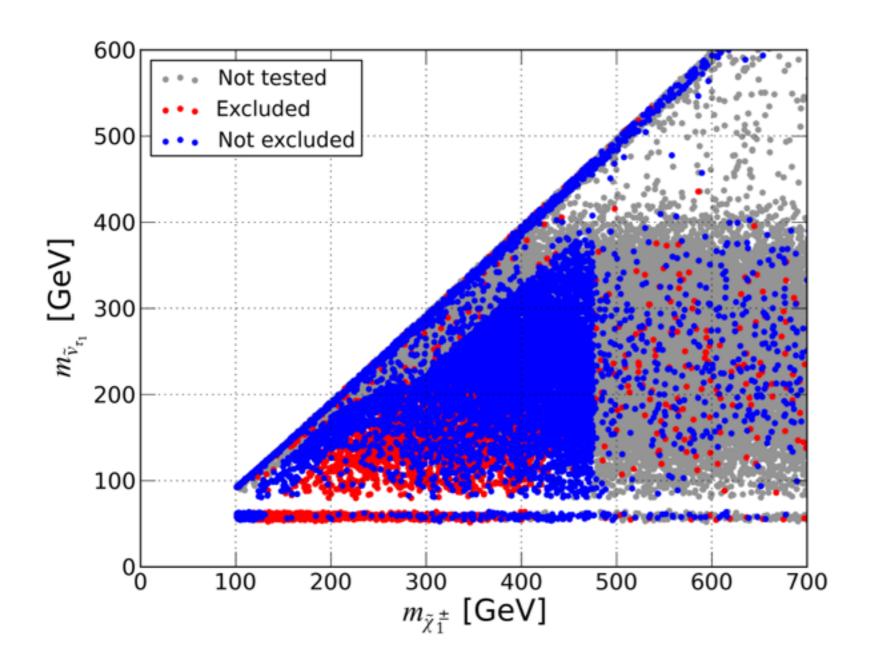Selection efficiencies somewhat different for individual cuts

Final efficiencies are comparable !

Cut	Slepton production	Chargino production
Common preselection		
Initial number of events	50000	50000
2 OS leptons	35133	33464
$m_{ll} > 20$ GeV	35038	33337
τ veto	35007	33318
ee leptons	35007	33318
jet veto	20176	19942
Z veto	19380	18984
Different m_{T2} regions		
$m_{T2} > 90$ GeV	11346	11594
$m_{T2} > 120$ GeV	8520	8828
$m_{T2} > 150$ GeV	5723	5926

Harder pT distribution for slepton production

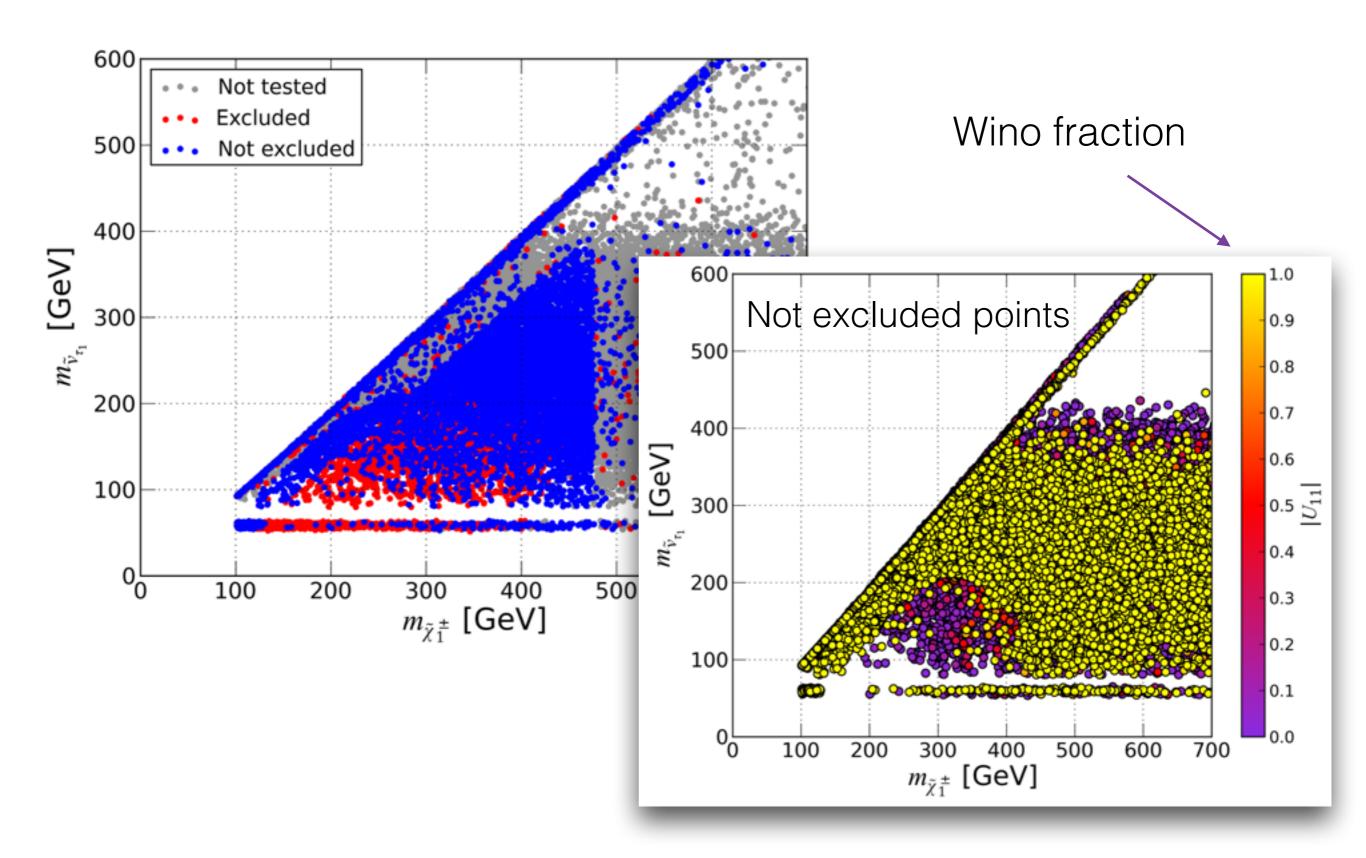Larger mT2 for chargino production
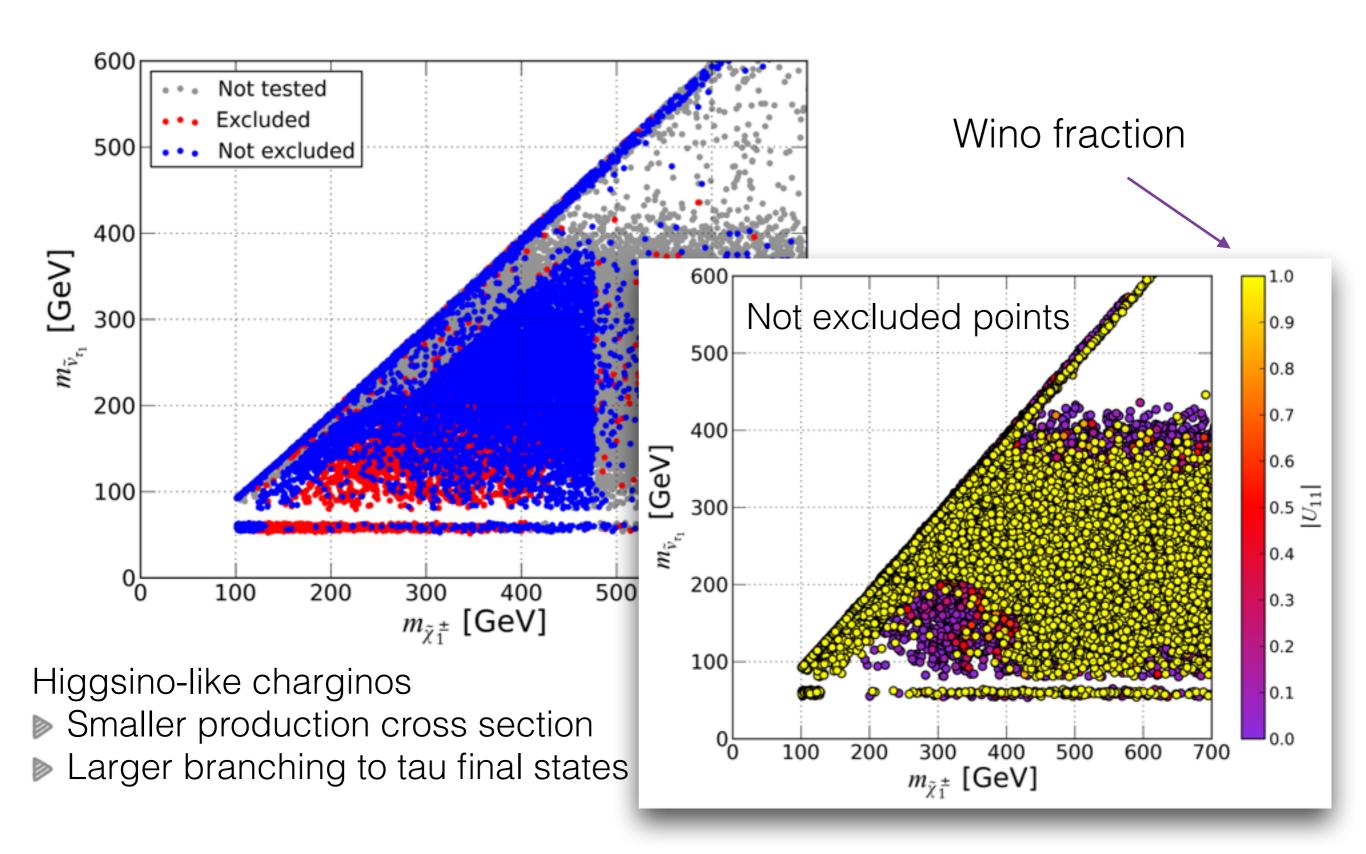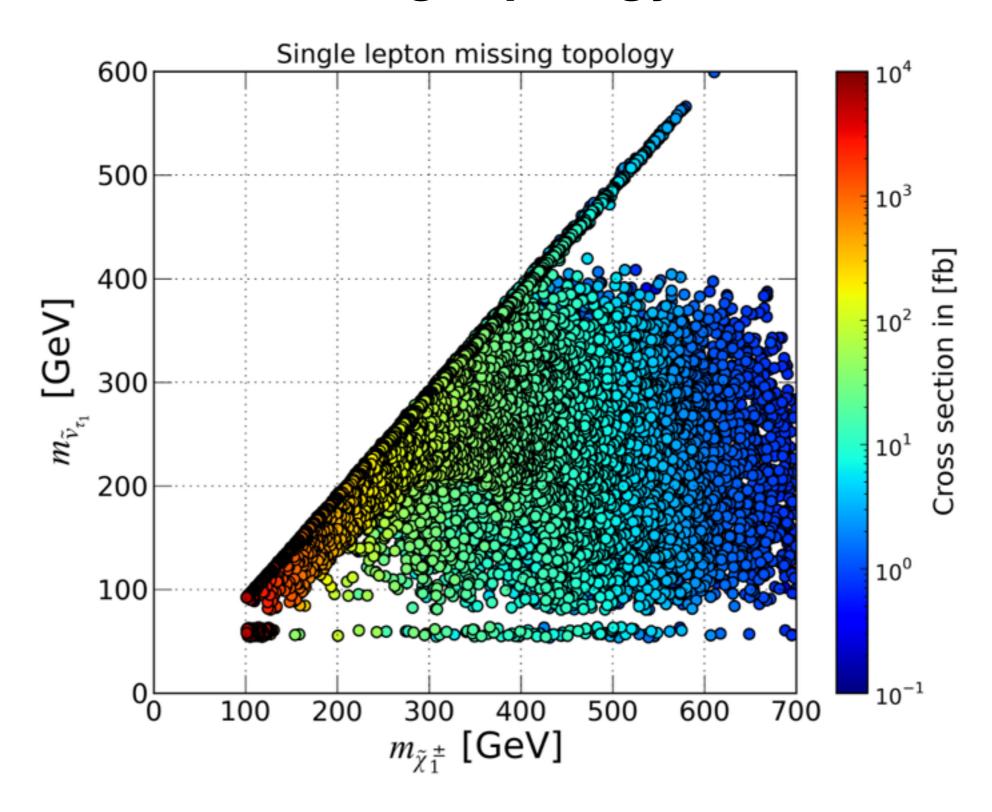
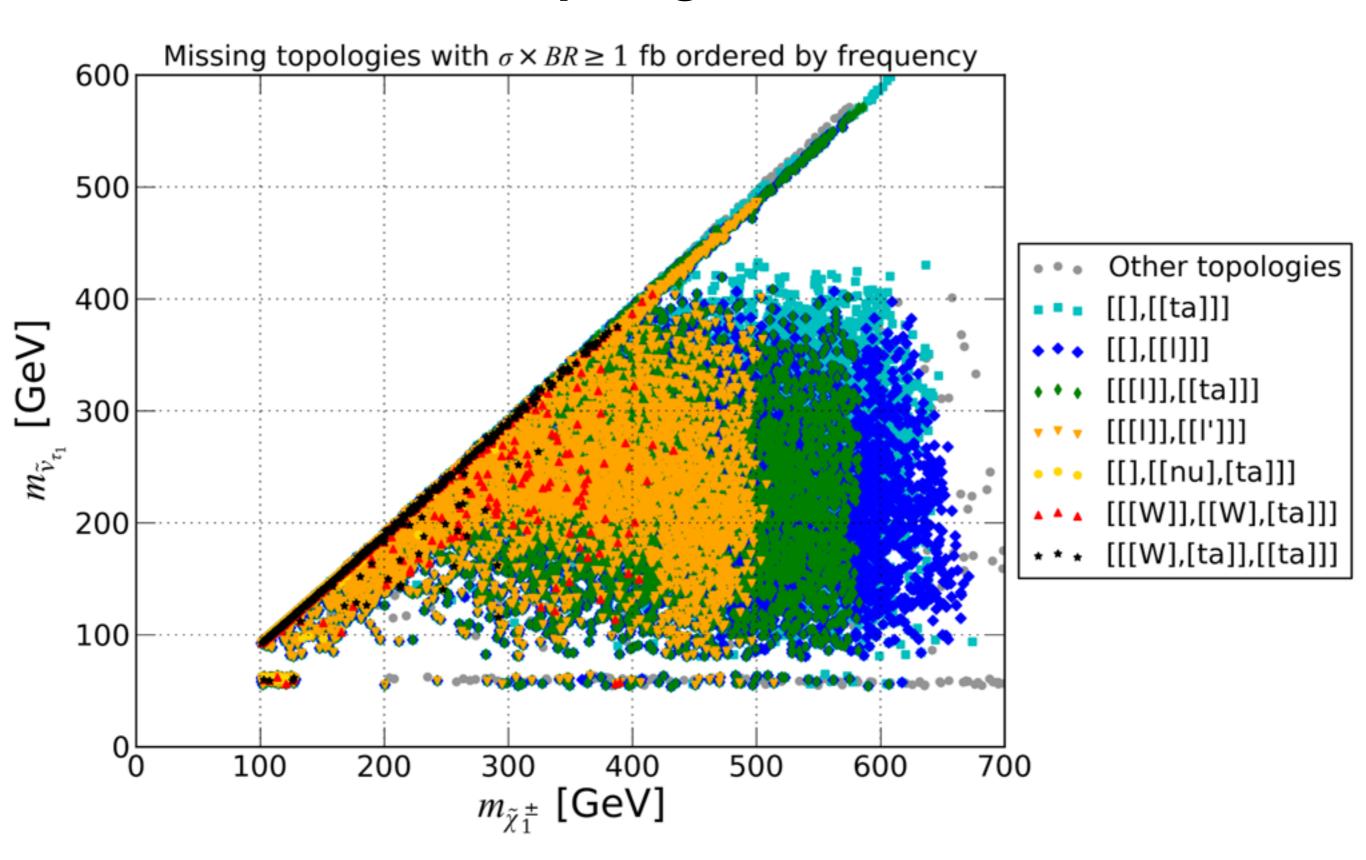# But many points are still allowed

But many points are still allowed

Wino fraction

Not excluded points

But many points are still allowed

Wino fraction

Not excluded points

Higgsino-like charginos
▷ Smaller production cross section
▷ Larger branching to tau final states

MSSM + RN Cross section for single lepton missing topology

Single lepton missing topology
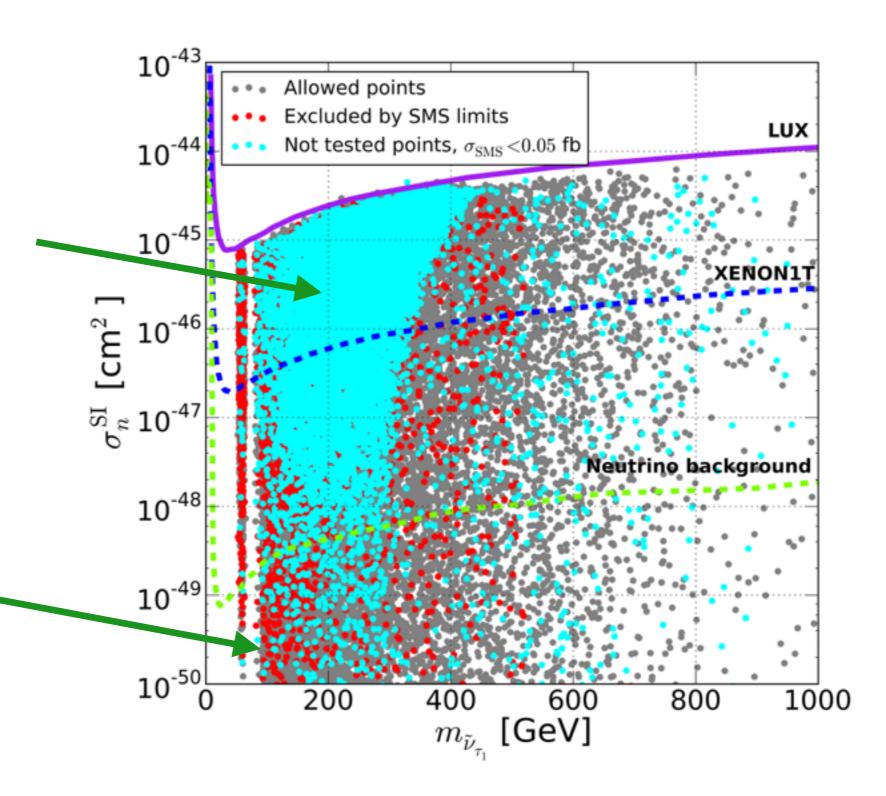
MSSM + RN most frequent missing topologies

Missing topologies with $\sigma \times BR \geq 1$ fb ordered by frequency

Legend:
- Other topologies
- [[],[[ta]]]
- [[],[[l]]]
- [[[l]],[[ta]]]
- [[[l]],[[l']]]
- [[],[[nu],[ta]]]
- [[[W]],[[W],[ta]]]
- [[[W],[ta]],[[ta]]]

Axes: $m_{\tilde{\chi}_1^{\pm}}$ [GeV] (x-axis), $m_{\tilde{\nu}_{\tau_1}}$ [GeV] (y-axis)
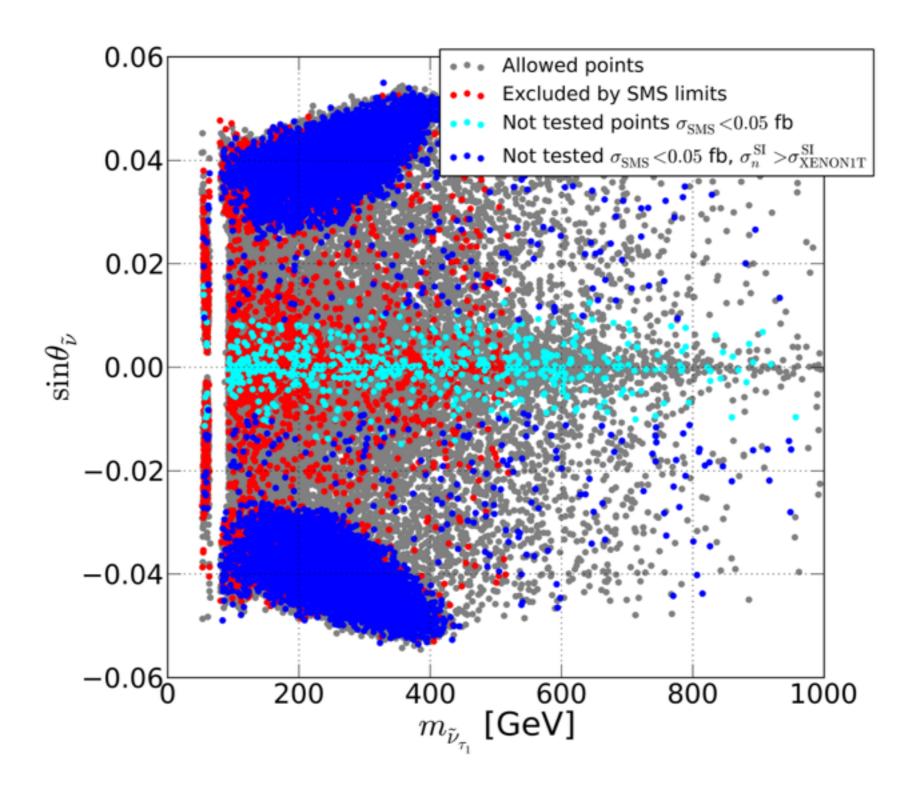
Collider Searches and Direct Detection experiments are highly complementary !

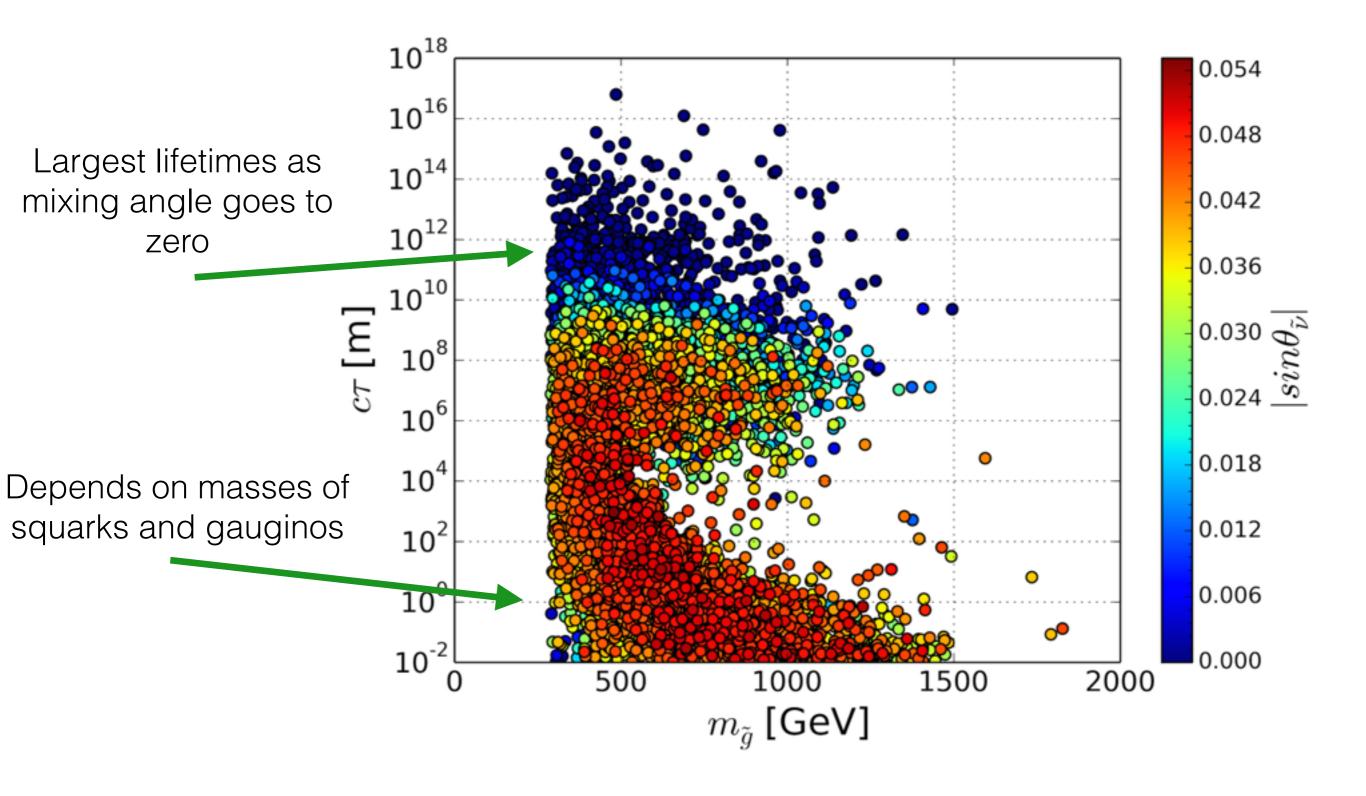Many points which are not at all tested by the SMS results are well in reach of XENON1T

Many parameter points below the neutrino background already excluded by SMS results
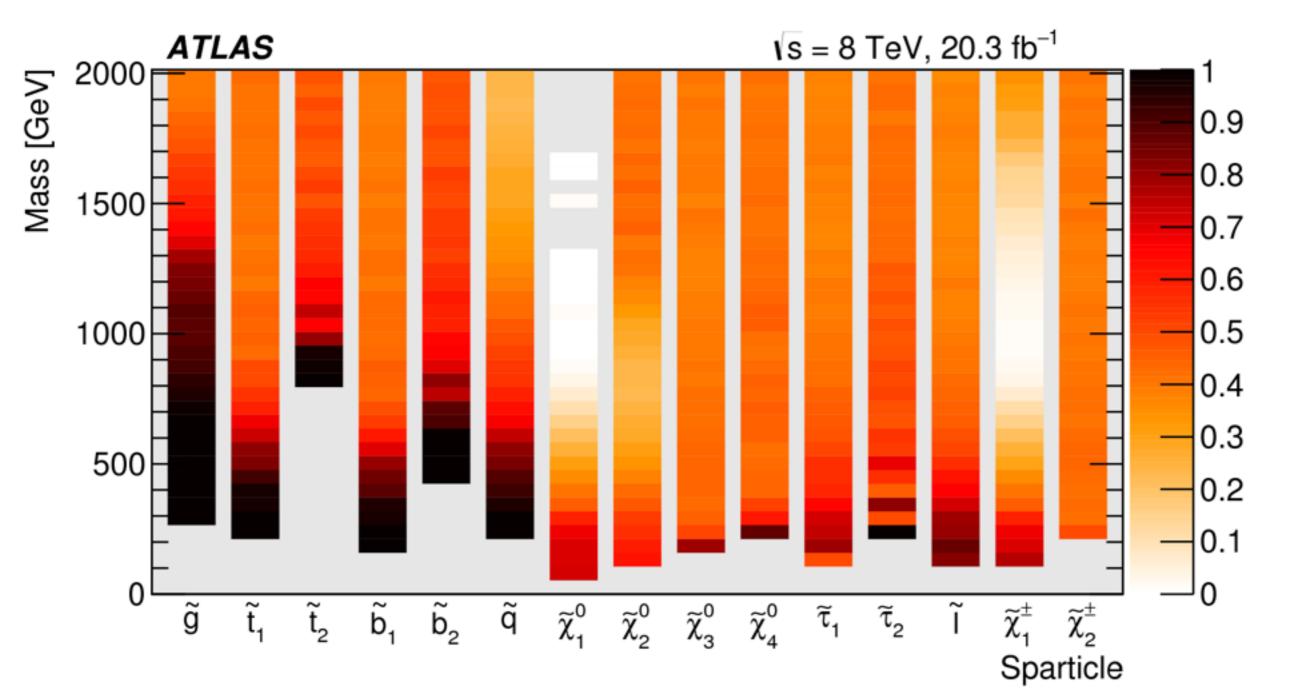
MSSM + RN Mixing Angle Dependence

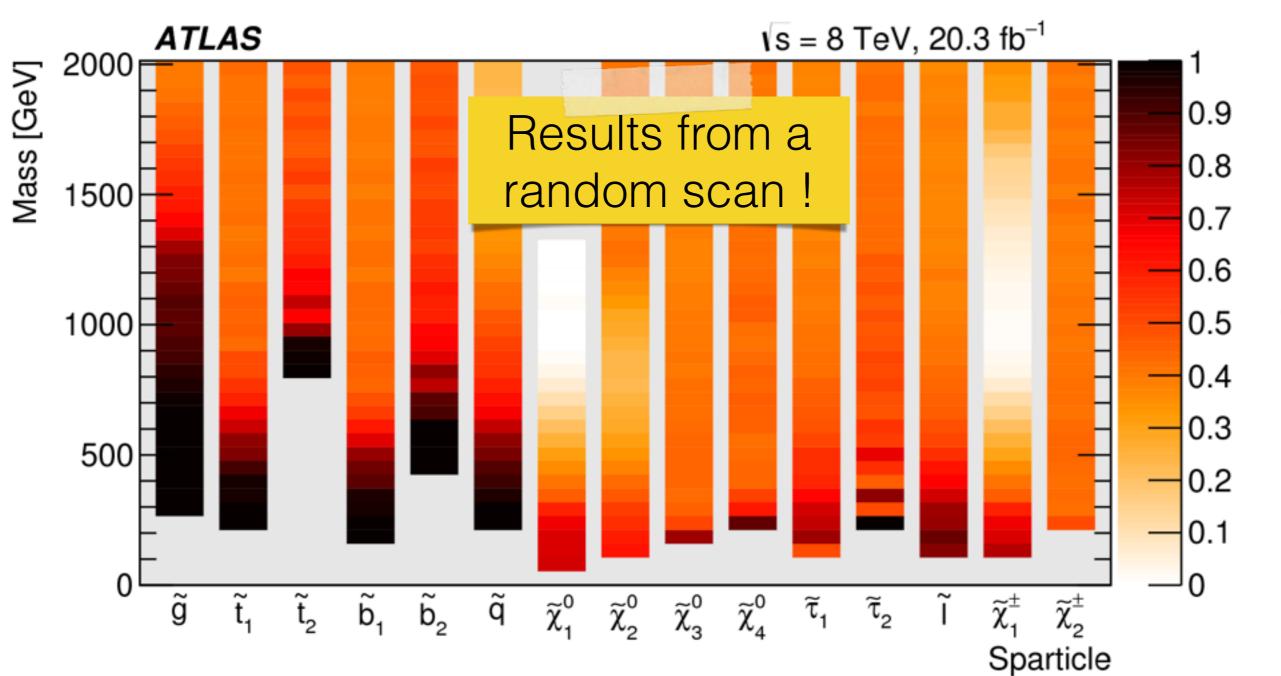# MSSM + RN Long-lived Gluinos

Largest lifetimes as mixing angle goes to zero

Depends on masses of squarks and gauginos

In a more generic 19 - parameter model (pMSSM)

In a more generic 19 - parameter model (pMSSM)

Results from a random scan !

UMSSM - many points with light gluino and LSP remain allowed

→ Check the missing topologies for non-excluded parameter points

Third generation final states preferred for "Higgs-like" couplings

UMSSM - many points with light gluino and LSP remain allowed

→ Check the missing topologies for non-excluded parameter points

Third generation final states preferred for "Higgs-like" couplings

No dominant decay channel , σ*BR reduced for each Simplified Model, "asymmetric" branches currently not covered

Legend:
- other topologies (gray)
- $(tb)(tt)$ (yellow)
- $(bb)(jj)$ (blue)
- $(j, tb)(tb)$ (red)
- $(bb)(tb)$ (green)
- $(jj)(\nu e)$ (purple)

Axes: $m_{\tilde{\chi}_1^0}$ [GeV] vs $m_{\tilde{g}}$ [GeV]