THE UNIVERSITY of ADELAIDE

Experimental SUSY searches (~LHC)
Lecture 3

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Outline

- Lecture 1: the basics

  - what do I mean by SUSY?
  - what happens in an LHC collision?
  - how do the LHC detectors work?
  - which objects can we use to hunt for SUSY?
  - what (roughly) does SUSY look like at the LHC?

- Lecture 2 (mostly for experimentalists)

  - how are the LHC SUSY analyses designed?
  - discriminating variables
  - background measurements
  - detailed worked example (0 lepton search)
  - summary of different approaches

- Lecture 3 (mostly for theorists)

  - what have we learned about SUSY from the LHC (and LEP, etc...)
  - how can a theorist constrain a new model of SUSY (or other BSM physics?)

What have we learned about SUSY from the LHC?

- This question is extremely hard to answer

    - we will struggle to answer it in the next hour

- Each search is optimised on a specific scenario

    - no search has seen evidence for SUSY

- Unfortunately this does not mean that SUSY is “ruled out”

    - there are lots of gaps between the limits
    - extreme optimisation means poor coverage of general models

- Will study instead how you should use LHC results to constrain SUSY models

    - some insight can be gained from random explorations of the model space
    - a proper answer requires a global fit

Simplified models

- For several years now, experimental searches have relied on simplified models

  - decouple most sparticles

  - scan two masses per plane

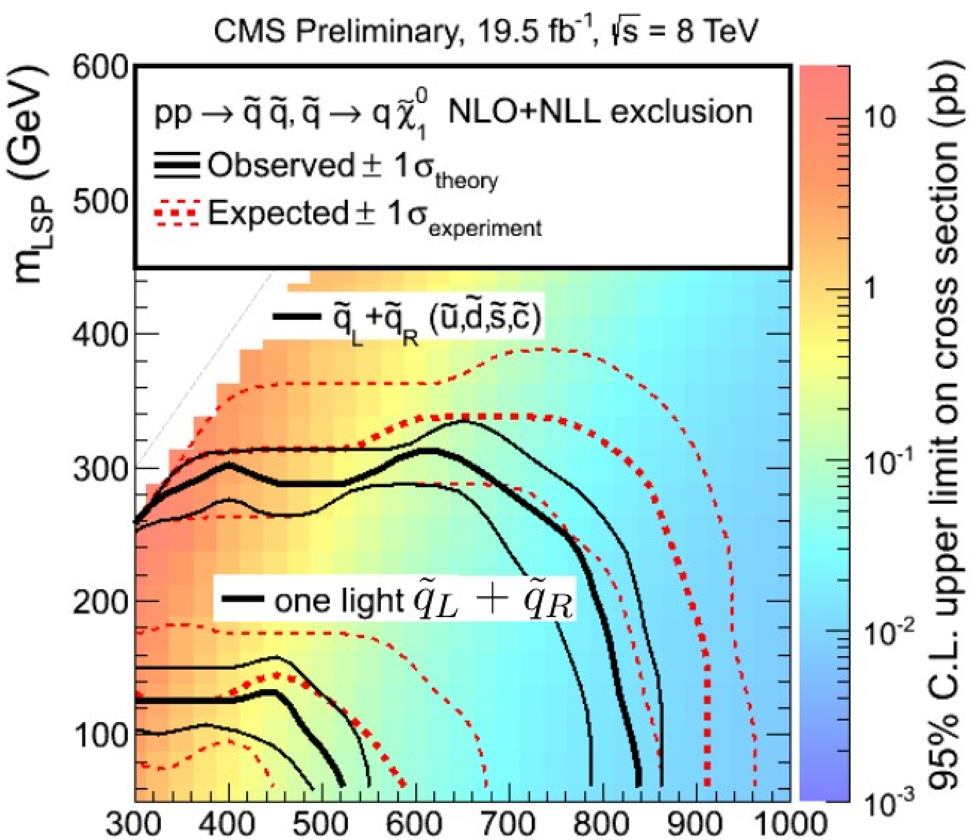
  - fix branching ratio to 100% for a specific process

- Simplified models are used for two specific things

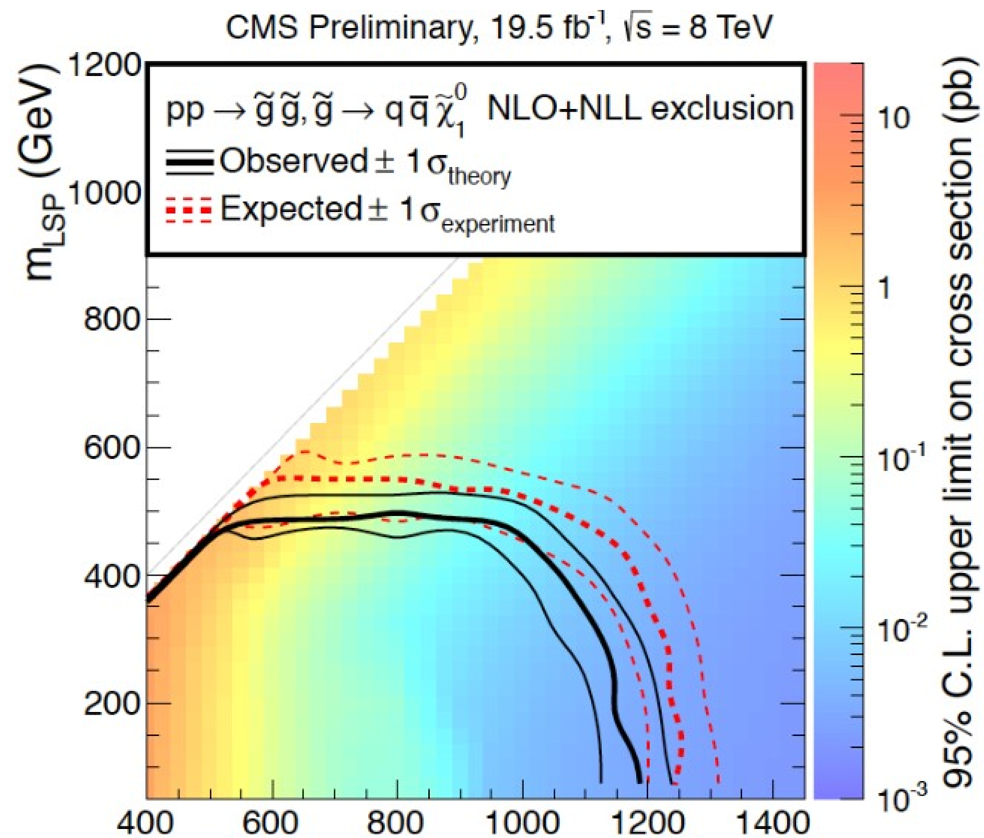
  - optimisation of analysis (based on signal kinematics in the plane)
  - presentation of limits

- Let's quickly review the Run I simplified model limits

CMS multijets (CMS-SUS-13-012)

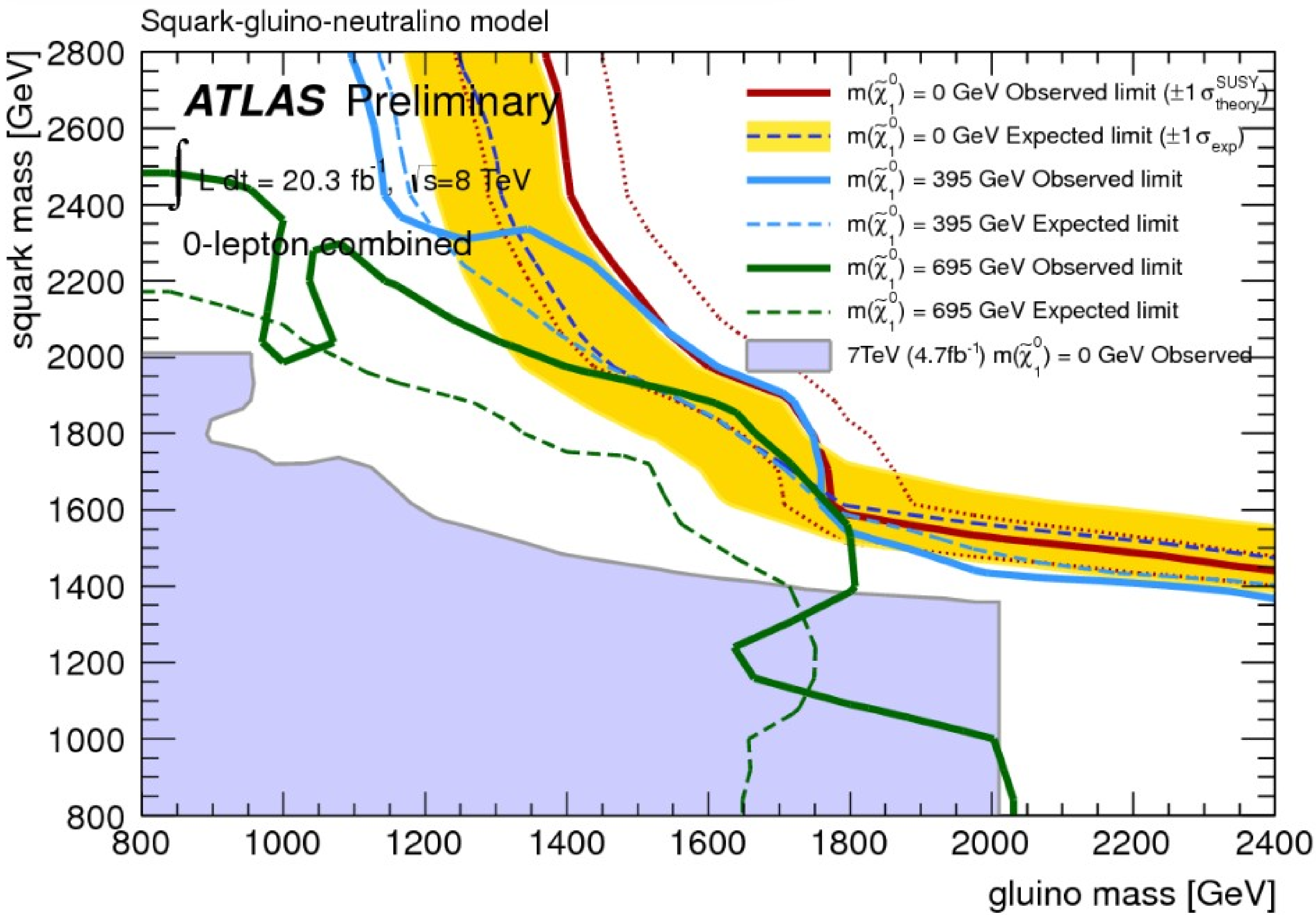


probe $m_{\tilde{q}}$ up to 0.8 TeV for light LSP



probe $m_{\tilde{g}}$ up to 1.15 TeV for light LSP

Squarks + gluinos gives tighter bounds (ATLAS-CONF-2013-047)



Light staus – Jet + MET + at least 1 hadronic tau

GMSB:

Gravitino is LSP (weak coupling to NLSP)

Signature depend on NLSP, e. g. $\tilde{\tau} \rightarrow \tau\tilde{G}$

cMSSM:

Fix A_0, tan β and μ such that m_H~125 GeV

For some models NLSP = stau → τs in decay chain

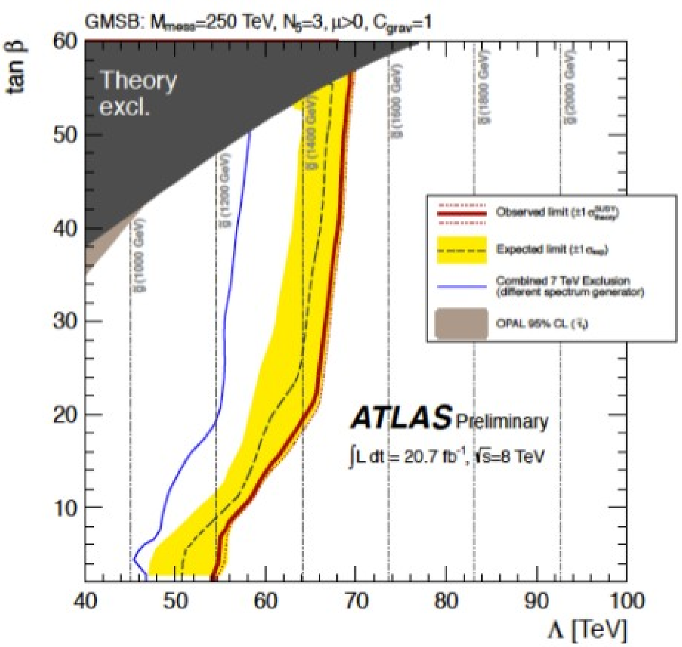
Natural GM:

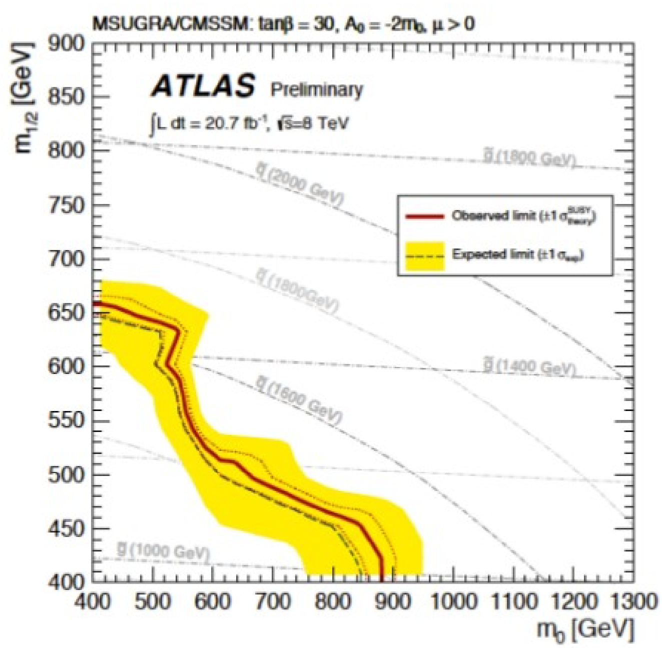
General Gauge Mediation + set weak scale parameters such to avoid fine tuning

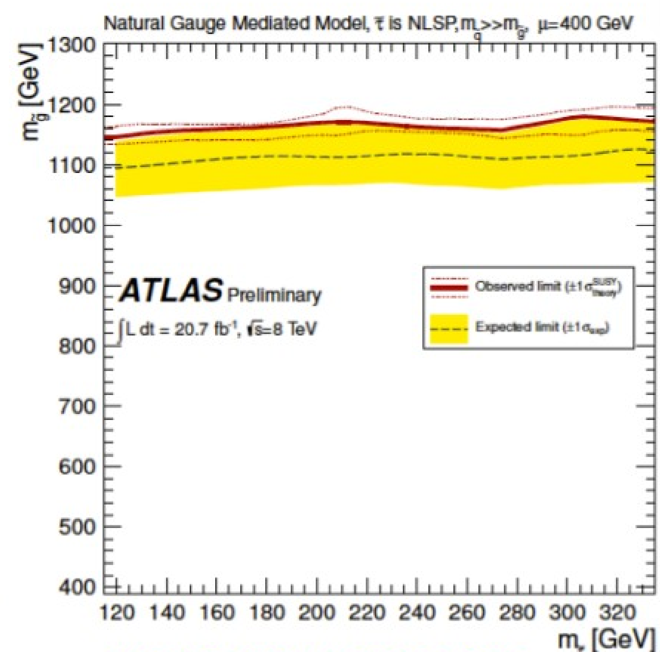
→ Light staus, accessible gluinos, other sparticles heavy

Common signature:

Strong production (squark & gluinos) dominates → jets; light staus → τs; LSPs → MET





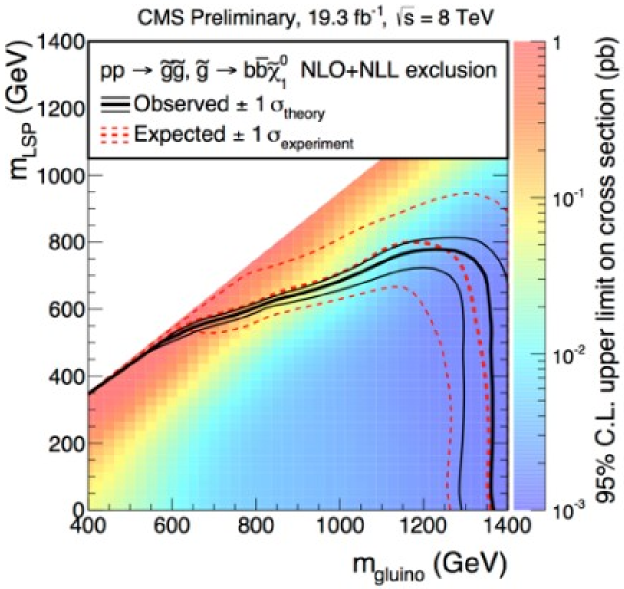


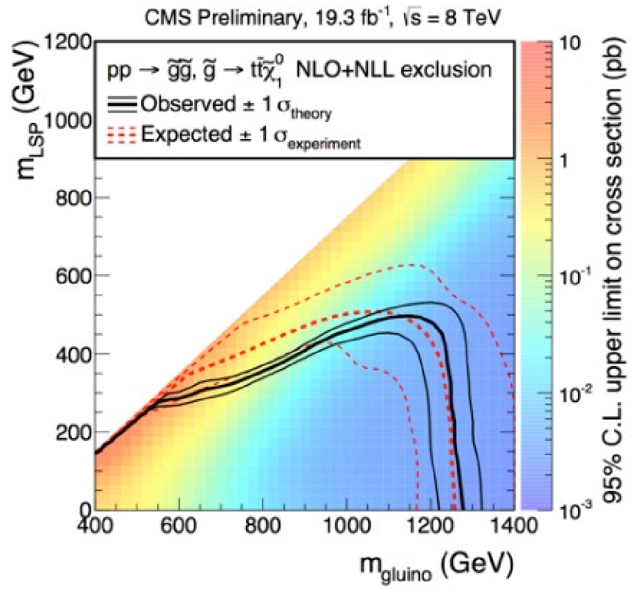
ATLAS-CONF-2013-026

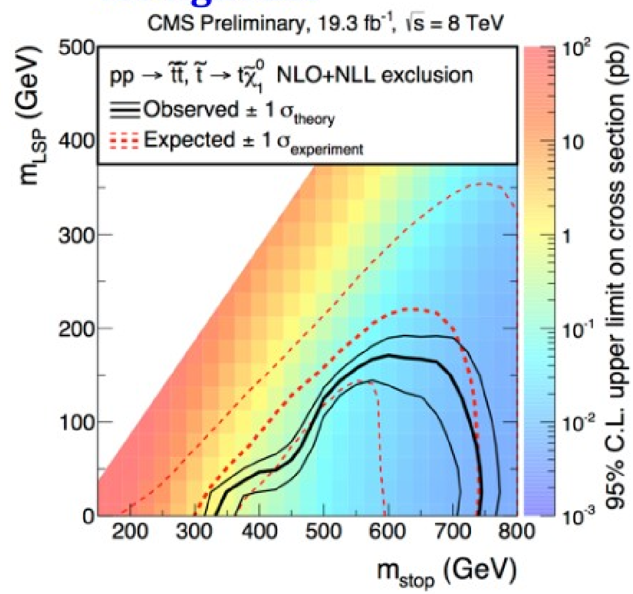
Extrapolation in various "boxes": with 0, 1, or 2 leptons; $N_{b\text{-tags}}$ and N_{jets}

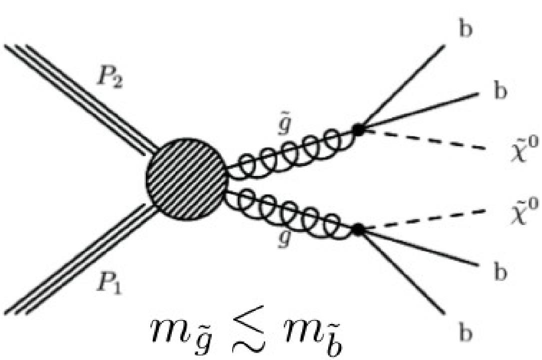
No excess → Limits in various SMSs

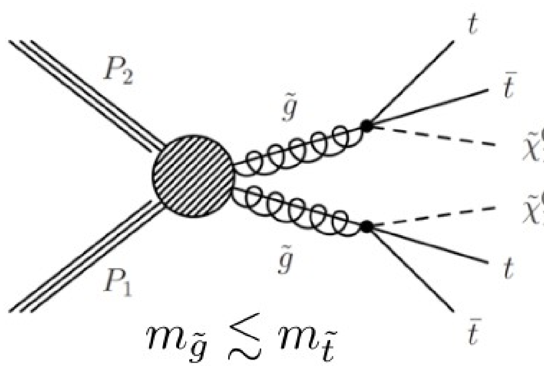
Probe $m_{\tilde{t}}$ up to 0.7 TeV for light LSP

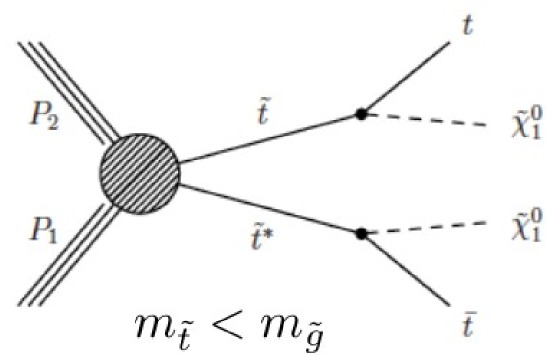




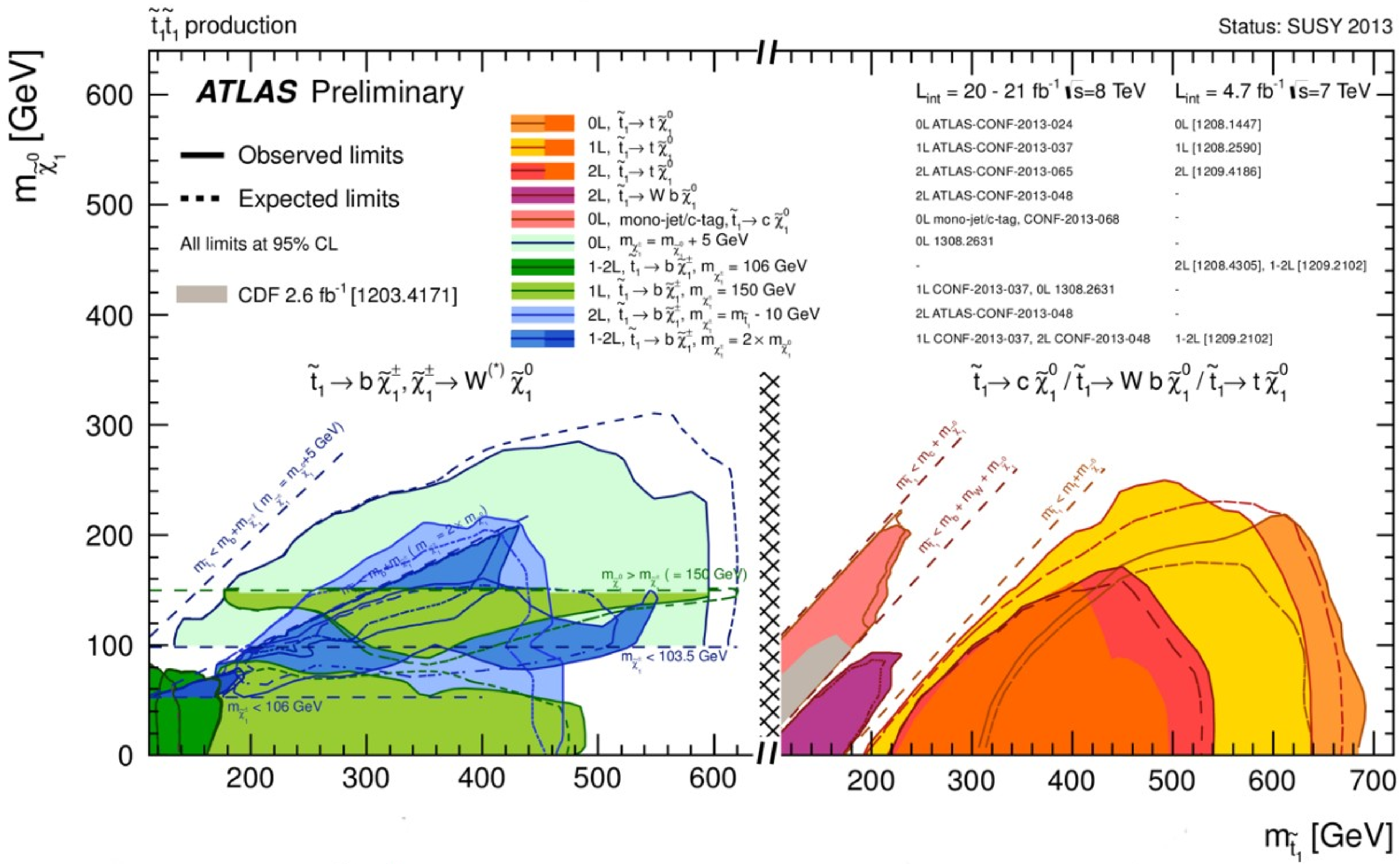




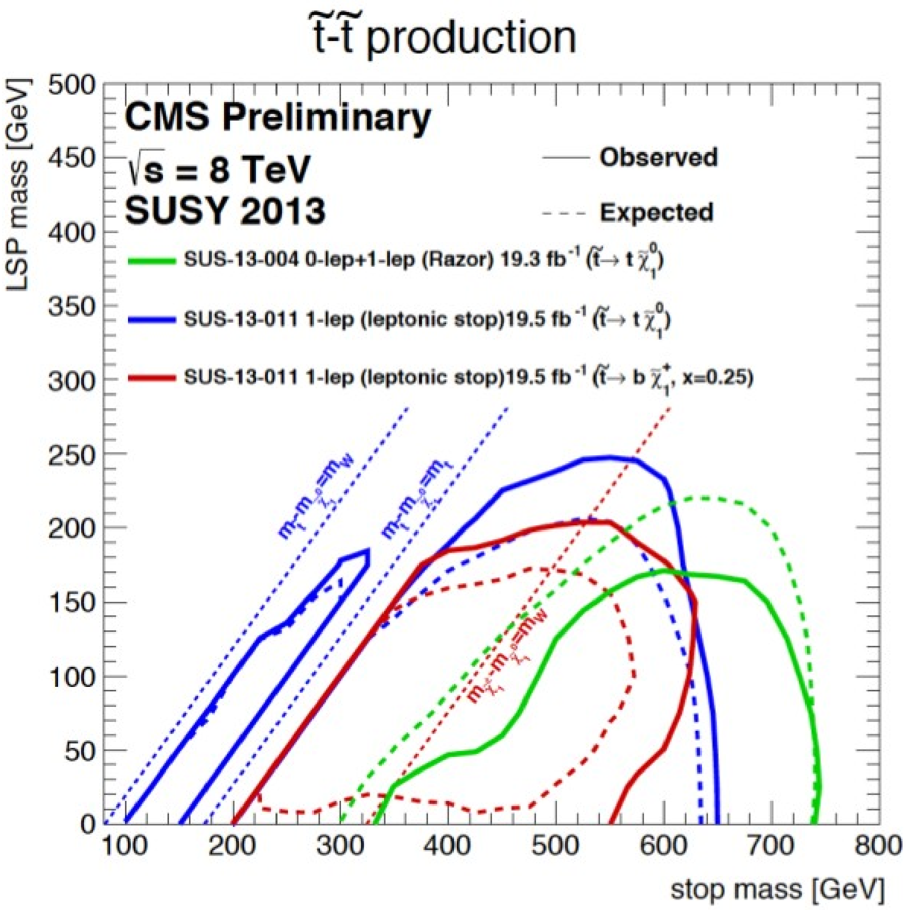


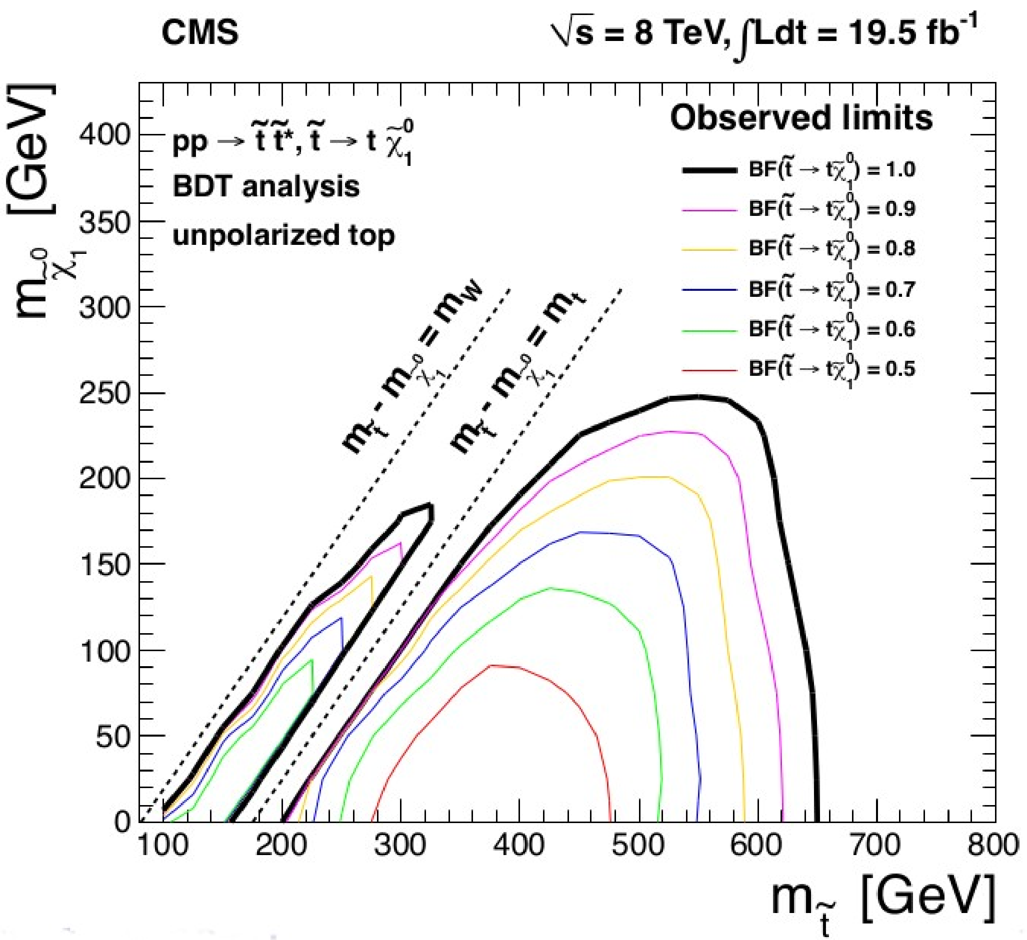


ATLAS stop search summary

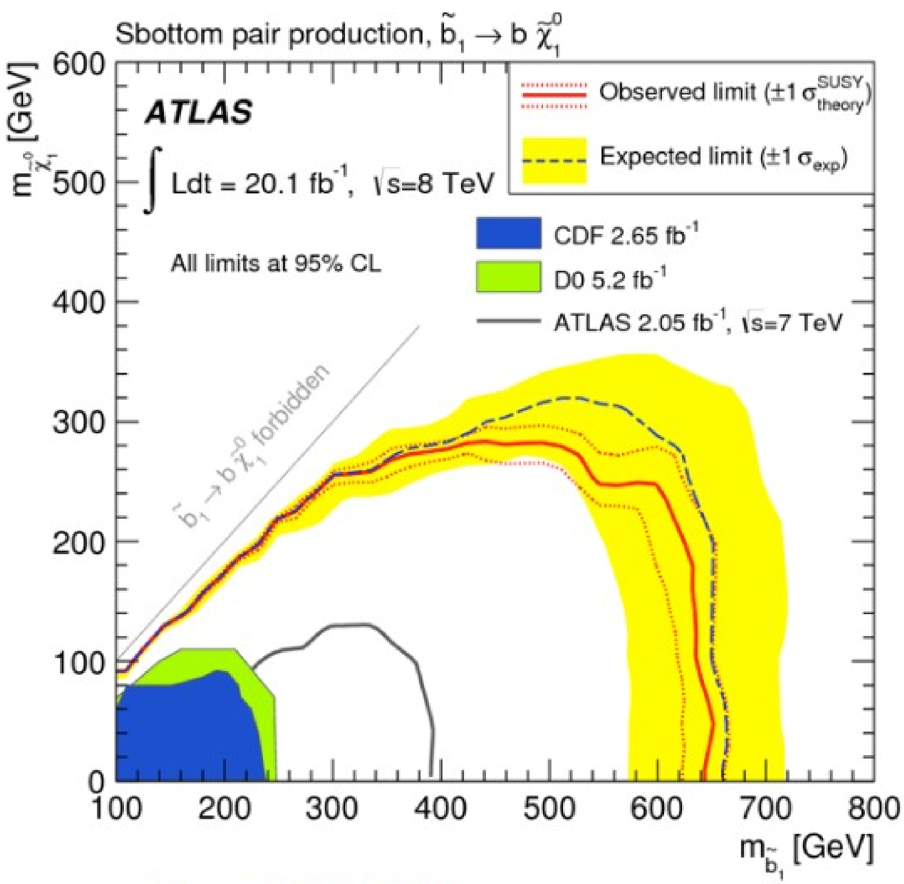


CMS stop summary

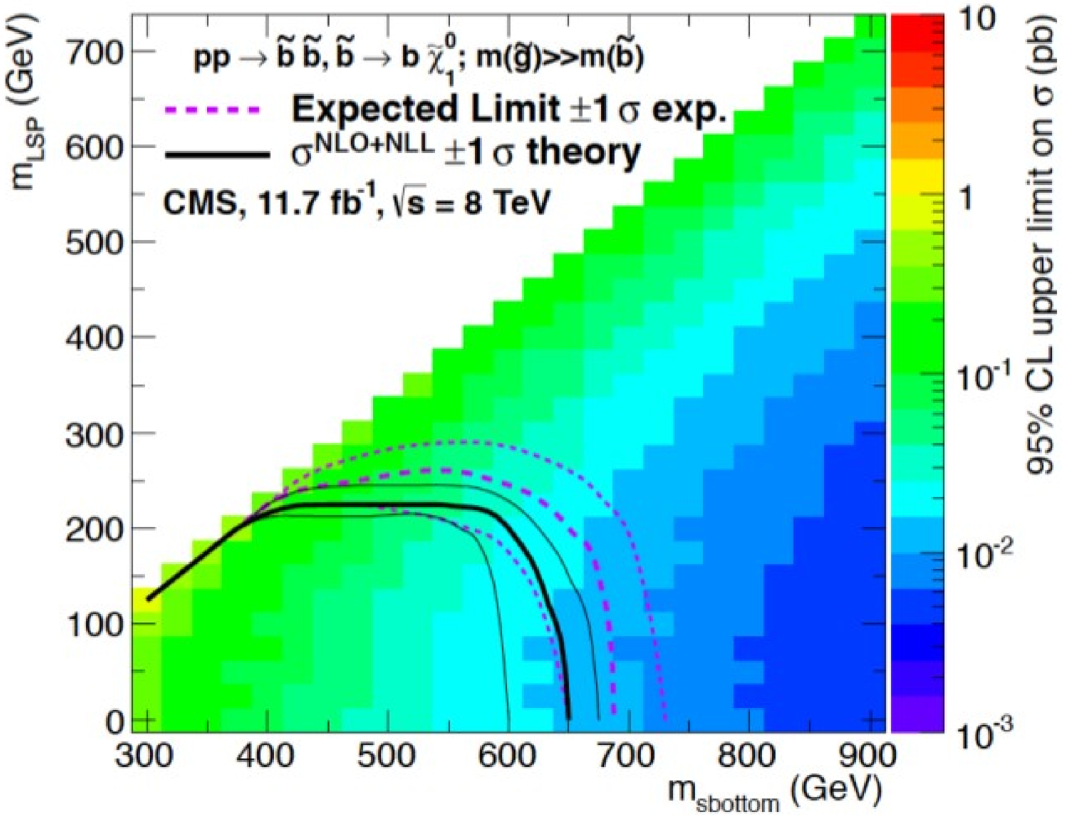




Sbottom searches

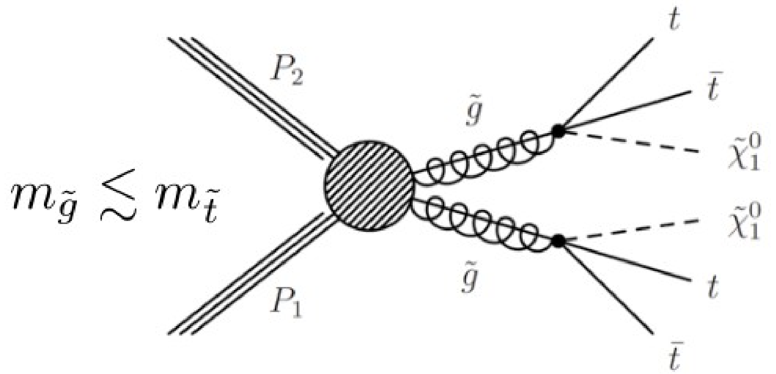


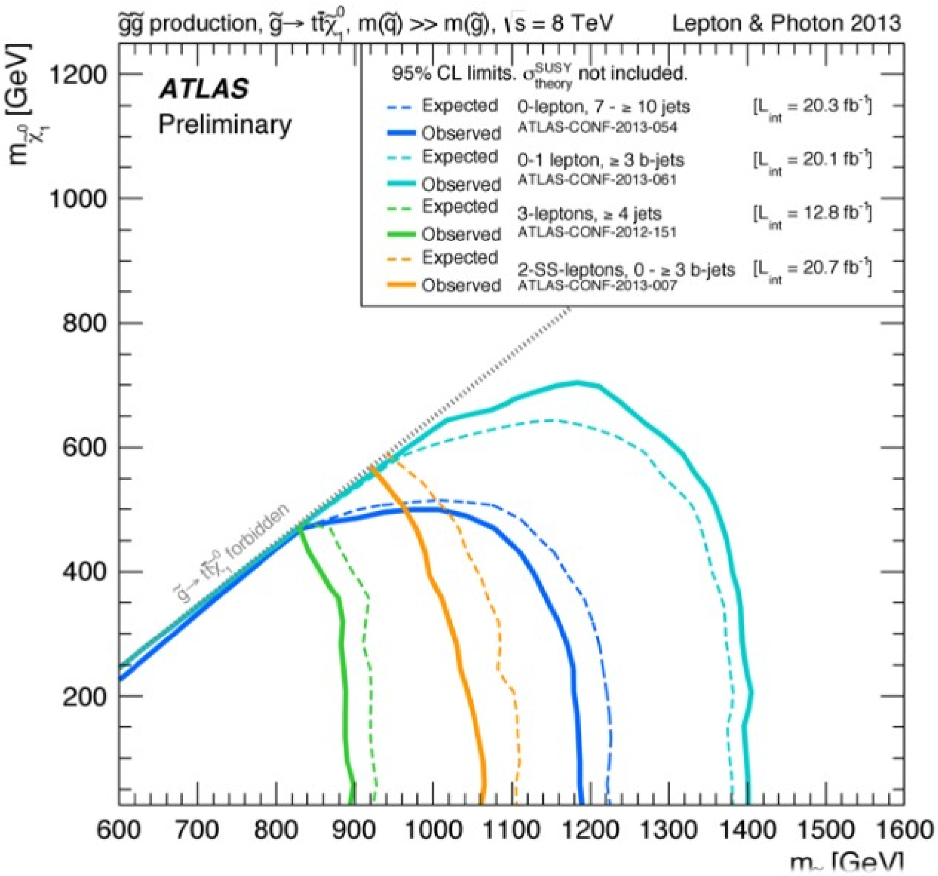
arXiv:1308.2631

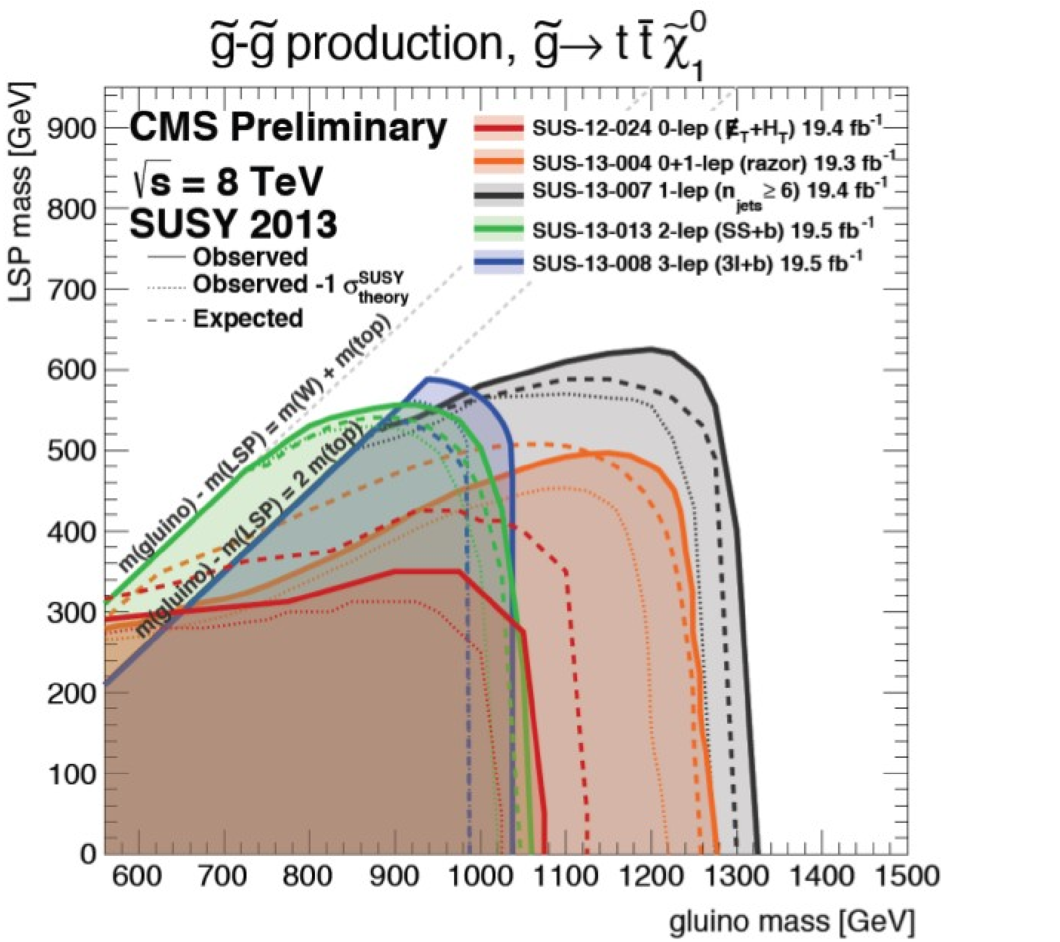


arXiv:1303.2985 (accepted by EPJC)

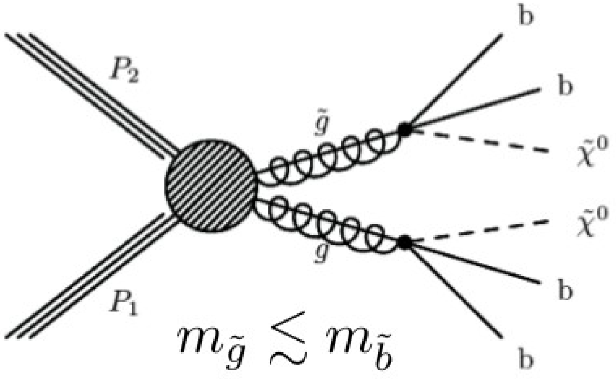
Four top searches

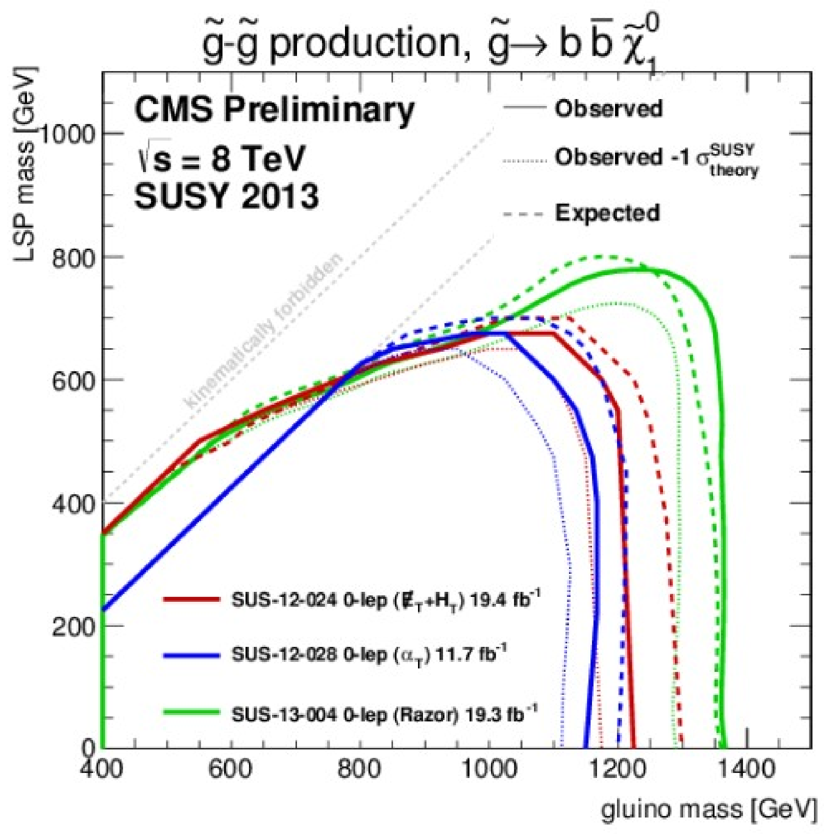


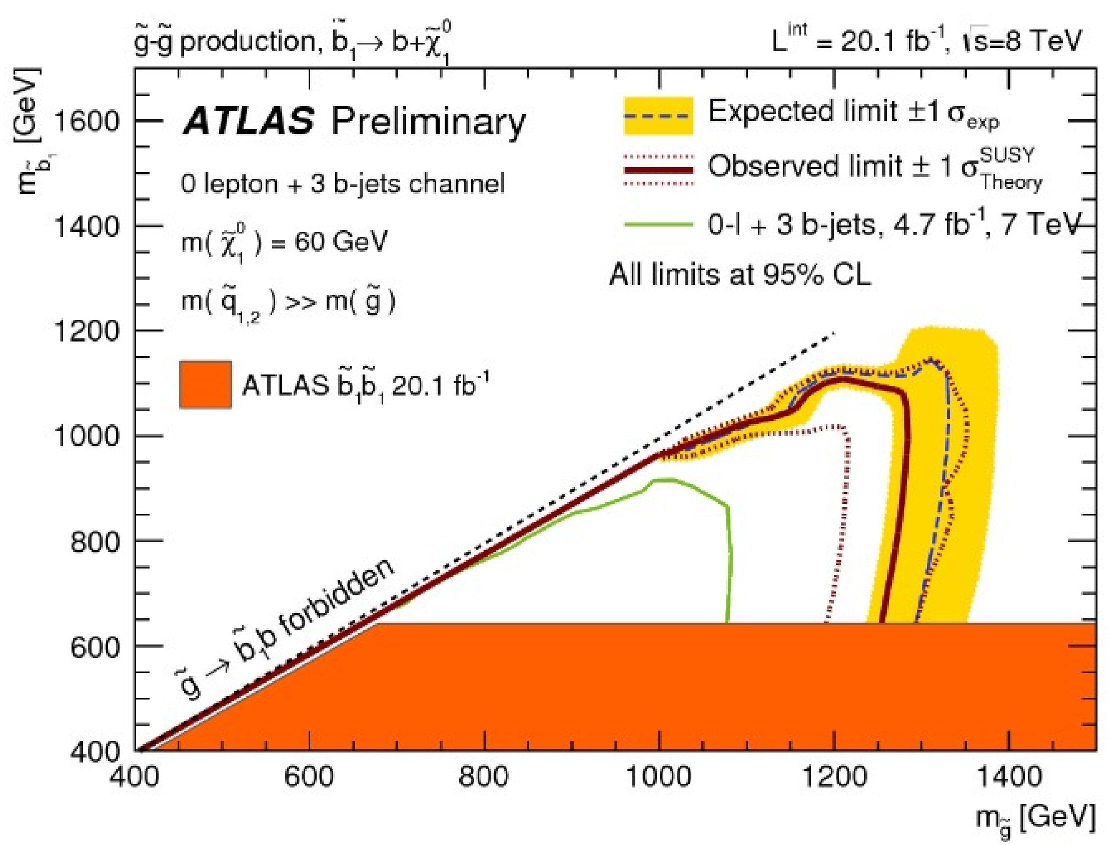




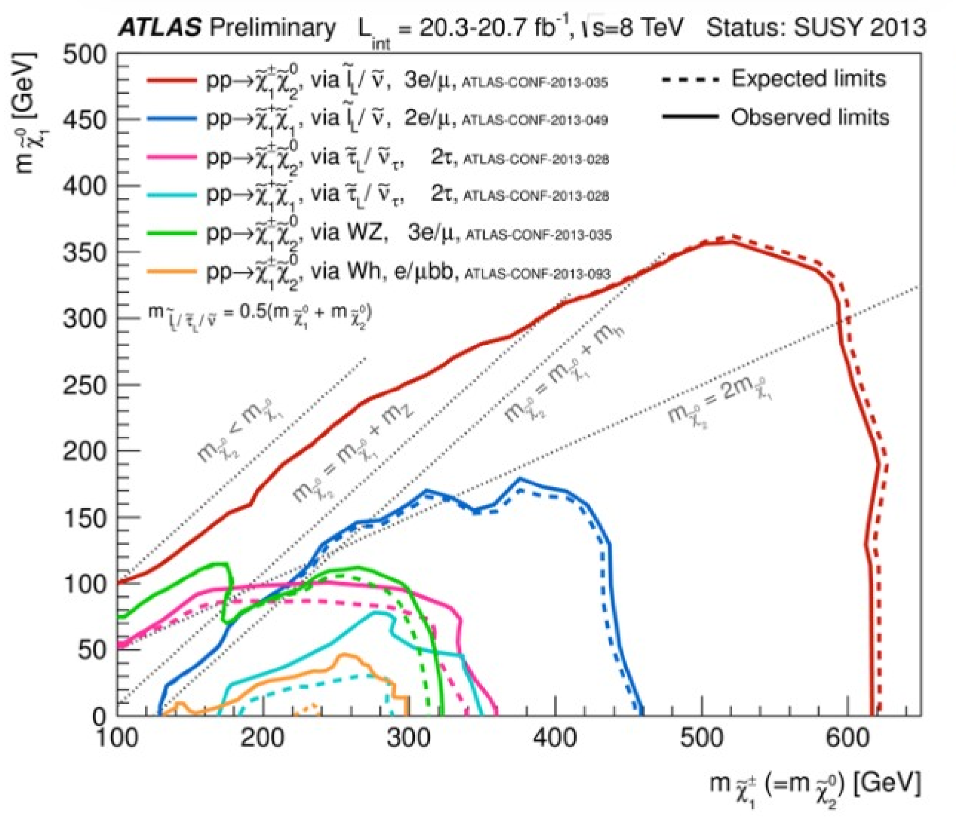
Four bottom searches (ATLAS-CONF-2013-061)

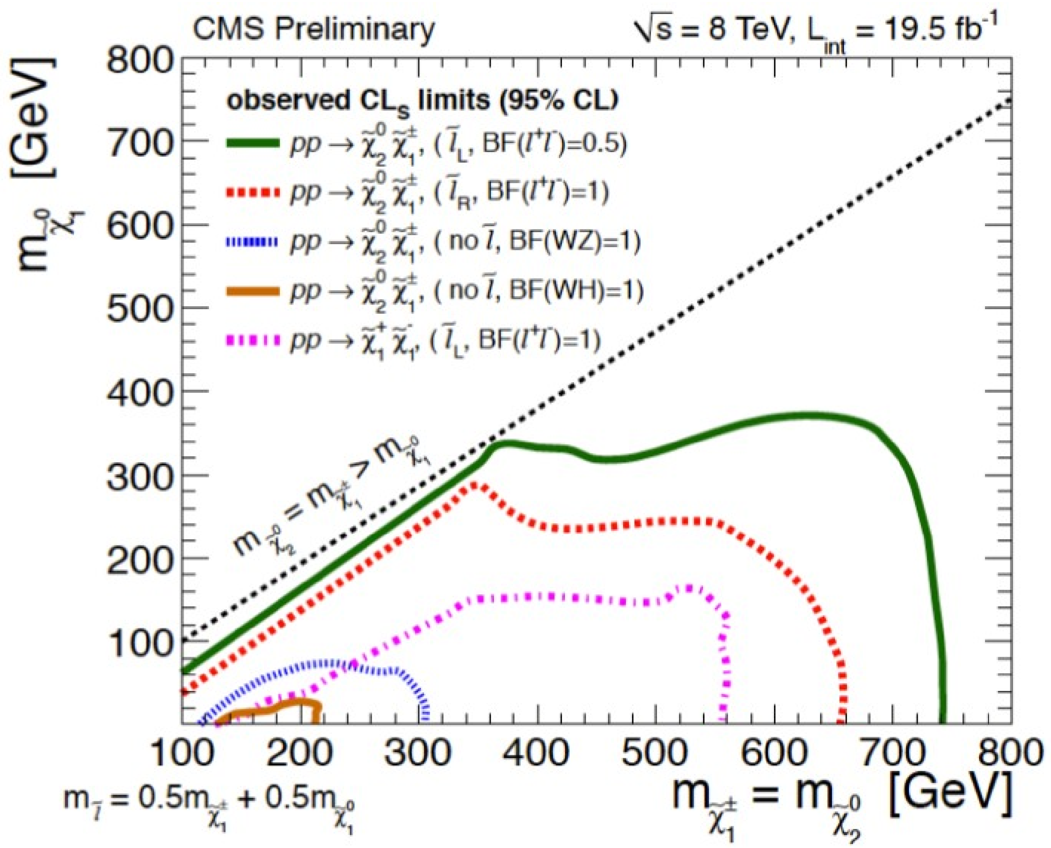




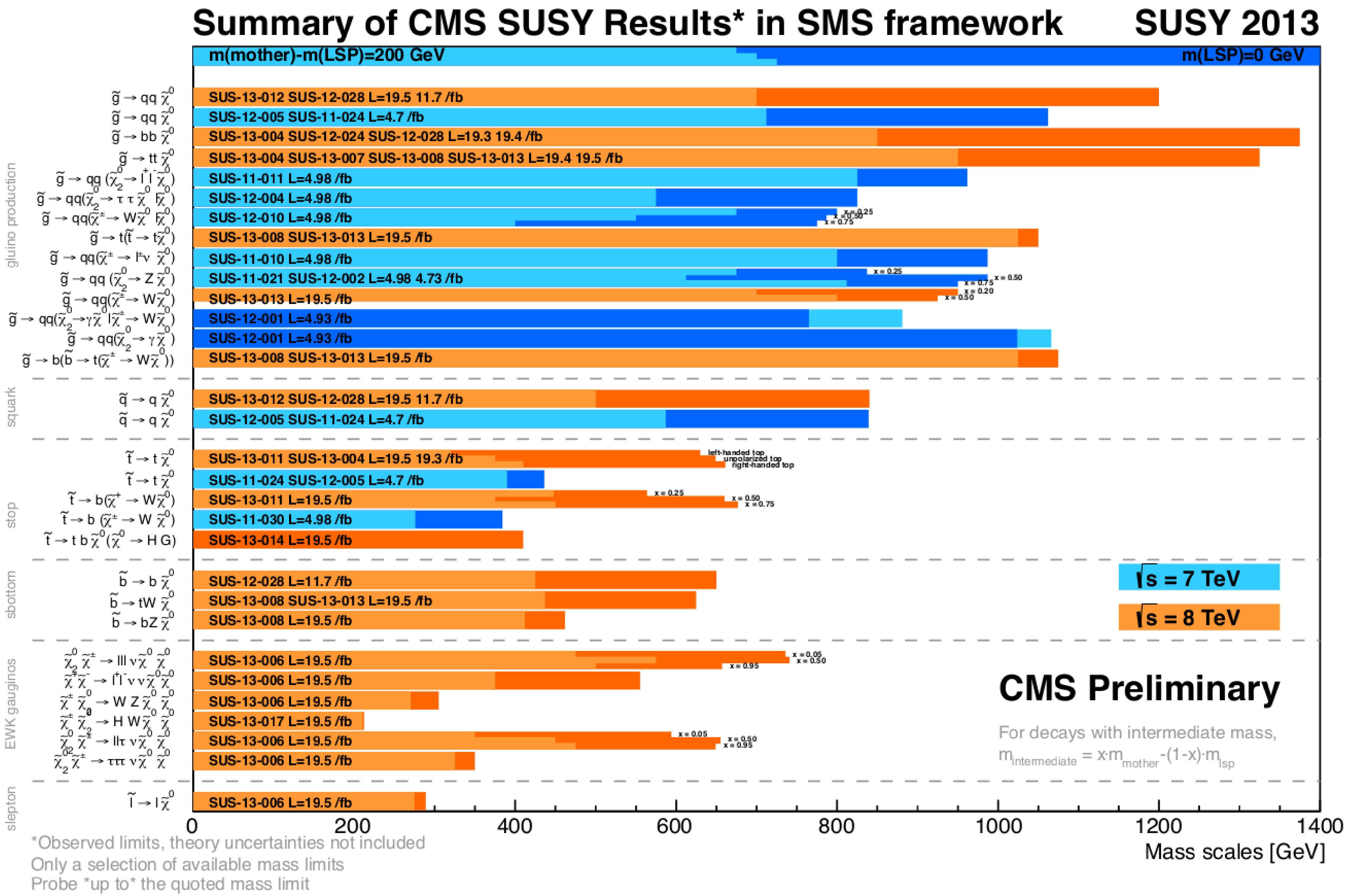


Multilepton searches

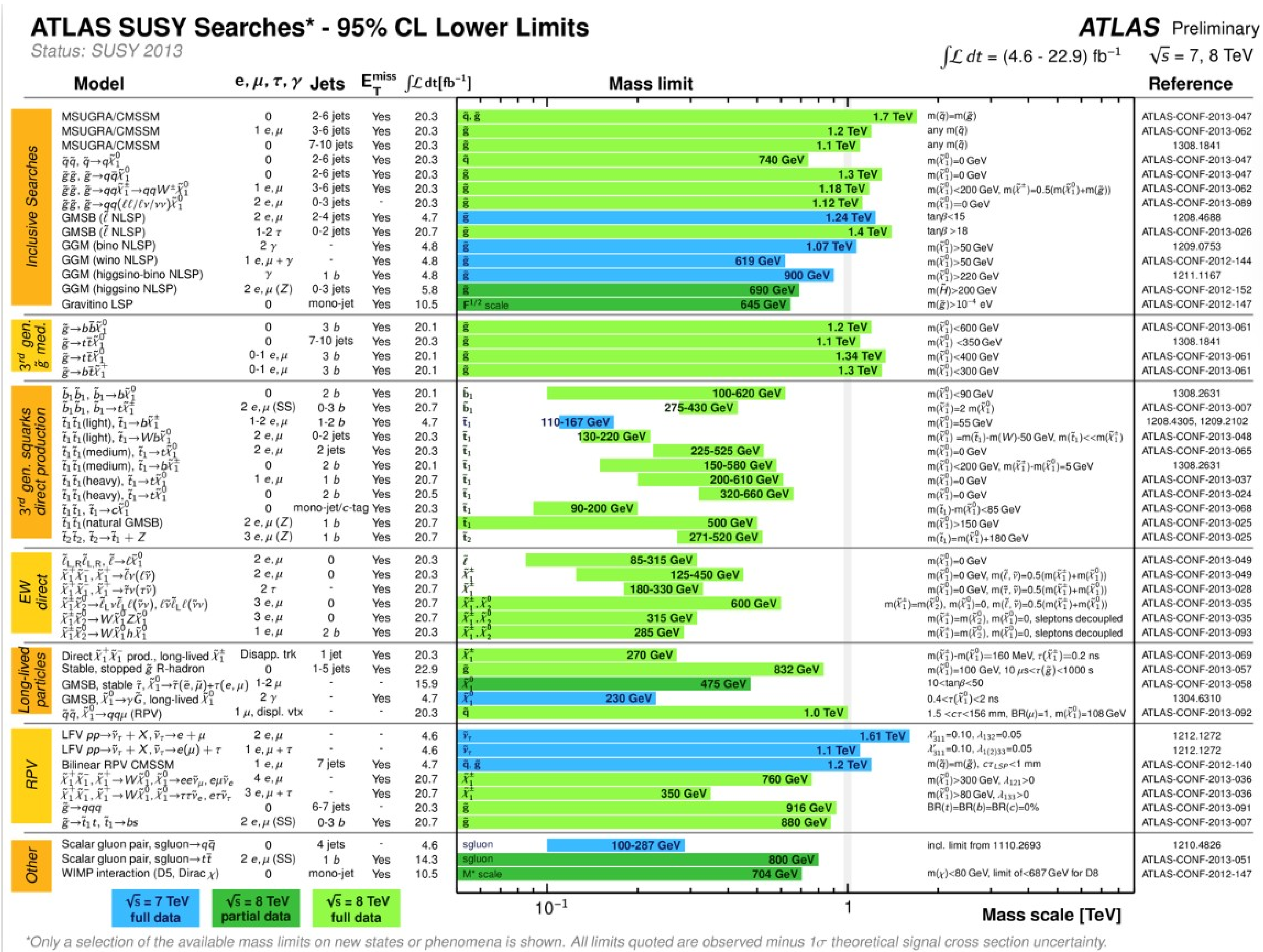




Total overview (CMS)



Total overview (ATLAS)



So SUSY is excluded then?

NOT SO FAST!

DISCLAIMER: The following work is taken from a quick exercise on my laptop for illustration. It is not endorsed by the ATLAS collaboration.

Stop searches: What's next?

- Naively the ATLAS results remove room for natural SUSY

  - things are not as they first appear

1) There are combinations of sparticle masses to which the analyses are not sensitive.

2) The relative branching ratio of the *b*-chargino and *t*-neutralino modes could differ from the value(s) assumed for optimisation

3) Realistic SUSY models contain extra decay modes, beyond those on which the analyses have been optimised

A quick scan

1) Have taken the ATLAS simplified model space and explored *all four parameters*

$$m_{\tilde{t}}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}, BR(\tilde{t}_1 \to t\tilde{\chi}_1^0)$$

2) Use Multinest Bayesian sampling algorithm, using the following analyses:

- **ATLAS-CONF-2013-024:** The ATLAS 0 lepton direct stop analysis using 20 fb^{-1} of data
- **ATLAS-CONF-2013-037:** The ATLAS 1 lepton direct stop analysis using 20 fb^{-1} of data
- **ATLAS-CONF-2013-048:** The ATLAS 2 lepton direct stop analysis using 20 fb^{-1} of data, based on the use of the leptonic M_{T2} variable
- **arXiv:1308.2631:** The ATLAS 2 b jets plus missing E_T search for direct stop and/or sbottom production, using 20 fb^{-1} of data.
- The "mixed" signal regions from the 2014 paper update to the ATLAS 0 lepton direct stop analysis, using 20 fb^{-1} of data

- I do not include compressed spectra in the scan

  - thus have not looked at monojet or *c*-neutralino searches
  - this is due to limited time rather than sound physical reasoning...

Summary of scan details

- Run Multinest scanning algorithm with parameters in the following range

Parameter	Range
$m_{\tilde{t}}$	100 – 700 GeV
$m_{\tilde{\chi}_1^0}$	1 – 700 GeV
$m_{\tilde{\chi}_1^\pm}$	103 – 700 GeV
$BR(\tilde{t}_1 \to t\tilde{\chi}_1^0)$	0 – 1

- $(m_{\tilde{t}} - m_{\tilde{\chi}_1^\pm}) > 10$ GeV.
- $(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}) > 1$ GeV
- ***Top quarks must be on shell!***

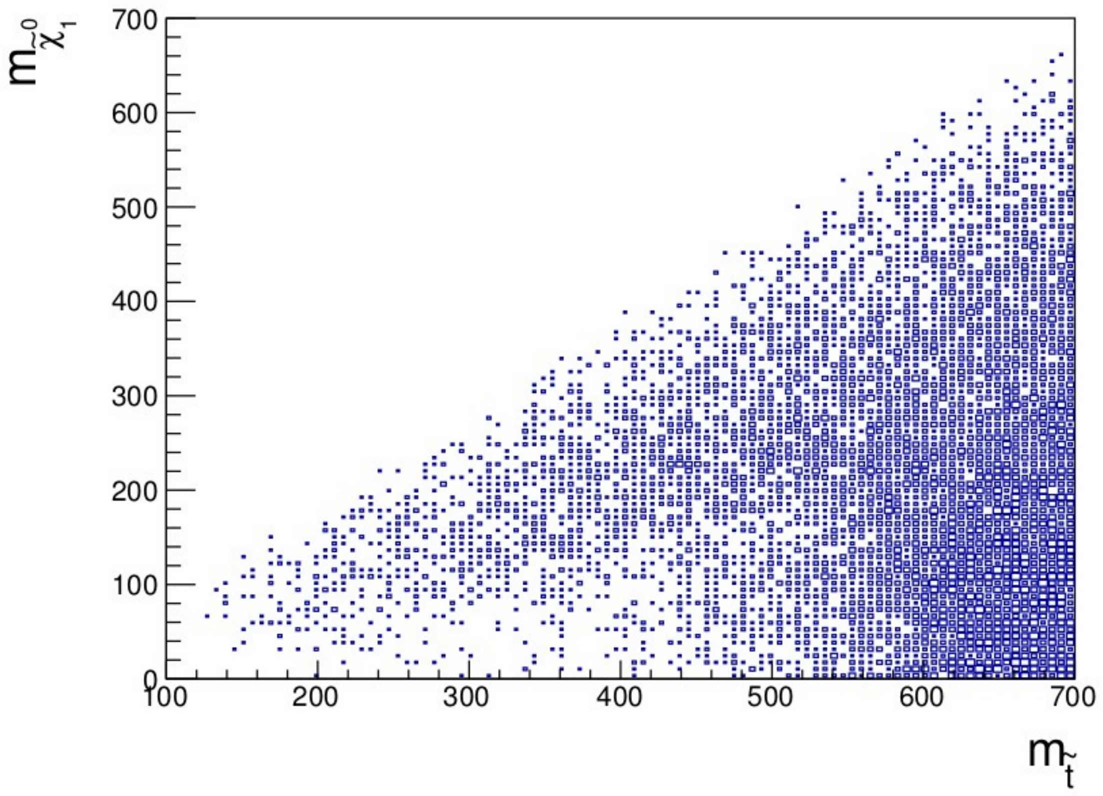
- At each point, generate 10,000 stop pair events

  - have parallelised Pythia 8 using Open MP
  - use NLLFAST for the production cross-section
  - use DELPHES with custom hacks for the detector simulation
  - apply ATLAS analysis cuts and derive approximate likelihood
  - parallelisation gives 10,000 events in ~3.5 seconds on 8 cores
  - get a convergent fit with 2,000 live points within a few hours
  - 10,000 live points $\Rightarrow$ ~ 3 days of running on 24 cores

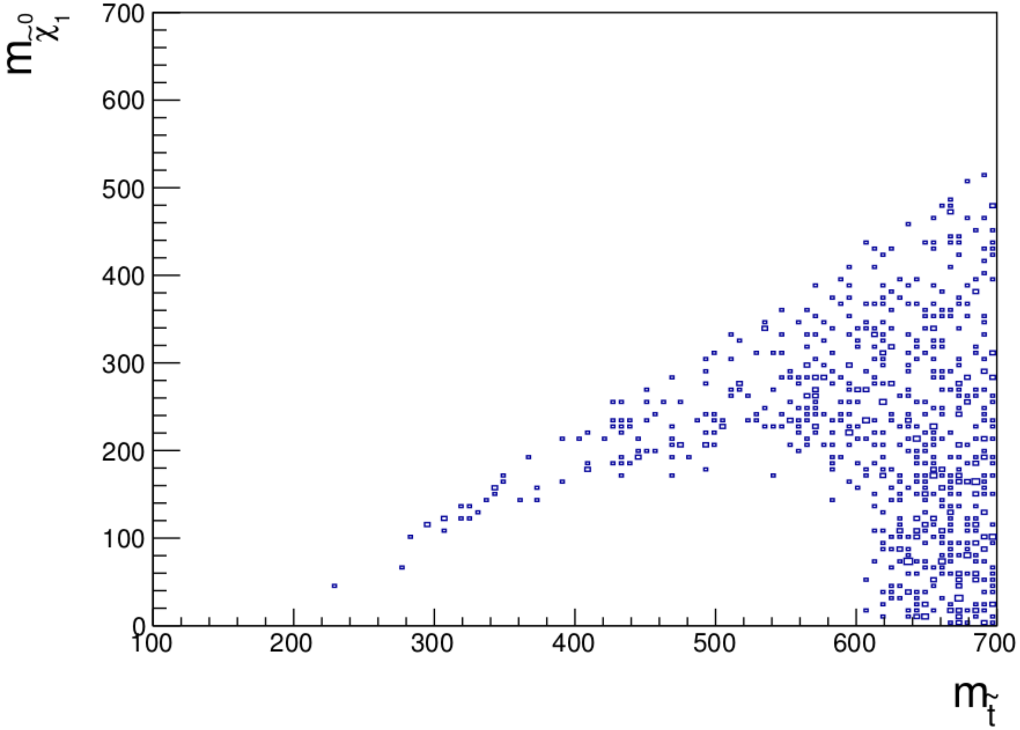
RESULTS

- A set of posterior samples in the 4D stop simplified model space
- All have likelihood 1 by construction $\Rightarrow$ we will use them as a set of equally likely benchmark points

Results: Stop-Neutralino mass plane



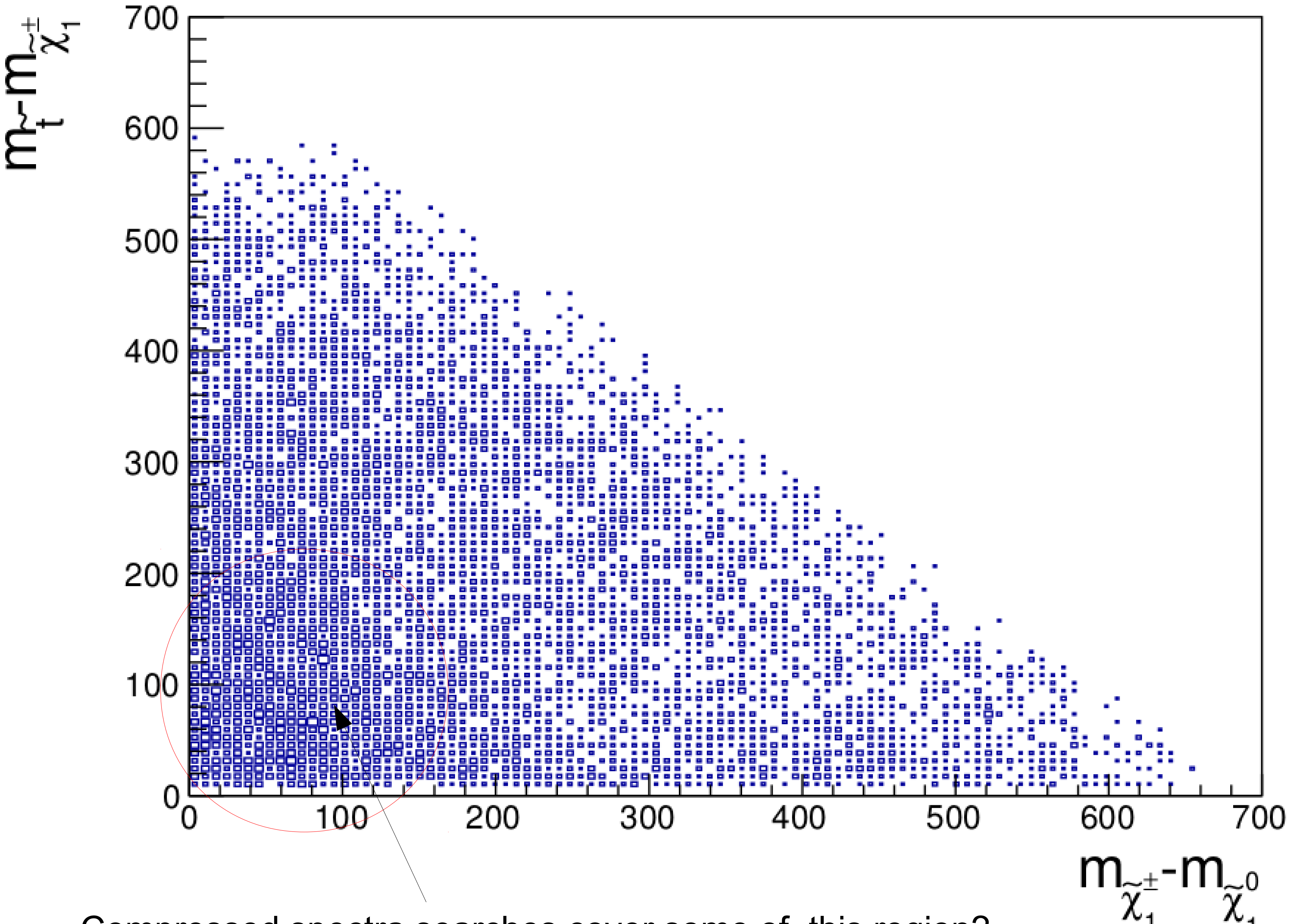
Results: Stop-Neutralino mass plane for *t*-neutralino decays



- This plot shows models with BR($\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$) > 0.9

  - we recover the ATLAS limit
  - provides a nice sanity check

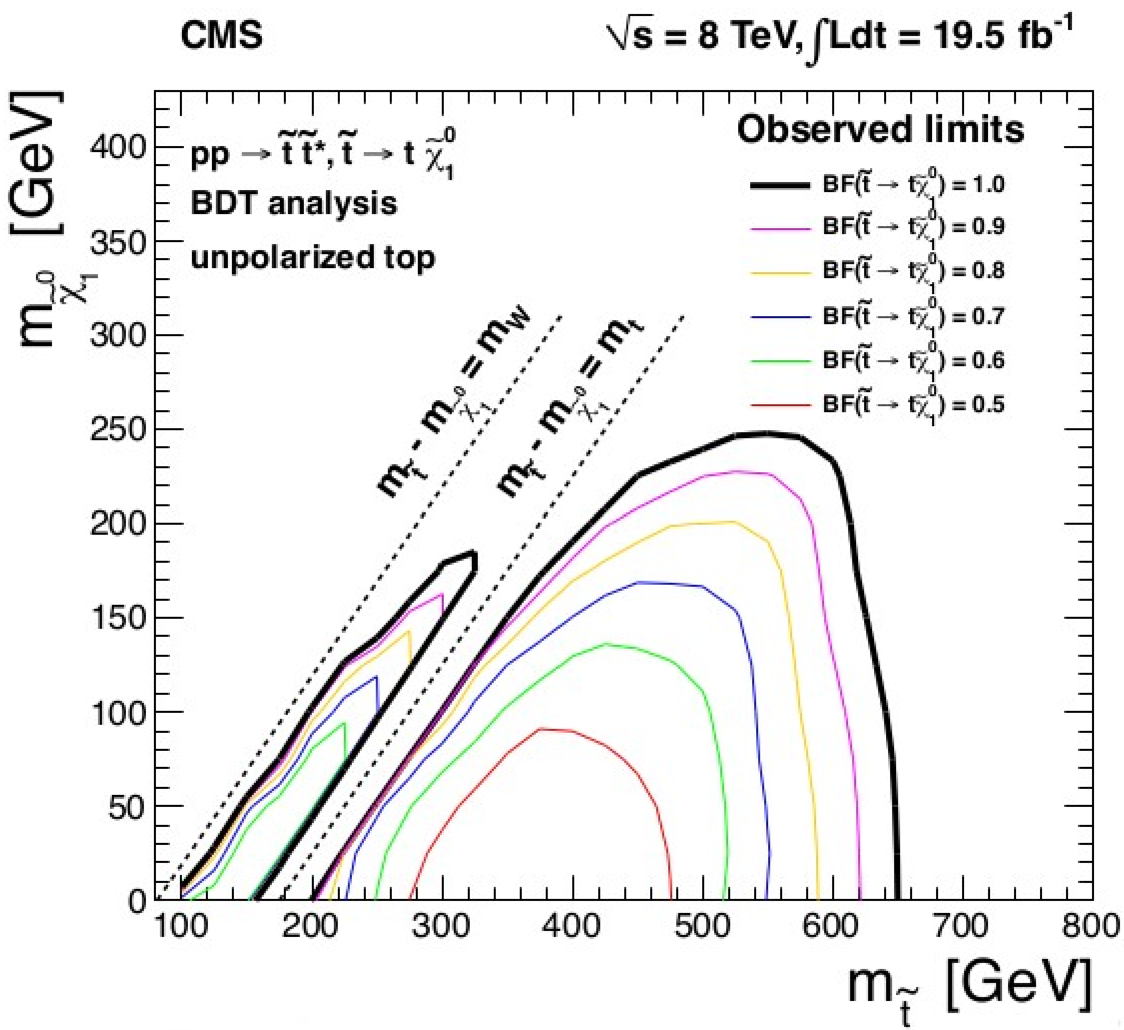
Results: Mass difference plane



Compressed spectra searches cover some of this region?

A case study: ATLAS stop searches

- There is apparently *no* limit on the stop mass from ATLAS
- You actually see this in the official limits (for both CMS and ATLAS)



More complex constraints (ATLAS pMSSM summary)

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: JHEP

CERN-PH-EP-2015-214
30th October 2015

Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM

The ATLAS Collaboration

- Most complete summary of ATLAS limits: lots of searches included

  - full ATLAS likelihood included
  - no statistical combination of analyses however

- Based on a large number of points in the pMSSM

  - 19 parameter version of MSSM (unify 1st and 2nd gen squark masses)

List of included searches

Analysis	Ref.	Category
0-lepton + 2–6 jets + E_T^{miss}	[58]	Inclusive
0-lepton + 7–10 jets + E_T^{miss}	[59]	
1-lepton + jets + E_T^{miss}	[60]	
$\tau(\tau/\ell)$ + jets + E_T^{miss}	[61]	
SS/3-leptons + jets + E_T^{miss}	[62]	
0/1-lepton + 3b-jets + E_T^{miss}	[63]	
Monojet	[64]	
0-lepton stop	[65]	Third generation
1-lepton stop	[56]	
2-leptons stop	[66]	
Monojet stop	[67]	
Stop with Z boson	[68]	
2b-jets + E_T^{miss}	[69]	
tb+E_T^{miss}, stop	[57]	
ℓh	[70]	Electroweak
2-leptons	[54]	
2-τ	[55]	
3-leptons	[53]	
4-leptons	[71]	
Disappearing Track	[72]	
Long-lived particle	[73, 74]	Other
$H/A \to \tau^+\tau^-$	[75]	

- Includes 7 TeV and 8 TeV results
- Most signal regions of each analysis are included

→ over 200 distinct signal regions!

pMSSM parameters and ranges

Parameter	Min value	Max value	Note
$m_{\tilde{L}_1} (= m_{\tilde{L}_2})$	90 GeV	4 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde{e}_1} (= m_{\tilde{e}_2})$	90 GeV	4 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde{L}_3}$	90 GeV	4 TeV	Left-handed stau doublet mass
$m_{\tilde{e}_3}$	90 GeV	4 TeV	Right-handed stau mass
$m_{\tilde{Q}_1} (= m_{\tilde{Q}_2})$	200 GeV	4 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde{u}_1} (= m_{\tilde{u}_2})$	200 GeV	4 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde{d}_1} (= m_{\tilde{d}_2})$	200 GeV	4 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde{Q}_3}$	100 GeV	4 TeV	Left-handed squark (third gen.) mass
$m_{\tilde{u}_3}$	100 GeV	4 TeV	Right-handed top squark mass
$m_{\tilde{d}_3}$	100 GeV	4 TeV	Right-handed bottom squark mass
$\|M_1\|$	0 GeV	4 TeV	Bino mass parameter
$\|M_2\|$	70 GeV	4 TeV	Wino mass parameter
$\|\mu\|$	80 GeV	4 TeV	Bilinear Higgs mass parameter
M_3	200 GeV	4 TeV	Gluino mass parameter
$\|A_t\|$	0 GeV	8 TeV	Trilinear top coupling
$\|A_b\|$	0 GeV	4 TeV	Trilinear bottom coupling
$\|A_\tau\|$	0 GeV	4 TeV	Trilinear τ lepton coupling
M_A	100 GeV	4 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

- Parameters are chosen at random, then constraints are applied

  - note: this is not statistically meaningful (we will return to this point)
  - allows at least some insight however

Non-LHC constraints

Parameter	Minimum value	Maximum value
$\Delta\rho$	-0.0005	0.0017
$\Delta(g-2)_\mu$	-17.7×10^{-10}	43.8×10^{-10}
$\mathrm{BR}(b \to s\gamma)$	2.69×10^{-4}	3.87×10^{-4}
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	1.6×10^{-9}	4.2×10^{-9}
$\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$	66×10^{-6}	161×10^{-6}
$\Omega_{\tilde{\chi}_1^0} h^2$	—	0.1208
$\Gamma_{\mathrm{invisible(SUSY)}}(Z)$	—	2 MeV
Masses of charged sparticles	100 GeV	—
$m(\tilde{\chi}_1^\pm)$	103 GeV	—
$m(\tilde{u}_{1,2},\ \tilde{d}_{1,2},\ \tilde{c}_{1,2},\ \tilde{s}_{1,2})$	200 GeV	—
$m(h)$	124 GeV	128 GeV

- Direct detection also considered

  - spin-independent: LUX
  - spin-dependent: COUPP and Xenon 100

Neutralino type

LSP type	Definition	Sampled	Simulated Number	Simulated Fraction	Weight
'Bino-like'	$N_{11}^2 > \max(N_{12}^2, N_{13}^2 + N_{14}^2)$	480×10^6	103,410	35%	1/24
'Wino-like'	$N_{12}^2 > \max(N_{11}^2, N_{13}^2 + N_{14}^2)$	$\}\ 20 \times 10^6\ \{$	80,233	26%	1
'Higgsino-like'	$(N_{13}^2 + N_{14}^2) > \max(N_{11}^2, N_{12}^2)$		126,684	39%	1
Total		500×10^6	310,327		

- Samples are chosen carefully to give ~ equal numbers of different neutralino types

- Most samples had pure neutralinos of a particular type

  - this is generically expected for their sampling method
  - does not mean in general that models with mixtures are not favoured
  - allows reasonable exploration of the extremes however

Applying ATLAS constraints

- 500, 000, 000 points were chosen at random

  - 310,327 points pass the non-ATLAS constraints

- For each of these points, the following is performed

  - check to see if cross-sections are high enough

  - if yes: truth level (+ basic efficiency) MC to see if acceptance values are high enough

  - separate into: a) obviously excluded, b) obviously not excluded, c) close to exclusion

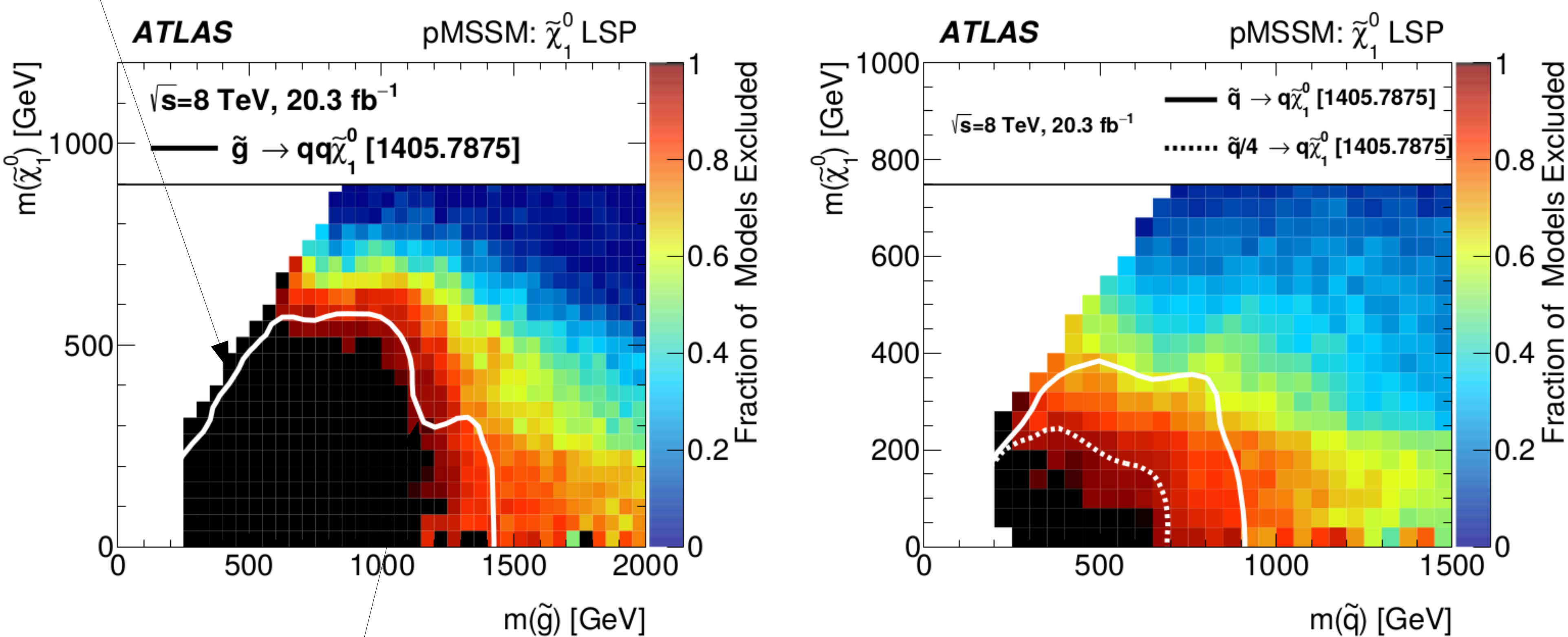
  - run proper ATLAS simulation on category (c) to clarify status

- Results are presented in mass planes, with fraction of excluded models

  - the paper is honest: this tells you **nothing** in general about exclusions
  - can give a sort of qualitative, hand-waving insight however
  - BONUS: get to check how accurate simplified model limits are

Gluino-LSP and squark-LSP planes

monojet search is good here

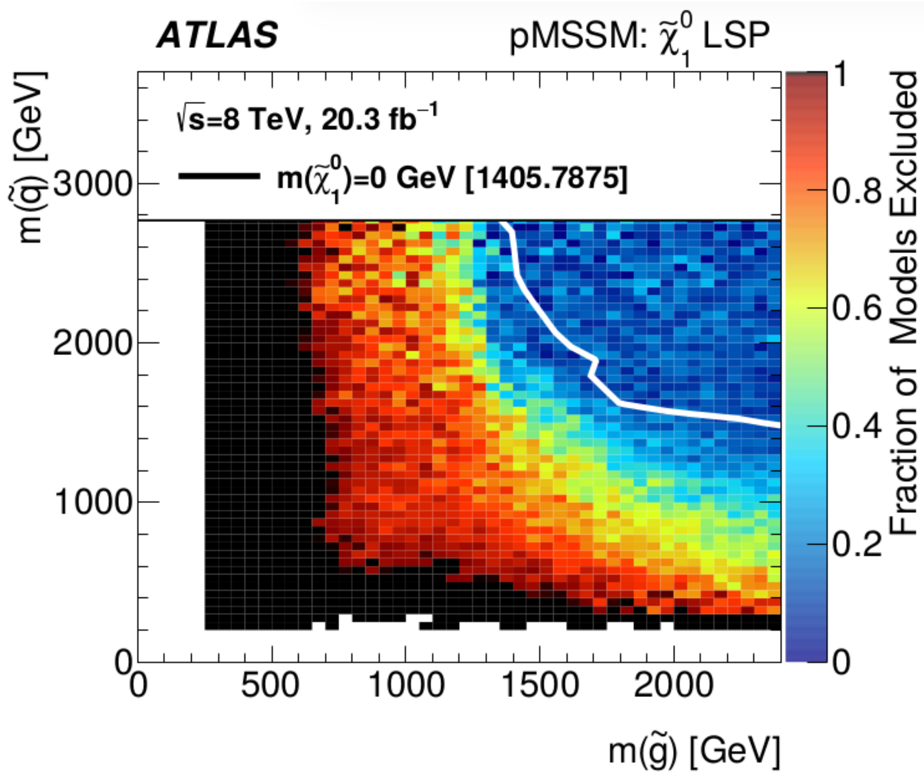


(a) Gluino / LSP

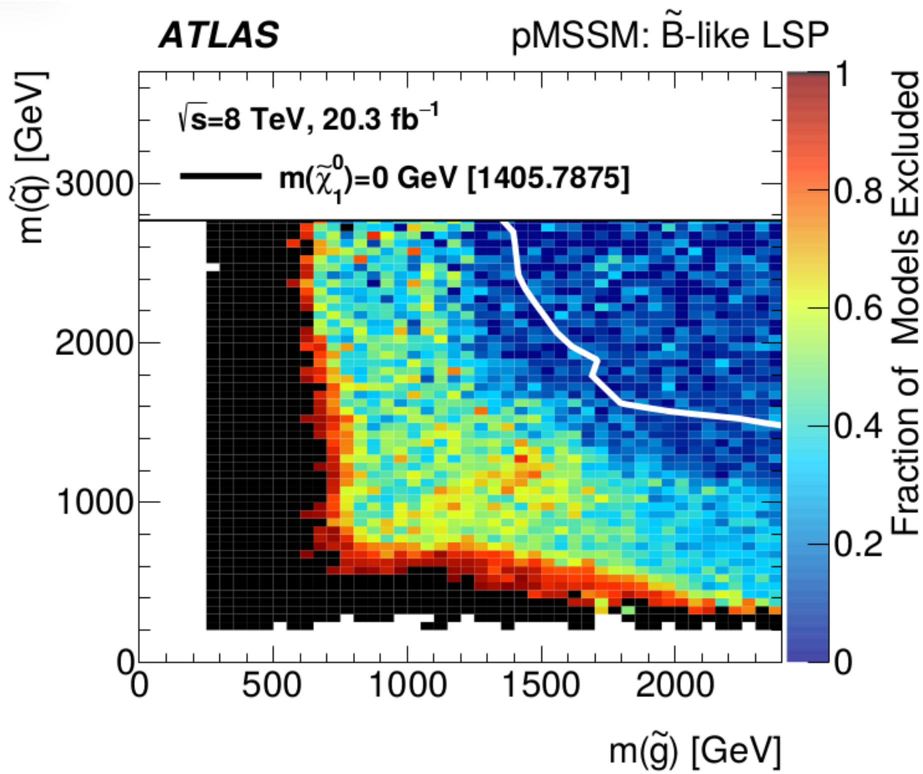
(b) Lightest (1st/2nd gen) squark / LSP

simplifed gluino model

Gluino-squark planes

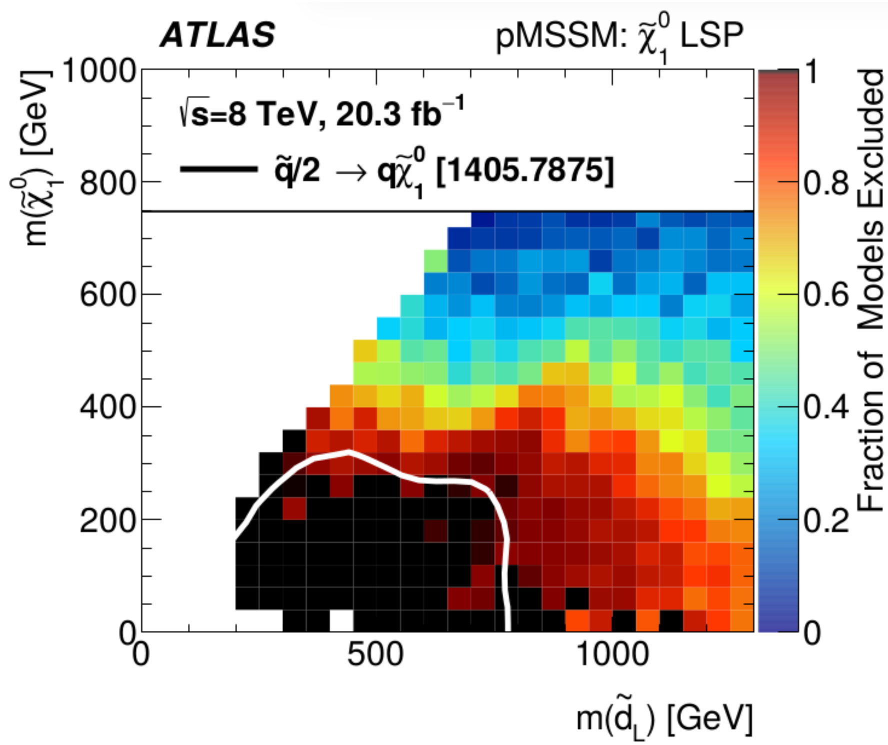


(a) All LSP types

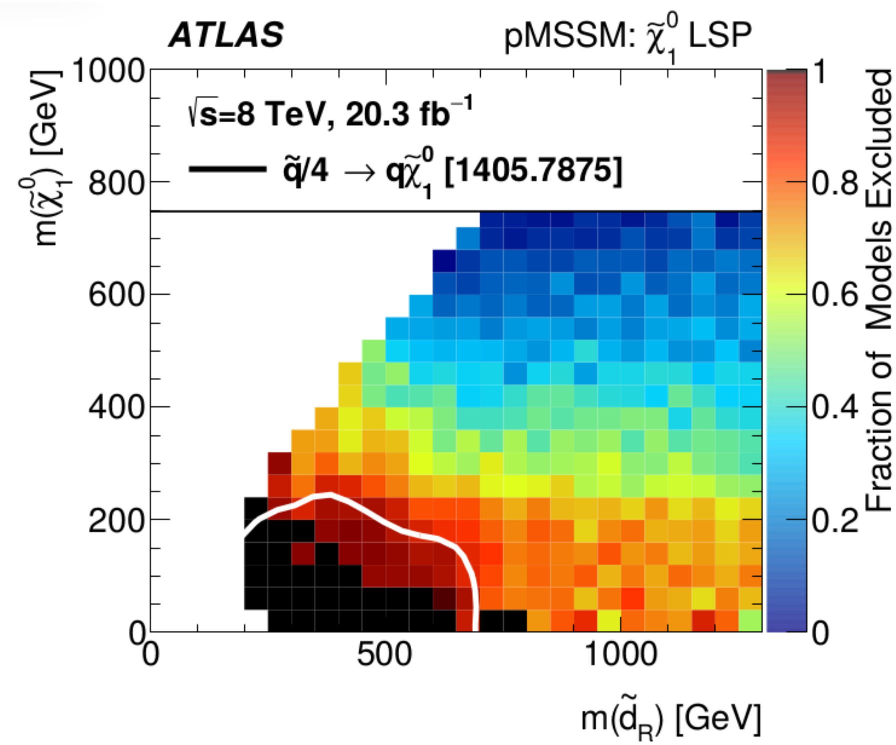


(b) Bino-like LSPs

Limits depend on squark L or R



(c) Left down squark



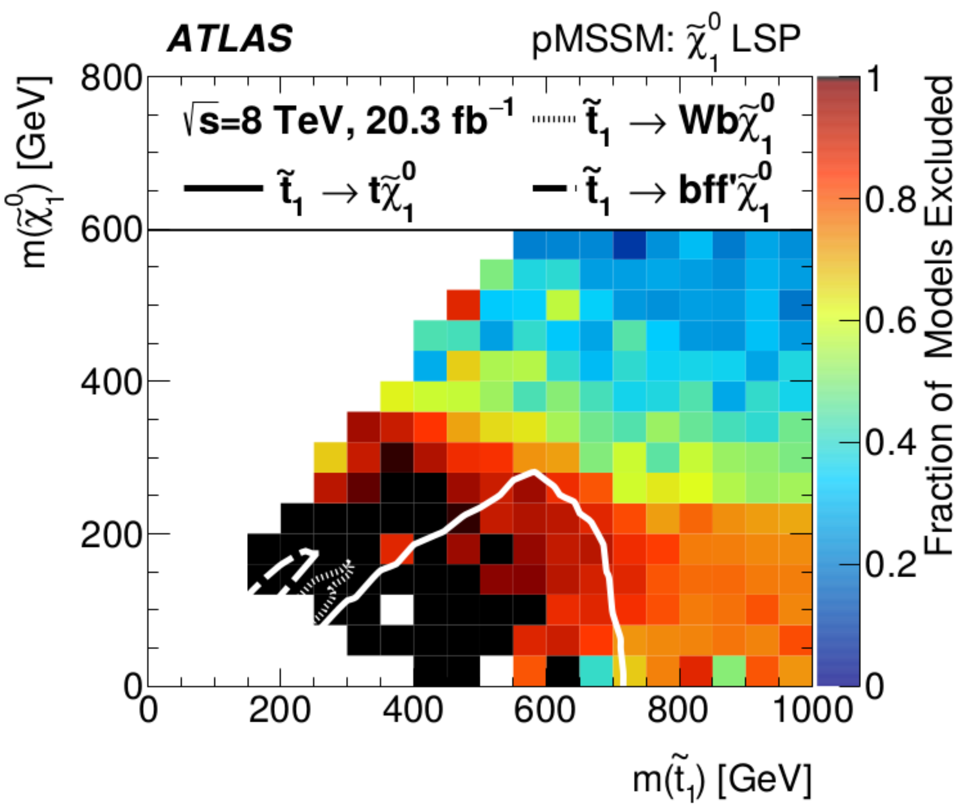
(d) Right down squark

- LH squarks form an EW doublet → roughly mass degenerate → higher cross-section

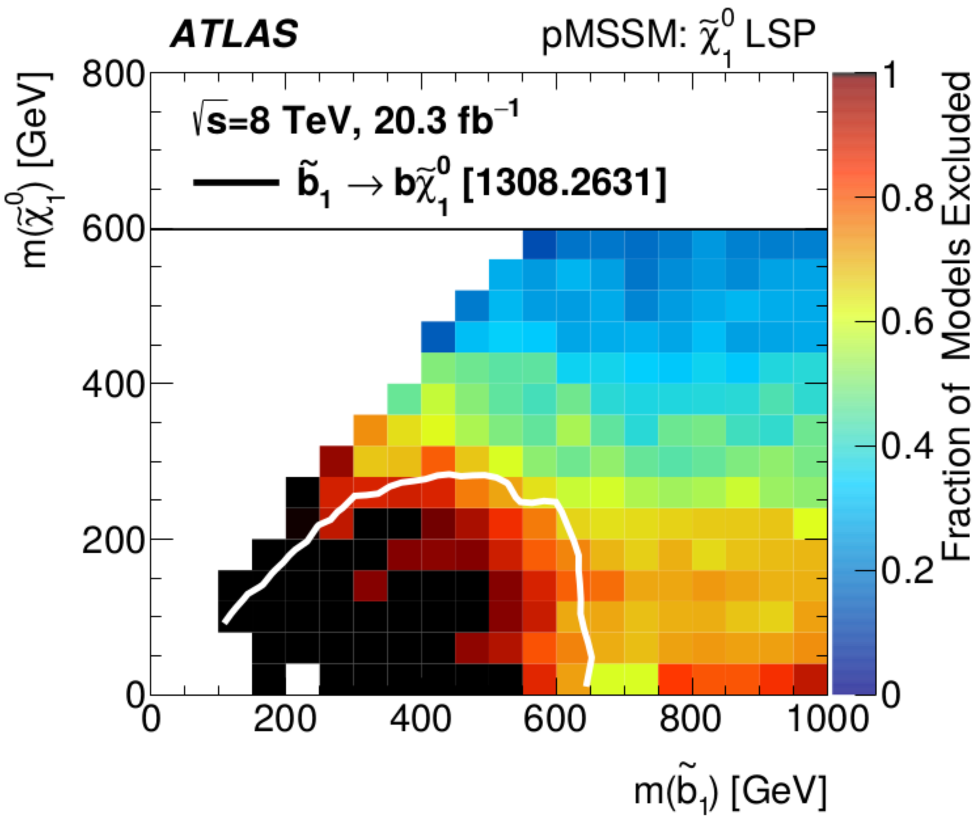
Also, get more cascade decays for RH squarks

- can more easily fall in the cracks between searches

3rd generation squarks



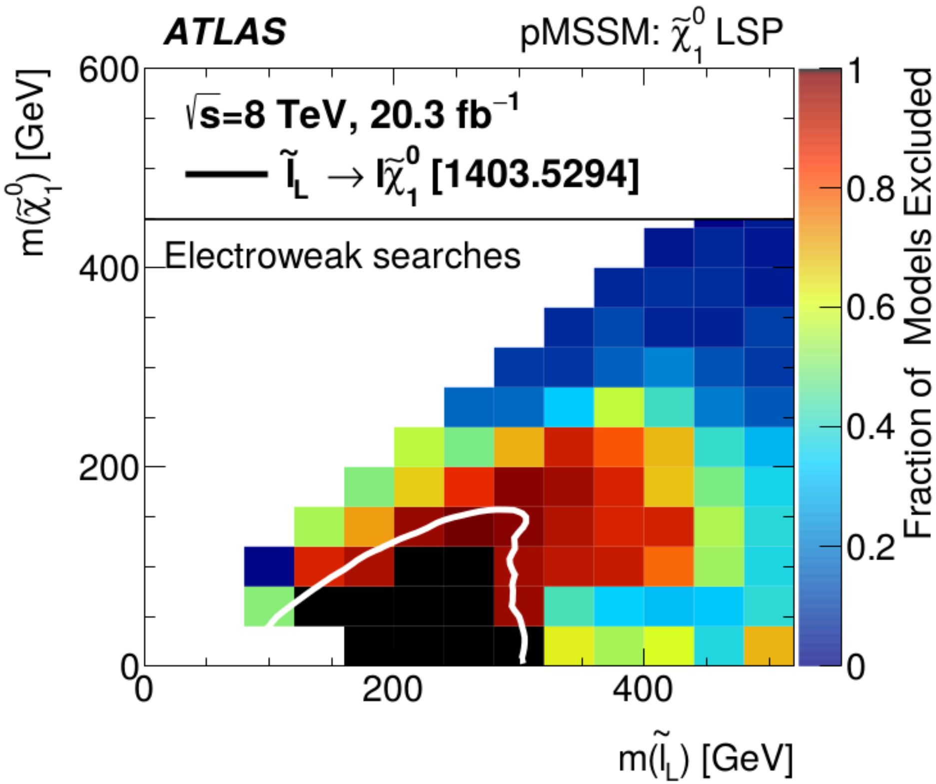
(a) All pMSSM points, all searches



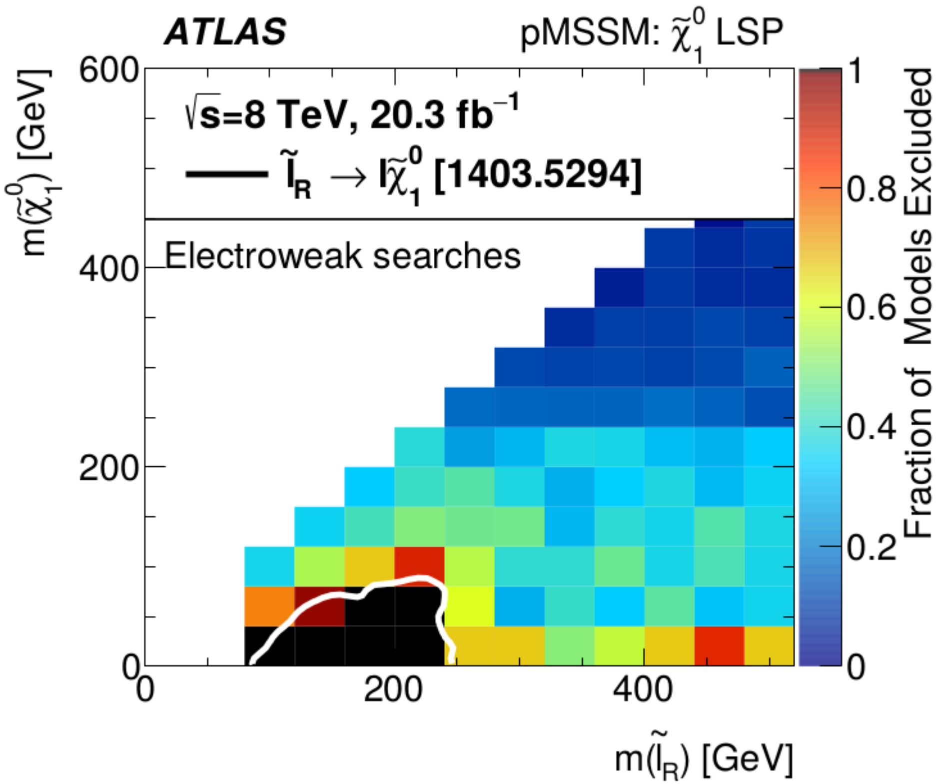
(a) All searches

- Note: scan has few points with low stop mass

  - due to the Higgs mass constraint (see lecture 1)

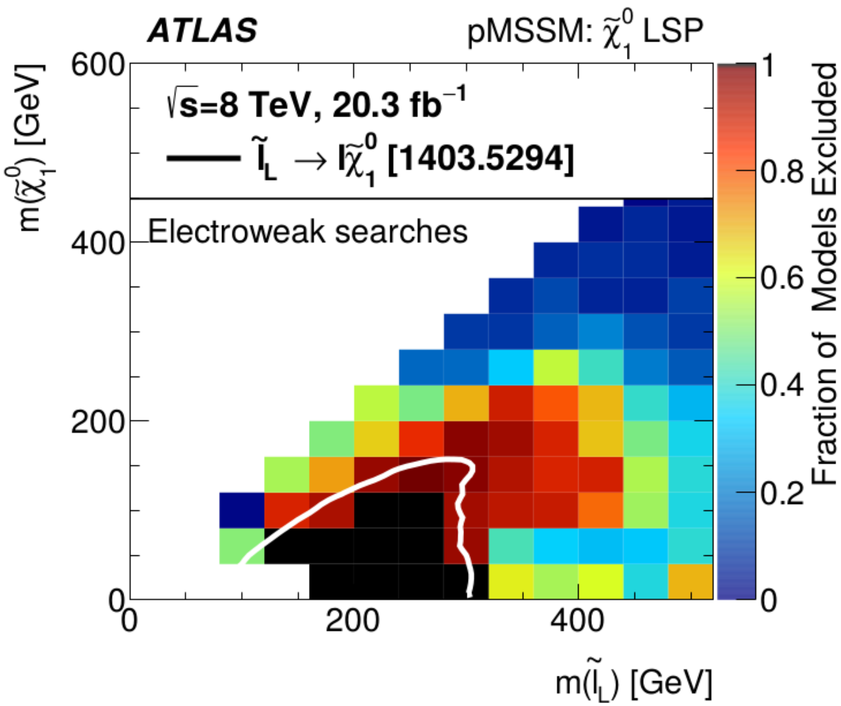


(a) All LSPs, $\tilde{\ell}_L$

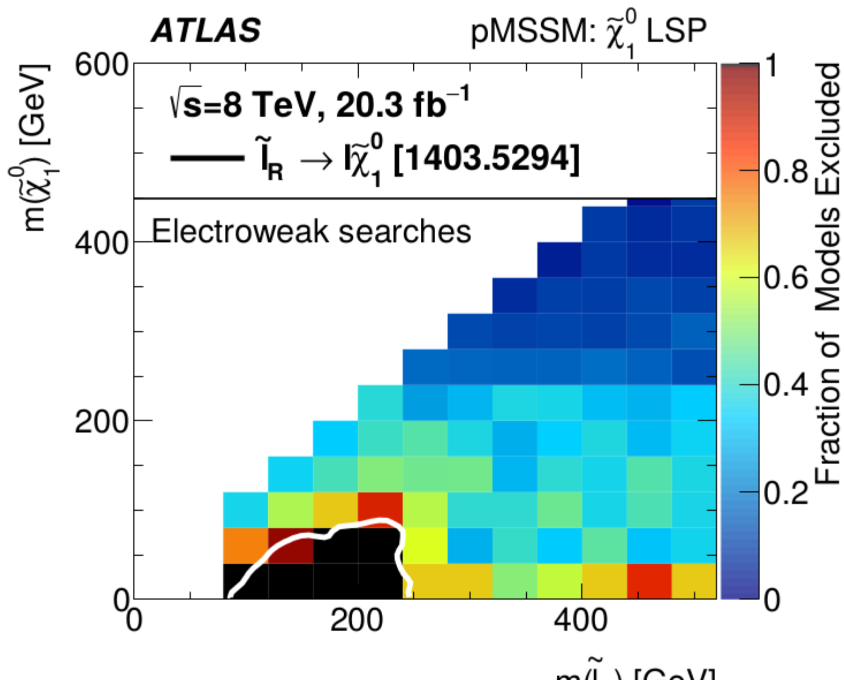


(b) All LSPs, $\tilde{\ell}_R$

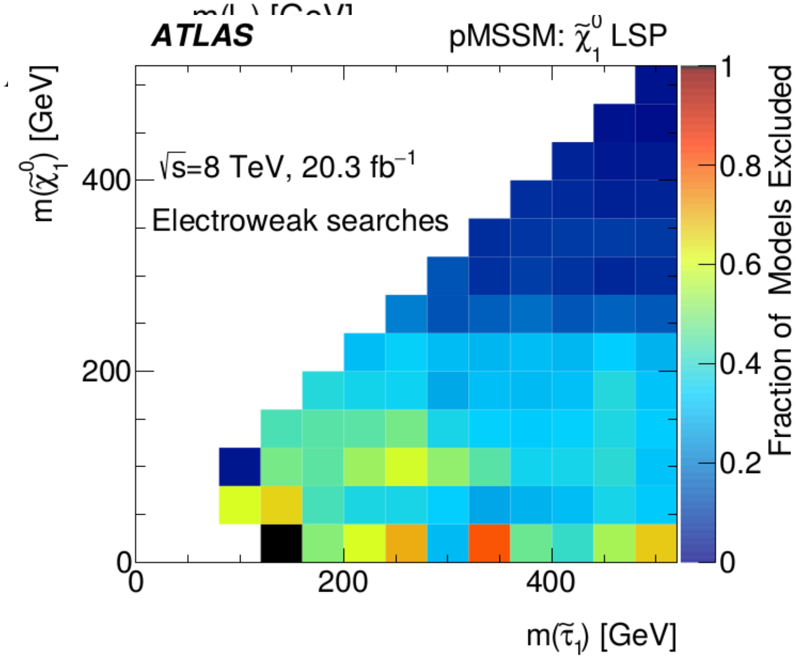
Sleptons



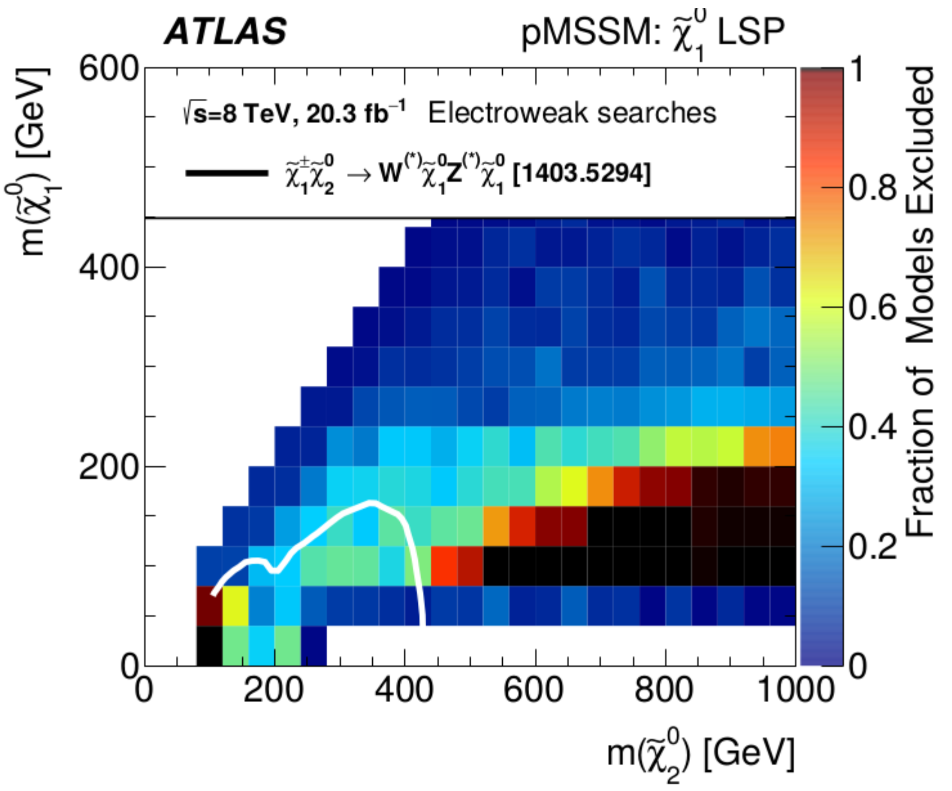
(a) All LSPs, $\tilde{\ell}_L$



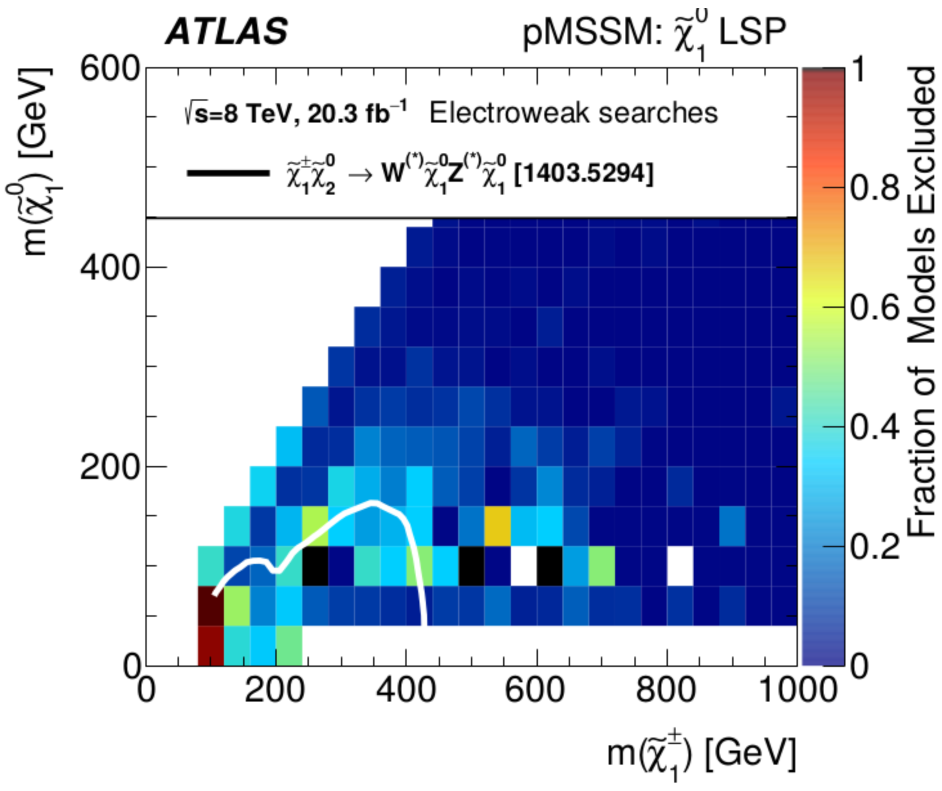
(b) .



Weak gauginos



(a) Neutralinos



(b) Chargino–neutralino

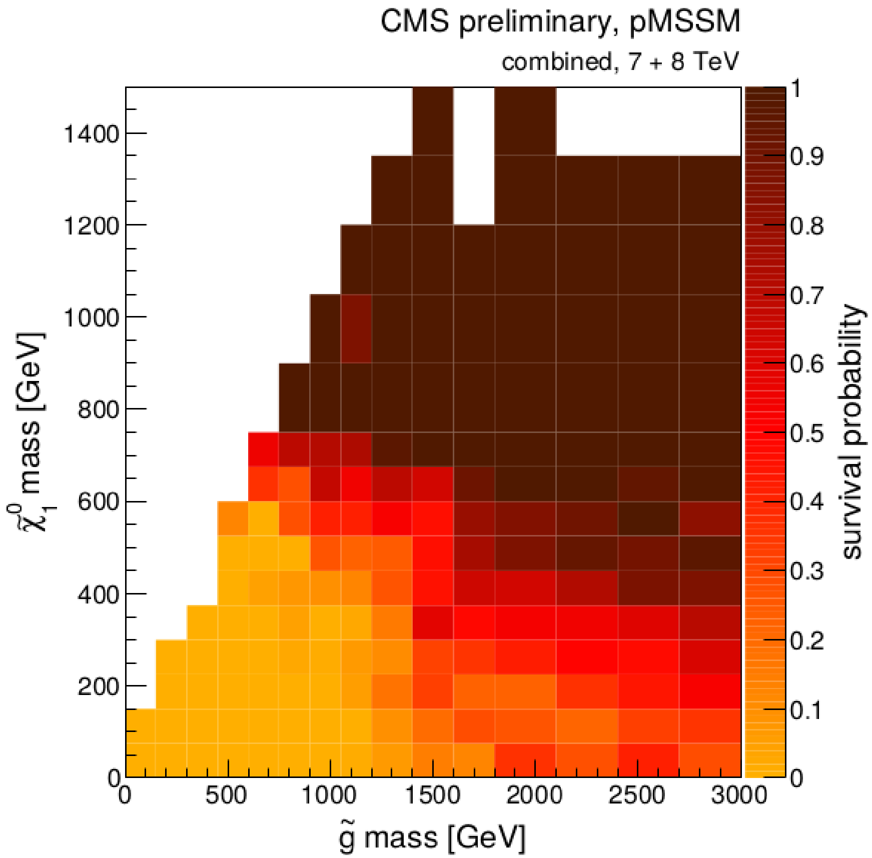
CMS pMSSM study

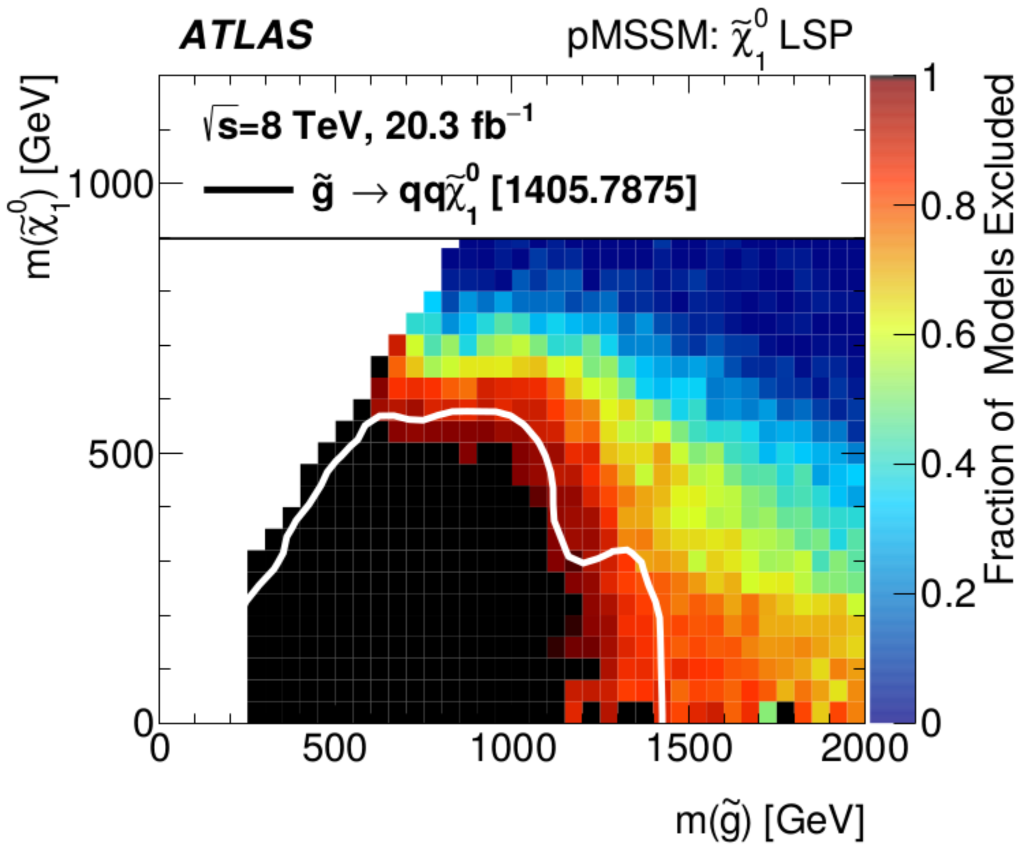
- Different methodology

  - sampled points come from an MCMC Bayesian scan of the pMSSM
  - but only 7200 points are selected for simulation studies!
  - 10,000 MC events per point

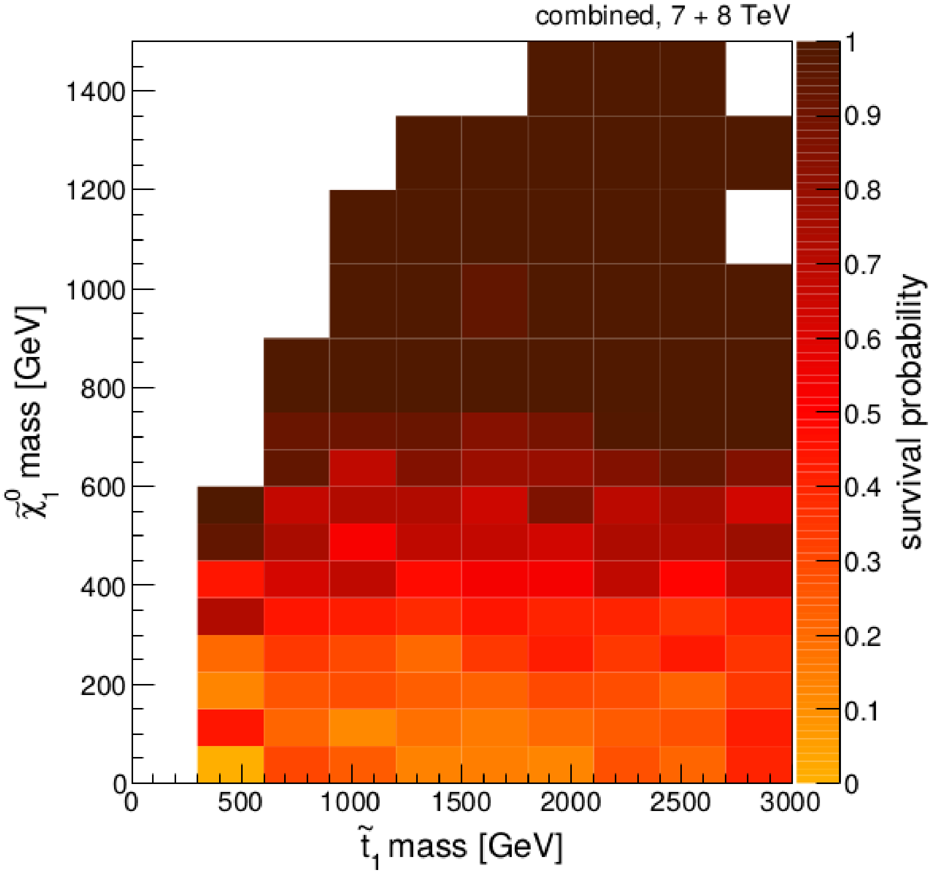
i	Observable $\mu_i(\theta)$	Constraint $D_i^{\text{non-DCS}}$	Likelihood function $L(D_i^{\text{non-DCS}} \| \mu_i(\theta))$	comment
1	$BR(b \to s\gamma)$ [40]	$(3.43 \pm 0.21^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.07^{\text{sys}}) \times 10^{-4}$	Gaussian	reweight
2	$BR(B_s \to \mu\mu)$ [41]	$(2.9 \pm 0.7 \pm 0.29^{th}) \times 10^{-9}$	Gaussian	reweight
3	$R(B_u \to \tau\nu)$[40]	1.04 ± 0.34	Gaussian	reweight
4	Δa_μ [42]	$(26.1 \pm 6.3^{\text{exp}} \pm 4.9^{\text{SM}} \pm 10.0^{\text{SUSY}}) \times 10^{-10}$	Gaussian	
5	m_t [43]	$173.20 \pm 0.87^{\text{stat}} \pm 1.3^{\text{sys}}$ GeV	Gaussian	reweight
6	$m_b(m_b)$ [44]	$4.19^{+0.18}_{-0.06}$ GeV	Two-sided Gaussian	
7	$\alpha_s(M_Z)$ [44]	0.1184 ± 0.0007	Gaussian	
8	m_h	LHC: $m_h^{low} = 120$, $m_h^{up} = 130$	1 if $m_h^{low} \leq m_h \leq m_h^{up}$ 0 if $m_h < m_h^{low}$ or $m_h > m_h^{up}$	reweight
9	μ_h	CMS and ATLAS in LHC RunI, Tevatron	`Lilith1.01` [36, 37]	post-MCMC
10	sparticle masses	LEP [45] (via micrOMEGAs [29–31])	1 if allowed 0 if excluded	

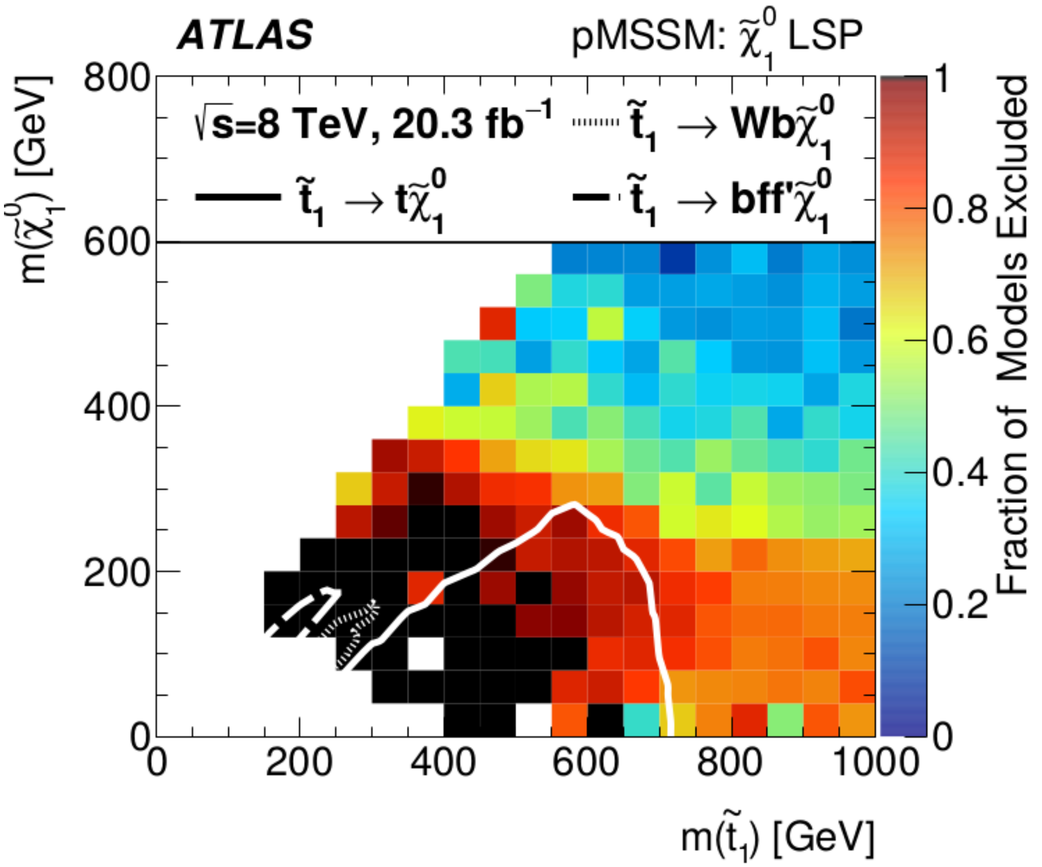
CMS v ATLAS: gluino mass





CMS v ATLAS: stop mass





How *should* we decide if SUSY is ruled out

- Both of the previous studies had statistical flaws:

  - ATLAS: ignore fitting entirely, density of points has no meaning
  - CMS: too few points simulated to ensure conclusions are meaningful
  (in both cases this was necessary to reduce computational complexity)

- In general, these studies need a more rigorous approach

- For simple models with only two parameters and a few constraints:

  - determining exclusion regions by overlapping limits is fine

- For lots of constraints, ought to use a **combined likelihood**:

  - can trade off constraints and still get a good fit to the data

- If there are lots of constraints *and* lots of parameters:

  - things are much harder

What if there are many parameters?

- Much harder in principle

- Need to:

  - scan the space (need very smart methods for a large number of parameters)
  - interpret the results (Bayesian/frequentist)
  - project down to parameters of interest (marginalise/profile)

i.e. need a global statistical fit

Reminder: LHC cut and count analyses

- Given *s* expected signal events, *b* background events and *o* observed events:

$$L = e^{-(s+b)} (s+b)^o \div o!$$

- Systematics on signal and background can be handled via:

$$\mathcal{L}(n|s,b) = \int_0^\infty \frac{[\xi(s+b)]^n \, e^{-\xi(b+s)}}{n!} P(\xi) \mathrm{d}\xi$$

- With, e.g. , $P(\xi|\sigma_\xi) = \frac{1}{\sqrt{2\pi}\sigma_\xi} \frac{1}{\xi} \exp\left[-\frac{1}{2}\left(\frac{\ln\xi}{\sigma_\xi}\right)^2\right]$

quadrature sum of signal and background systematics

How to calculate *s*

$$s = \sigma \times \varepsilon \times L$$

Read this from the title of the paper

Need to calculate SUSY production cross-sections. Best tool is probably Prospino (general NLO cross-sections). Fast NLO+NLL cross-sections exist in NLLFAST for some models.

Need to run an MC generator (see Skands lectures) and pass the events through a detector simulation. Also need to apply LHC analysis cuts.

Current tools for applying LHC constraints to SUSY models

• Several tools for the application of collider limits have appeared in recent years:

CHECKMATE: Contains a custom version of the DELPHES event simulation plus analysis code for lots of LHC searches. Does not do any MC event generation or cross-section calculation (but version 2 is coming soon).

SMODELS: Looks at LHC "simplified model" limits and checks to see if a given model is excluded by those limits (by scaling each topology by the appropriate cross-section times branching ratio). Gives very conservative limits and is only applicable to SUSY.

FASTLIM: Uses simplified model limits plus efficiency tables to approximate the efficiency for general SUSY models. Only applicable to SUSY.

• Although some of the approaches taken above may generalise, there is no fully general package capable of quickly applying LHC limits to new models out of the box

Coming soon: SUSY-AI, GAMBIT

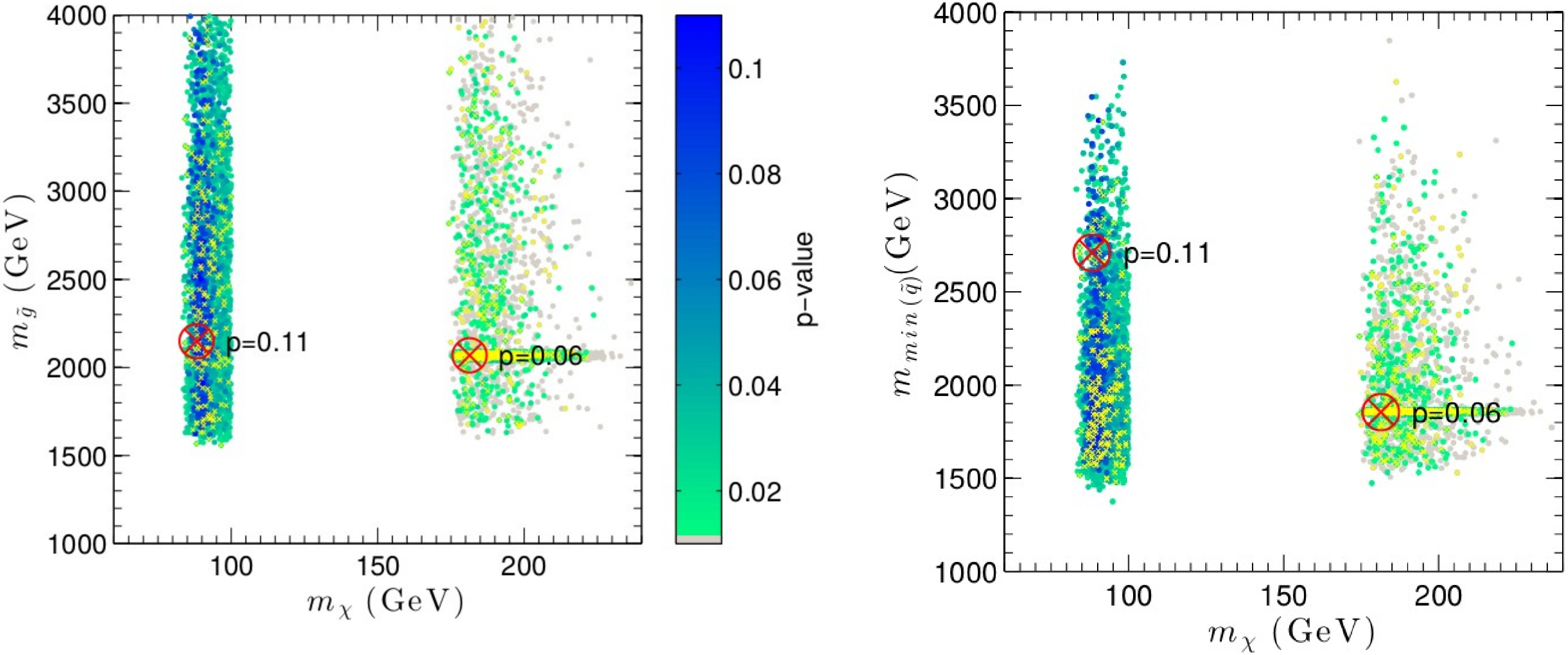
Global analysis of the pMSSM in light of the Fermi GeV excess: prospects for the LHC Run-II and astroparticle experiments

Gianfranco Bertone,[a] Francesca Calore,[a] Sascha Caron,[b] Roberto Ruiz,[c] Jong Soo Kim,[d] Roberto Trotta,[e] Christoph Weniger.[a]

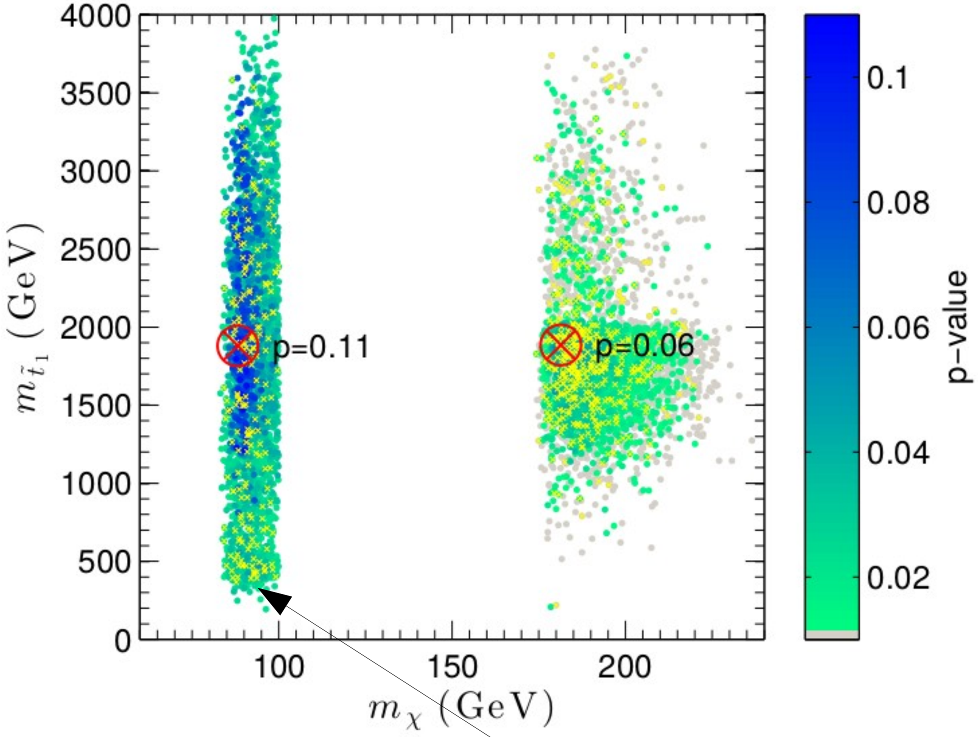
- A proper global fit of the pMSSM
  - LHC constraints applied posthoc, but to 100,000 points
  - uses Fermi-LAT data, EW precision constraints, flavour observables, relic density, LUX constraints, IceCube constraints, Higgs constraints + LHC sparticle searches (CheckMATE)

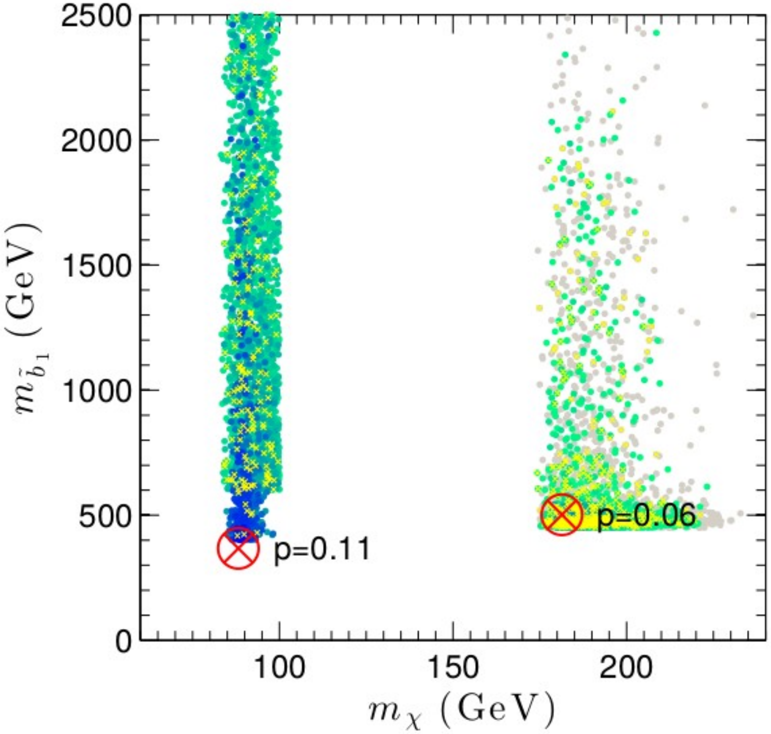
$$\ln \mathcal{L}_{\rm Joint} = \ln \mathcal{L}_{\rm GCE} + \ln \mathcal{L}_{\rm EW} + \ln \mathcal{L}_{\rm B(D)} + \ln \mathcal{L}_{\Omega_\chi h^2} + \ln \mathcal{L}_{\rm LUX} + \ln \mathcal{L}_{\rm IC} + \ln \mathcal{L}_{\rm Higgs} + \ln \mathcal{L}_{\rm SUSY},$$

Gluino and minimum squark mass



Stop and sbottom masses





Light stop points not excluded
by LHC searches

Introducing GAMBIT

GAMBIT: The Global And Modular BSM Inference Tool

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

ATLAS	A. Buckley, P. Jackson, C. Rogan, M. White,
LHCb	M. Chrząszcz, N. Serra
Belle-II	F. Bernlochner, P. Jackson
Fermi-LAT	J. Conrad, J. Edsjö, G. Martinez, P. Scott
CTA	C. Balázs, T. Bringmann, J. Conrad, M. White
HESS	J. Conrad
IceCube	J. Edsjö, P. Scott
XENON/DARWIN	J. Conrad, R. Trotta
Theory	P. Athron, C. Balázs, T. Bringmann, J. Cornell, J. Edsjö, B. Farmer, T. Gonzalo, S. Hoof, F. Kahlhoefer, A. Krislock, A. Kvellestad, M. Pato, F. Mahmoudi, J. McKay, A. Raklev, R. Ruiz, P. Scott, R. Trotta, C. Weniger, M. White

27 Members, 9 Experiments, 4 major theory codes, 10 countries

Summary

- This lecture, we have learnt that SUSY limits are complicated in general

  - LHC gluino limit is relatively stringent
  - much evidence suggests that light stops are not ruled out
  - light squark mass limits are not watertight either

- SUSY can apparently be perfectly healthy, except:

  - Higgs mass makes things interesting
  - naturalness is complicated
  - SUSY is **fine** if you don't care at all about fine tuning

- Lots still to do

  - this year is an extremely important year
  - could get as much as 30 fb^{-1} of LHC data at 13 TeV

Pay close attention to the new results presented at this conference!