Sabine Kraml
LPSC Grenoble

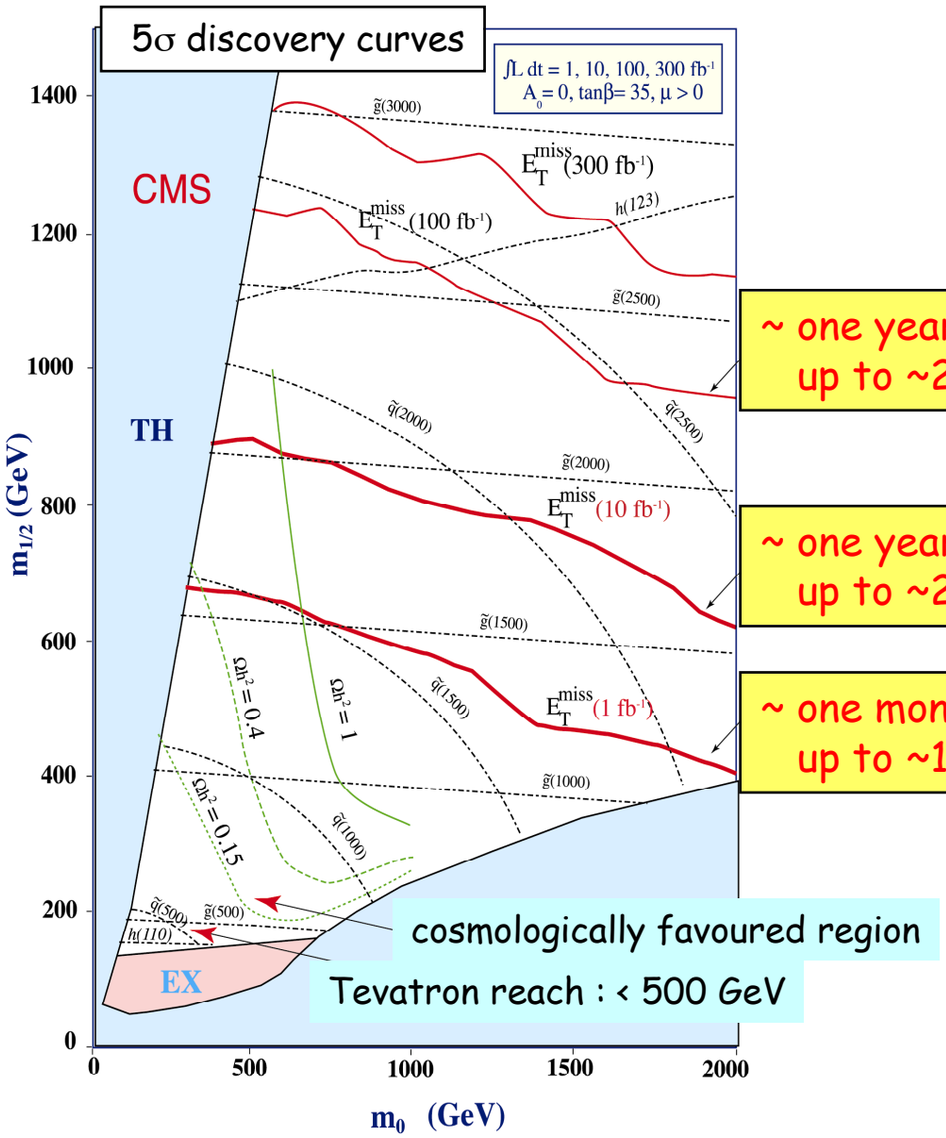
SUSY phenomenology at colliders

or: Considerations after Run-I of the LHC

22nd International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY2014), 21 - 26 July 2014, Manchester, England

High expectations

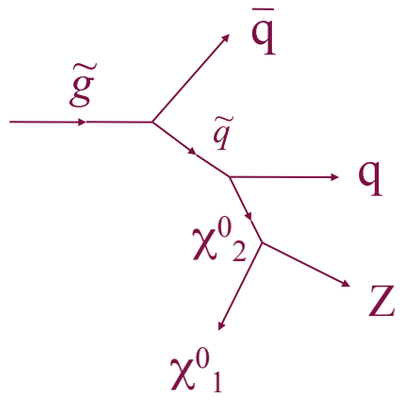
Before the start of the LHC, our expectations were quite high:
If SUSY is light (as we expect ...) it should be discovered early on

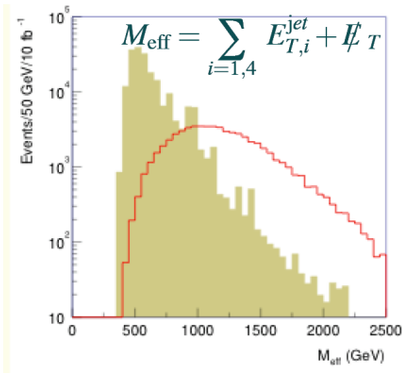


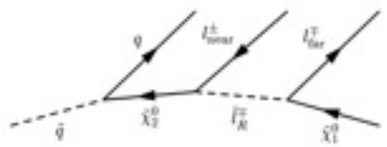
~ one year at 10^{34}: up to ~2.5 TeV

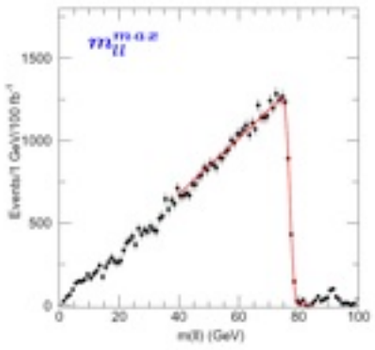
~ one year at 10^{33} : up to ~2 TeV

~ one month at 10^{33} : up to ~1.5 TeV







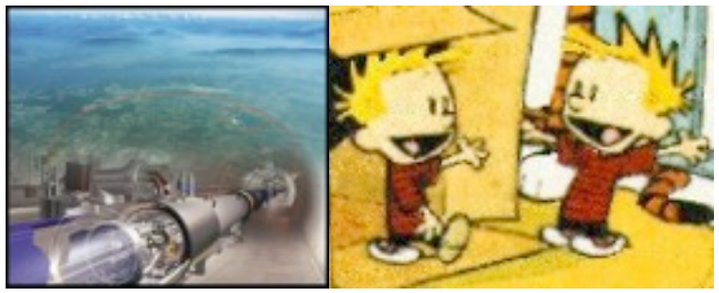


Large gluino/squark production cross sections
➪ ~100 events/day for M_{SUSY} ~ 1 TeV
➪ Spectacular signatures, much easier than Higgs search

Plot taken from an old talk by A. De Roeck

From one of my colloquia in 2007:

If TeV-scale SUSY is realized in Nature,
the LHC will discover a wealth of new states:
the superpartner world!

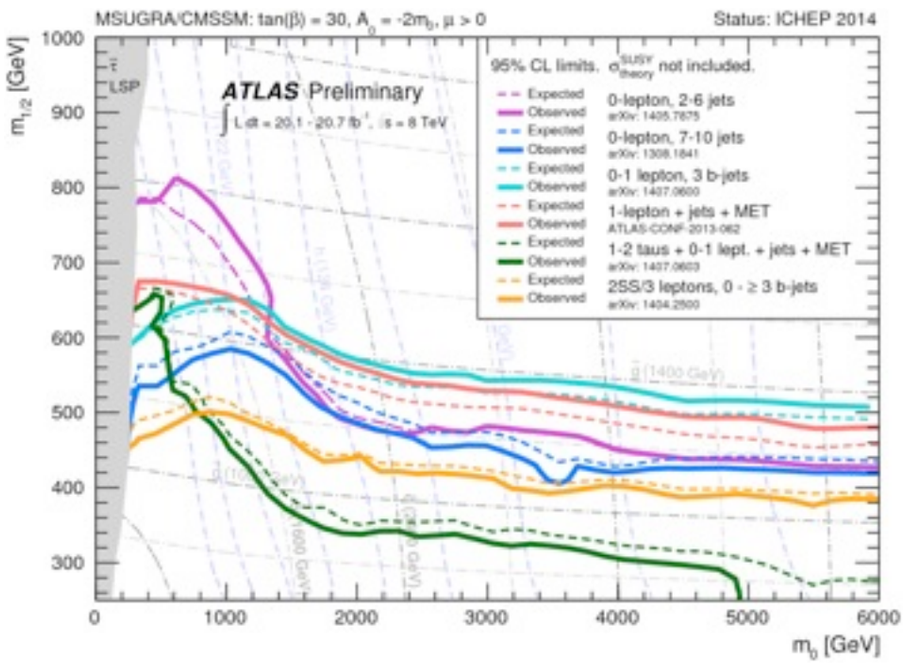


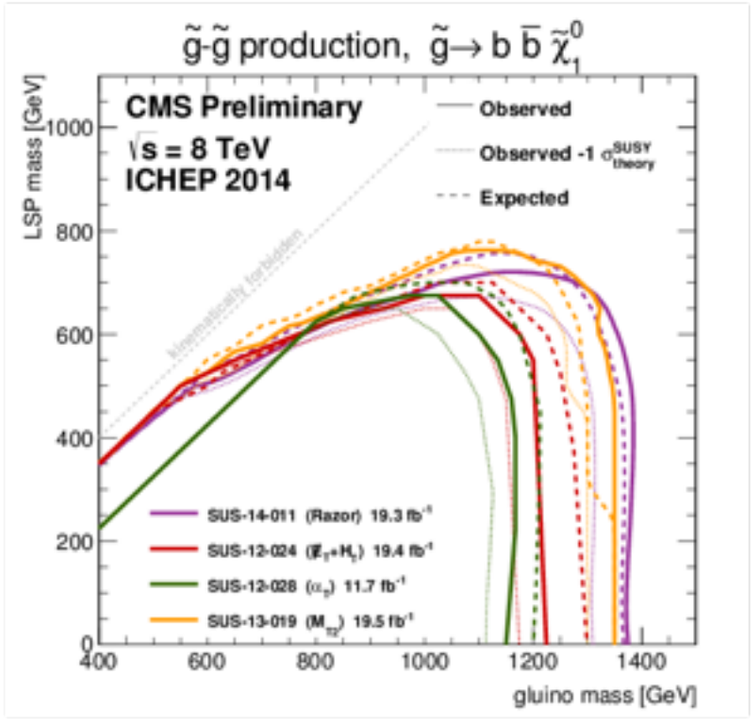
would also revolutionize our understanding of space-time

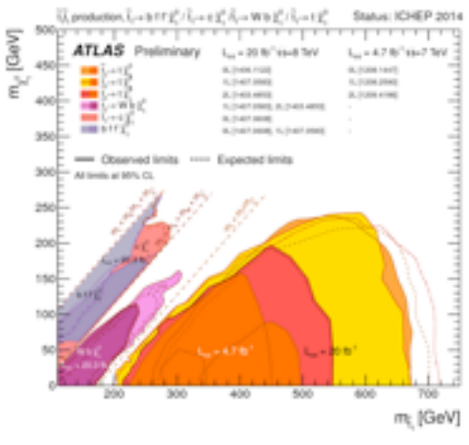
The Quest for Supersymmetry, Univ. of Innsbruck, 8 May 2007

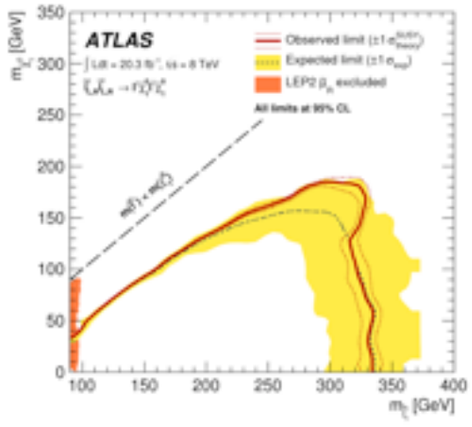
In reality, nothing found so far

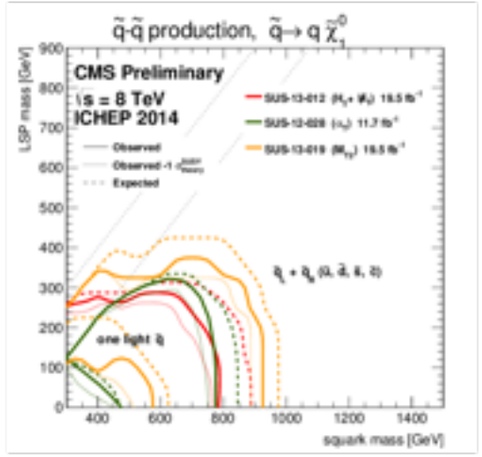
ATLAS and CMS searches are but pushing mass limits higher and higher

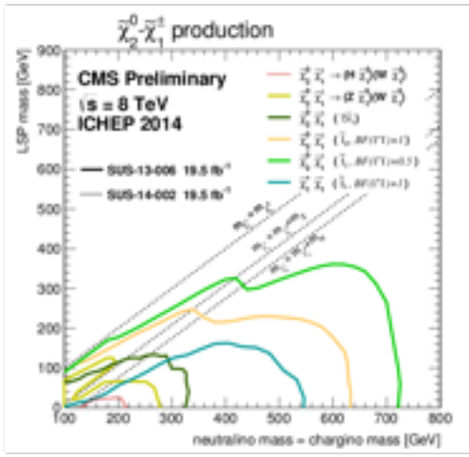












and a plethora of other results, see talks by Monica d'Onofrio and Henning Flaecher

2013
Les Houches
PhysTeV
workshop

Imagine there is no SUSY
It's easy if you try
Only Higgs below us
Above us only Planck
Imagine all the people, [...] in Les Houches.

Imagine there's no signal
It isn't hard to do
Nothing to kill or exclude
And no background too
Imagine all the people, living by SU(2)

Imagine no trileptons
I wonder if you can
No need for razor or MT2
Standard Model for all
Imagine all the people, fitting just the Higgs

What went wrong?

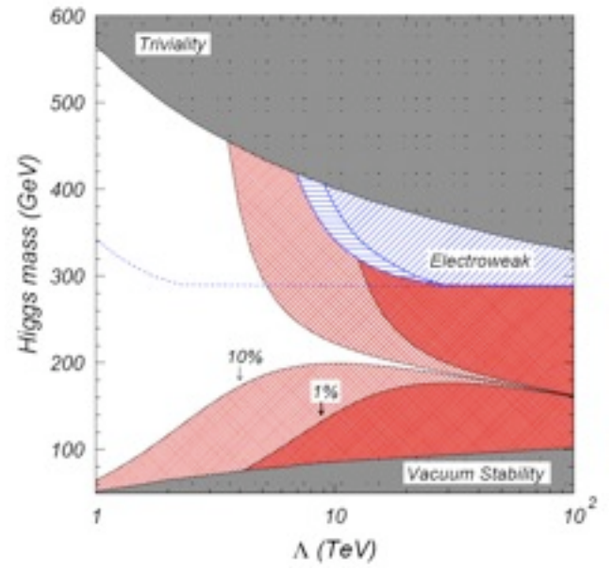
The hierarchy problem

The expectation of new physics at the TeV scale primarily comes from the "need" to stabilize the EW scale against quadratically divergent radiative corrections. We want

* to explain in the first place why $m_H^2 \ll m_{\rm Planck}^2$
* to ensure $\delta m_H^2 \lesssim m_H^2$

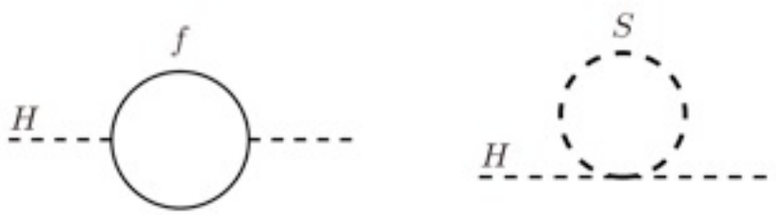
→ Some new dynamics connected with v~200 GeV

Finetuning and the scale of new physics



[Kolda, Murayama, hep-ph/0003170]

The standard paradigm:



$$\begin{aligned}\delta m_H^2 &= \left(\frac{g_f^2}{16\pi^2}\right)(\Lambda^2 + m_f^2) - \left(\frac{g_S^2}{16\pi^2}\right)(\Lambda^2 + m_S^2) \\ &= \mathcal{O}\left(\frac{\alpha}{4\pi}\right)|m_S^2 - m_f^2|\end{aligned}$$

SUSY solves the hierarchy problem provided $M_{\rm SUSY} \lesssim 1\text{TeV}$

One Ring to rule them all, One Ring to find them,
One Ring to bring them all and in the darkness bind them.

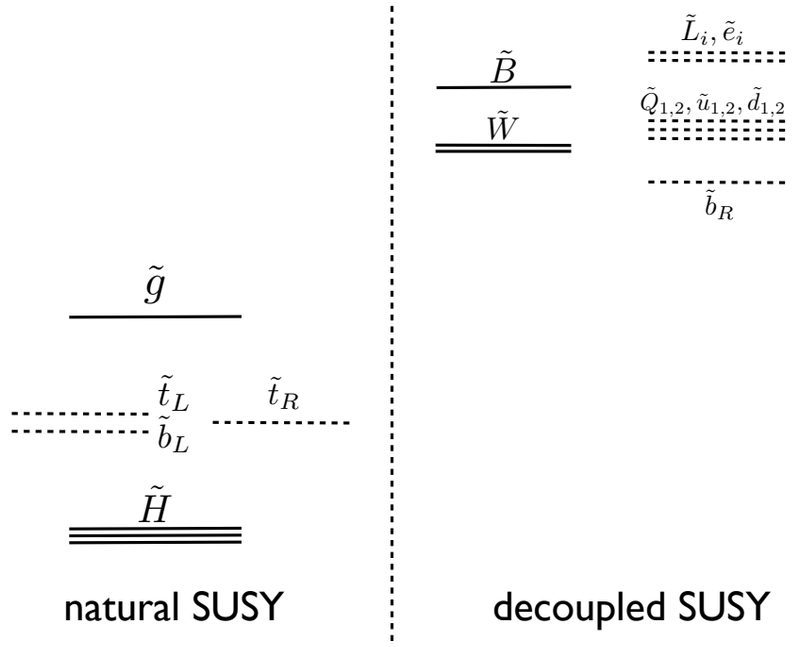
Natural SUSY ?

More precisely, for naturalness arguments, we want to avoid too much tuning in the relation

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

Standard paradigm:

- ➡ stops and left sbottom should weigh below around 500−700 GeV
- ➡ higgsinos should be light, below about 200−350 GeV
- ➡ gluinos should not be too heavy either, at most about 1500 GeV



taken from arXiv:1110.6926

→ see talks by Marcela Carena and by Howie Baer

This is getting tight, though not yet excluded.

However, m_h~126 GeV in the MSSM requires heavy or maximally mixed stops → tension!

c.f. talk by Sven Heinemeyer

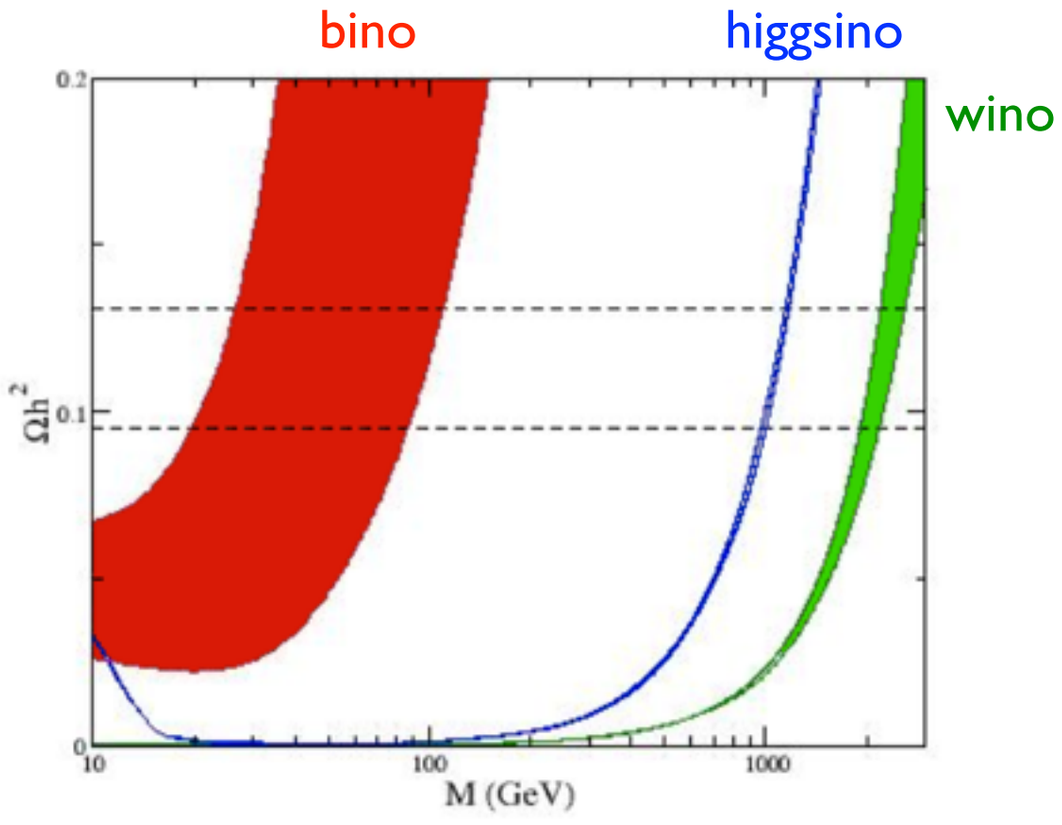
Neutralino dark matter

- Many popular models imply "GUT" relations for gaugino masses, so that gluino : wino : bino masses roughly scale as 7 : 2 : 1.

- The LSP then typically is a mostly bino-like neutralino, and to have the correct relic density it cannot be too heavy → weak-scale WIMP, $m_\chi \sim$ O(10-100) GeV

- However this need not be the case: higgsino or wino LSPs achieve $\Omega h^2 \sim 0.1$ for a mass of order 1 TeV !

- Besides, dark matter could be the gravitino, RH sneutrino, axions or axinos ....



Arkani-Hamed, Delgado, Giudice, hep-ph/0601041

Ways out

- Decouple the hierarchy problem

  The cosmological constant problem, also connected to UV power divergences, may be explained by anthropic requirements for an observable universe (multiverse solution suggested by the plethora of string theory vacua)

  Why not invoke the same mechanism for explaining the weak scale?

  v ~ 200 GeV is then independent of any new dynamics, though the underlying theory should still be supersymmetric, for the sake of string theory

  → High-scale, Split, Spread, etc. SUSY

- Hide weak-scale SUSY through non-standard / hard-to-observe signatures
  - Compressed spectra
  - Hidden valleys, "stealth" SUSY, RPV
  - Non-minimal particle content: NMSSM, BMSSM, RH sneutrino, ...
  - Revisit the naturalness argument (light stops or not?)

Heavy, split or spread SUSY

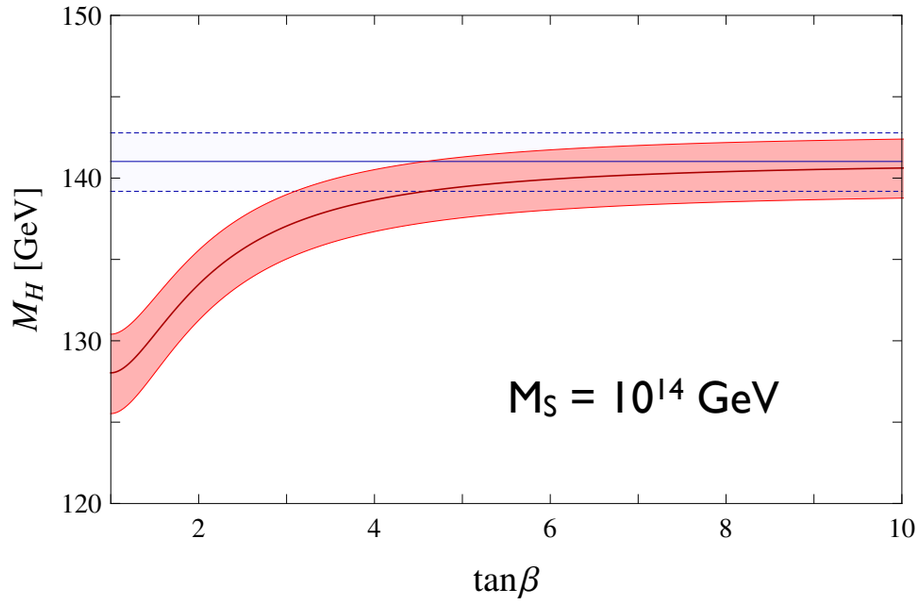
High-scale SUSY:

Supersymmtry broken at some high scale, $M_S \gg$ TeV (could be as high as M_{GUT}) with all SUSY particles very heavy.

All we can observe is a finely tuned light Higgs; dark matter could be axions.

Absence of any BSM at colliders as an indication of the Multiverse ??

Hall, Nomura, 0910.2235



Precision measurements of Higgs couplings: sensitivity to new physics up to a few TeV

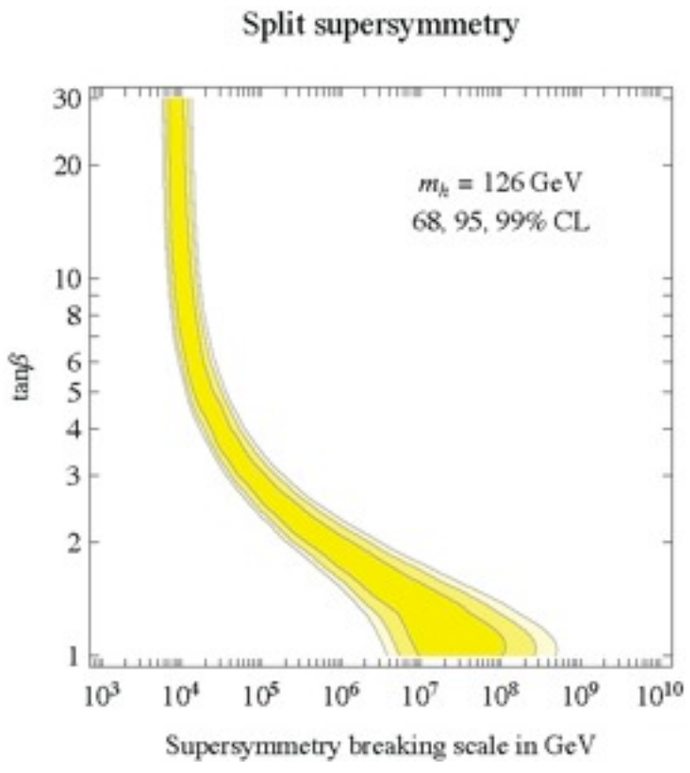
see talk by Maggie Mühlleitner

Heavy, split or spread SUSY

Split SUSY

Arkani-Hamed, Dimopoulos, hep-th/0405159
Giudice, Romanino, hep-ph/0406088

- All scalars apart from one Higgs doublet are ultra-heavy
- Gauginos and higgsinos are kept light to achieve gauge-coupling unification and to account for dark matter
- Collider phenomenology: characterized by gaugino-mass pattern. If gravity-mediation dominates, possibly mixed bino-higgsino LSP:
  - ➡ search for charginos and neutralinos decaying into Higgs
  - ➡ heavy long-lived gluinos (R-hadrons)
- Dark matter can be neutralino, gravitino and/or again axions
- Heavy gravitino decays can give non-thermal neutralino DM production



Giudice, Strumia, 1108:6077

Heavy, split or spread SUSY

Spread SUSY

SUSY breaking transferred to the MSSM via operators $X^\dagger X$: scalar and gravitino masses

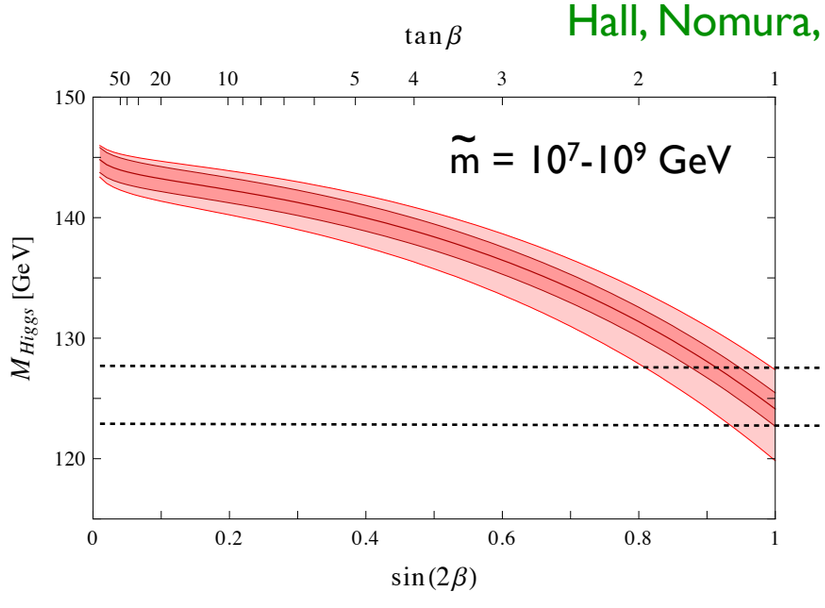
$$\tilde{m} = F_X/M_*, \quad m_{3/2} = \epsilon_* \tilde{m}$$

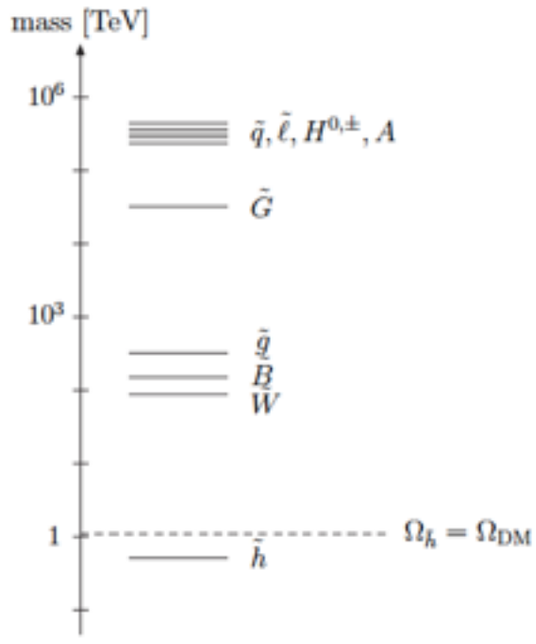
Anomaly mediation leads to gaugino masses of order $m_{3/2}/16\pi^2$

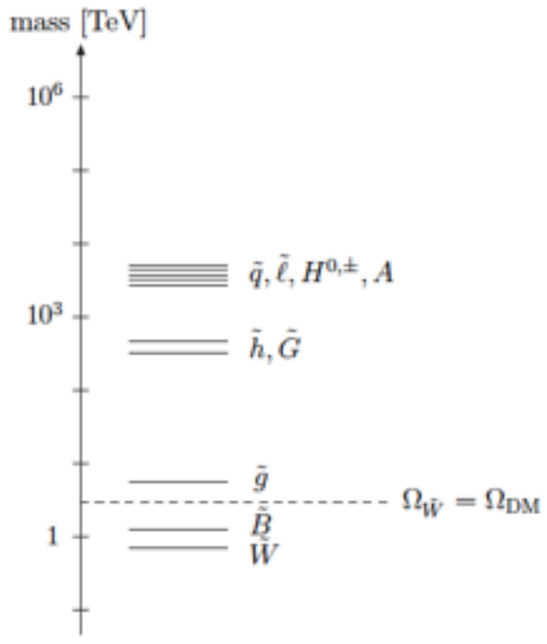
Very difficult for colliders: ~1 TeV LSP

- Higgsino LSP scenario: $\Delta m \gtrsim 300$ MeV would lead to chargino/neutralino decays into soft pions/e^+e^-, $c\tau \lesssim 1$cm
- Wino LSP scenario: $\Delta m \sim 160$ MeV would give disappearing charged tracks O(10 cm) from long-lived charginos

Hall, Nomura, 1111.4519







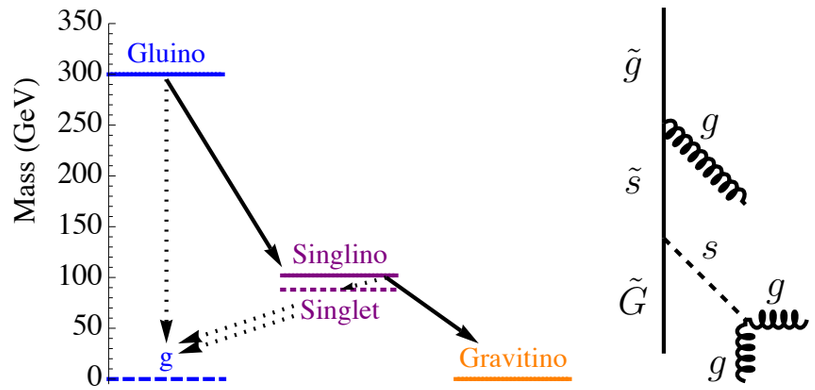
Stealth SUSY

- Broad class of SUSY models with R-parity that lack missing energy signatures.

- Occurs for small mass splittings at the end of the decay chain and hence small phase space for decays carrying away MET.

- Here: add new hidden sector fields $\tilde{X}, X$ lighter than the LVSP. Then LSVP decays to X, followed by $X \to GX$ and $X \to jj$ (soft)

Fan, Reece, Ruderman, 1105.5135

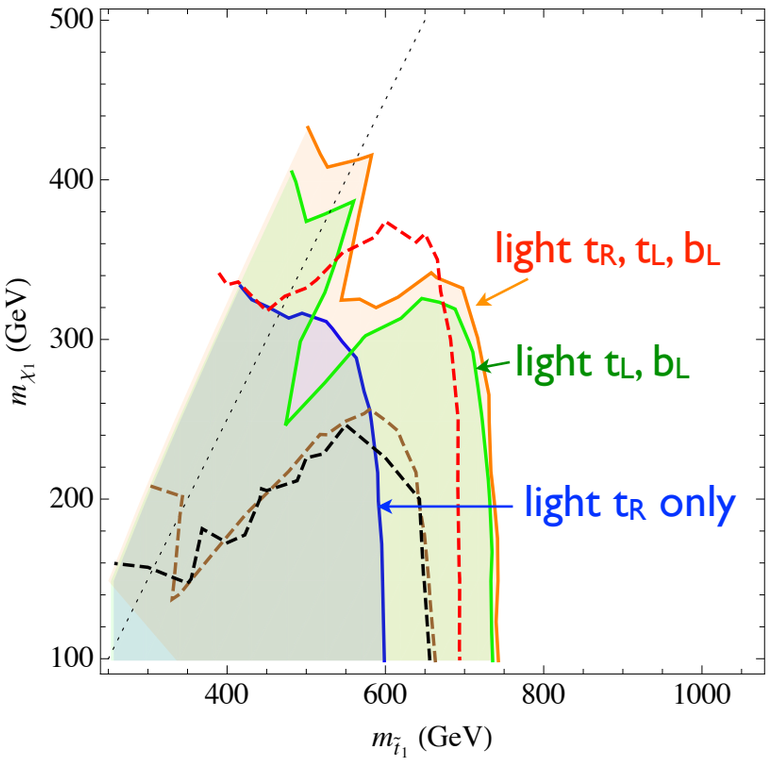


- A light quasi-degenerate hidden sector can thus eliminate MET signatures; very similar to "hidden valley" idea M. Strassler, hep-ph/0607160

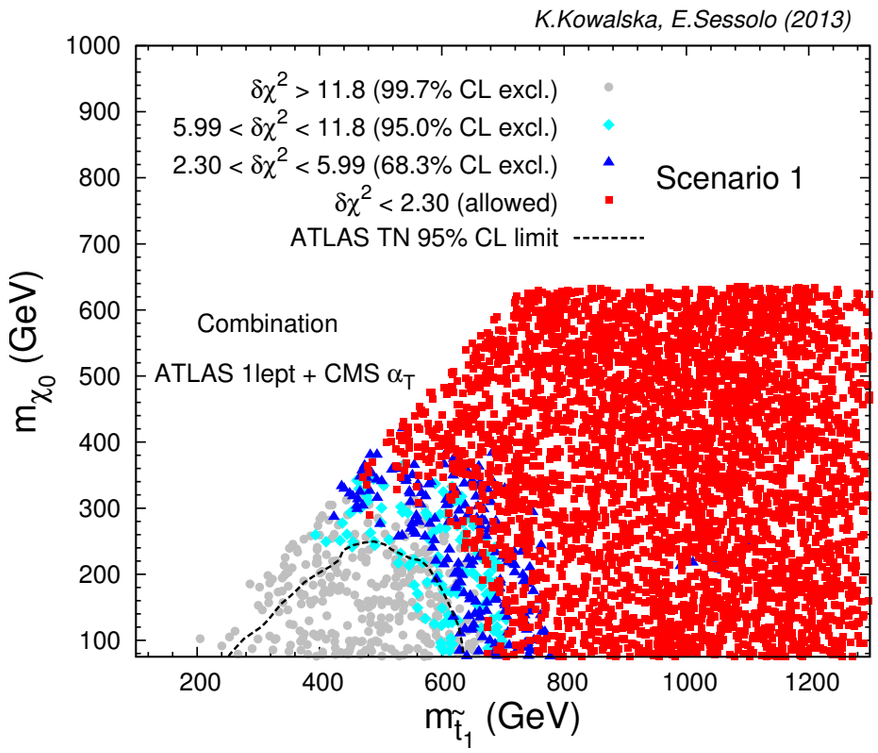
- Analogous "missing missing energy" situations can also occur in the NMSSM with a light singlino LSP and a light singlet Higgs. (through decays into $\tilde{s}$+s) NMSSM scenarios with all sparticles below 1 TeV can thus escape all limits from the 8 TeV searches Ellwanger, Teixeira, 1406.7221

Light stops with higgsino LSP

- The standard natural SUSY scenario with light stops and light higgsinos is not yet excluded, but it's getting under siege. Might live on the edge of O(1)% EWFT.



Kribbs, Martin, Menon, 1305.1313



Kowalska, Sessolo, 1307.5790
(see talk in parallel session)

- Still open: compressed spectra with very small stop-LSP mass difference
  → mono-photon or mono-jet signatures

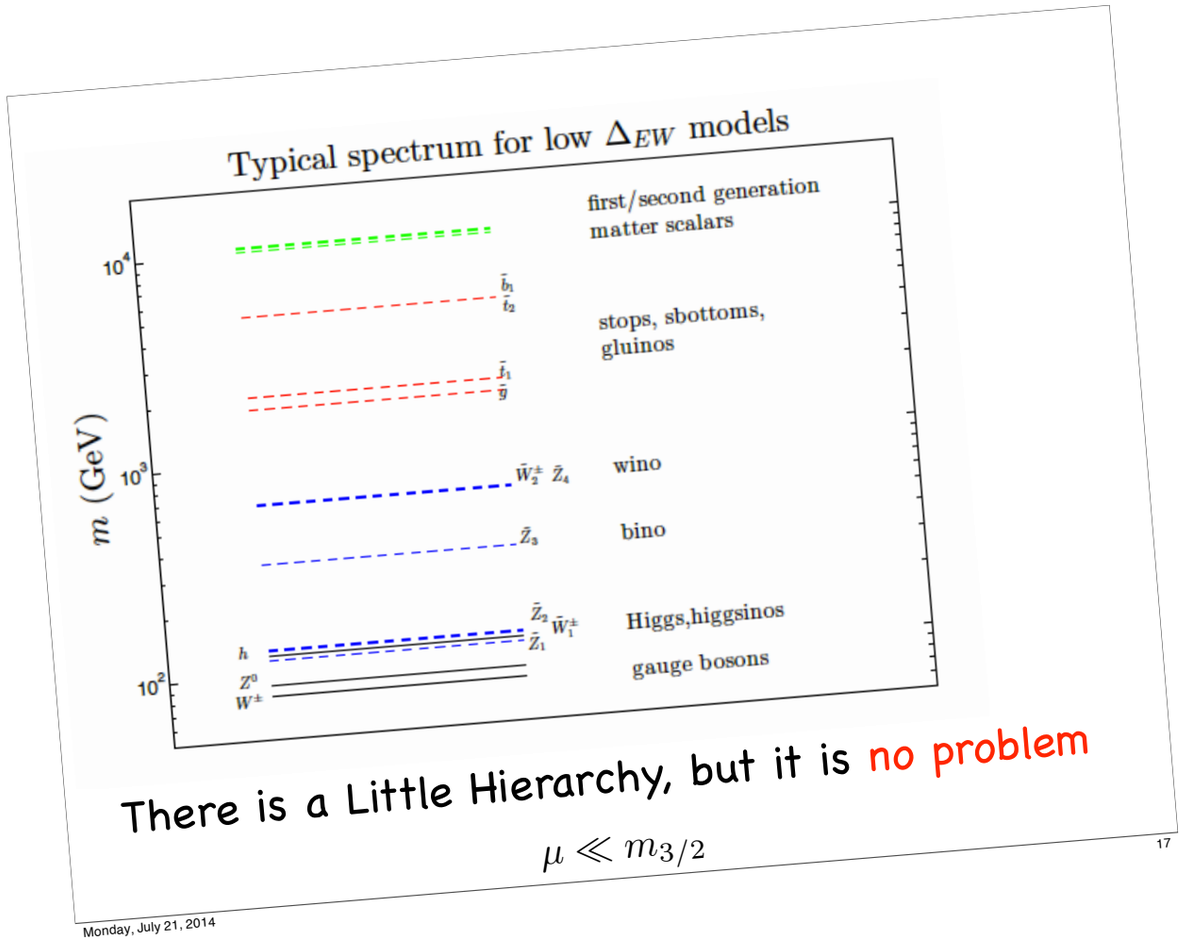
Carena, Freitas, Wagner, 0808.2298

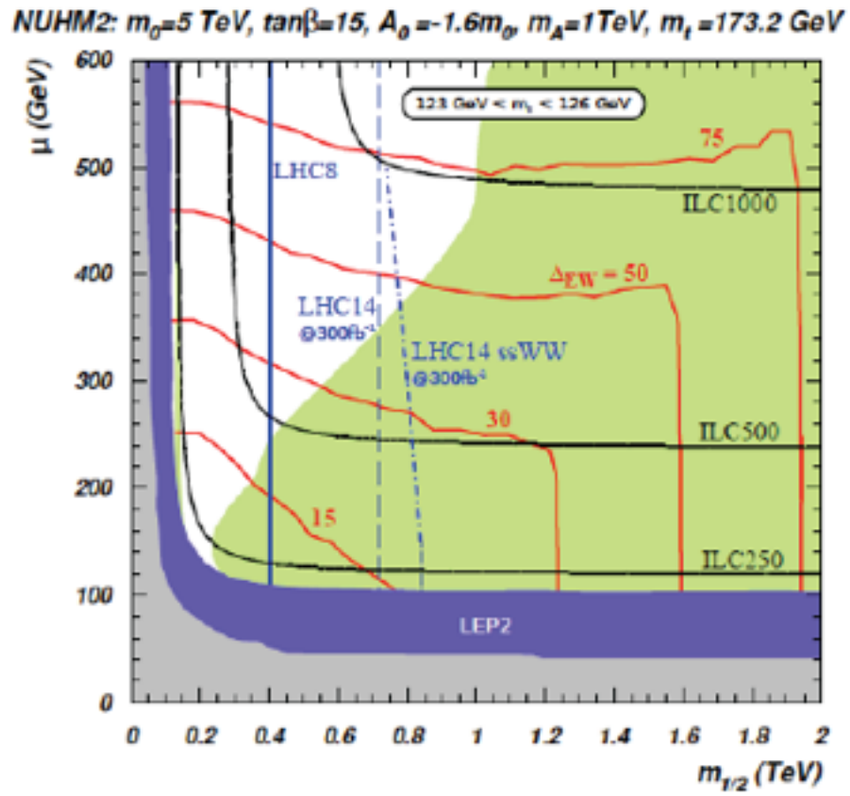
new ATLAS analysis covers m(stop)<300 GeV

Revisit SUSY naturalness

talk by Howie Baer

Radiative natural SUSY (RNS) needs light higgsinos, but not (so) light stops





$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

↑

express weak scale value in terms of high scale parameters

Non-minimal SUSY

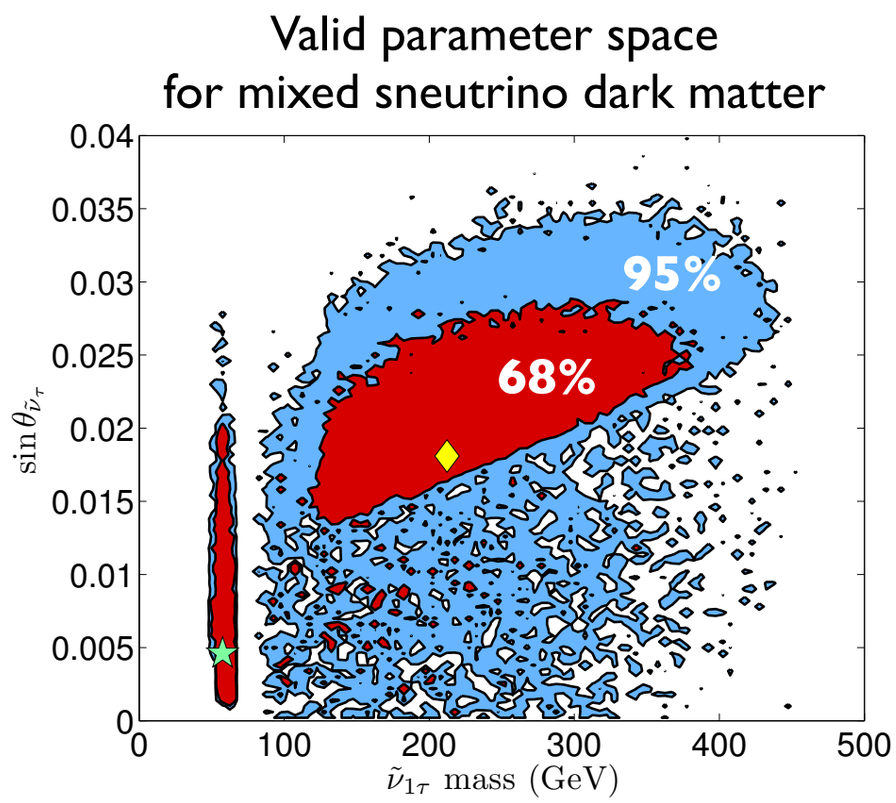
Non-minimal sparticle content can significantly alter SUSY pheno at the LHC.

Consider e.g. the MSSM plus a mostly RH sneutrino as the LSP:

RH sneutrino with large L-R mixing:
Arkani-Hamed et al., hep-ph/0006312
Borzumati, Nomura, hep-ph/0007018

Signatures at the LHC:

- Charginos decay to $l^{\pm}\tilde{\nu}_l$
- Neutralinos decay to $\nu\tilde{\nu}_l$ [invisible]
- Several different invisible masses in decay chains → different MET scales!
- Dilepton signal from chargino-pair production, but uncorrelated flavor
- Mono-lepton signal from chargino-neutralino production
- Slepton-pair production: WW+MET



B. Dumont et al., 1206.1521
updated for PhD thesis 2014

should re-assess LHC limits

for public tools

The need for interpretation studies:

what do the LHC results really tell us about weak-scale SUSY?

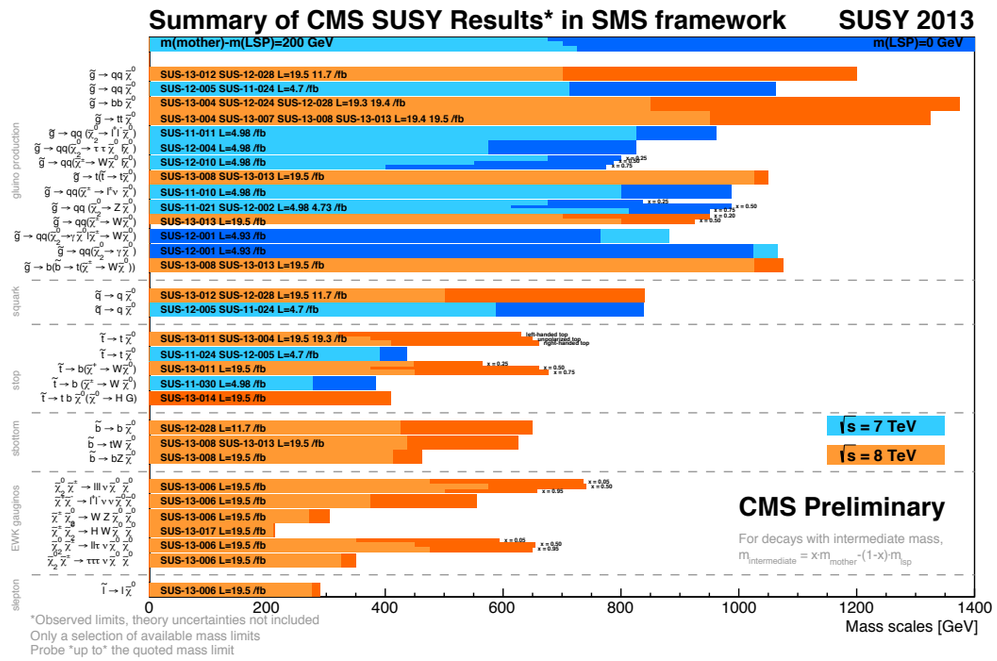
The need for interpretation studies

- ATLAS and CMS perform searches for new physics in many different channels; they interpret their results within specific minimal models and/or within simplified model spectra.

- Limits depend a lot (by 200-600 GeV) on the assumptions on the mass spectrum, and disappear for small mass splittings, m_{LSP}>600 GeV, etc.

- Limits also depend on sparticle content of the model (different decay modes and branching ratios, reduced MET, ...)

- We need to interpret the experimental results in a large variety of scenarios, test all kinds of models, beyond the MSSM and beyond SUSY → community-wide effort.



similar for ATLAS

Interpretation tools

- Several groups have been developing private codes for recasting BSM searches
- A number of public tools have become available recently

Simplified Models (SMS)

- SModelS: generic decomposition into SMS topologies, cross section upper limits from more than 50 ATLAS and CMS SMS results
  [SK, Kulkarni, et al., 1312.4175]
  this talk
- Fastlim: reconstructs visible cross sections for SMS topologies from pre-calculated efficiency and cross section tables; currently 11 ATLAS analyses implemented.
  [Papucci et al., 1402.0492]
  see talk by K. Sakurai

Event simulation

- CheckMATE : checks 95% CL limits for simulated events of any model; currently has 8 ATLAS and 1 CMS SUSY analyses implemented
  [Drees et al., 1312.2591]
- MA5 PAD: public analysis database within the MadAnalysis5 framework; currently 2 ATLAS + 3 CMS analyses, more in progress
  [Dumont et al., 1407.3278]
  this talk

- Public tools are useful to and get tested by a large number of people. Helps remove bugs, and we do not constantly need to re-invent the wheel!

SModelS

arXiv:1312.4175

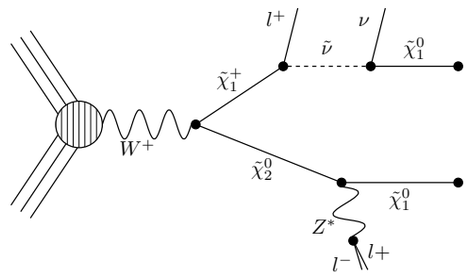
http://smodels.hephy.at

- Automatically decomposes the signatures of any BSM spectrum with a Z_2 symmetry into simplified-model topologies

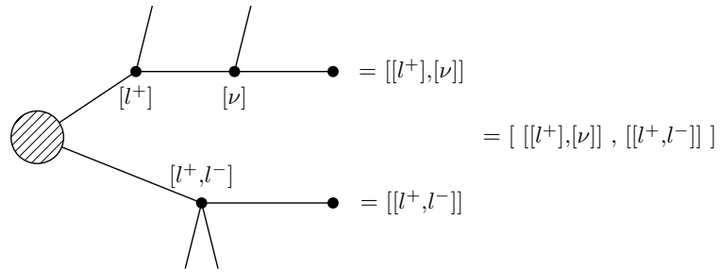
- Computes ($\sigma \times BR$) weights and compares model predictions to experimental 95% CL cross section upper limits

- Comprises large database of ATLAS and CMS simplified-model results:
  - All relevant CMS results implemented (easy because systematic SMS interpretation and all upper limit maps available numerically)
  - Most ATLAS results, as far as ATLAS provides an applicable SMS interpretation (not always the case; e.g. for 2-step decays we need several intermediate mass values)

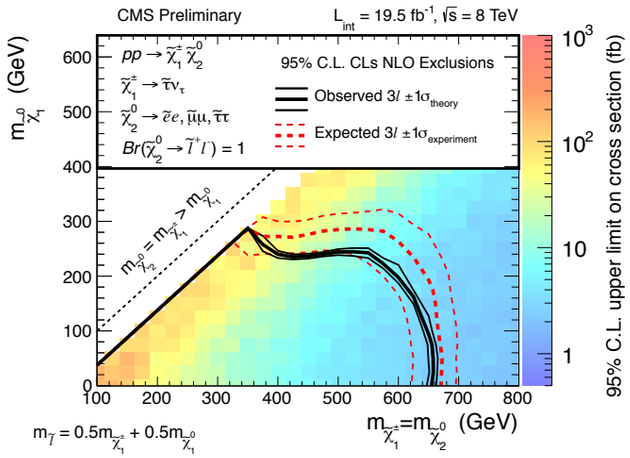
- Powerful tool e.g. for model surveys



⬇ decompose into SMS topos

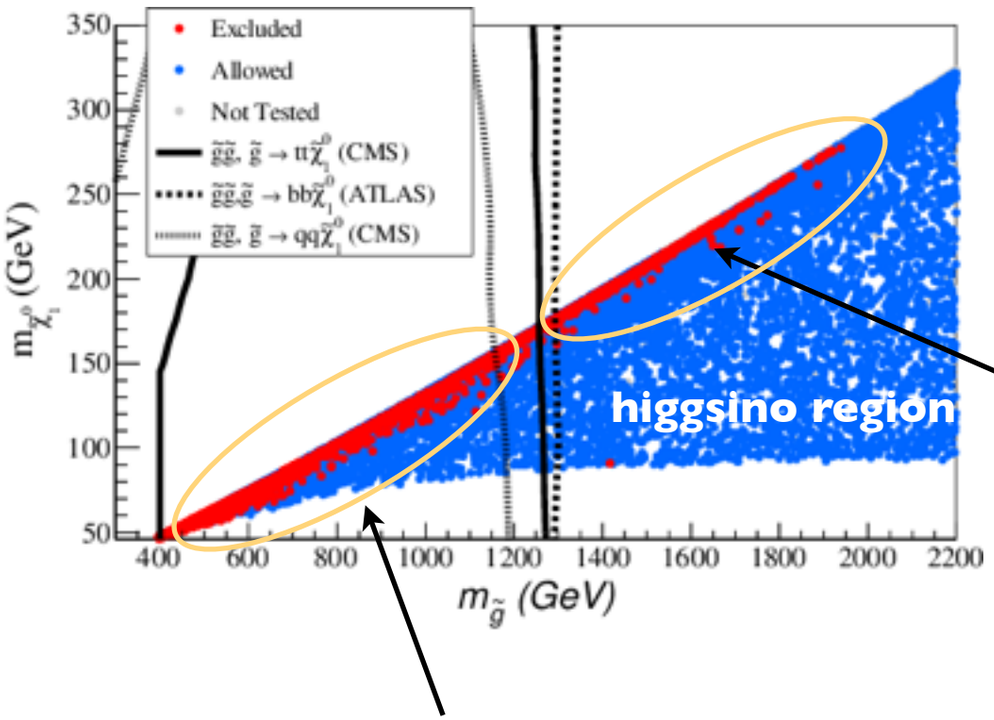


⬍ compare with 95% CL cross section upper limits



SModelS results: 7-parameter (p)MSSM

- Excluded points on top of allowed ones

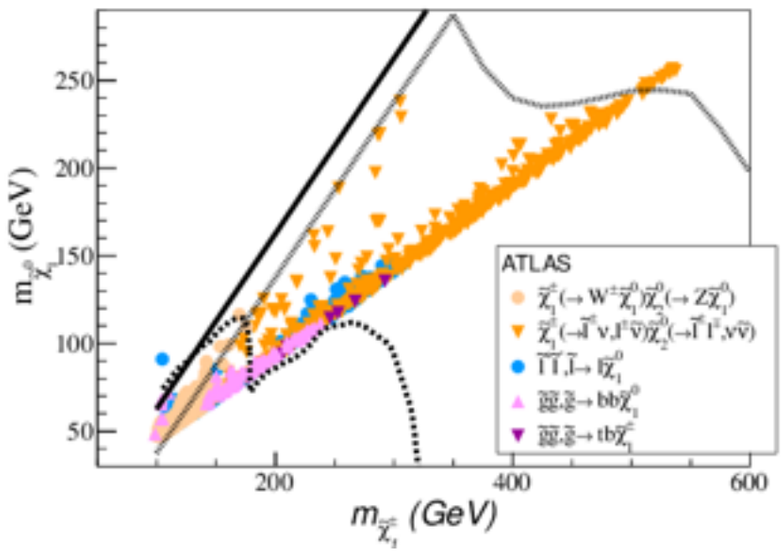


Scan over:
$M_3 = 3M_2 = 6M_1$
slepton mass parameters
tanβ, μ
(squarks decoupled)

mh = 123-128 GeV, B-physics constraints, ...

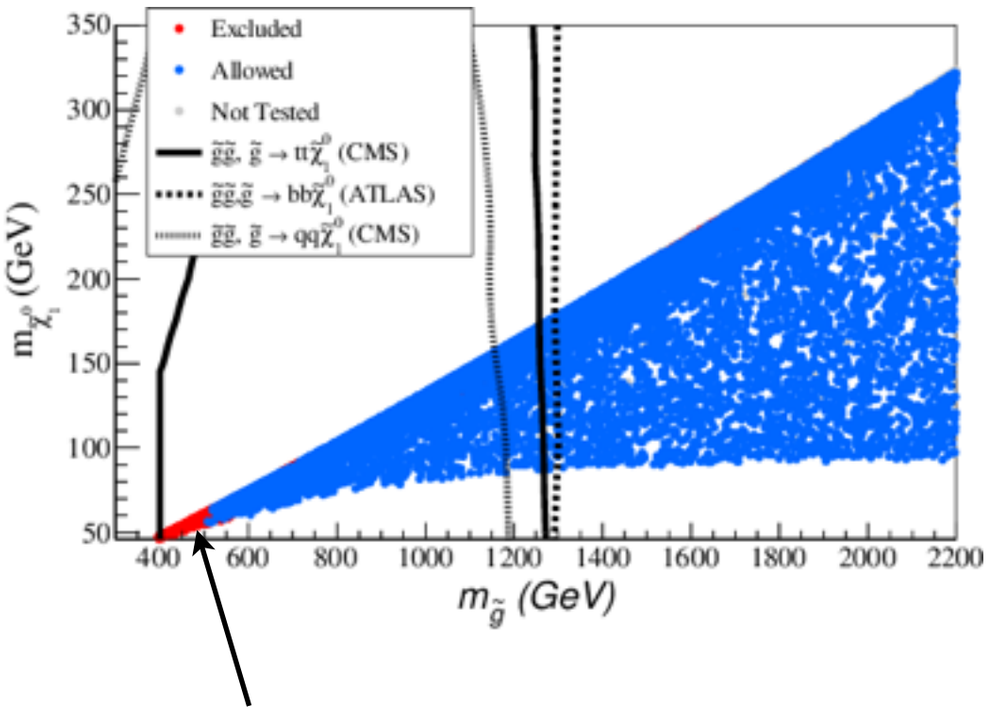
constrained by electroweak chargino/neutralino production

constrained by gluino-pair production with 3-body decay into LSP + tt, bb, qq



SModelS results: 7-parameter (p)MSSM

- Allowed points on top of excluded ones

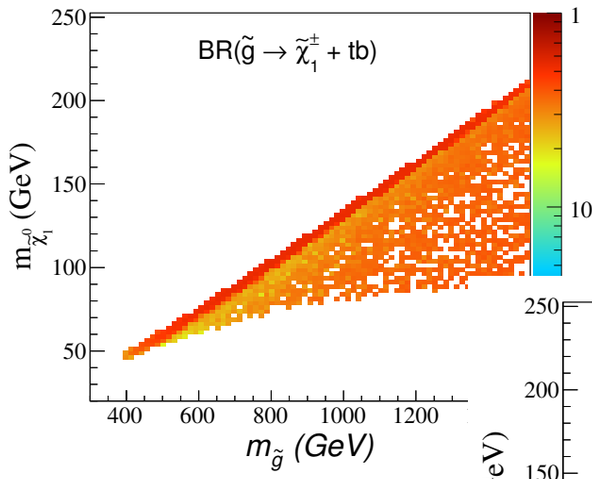


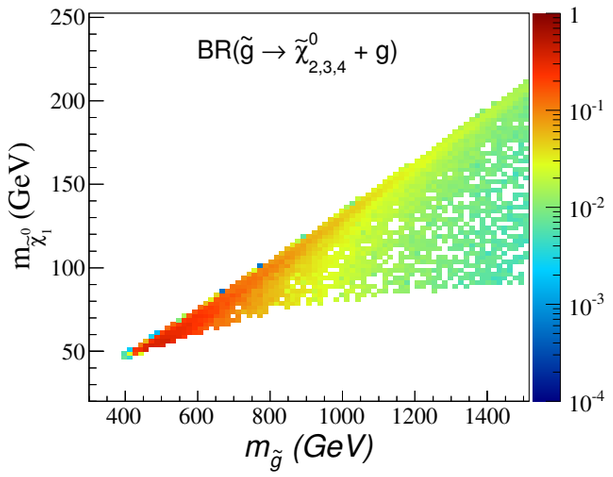
only small region strictly excluded by SMS results

Scan over:
$M_3 = 3M_2 = 6M_1$
slepton mass parameters
tanβ, μ
(squarks decoupled)

mh = 123-128 GeV, B-physics constraints, ...

NB: large BR's but no SMS results available

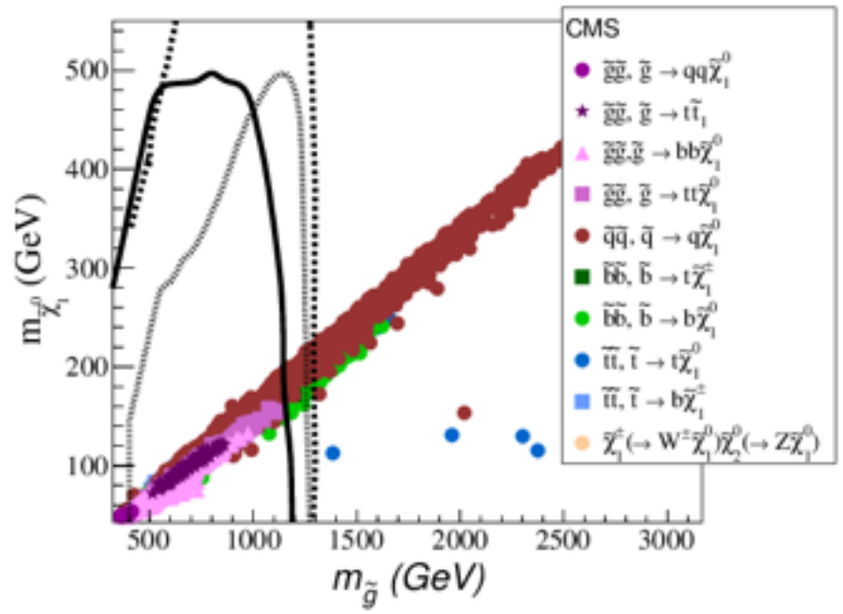


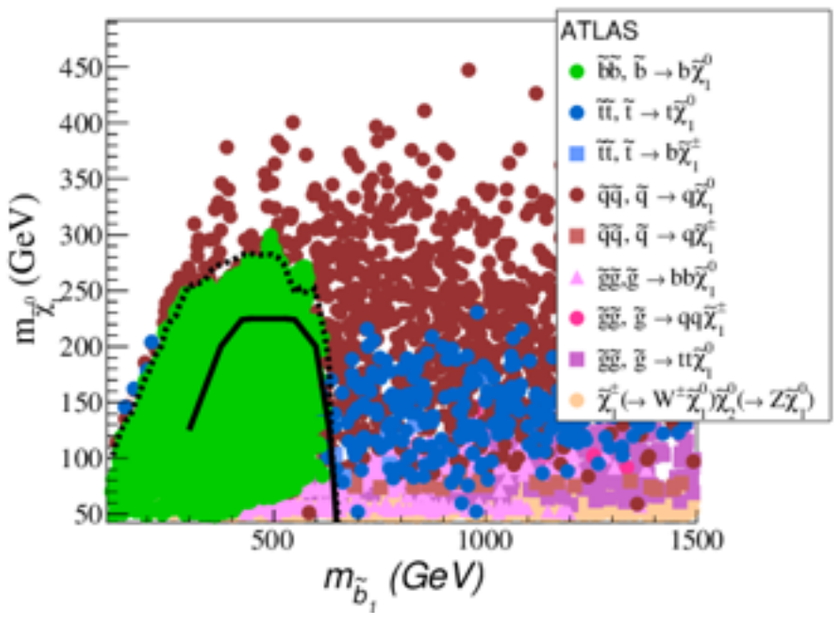


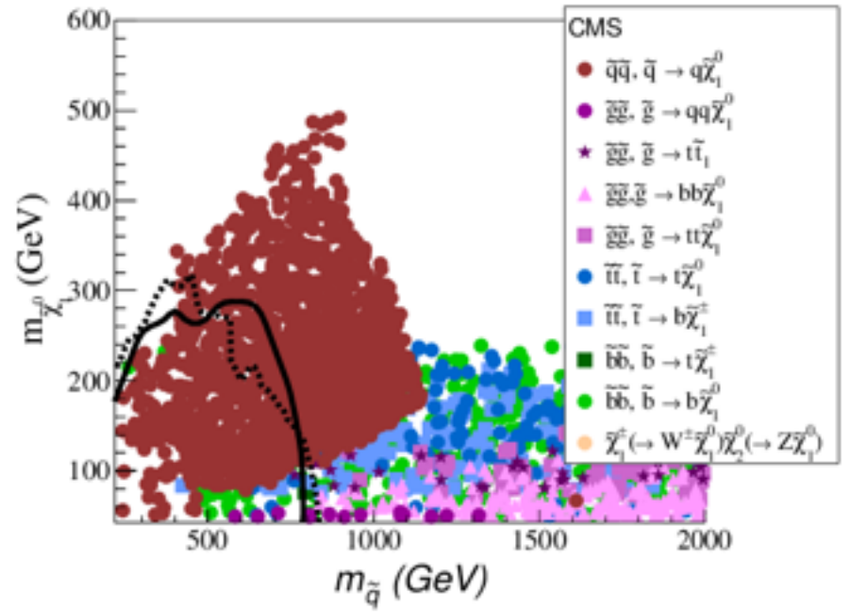
SModelS results: 9-parameter (p)MSSM

Scan over:
- $M_3 = 3M_2 = 6M_1$
- stop and sbottom masses
- light-flavor squark mass
- tanβ, μ
- (sleptons decoupled)

mh = 123-128 GeV, B-physics constraints, ...



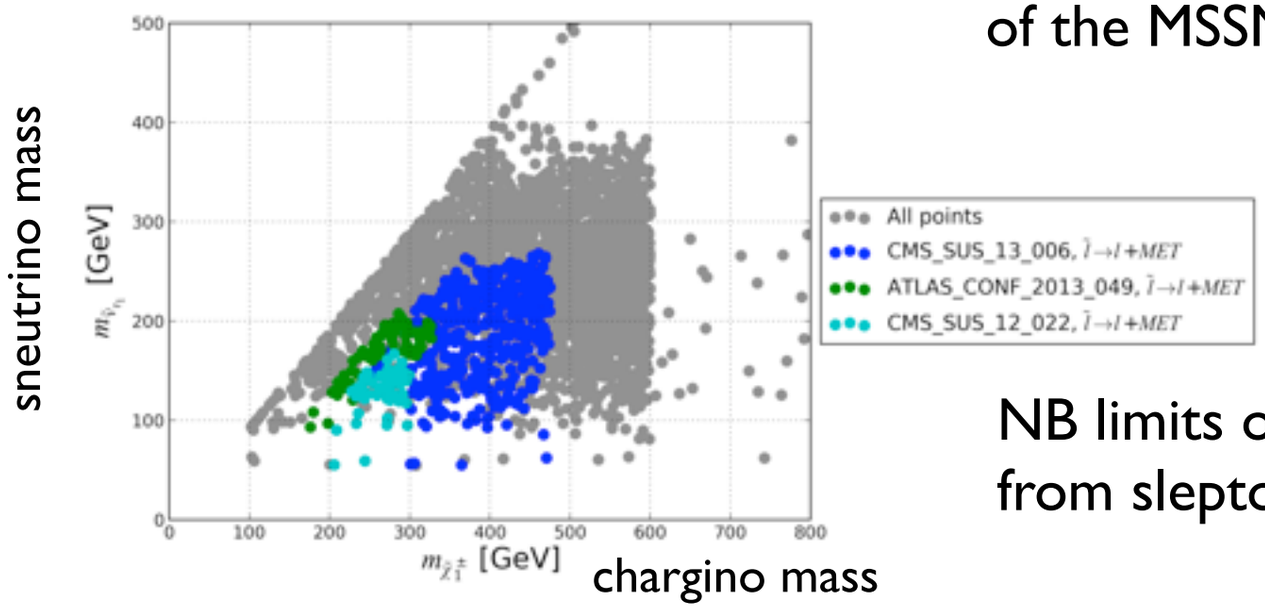




excluded points, labelled by most constraining topology; analogous results for ATLAS ↔ CMS

Mixed sneutrino dark matter model

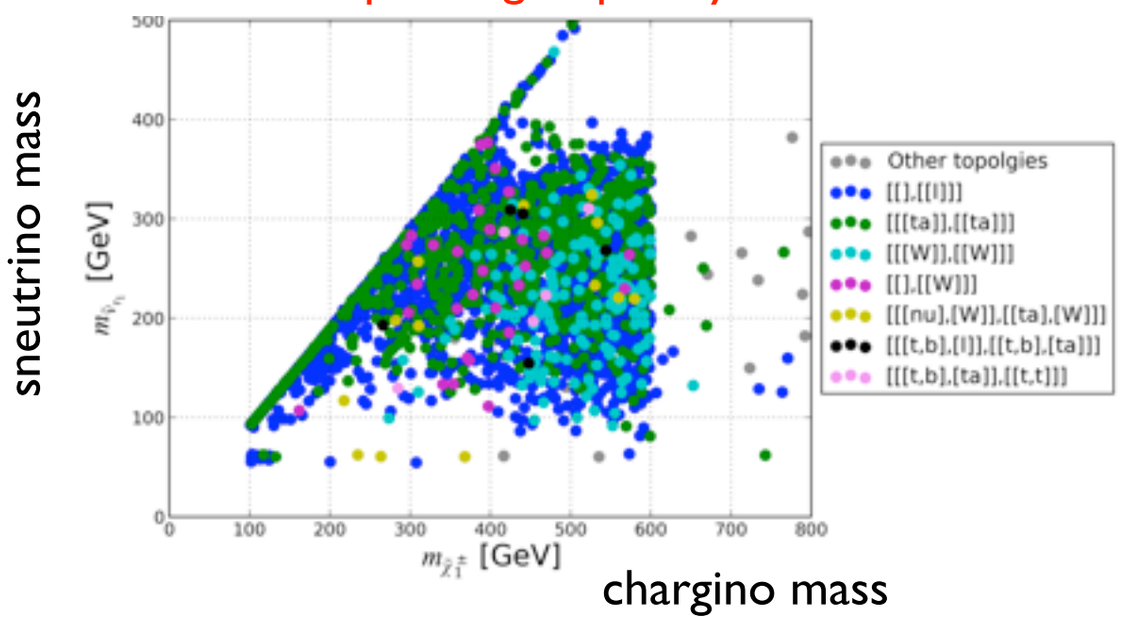
excluded points grouped by analysis



SModelS works "out of the box" for extensions of the MSSM, like the MSSM + RH sneutrino LSP

NB limits on charginos here actually come from slepton searches (dilepton channel)

not-excluded points grouped by final state



Most important "missing topology", i.e. for which no SMS results exists, is single lepton+MET

Work in progress with C. Arina, S. Kulkarni and U. Laa

SMS Caveats

- A realistic SUSY spectrum does not necessarily fully decompose into SMS's. For instance, long decay chains have no SMS-equivalent by definition.

- Effects of off-shell particles in production and/or decay modes may influence the kinematic distributions.

- In SModelS, we decompose a spectrum according to the masses of the R-odd particles in each decay chain, and the number and nature of the R-even (SM) particles produced in each vertex. However, we do not use information on the nature of the R-odd particles → spin/helicity effects are not taken care of (in other words, don't use it blindly)

To circumvent these caveats: simulate events, emulate detector response, apply analysis cuts, ... → fastsim

The difficulty of recasting with fastsim

Non-collaboration members do not have access to the experimental data, nor the Monte Carlo (MC) event set simulated with an official collaboration detector simulation.

Therefore, the implementation and validation of ATLAS and CMS analyses for re-interpretation of the experimental results in general contexts is a tedious task, even more so as the information given in the experimental papers is often incomplete.

Les Houches Recommendations

arXiv:1203.2489

"The community should identify, develop and adopt a common platform to store analysis databases, collecting object definitions, cuts, and all other information, including well-encapsulated functions, necessary to reproduce or use the results of the analyses [...]"

"The tools needed to provide extended experimental information will require some dedicated efforts in terms of resources and manpower, to be supported by both the experimental and the theory communities."

arXiv:1407.3278

Towards a public analysis database

We think it would be of great value for the whole community to have a database of LHC analyses based on fast simulation.

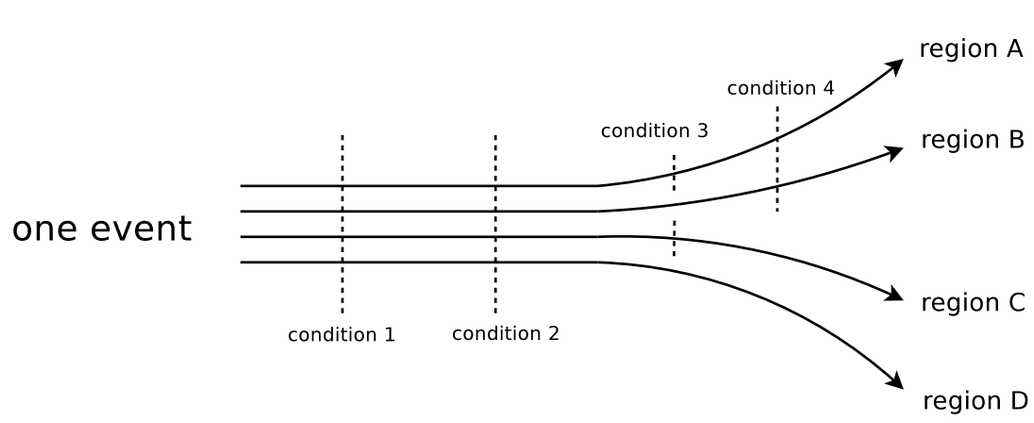
→ we propose to create such a database using the MadAnalysis 5 framework

- Validated analysis codes, easy to check and to use for everybody.
- Can serve for the interpretation of the LHC results in a large variety of models.
- Convenient way of documentation; helps long-term preservation of the analyses performed by ATLAS and CMS.
- Modular approach, easy to extend, everybody who implements and validates an existing ATLAS or CMS analysis can publish it within this framework.
- Provides feedback to the experiments about documentation and use of their results. (The ease with which an experimental analysis can be implemented and validated may actually serve as a useful check for the experimental collaborations for the quality of their documentation.)

Recasting LHC analyses with MadAnalysis 5

E. Conte, B. Dumont, B. Fuks, C. Wymant
arXiv:1405.3982

- MadAnalysis 5 is a public user-friendly framework for analysing Monte Carlo events
- Recently extended for an efficient treatment of different signal regions in the same analysis
- New optimized handling of cuts and histograms



Conventional nesting of conditions is not efficient:

```
count the event in region D
if (condition 3)
{
  count the event in region C
  if (condition 4)
  {
    count the event in region A
  }
}
if (condition 4)
{
  count the event in region B
}
```

- Every cut is evaluated only once and applied to all relevant signal regions simultaneously

```
string SRForMet150Cut[] = {
  "Stop->b+chargino,LowDeltaM,MET>150",
  "Stop->b+chargino,HighDeltaM,MET>150",
Manager()->AddCut("MET>150GeV",SRForMet150Cut);
```

- Emulation of detector response using DELPHES 3

MadAnalysis 5 physics analysis database

Available Analyses

!! please properly cite all the re-implementation codes you are using (see Inspire citation entry) !!

ATLAS analyses, 8 TeV

Analysis	Short Description	Implemented by	Code	Validation note	Status
ATLAS-SUSY-2013-05 (published)	stop/sbottom search: 0 leptons + 2 b-jets	G. Chalons	Inspire	PDF (figures)	done
ATLAS-SUSY-2013-11 (published)	EWK-inos, 2 leptons + MET	B. Dumont	Inspire	PDF (source)	done

CMS analyses, 8 TeV

Analysis	Short Description	Implemented by	Code	Validation note	Status
CMS-SUS-13-011 (published)	stop search in the single lepton mode	B. Dumont, B. Fuks, C. Wymant	Inspire [1]	PDF (source)	done
CMS-SUS-13-012 (published)	gluino/squark search in jet multiplicity and missing energy	S. Bein, D. Sengupta	Inspire	PDF (source)	done
CMS-SUS-13-016 (PAS)	search for gluinos using OS dileptons and b-jets	D. Sengupta, S. Kulkarni	Inspire	PDF (source)	done

several more in preparation

Analysis implementation and validation

1. Read and understand the experimental paper

2. Write the C++ analyzer code for MadAnalysis 5

easy

3. The difficult part: get missing information from the experimental collaboration.
   Needed, but not always publicly available, are:

   - efficiencies for trigger, electron, muons, b-tagging, event cleaning, ... } p_T dependence
   - treatment of ISR, jet energy scale
   - exact configuration of MC tools (versions, run card settings)
   - benchmark points: SLHA or LHE files
   - cut flows for the benchmark points
   - expected final number of events in each signal region

–essential–
but often quite difficult

4. Digitize the histograms from the experimental paper
   (stupid work; direct numerical form would be highly welcome → HepData, Twiki !)

5. Produce your own cut flows and histograms and compare,
   iterate until reasonable agreement is achieved

Search for direct top squark pair production in the single lepton final state at √s = 8 TeV (SUS-13-011)

Contents:

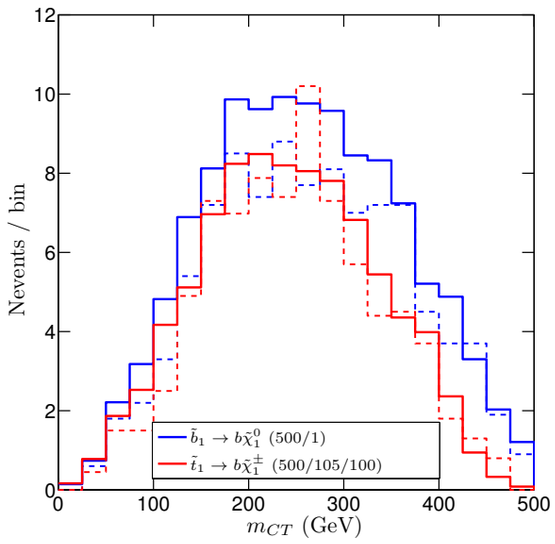
- Further information
- Abstract
- Analysis summary
- Approved tables and plots (*click on plot to get larger version*)
  - (pseudo) Feynman diagrams
  - Results: yields vs. background prediction, kinematical distributions of (near-)final event sample
  - Interpretation: SUSY summary plots
  - Interpretation: limits on SUSY parameters
  - Kinematical quantities used in the event selection
  - Signal Region definitions
  - Sample BDT outputs at the preselection stage
  - Control region studies
  - Systematic uncertainties on the background prediction
  - Additional MT and BDT output distributions
  - Monte Carlo modeling of initial state radiation
  - Signal Regions used for limit extraction
  - Acceptance maps, not in paper
  - Additional plots, not in paper
  - Code
  - Electronic material
  - Additional Material to aid the Phenomenology Community with Reinterpretations of these Results

CMS very unbureaucratically provided us missing information on e.g. benchmark points, efficiencies, and cut flows

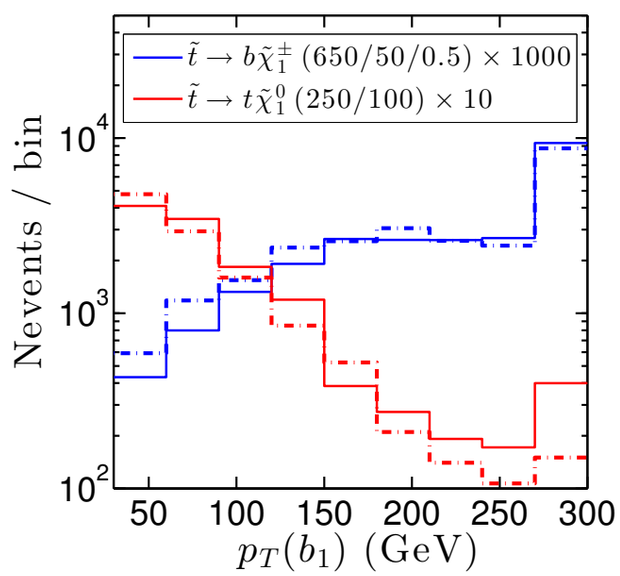
Validation: cut flows, distributions, limits

broken lines: official ATLAS or CMS results, full lines: MadAnalysis 5 results

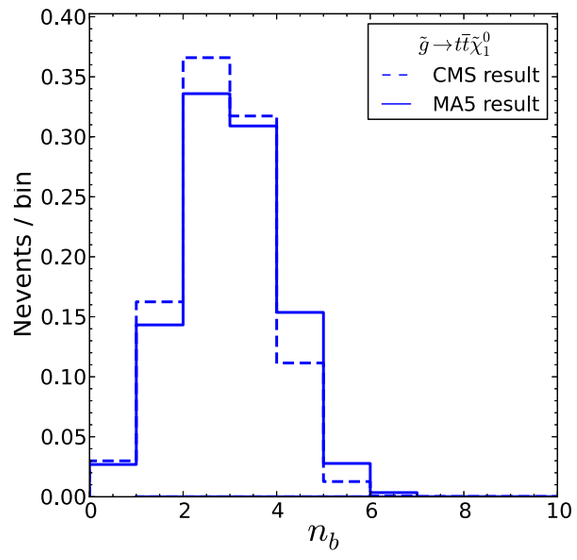
ATLAS 0 lepton 2b



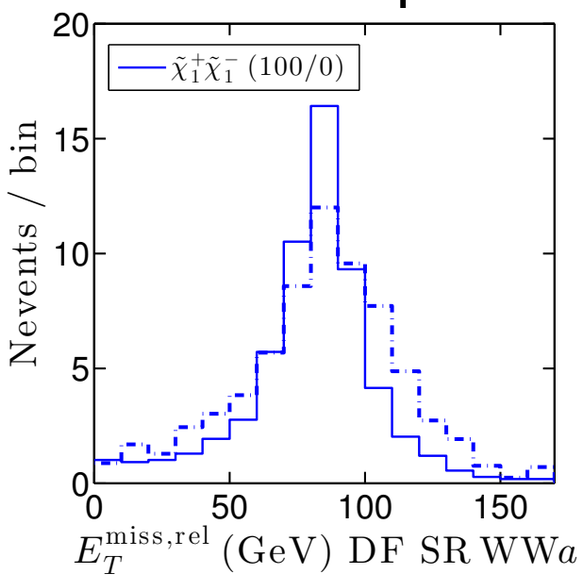
CMS 1 lepton



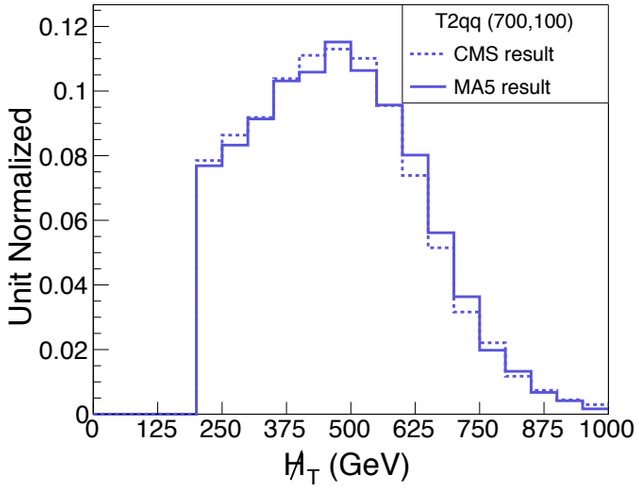
CMS dileptons + b's

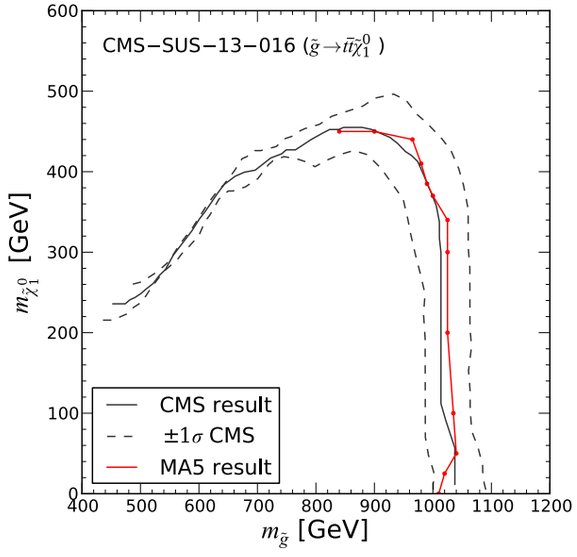


ATLAS dilepton

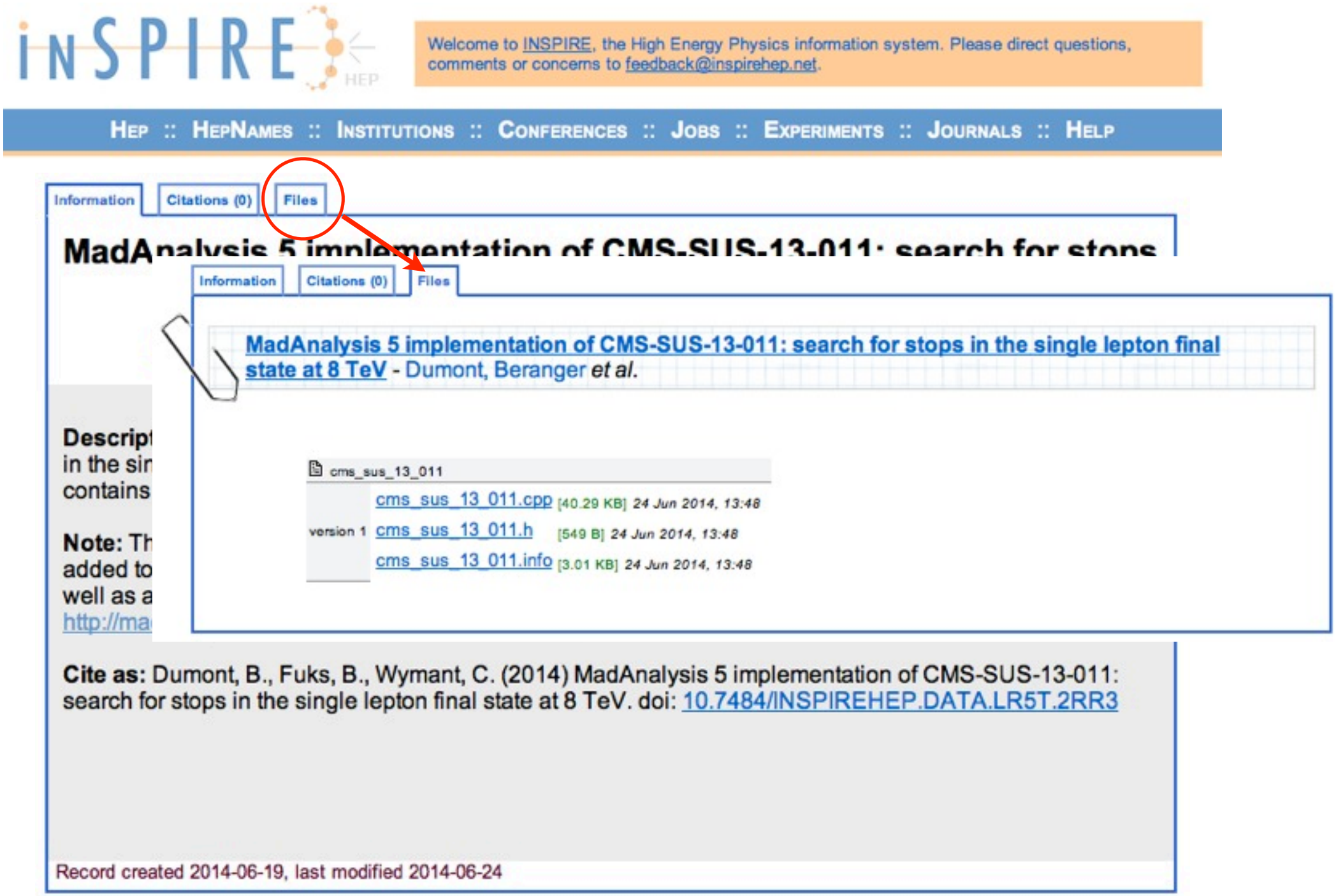


CMS multi-jet

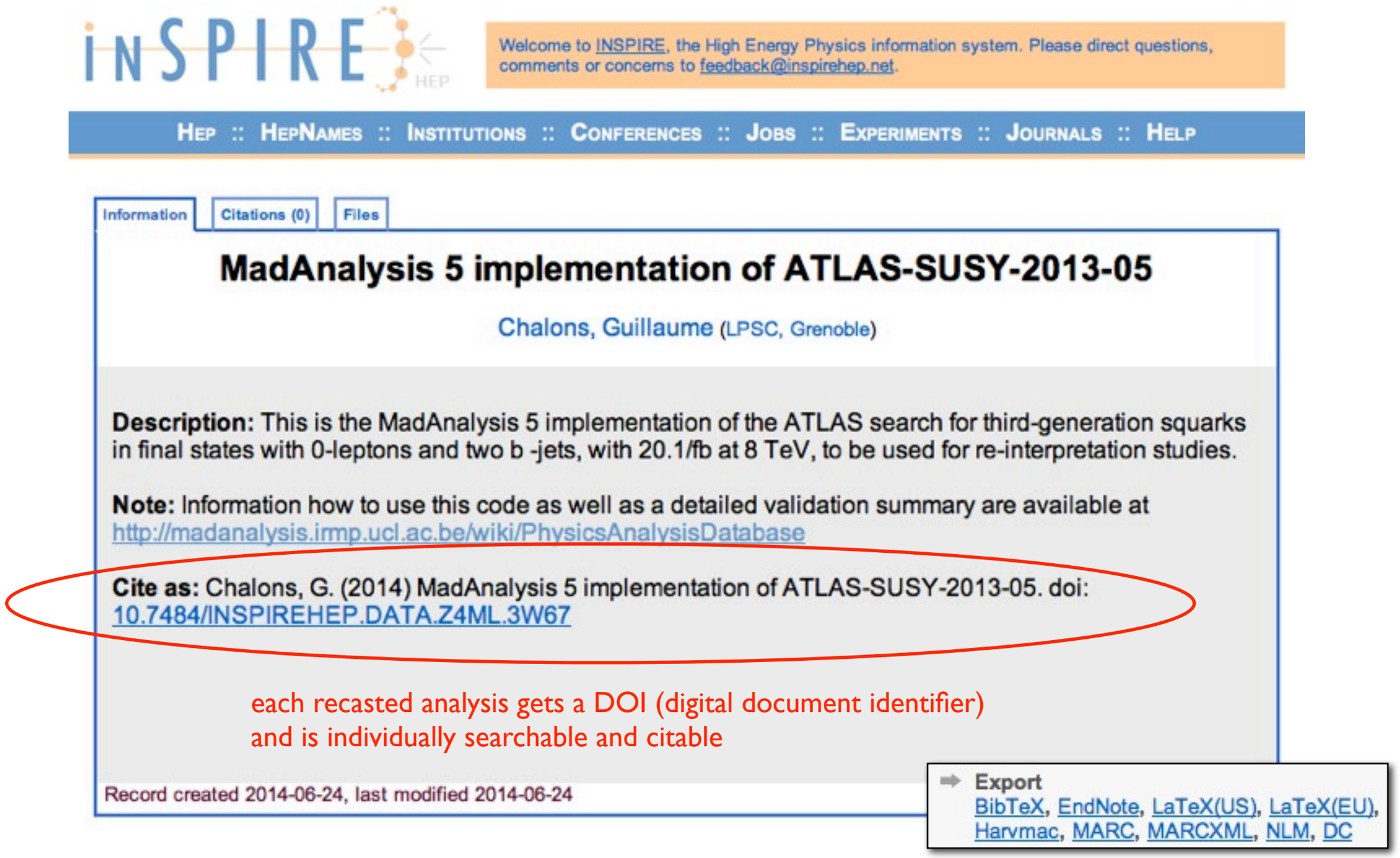




PAD: Submit your code with your paper



PAD: Submit your code with your paper



To take home

- In the multiverse picture, the scale of SUSY breaking may have nothing to do with stabilizing the weak scale. In this case the Higgs may be the only discovery at the LHC (and other colliders provided there will be any).

- Nonetheless weak-scale SUSY is by no means excluded, and naturalness remains a very well-motivated guideline.

- There's a multitude of possible SUSY scenarios, with complex interrelations between parameters and signatures. It is a challenge for the whole community to work out the implications of the LHC results in the contexts of all these different models.

- Much more experiment–theory interaction is needed to make the most out of the LHC results. We need to develop theoretical tools but we also need more information on the experimental analyses.

search for SUSY with an open (access) mind

You may say I'm a dreamer
But I'm not the only U(1)
I hope some day with more data
New physics will have won!