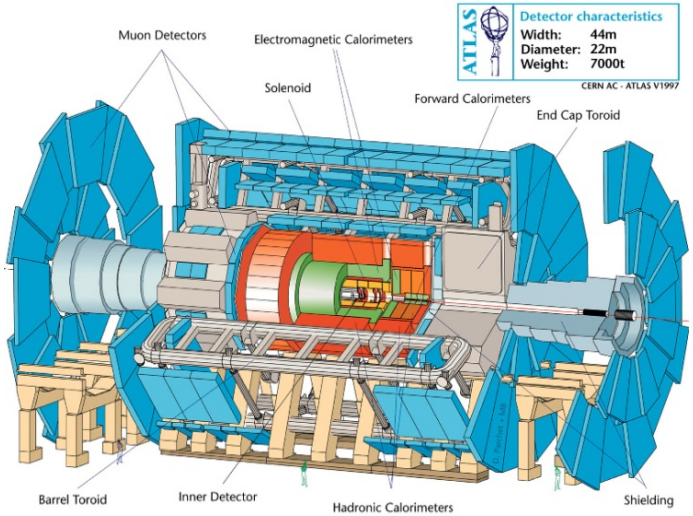
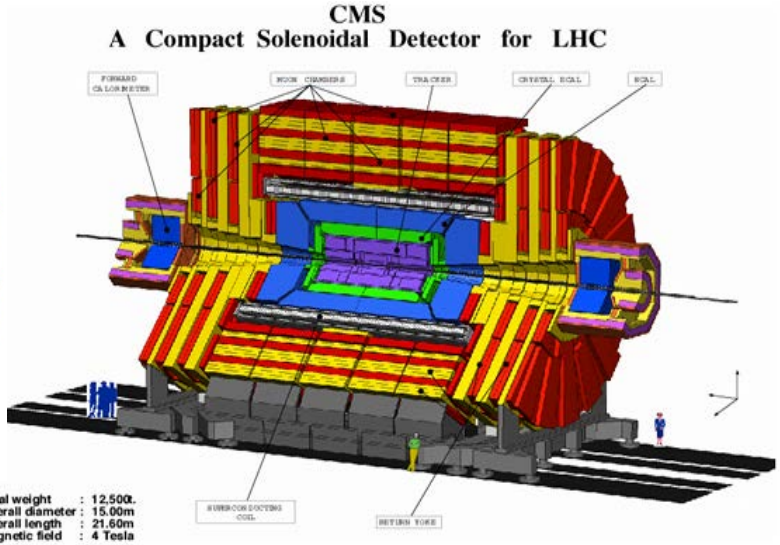
New 'No Prejudice' pMSSM SUSY Scans



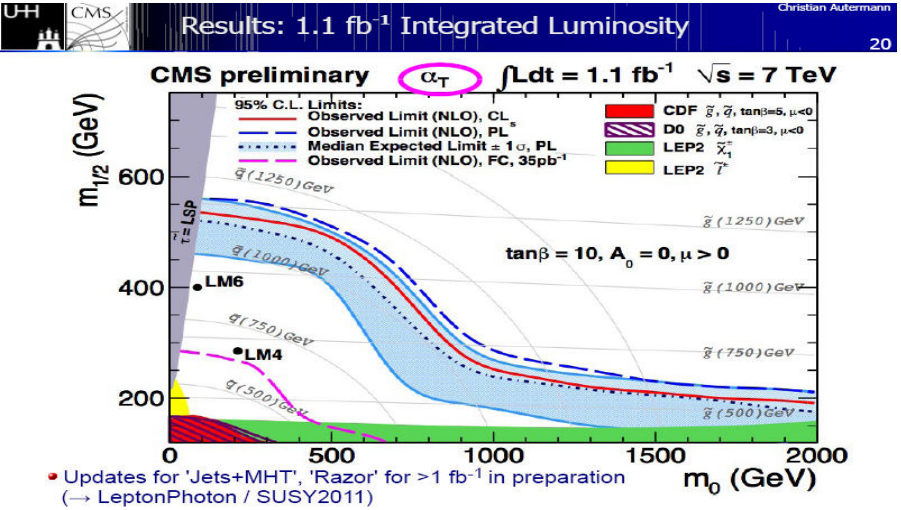


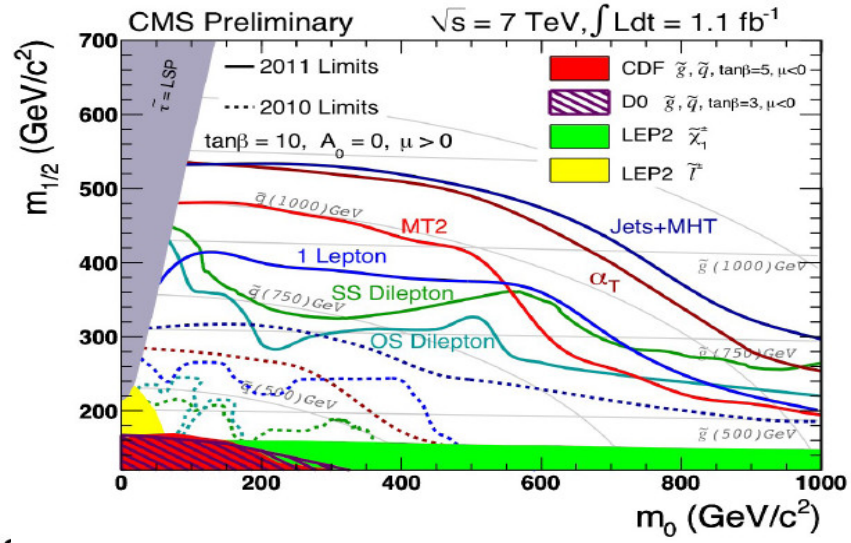
C. Berger, J. Conley, R. Cotta, J. Gainer, J. Hewett, K. Howe, A. Ismail, M.-P. Le, T. Rizzo, M. Rowley

SLAC NATIONAL ACCELERATOR LABORATORY

arXiv:0812.0980, 0903.4409, 0909.4088, 1007.5520, 1009.2439, 1103.1697, 1105.1199, 1109.xyzt, …

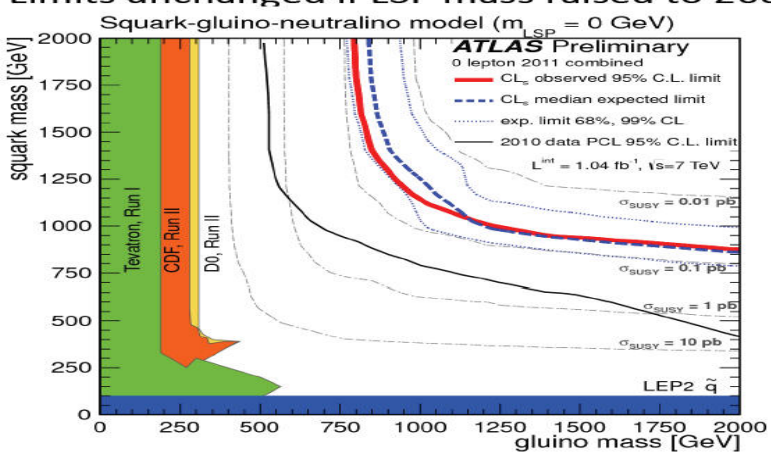
So far there are no obvious signs of SUSY :

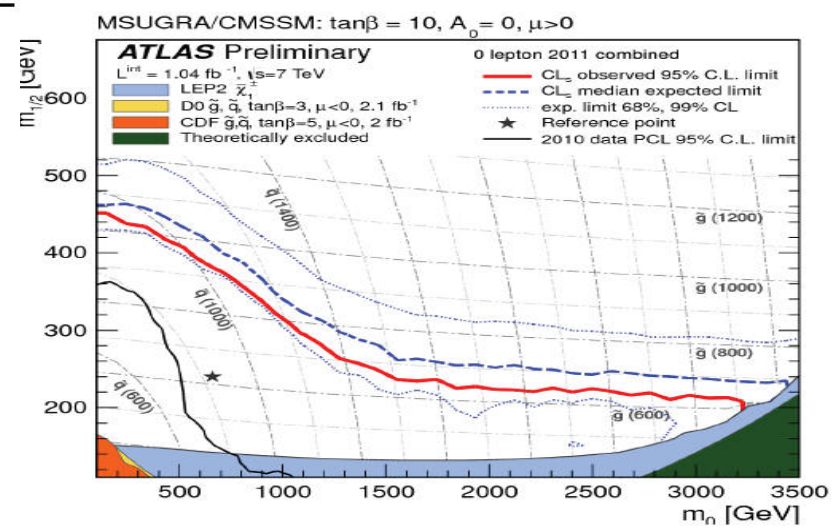




Phenomenological MSSM squark-gluino grids:

- ✓ masses from 100 GeV to 2 TeV, neutralino mass of 0
- ✓ Limits unchanged if LSP mass raised to 200 GeV





Options: no SUSY, SUSY is 'just heavier', or it doesn't look like the CMSSM

→→ enter the pMSSM…

What is our pMSSM ??? *

- The most general, CP-conserving MSSM w/ R-parity conservation
- Minimal Flavor Violation at the TeV scale
- The first two sfermion generations are degenerate & have negligible Yukawa couplings
- The lightest neutralino or the gravitino is the LSP

* Beware of the various alternative uses of this nomenclature

The 19(20) Parameter pMSSM

10 sfermion masses: m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}

3 gaugino masses: M_1, M_2, M_3

3 tri-linear couplings: A_b, A_t, A_τ

3 Higgs/Higgsino: μ, M_A, $\tan\beta$

$\rightarrow\rightarrow$ (1 gravitino mass : $m_{3/2}$)

Choose the ranges of these parameters & how they're selected

Scan: look for points in this space satisfying all existing data & then study their signatures @ the LHC & elsewhere.. NO FITS!

Our Original χ LSP Random Scans

(via SuSpect)

Flat Priors

emphasizes moderate masses

$100\ \text{GeV} \leq m_{sfermions} \leq 1\ \text{TeV}$

$50\ \text{GeV} \leq |M_1, M_2, \mu| \leq 1\ \text{TeV}$

$100\ \text{GeV} \leq M_3 \leq 1\ \text{TeV}$

$\sim 0.5\ M_Z \leq M_A \leq 1\ \text{TeV}$

$1 \leq \tan\beta \leq 50$

$|A_{t,b,\tau}| \leq 1\ \text{TeV}$

Log Priors

emphasizes lower masses but also extends to higher masses

$100\ \text{GeV} \leq m_{sfermions} \leq 3\ \text{TeV}$

$10\ \text{GeV} \leq |M_1, M_2, \mu| \leq 3\ \text{TeV}$

$100\ \text{GeV} \leq M_3 \leq 3\ \text{TeV}$

$\sim 0.5\ M_Z \leq M_A \leq 3\ \text{TeV}$

$1 \leq \tan\beta \leq 60$ (flat prior)

$10\ \text{GeV} \leq |A_{t,b,\tau}| \leq 3\ \text{TeV}$

- Flat Priors : 10^7 points scanned , 68422 survive
- Log Priors : 2×10^6 points scanned , 2908 survive

Important Experimental Constraints

- Precision Measurements & Heavy Flavors
  - W mass
  - $\Delta(g-2)_\mu$
  - Meson-Antimeson Mixing
  - $B_s \to \mu\mu$
  - $b \to s\,\gamma$
  - $\Gamma(Z \to \text{invisible})$
  - $B \to \tau\nu$
- Relic density: $\Omega h^2 < 0.121$. We treat this only as an *upper bound* on the neutralino thermal relic contribution
- Direct Detection Searches for DM (CDMS, XENON…)
- Higgs & SUSY searches @ colliders: there are *many* searches & they are quite complicated with many caveats. These needed to be 'revisited' in detail for the more general pMSSM models , e.g., fast detector sims for the Tevatron

Comments

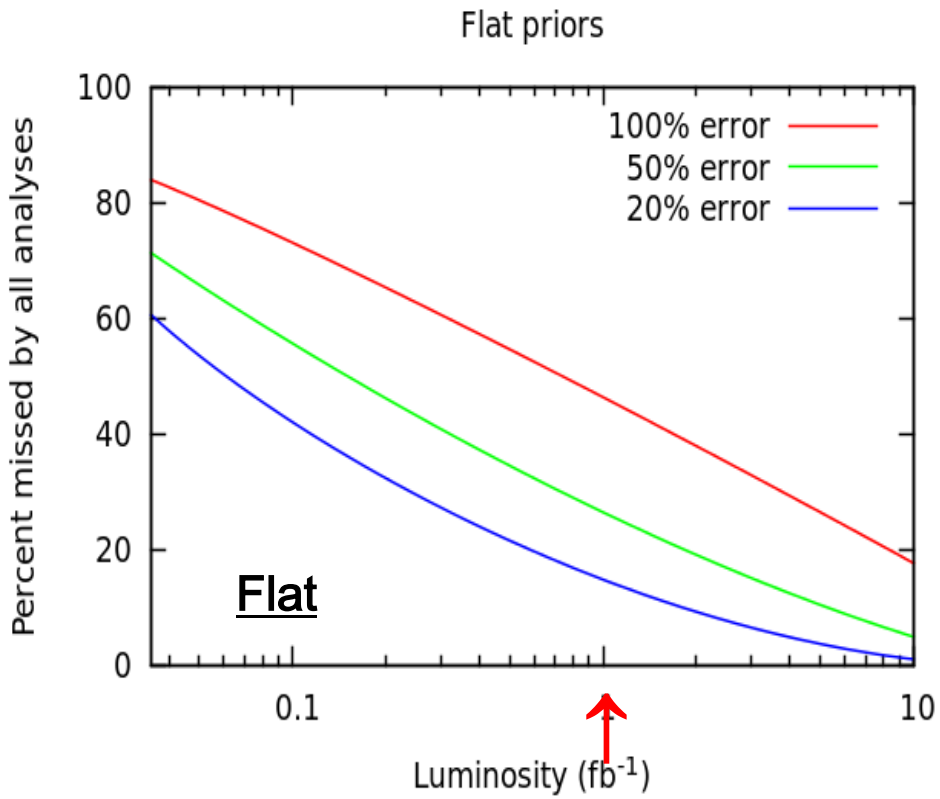
- All public codes (Pythia, SuSpect, Prospino, S/HDECAY,…) required 'modifications' (due to 'features') in order to handle our original pMSSM model sets

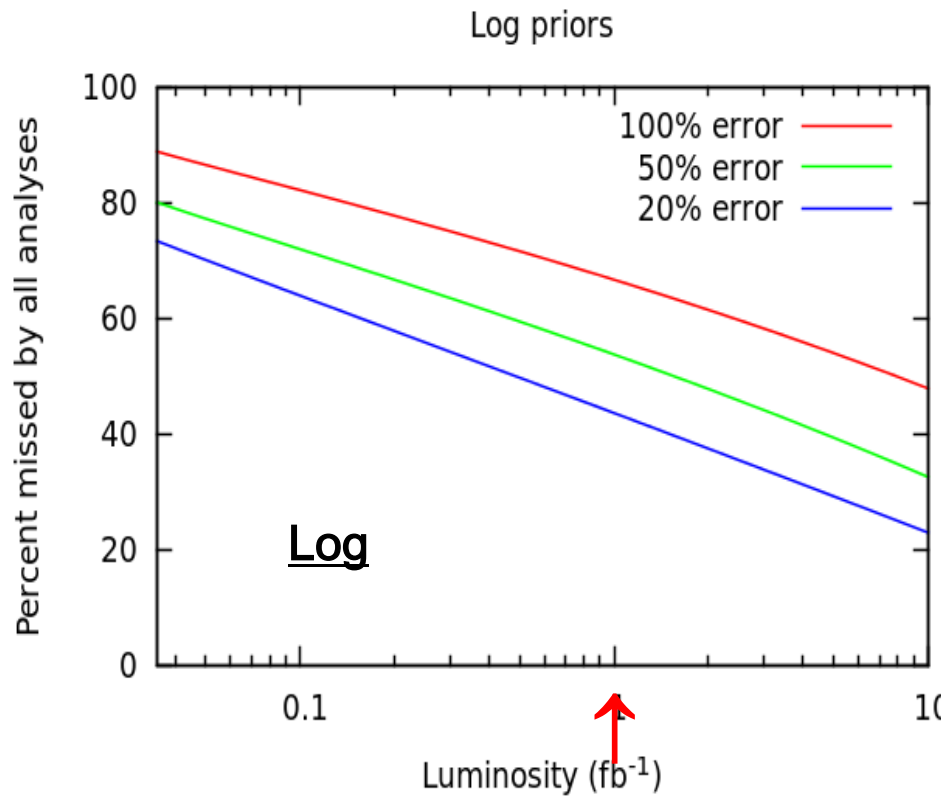
- Original model generation itself was fairly compute-intensive as were the subsequent ATLAS studies (~1/4 core-millennium)

- The complete set of the SUSY-Hit model files are publically available @ www.slac.stanford.edu/~rizzo

• Combining the 7 TeV ATLAS searches, what fraction of the model sets should not (yet) have shown a signal w/ Sig ≥ 5 ??

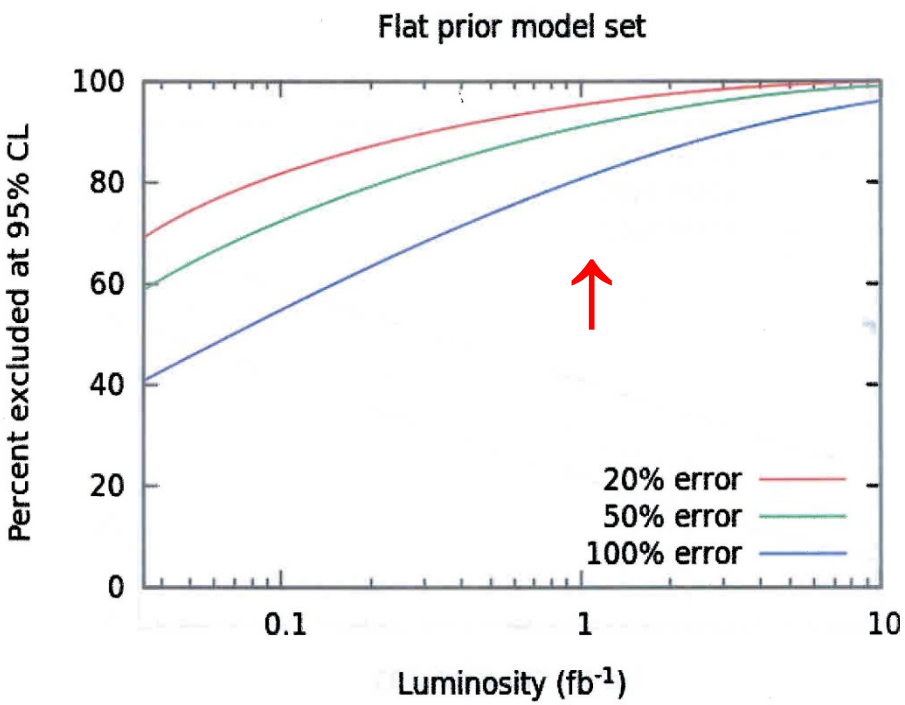
→ The coverage is quite good for both model sets !

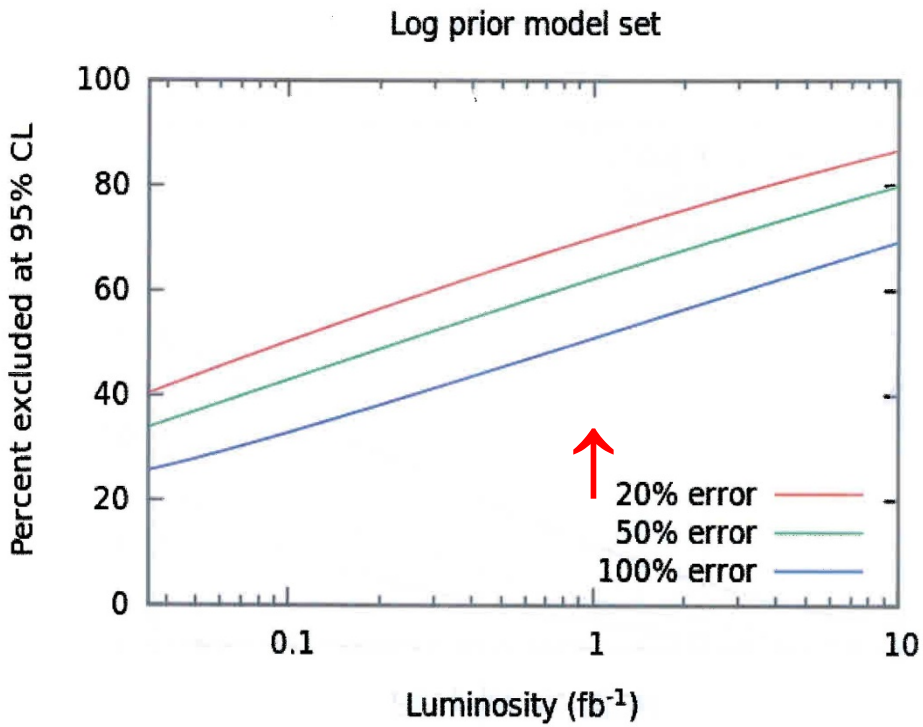




- However, certainly in the FLAT case, there is not much model space left ! Even worse, we ask…

- What fraction of these models are excluded ??





- We need to generate some new FLAT model sets going out to larger SUSY masses PLUS we need to cover the gravitino cases !

→ Develop a common framework for future scans

New pMSSM FLAT Scans

(via SOFTSUSY)

$100\ \text{GeV} \leq m_{Ll1,2,3} \leq 4\ \text{TeV}$

$400\ \text{GeV} \leq m_{Qud1,2} \leq 4\ \text{TeV}$ $\quad$ $200\ \text{GeV} \leq m_{Qud3} \leq 4\ \text{TeV}$

$50\ \text{GeV} \leq |M_1| \leq 4\ \text{TeV}$ $\quad$ $100\ \text{GeV} \leq |M_2, \mu| \leq 4\ \text{TeV}$

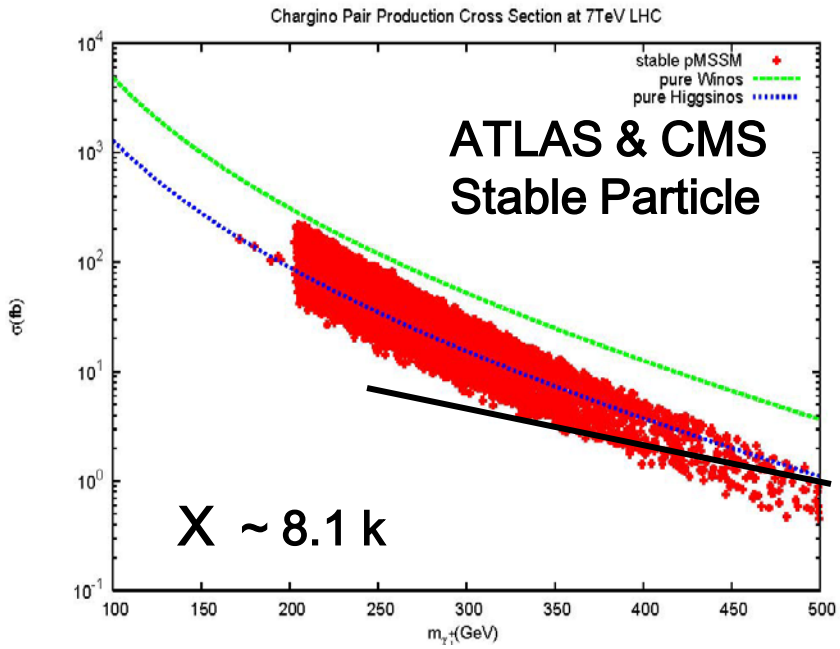
$400\ \text{GeV} \leq M_3 \leq 4\ \text{TeV}$ $\quad$ $|A_{t,b,\tau}| \leq 4\ \text{TeV}$

$100\ \text{GeV} \leq M_A \leq 4\ \text{TeV}$

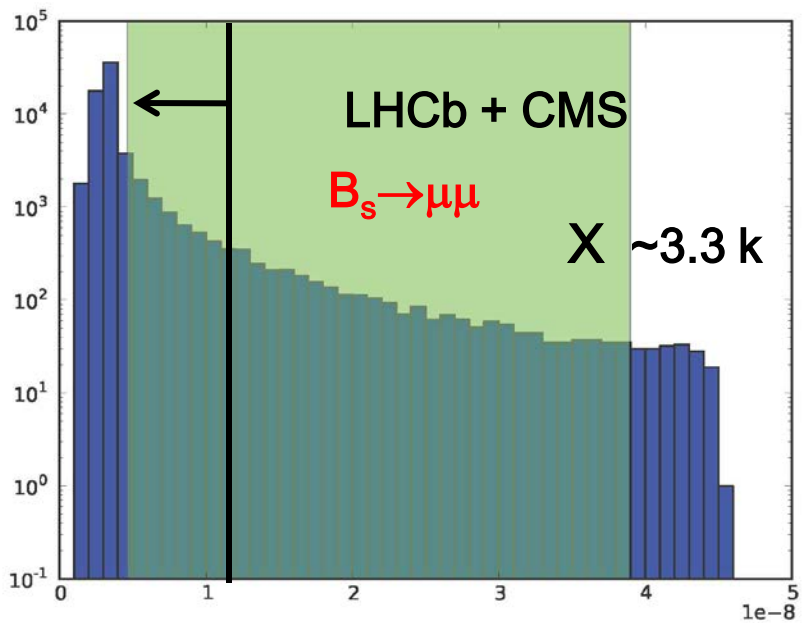
$1 \leq \tan\beta \leq 60$ (both flat & log scans)

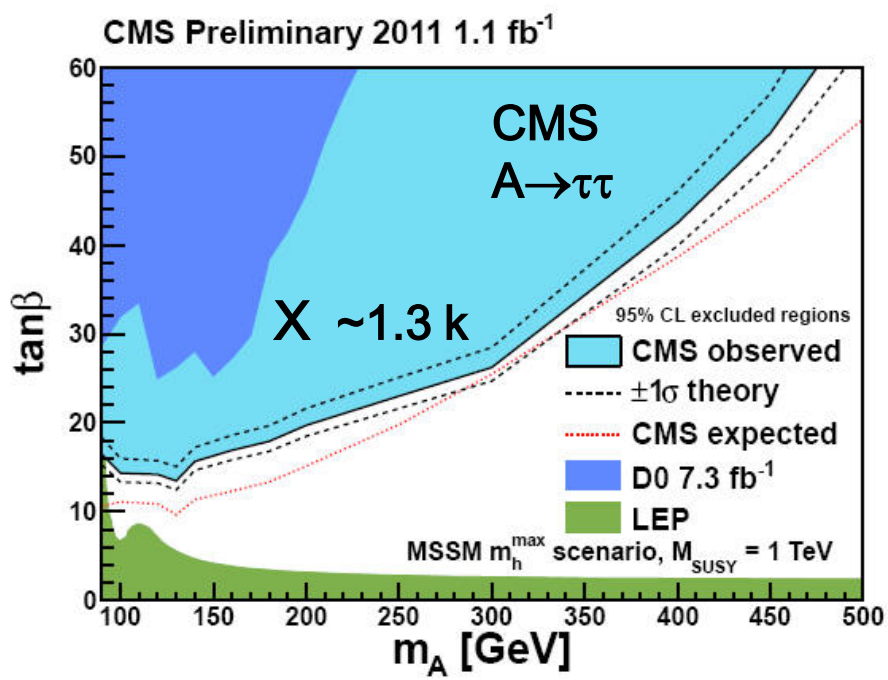
$\rightarrow\rightarrow$ For the gravitino LSP: $1\ \text{ev} \leq m_{3/2} \leq 500\ \text{GeV}$, log scan

- All new non-MET constraints from EPS, DPF & L-γ incorporated and all codes updated to latest versions w/ fixes. Additional complexities, eg, BBN constraints, for the gravitino LSP case



Non-MET LHC searches are very important and have a significant impact on the pMSSM as shown here for the original model sets..some more so for gravitino LSPs !





Results

- Produced a single code to handle BOTH neutralino & gravitino LSPs. This work is still at an early stage & only some results from the neutralino LSP scans are now available in a very preliminary form. (The gravitino cases will soon follow but we found it's best to 'debug' w/ the more familiar neutralino LSP !)

  - Flat tan β Priors : 2×10^6 points scanned , ~158k survived
  - Log tan β Priors : 2×10^6 points scanned , ~133k survived

- Higher masses $\rightarrow$ weaker impact of the non-MET/LEP/Tevatron constraints $\rightarrow$ greater efficiencies for finding successful models

- Log tan β scan is somewhat more sensitive to the M_A - tan β constraints (as expected) since it peaks at lower values

- Note fast changing data base of constraints thanks to LHC !

Comments

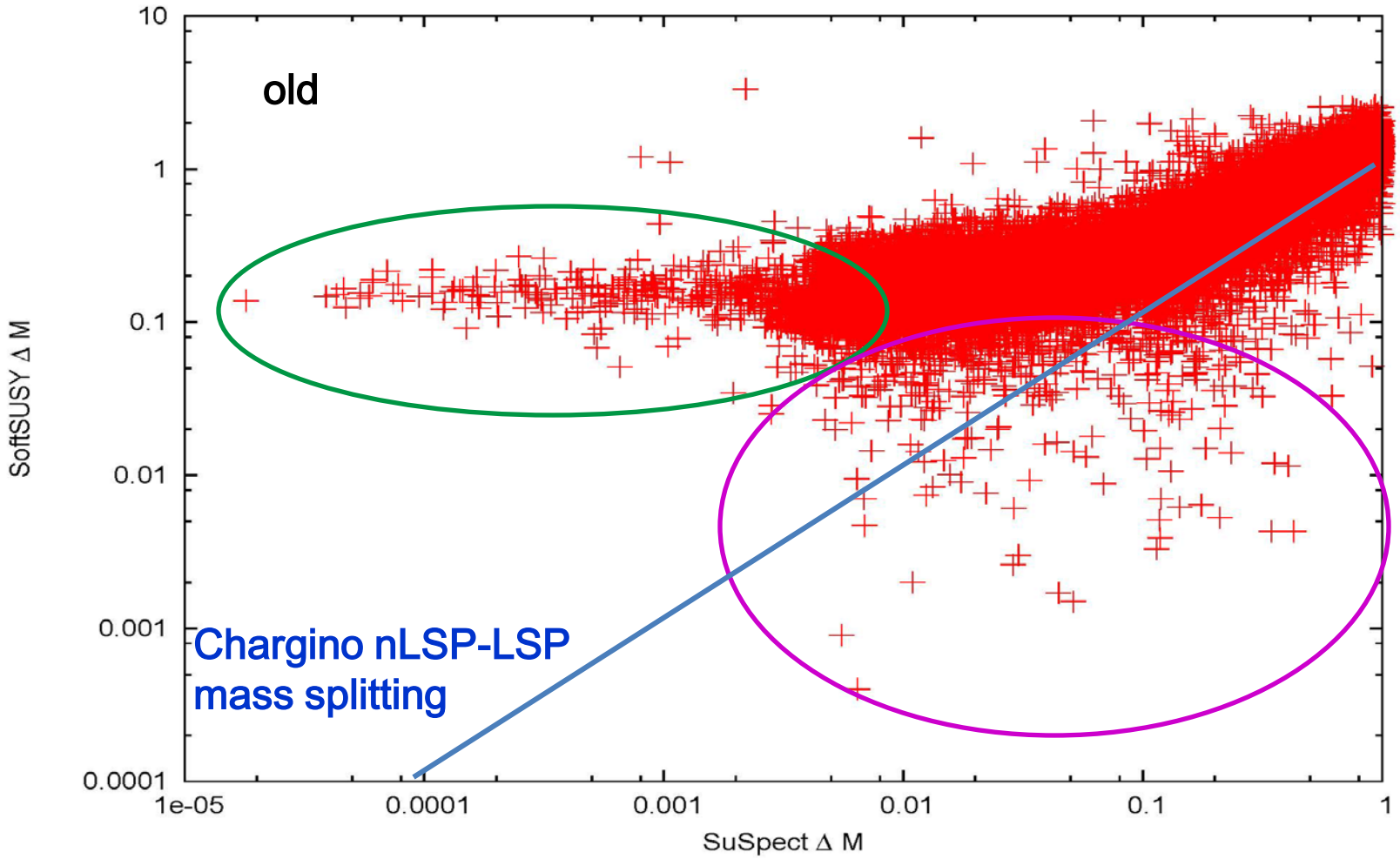
- No LHC MET analyses have yet been performed using these new model points

- Spectrum generator issues: SOFTSUSY (for new sets) vs. SuSpect (for the original ones) … interesting comparisons

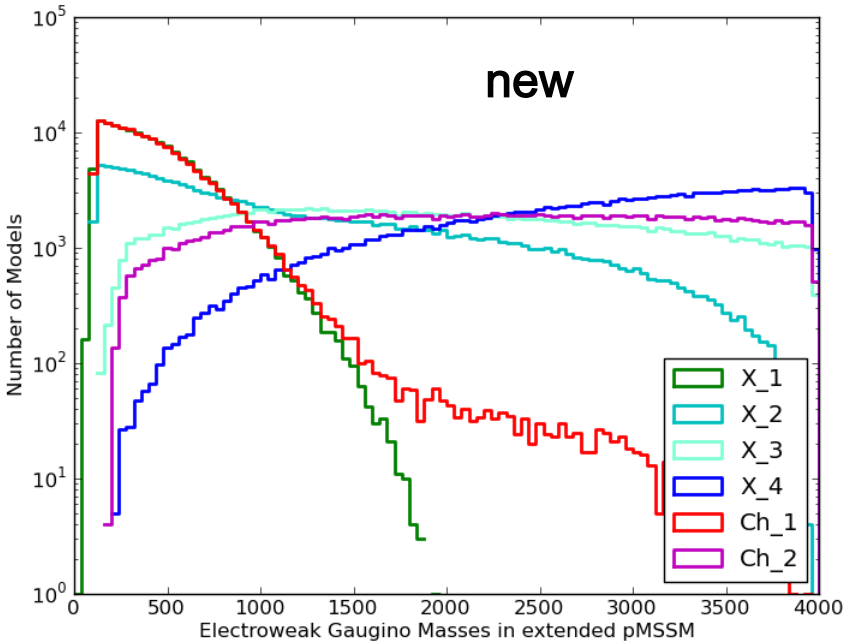
- History: SuSpect has a tendency to generate highly degenerate LSPs in wino/Higgsino cases (with $\Delta m << \sim 100$ MeV) .. .the common wisdom is that this 'can't happen'. It was then 'suggested' to use a different generator, e.g., SOFTSUSY

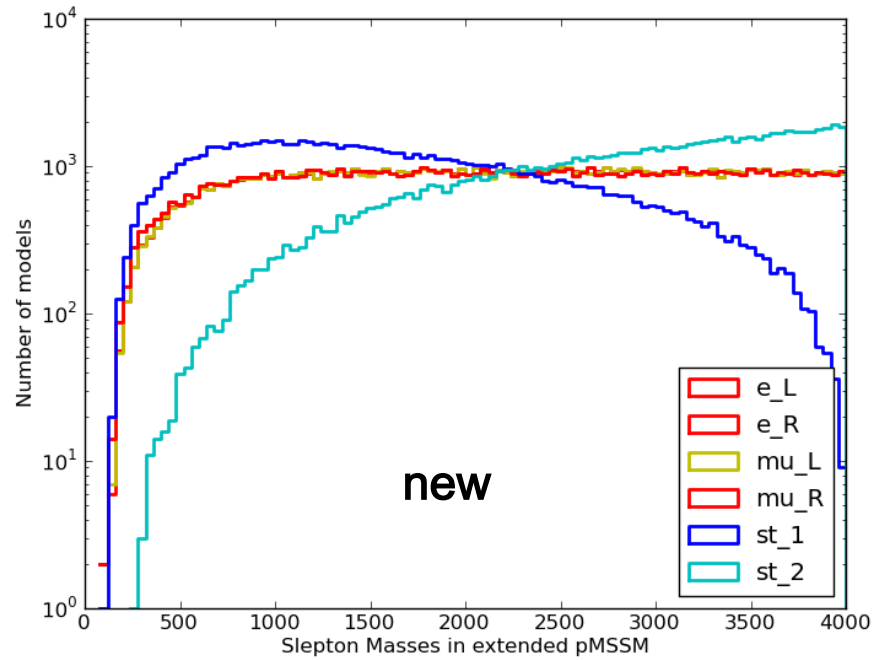
- Here we'll look at some plots from the FLAT tan β scan….

- But first what is this degeneracy issue ?

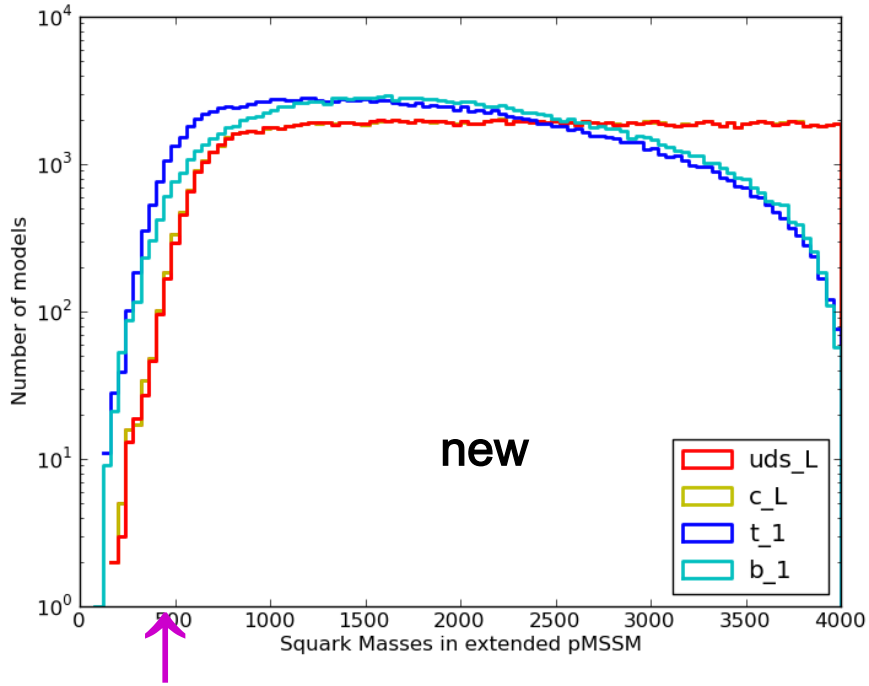


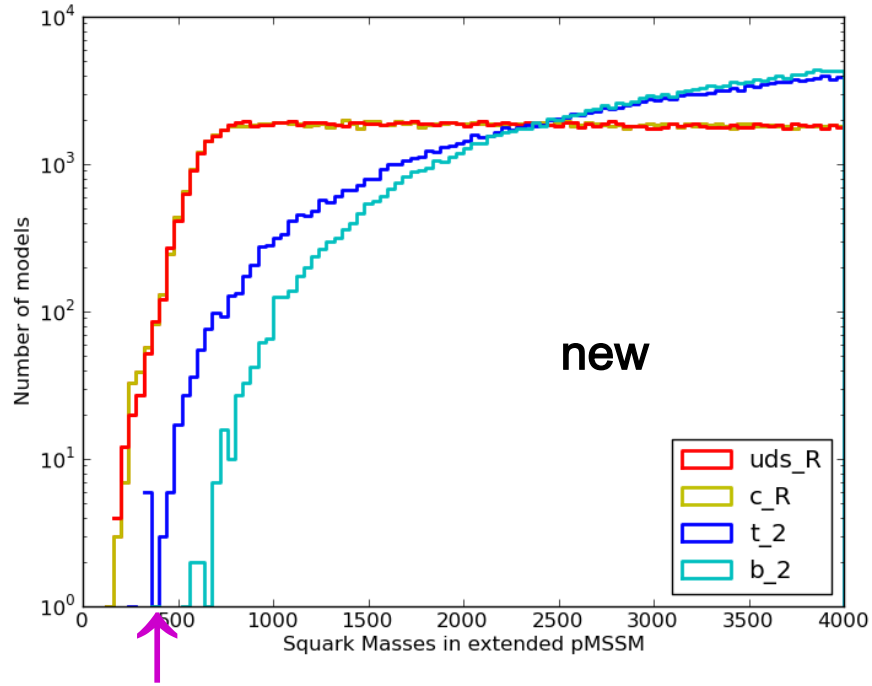
Note that SOFTSUSY <u>also</u> produces small Δm's << ~ 100 MeV though maybe less frequently than SuSpect.. problem ?





- Basic spectra will persist in both neutralino/gravitino cases
- Pretty standard gaugino & slepton mass spectra given the input ranges
- Note the charginos & neutralinos 'tracking' each other… gluinos also look fairly vanilla

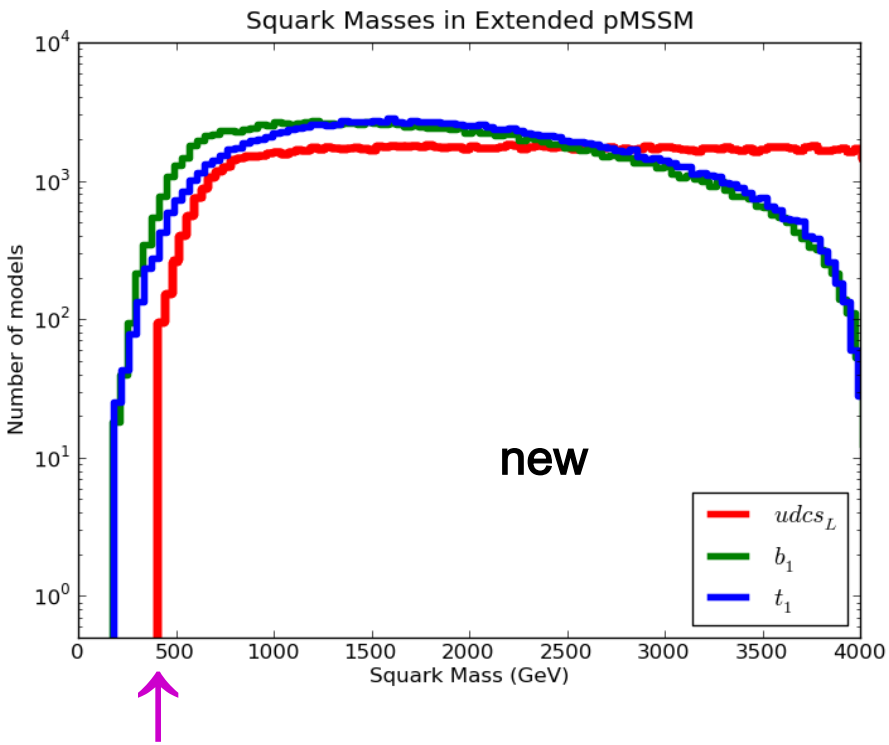


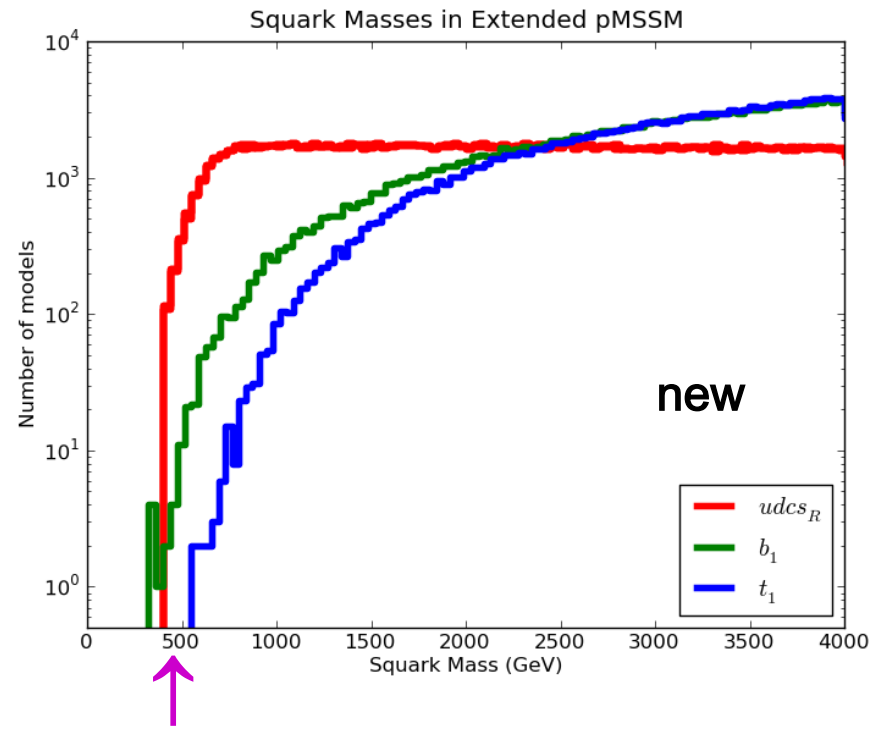


- Wait…1st/2nd generation squarks are seen far below 400 GeV while their associated Lagrangian parameters were so constrained. What the..? → check w/ SuSpect ..

- For some parameter values the radiative corrections to the squark masses are extremely large ~O(1) in both codes (though they don't agree!).

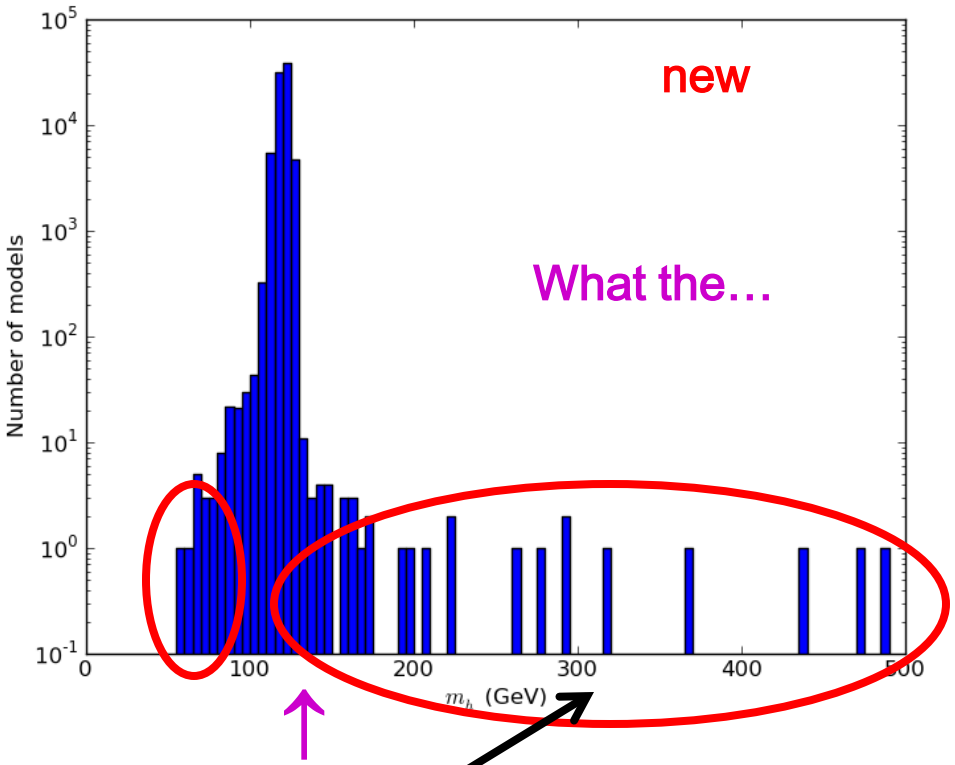
→ Poor scale choice &/or a need to re-sum??…an issue?

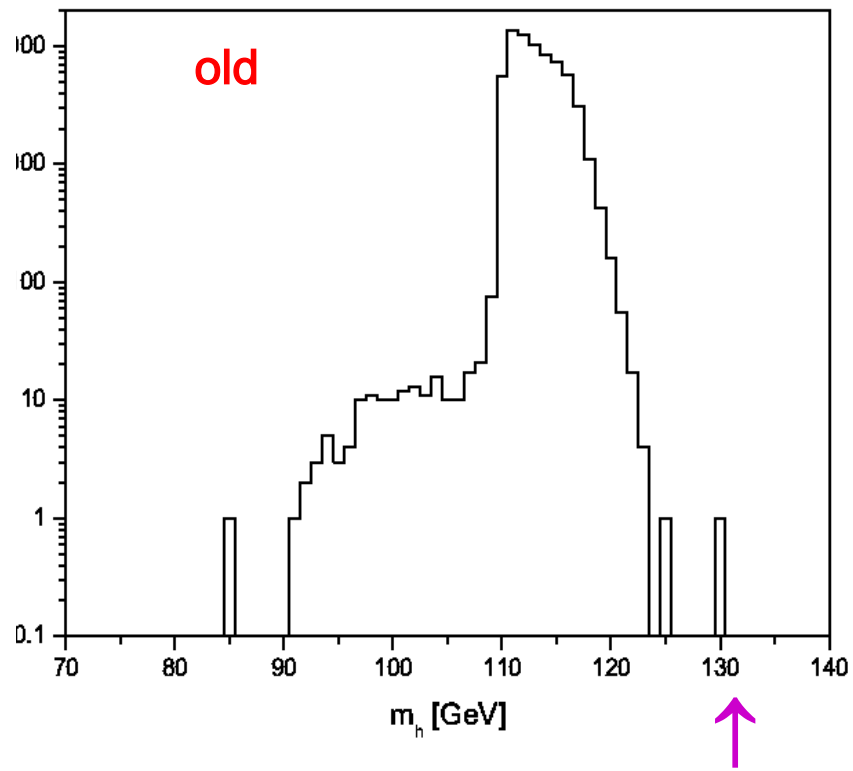




- Compare SuSpect & SOFTSUSY requiring that both generators produce spectra which are 'compatible'…all the 'offending' models go away !

- We are now investigating the source of these large RCs…

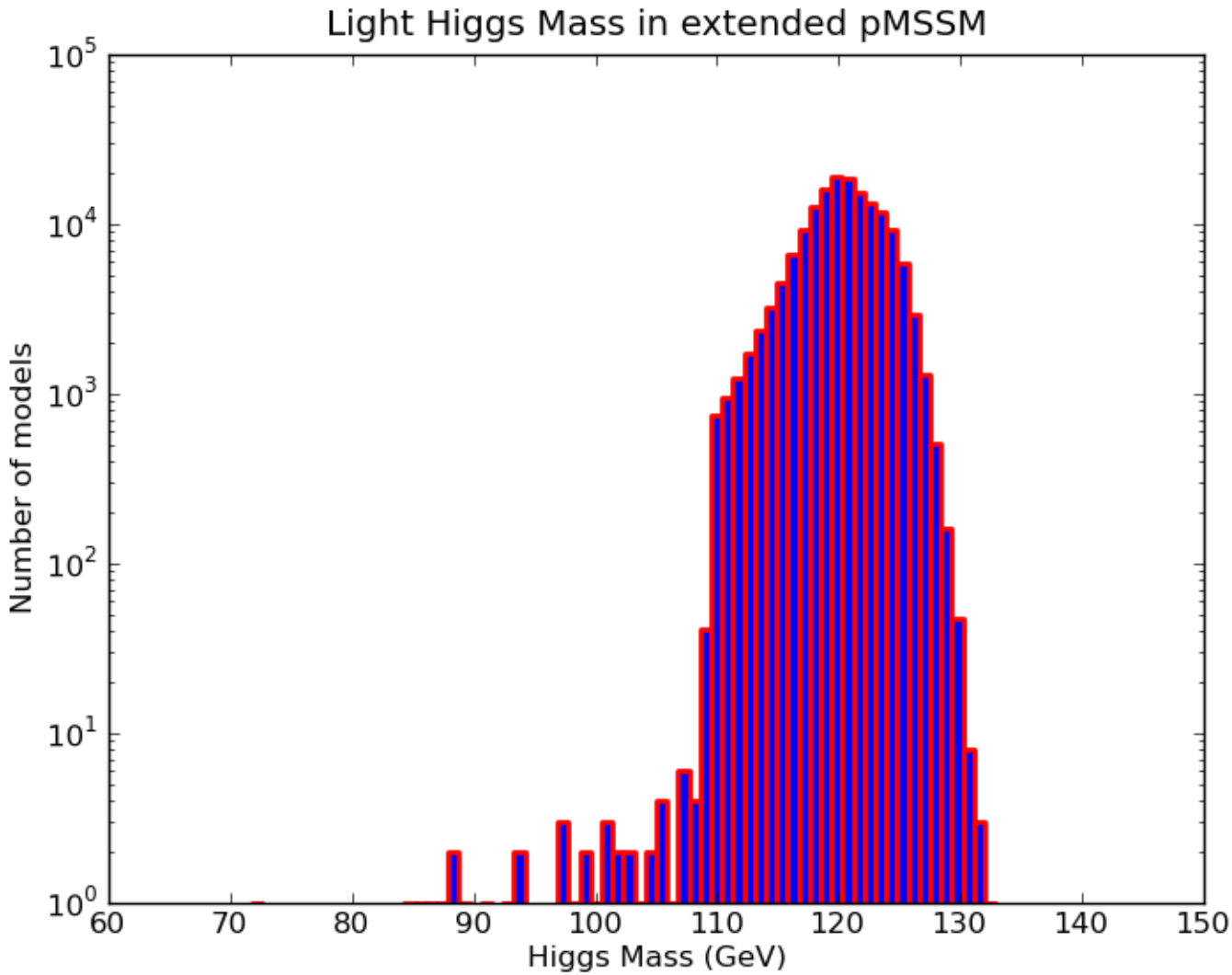


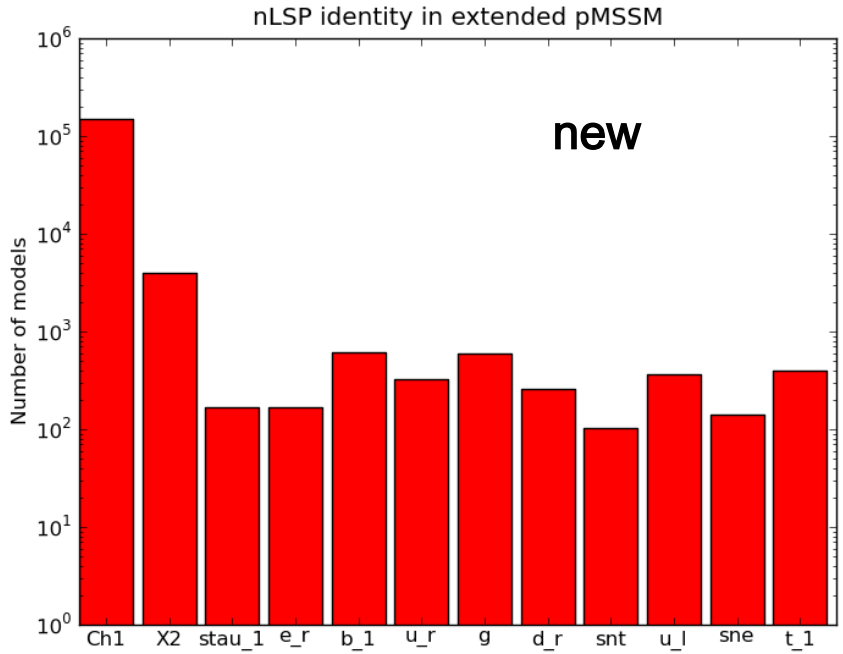


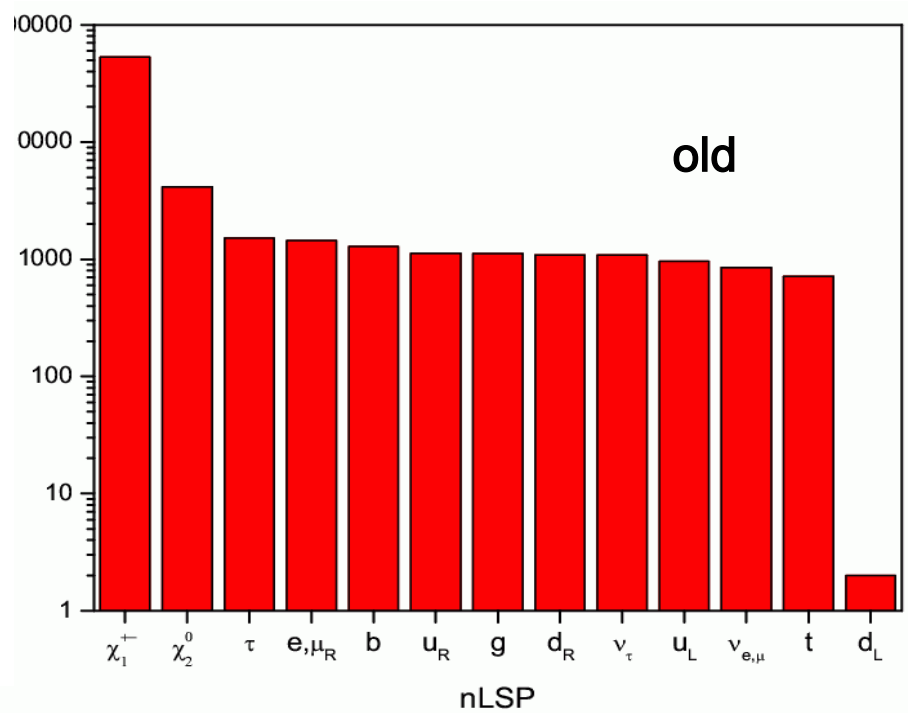
- Some had SOFTSUSY accuracy warnings. For 32/33 of these cases, SuSpect (for the same inputs) gives an error message (31 RGE/tachyon issues) & a 'normal' value in the other case

- Remove models where significant disagreement occurs between the generators

Completely Fine !

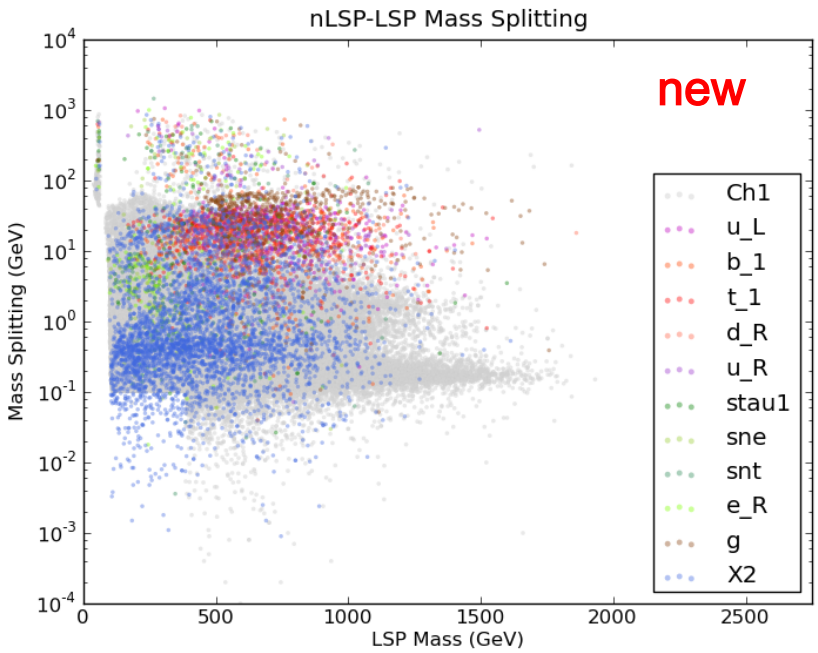


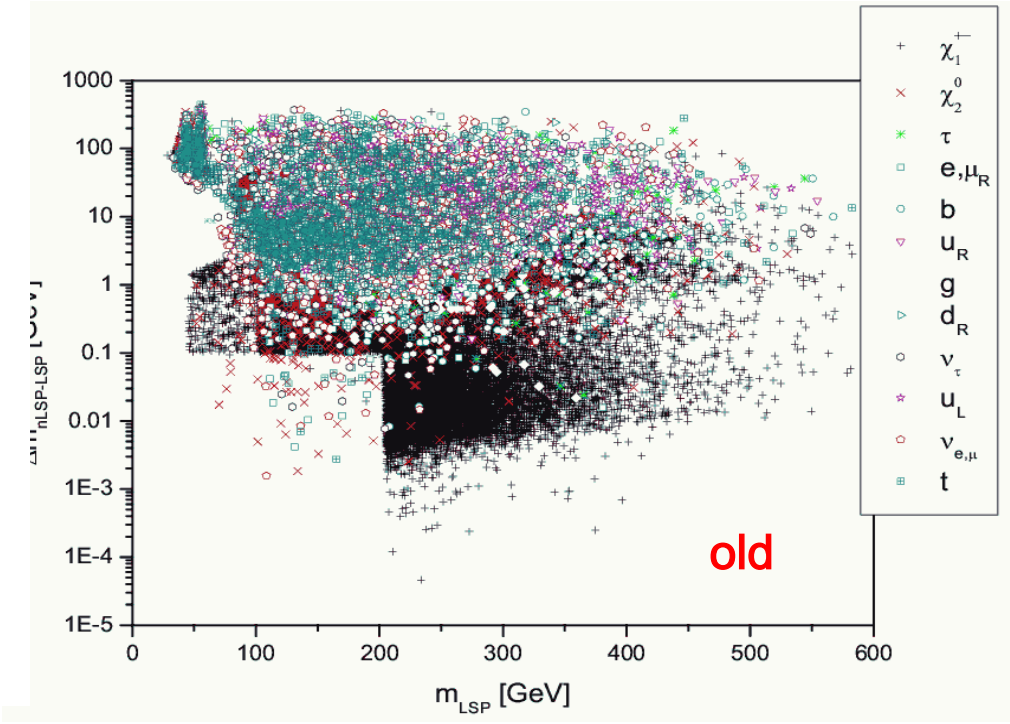




- While any sparticle can be the nLSP as before, charginos (followed by the 2nd neutralino) are now seen to be even MORE dominant than in earlier sets

- This can again be mostly traced to the parameter scan ranges chosen… it will be interesting to contrast the gravitino case





- Incredibly wide range of nLSP-LSP mass splittings! Some very small values (below ~10 MeV) are seen in both scans

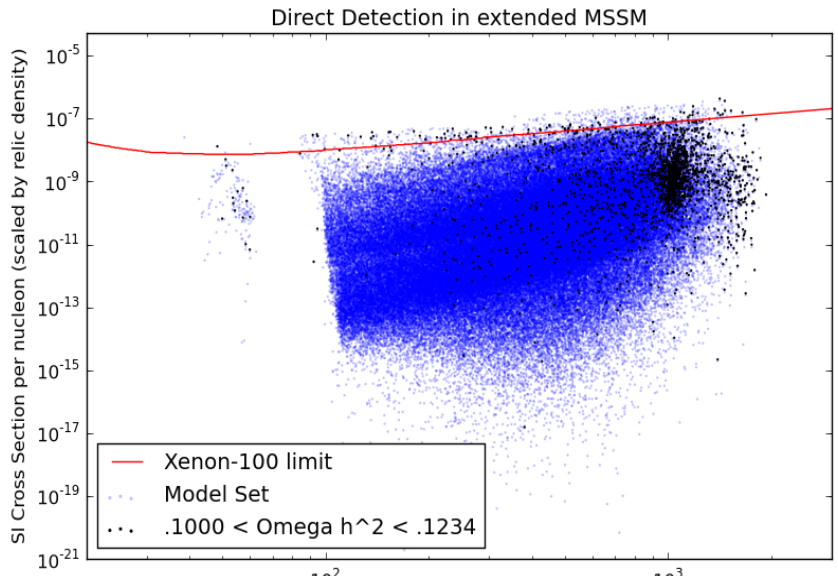
- Note 'hole' from stable sparticle collider searches

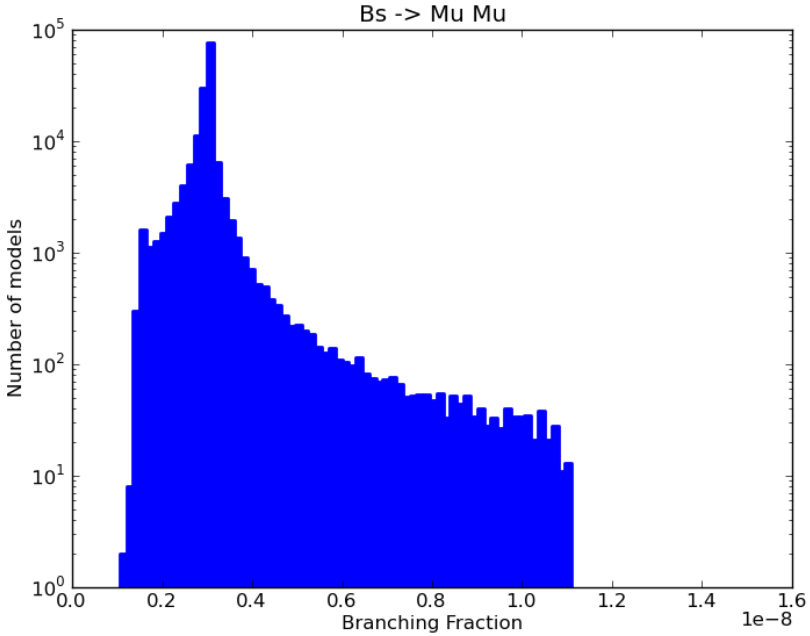
- Note also cases with mass splittings in excess of ~1 TeV ! Yikes!

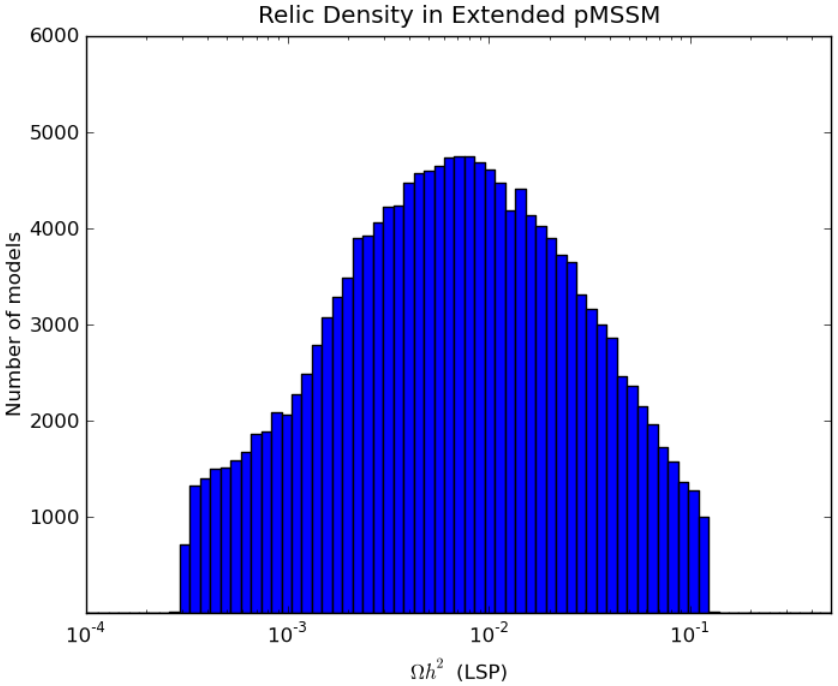
Conclusions

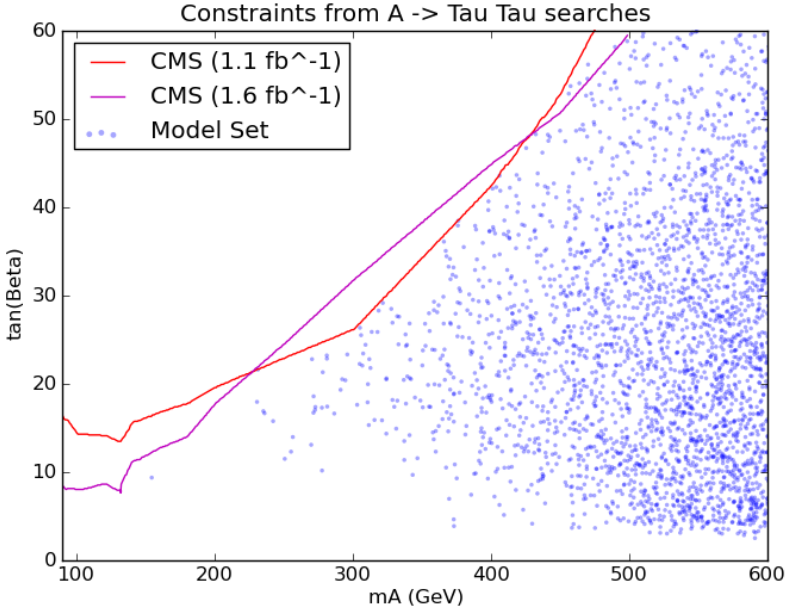
- Generating pMSSM model sets, if taken seriously, is a great learning experience for physicists of all ages
- It is useful to employ more than one spectrum generator to make tests & comparisons wrt 'funny' parameter regions that lead to 'unexpected' sparticle masses as well as a check for 'features'
- Best to test complex codes using the more familiar neutralino LSPs…
- There may be some not well understood pMSSM regions not adequately described by the public generators
- Plenty more results coming soon -- including gravitino LSPs!

BACKUP SLIDES

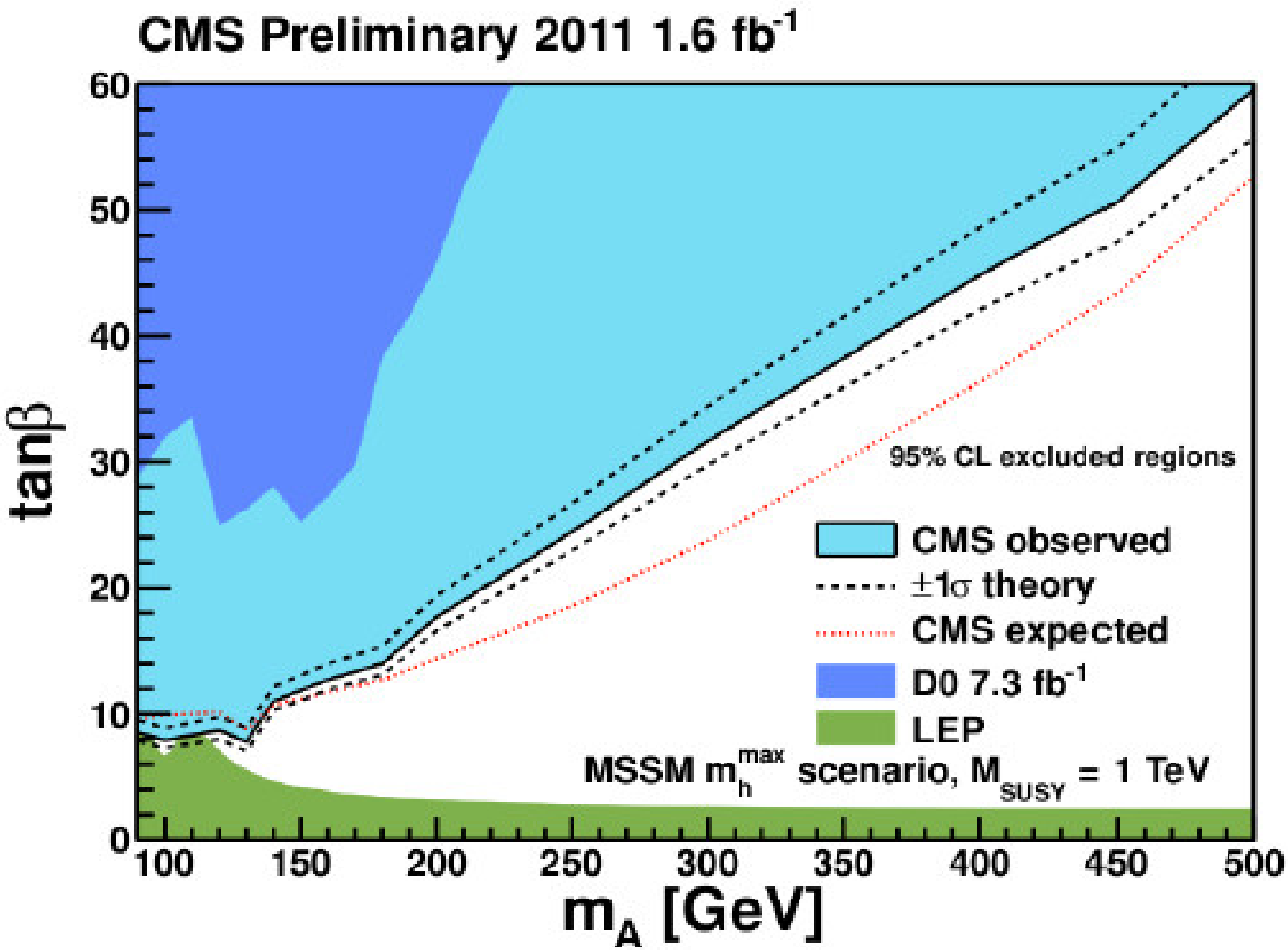

Direct Detection in extended MSSM
SI Cross Section per nucleon (scaled by relic density)
Xenon-100 limit
Model Set
.1000 < Omega h^2 < .1234


Bs -> Mu Mu
Number of models
Branching Fraction
1e−8


Relic Density in Extended pMSSM
Number of models
Ωh^2 (LSP)


Constraints from A -> Tau Tau searches
CMS (1.1 fb^-1)
CMS (1.6 fb^-1)
Model Set
tan(Beta)
mA (GeV)

Now Included….



SUSY is so much more than mSUGRA !

Problem: SUSY might be complex & could be missed by standard searches if only signatures within specific breaking scenarios (mSUGRA, GMSB, AMSB ..) are employed. How complex we don't know..

So a more general study of SUSY is clearly warranted. Such a study can also have important impact on other BSM searches

But SUSY is a very messy theory…even the (100+parameter) MSSM is too difficult to study in full detail

What are (aren't) the Goals of this Study ?

- Original scans: Obtain a large 'model' sample, ~50k, satisfying 'all' experimental constraints & which are kinematically accessible in early 7 TeV LHC runs & check for any 'holes' left in LEP/Tevatron 'low-E' searches for lighter sparticles ✓

- Perform LHC, DM & other analyses with these models. ✓

- Our goal was NOT to find the 'best-fit' model(s) but to search for any new physics that is different/unusual

- We are interested in the capability of the LHC (here mostly ATLAS) & Dark Matter experiments to discover signals for all these models. ✓

ATLAS SUSY Analyses w/ pMSSM Sets

- Issue: Can the LHC find all the pMSSM model points?

- Question: We asked whether or not a standard set of LHC MET analyses, designed for the CMSSM, would find them.

- To be as realistic as possible we worked closely w/ ATLAS employing their SUSY analysis suite at the fast simulation level. We obtained their pre-data SM background estimates & employed their anticipated range of systematic errors.

- We followed their search analyses in detail (same cuts, etc.) as well as their statistical criterion for SUSY discovery for direct comparisons.

ATLAS	US
ISASUGRA generates spectrum & sparticle decays	SuSpect generates spectra with SUSY-HIT# for decays
Partial NLO cross sections using PROSPINO & CTEQ6M	NLO cross section for all 85 processes using PROSPINO** & CTEQ6.6M (~6M K-factors)
Herwig for fragmentation & hadronization	PYTHIA for fragmentation & hadronization
GEANT4 for full detector sim	PGS-ATLAS for fast detector simulation

** version w/ negative K-factor errors corrected

version w/o negative QCD corrections, with 1st & 2nd generation fermion masses & other very numerous PS fixes included. e.g., explicit small Δm chargino decays, etc.

- We first verified that we can approximately reproduce both the 7 & 14 TeV ATLAS results for their benchmark CMSSM models with our analysis techniques for each channel. .. BUT there were some analysis differences

- Finally, we passed all of ~71k points through the full suite of ATLAS MET analyses (~150 core-yrs of CPU)

- SuSpect → SUSY-Hit → PROSPINO (~12M K-factors!) → PYTHIA → ATLAS-tuned PGS4 fast simulation

→ Many results! Here only the most basic: How well do the 7 TeV ATLAS analyses do at pMSSM model coverage?

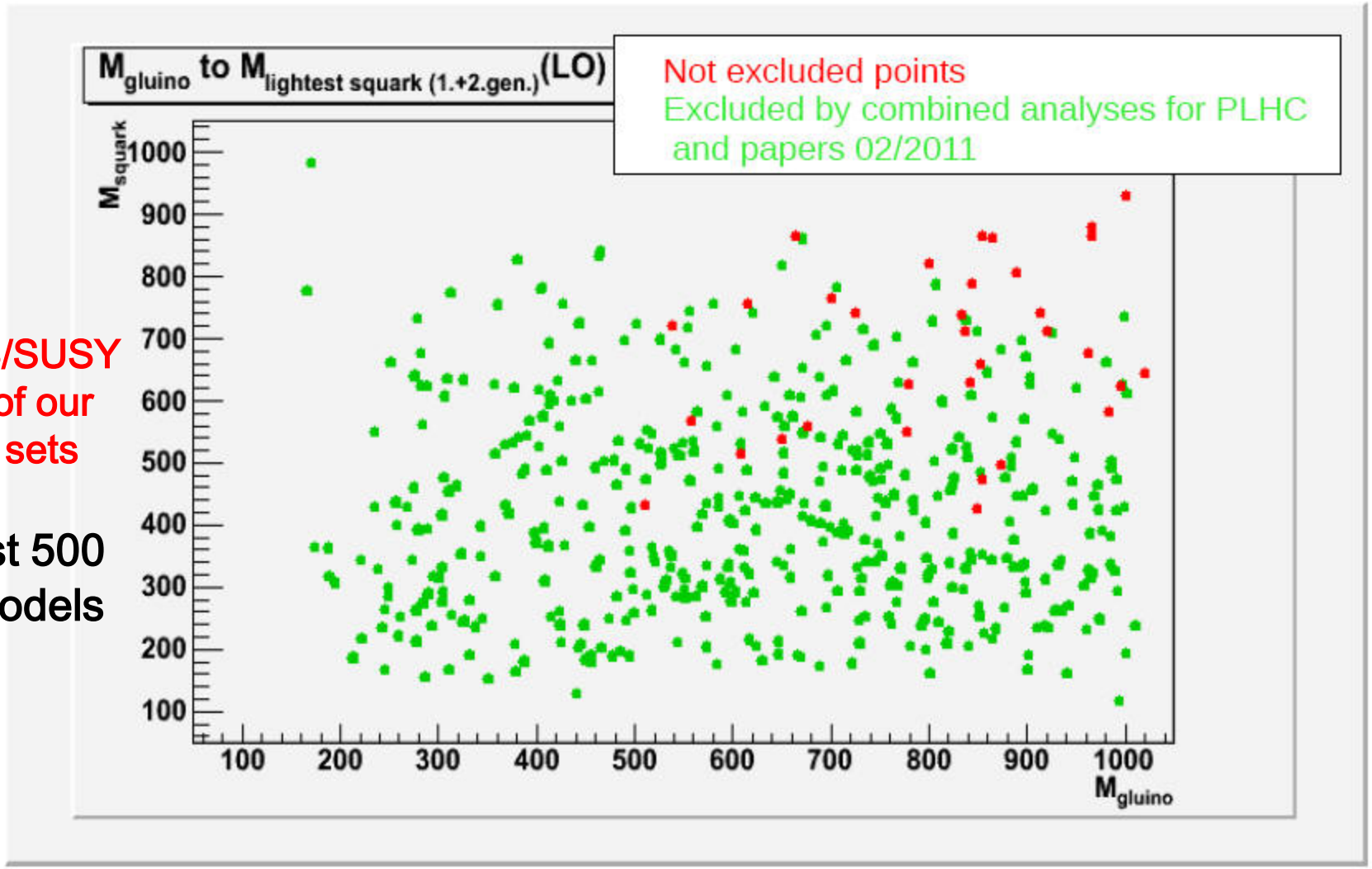
(ATLAS = A Tool for Locating Any SUSY ?)

Exclusion plot for 164 pb^{-1}

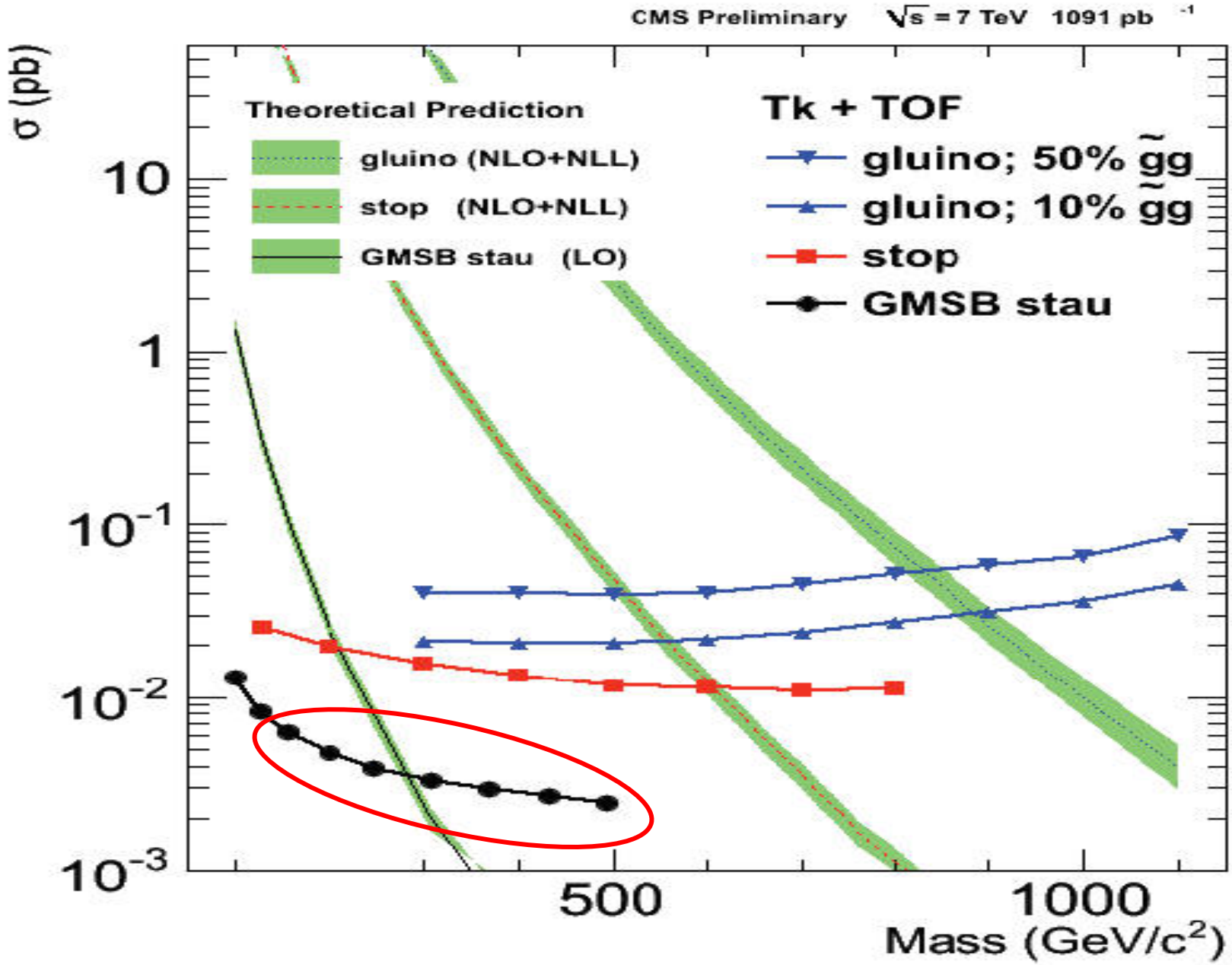
S. Caron & A. Stuebing
U Freiberg

ATLAS/SUSY study of our model sets

The 1st 500 Flat Models



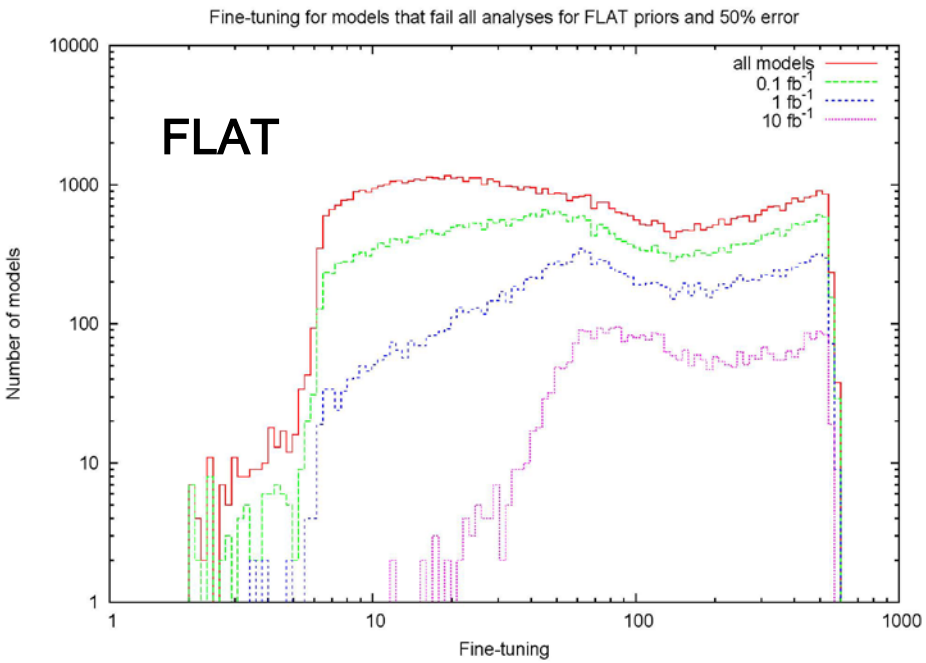
CMS Long-Lived Stable Particle Search

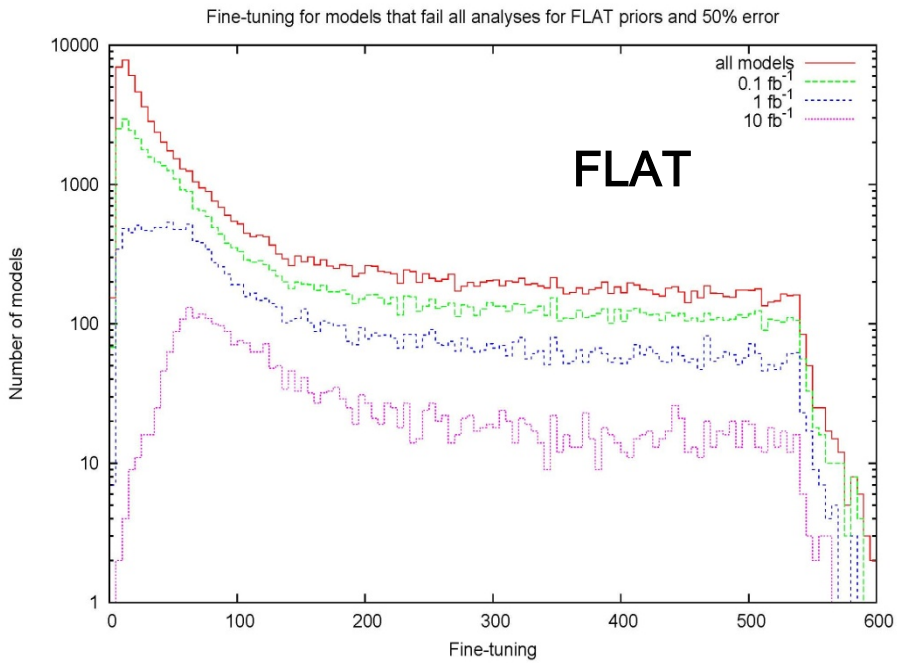


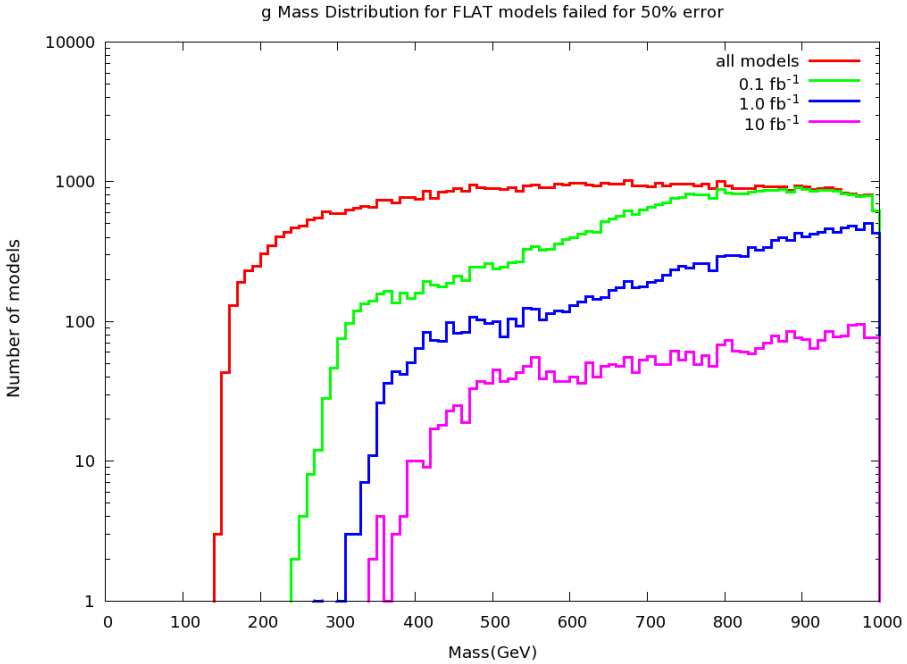
Fine-Tuning SUSY ?

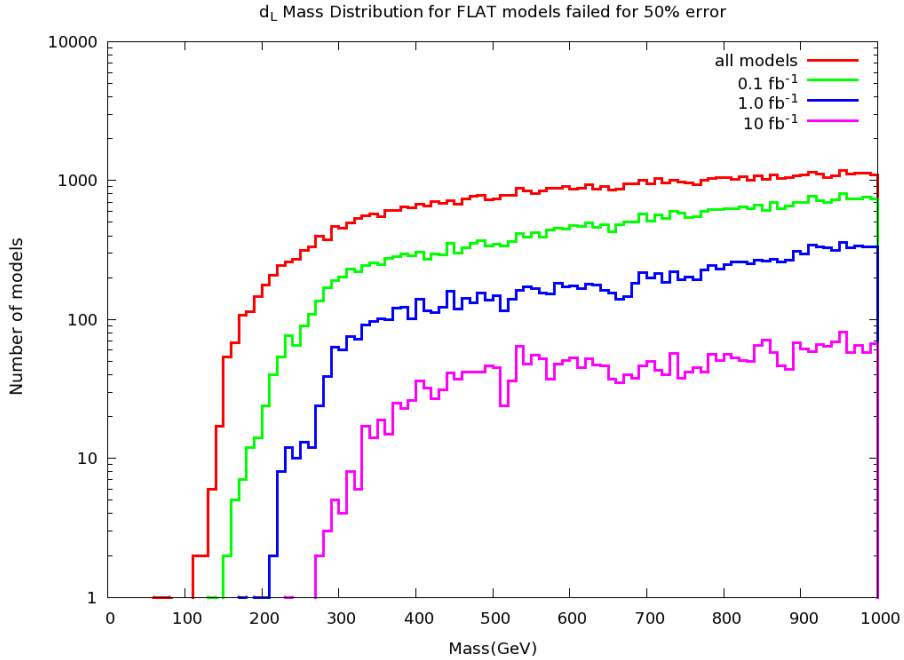
- It is often claimed that if the LHC (@7 TeV) does not find anything then SUSY must be VERY fine-tuned & so 'less likely'.

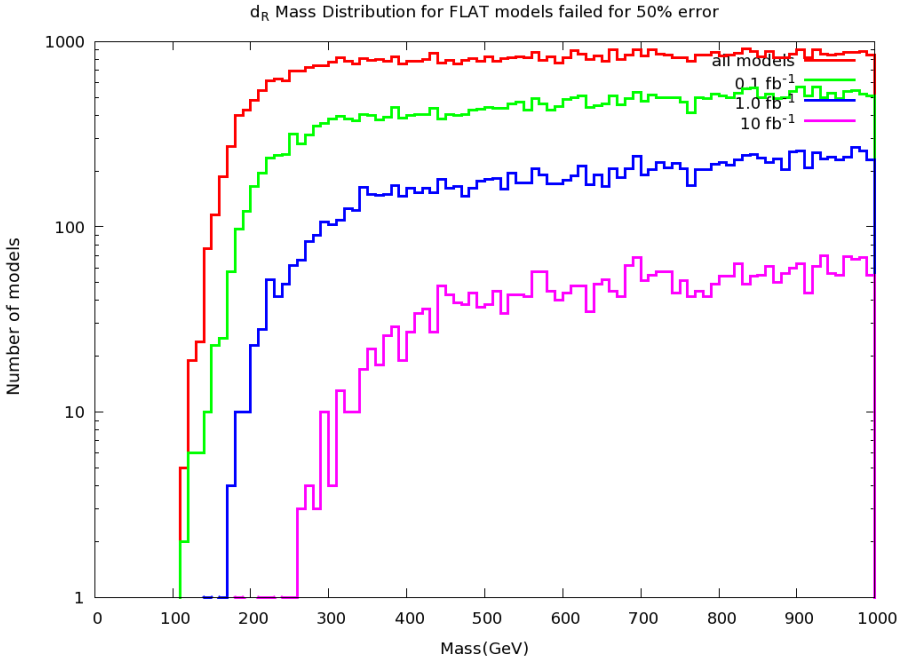
Is this true for our pMSSM model sets??

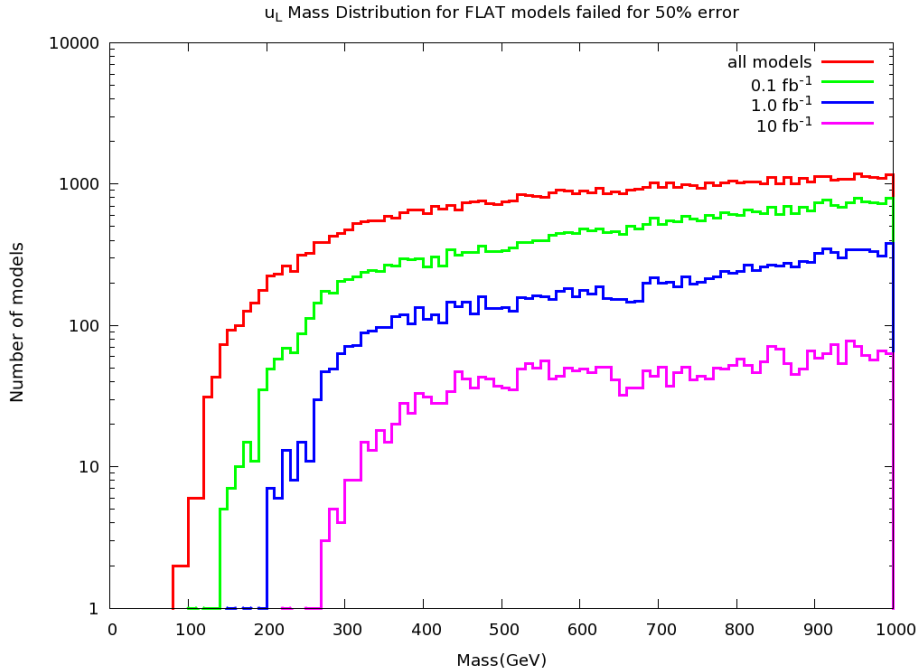


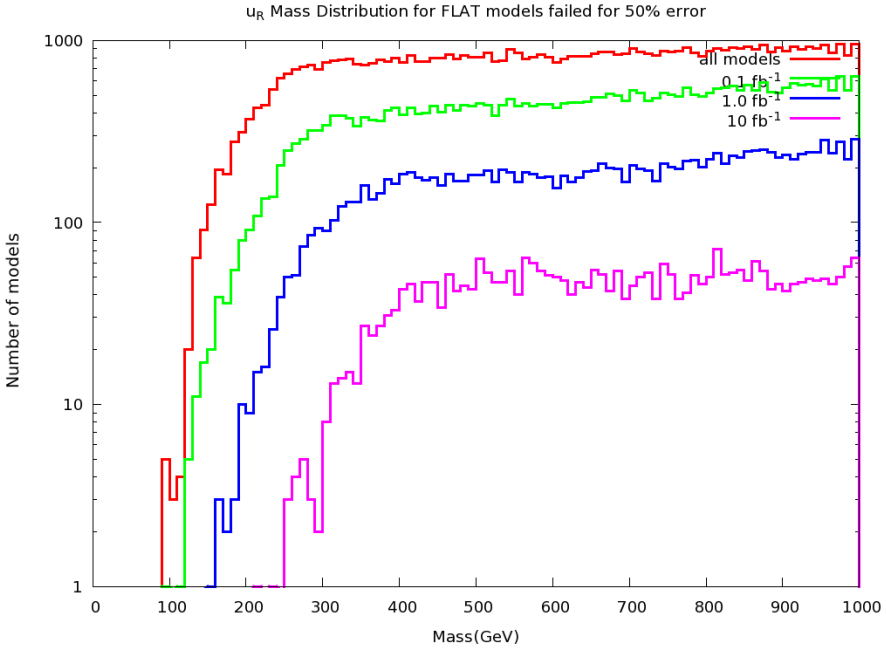


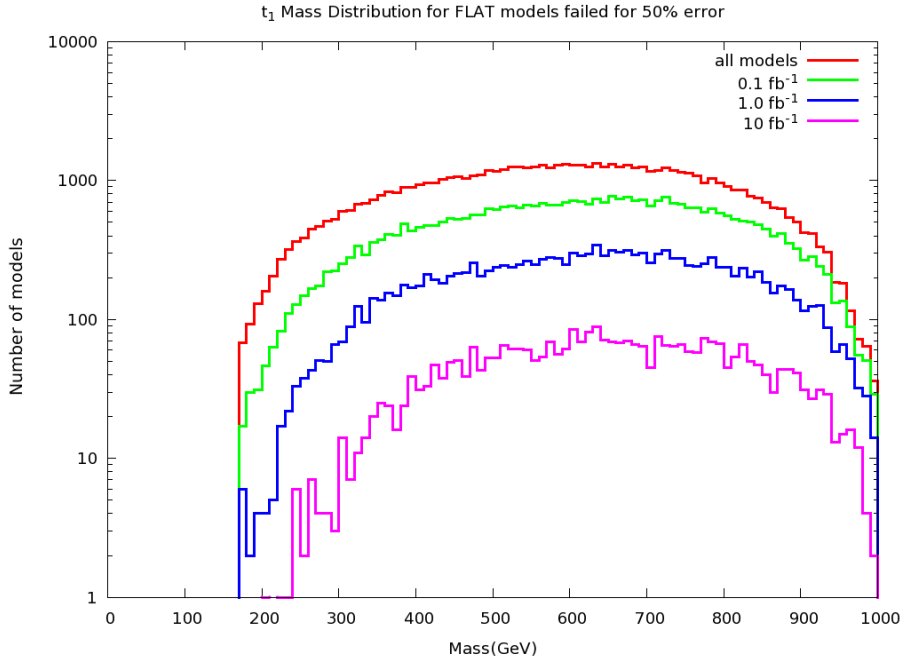

g Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb-1
1.0 fb-1
10 fb-1
Number of models
Mass(GeV)
10000
1000
100
10
1
0
100
200
300
400
500
600
700
800
900
1000

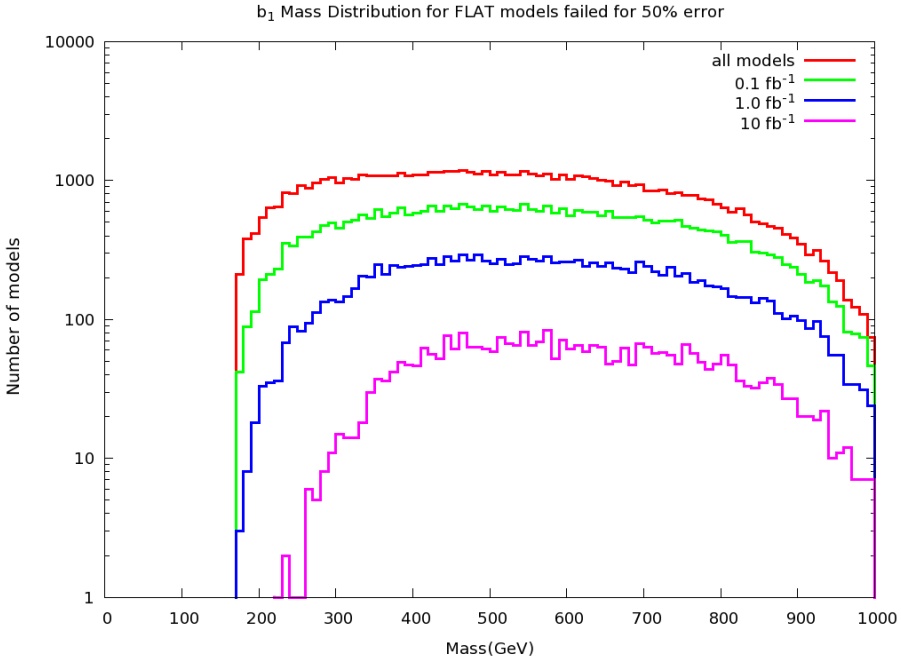

dL Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb-1
1.0 fb-1
10 fb-1
Number of models
Mass(GeV)
10000
1000
100
10
1
0
100
200
300
400
500
600
700
800
900
1000

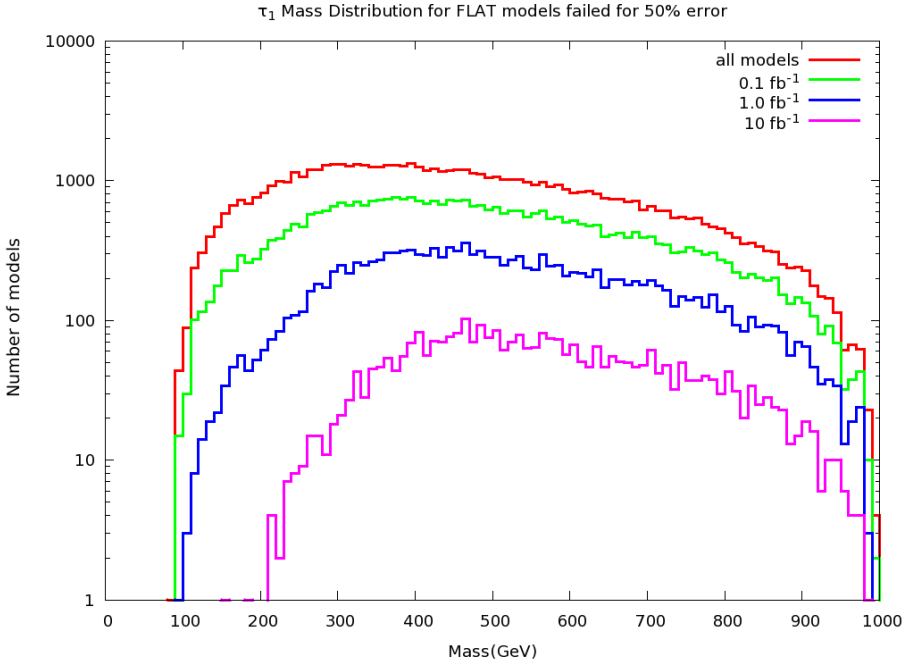

dR Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb-1
1.0 fb-1
10 fb-1
Number of models
Mass(GeV)
1000
100
10
1
0
100
200
300
400
500
600
700
800
900
1000

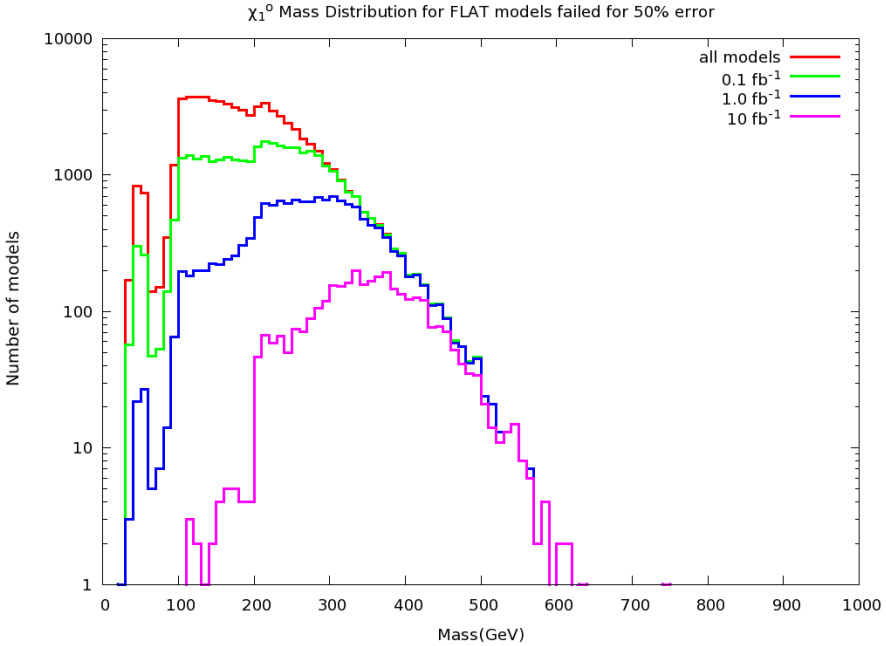

uL Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb-1
1.0 fb-1
10 fb-1
Number of models
Mass(GeV)
10000
1000
100
10
1
0
100
200
300
400
500
600
700
800
900
1000

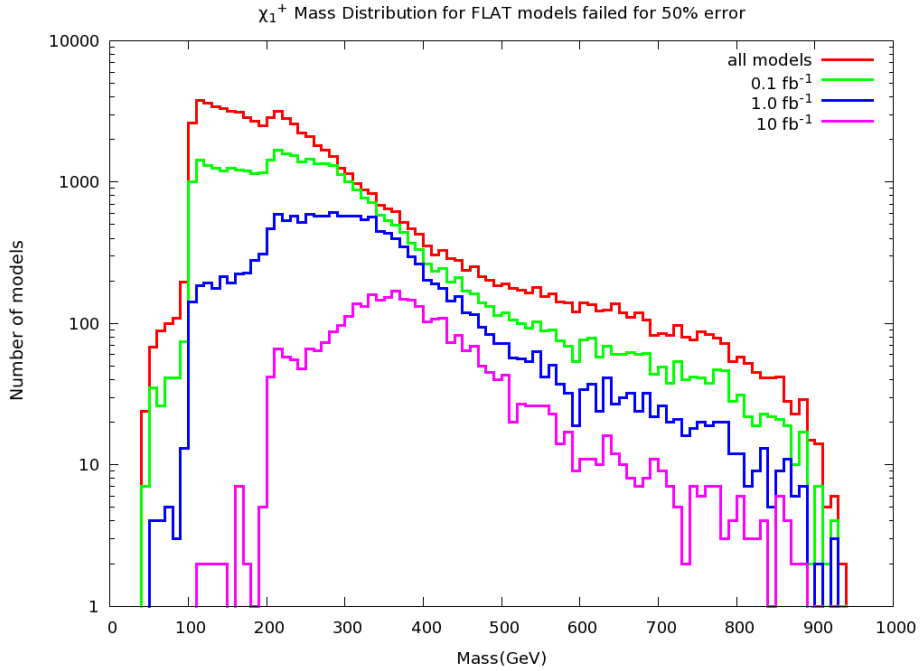

u_R Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}
Number of models
Mass(GeV)

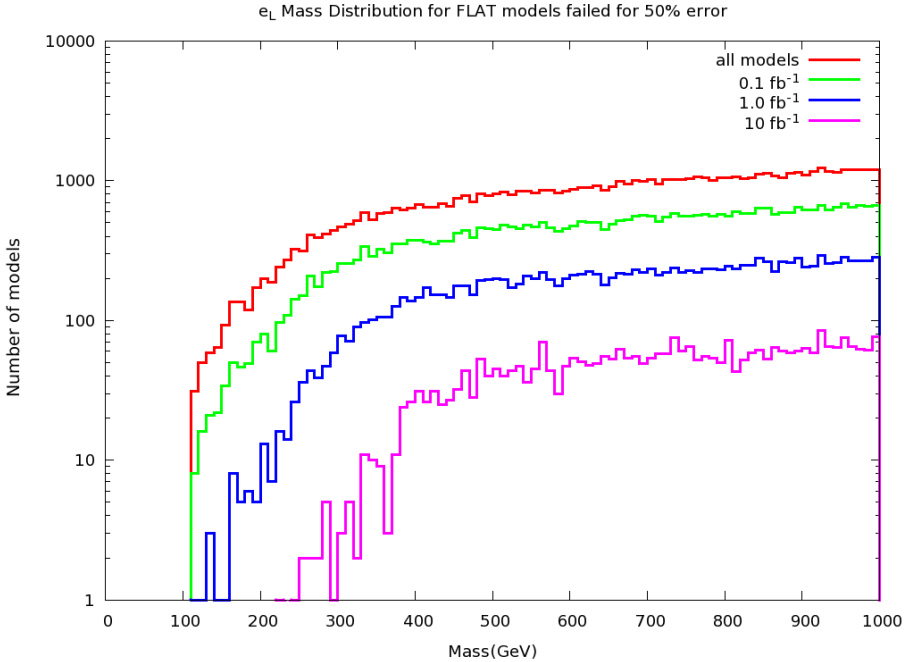

t_1 Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}
Number of models
Mass(GeV)

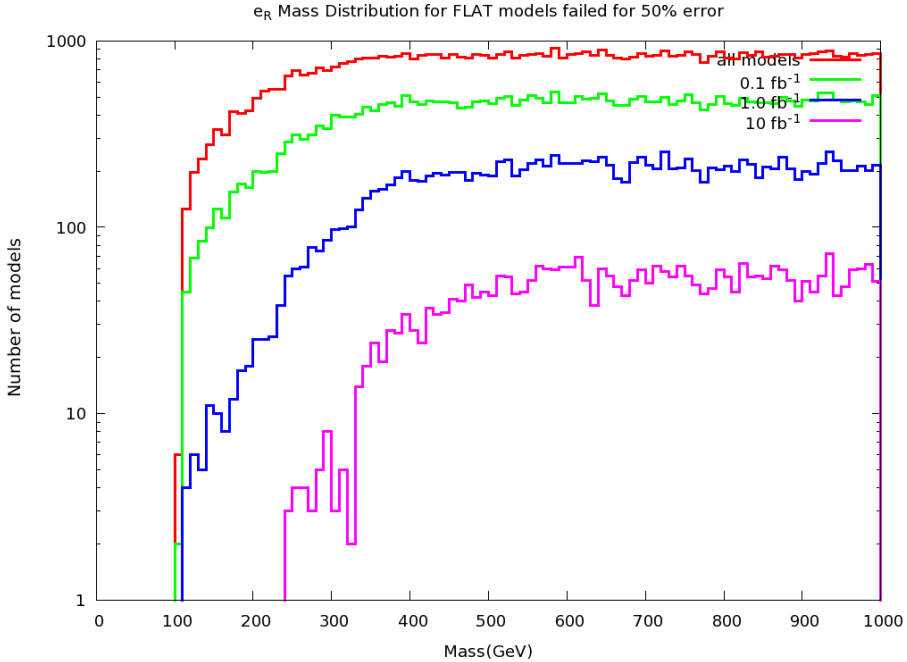

b_1 Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}
Number of models
Mass(GeV)


τ_1 Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}
Number of models
Mass(GeV)


χ_1^o Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}
Number of models
Mass(GeV)


χ_1^+ Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}
Number of models
Mass(GeV)


e_L Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}
Number of models
Mass(GeV)


e_R Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}
Number of models
Mass(GeV)