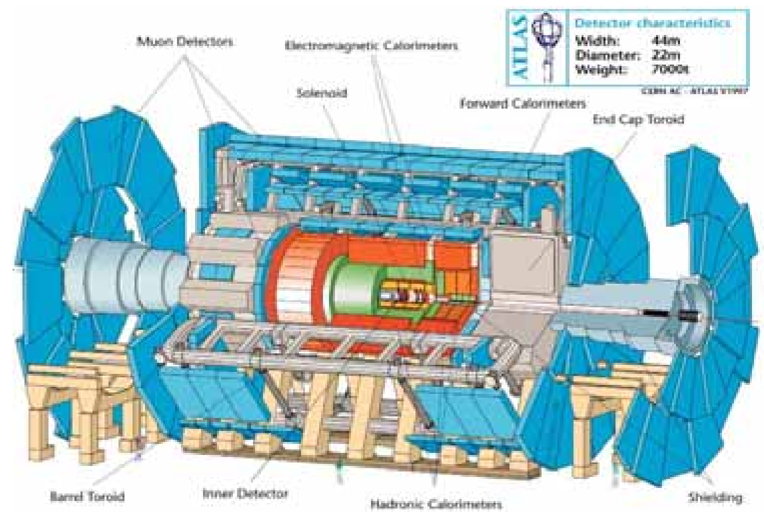
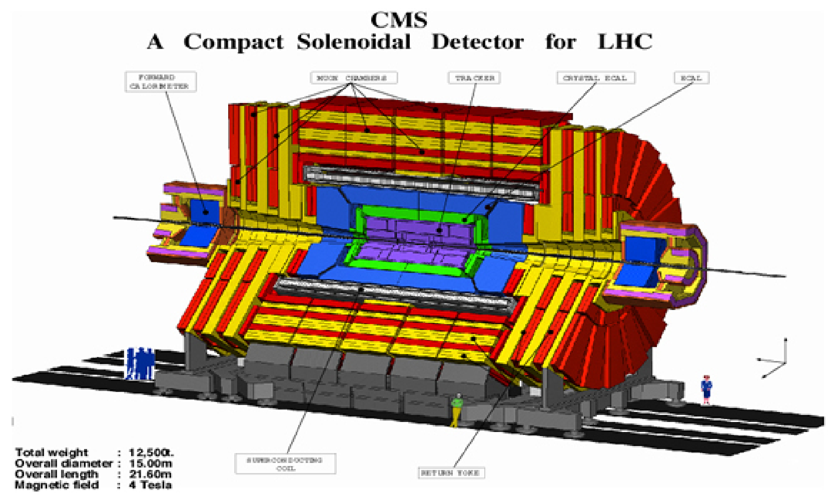
SUSY Without Prejudice at the LHC





SLAC NATIONAL ACCELERATOR LABORATORY

C. F. Berger, J.A. Conley, R.C. Cotta, J. S. Gainer,
J. L. Hewett , M.-P. Le & TGR

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• The MSSM is very difficult to study due to the very large number of soft SUSY breaking parameters (~ 100).

• Analyses generally limited to a specific SUSY scenario(s) such as mSUGRA, GMSB, AMSB,… having few parameters.

• But how well do any or all of these reflect the true breadth of the MSSM?? Do we really know the MSSM as well as we think??

• Is there another way to approach this problem & yet remain *more general*? *Some* set of assumptions are necessary to make any such study practical. But what? There are many possibilities.

FEATURE Analysis Assumptions :

- The most general, CP-conserving MSSM with R-parity
- Minimal Flavor Violation at the TeV scale
- The lightest neutralino is the LSP.
- The first two sfermion generations are degenerate (sfermion type by sfermion type).
- The first two generations have negligible Yukawa's.
- No assumptions about SUSY-breaking or GUT

This leaves us with the pMSSM:

→ the MSSM with 19 real, TeV/weak-scale parameters…

What are they??

19 pMSSM Parameters

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}

gaugino masses: M_1, M_2, M_3

tri-linear couplings: A_b, A_t, A_τ

Higgs/Higgsino: μ, M_A, $\tan\beta$

Note: These are TeV-scale Lagrangian parameters

What are the Goals of this Study???

- Prepare a large sample, ~50k, of MSSM models (= parameter space points) satisfying 'all' of the experimental constraints. A large sample is necessary to get a good feeling for the variety of possibilities. (Done)

- Examine the properties of the models that survive. Do they look like the model points that have been studied up to now? What are the differences? (In progress)

- Do physics analyses with these models for LHC, ILC/CLIC, dark matter, etc. etc. (In progress)

NB :

Our goal is NOT to find the ‘best-fit’ model(s) but, e.g., to discover new SUSY spectra & decay scenarios which are different from those seen in the more familiar SUSY breaking frameworks that can lead to unexpected surprises at colliders and elsewhere.

How? Perform 2 Random Scans

Linear Priors

10^7 points – 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

$2\text{x}10^6$ points – emphasizes lower masses but extends to higher masses

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

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

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

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

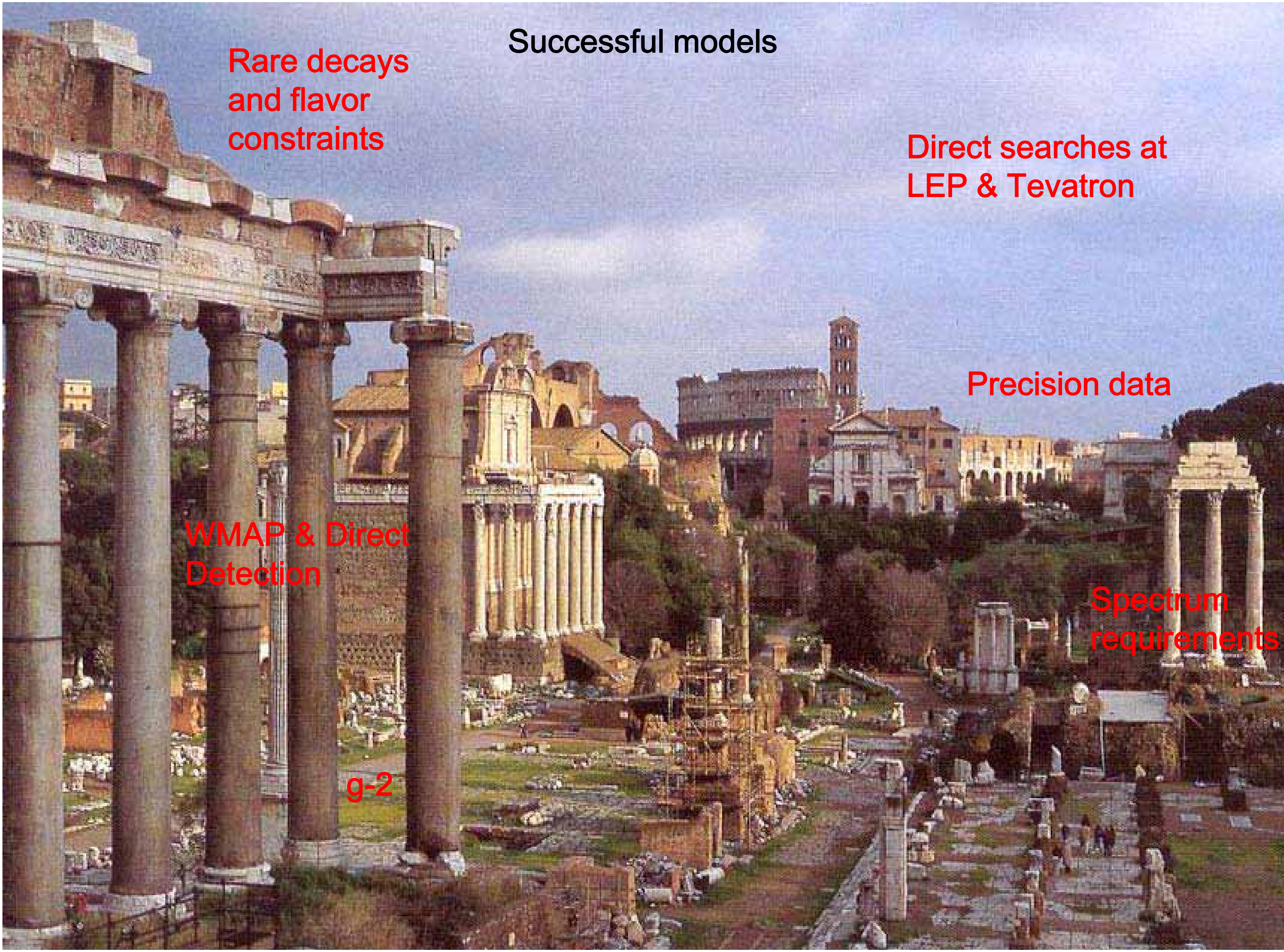
$1 \leq \tan\beta \leq 60$

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

→Comparison of these two scans will show the prior sensitivity.

→This analysis required ~ 1 core-century of CPU time…this was the real limitation of this study.

Successful models



Constraints

- $-0.0007 < \Delta\rho < 0.0026$ [W-mass, etc.] (PDG'08)

- $b \to s\,\gamma$: $B = (2.5 - 4.1) \times 10^{-4}$; (HFAG) + Misiak etal. & Becher & Neubert

- $\Delta(g-2)_\mu$??? $(30.2 \pm 8.8) \times 10^{-10}$ (0809.4062)
  $(29.5 \pm 7.9) \times 10^{-10}$ (0809.3085)
  $[\sim 14.0 \pm 8.4] \times 10^{-10}$ [Davier/BaBar-Tau08]
  $\to (-10 \text{ to } 40) \times 10^{-10}$ to be conservative..

- $\Gamma(Z \to \text{invisible}) < 2.0$ MeV (LEPEWWG)

- Meson-Antimeson Mixing $0.2 < R_{13} < 5$

- $B \to \tau\nu$ $B = (55 \text{ to } 227) \times 10^{-6}$ Isidori & Paradisi, hep-ph/0605012 & Erikson etal., 0808.3551 for loop corrections

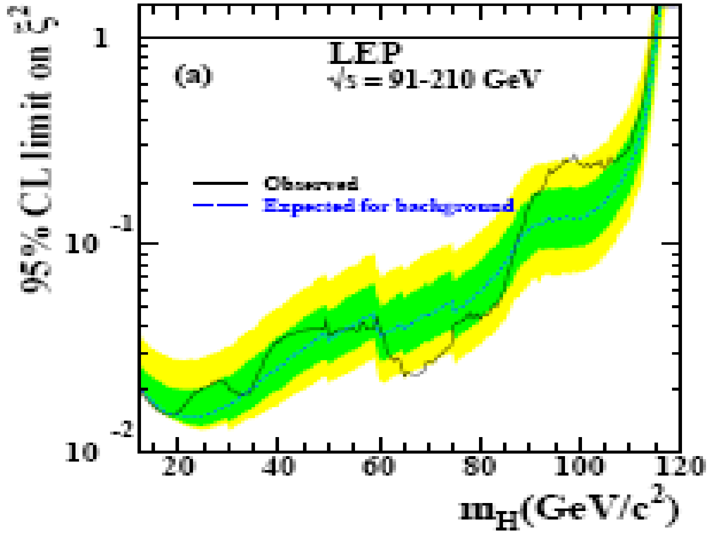
- $B_s \to \mu\mu$ $B < 4.5 \times 10^{-8}$ (CDF + D0)

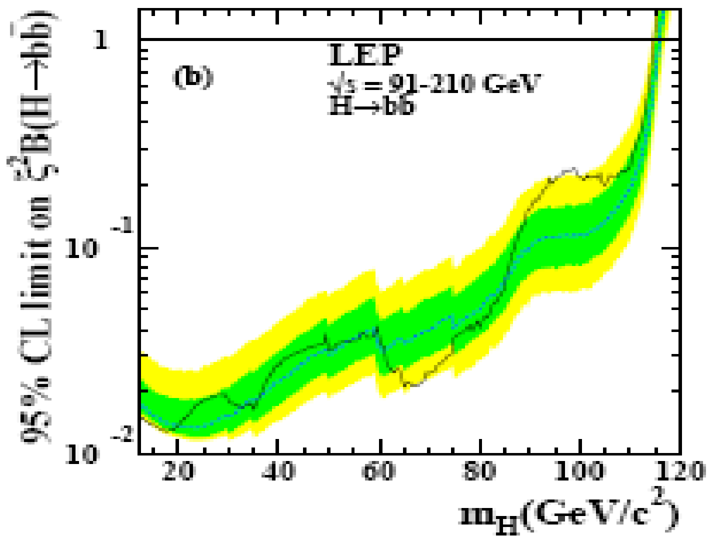
- Direct Detection of Dark Matter → Spin-independent limits are completely dominant here. We allow for a factor of 4 variation in the cross section from input uncertainties.

- Dark Matter density: $\Omega h^2 < 0.1210$ → 5yr WMAP data +…. We treat this only as an *upper bound* on the LSP DM density to allow for multi-component DM, e.g., axions, etc. Recall the lightest neutralino is the LSP & is a thermal relic here

- LEP and Tevatron Direct Higgs & SUSY searches : there are *many* of these searches but they are very complicated with many caveats…. We need to be cautious here in how the constraints are used.

Zh, h-> bb, ττ





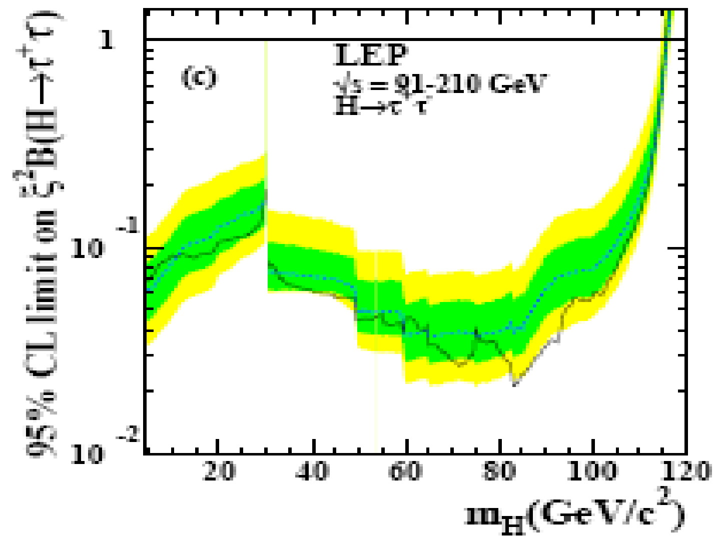


Figure 1: *The 95% c.l. upper bound on the coupling ratio* $\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$ *(see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling. (a): For Higgs boson decays predicted by the Standard Model; (b): for the Higgs boson decaying exclusively into* $b\bar{b}$ *and (c): into* $\tau^+\tau^-$ *pairs.*

LEP II: Associated Higgs Production

$Z \rightarrow hA \rightarrow 4b, 2b2\tau, 4\tau$

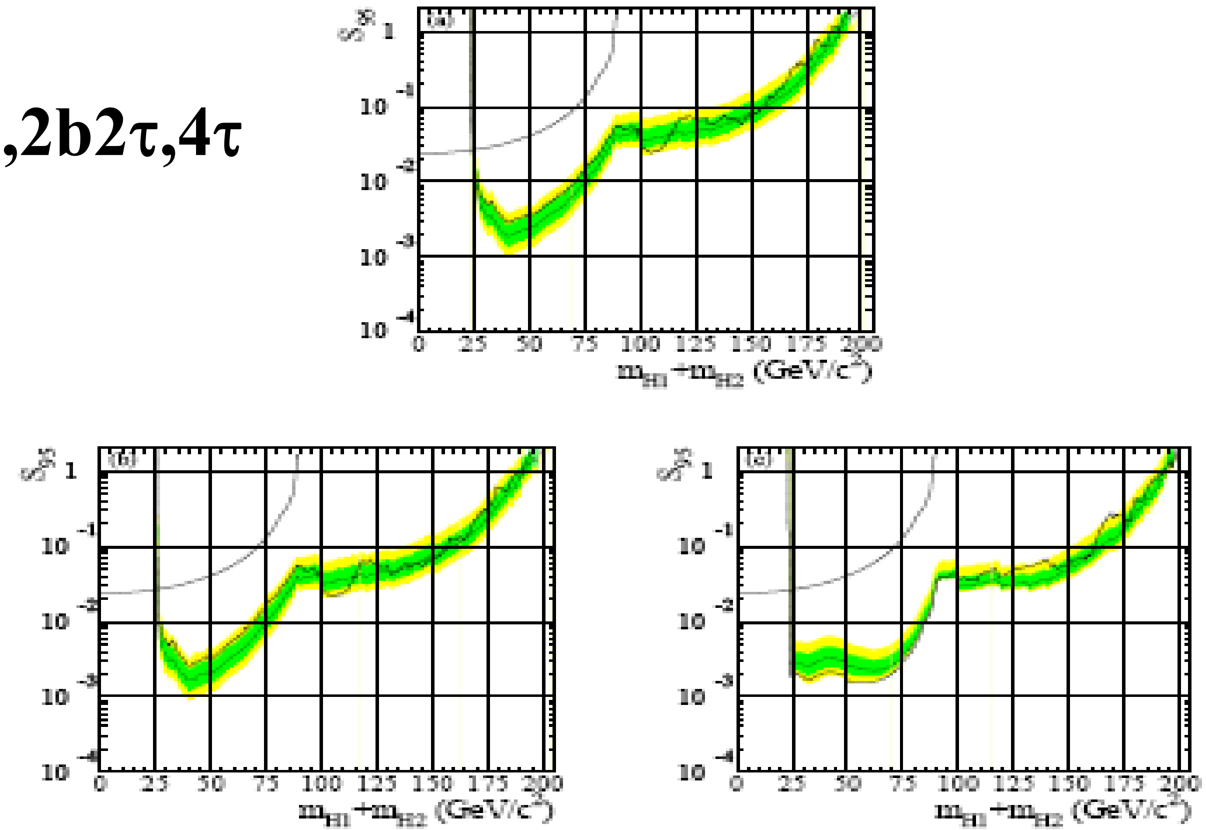
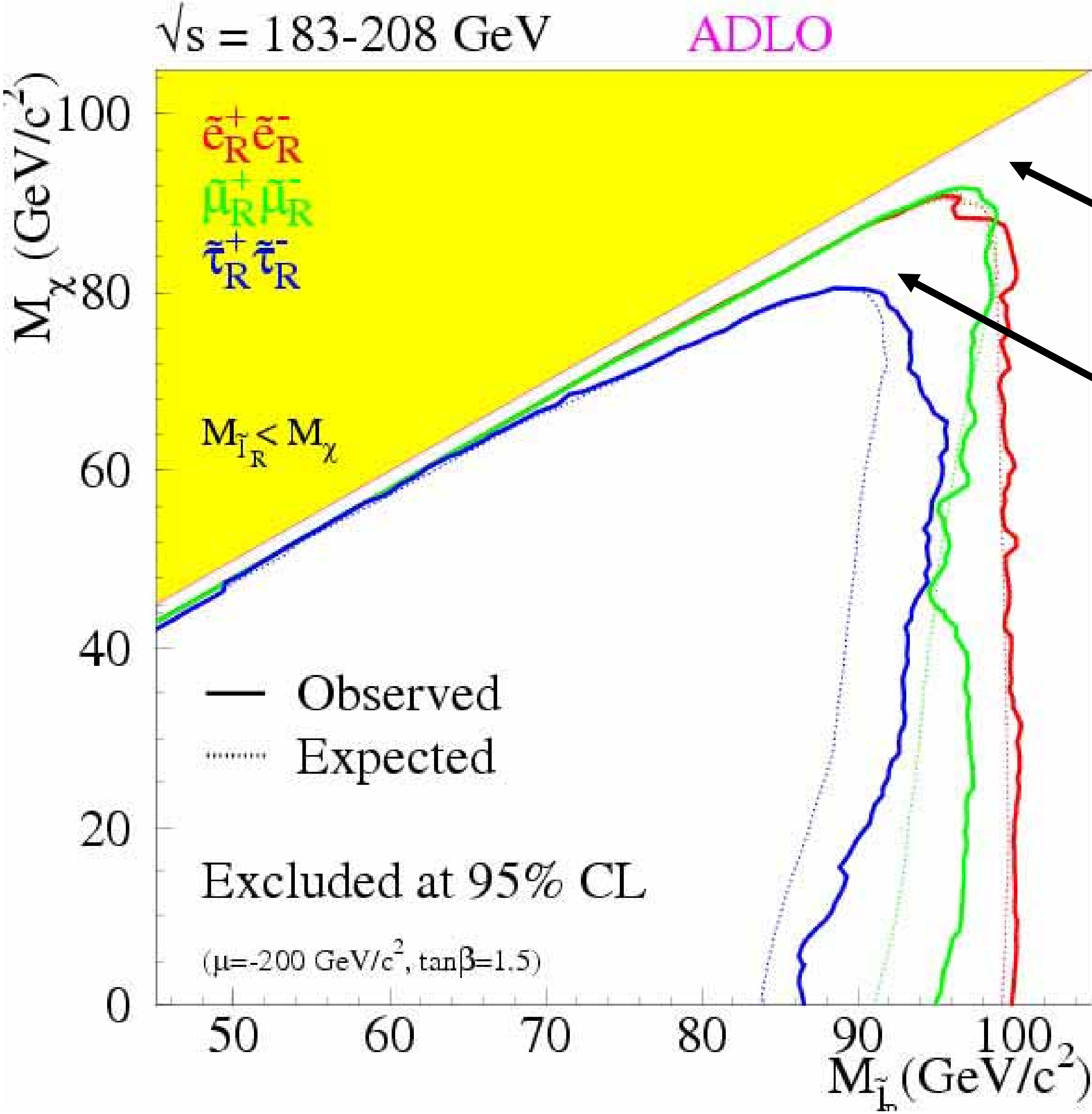


Figure 3: Model-independent 95% c.l. upper bounds, S_{95}, for various topological cross sections motivated by the pair-production process $e^+e^- \rightarrow \mathcal{H}_2\mathcal{H}_1$, for the particular case where $m_{\mathcal{H}_1}$ and $m_{\mathcal{H}_2}$ are approximately equal. Such is the case, for example, in the CP-conserving MSSM scenarios for $\tan\beta$ greater than 10. The abscissa represents the sum of the two Higgs boson masses. The full line represents the observed limit. The dark (green) and light (yellow) shaded bands around the median expectation (dashed line) correspond to the 68% and 95% probability bands. The curves which complete the exclusion at low masses are obtained using the constraint from the measured decay width of the Z boson, see Section 3.2. Upper plot: the Higgs boson decay branching ratios correspond to the m_h-max benchmark scenario with $\tan\beta$=10, namely 94% $\mathcal{H}_1 \rightarrow b\bar{b}$, 6% $\mathcal{H}_1 \rightarrow \tau^+\tau^-$, 92% $\mathcal{H}_2 \rightarrow b\bar{b}$ and 8% $\mathcal{H}_2 \rightarrow \tau^+\tau^-$; lower left: both Higgs bosons are assumed to decay exclusively to $b\bar{b}$; lower right: the Higgs bosons are assumed to decay, one into $b\bar{b}$ only and the other one into $\tau^+\tau^-$ only. For the case where both Higgs bosons decay to $\tau^+\tau^-$, the corresponding upper bound can be found in Ref. [31], Figure 15.

RH Sleptons



Note the holes where the leptons are too soft…

We need to allow for a mass gap w/ the LSP & also in the squark case when soft jets are possible..light guys may slip through

Tevatron Constraints : I   Squark & Gluino Search

- This is the first SUSY analysis to include these constraints

- 2,3,4 Jets + Missing Energy (D0)

TABLE I: Selection criteria for the three analyses (all energies and momenta in GeV); see the text for further details.

Preselection Cut	All Analyses		
$\not{E}_T$	≥ 40		
|Vertex z pos.|	< 60 cm		
Acoplanarity	$< 165°$		
Selection Cut	**"dijet"**	**"3-jets"**	**"gluino"**
Trigger	dijet	multijet	multijet
jet$_1$ p_T[a]	≥ 35	≥ 35	≥ 35
jet$_2$ p_T[a]	≥ 35	≥ 35	≥ 35
jet$_3$ p_T[b]	–	≥ 35	≥ 35
jet$_4$ p_T[b]	–	–	≥ 20
Electron veto	yes	yes	yes
Muon veto	yes	yes	yes
$\Delta\phi(\not{E}_T, \text{jet}_1)$	$\geq 90°$	$\geq 90°$	$\geq 90°$
$\Delta\phi(\not{E}_T, \text{jet}_2)$	$\geq 50°$	$\geq 50°$	$\geq 50°$
$\Delta\phi_{\min}(\not{E}_T, \text{any jet})$	$\geq 40°$	–	–
H_T	≥ 325	≥ 375	≥ 400
$\not{E}_T$	≥ 225	≥ 175	≥ 100

[a]First and second jets are also required to be central ($|\eta_{\text{det}}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.

[b]Third and fourth jets are required to have $|\eta_{\text{det}}| < 2.5$, with an electromagnetic fraction below 0.95.

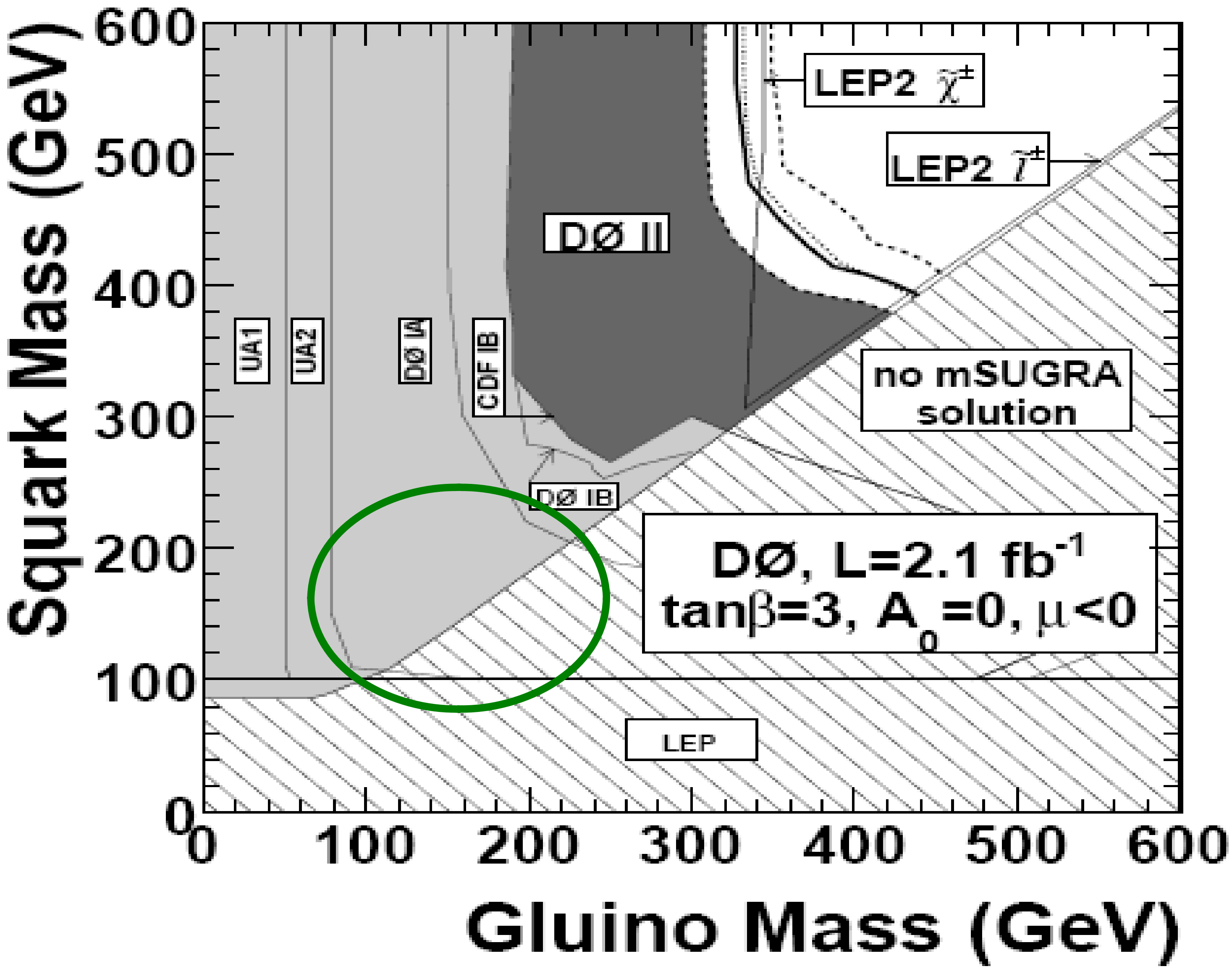
Multiple analyses keyed to look for:

Squarks-> jet +MET

Gluinos -> 2 j + MET

The search is based on mSUGRA type sparticle spectrum assumptions which can be VERY far from our model points

This D0 search provides strong constraints in mSUGRA.. squarks & gluinos > 330-400 GeV…our limits can be *much weaker* on both these sparticles as we'll see !!



D0 benchmarks

TABLE II: For each analysis, information on the signal for which it was optimized (m_0, $m_{1/2}$, $m_{\tilde{g}}$, $m_{\tilde{q}}$, and nominal NLO cross section), signal efficiency, the number of events observed, the number of events expected from SM backgrounds, the number of events expected from signal, and the 95% C.L. signal cross section upper limit. The first uncertainty is statistical and the second is systematic.

Analysis	$(m_0, m_{1/2})$ (GeV)	$(m_{\tilde{g}}, m_{\tilde{q}})$ (GeV)	σ_{nom} (pb)	$\epsilon_{sig.}$ (%)	$N_{obs.}$	$N_{backgrd.}$	$N_{sig.}$	σ_{95} (pb)
"dijet"	(25,175)	(439,396)	0.072	$6.8 \pm 0.4^{+1.2}_{-1.2}$	11	$11.1 \pm 1.2^{+2.9}_{-2.3}$	$10.4 \pm 0.6^{+1.8}_{-1.8}$	0.075
"3-jets"	(197,154)	(400,400)	0.083	$6.8 \pm 0.4^{+1.4}_{-1.3}$	9	$10.7 \pm 0.9^{+3.1}_{-2.1}$	$12.0 \pm 0.7^{+2.5}_{-2.3}$	0.065
"gluino"	(500,110)	(320,551)	0.195	$4.1 \pm 0.3^{+0.8}_{-0.7}$	20	$17.7 \pm 1.1^{+5.5}_{-3.3}$	$17.0 \pm 1.2^{+3.3}_{-2.9}$	0.165

TABLE III: Definition of the analysis combinations, and number of events observed in the data and expected from the SM backgrounds.

Selection	"dijet"	"3-jets"	"gluino"	$N_{obs.}$	$N_{backgrd.}$
Combination 1	yes	no	no	8	9.4 ± 1.2 (stat.) $^{+2.3}_{-1.8}$ (syst.)
Combination 2	no	yes	no	2	4.5 ± 0.6 (stat.) $^{+0.7}_{-0.5}$ (syst.)
Combination 3	no	no	yes	14	12.5 ± 0.9 (stat.) $^{+3.6}_{-1.9}$ (syst.)
Combination 4	yes	yes	no	1	1.1 ± 0.3 (stat.) $^{+0.5}_{-0.3}$ (syst.)
Combination 5	yes	no	yes		kinematically not allowed
Combination 6	no	yes	yes	4	4.5 ± 0.6 (stat.) $^{+1.8}_{-1.3}$ (syst.)
Combination 7	yes	yes	yes	2	0.6 ± 0.2 (stat.) $^{+0.1}_{-0.2}$ (syst.)
At least one selection				31	32.6 ± 1.7 (stat.) $^{+9.0}_{-5.8}$ (syst.)

Combos of the 3 analyses

→ Feldman-Cousins 95% CL Signal limit: 8.34 events

SuSpect -> SUSY-Hit -> PROSPINO -> PYTHIA -> D0-tuned PGS4 fast simulation (to reproduce the benchmark points)…

redo this analysis ~ 10^5 times !

Tevatron II: CDF Tri-lepton Analysis

CDF RUN II Preliminary $\int \mathcal{L}dt = 2.0\ \text{fb}^{-1}$: Search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$

Channel	Signal	Background	Observed
3tight	$2.25 \pm 0.13(\text{stat}) \pm 0.29(\text{syst})$	$0.49 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})$	1
2tight,1loose	$1.61 \pm 0.11(\text{stat}) \pm 0.21(\text{syst})$	$0.25 \pm 0.03(\text{stat}) \pm 0.03(\text{syst})$	0
1tight,2loose	$0.68 \pm 0.07(\text{stat}) \pm 0.09(\text{syst})$	$0.14 \pm 0.02(\text{stat}) \pm 0.02(\text{syst})$	0
Total Trilepton	$4.5 \pm 0.2(\text{stat}) \pm 0.6(\text{syst})$	$0.88 \pm 0.05(\text{stat}) \pm 0.13(\text{syst})$	1
2tight,1Track	$4.44 \pm 0.19(\text{stat}) \pm 0.58(\text{syst})$	$3.22 \pm 0.48(\text{stat}) \pm 0.53(\text{syst})$	4
1tight,1loose,1Track	$2.42 \pm 0.14(\text{stat}) \pm 0.32(\text{syst})$	$2.28 \pm 0.47(\text{stat}) \pm 0.42(\text{syst})$	2
Total Dilepton+Track	$6.9 \pm 0.2(\text{stat}) \pm 0.9(\text{syst})$	$5.5 \pm 0.7(\text{stat}) \pm 0.9(\text{syst})$	6

Table 3: Number of expected signal and background events and number of observed events in 2 fb^{-1}. Uncertainties are statistical(stat) and full systematics(syst). The signal is for the benchmark point described in section 5.

We need to perform the 3 tight lepton analysis ~ 10^5 times

We perform this analysis using CDF-tuned PGS4, PYTHIA in LO plus a PROSPINO K-factor

→ Feldman-Cousins 95% CL Signal limit: 4.65 events

- This is the first SUSY analysis to include these constraints

The non-'3-tight' analyses are not reproducible w/o a better detector simulation

Tevatron III: D0 Stable Particle (= Chargino) Search

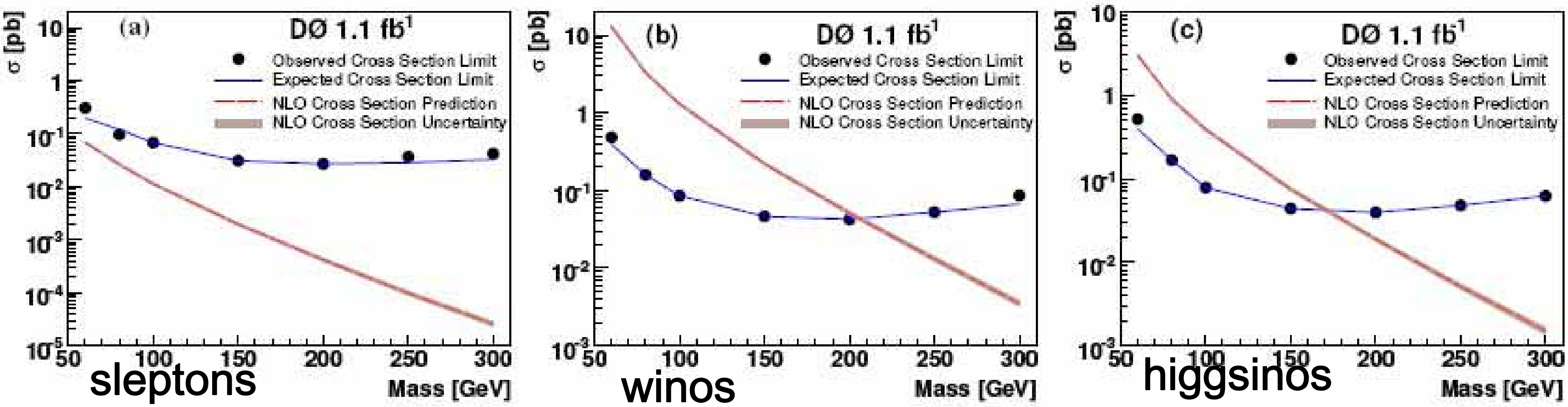


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos, and (c) chargino mass for pair produced higgsino-like charginos.

Interpolation: $M_\chi > 206\,|U_{1w}|^2 + 171\,|U_{1h}|^2$ GeV

This is an *incredibly* powerful constraint on our model set as we will have many close mass chargino-neutralino pairs. This search cuts out a huge parameter region as you will see later.

- No applicable bounds on charged sleptons..the cross sections are too small.

- This is the first SUSY analysis to include these constraints

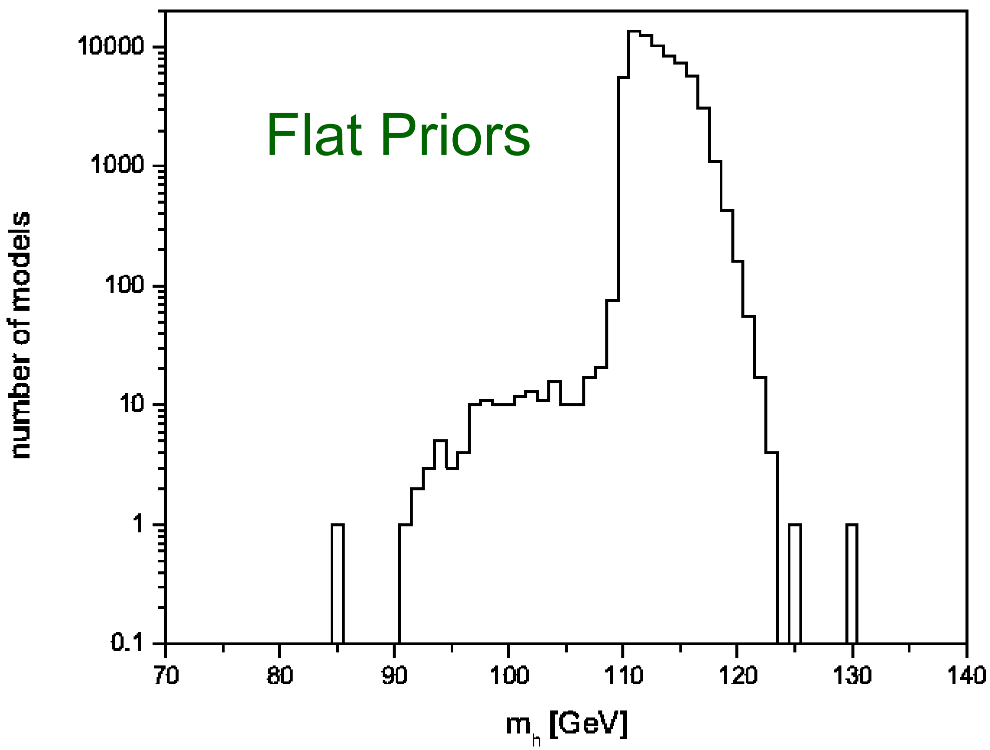
Survival Rates

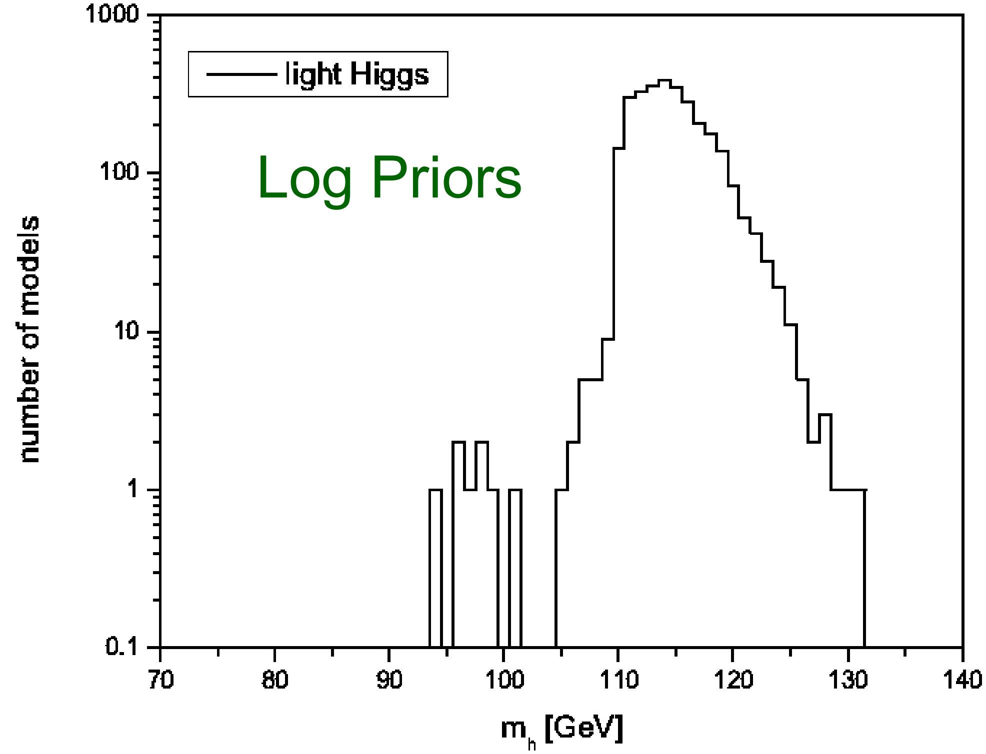
file	Description	Percent of Models Remaining
slha-okay.txt	SuSpect generates SLHA file	99.99 %
error-okay.txt	Spectrum tachyon, other error free	77.29%
lsp-okay.txt	LSP the lightest neutralino	32.70 %
deltaRho-okay.txt	$\Delta\rho$	32.61 %
gMinus2-okay.txt	$g-2$	21.69 %
b2sGamma-okay.txt	$b \longrightarrow s\gamma$	6.17 %
Bs2MuMu-okay.txt	$B \longrightarrow \mu\mu$	5.95 %
vacuum-okay.txt	No CCB, potential not UFB	5.92 %
Bu2TauNu-okay.txt	$B \longrightarrow \tau\nu$	5.83 %
LEP-sparticle-okay.txt	LEP sfermion checks	4.72 %
invisibleWidth-okay.txt	Invisible Width of Z	4.71 %
susyhitProb-okay.txt	Heavy Higgs not problematic for SUSY-HIT	4.69 %
stableParticle-okay.txt	Tevatron stable chargino search	4.19 %
chargedHiggs-okay.txt	LEP/ Tevatron charged Higgs search	4.19 %
neutralHiggs-okay.txt	LEP neutral Higgs search	1.73 %
directDetection-okay.txt	WIMP direct detection	1.55 %
omega-okay.txt	Ωh^2	0.74 %
Bs2MuMu-2-okay.txt	$B \longrightarrow \mu\mu$	0.74 %
stableChargino-2-okay.txt	Tevatron stable chargino search	0.72 %
triLepton-okay.txt	Tevatron trilepton	0.72 %
jetMissing-okay.txt	Tevatron jet plus missing	0.70 %
final-okay.txt	Final after cutting models with e.g. light stop, sbottoms	0.68 %

- Flat Priors : 10^7 models scanned , ~ 68.4 K (0.68%) survive

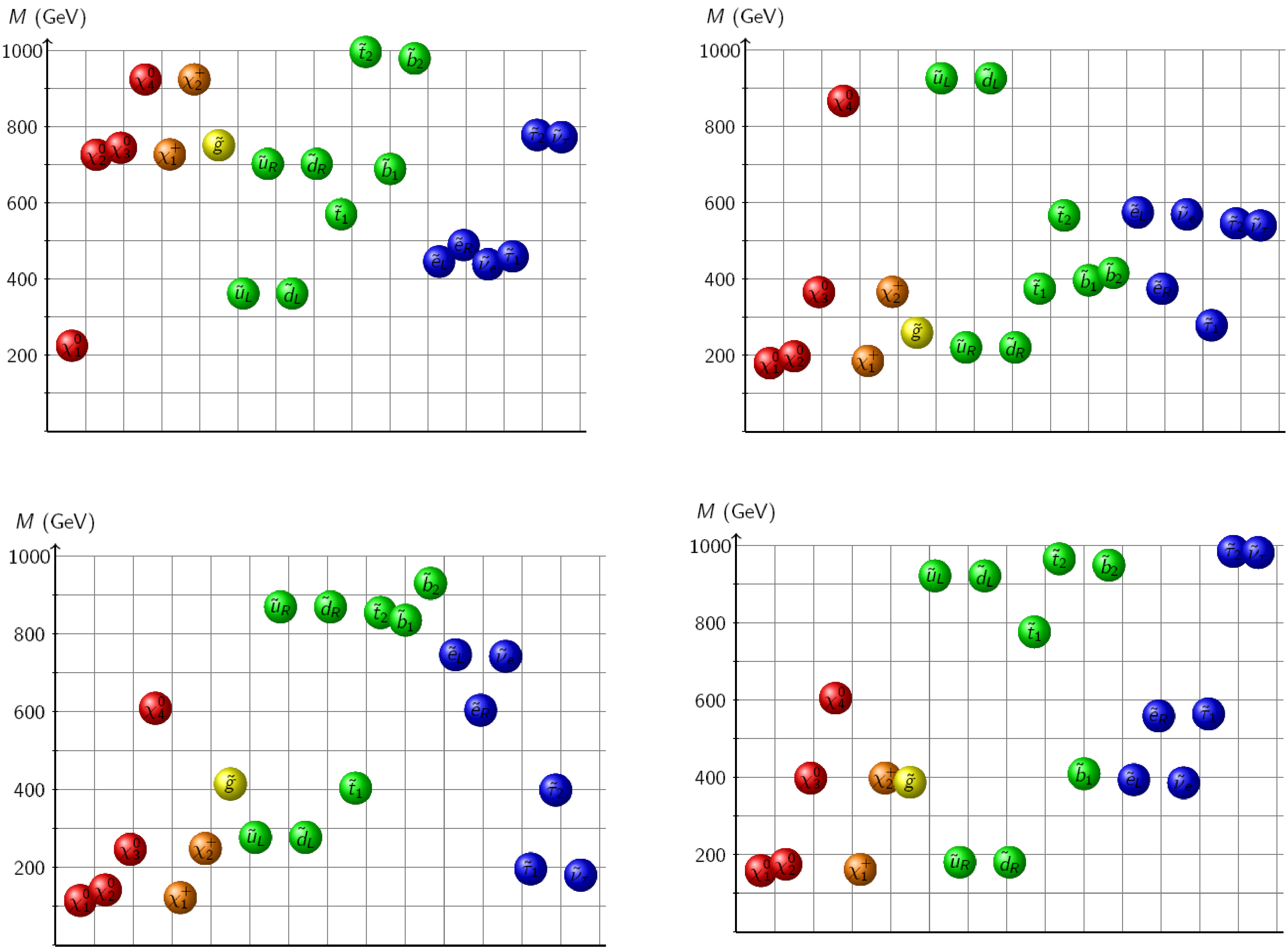
- Log Priors : 2×10^6 models scanned , ~ 2.8 K (0.14%) survive

Light Higgs Mass Predictions





LEP Higgs mass constraints avoided by either reducing the ZZh coupling and/or reducing the, e.g., $h \to b\bar{b}$ branching fraction by decays to LSP pairs. We have both of these cases in our final model sets.


M (GeV)
1000
800
600
400
200
M (GeV)
1000
800
600
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M (GeV)
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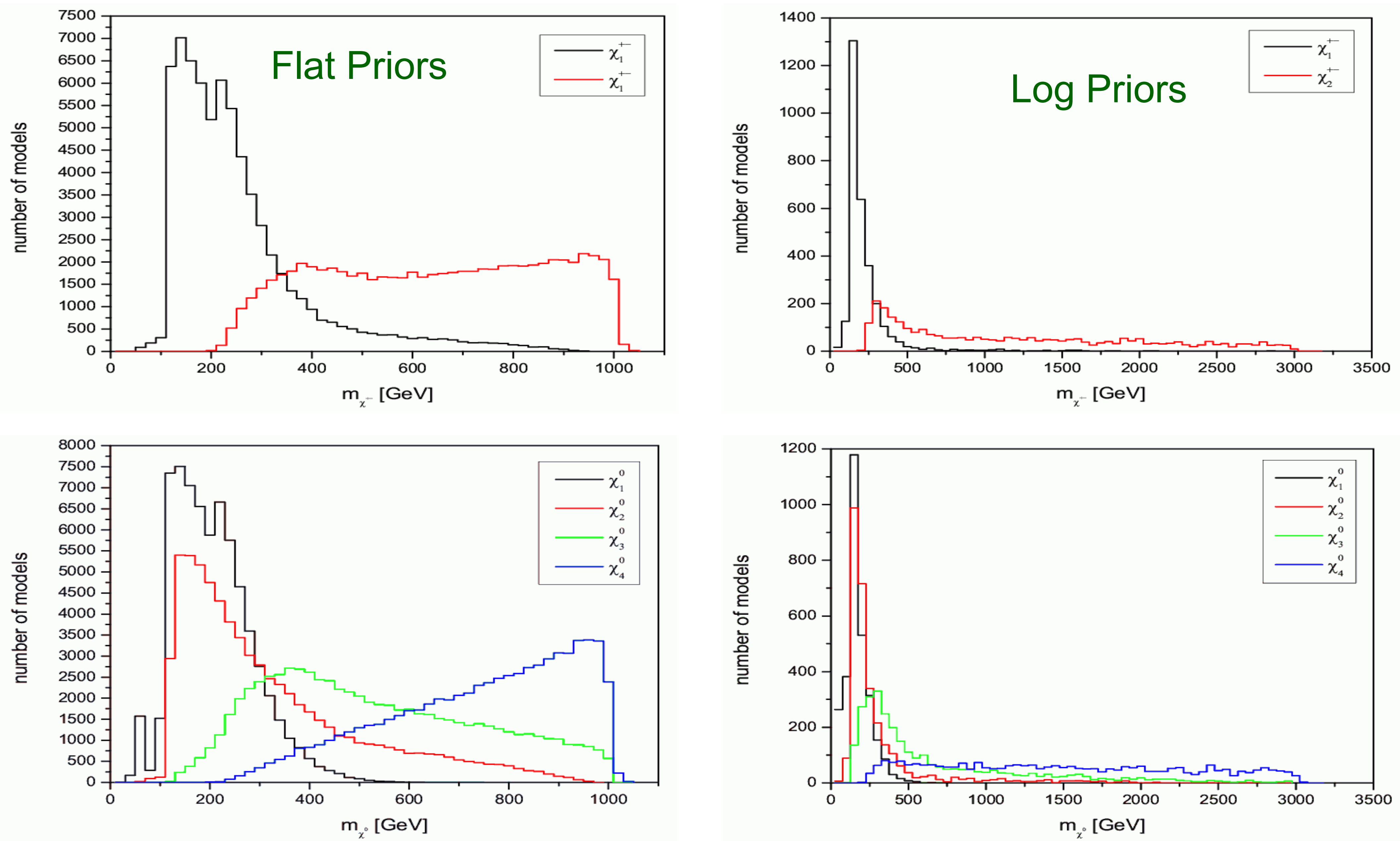
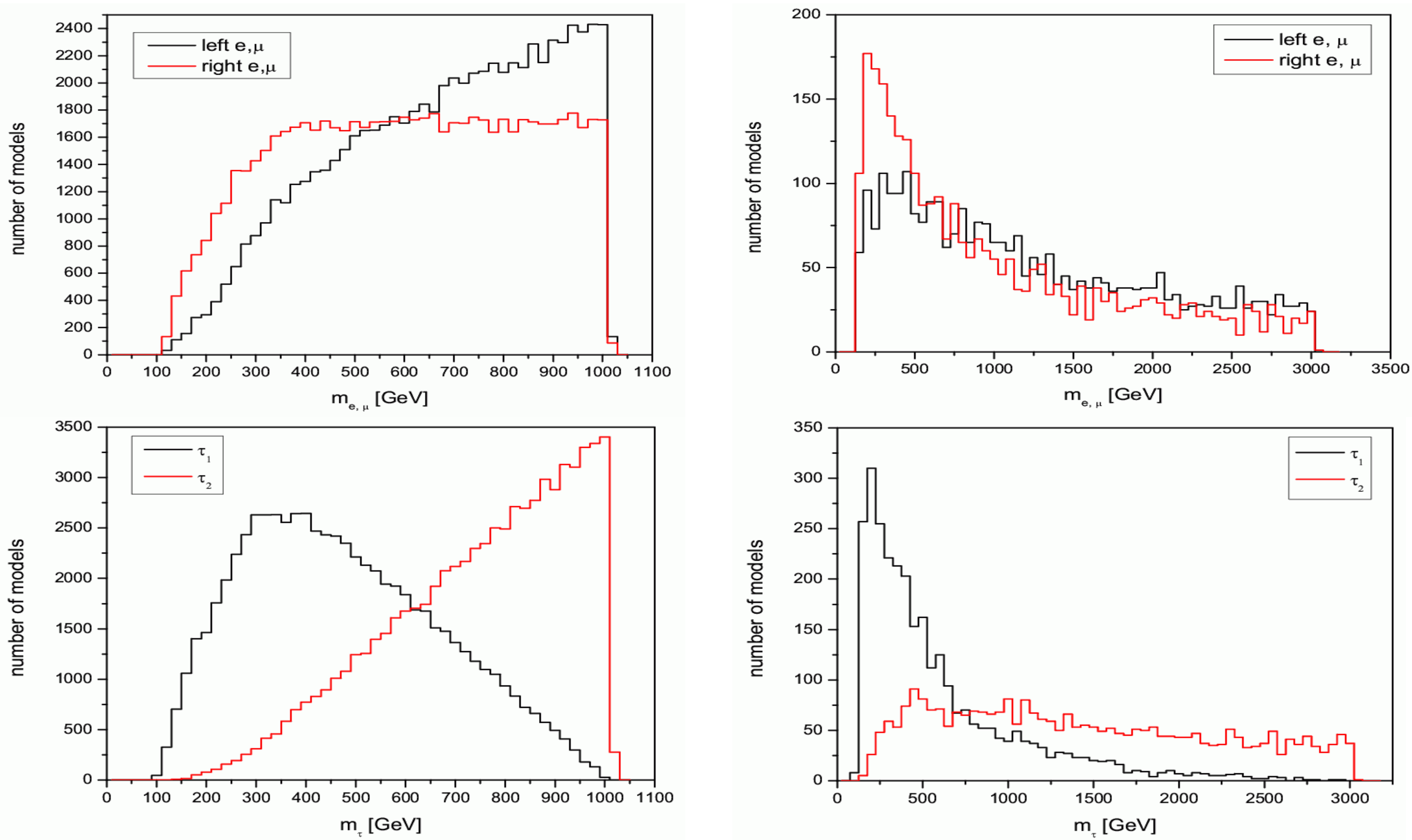
800
600
400
200
M (GeV)
1000
800
600
400
200

Distribution of Sparticle Masses By Species

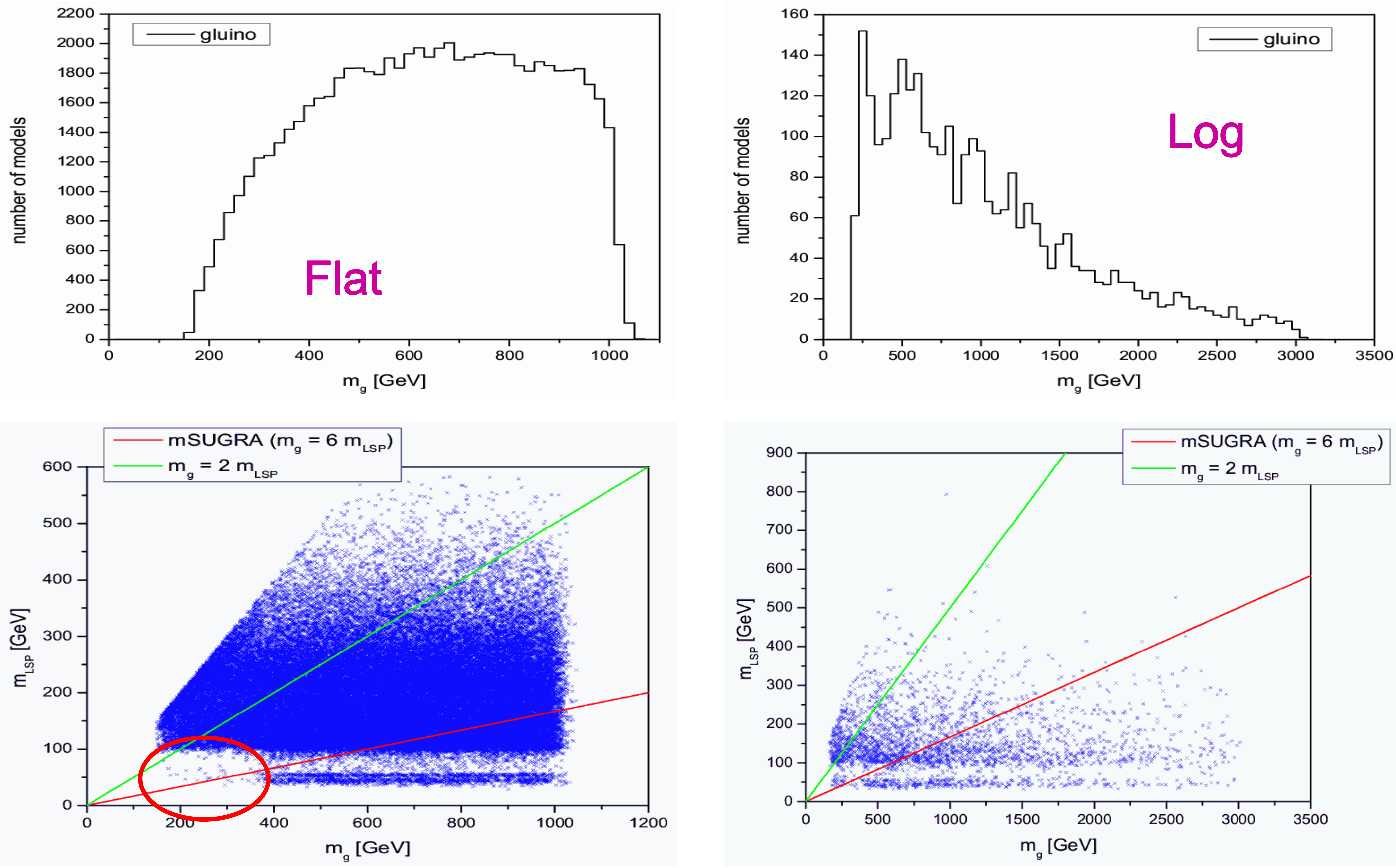


Distribution of Sparticle Masses By Species

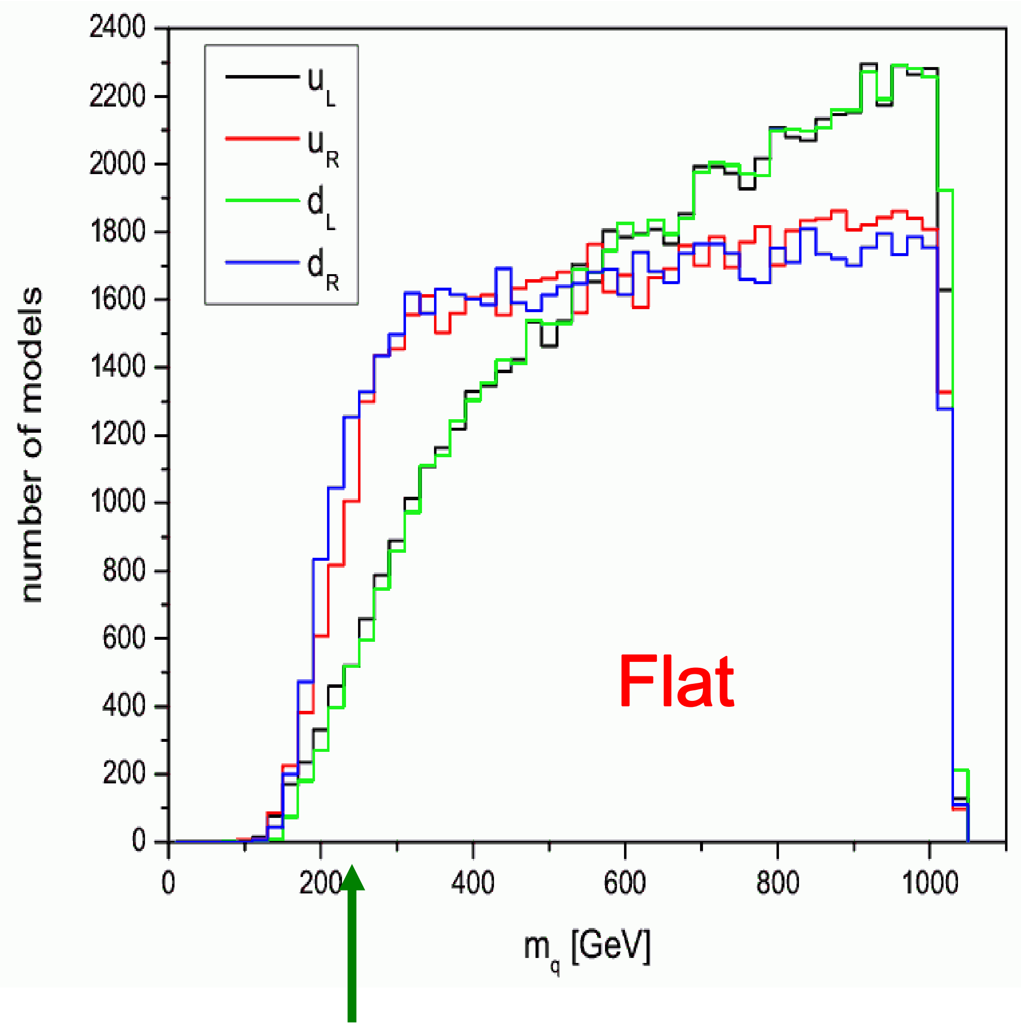
Flat Priors | Log Priors

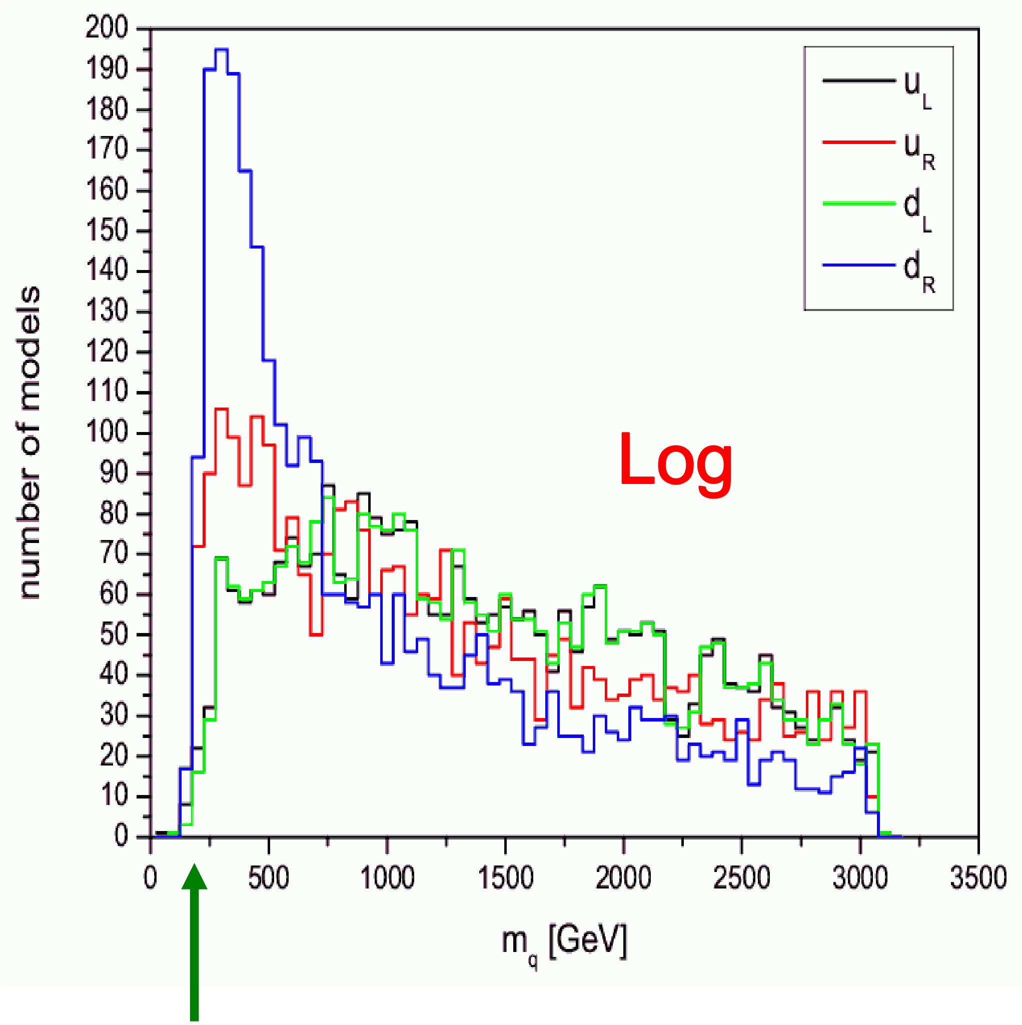


Gluino Can Be Light !!



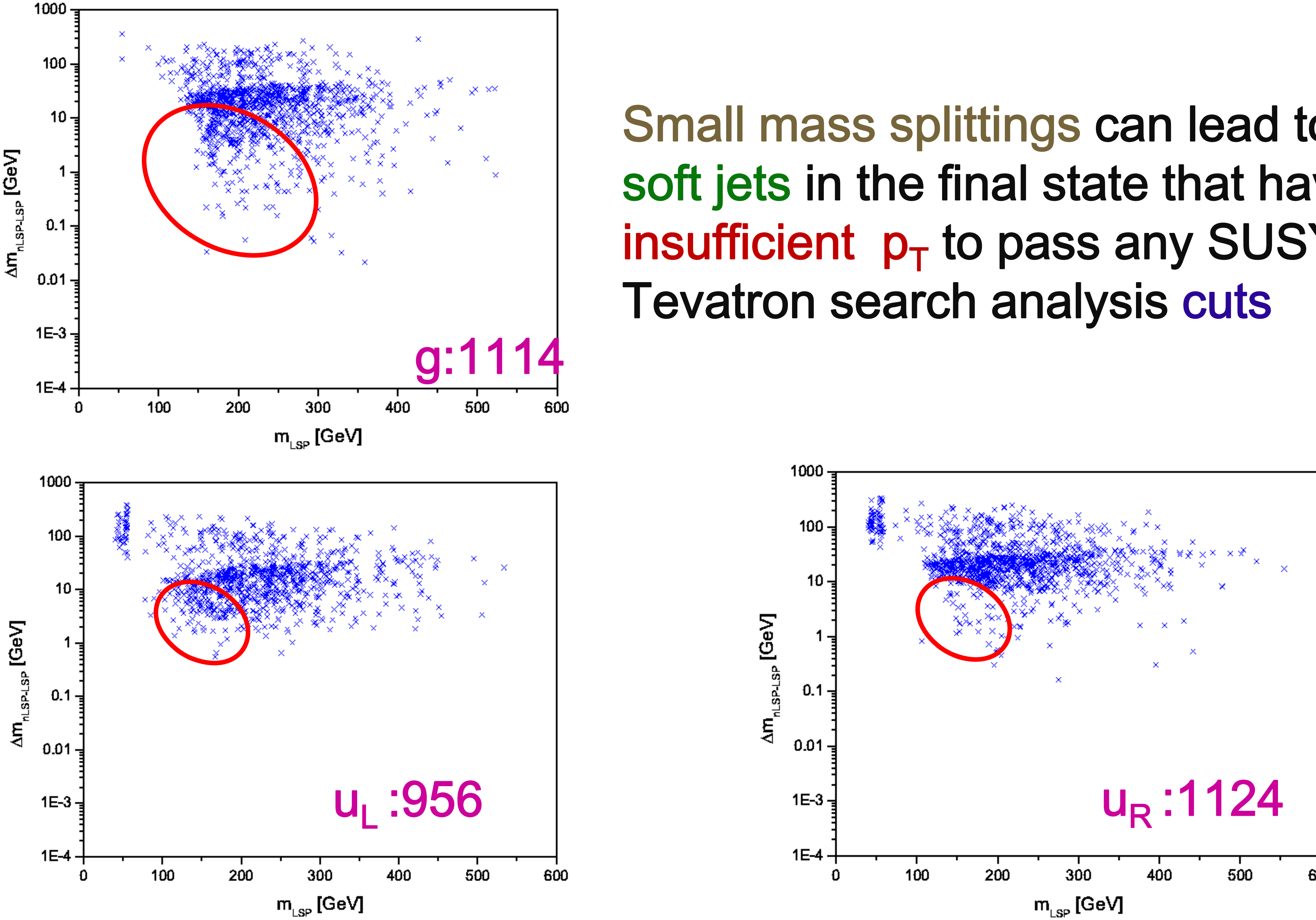
Squarks CAN Be Light !!!





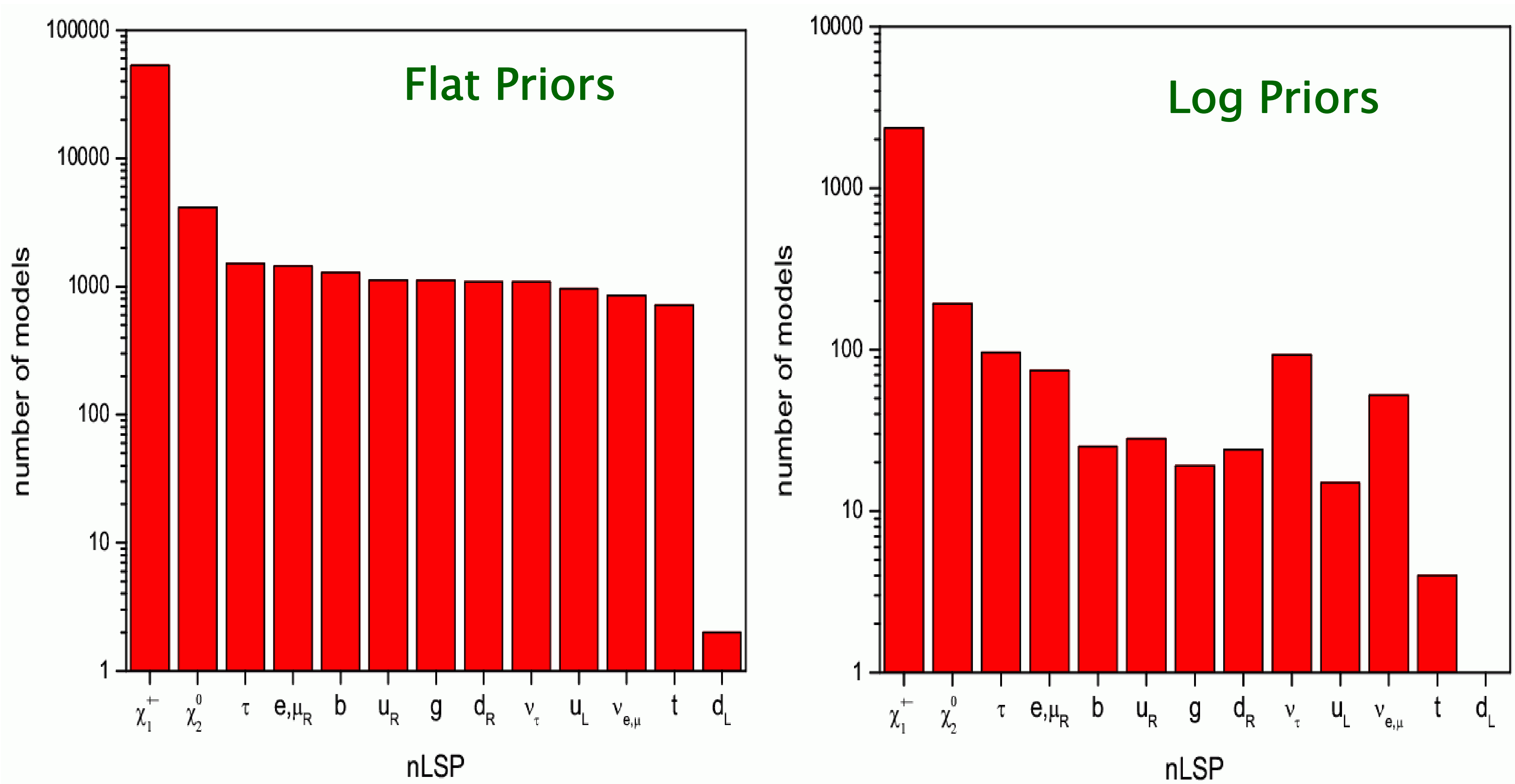
Light squarks can be missed by Tevatron searches for numerous reasons..

In many cases, but not exclusively, this is due to the small splittings between the squarks and/or gluinos and the LSP…

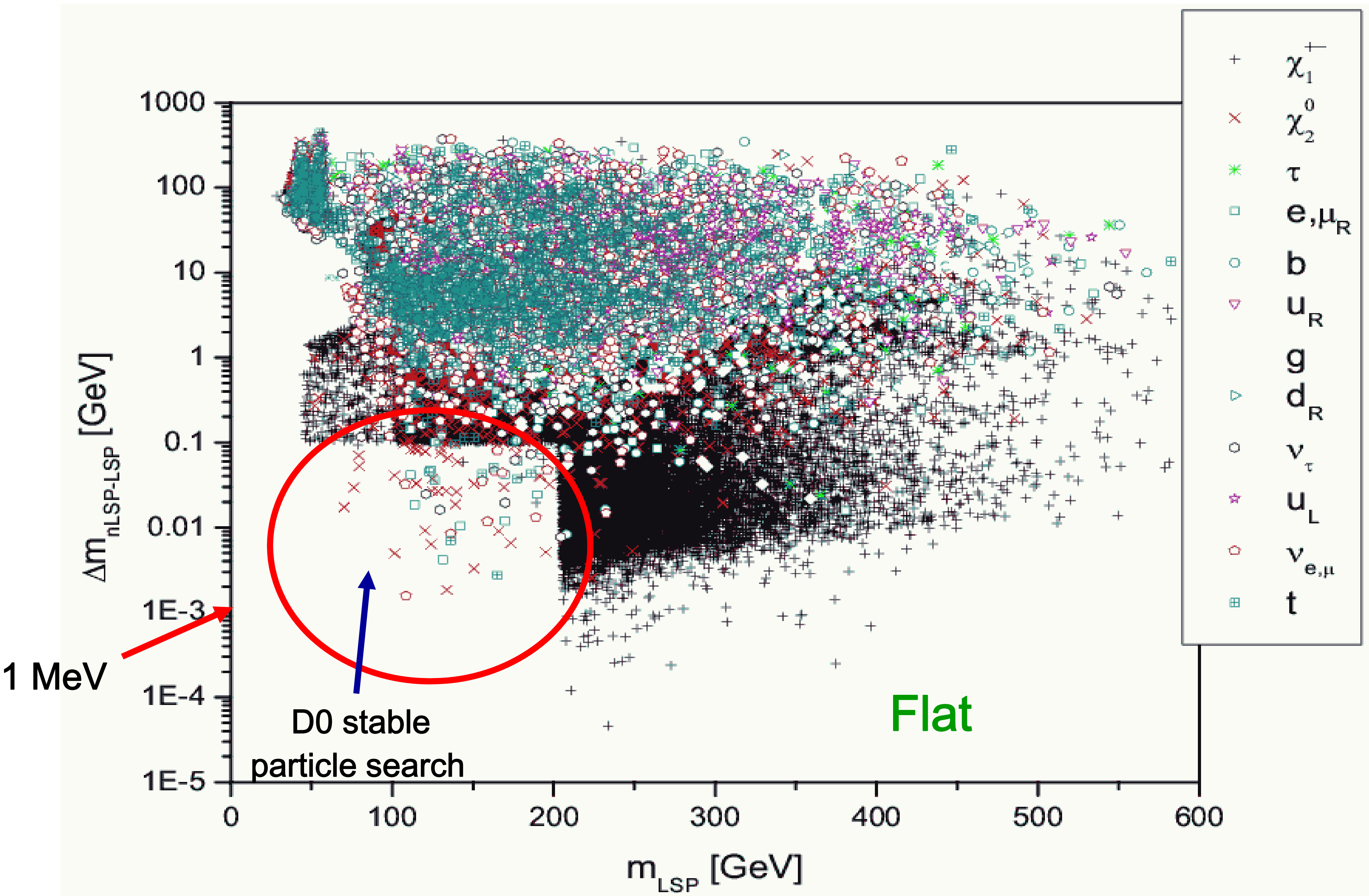


Small mass splittings can lead to soft jets in the final state that have insufficient p_T to pass any SUSY Tevatron search analysis cuts

The identity of the nLSP is a critical factor in looking for SUSY signatures..who can play that role here????? Just about ANY of the 13 possibilities !



nLSP-LSP Mass Difference

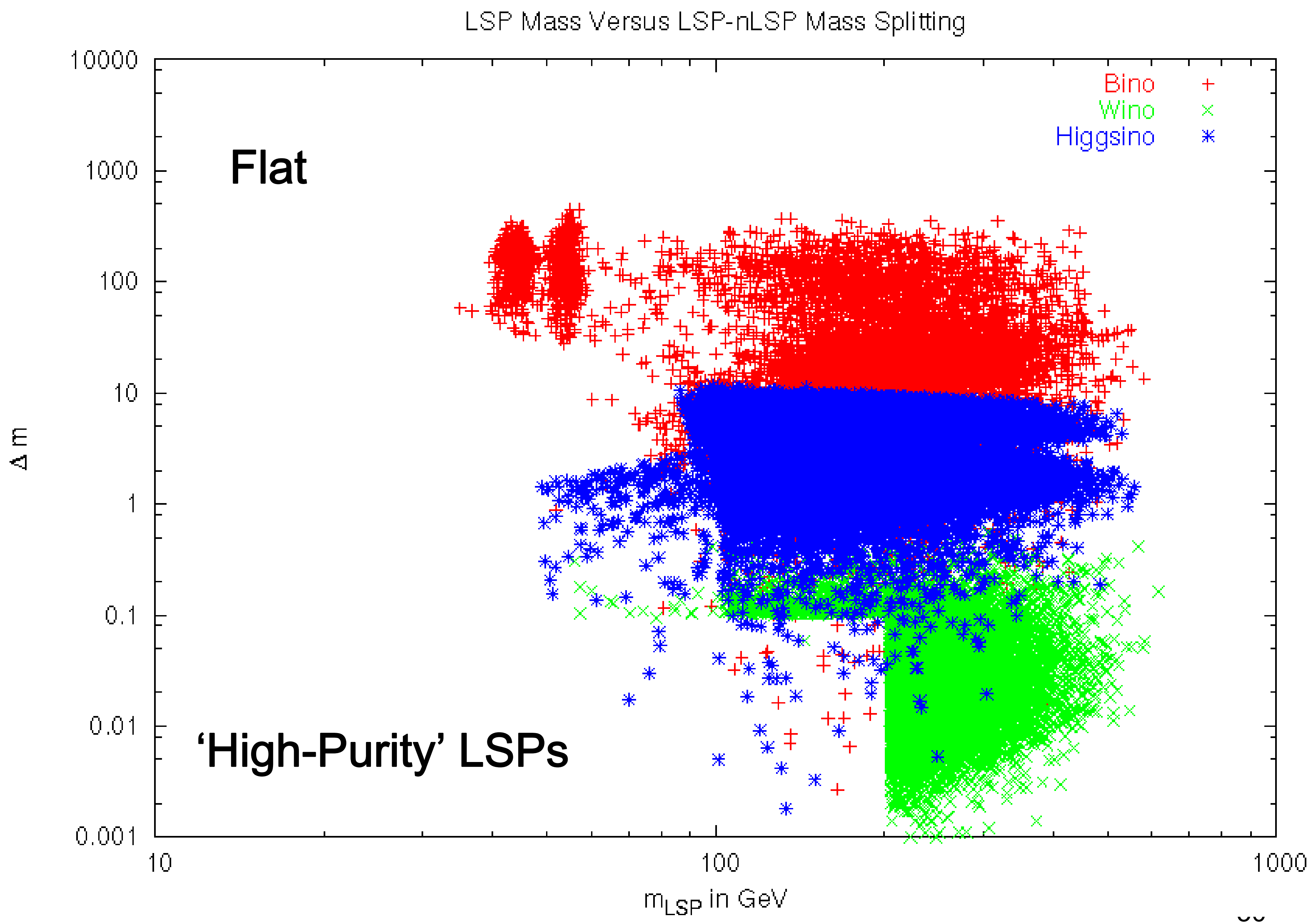


LSP Identity

Many models have LSPs which are close to the weak interaction eigenstates

..e.g., for the flat case:

LSP Type	Definition	Percent of Models
Bino	$\|Z_{11}\|^2 > 0.95$	13.94
Mostly Bino	$0.8 < \|Z_{11}\|^2 \le 0.95$	3.10
Wino	$\|Z_{12}\|^2 > 0.95$	14.16
Mostly Wino	$0.8 < \|Z_{12}\|^2 \le 0.95$	9.14
Higgsino	$\|Z_{13}\|^2 + \|Z_{14}\|^2 > 0.95$	32.19
Mostly Higgsino	$0.8 < \|Z_{13}\|^2 + \|Z_{14}\|^2 \le 0.95$	12.38
All other models		15.09


LSP Mass Versus LSP-nLSP Mass Splitting
Flat
'High-Purity' LSPs
Bino
Wino
Higgsino
Δ m
m_{LSP} in GeV
10000
1000
100
10
1
0.1
0.01
0.001
10
100
1000

Flat

Log

Linear Priors		Log Priors	
Mass Pattern	% of Models	Mass Pattern	% of Models
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\chi_3^0$	9.82	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\chi_3^0$	18.59
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\ell_R$	5.39	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\nu_\tau$	7.72
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\tau_1$	5.31	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\ell_R$	6.67
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\nu_\tau$	5.02	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\tau_1$	6.64
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde b_1$	4.89	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde d_R$	5.18
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde d_R$	4.49	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\nu_\ell$	4.50
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde u_R$	3.82	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde b_1$	3.76
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde g$	2.96	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde g$	3.73
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde\nu_\ell$	2.67	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde u_R$	2.74
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde u_L$	2.35	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\nu_\tau < \tilde\tau_1$	2.27
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\nu_\tau < \tilde\tau_1$	2.19	$\tilde\chi_1^0 < \tilde\chi_2^0 < \tilde\chi_1^\pm < \tilde\chi_3^0$	2.24
$\tilde\chi_1^0 < \tilde\chi_2^0 < \tilde\chi_1^\pm < \tilde\chi_3^0$	2.15	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\ell_R < \tilde\chi_2^0$	1.42
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < A$	2.00	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde u_L$	1.32
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < \tilde t_1$	1.40	$\tilde\chi_1^0 < \tilde\tau_1 < \tilde\chi_1^\pm < \tilde\chi_2^0$	1.22
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\nu_\ell < \tilde\ell_L$	1.37	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\tau_1 < \tilde\chi_2^0$	1.19
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\tau_1 < \tilde\chi_2^0$	1.35	$\tilde\chi_1^0 < \tilde\chi_2^0 < \tilde\chi_1^\pm < \tilde\nu_\tau$	1.15
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\ell_R < \tilde\chi_2^0$	1.32	$\tilde\chi_1^0 < \tilde\ell_R < \tilde\chi_1^\pm < \tilde\chi_2^0$	1.05
$A < H < H^\pm < \tilde\chi_1^0$	1.24	$\tilde\chi_1^0 < \tilde\nu_\tau < \tilde\tau_1 < \tilde\chi_1^\pm$	1.02
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde d_R < \tilde\chi_2^0$	1.03	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\nu_\ell < \tilde\ell_L$	0.95
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde u_L < \tilde d_L$	0.95	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde d_R < \tilde\chi_2^0$	0.71
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde b_1 < \tilde\chi_2^0$	0.89	$\tilde\chi_1^0 < \tilde\nu_\tau < \tilde\chi_1^\pm < \tilde\chi_2^0$	0.68
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde u_R < \tilde\chi_2^0$	0.84	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\chi_2^0 < A$	0.64
$\tilde\chi_1^0 < \tilde\chi_1^\pm < A < H$	0.74	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\nu_\tau < \tilde\chi_2^0$	0.61
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde g < \tilde\chi_2^0$	0.65	$\tilde\chi_1^0 < \tilde\chi_2^0 < \tilde\chi_1^\pm < \tilde d_R$	0.54
$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\tau_1 < \tilde\nu_\tau$	0.51	$\tilde\chi_1^0 < \tilde\chi_1^\pm < \tilde\tau_1 < \tilde\nu_\tau$	0.54

SUSY decay chains are very important…especially the end of the chain at the LHC.

Top 25 most common mass patterns for the 4 lightest SUSY & heavy Higgs particles.

There were 1109 (267) such patterns found for the case of flat (log) priors

Only ~20 are found to occur in mSUGRA!!

Long Lived/Stable Sparticles in the 71k Sample with $c\tau > 450\ \mu m$

- 17407 models with at least 1 long-lived/stable state
- 353 have 2 long-lived states (e.g., 25 w/ chargino + gluino!)
- 12 have 3 of them!

- 16061 are charginos
- 555 are second neutralinos
- 339 are sbottoms
- 179 are staus
- 100 are stops
- 79 are gluinos
- 49 are c_R
- 18 are μ_R
- 11 are 2^{nd} charginos
- 8 are c_L

etc.

Particles with $c\tau > 20m$ will be declared 'detector stable' in our analysis

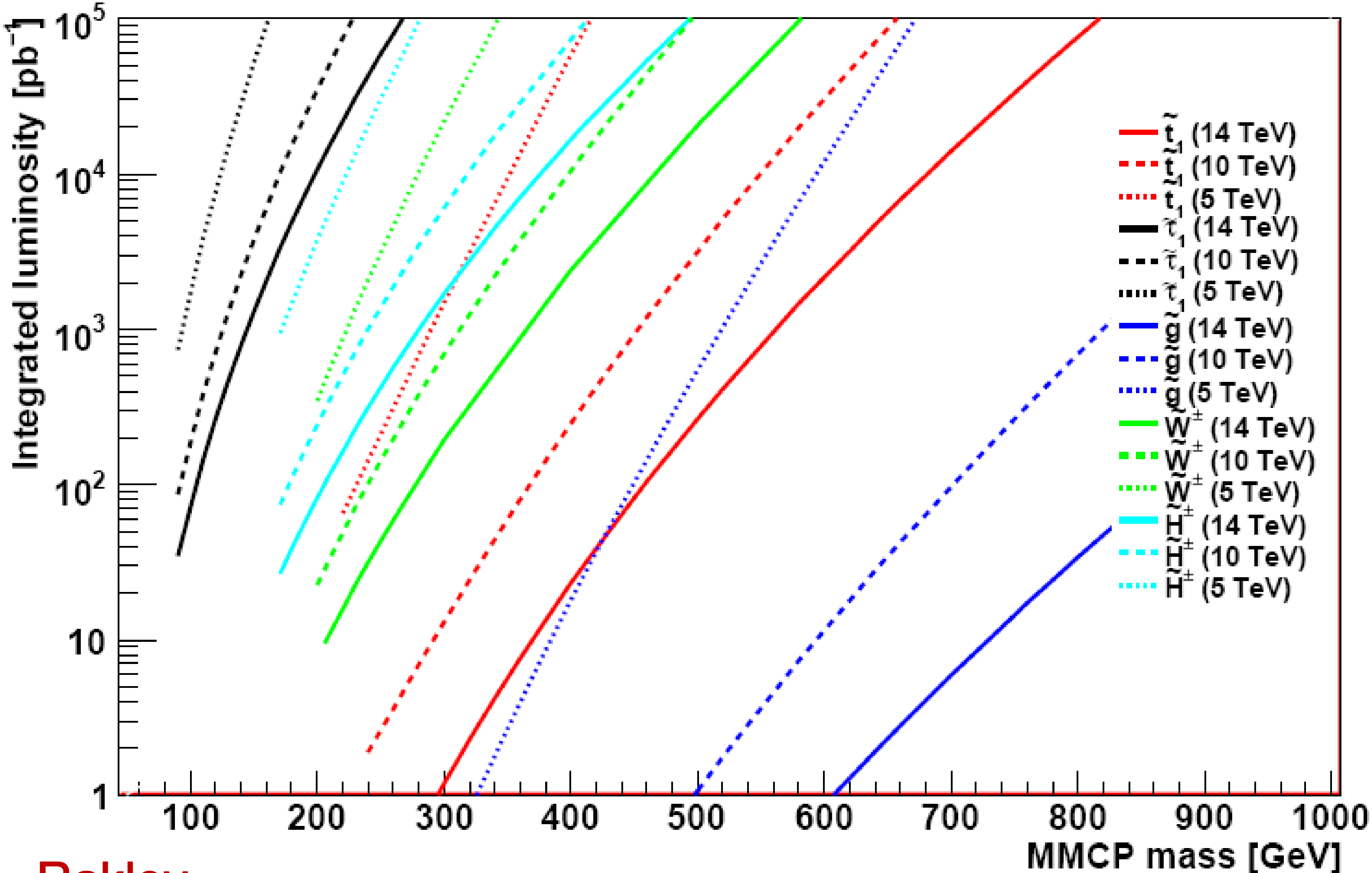
Semi-Stable Sparticles in the 71k Sample with 1 μm < $c\tau$ < 450 μm

- 1551 models with at least 1 semi-stable state
- 154 have 2 of them

- 1437 are charginos
- 213 are second neutralinos
- 33 are stops
- 22 are gluinos

Particles decaying inside the detector will require some special analyses to study but likely not influence traditional SUSY searches since their decay products are very soft.

Stable SUSY Searches at LHC



A. Raklev

ATLAS SUSY Analyses w/ a Large Model Set

- We are running our ~71k MSSM models through the ATLAS SUSY (10&14 TeV) analysis suite, essentially designed for mSUGRA , to explore its sensitivity to this far broader class of SUSY models employing the ATLAS background estimates

- We first need to verify that we can approximately reproduce the ATLAS results for their benchmark mSUGRA models with our analysis techniques for each channel. (Done)

- One finds MANY problems w/ our models not encountered in vanilla mSUGRA …not to mention SDECAY/PYTHIA issues!

- By necessity there are some differences between the two analyses as we will soon see….

- This is extremely CPU intensive , e.g., 6M K-factors to compute

ATLAS has already made use of some of these models!

ATLAS NOTE

ATL-PUB-2009-XXX

July 20, 2009

Prospects for Supersymmetry and Univeral Extra Dimensions discovery based on inclusive searches at a 10 TeV centre-of-mass energy with the ATLAS detector

The ATLAS collaboration

Abstract

This note presents an evaluation of the discovery potential of Supersymmetry and Universal Extra Dimensions for channels with jets, leptons and missing transverse energy. The LHC running scenario at a centre-of-mass energy of 10 TeV, delivering an integrated luminosity of 200 pb^{-1} for the 2009-2010 run is investigated.

ATLAS	FEATURE
ISASUGRA generates spectrum & sparticle decays	SuSpect generates spectra with SUSY-HIT# for decays
Partial NLO cross section using PROSPINO & CTEQ6M	NLO cross section for ~85 processes using PROSPINO** & CTEQ6.6M
Herwig for fragmentation & hadronization	PYTHIA for fragmentation & hadronization
GEANT4 for full detector sim	PGS4-ATLAS for fast detector sim

** version w/ negative K-factor errors corrected

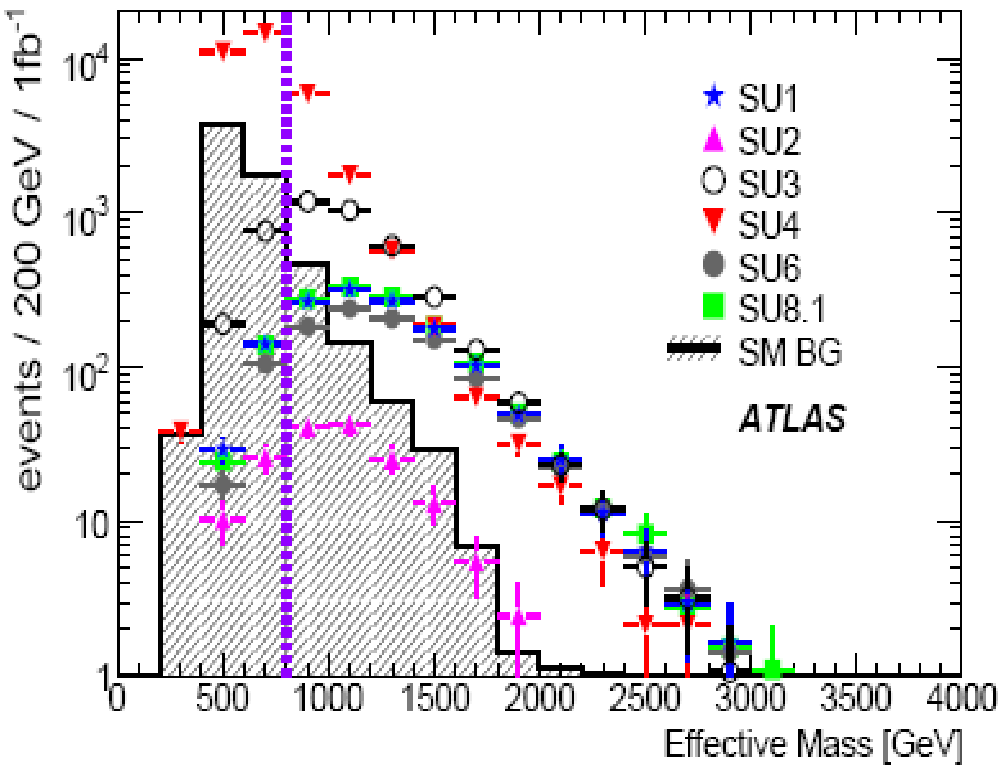
version w/o negative QCD corrections & with 1st & 2nd generation fermion masses included as well as explicit small Δm chargino decays

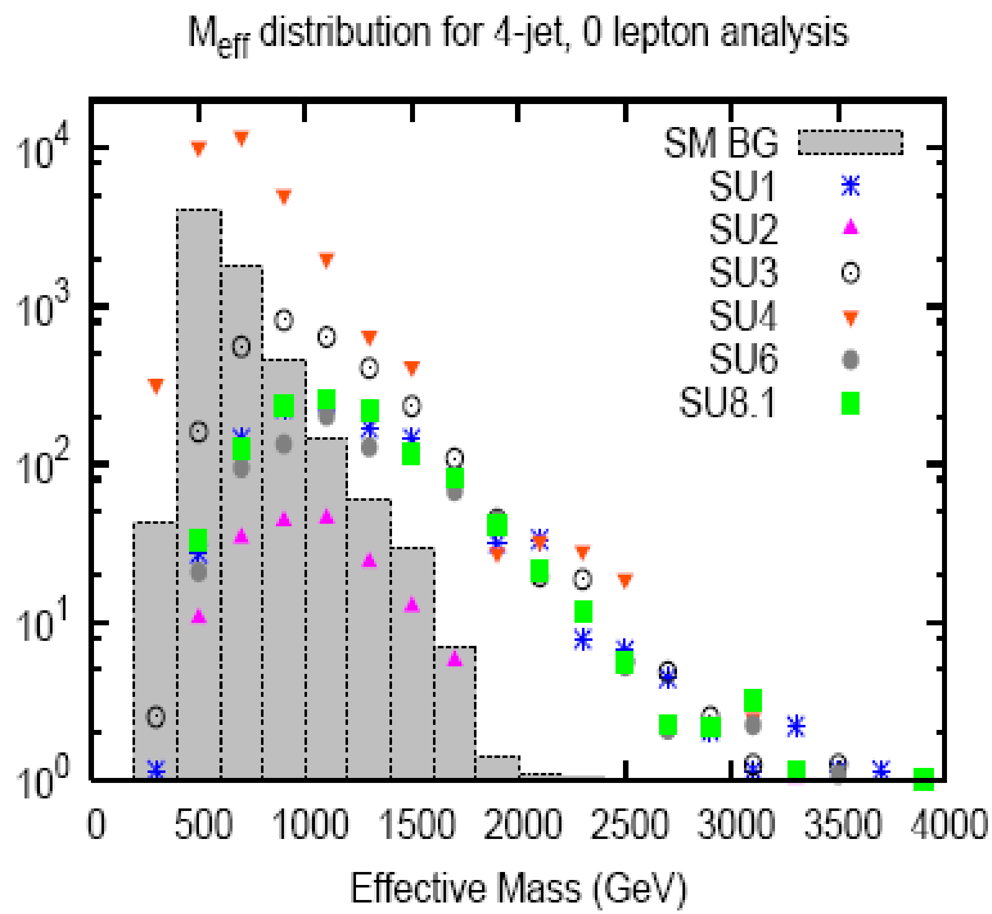
The set of ATLAS SUSY analyses is large:

- 2,3,4-jet +MET
- 1–l, ≥4-jet +MET
- SSDL
- OSDL
- Trileptons + (0,1)-j +MET
- etc.

- τ +≥ 4j +MET
- ≥4j w/ ≥ 2btags + MET
- Stable particle search

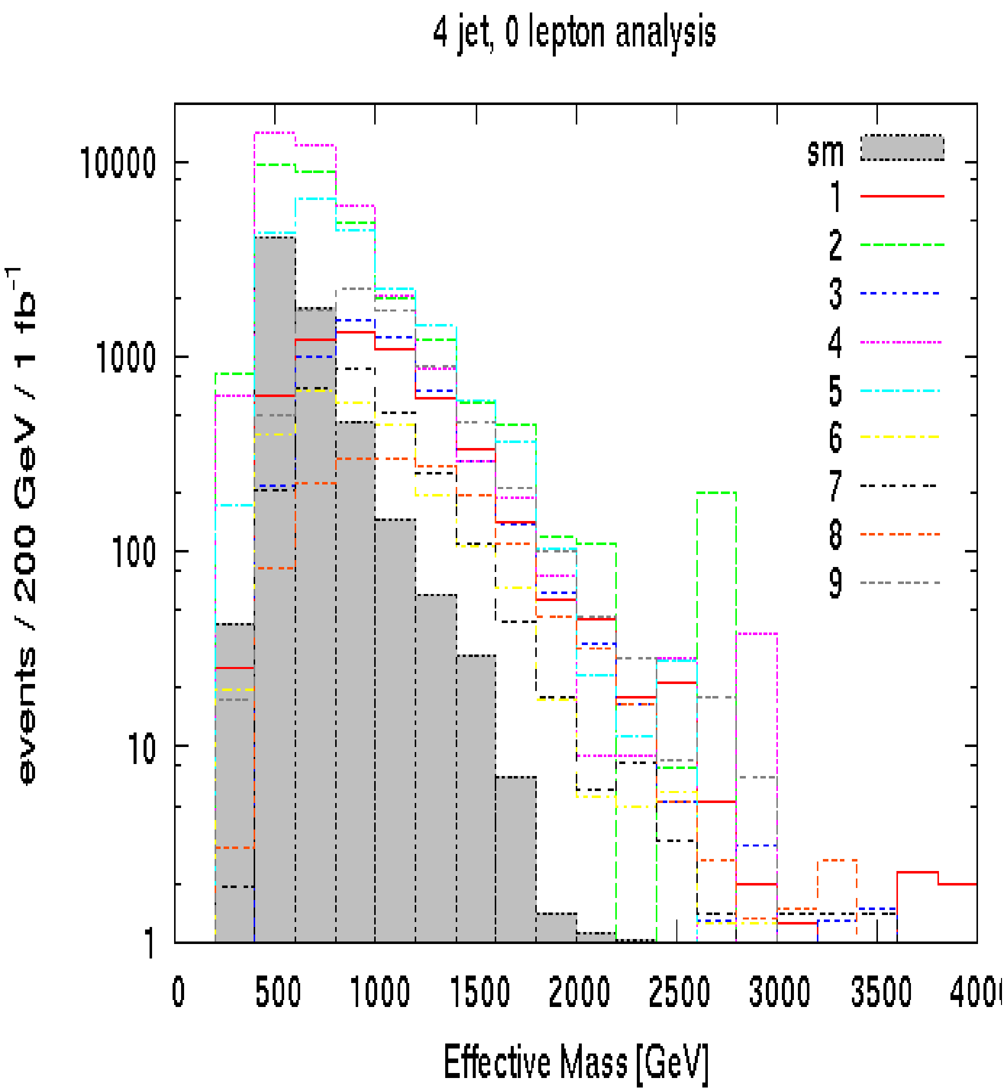
4-jet +MET

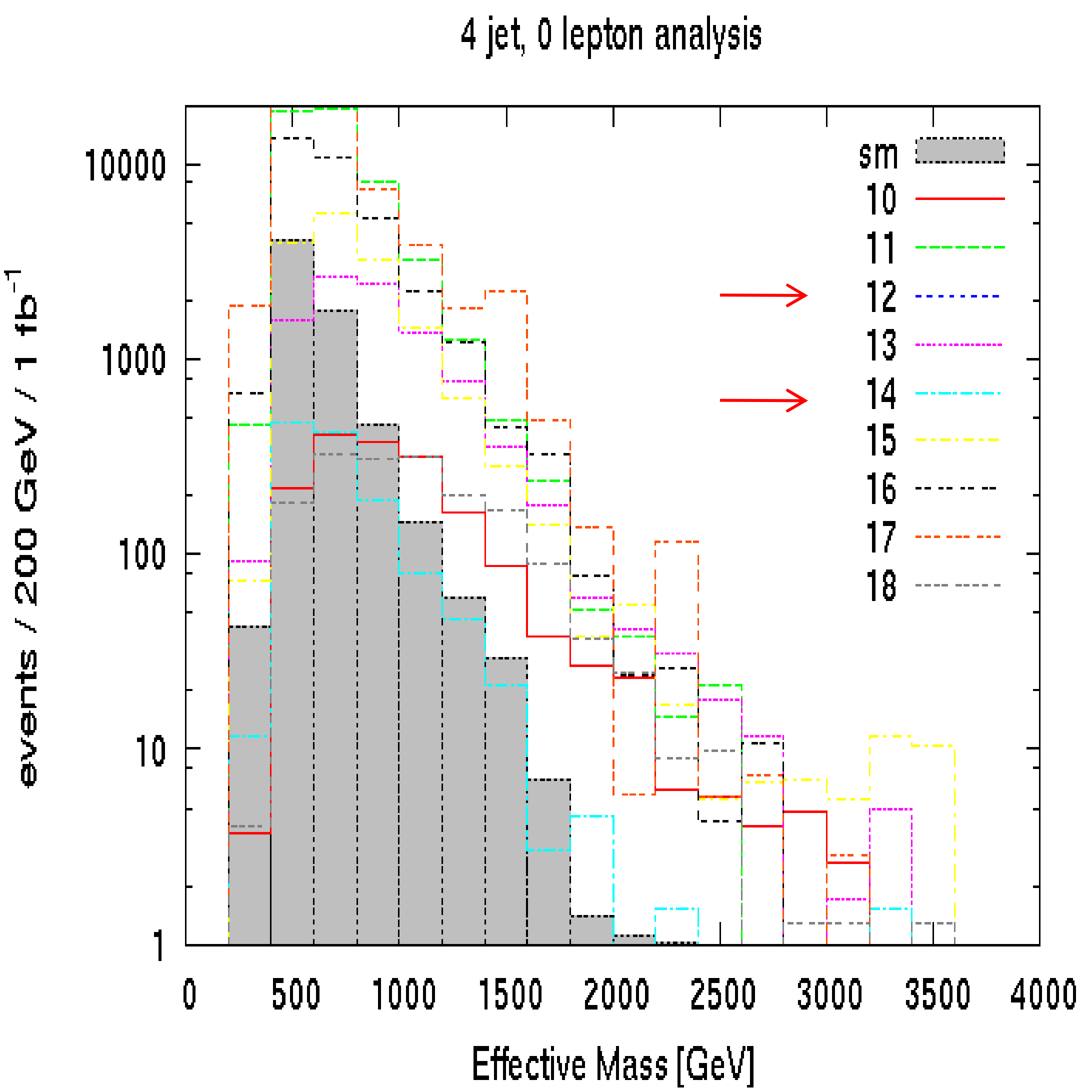


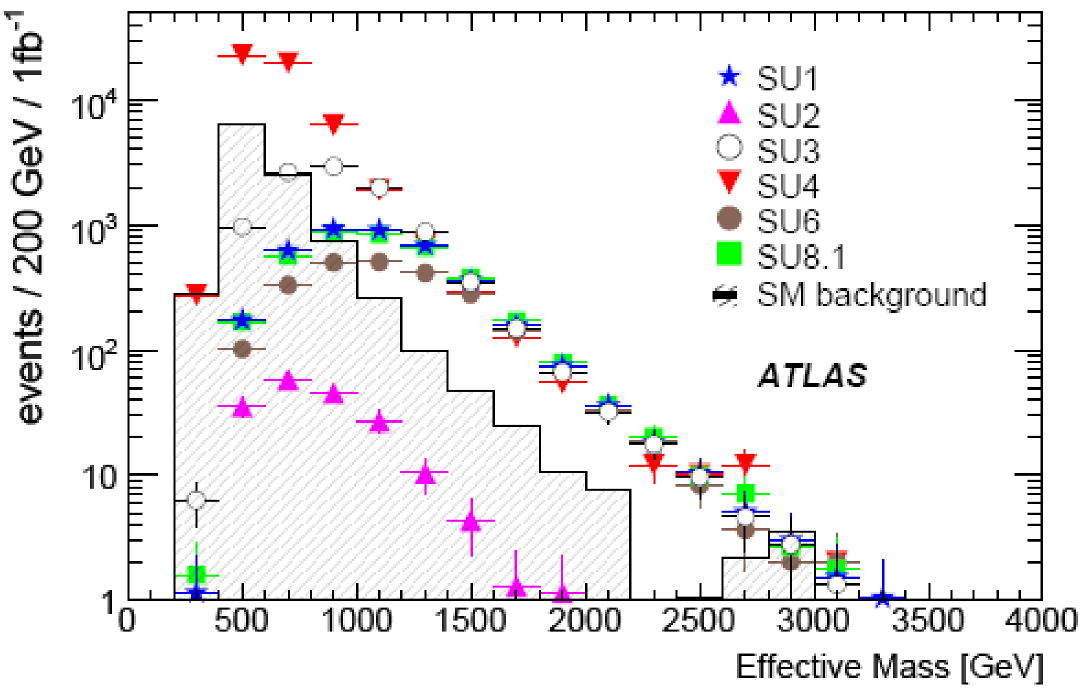


We do a good job at reproducing the mSUGRA benchmarks in this channel . If anything, our rates are a bit LOWER than are those obtained by ATLAS. We ONLY generate the required lumi & cap large QCD event rates

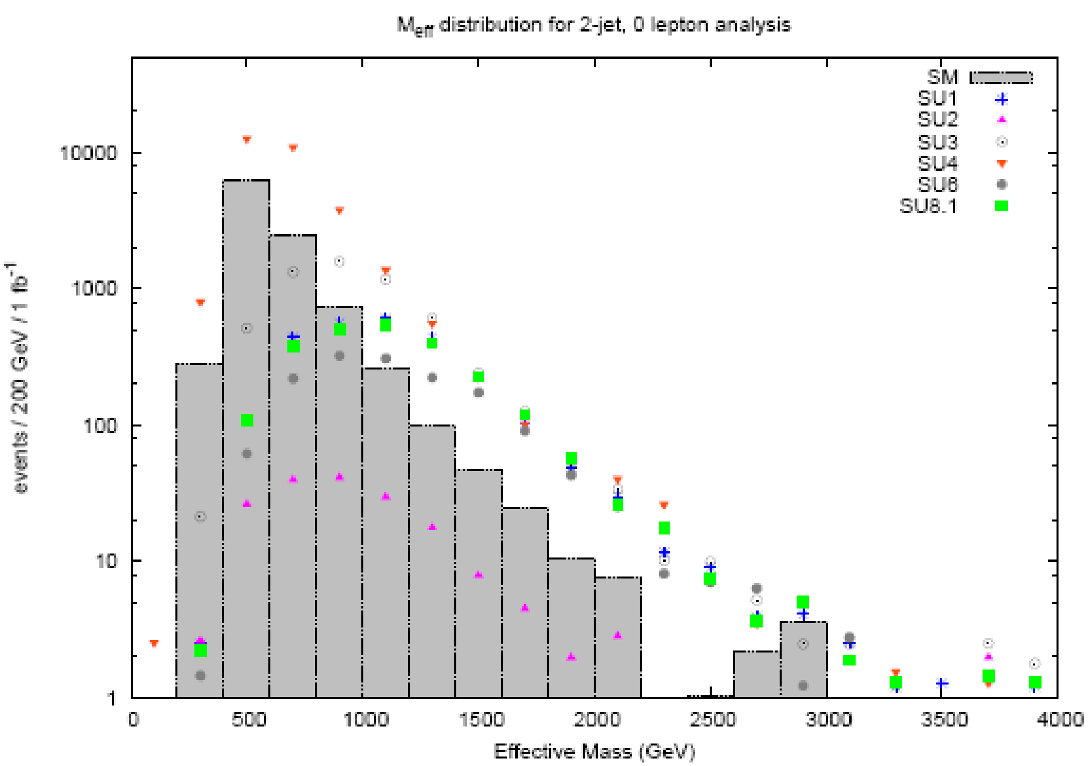
Sample Model Results





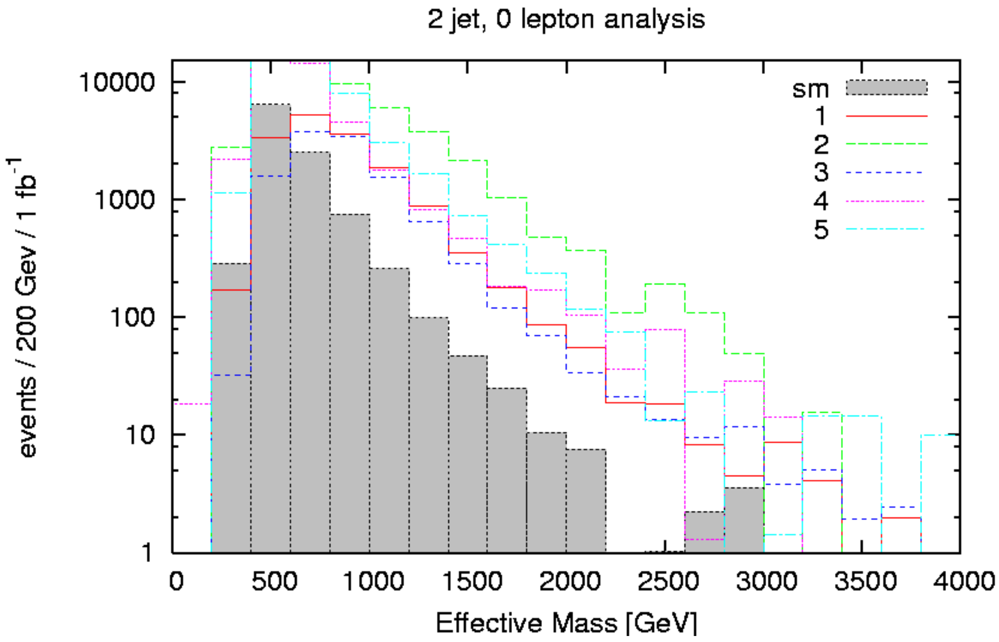


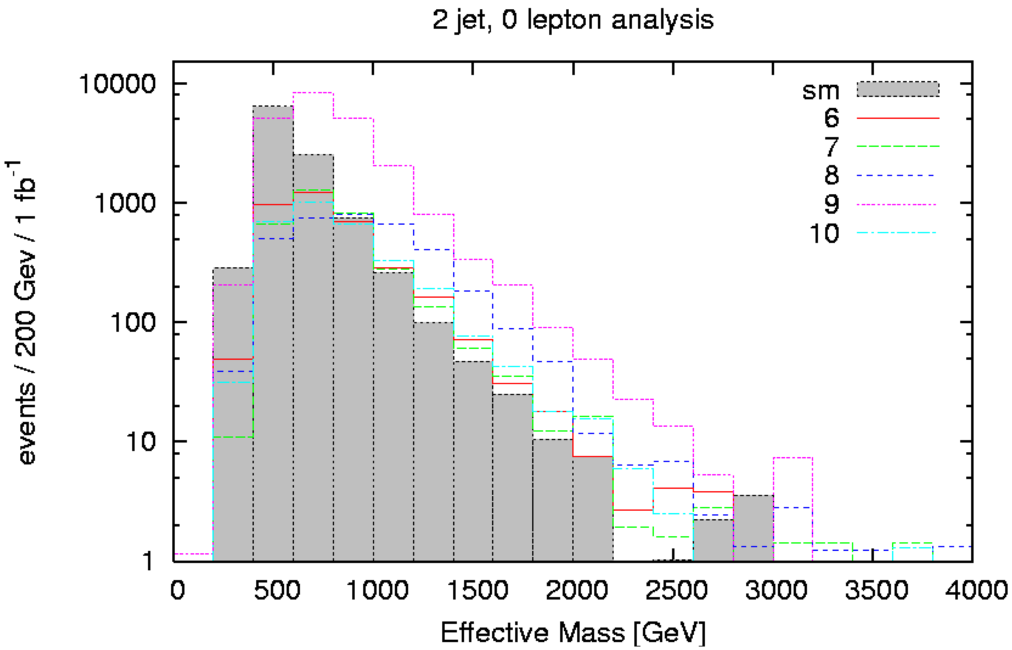
2j +MET

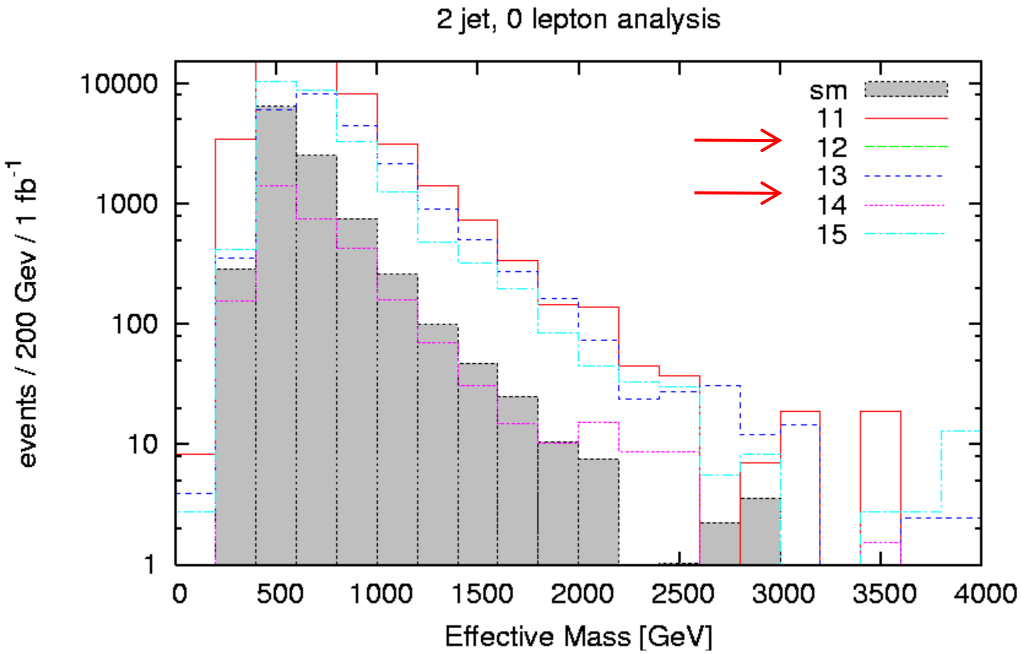


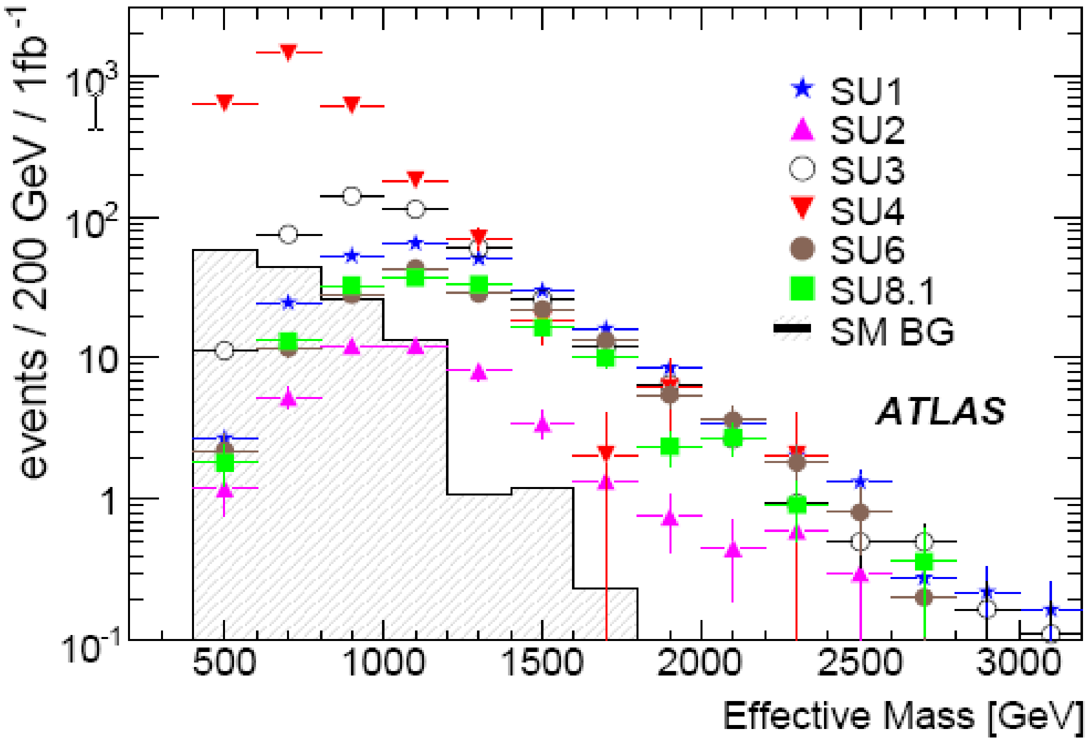
Looks good !

2j+MET Analysis

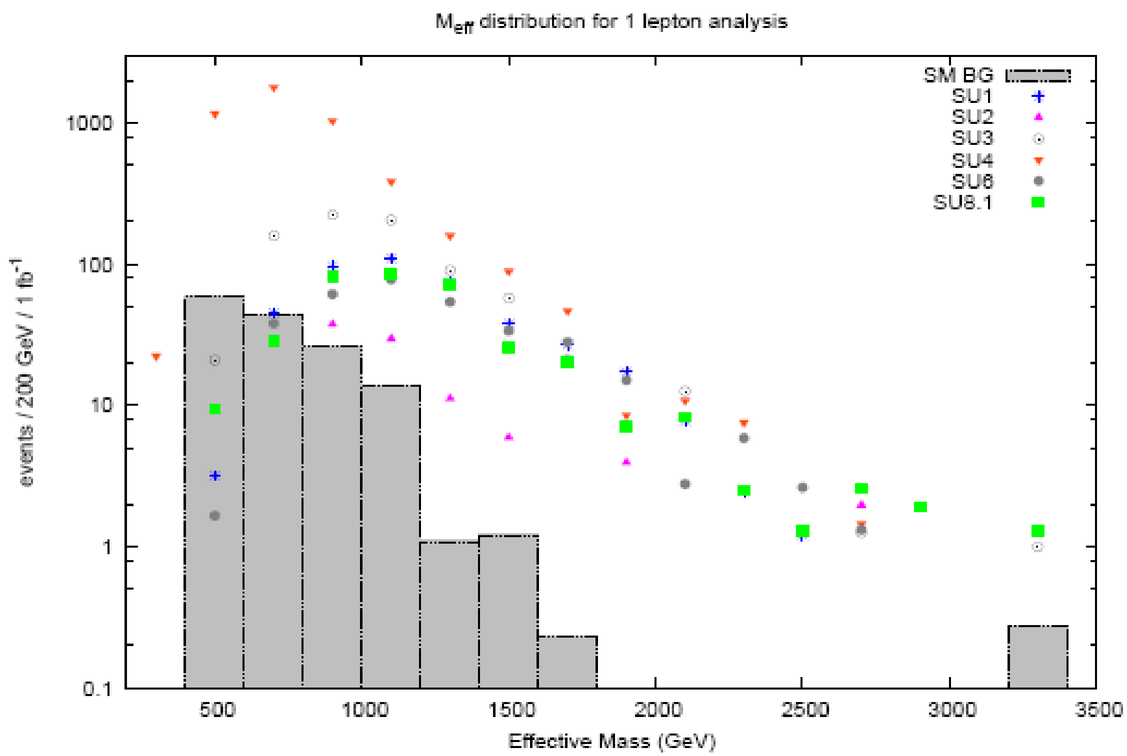




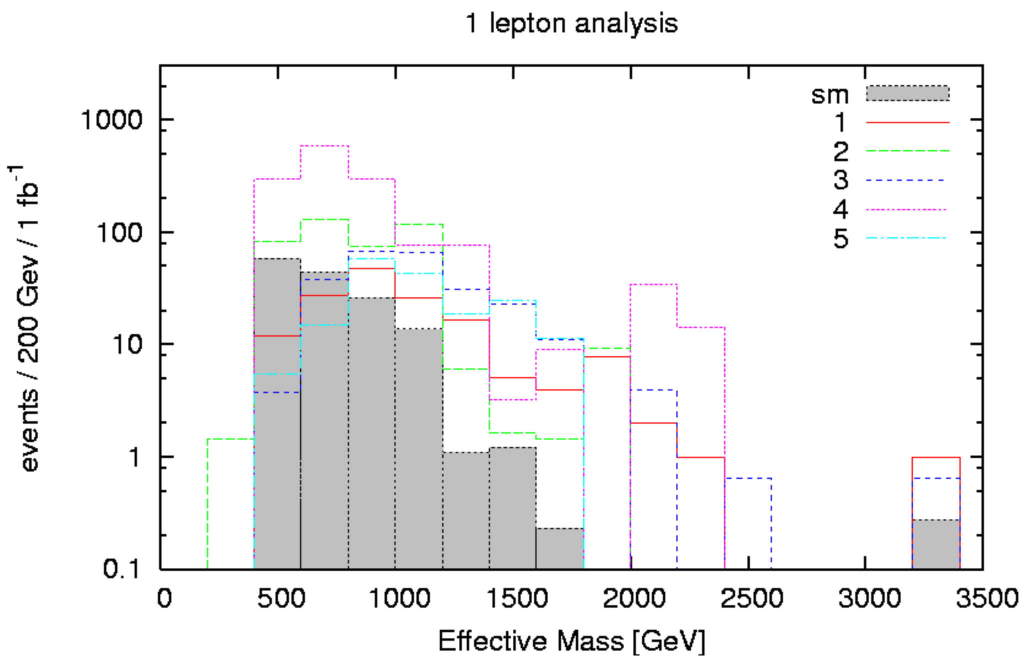




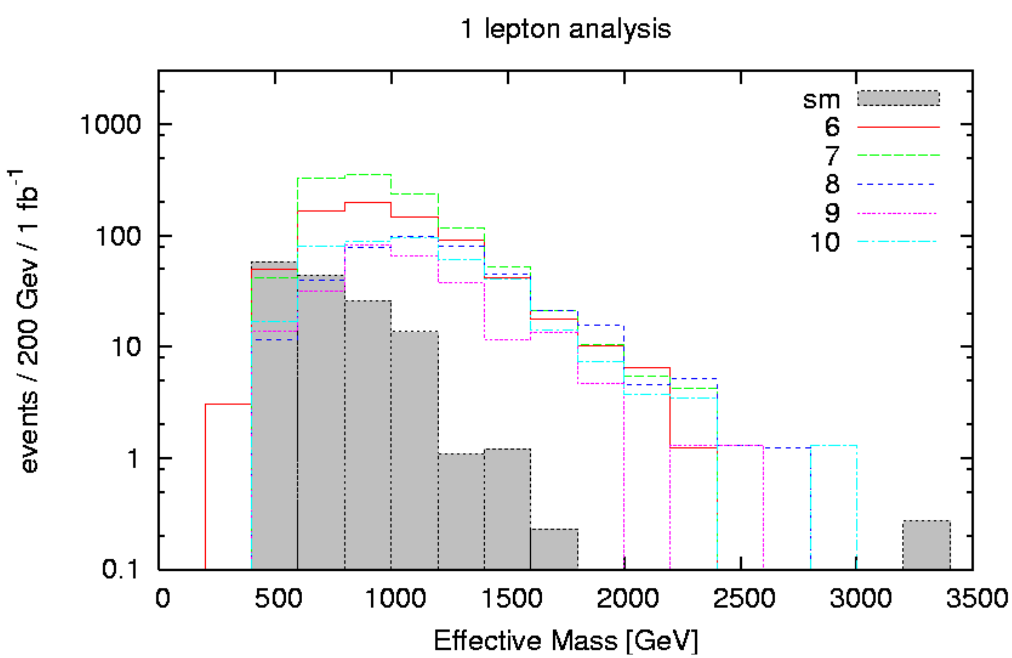
1l+4j+MET

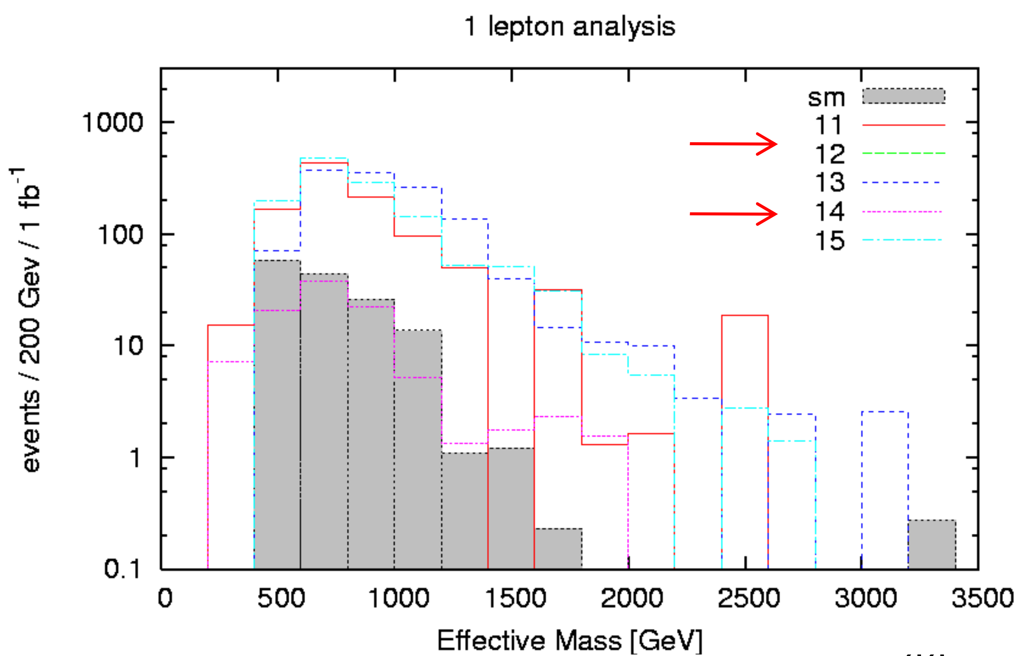


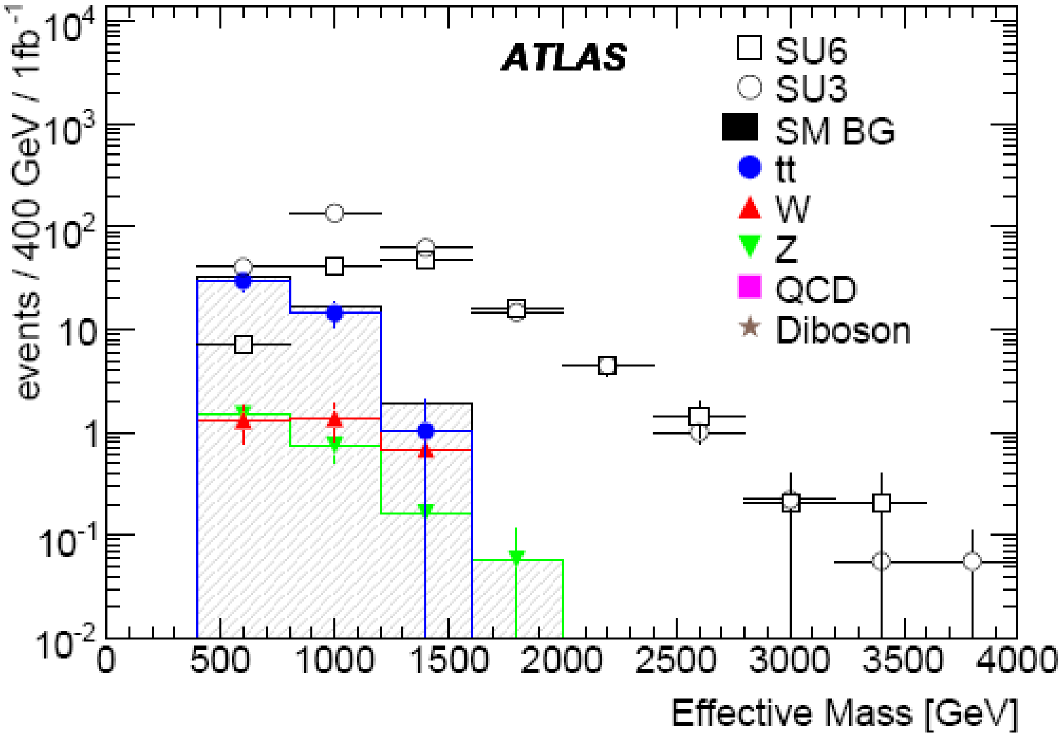
Great !

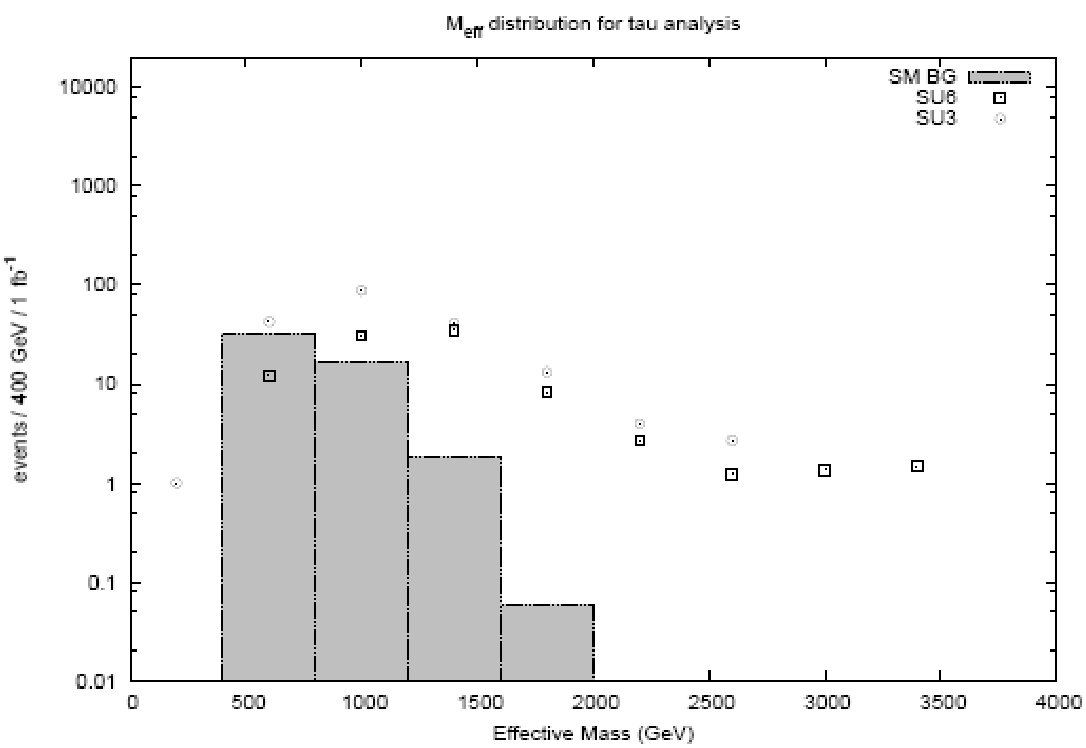


Single Lepton Analysis





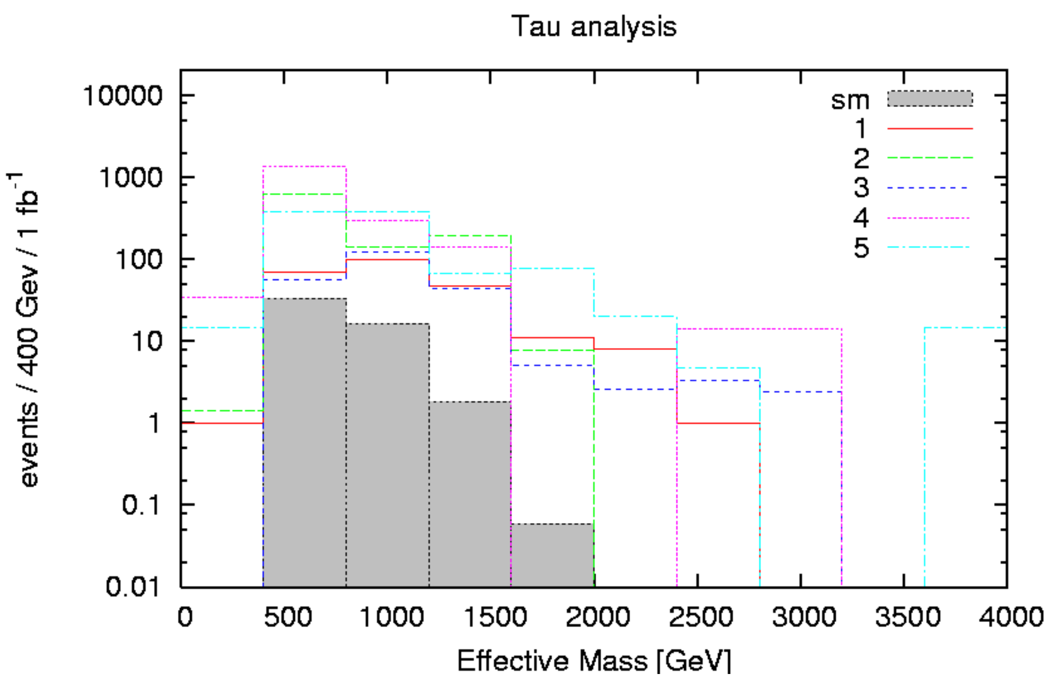




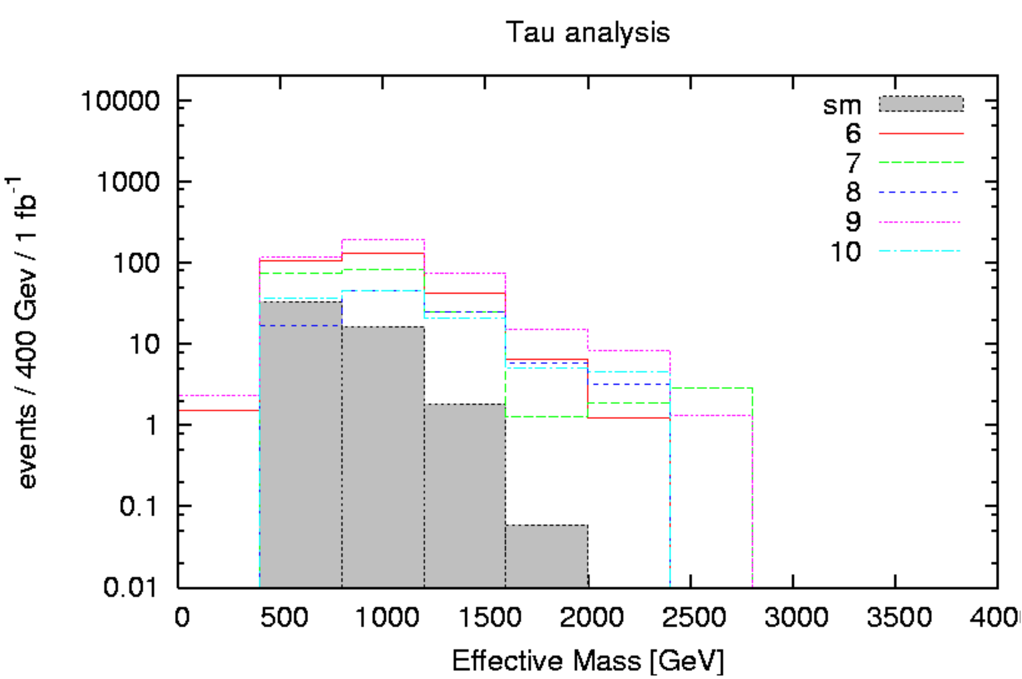
τ-analysis

Looks OK except at the high end where the statistics are poor..

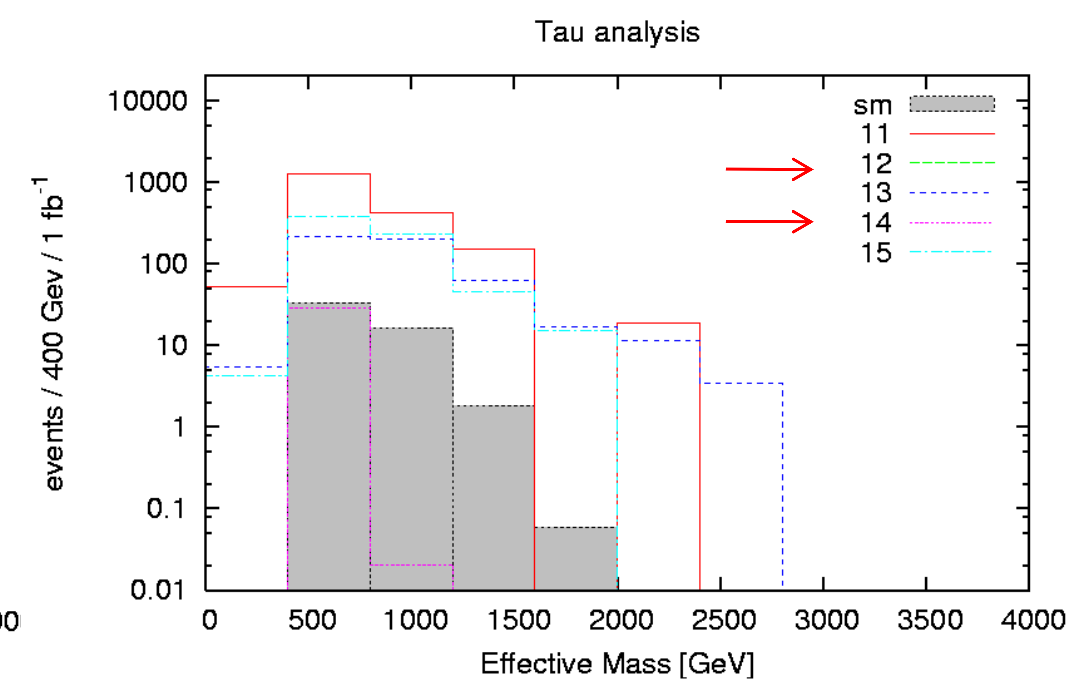
τ-analysis



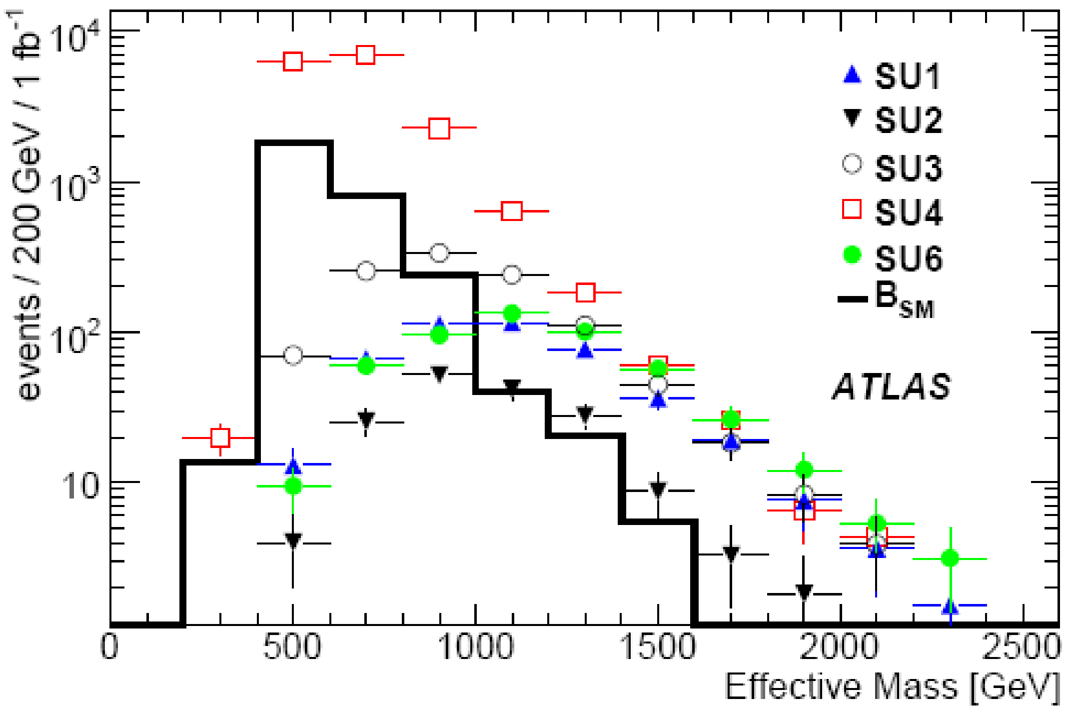
Tau analysis
events / 400 Gev / 1 fb-1
Effective Mass [GeV]
0.01 0.1 1 10 100 1000 10000
0 500 1000 1500 2000 2500 3000 3500 4000
sm
1
2
3
4
5

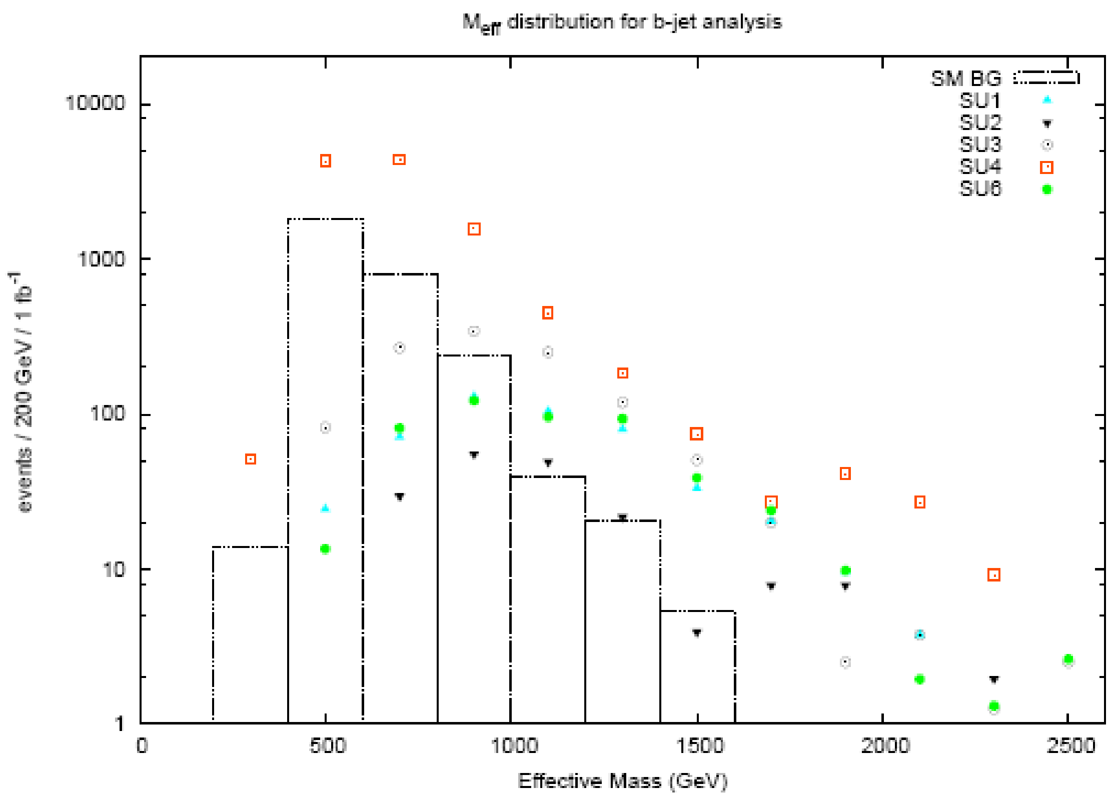


Tau analysis
events / 400 Gev / 1 fb-1
Effective Mass [GeV]
0.01 0.1 1 10 100 1000 10000
0 500 1000 1500 2000 2500 3000 3500 400
sm
6
7
8
9
10



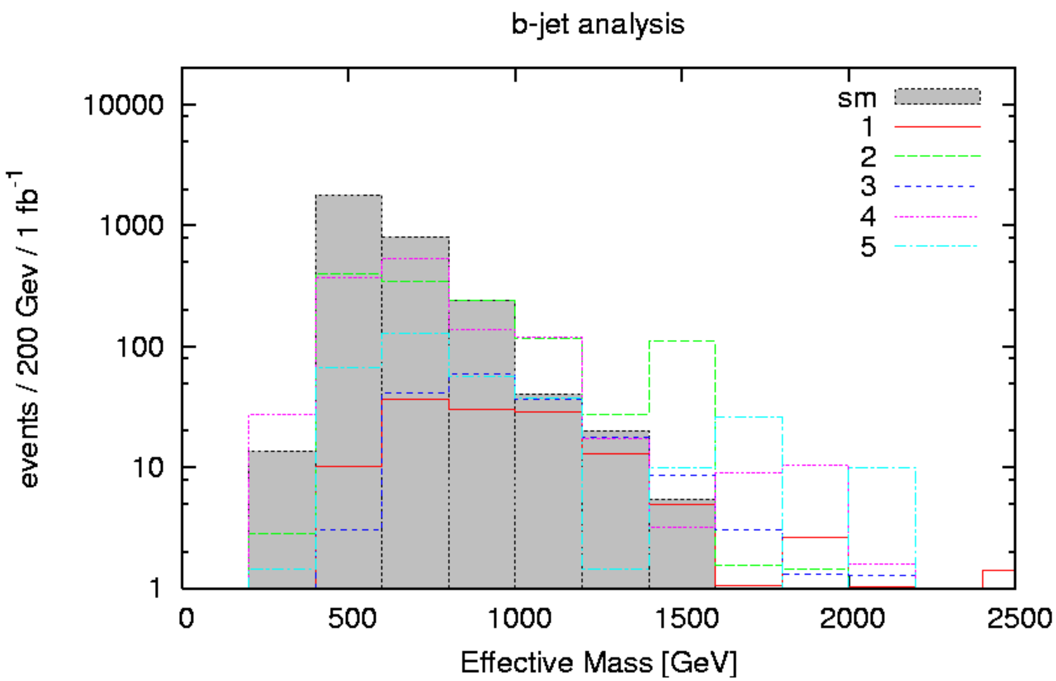
Tau analysis
events / 400 Gev / 1 fb-1
Effective Mass [GeV]
0.01 0.1 1 10 100 1000 10000
0 500 1000 1500 2000 2500 3000 3500 4000
sm
11
12
13
14
15



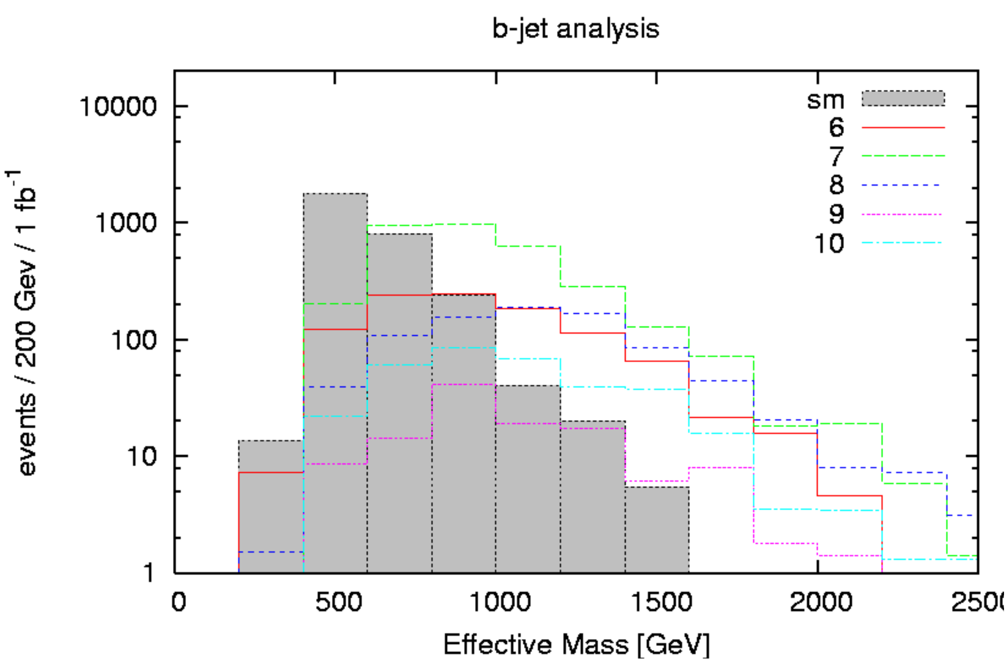


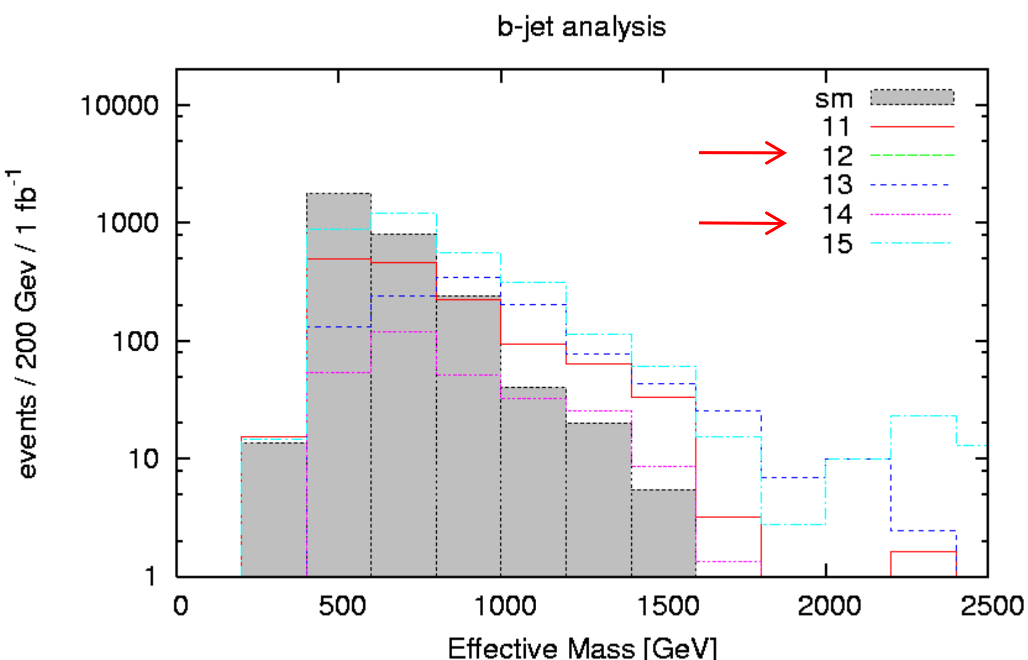
b-jet analysis

Great !



b-jet analysis





Some Results From the First 20k Models @ 14 TeV & $1 fb^{-1}$

- 'Remove' some possibly difficult models which may require some specialized analyses (note PYSTOP issues)

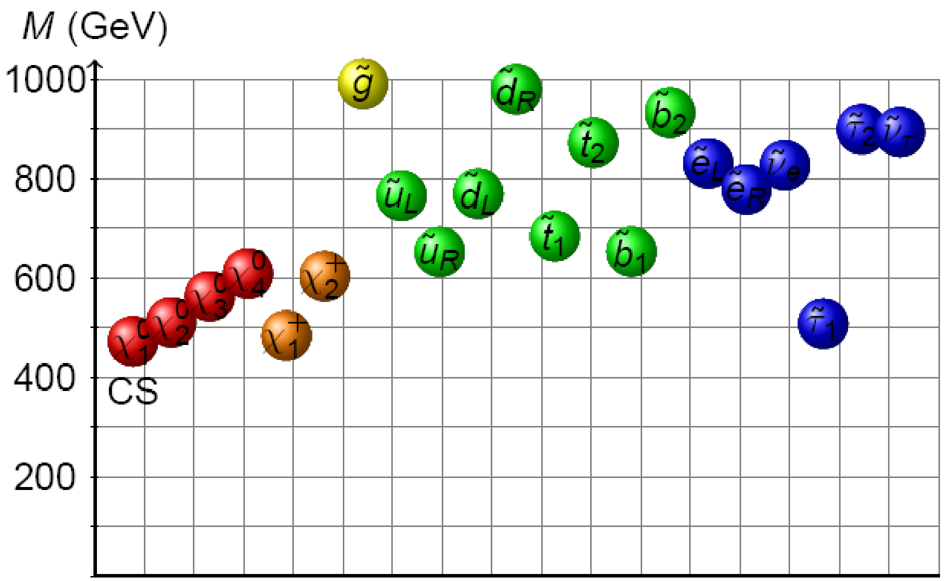
- Determine how many models are visible or not in each analysis @ the 5σ level allowing for a 20% systematic un-certainty in the ATLAS generated SM backgrounds

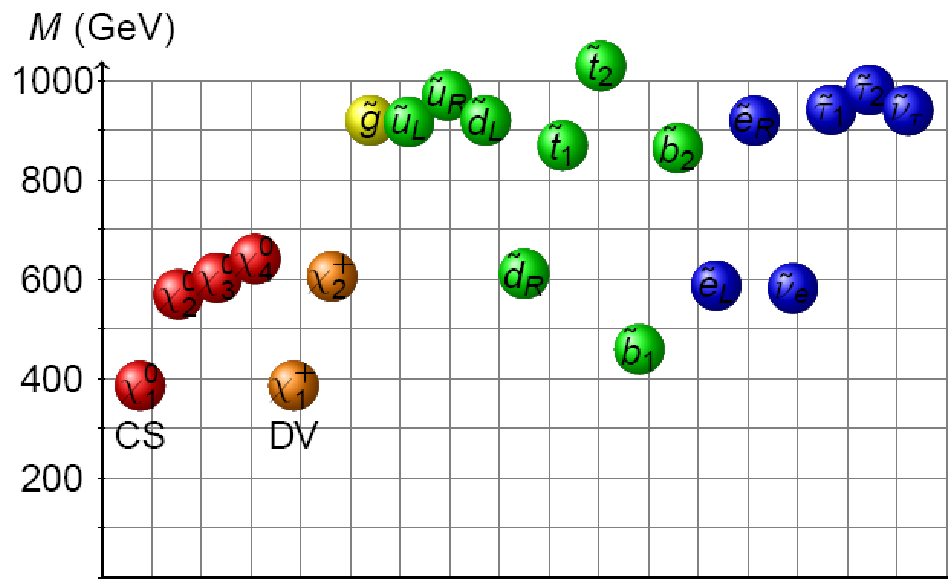
- The results are still HIGHLY PRELIMINARY and we are just at the very beginning of trying to understand what they all mean ! The remaining ~51k models will be run soon…

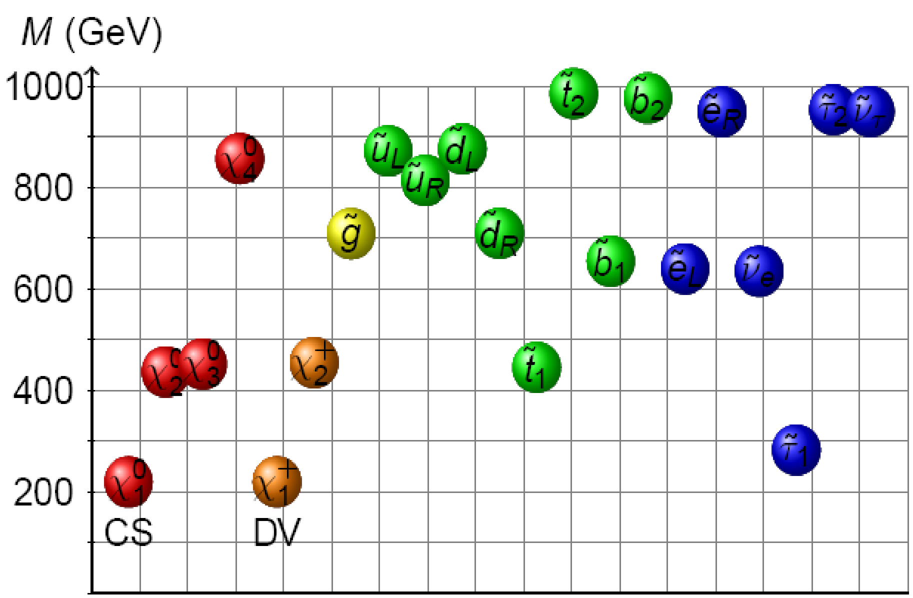
Some Results From the First 20k Models

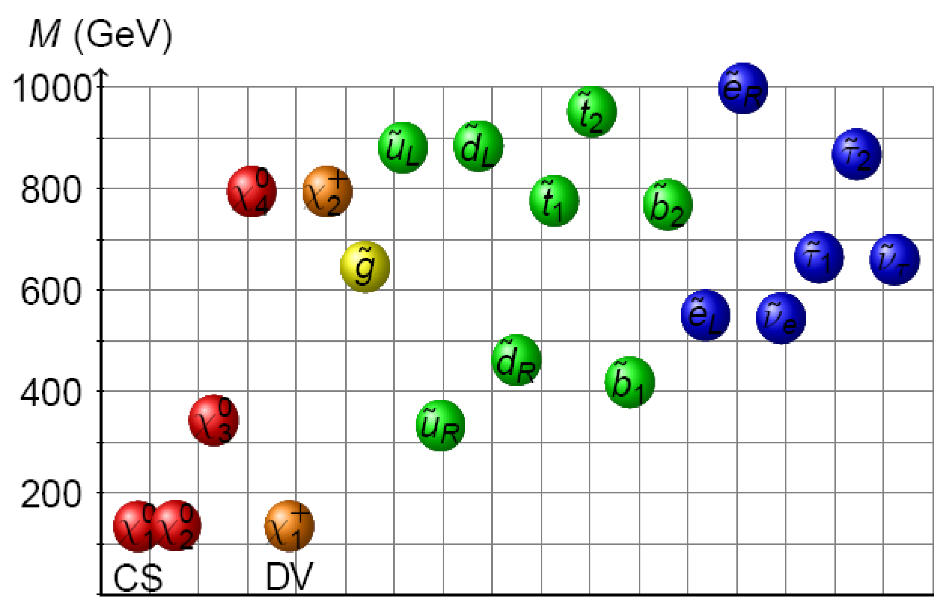
Percentage of models missed by ATLAS analyses		
Analysis	with PYSTOPS	without PYSTOPS
4 jets + M_{E_T}	2.62	1.53
2 jets + M_{E_T}	3.47	2.43
1 lepton + 4 jets + M_{E_T}	42.10	40.52
1 lepton + 2 jets + M_{E_T}	45.68	44.09
1 lepton + 3 jets + M_{E_T}	38.94	37.41
SSDL + 4 jets + M_{E_T}	78.73	76.99
τ + 4 jets + M_{E_T}	3.04	1.95
b jets + M_{E_T}	54.82	53.38
SSDL + 4 jets + M_{E_T}	92.42	90.62
3 leptons + jet	83.64	81.87
3 leptons + M_{E_T}	97.32	95.51

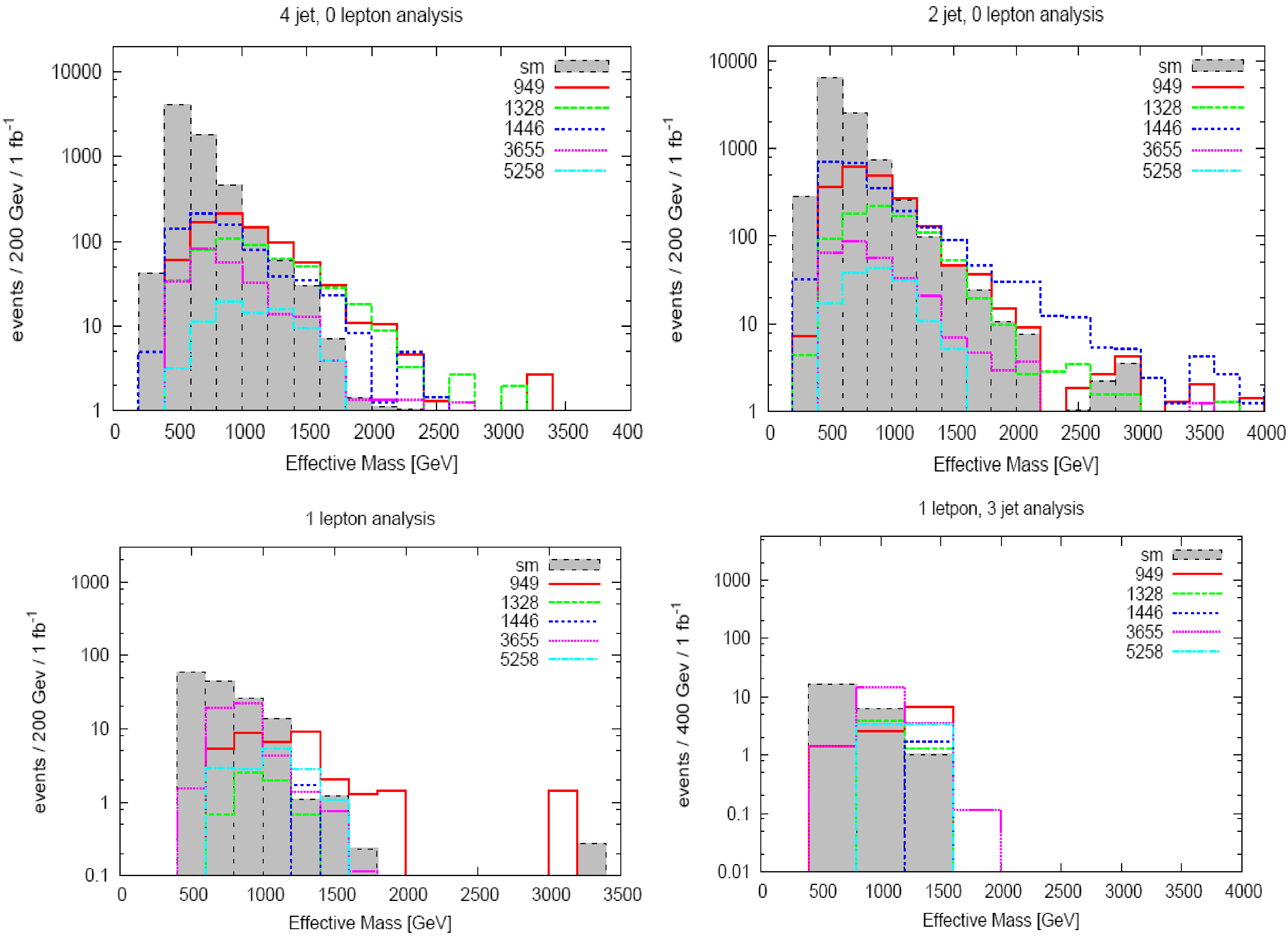
Percentage of models missed by ATLAS analyses	
Number of analyses missed	% of models
0	2.87
1	3.55
2	5.07
3	10.22
4	17.54
5	16.56
6	5.83
7	13.89
8	23.42
9	0.78
10	0.19
11	0.09

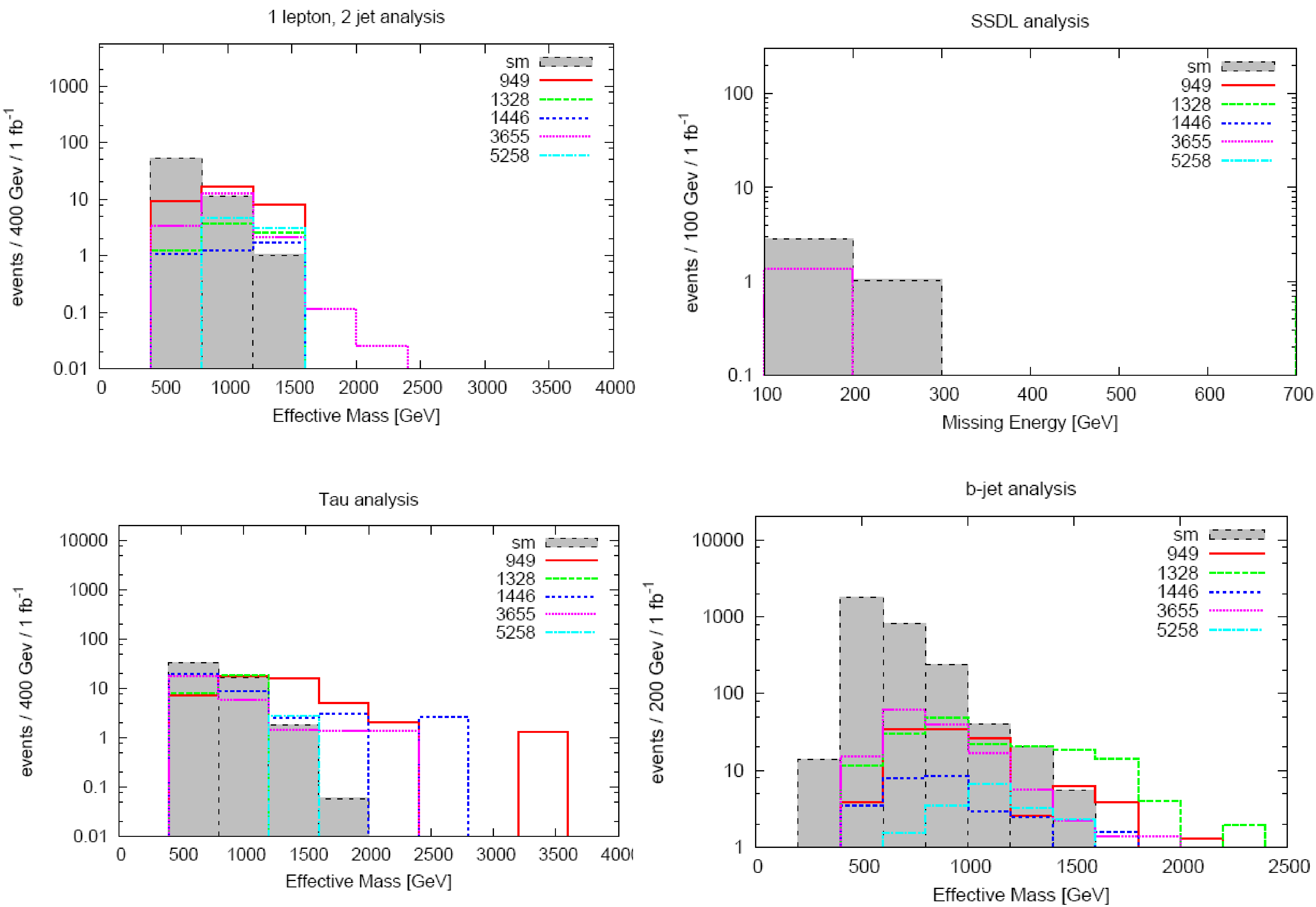

M (GeV)
1000
800
600
400
200
CS


M (GeV)
1000
800
600
400
200
CS
DV


M (GeV)
1000
800
600
400
200
CS
DV


M (GeV)
1000
800
600
400
200
CS
DV


4 jet, 0 lepton analysis
2 jet, 0 lepton analysis
1 lepton analysis
1 letpon, 3 jet analysis
sm
949
1328
1446
3655
5258
events / 200 Gev / 1 fb-1
events / 400 Gev / 1 fb-1
Effective Mass [GeV]
10000
1000
100
10
1
0.1
0.01
0
500
1000
1500
2000
2500
3000
3500
400
4000



1 lepton, 2 jet analysis
events / 400 Gev / 1 fb^{-1}
Effective Mass [GeV]
sm
949
1328
1446
3655
5258
SSDL analysis
events / 100 Gev / 1 fb^{-1}
Missing Energy [GeV]
sm
949
1328
1446
3655
5258
Tau analysis
events / 400 Gev / 1 fb^{-1}
Effective Mass [GeV]
sm
949
1328
1446
3655
5258
b-jet analysis
events / 200 Gev / 1 fb^{-1}
Effective Mass [GeV]
sm
949
1328
1446
3655
5258

What can we conclude so far ???

- There are many models which will show a respectable signal in these specific channels but a reasonably large fraction will --*not* . We will need to understand why models 'fail' on a case by case basis and how analyses would need to be modified (cuts, etc.) to cover them. However, what we have completed so far is only a ONLY a subset due to delays caused by PYTHIA & SDECAY issues.

- Once we know why models fail we need to ask (i) how the LHC analyses might be changed & (ii) what a linear collider can do to assist in these many problematic cases. There is likely to be a sizeable set that require ILC/CLIC to discover a large fraction of the SUSY spectrum.

Summary

- The pMSSM has a far richer phenomenology than any of the conventional SUSY breaking scenarios. The sparticle properties can be vastly different, e.g., the nLSP can be any other sparticle!

- Light partners may exist which have avoided LEP & Tevatron constraints and may be difficult to observe at the LHC due to rather common small mass differences or strange spectra

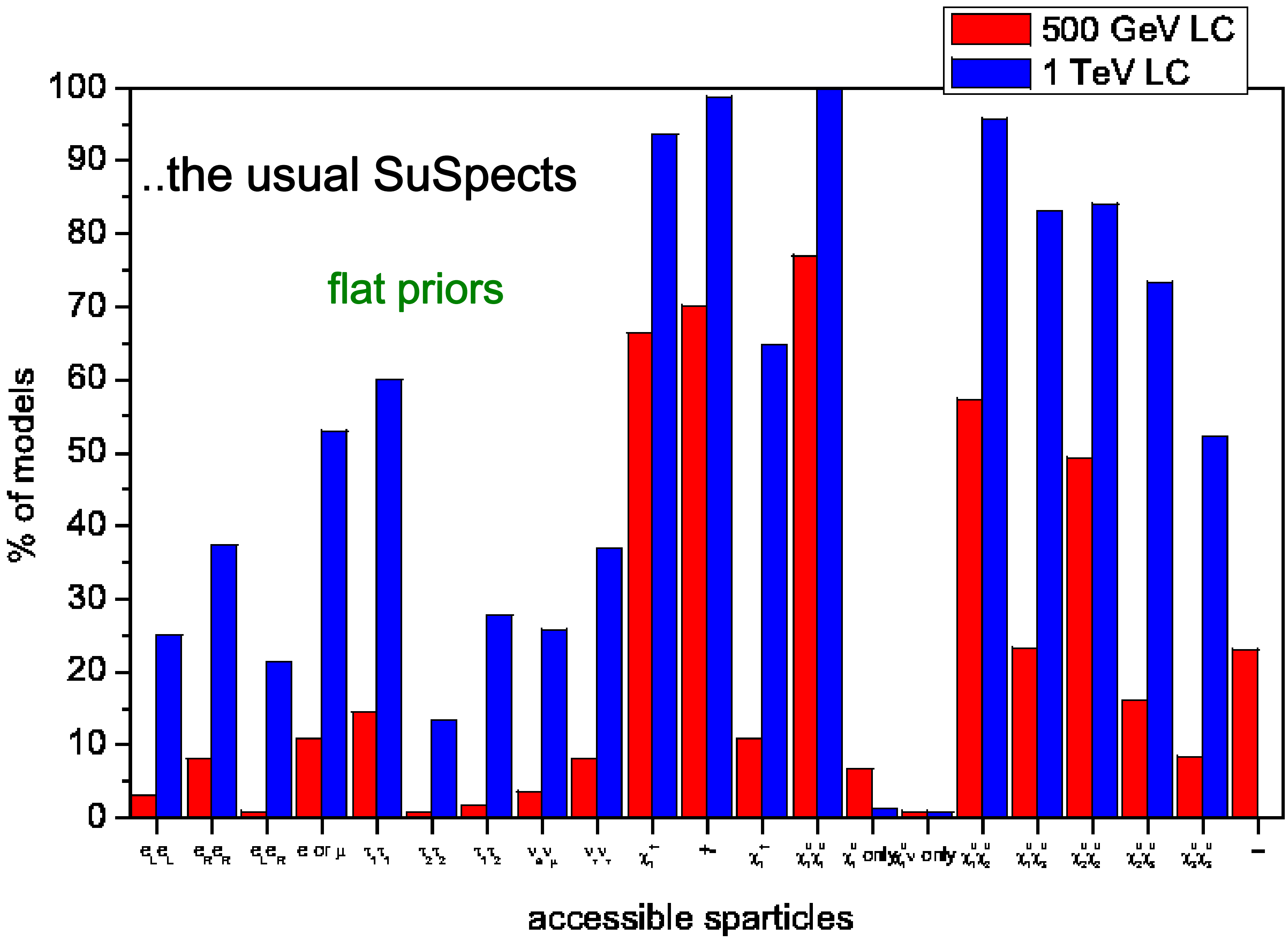
- Squarks may exist within the range accessible to a 500 GeV ILC but have not been well studied there.

- With the WMAP constraint employed as a bound the LSP is not likely to be the dominant source of DM…but it can be.

- The study of these complex models is still at early stage..

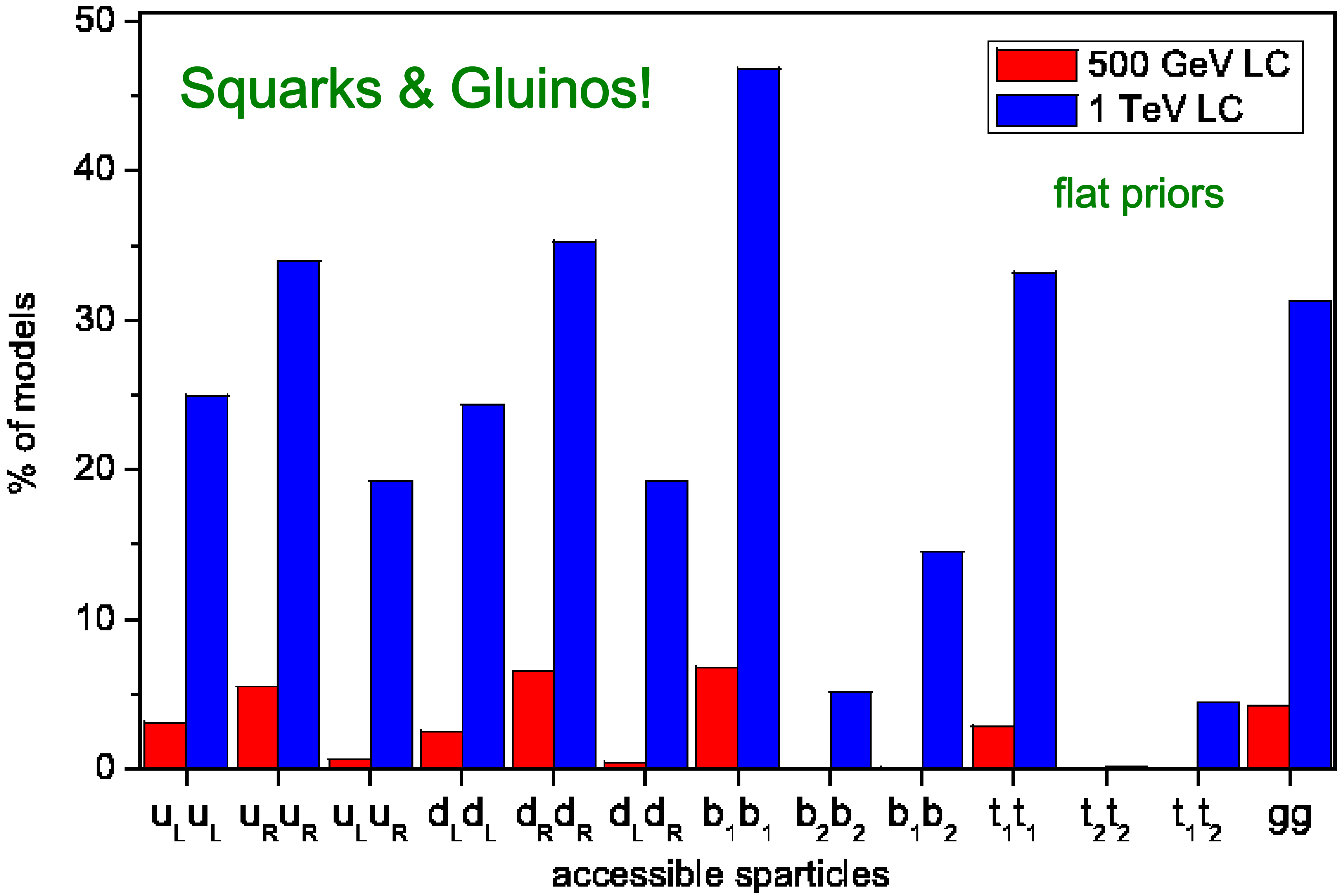
BACKUP SLIDES

Kinematic Accessibility at the ILC : I



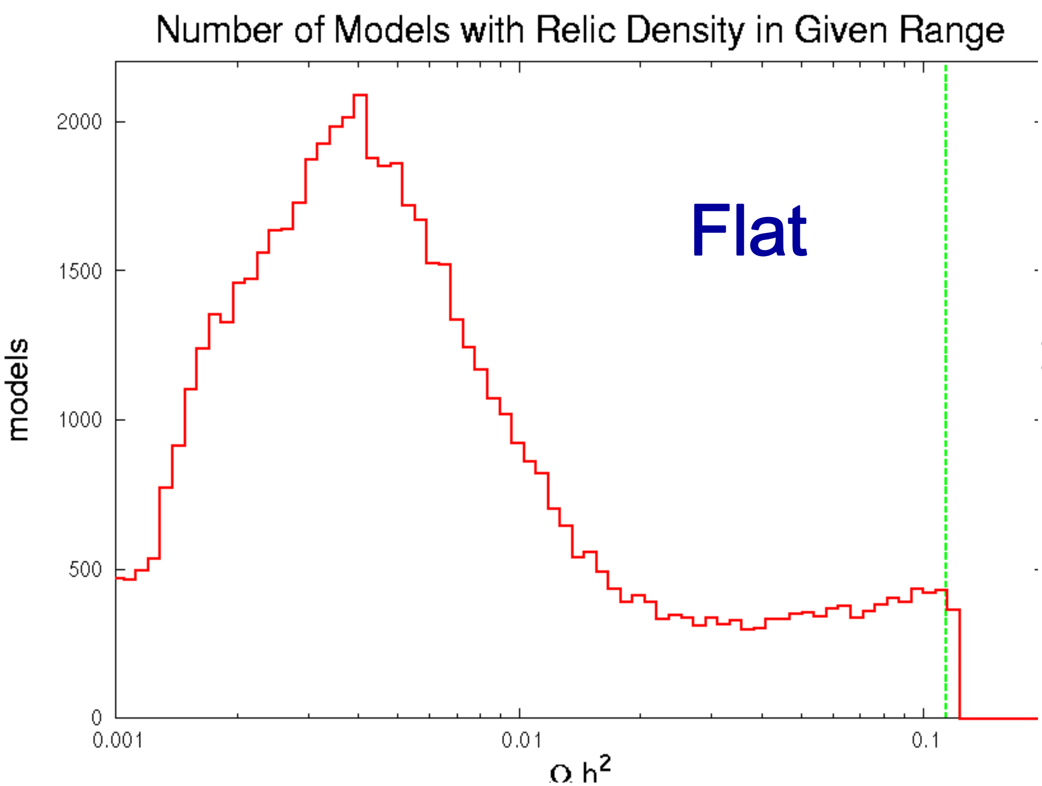
Final State
$\tilde{e}_L^+\tilde{e}_L^-$
$\tilde{e}_R^+\tilde{e}_R^-$
$\tilde{e}_L^\pm\tilde{e}_R^\mp$
$\tilde{\mu}_L^+\tilde{\mu}_L^-$
$\tilde{\mu}_R^+\tilde{\mu}_R^-$
Any selectron or smuon
$\tilde{\tau}_1^+\tilde{\tau}_1^-$
$\tilde{\tau}_2^+\tilde{\tau}_2^-$
$\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$
$\tilde{\nu}_{e\mu}\tilde{\nu}_{e\mu}^*$
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$
$\tilde{\chi}_1^+\tilde{\chi}_1^-$
Any charged sparticle
$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$
$\tilde{\chi}_1^0\tilde{\chi}_1^0$
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ only
$\tilde{\chi}_1^0 + \tilde{\nu}$ only
$\tilde{\chi}_1^0\tilde{\chi}_2^0$
$\tilde{\chi}_1^0\tilde{\chi}_3^0$
$\tilde{\chi}_2^0\tilde{\chi}_2^0$
$\tilde{\chi}_2^0\tilde{\chi}_3^0$
$\tilde{\chi}_3^0\tilde{\chi}_3^0$
Nothing

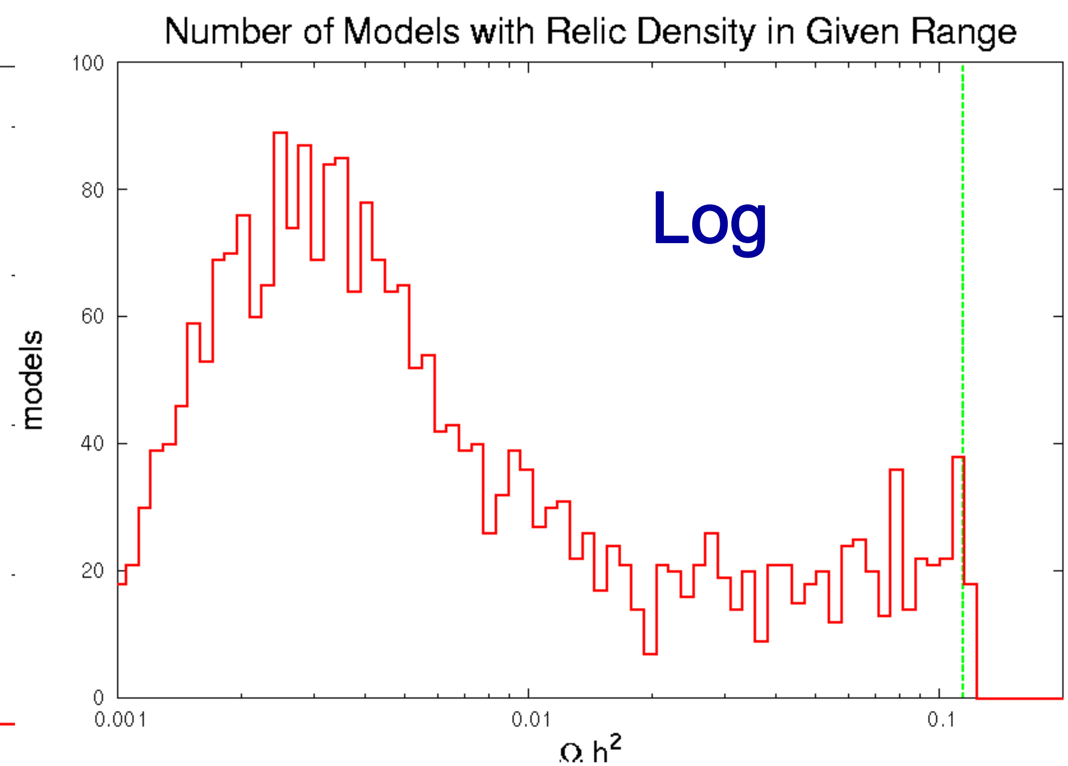
Kinematic Accessibility at the ILC : III



Predicted Dark Matter Density : Ωh^2

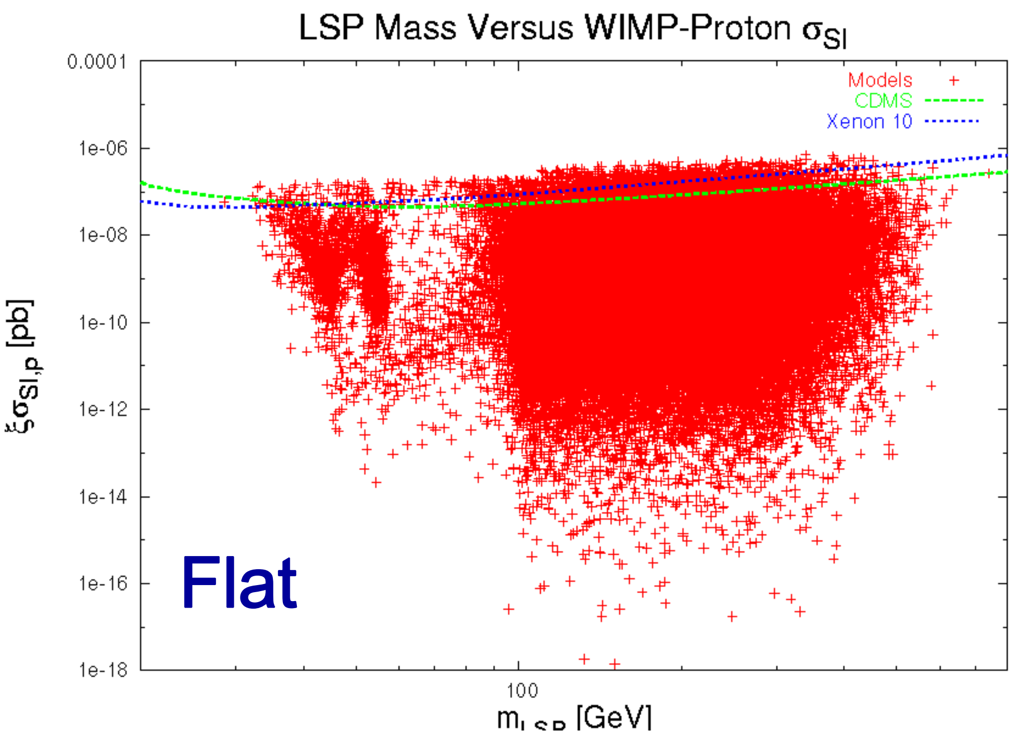
It is not likely that the LSP is the dominant component of dark matter in ‘conventional’ cosmology…but it can be in some model cases.. (1240 + 76)

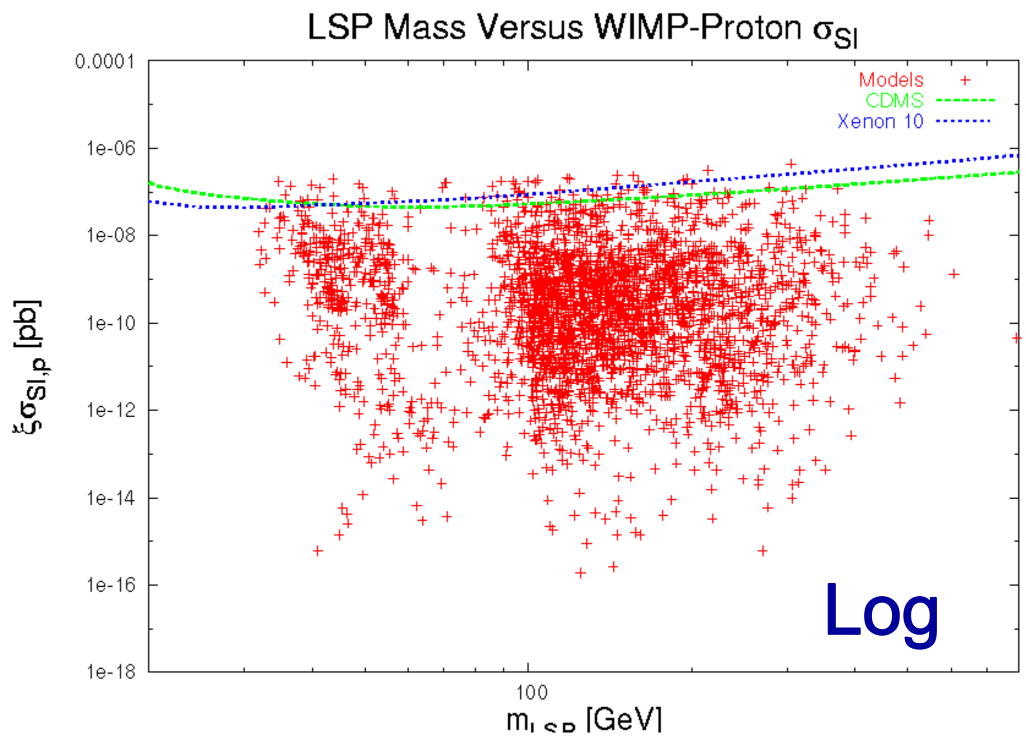




Direct Detection Expectations

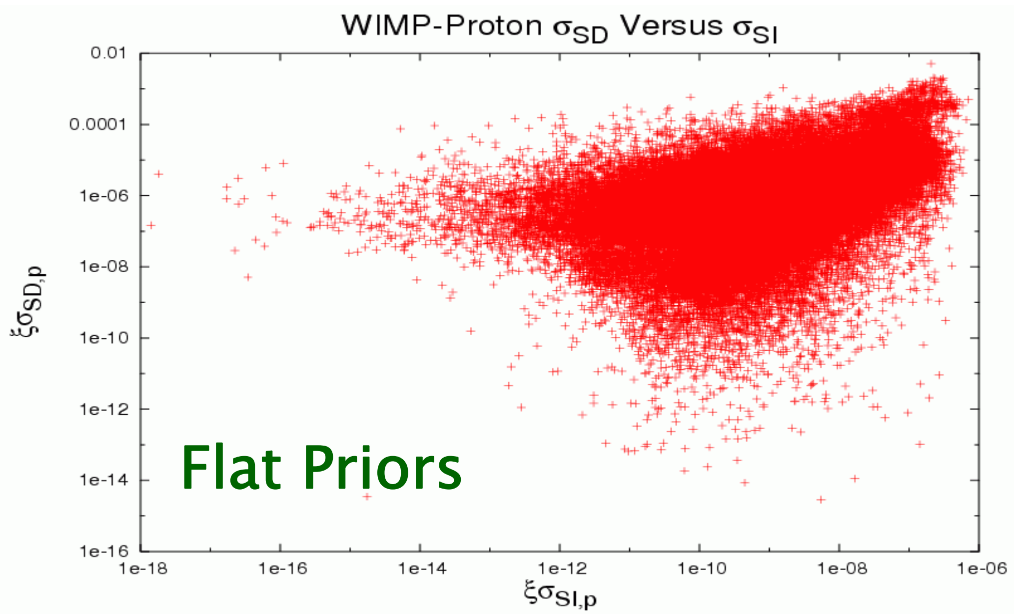
Extremely small cross sections are possible in either the flat or log prior cases…far smaller than expected in, e.g., mSUGRA….

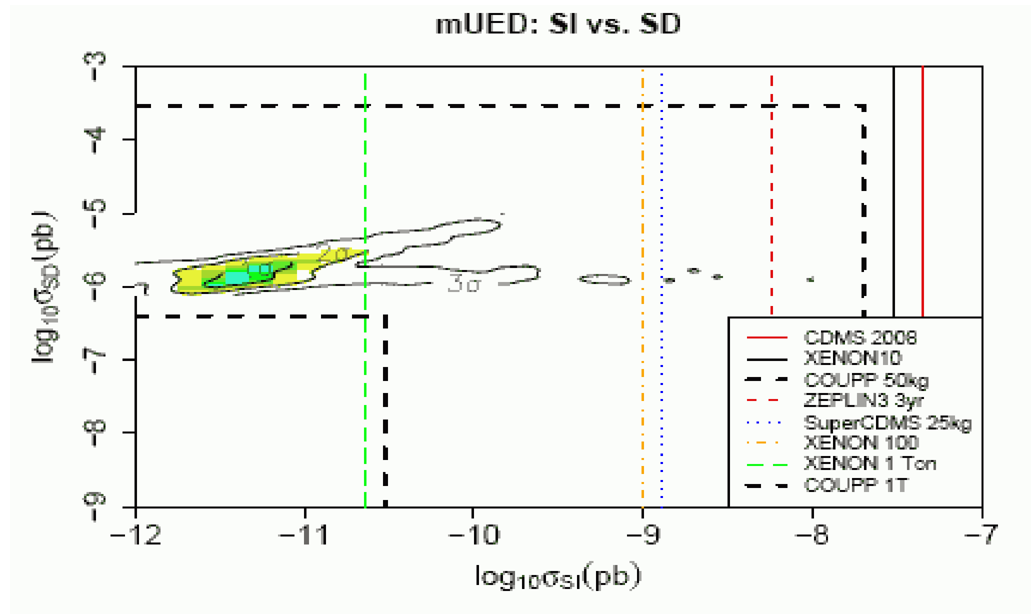


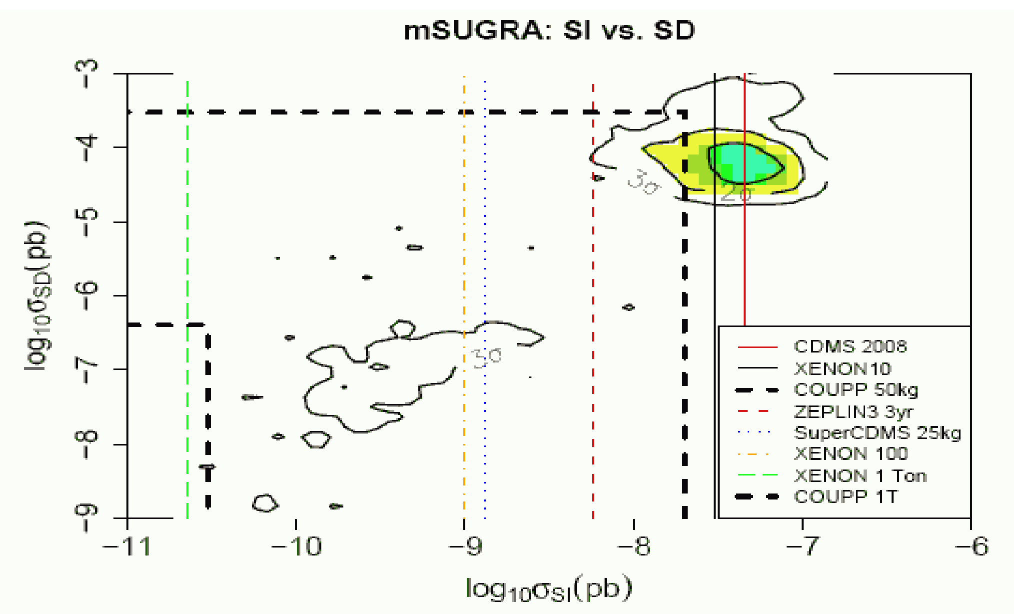


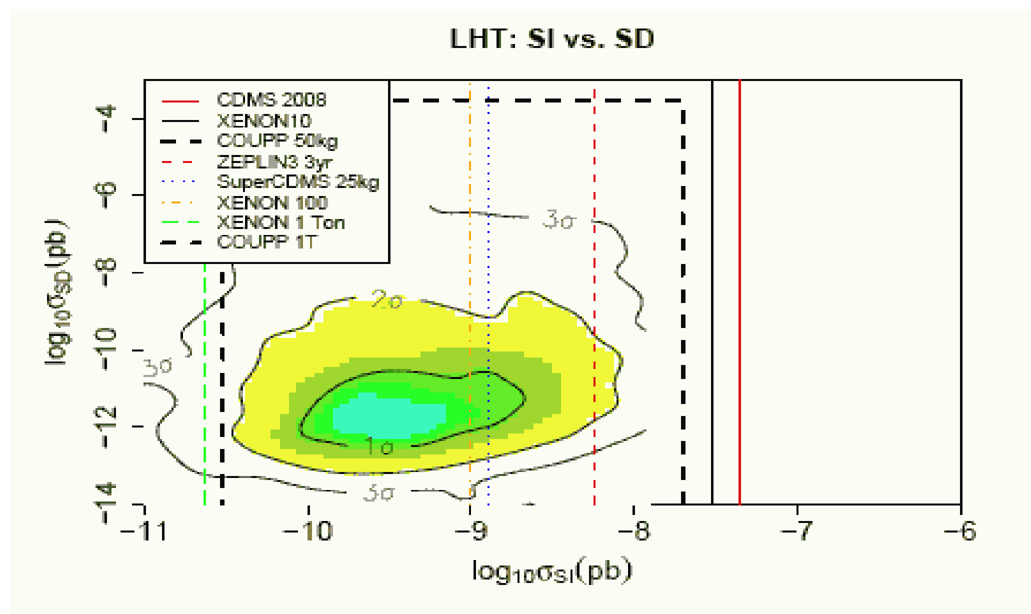
Distinguishing Dark Matter Models

Barger etal



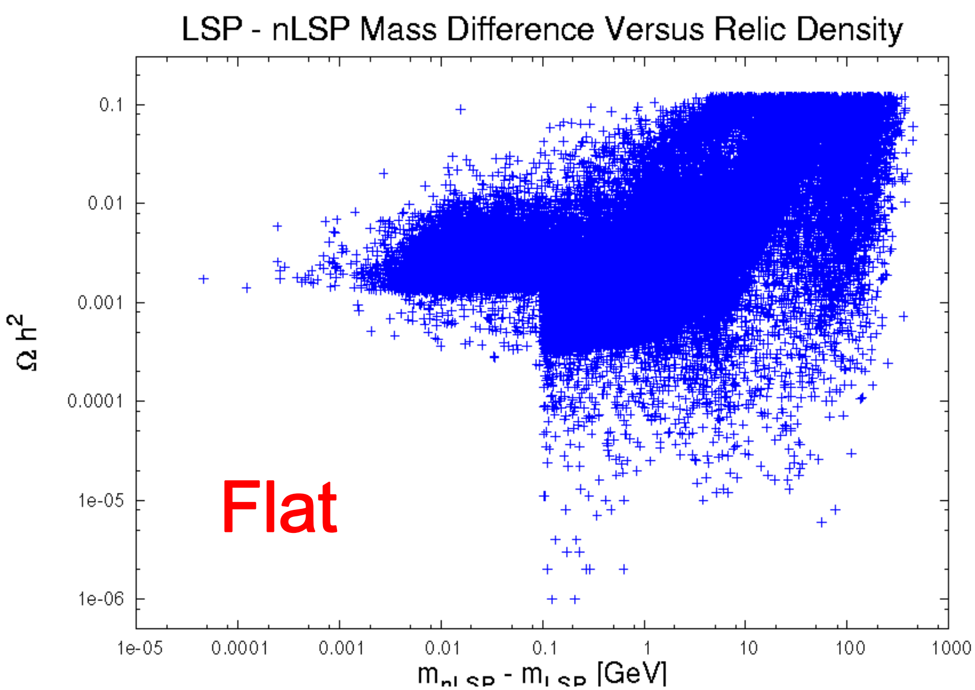


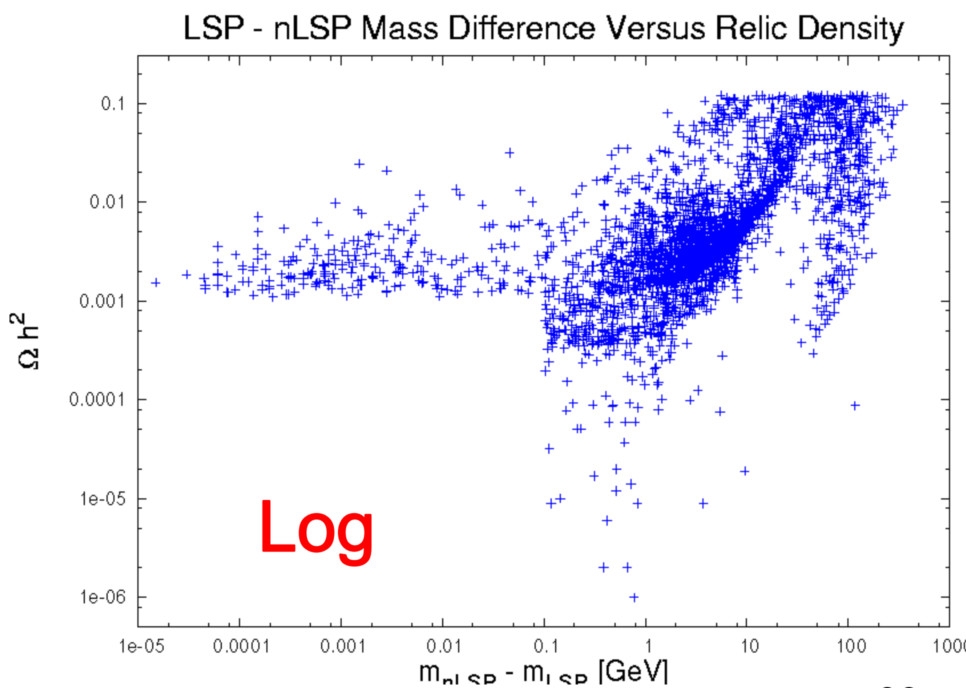




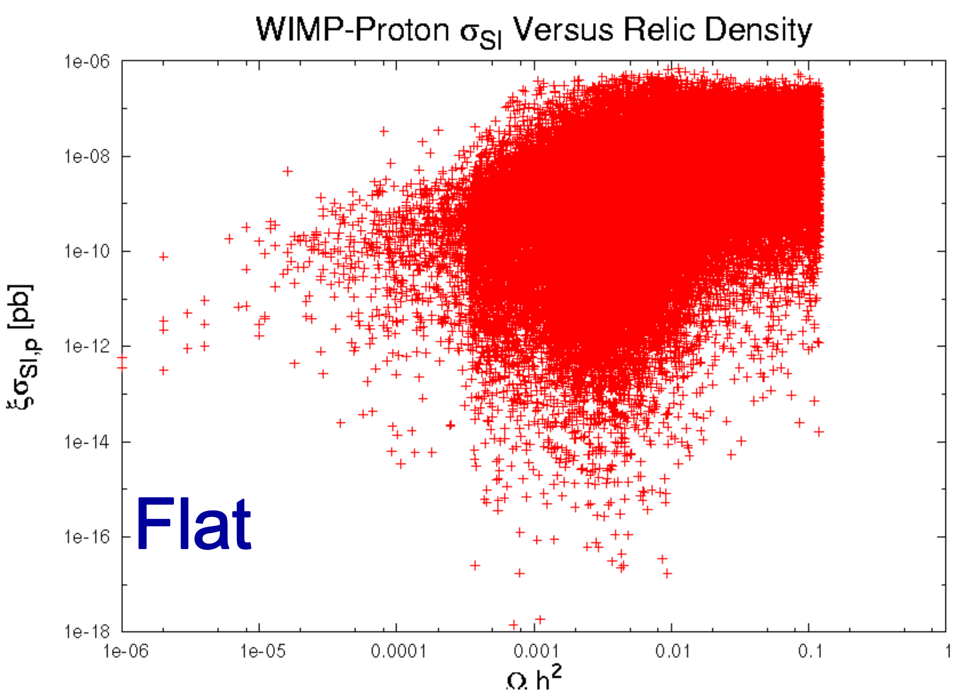
Correlation Between Dark Matter Density & the LSP-nLSP Mass Splitting

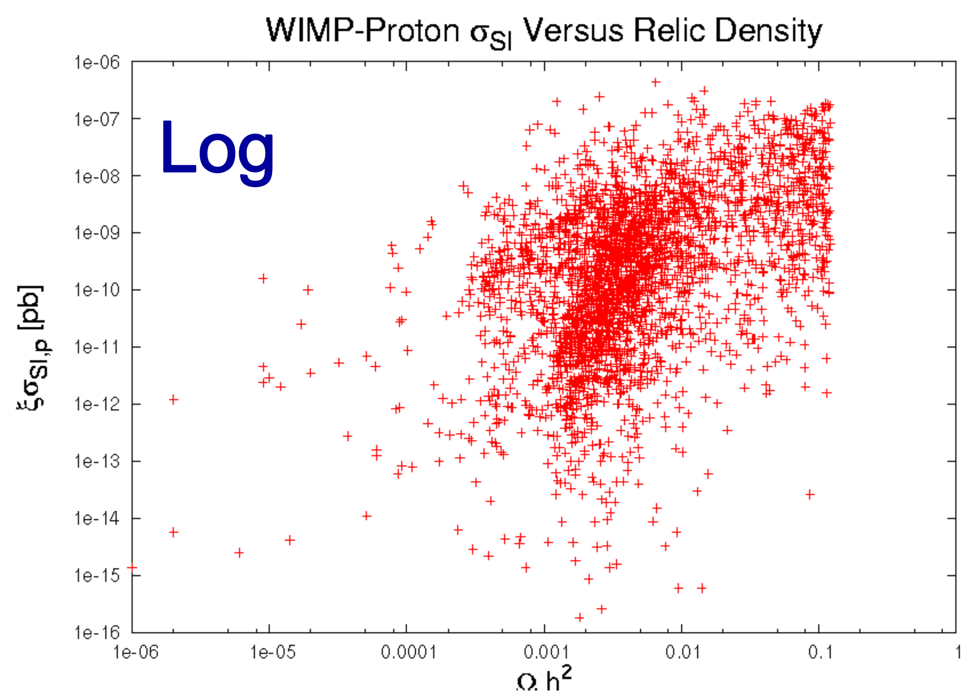
Small mass differences can lead to rapid co-annihilations reducing the dark matter density….





Dark Matter Density Correlation with the Direct Search Cross Section





ATLAS

SU1 OK
SU2 killed by LEP
SU3 killed by Ωh^2
SU4 killed by $b \rightarrow s\gamma$
SU8 killed by g-2

CMS

LM1 killed by Higgs
LM2 killed by g-2
LM3 killed by $b \rightarrow s\gamma$
LM4 killed by Ωh^2
LM5 killed by Ωh^2
LM6 OK
LM7 killed by LEP
LM8 killed by Ωh^2
LM9 killed by LEP
LM10 OK
HM2 killed by Ωh^2
HM3 killed by Ωh^2
HM4 killed by Ωh^2

For the curious:

Most well-studied models do not survive confrontation with the latest data.

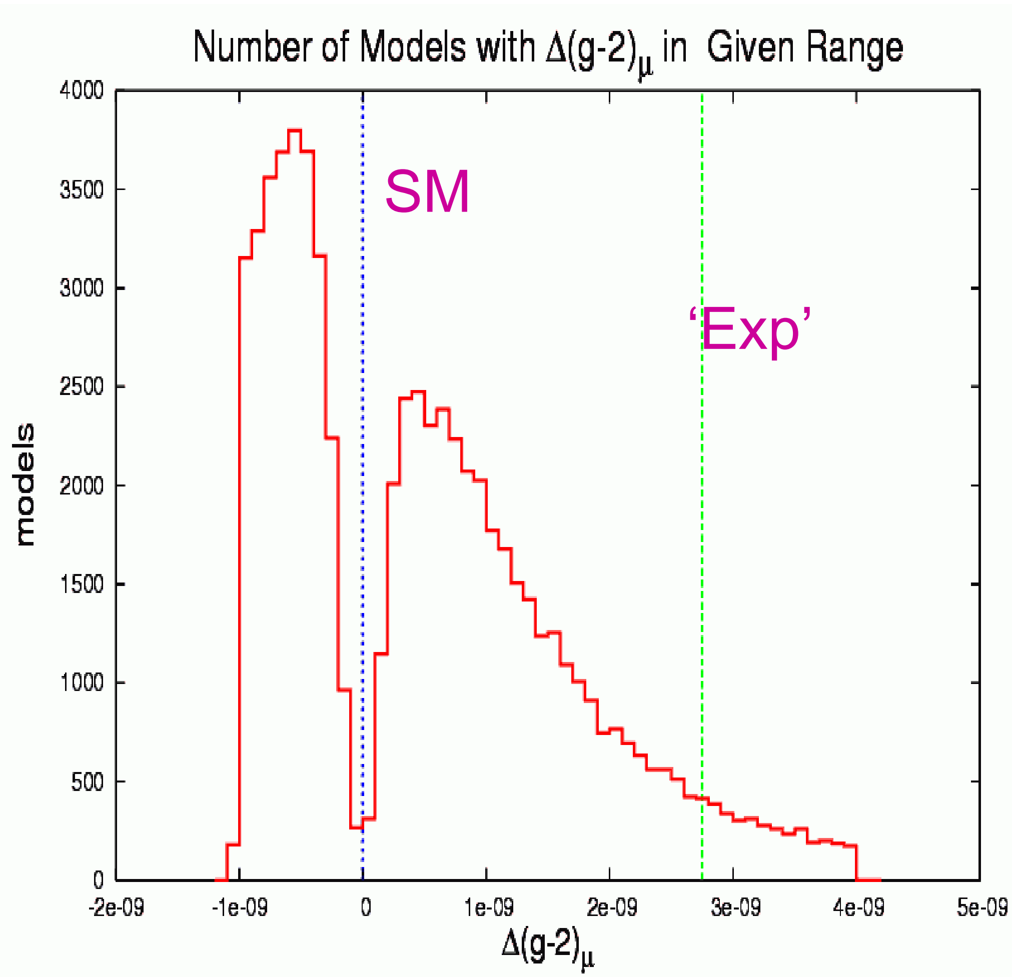
For many models this is not the unique source of failure

Similarly for the SPS Points

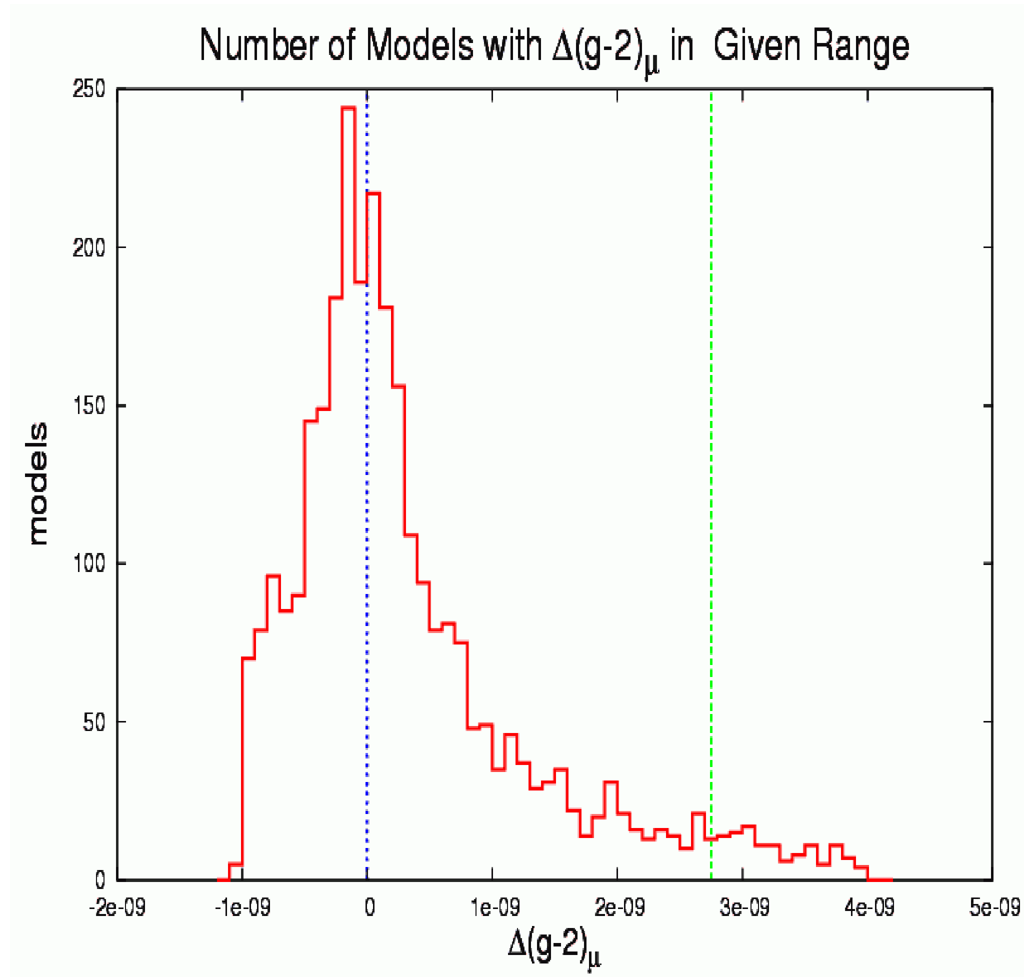
SPS1a	killed by b $\rightarrow s\gamma$
SPS1a'	OK
SPS1b	killed by b $\rightarrow s\gamma$
SPS2	killed by Ωh^2 (GUT) / OK(low)
SPS3	killed by Ωh^2 (low) / OK(GUT)
SPS4	killed by g-2
SPS5	killed by Ωh^2
SPS6	OK
SPS9	killed by Tevatron stable chargino

Predictions for $\Delta(g\text{-}2)_\mu$

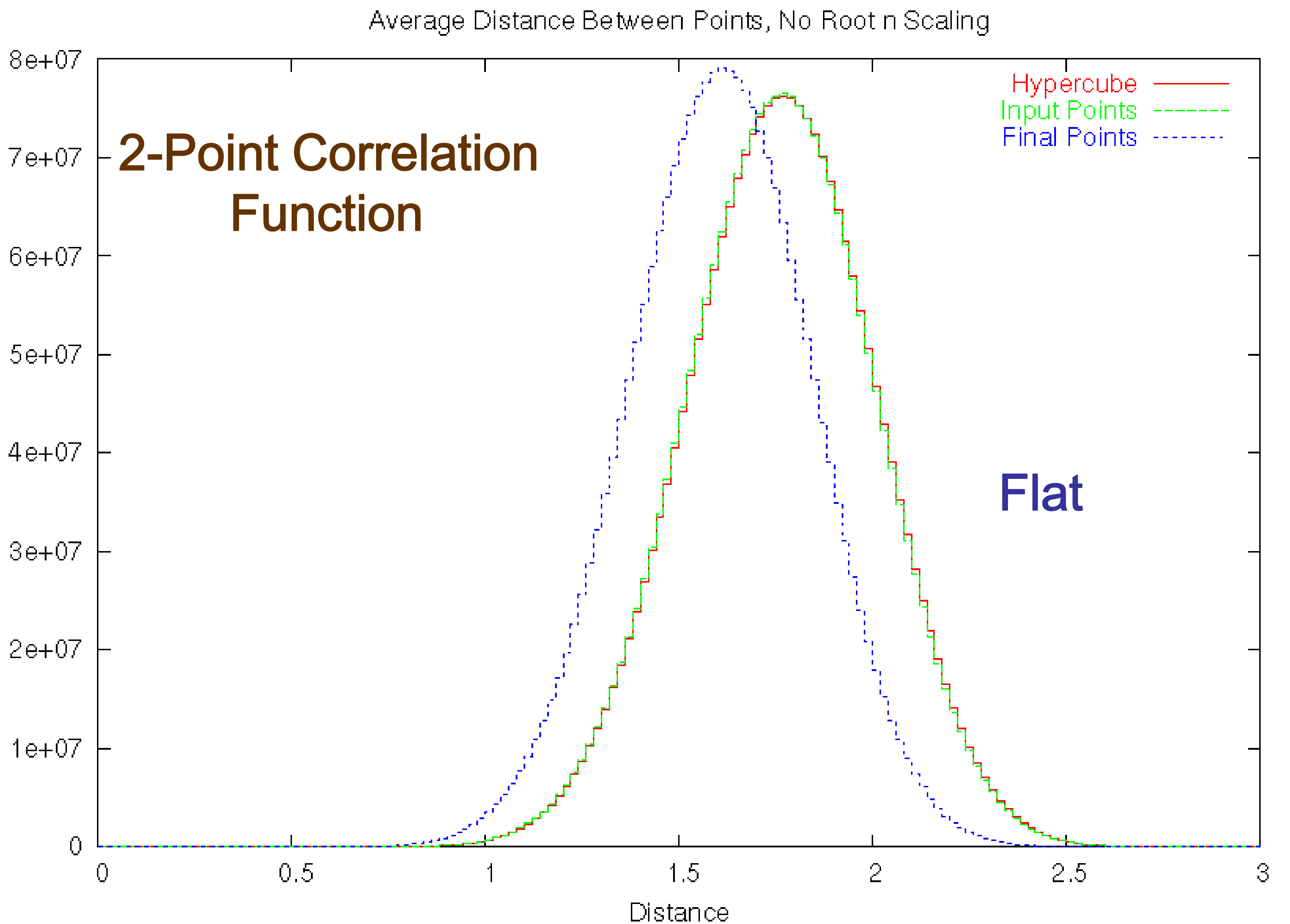
flat

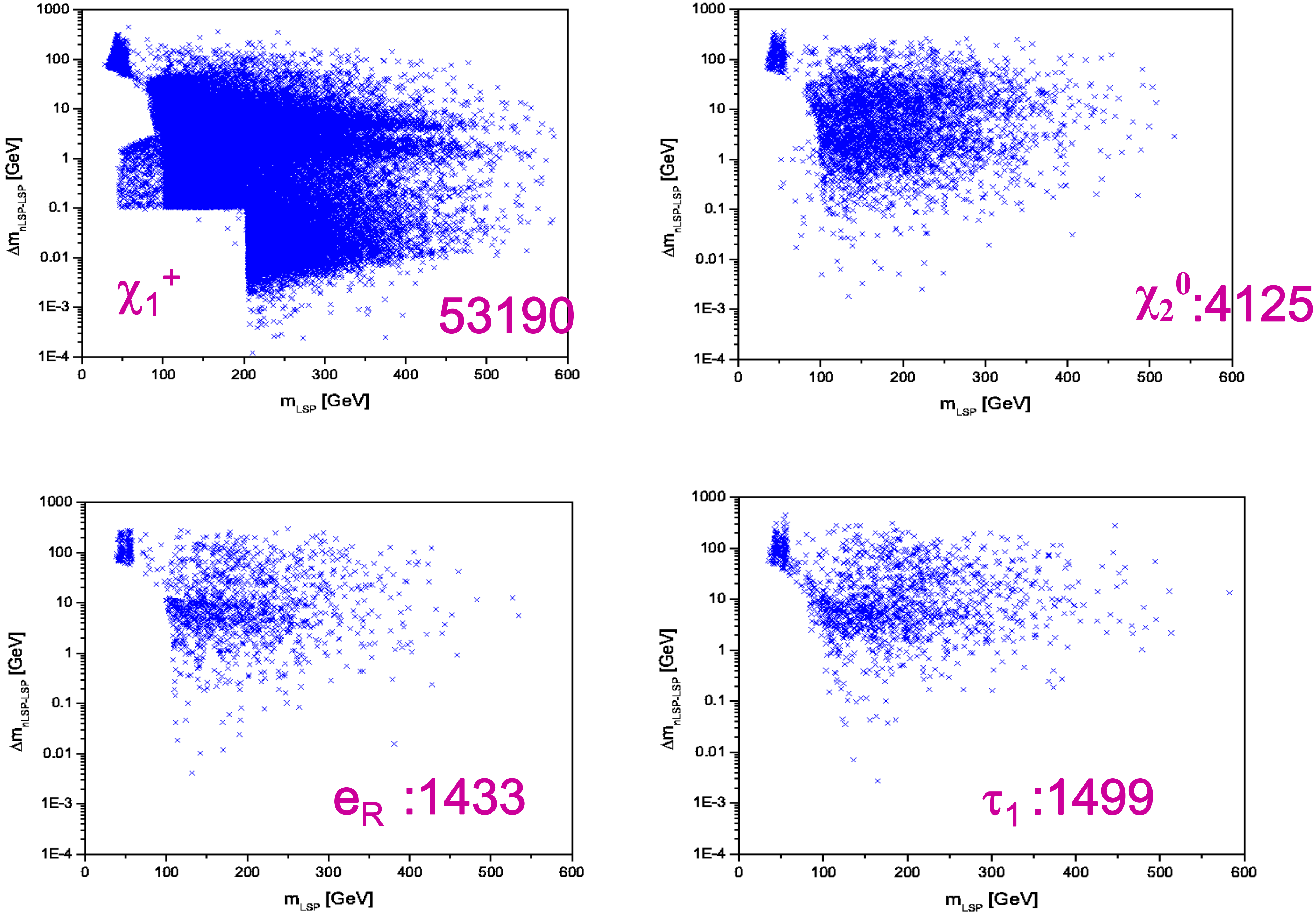


log

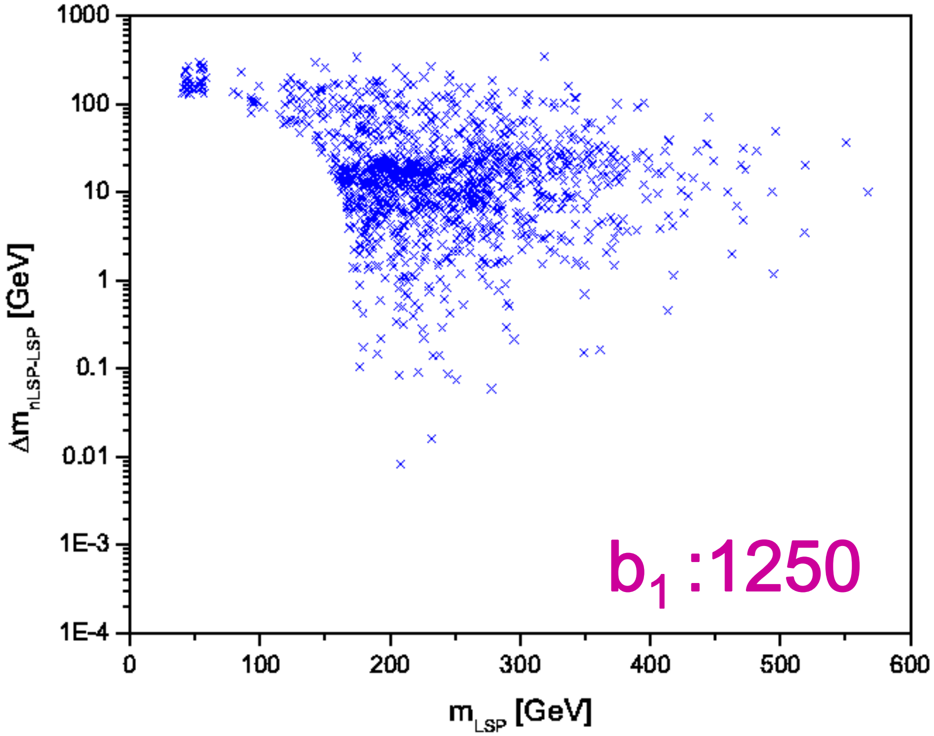


Clustering of Model Points in 19-Dimensional Space

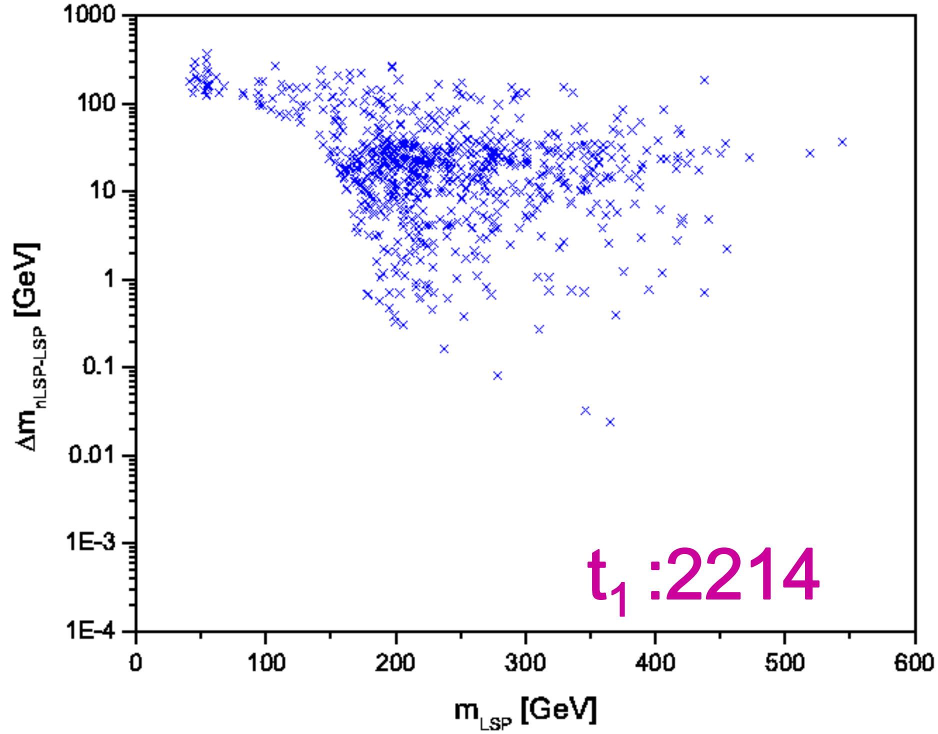




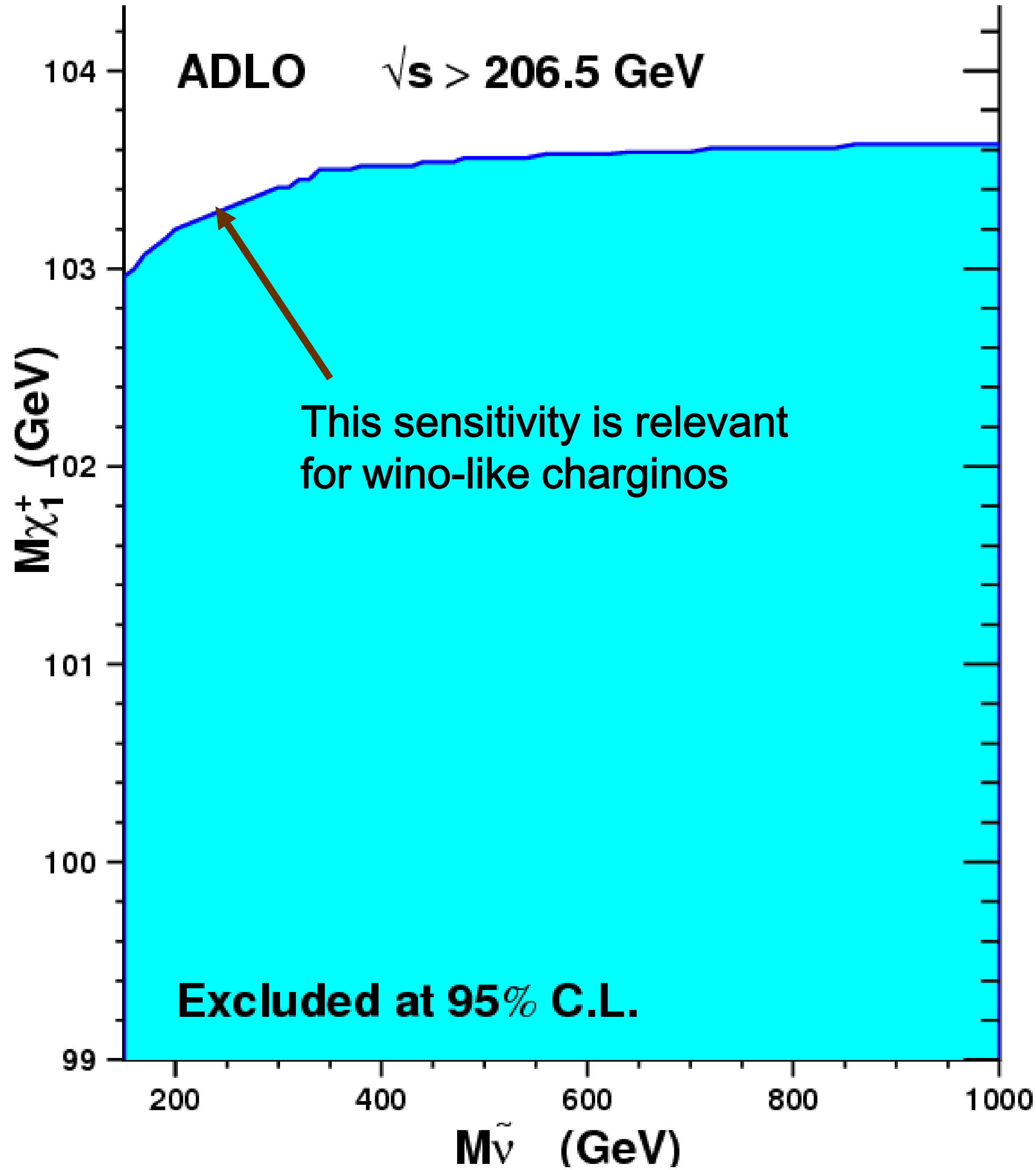
χ_1^+
53190
χ_2^0:4125
e_R :1433
τ_1 :1499
$\Delta m_{nLSP-LSP}$ [GeV]
m_{LSP} [GeV]



1000
100
10
1
0.1
0.01
1E-3
1E-4
Δm_nLSP-LSP [GeV]
0
100
200
300
400
500
600
m_LSP [GeV]
b1 :1250



1000
100
10
1
0.1
0.01
1E-3
1E-4
Δm_nLSP-LSP [GeV]
0
100
200
300
400
500
600
m_LSP [GeV]
t1 :2214

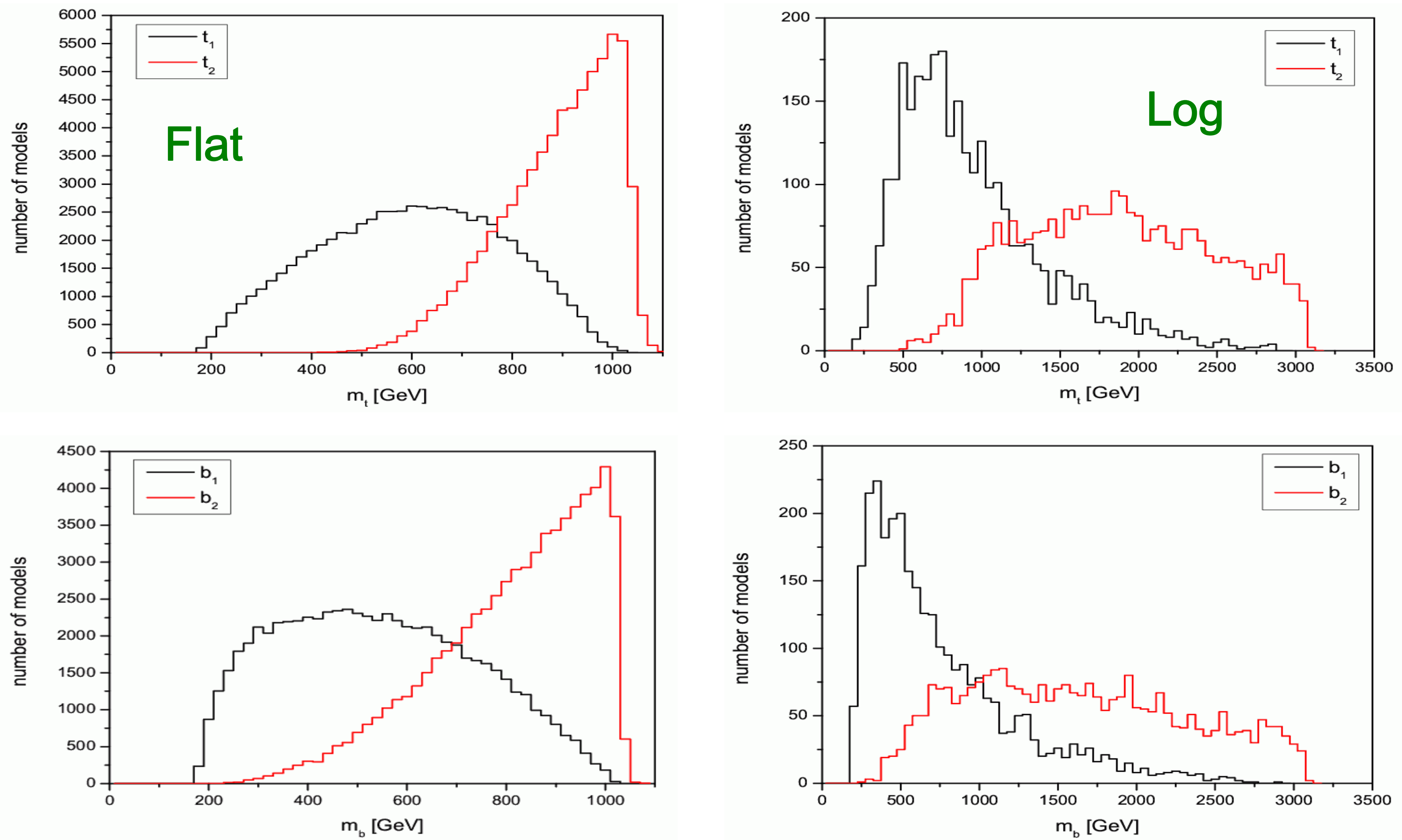


Large mass gap chargino search

Depends on the sneutrino mass in the t-channel if less than ~ 160 GeV due to interference if large wino content

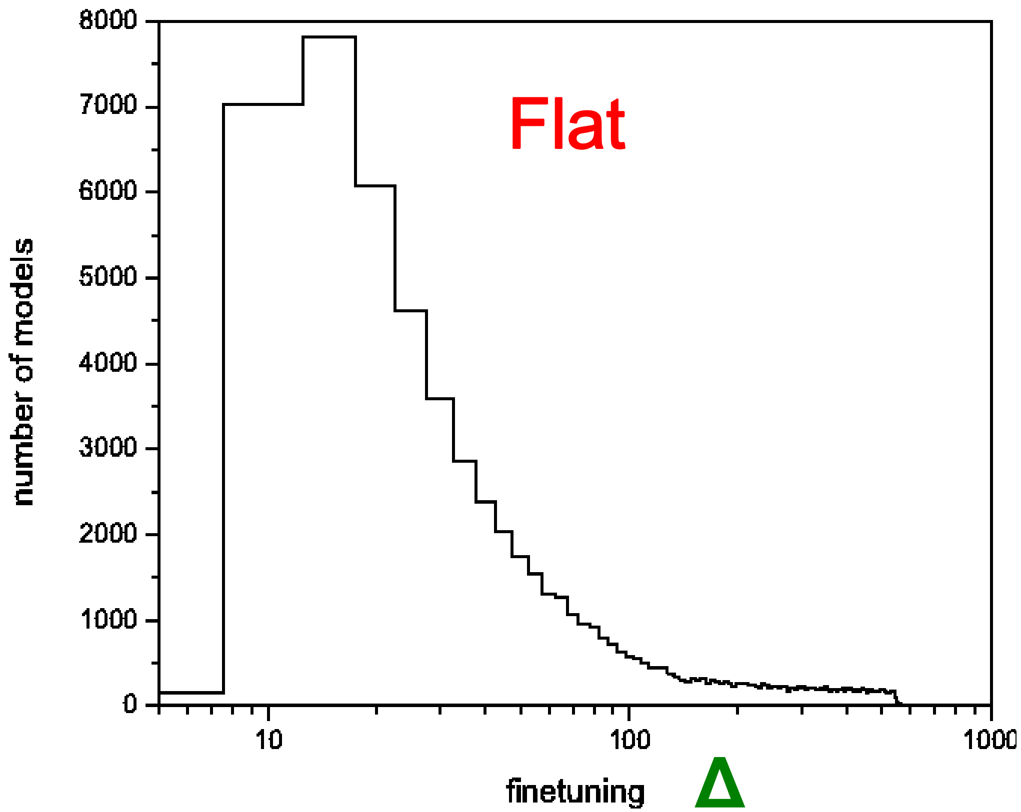
Some 'light' charginos may slip through as search reach is degraded

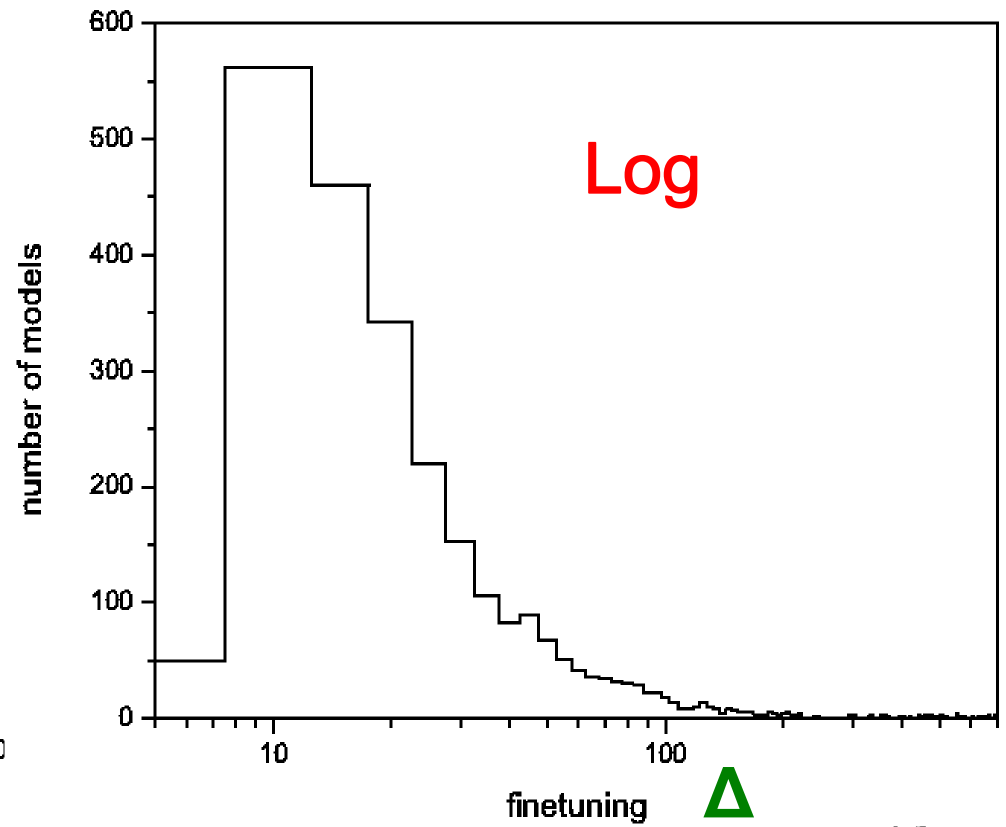
Distribution of Sparticle Masses By Species



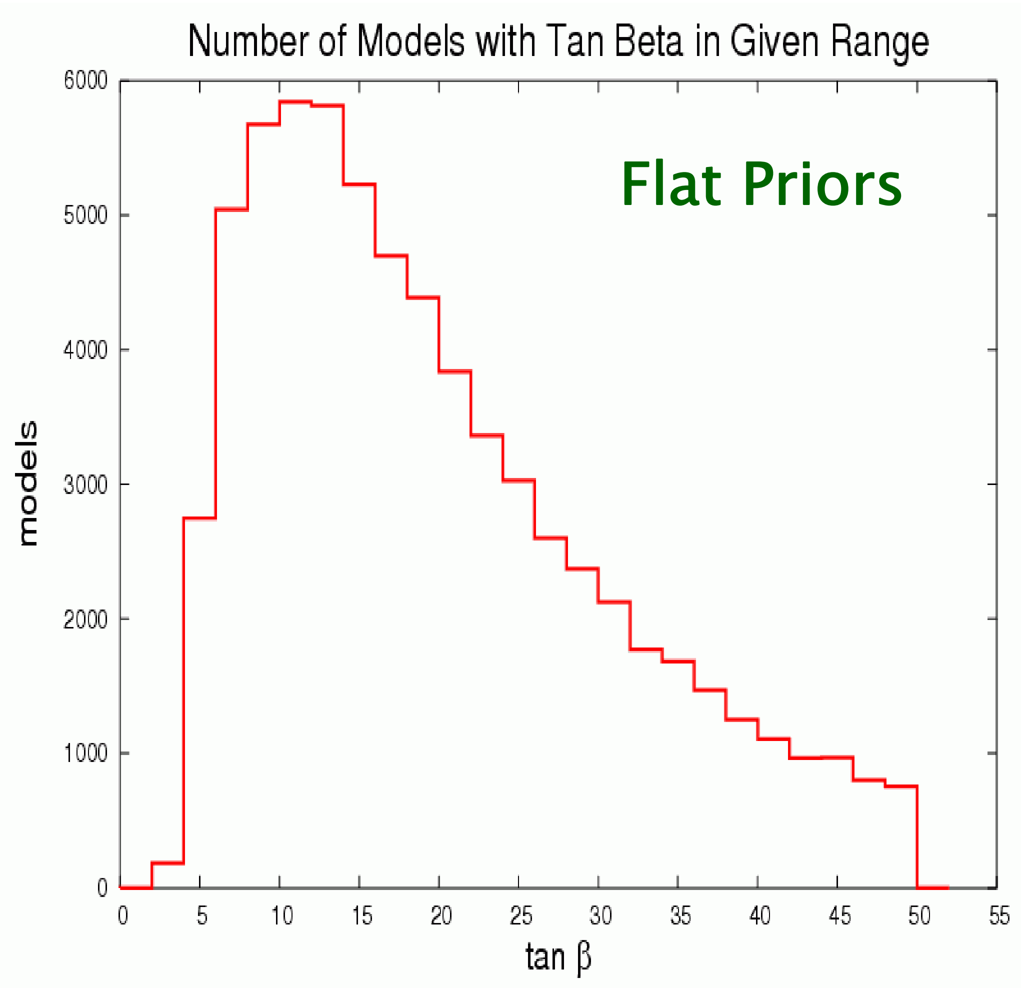
‘Fine-Tuning’ or Naturalness Criterion

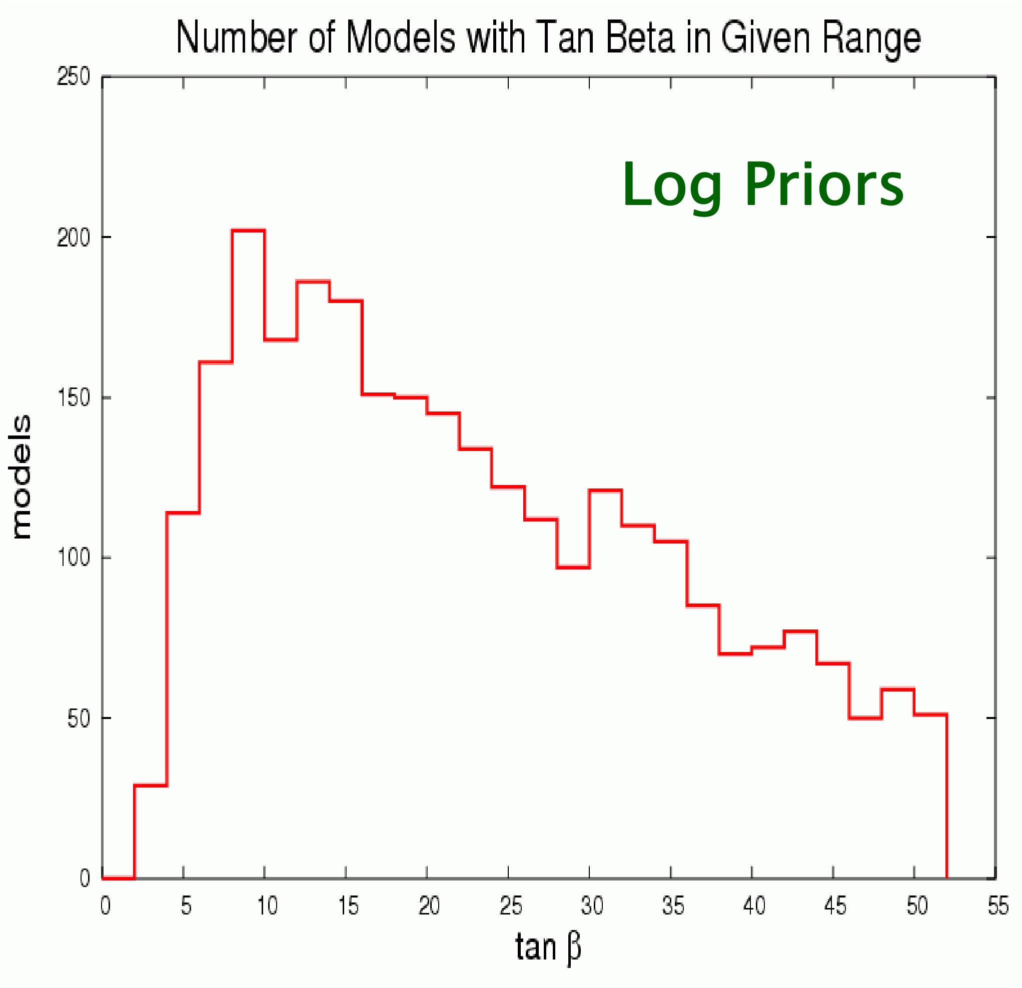
We find that small values of `fine-tuning’ are very common !





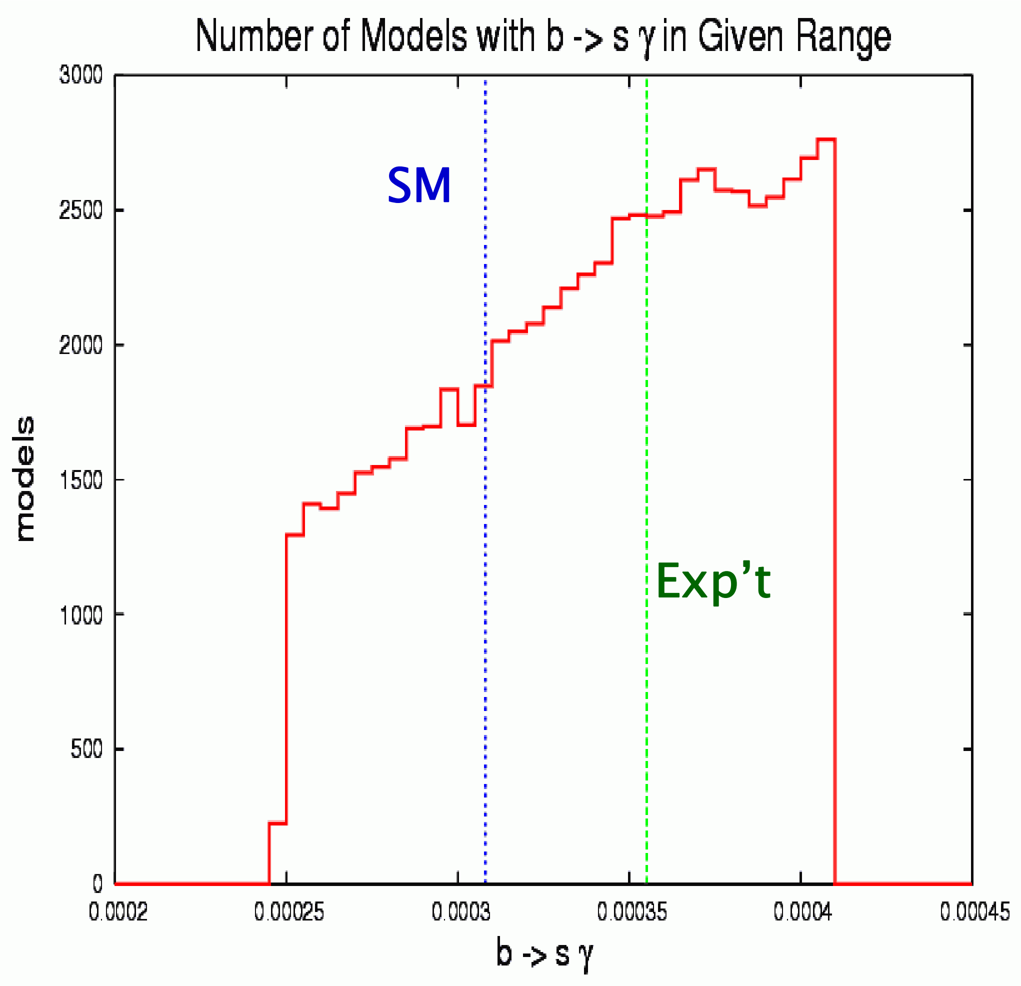
Distribution for tan beta



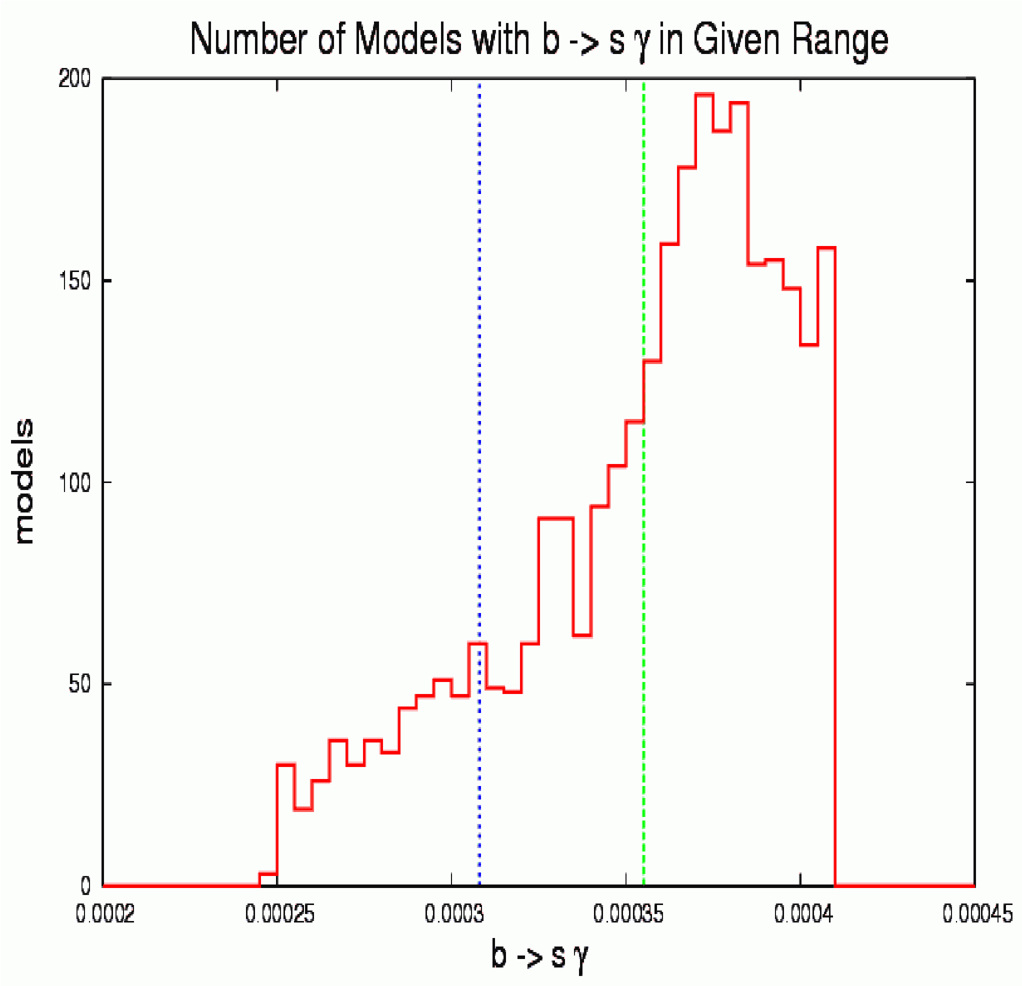


Predictions for b→sγ

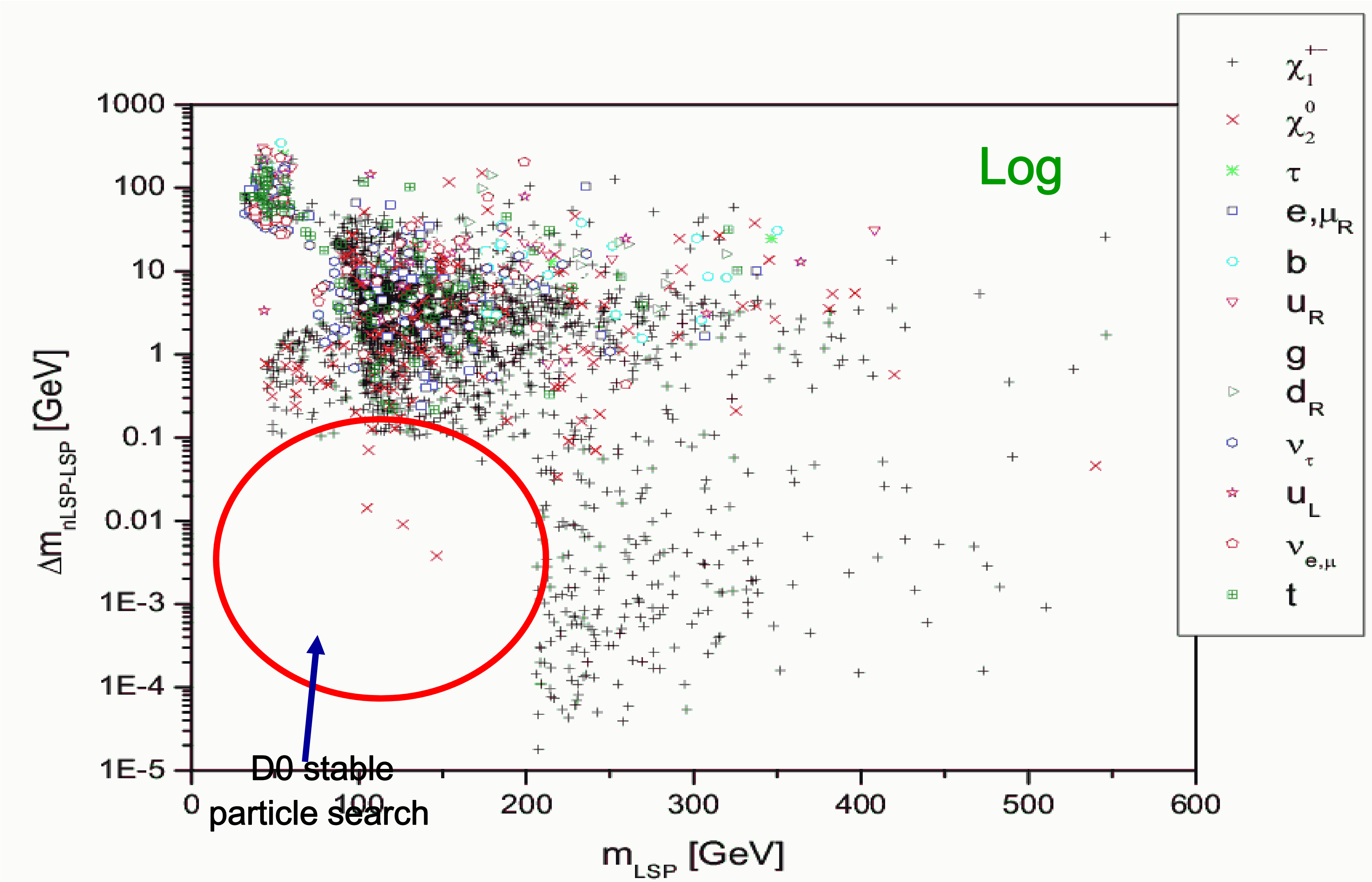
Flat Priors



Log Priors



nLSP-LSP Mass Difference



LSP Composition