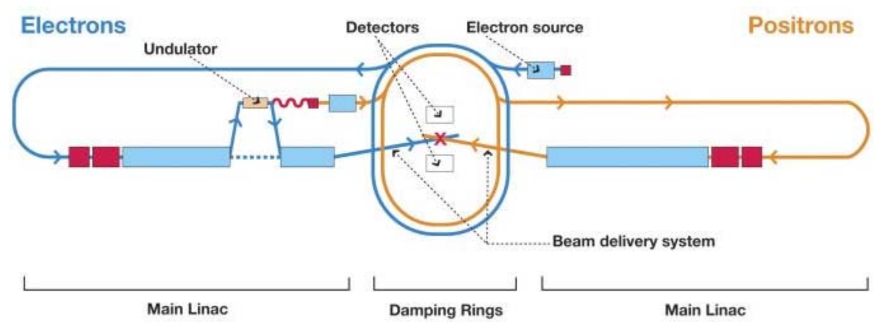
Supersymmetry Without (Much) Prejudice



SLAC NATIONAL ACCELERATOR LABORATORY

C. F. Berger, J.A. Conley, R.C. Cotta, J. S. Gainer,
J. L. Hewett & 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)

How? Perform 2 Random Scans

Linear Priors

10^7 points – emphasizes moderate masses

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

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

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

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

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

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

Log Priors

2×10^6 points – emphasizes lower masses but extends to higher masses

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

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

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

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

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

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

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

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

Successful models

Constraints

- $-0.0007 < \Delta\rho < 0.0026$ (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.

Example :

Zh, h-> bb, ττ

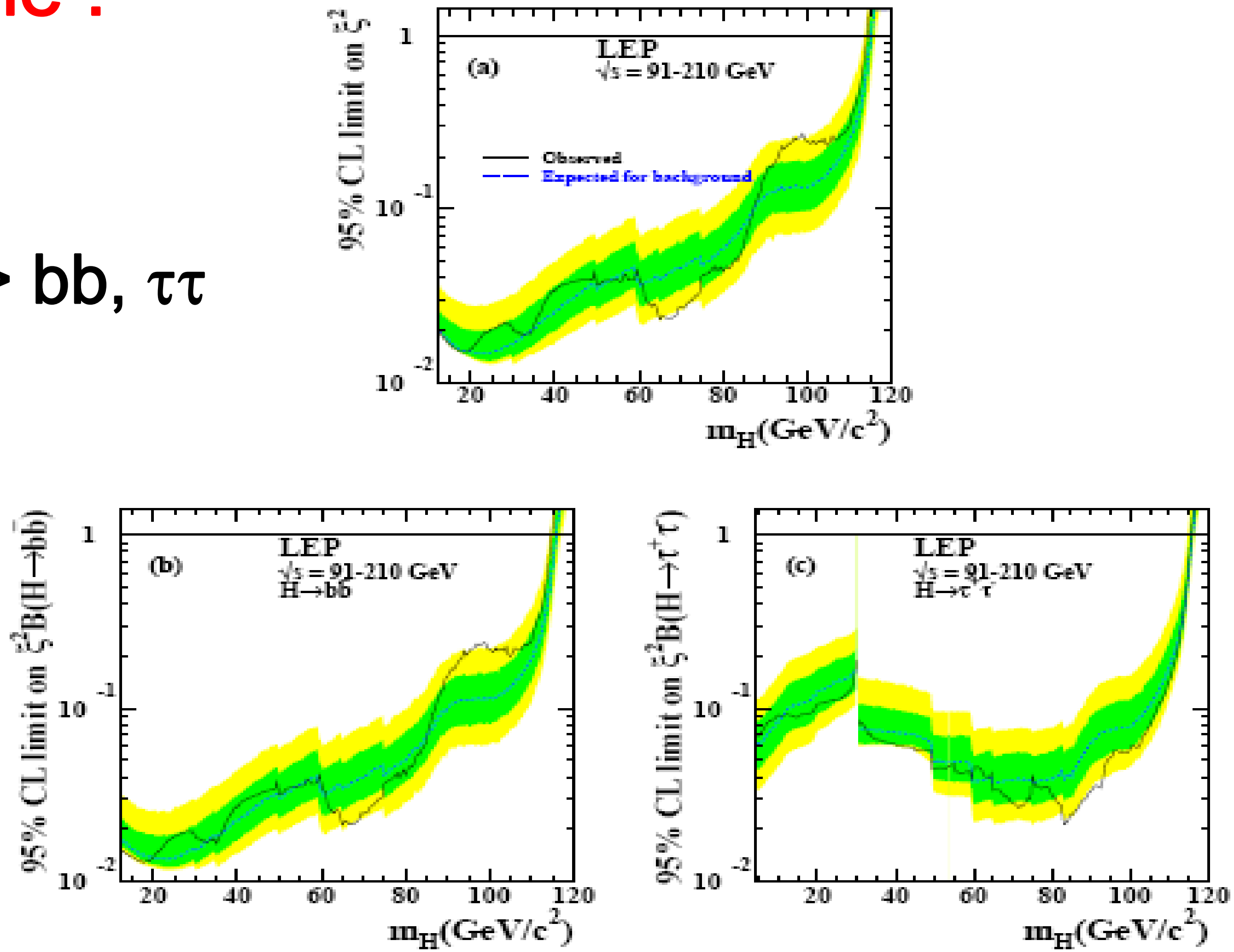
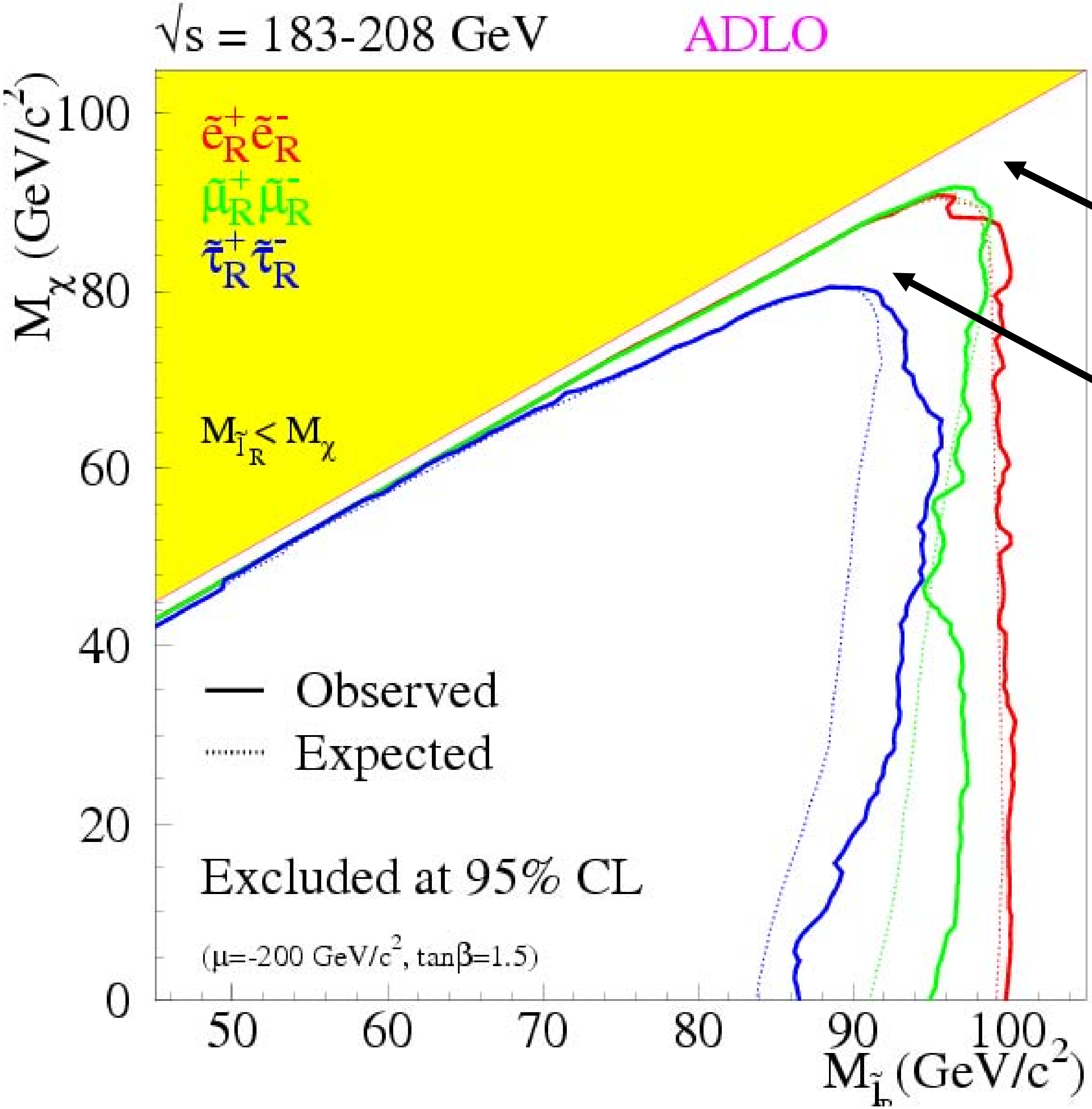


Figure 1: *The 95% c.l. upper bound on the coupling ratio $\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$ (see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling. (a): 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.*

Example :

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

Example :

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 ($|\eta_{det}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.
[b] Third and fourth jets are required to have $|\eta_{det}| < 2.5$, 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

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)	$\sigma_{\rm nom}$ (pb)	$\epsilon_{\rm sig.}$ (%)	$N_{\rm obs.}$	$N_{\rm backgrd.}$	$N_{\rm sig.}$	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"	$N_{\rm obs.}$	$N_{\rm backgrd.}$
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 ± 0.13(stat) ± 0.29(syst)	0.49 ± 0.04(stat) ± 0.08(syst)	1
2tight,1loose	1.61 ± 0.11(stat) ± 0.21(syst)	0.25 ± 0.03(stat) ± 0.03(syst)	0
1tight,2loose	0.68 ± 0.07(stat) ± 0.09(syst)	0.14 ± 0.02(stat) ± 0.02(syst)	0
Total Trilepton	4.5 ± 0.2(stat) ± 0.6(syst)	0.88 ± 0.05(stat) ± 0.13(syst)	1
2tight,1Track	4.44 ± 0.19(stat) ± 0.58(syst)	3.22 ± 0.48(stat) ± 0.53(syst)	4
1tight,1loose,1Track	2.42 ± 0.14(stat) ± 0.32(syst)	2.28 ± 0.47(stat) ± 0.42(syst)	2
Total Dilepton+Track	6.9 ± 0.2(stat) ± 0.9(syst)	5.5 ± 0.7(stat) ± 0.9(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

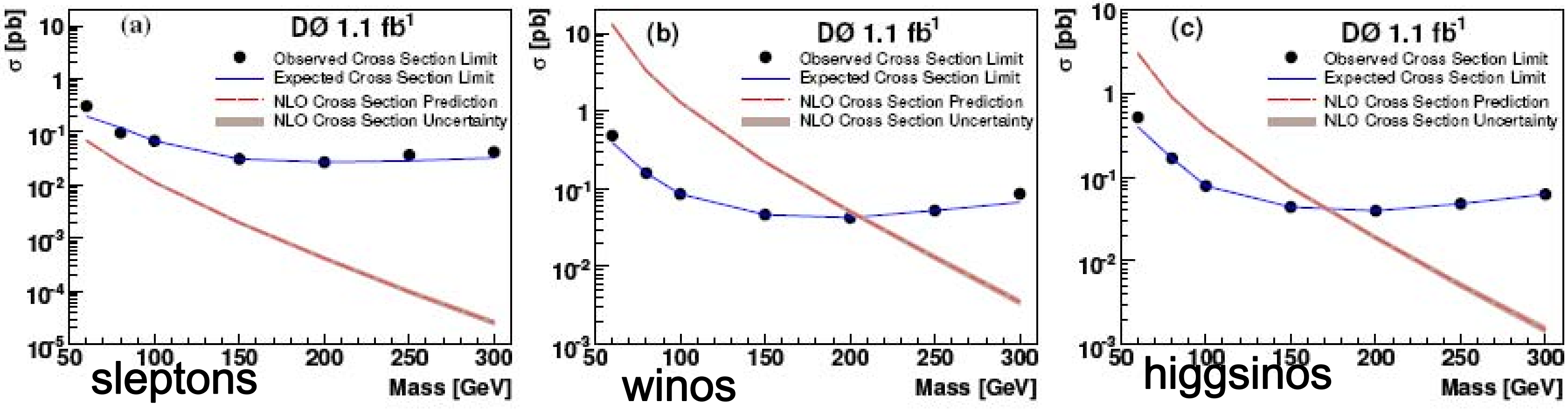


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos,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

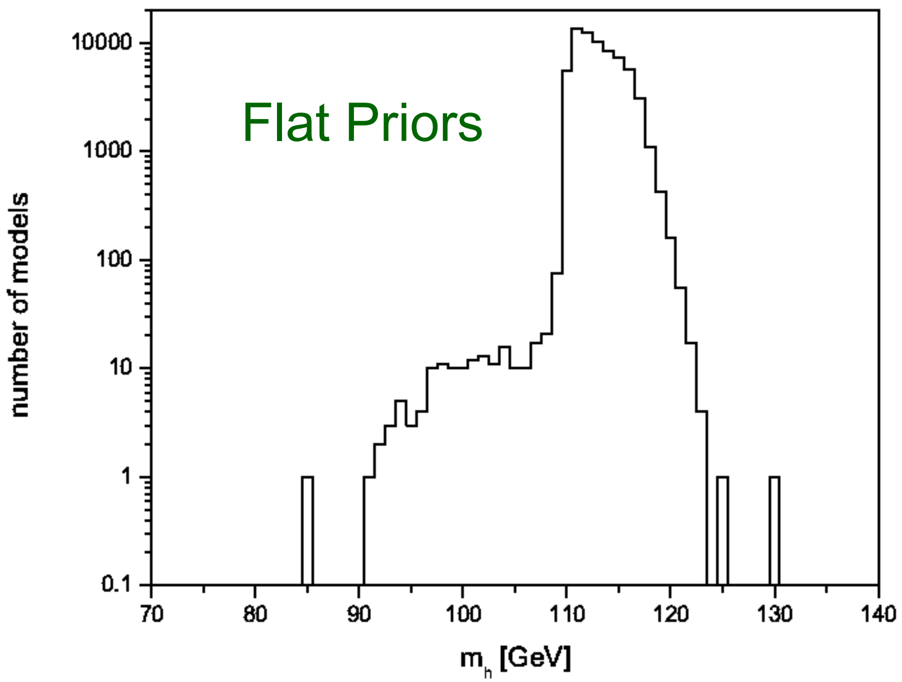
Survival Rates

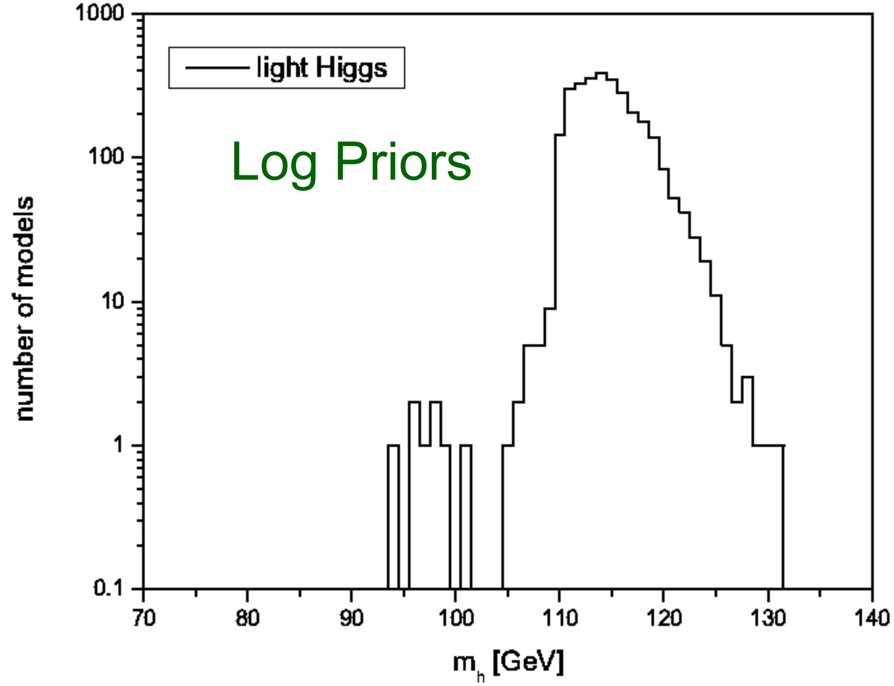
file	Description	Percent of Models Remaining
slha-okay.txt	SuSpect generates SLHA file	99.99 %
error-okay.txt	Spectrum tachyon, other error free	77.29%
lsp-okay.txt	LSP the lightest neutralino	32.70 %
deltaRho-okay.txt	$\Delta\rho$	32.61 %
gMinus2-okay.txt	$g - 2$	21.69 %
b2sGamma-okay.txt	$b \longrightarrow s\gamma$	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

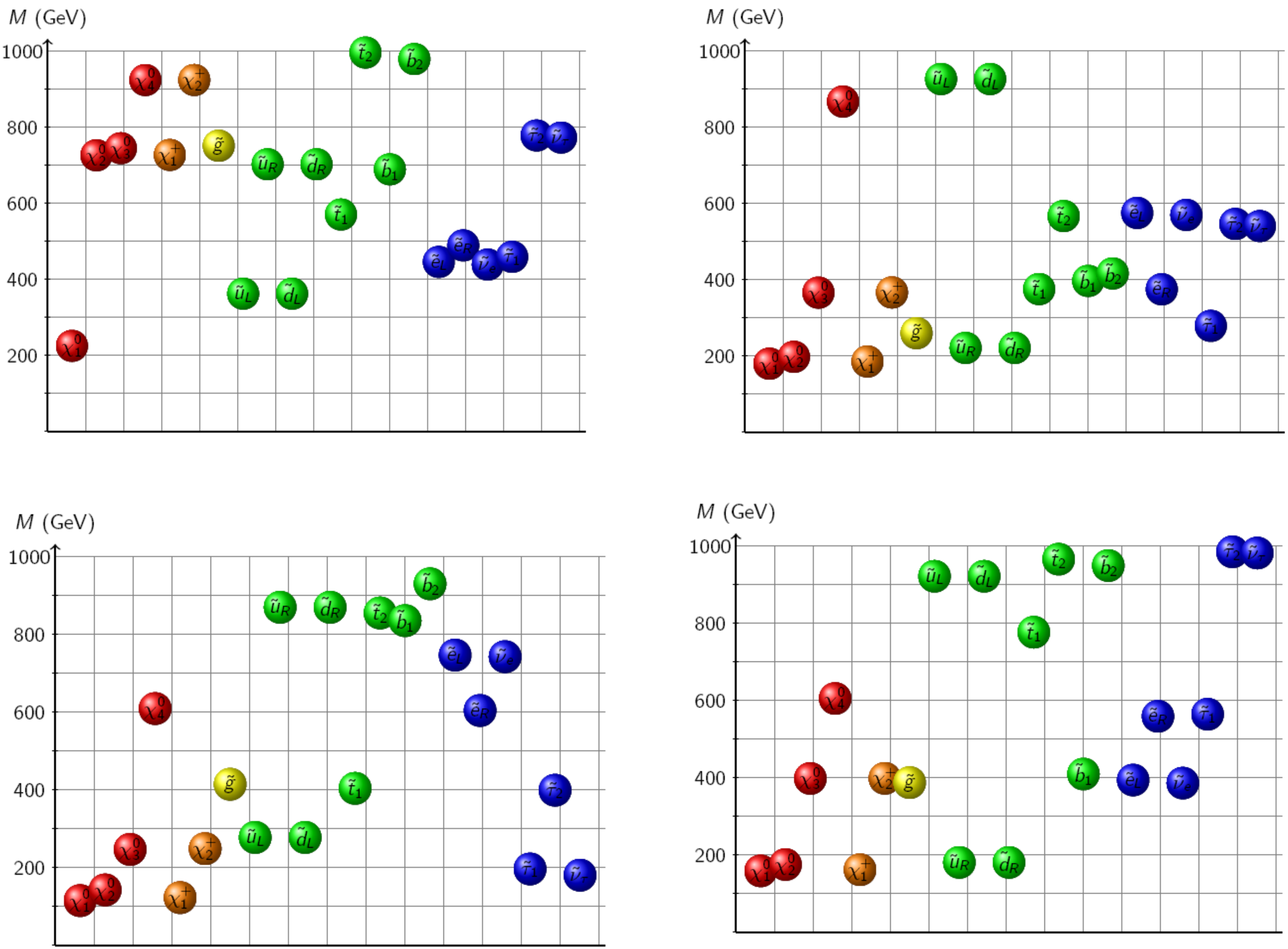
- Log Priors : 2×10^6 models scanned , ~ 2.7 K (0.13%) survive

Light Higgs Mass Predictions



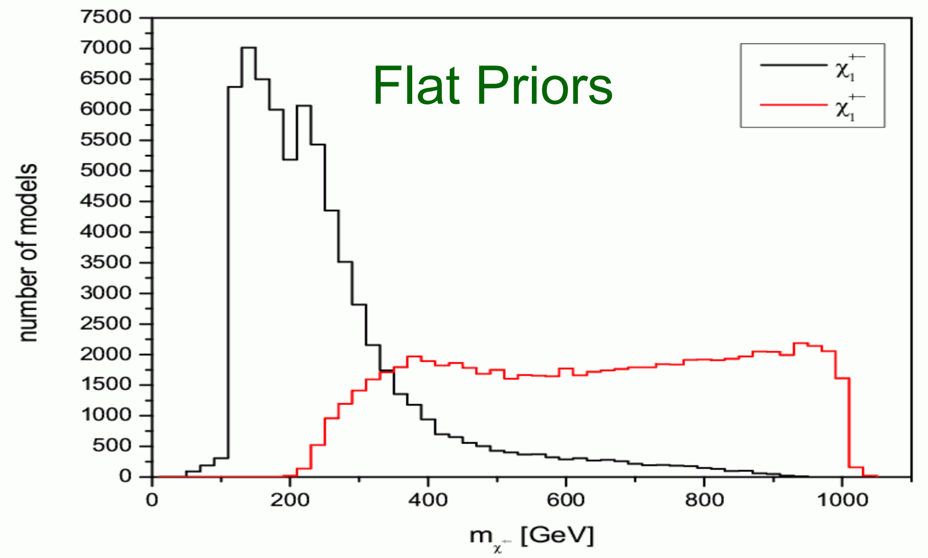


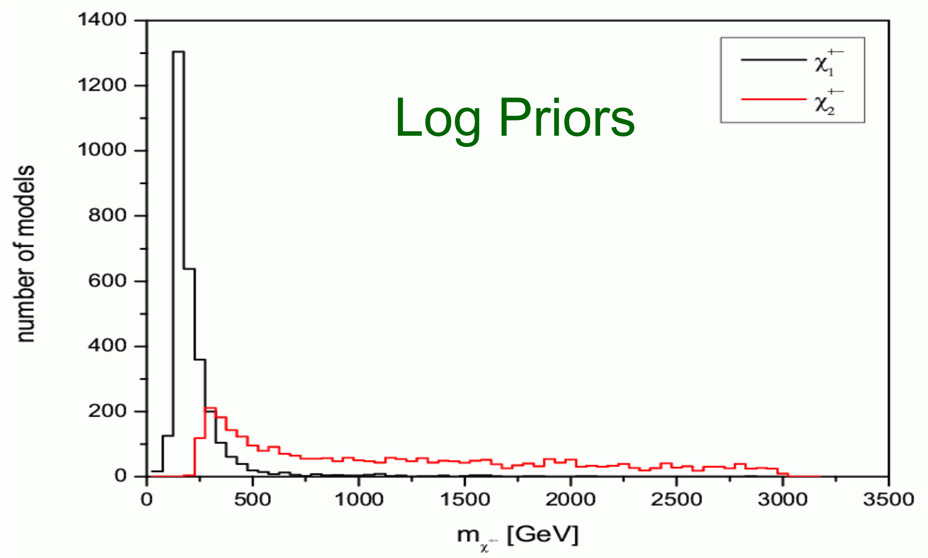
LEP Higgs mass constraints avoided by either reducing the ZZh coupling and/or reducing the, e.g., $h \rightarrow b\bar{b}$ branching fraction by decays to LSP pairs. We have both of these cases in our final model sets.

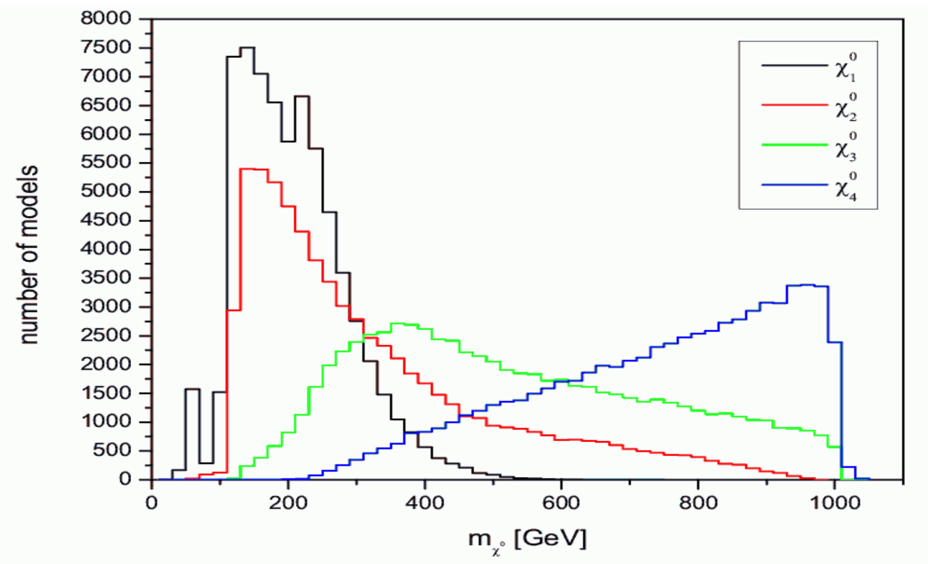


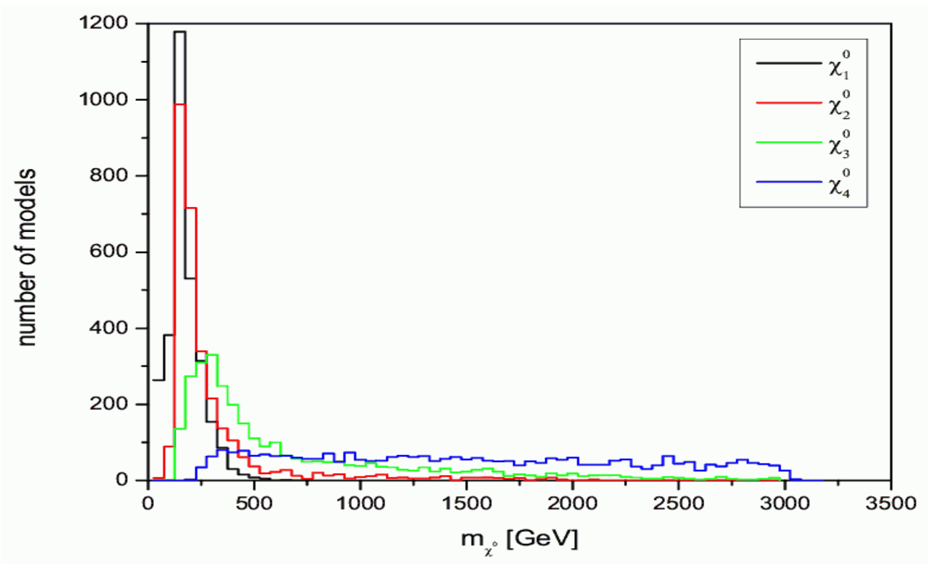
M (GeV)
1000
800
600
400
200
χ_4^0 χ_2^+ $\tilde{t}_2$ $\tilde{b}_2$
χ_2^0 χ_3^0 χ_1^+ $\tilde{g}$ $\tilde{u}_R$ $\tilde{d}_R$ $\tilde{b}_1$ $\tilde{\tau}_2$ $\tilde{\nu}_\tau$
$\tilde{t}_1$ $\tilde{e}_R$ $\tilde{e}_L$ $\tilde{\nu}_e$ $\tilde{\tau}_1$
$\tilde{u}_L$ $\tilde{d}_L$ χ_1^0
M (GeV)
1000
800
600
400
200
$\tilde{u}_L$ $\tilde{d}_L$ χ_4^0
$\tilde{t}_2$ $\tilde{e}_L$ $\tilde{\nu}_e$ $\tilde{\tau}_2$ $\tilde{\nu}_\tau$
χ_3^0 χ_2^+ $\tilde{t}_1$ $\tilde{b}_1$ $\tilde{b}_2$ $\tilde{e}_R$ $\tilde{\tau}_1$
$\tilde{g}$ $\tilde{u}_R$ $\tilde{d}_R$
χ_1^0 χ_2^0 χ_1^+
M (GeV)
1000
800
600
400
200
$\tilde{b}_2$ $\tilde{u}_R$ $\tilde{d}_R$ $\tilde{t}_2$ $\tilde{b}_1$
$\tilde{e}_L$ $\tilde{\nu}_e$
χ_4^0 $\tilde{e}_R$
$\tilde{g}$ $\tilde{t}_1$ $\tilde{\tau}_2$
$\tilde{u}_L$ $\tilde{d}_L$ χ_3^0 χ_2^+
$\tilde{\tau}_1$ $\tilde{\nu}_\tau$
χ_1^0 χ_2^0 χ_1^+
M (GeV)
1000
800
600
400
200
$\tilde{\tau}_2$ $\tilde{\nu}_\tau$ $\tilde{u}_L$ $\tilde{d}_L$ $\tilde{t}_2$ $\tilde{b}_2$
$\tilde{t}_1$
χ_4^0 $\tilde{e}_R$ $\tilde{\tau}_1$
χ_3^0 χ_2^+ $\tilde{g}$ $\tilde{b}_1$ $\tilde{e}_L$ $\tilde{\nu}_e$
$\tilde{u}_R$ $\tilde{d}_R$
χ_1^0 χ_2^0 χ_1^+

Distribution of Sparticle Masses By Species



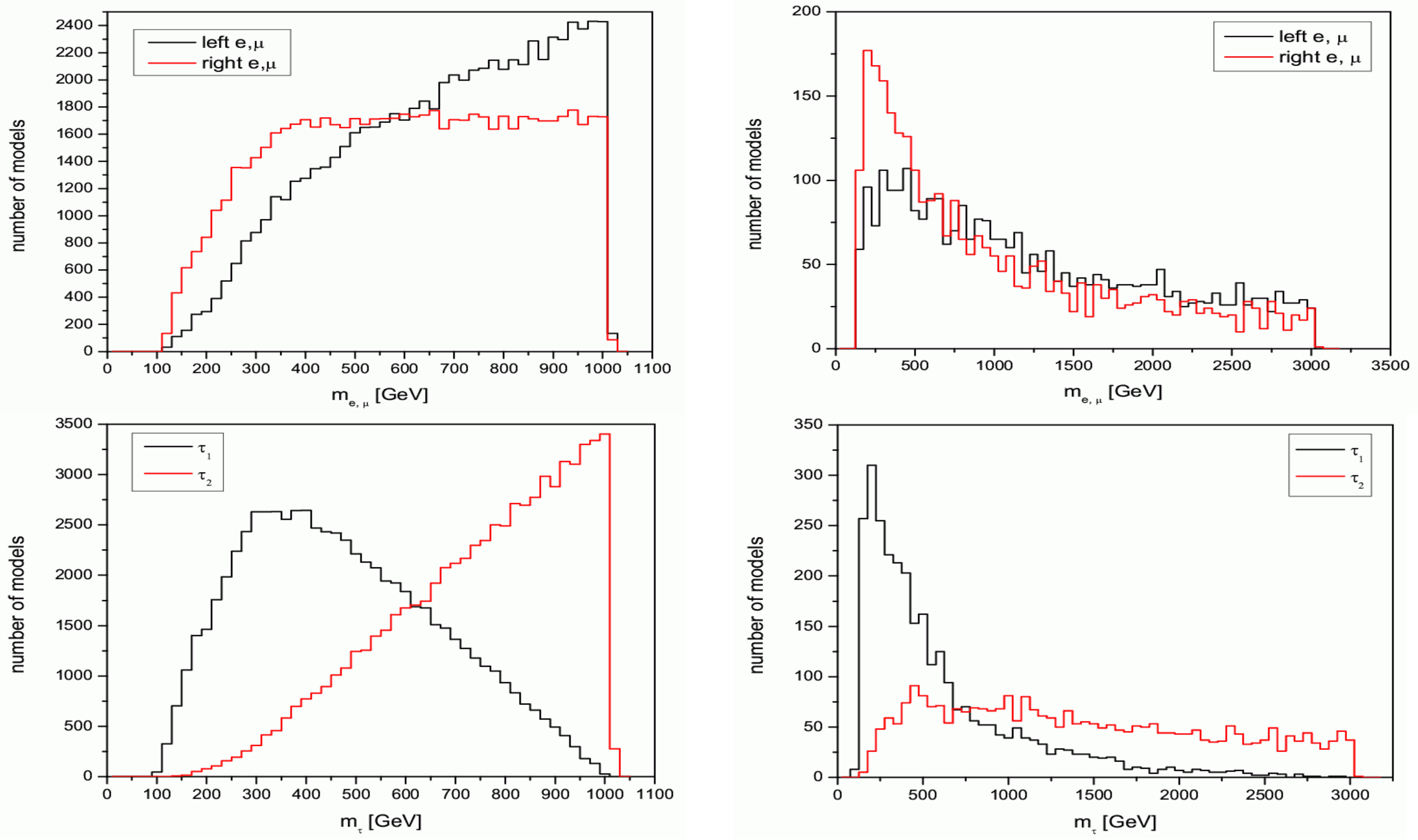




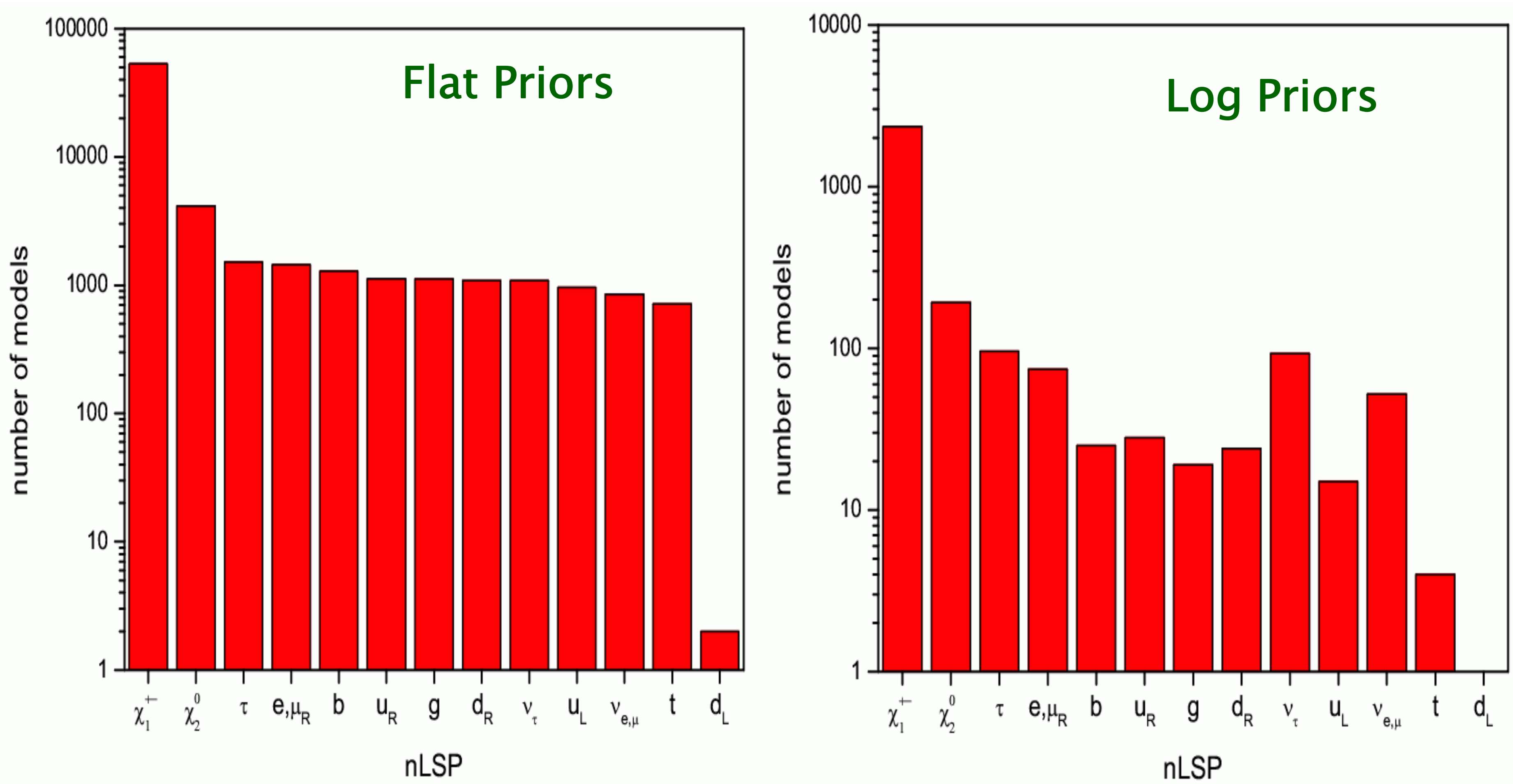


Distribution of Sparticle Masses By Species

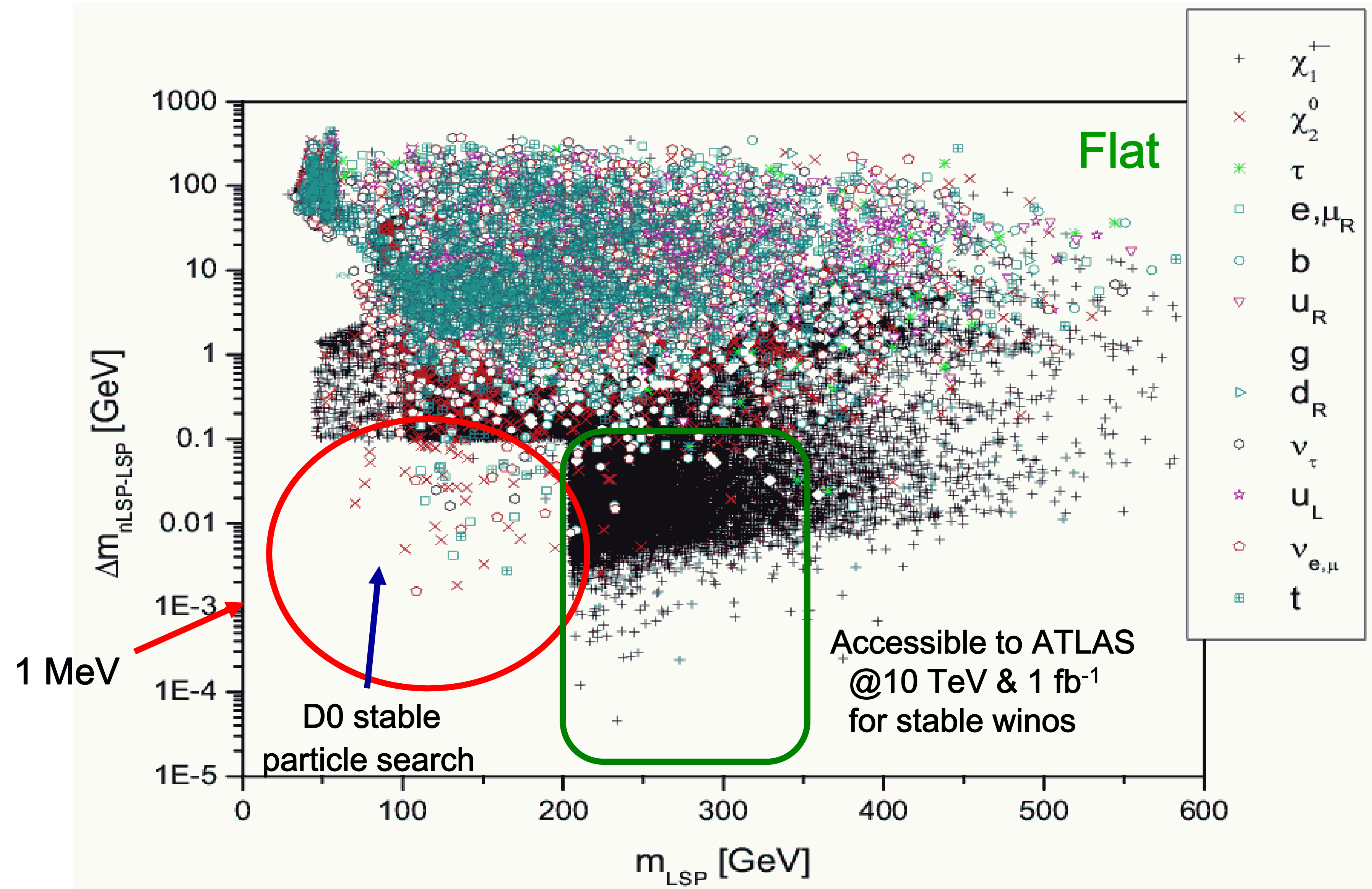
Flat Priors | Log Priors

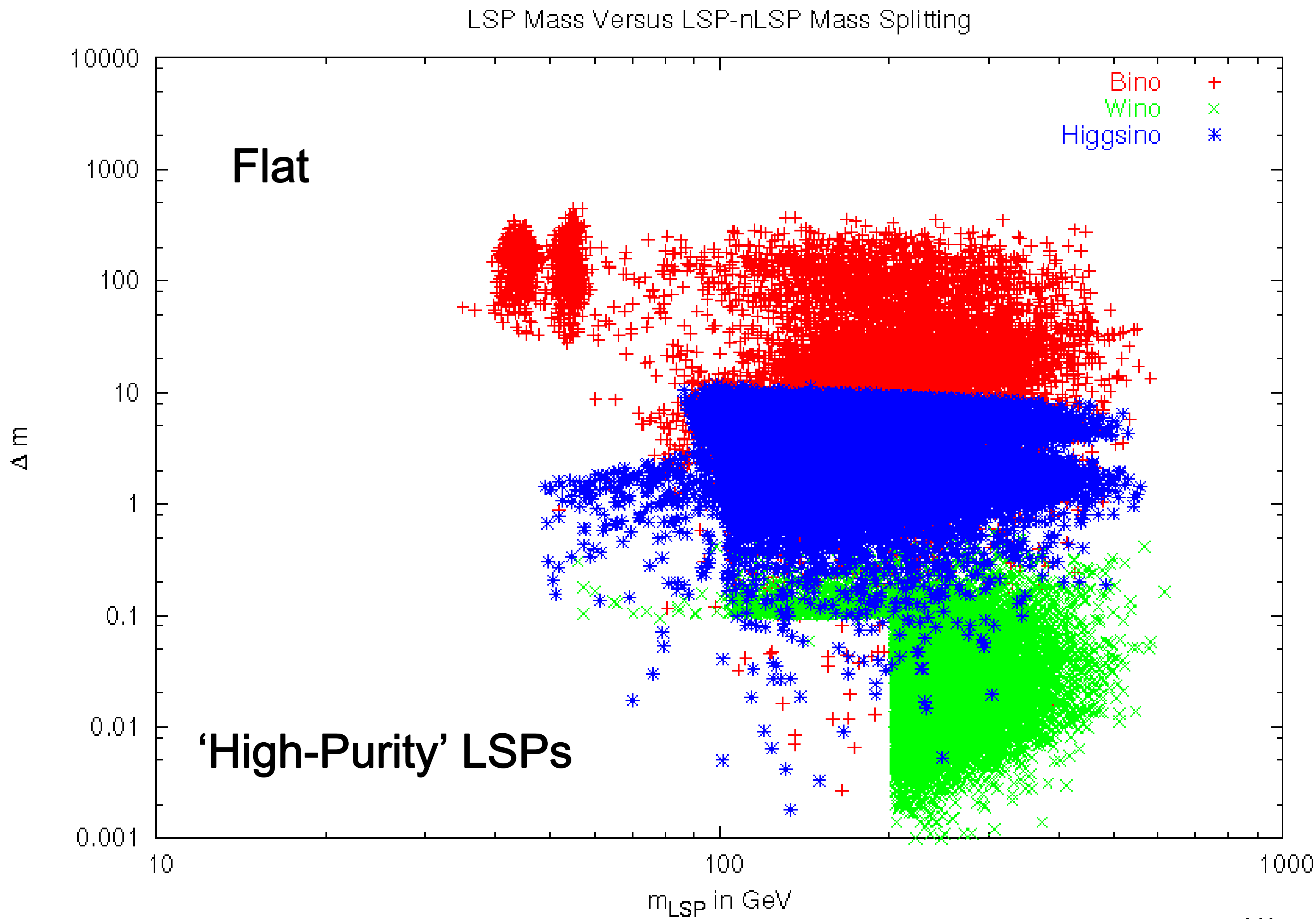


The identity of the nLSP is a critical factor in looking for SUSY signatures..who can play that role here????? Just about ANY of the 13 possibilities !



nLSP-LSP Mass Difference





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

• I have previously discussed the observation of hard jets resulting from possible squark/gluino production, the shortfall of simulation studies & our lack of knowledge of the final state.

• But here we see that another concern is generic stable and/or long-lived particles. These can have soft decay products (that may involve leptons, photons or 'jets') due to, e.g., some small mass splittings between the many possible nLSP's & the LSP.

• Searches for detector-stable charged particles at the LHC should be relatively straightforward depending upon cross sections & whether or not they are 'R-hadrons' . But note that the reaches for stable sleptons & charginos *are NOT so great* even at 14 TeV & full lumi .. leaving 'open space' for a TeV ILC.

• A more 'problematic' example of the long-lived possibility is provided by the second neutralino as the nLSP in the Higgsino limit. The decay products are often too soft to observe.

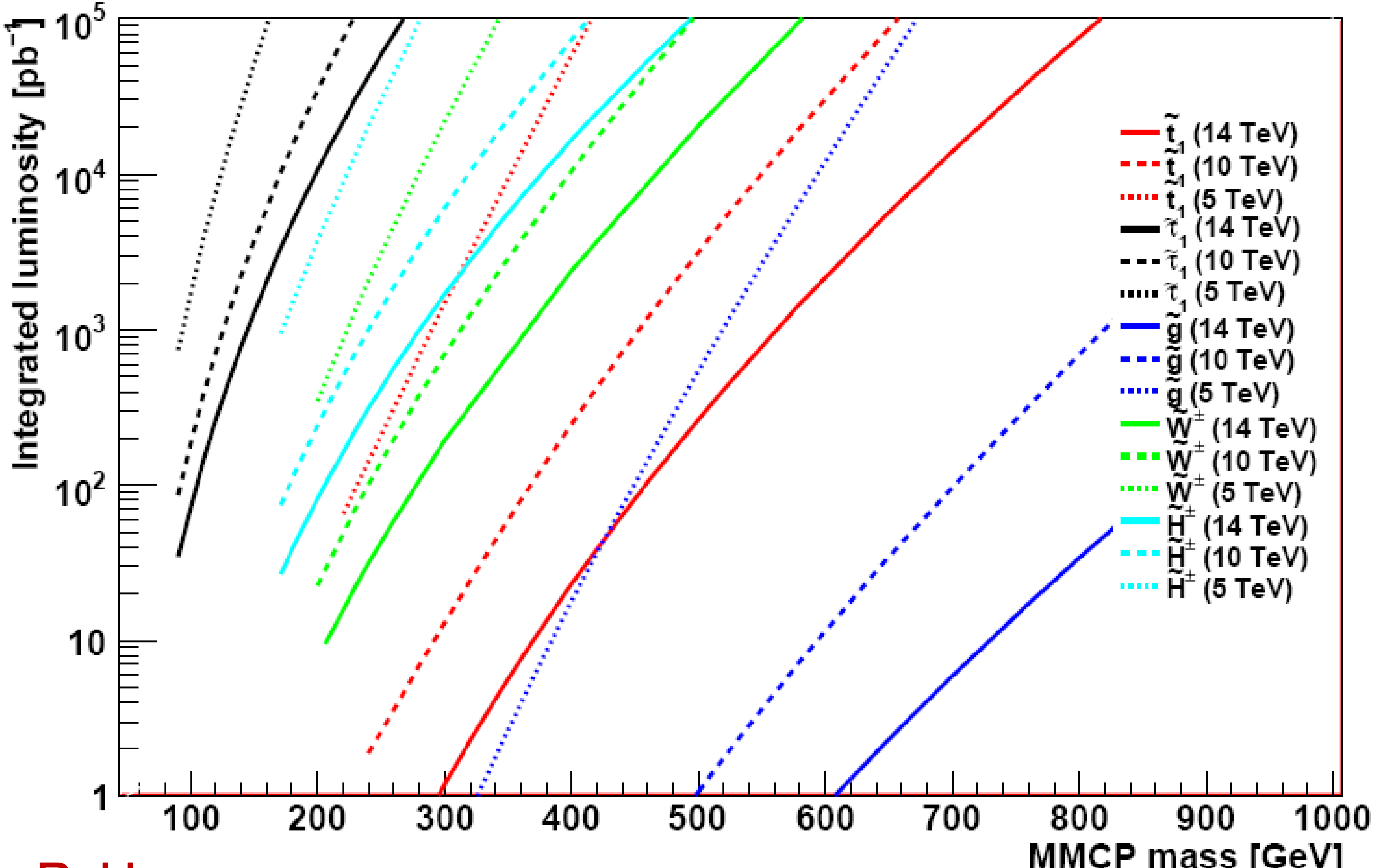
Long Lived/Stable Sparticles in the 71k Sample

- 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!

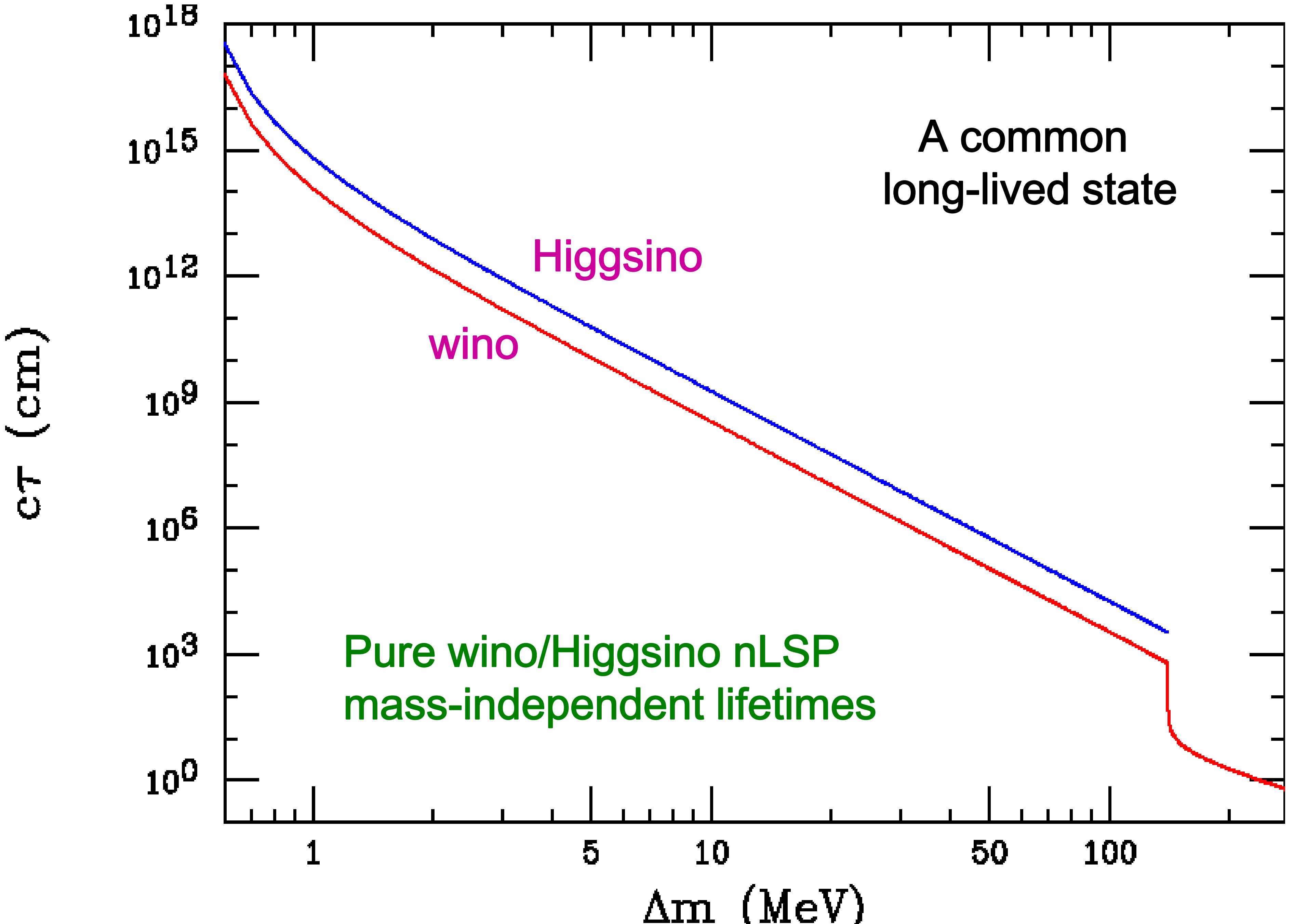
- 16061 are charginos
- 555 are second neutralinos
- 339 are sbottoms
- 179 are staus
- 100 are stops
- 79 are gluinos
- 49 are c_R
- 18 are μ_R
- 11 are 2^{nd} charginos
- 8 are c_L

etc.

Stable SUSY Searches at LHC



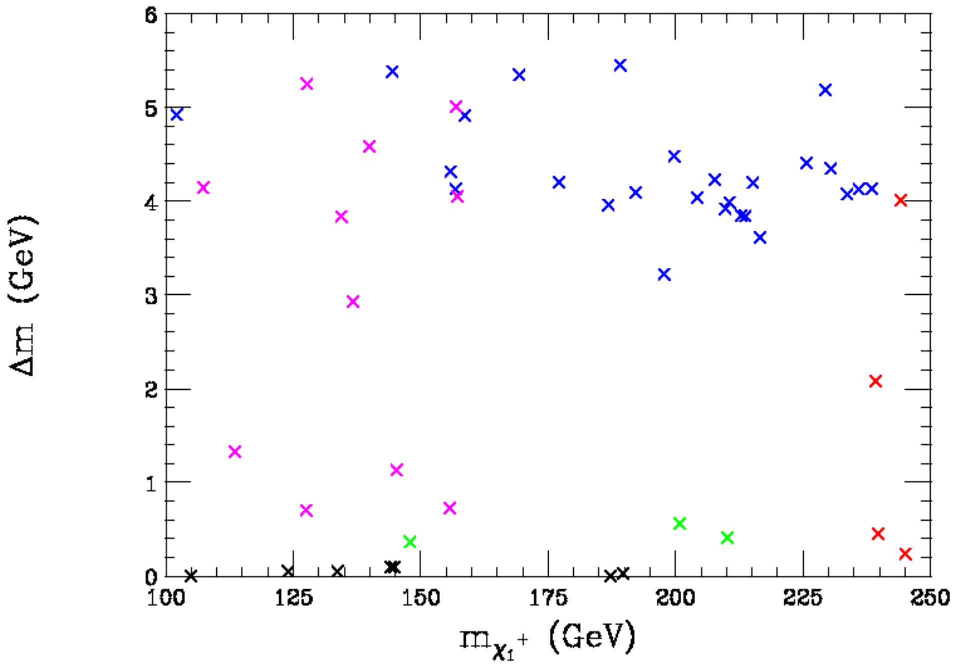
A. Raklev



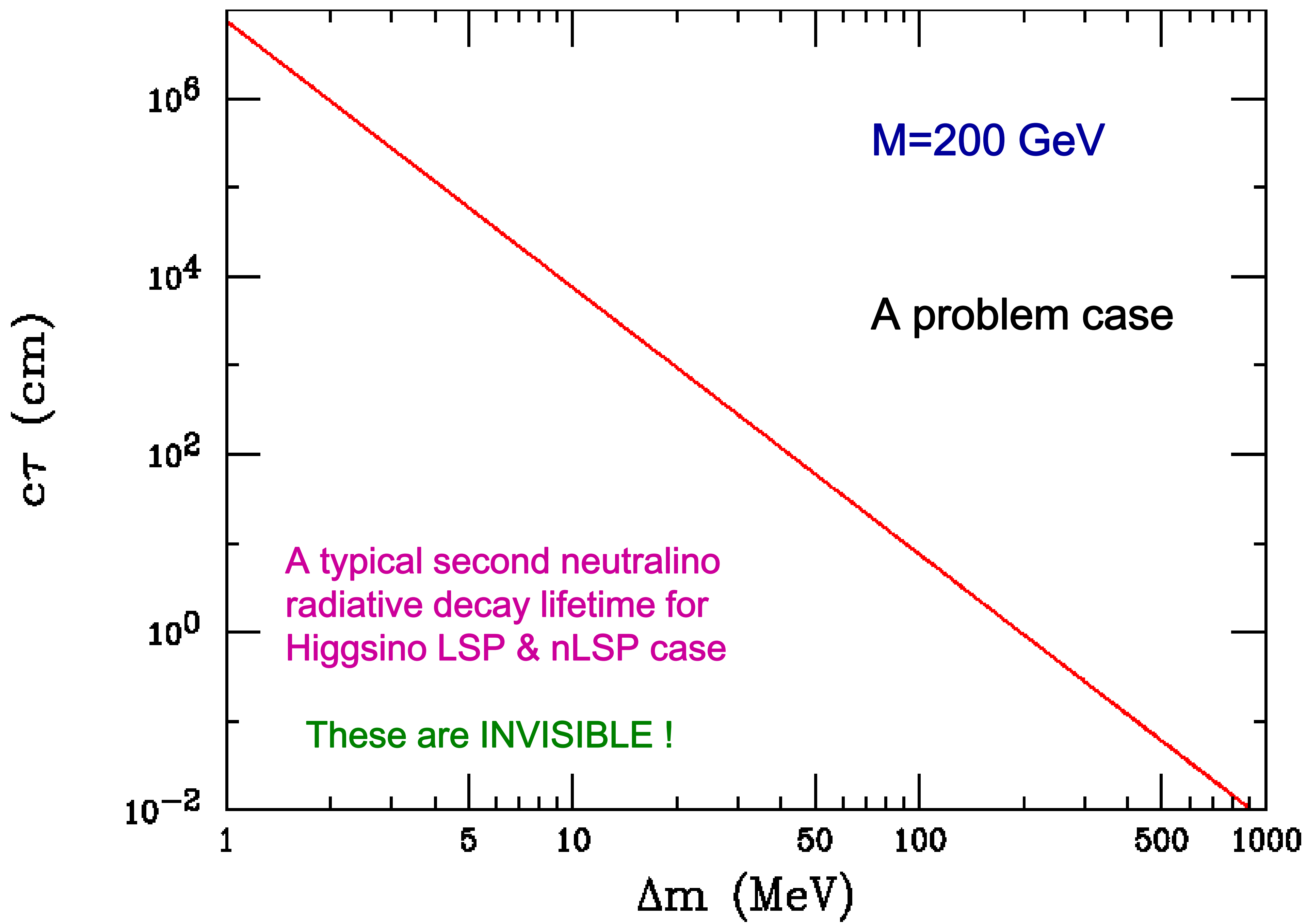
A common
long-lived state
Higgsino
wino
Pure wino/Higgsino nLSP
mass-independent lifetimes
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
$c\tau$ (cm)
1
5
10
50
100
Δm (MeV)

As is well-known the observation of close mass objects is generally difficult at all colliders, even in $e^+ e^-$ collisions.

As an example, in our past SUSY@ILC analysis we saw that charginos having small mass splittings with the LSP required many different searches: stable particles, photon tagging, soft jets, or a combination to cover all of the model space (47/53) for charginos as seen below.

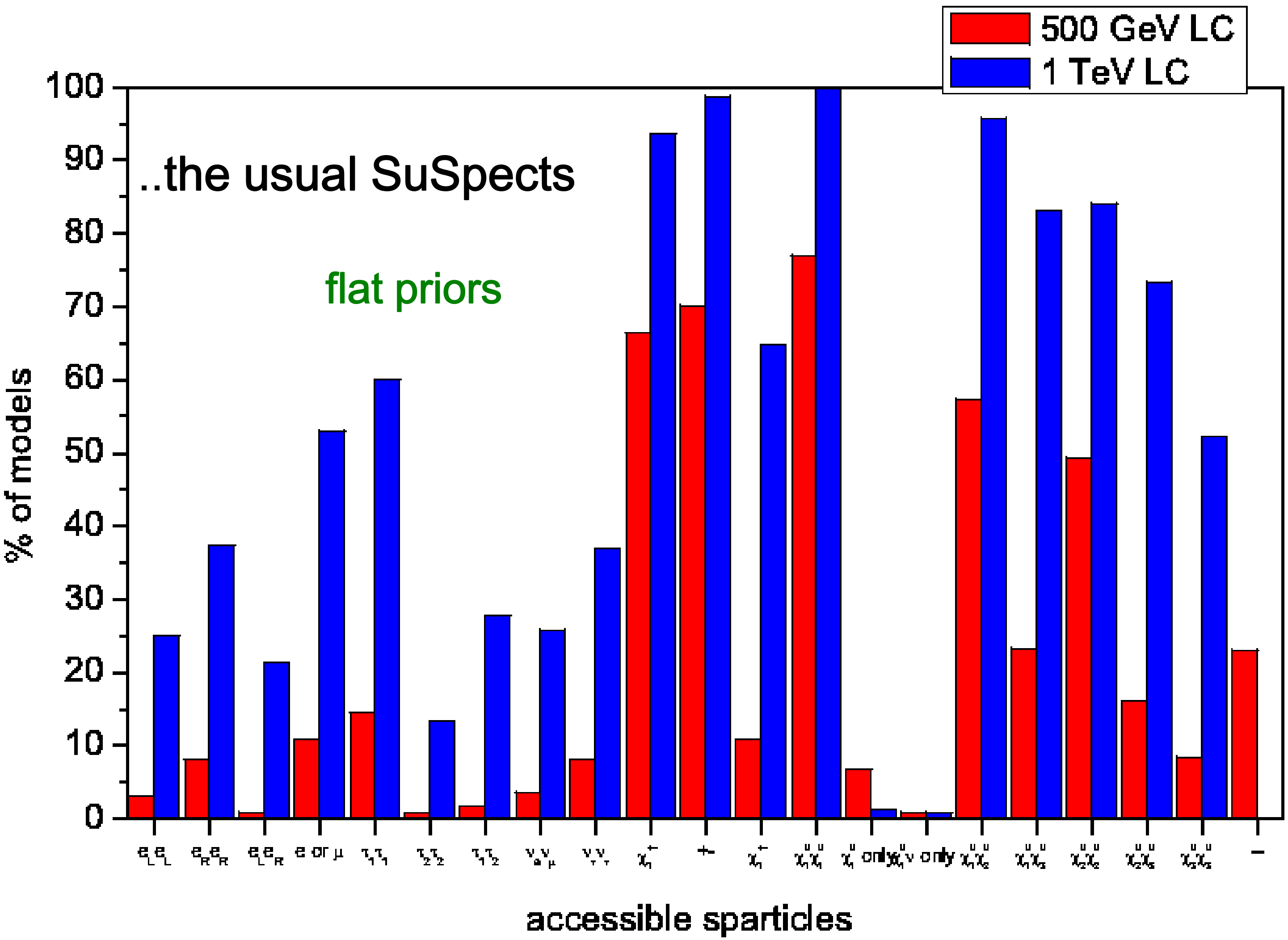


We have MANY close mass possibilities in our two model samples. Can $\gamma\gamma$ colliders possibly do any better??? For example, in the case of smuons (squarks) <2(10) GeV heavier than the LSP??



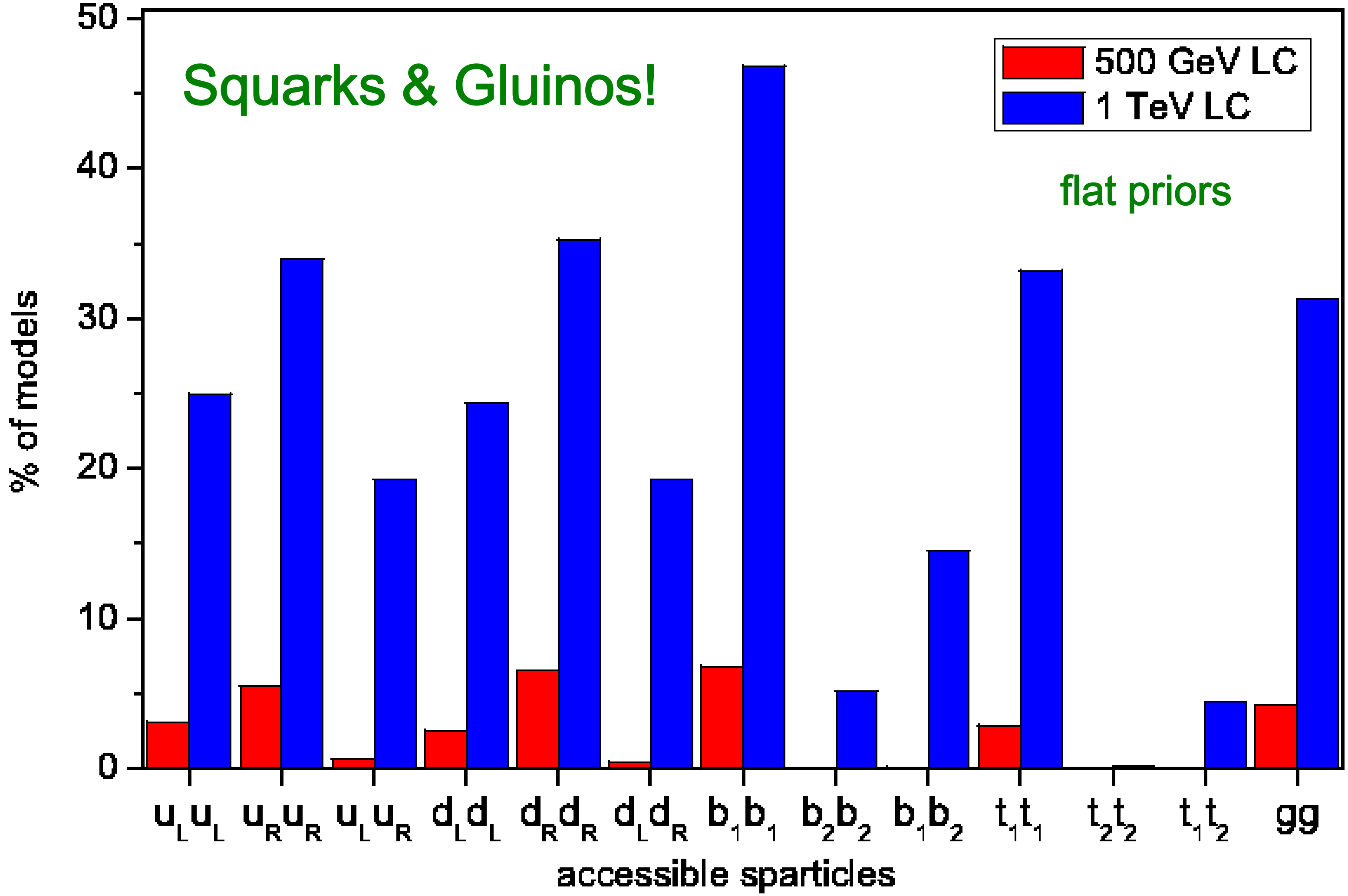
M=200 GeV
A problem case
A typical second neutralino
radiative decay lifetime for
Higgsino LSP & nLSP case
These are INVISIBLE !
cτ (cm)
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
1
5
10
50
100
500
1000
Δm (MeV)

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



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 PYTHIA ,etc., issues!

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

- This is extremely CPU intensive , e.g., 7M K-factors to compute

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

The set of ATLAS SUSY analyses is large:

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

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

Note the importance of MET

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

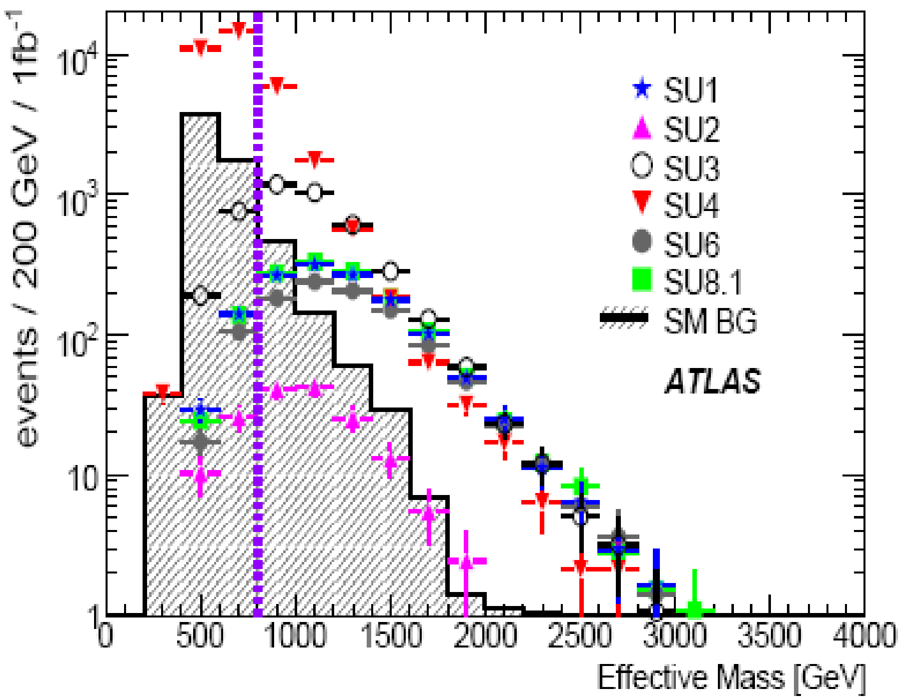
The ATLAS collaboration

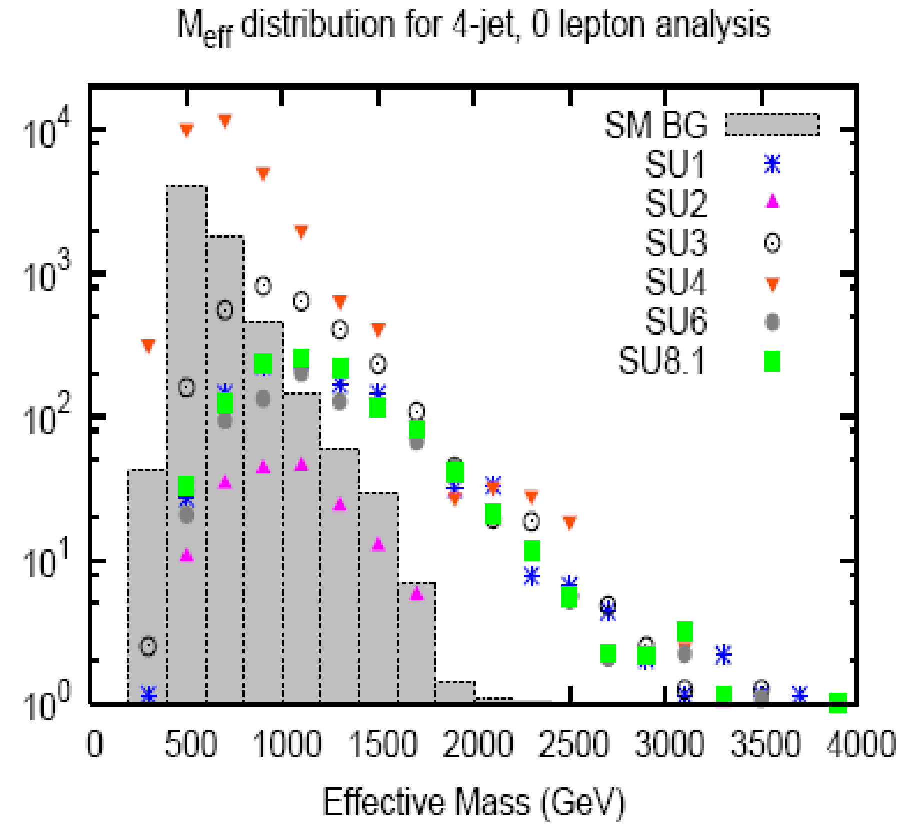
Abstract

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.

ATL-PHYS-PUB-2009-081
22 July 2009

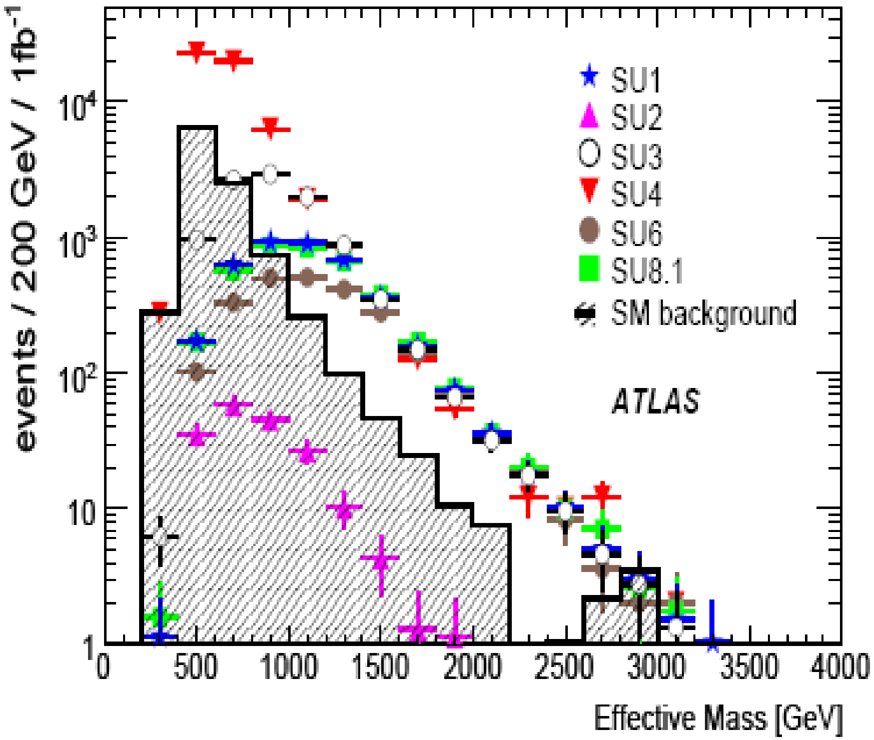
4-jet +MET



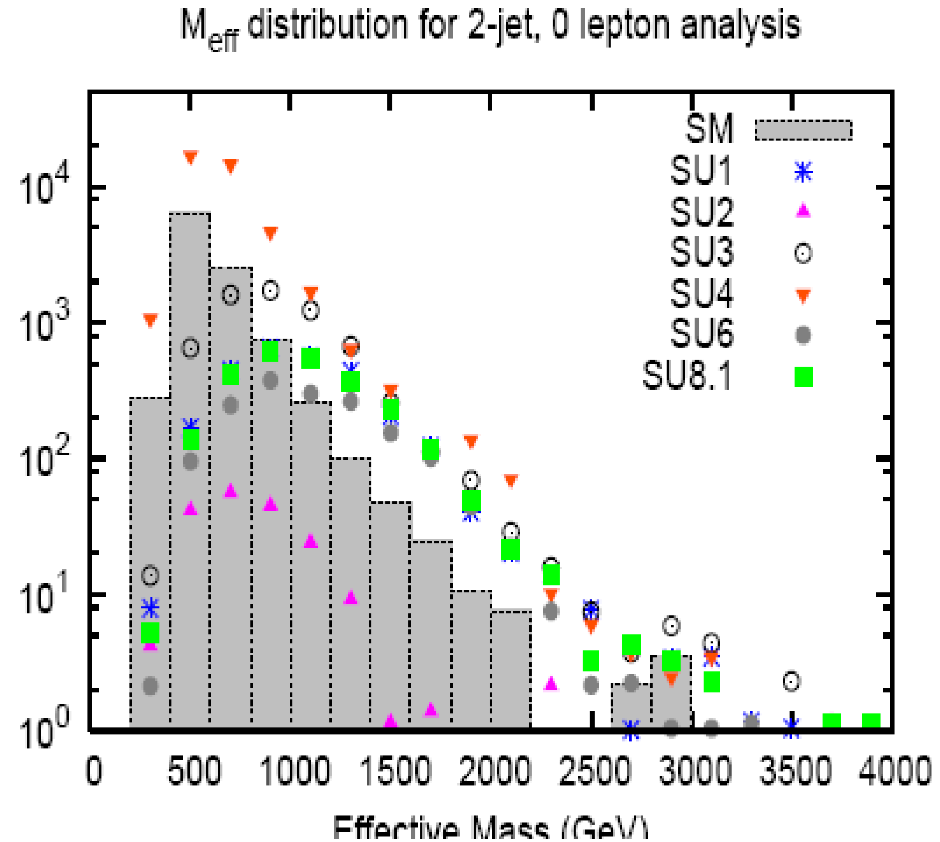


We do a good job at reproducing the mSUGRA benchmarks in this channel .

2j +MET

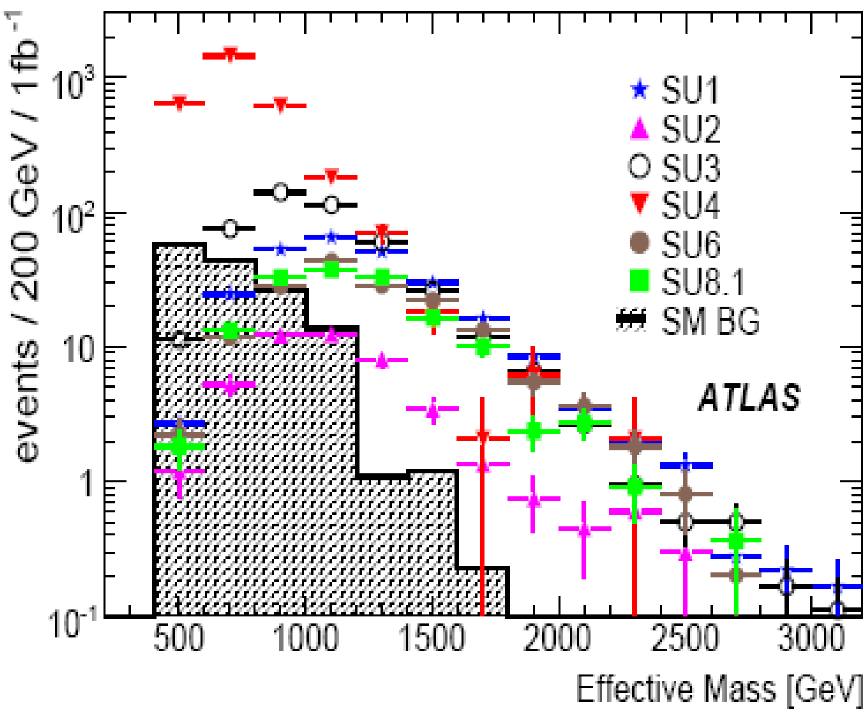


events / 200 GeV / 1fb^{-1}
SU1
SU2
SU3
SU4
SU6
SU8.1
SM background
ATLAS
Effective Mass [GeV]

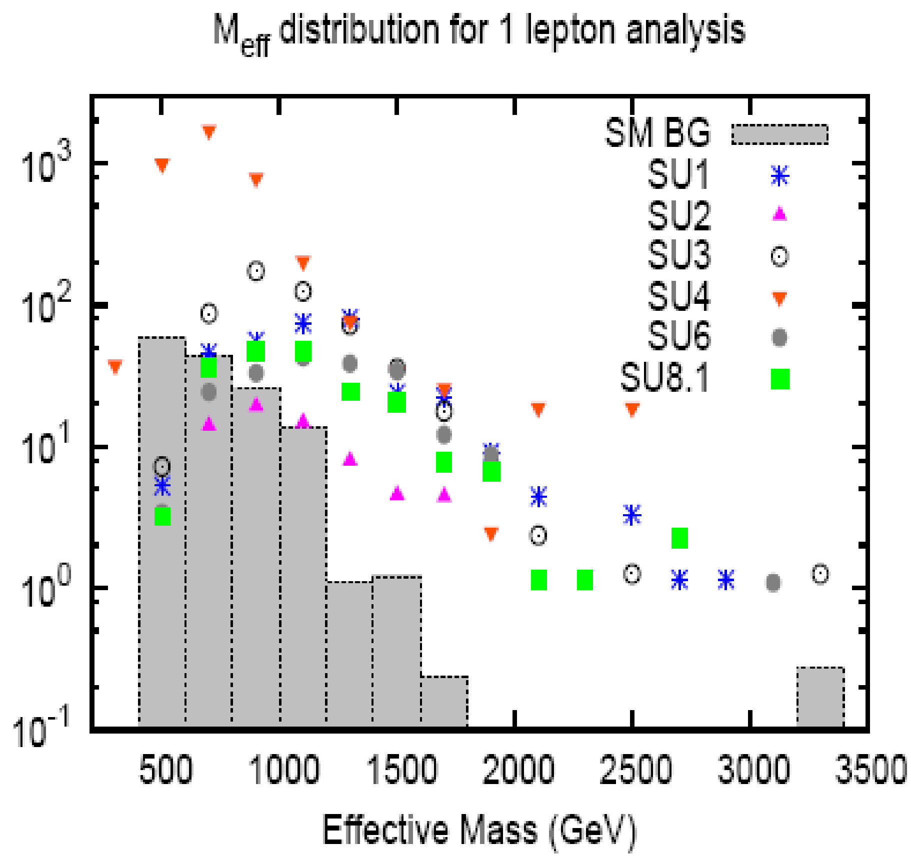


M_{eff} distribution for 2-jet, 0 lepton analysis
SM
SU1
SU2
SU3
SU4
SU6
SU8.1

1l+4j+MET



events / 200 GeV / 1fb^{-1}
SU1
SU2
SU3
SU4
SU6
SU8.1
SM BG
ATLAS
Effective Mass [GeV]



M_{eff} distribution for 1 lepton analysis
SM BG
SU1
SU2
SU3
SU4
SU6
SU8.1
Effective Mass (GeV)

Some Results From the First 6k Models @ 14 TeV & 1fb^{-1}

- Remove possibly difficult models where the nLSP is obviously long-lived which may require some specialized analyses

- Determine how many models are visible or not in each analysis @ the 5σ level allowing for a 50% systematic un-certainty in the ATLAS SM backgrounds

- The results are still HIGHLY PRELIMINARY with some exotic features, e.g., there are long-lived objects that can be fairly high in the mass spectrum & not just be the nLSPs…

Some Results From the First 6k Models

Analysis	Number missed at 5σ
• 4j + MET	230
• 2j + MET	225
• 1 lepton	2125
• 1 lepton+2j	1864
• 1 lepton+3j	1873
• SSDL	4814
• tau	264
• b	1217

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 SMALL subset due to 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 tobe 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 many 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 = long-lived states

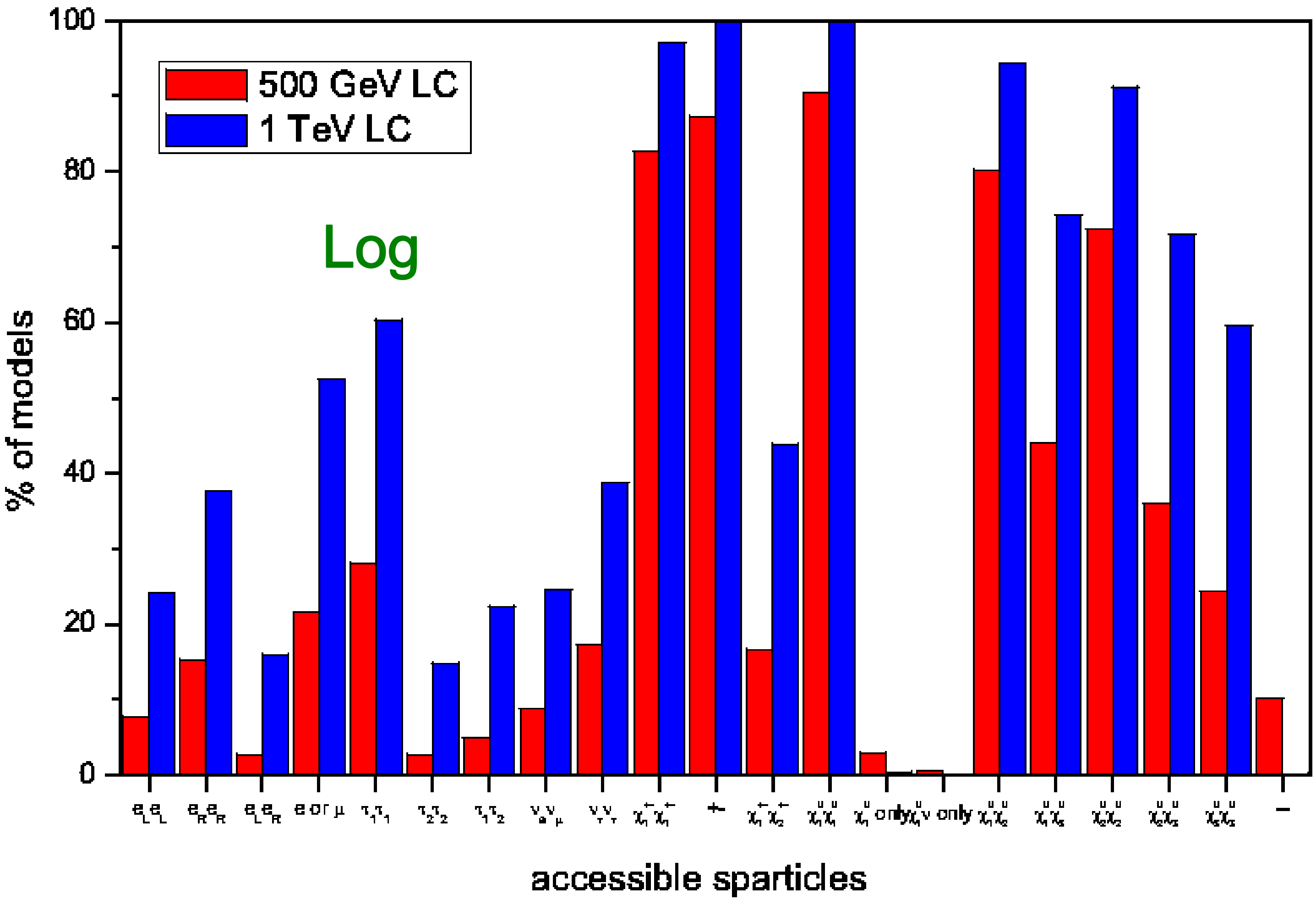
- Squarks may exist within the range accessible to a 0.5 -1TeV linear collider but have not been well studied there.

- A linear collider will likely be necessary to discover & study all of these new states in detail especially if the spectrum is ‘unusual’.

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

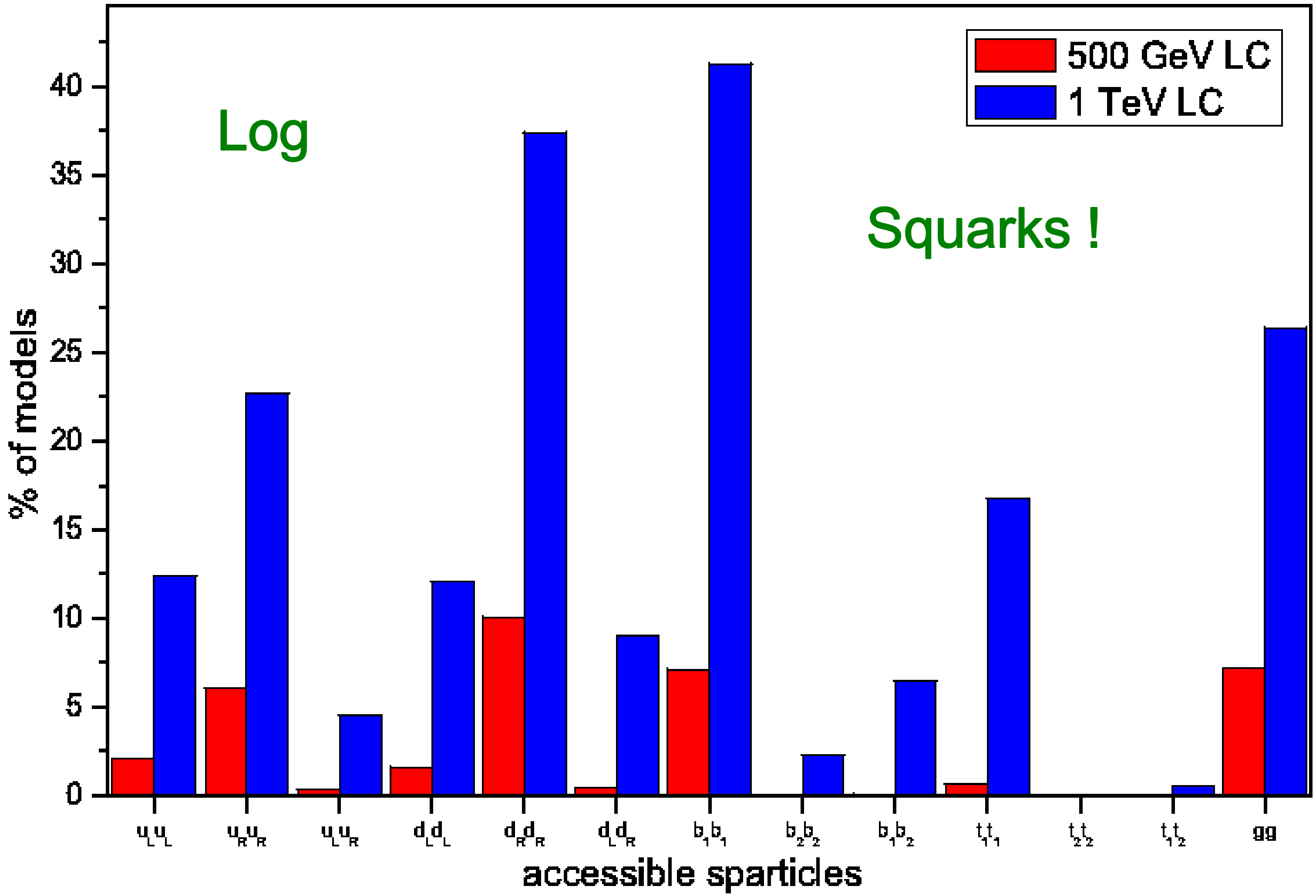
BACKUP SLIDES

Kinematic Accessibility at the ILC : II



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 : IV



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.

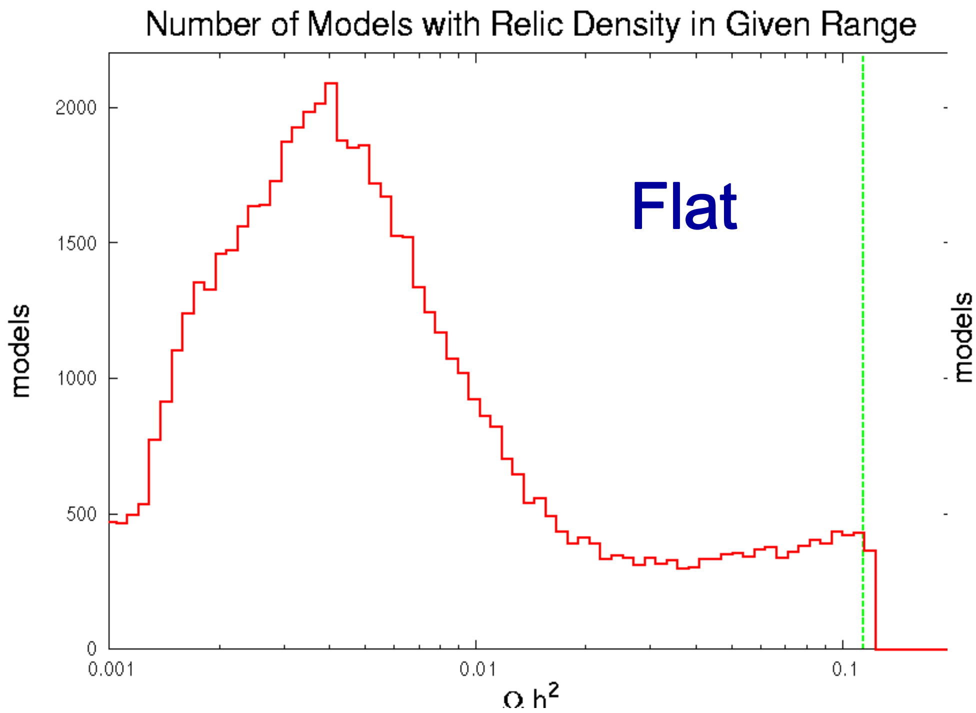
Top 25 most common mass patterns for the 4 lightest SUSY & heavy Higgs particles.

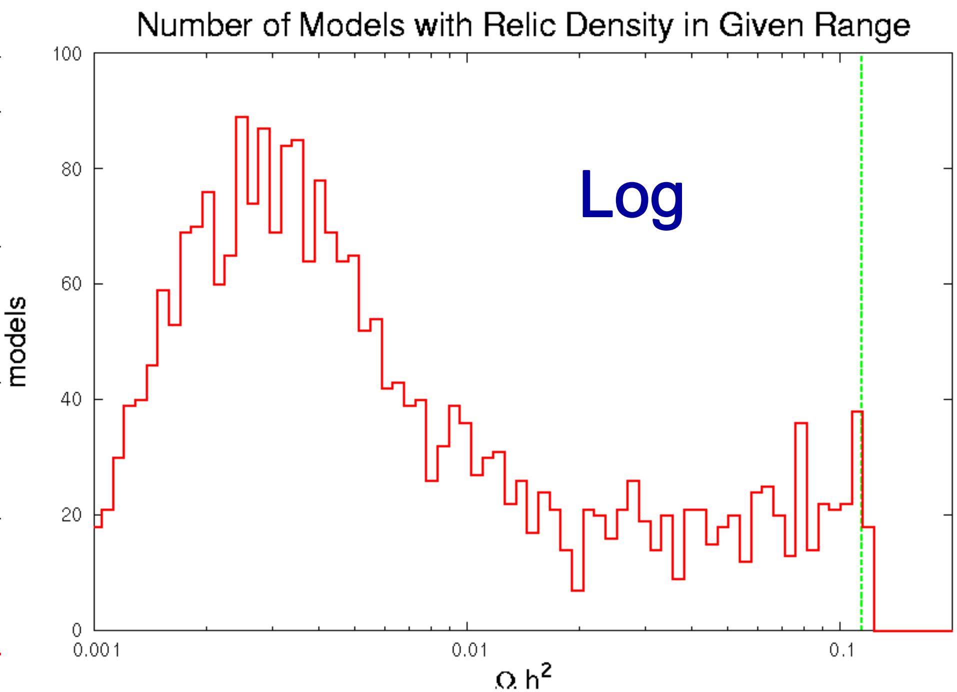
There were 1109 (267) such patterns found for the case of flat (log) priors

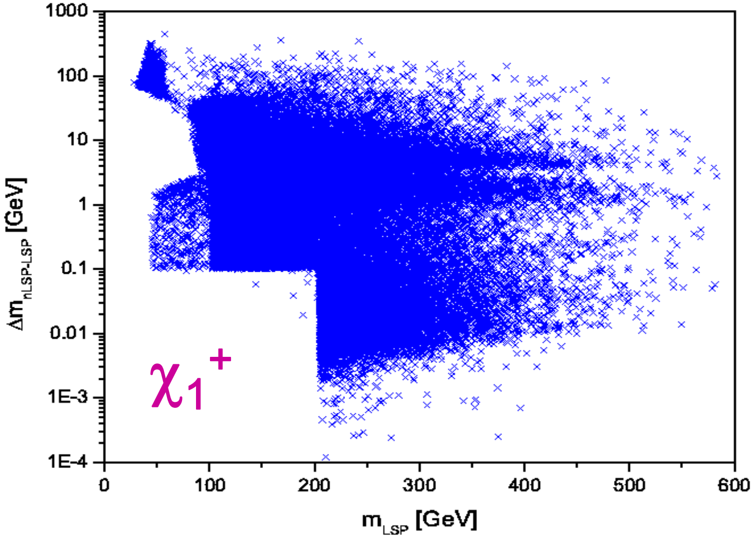
Only ~20 are found to occur in mSUGRA!!

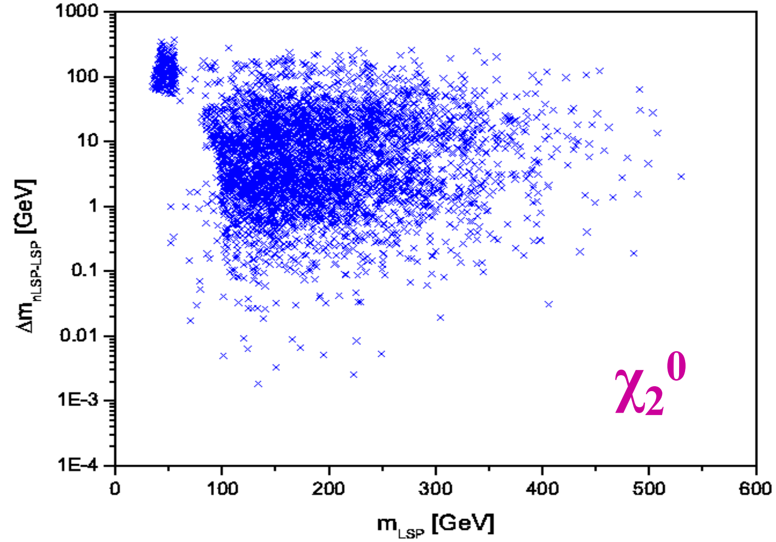
Predicted Dark Matter Density : Ωh^2

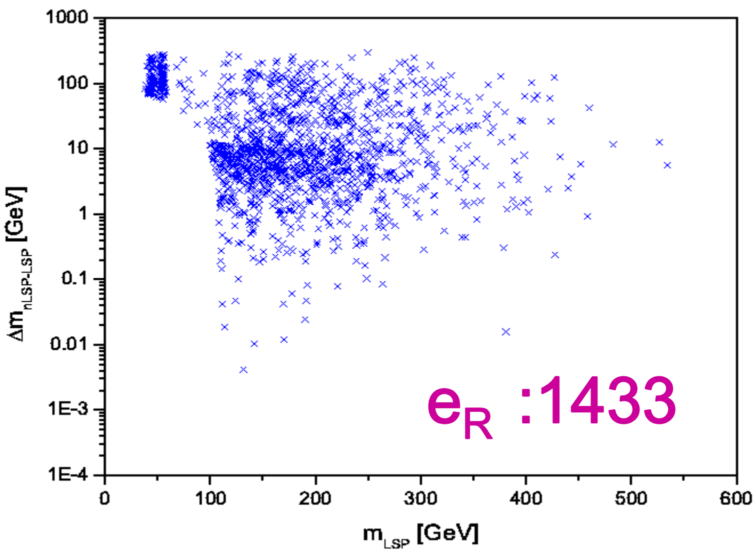
It is not likely that the LSP is the dominant component of dark matter in 'conventional' cosmology…but it can be in some model cases.. (1240+76)

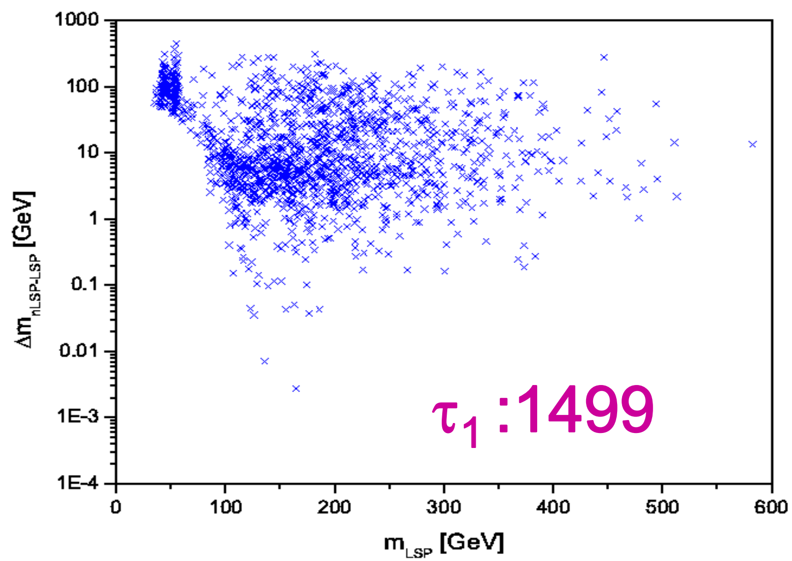


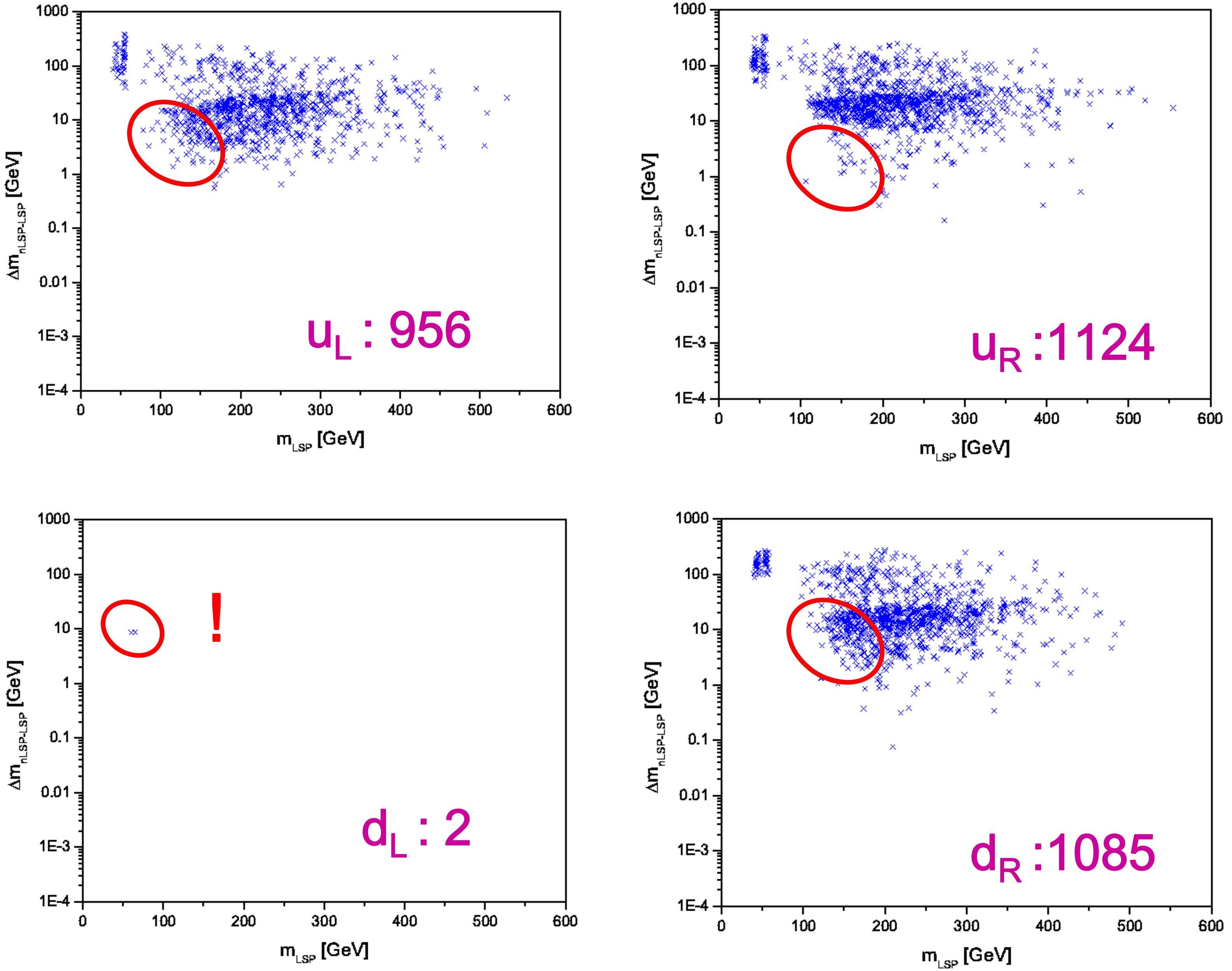


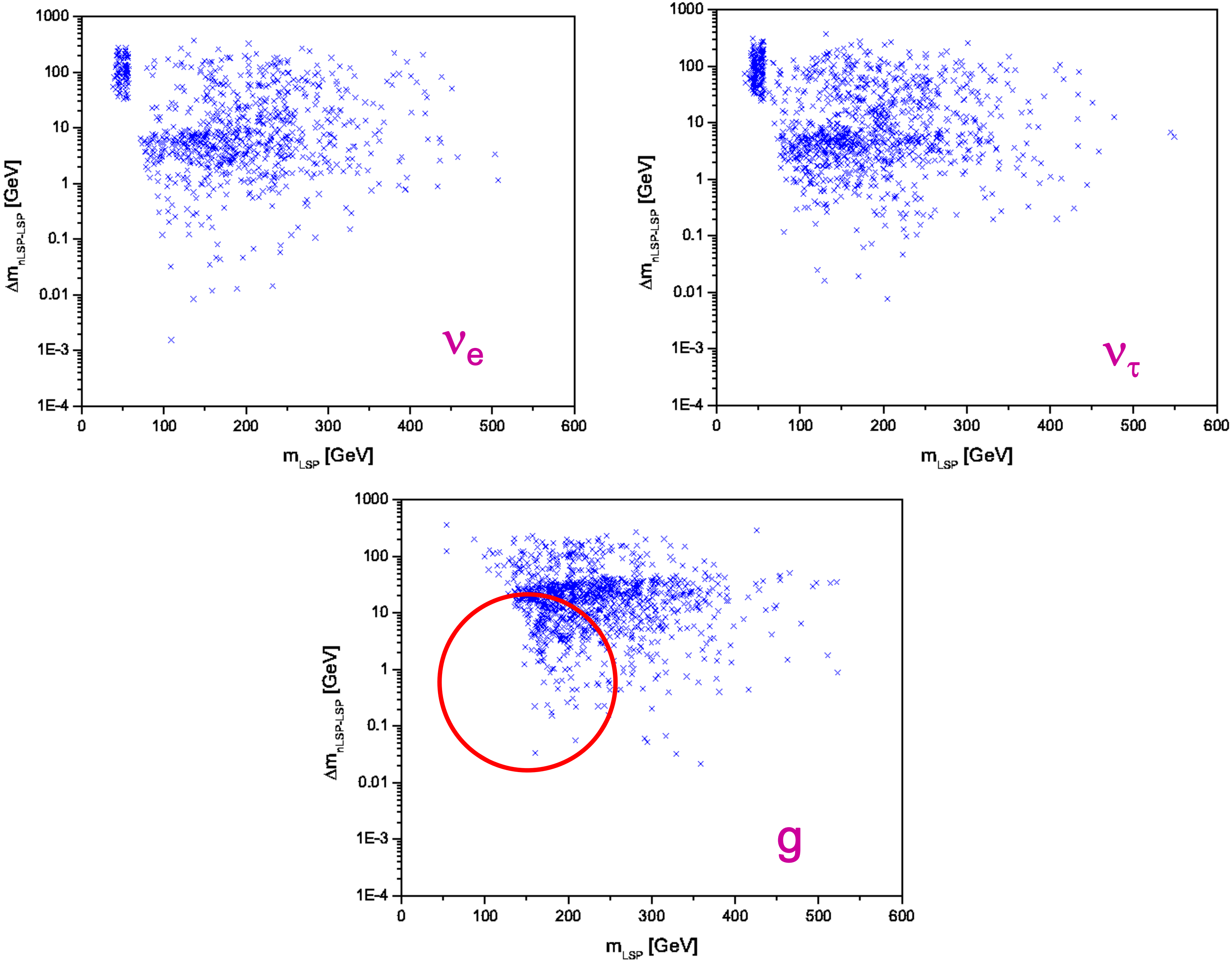

$\Delta m_{nLSP-LSP}$ [GeV]
m_{LSP} [GeV]
χ_1^+


$\Delta m_{nLSP-LSP}$ [GeV]
m_{LSP} [GeV]
χ_2^0


$\Delta m_{nLSP-LSP}$ [GeV]
m_{LSP} [GeV]
e_R :1433

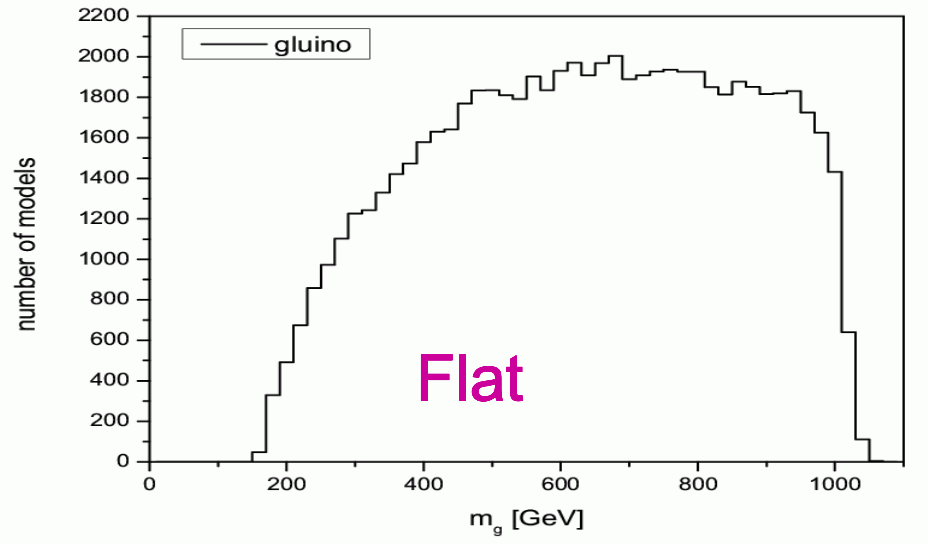

$\Delta m_{nLSP-LSP}$ [GeV]
m_{LSP} [GeV]
τ_1 :1499

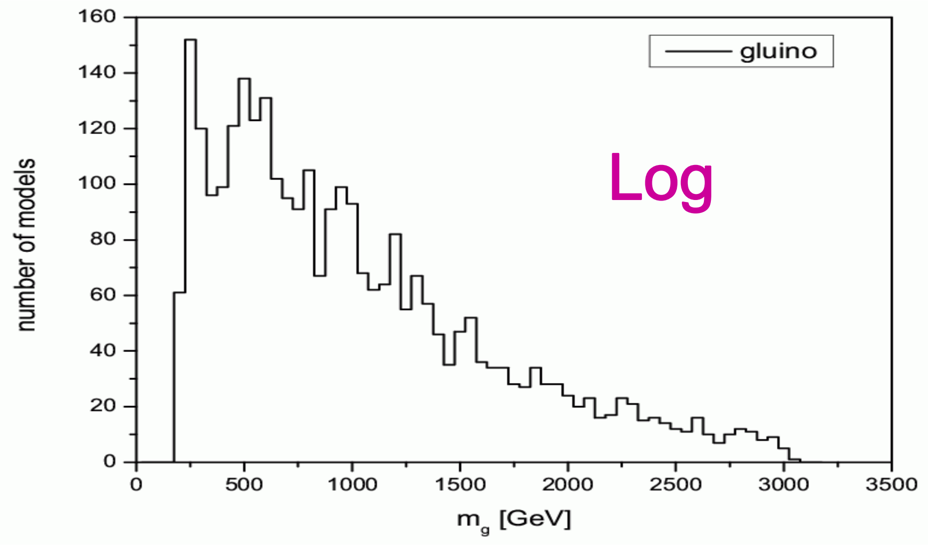

u_L : 956
u_R :1124
d_L : 2
!
d_R :1085
Δm_nLSP-LSP [GeV]
m_LSP [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600

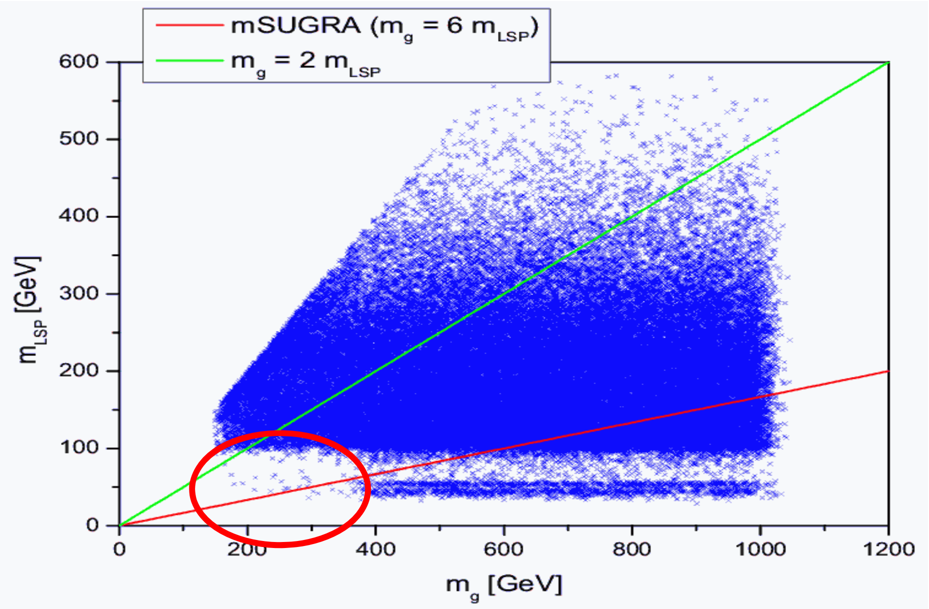


1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
Δm_nLSP-LSP [GeV]
m_LSP [GeV]
νe
ντ
g

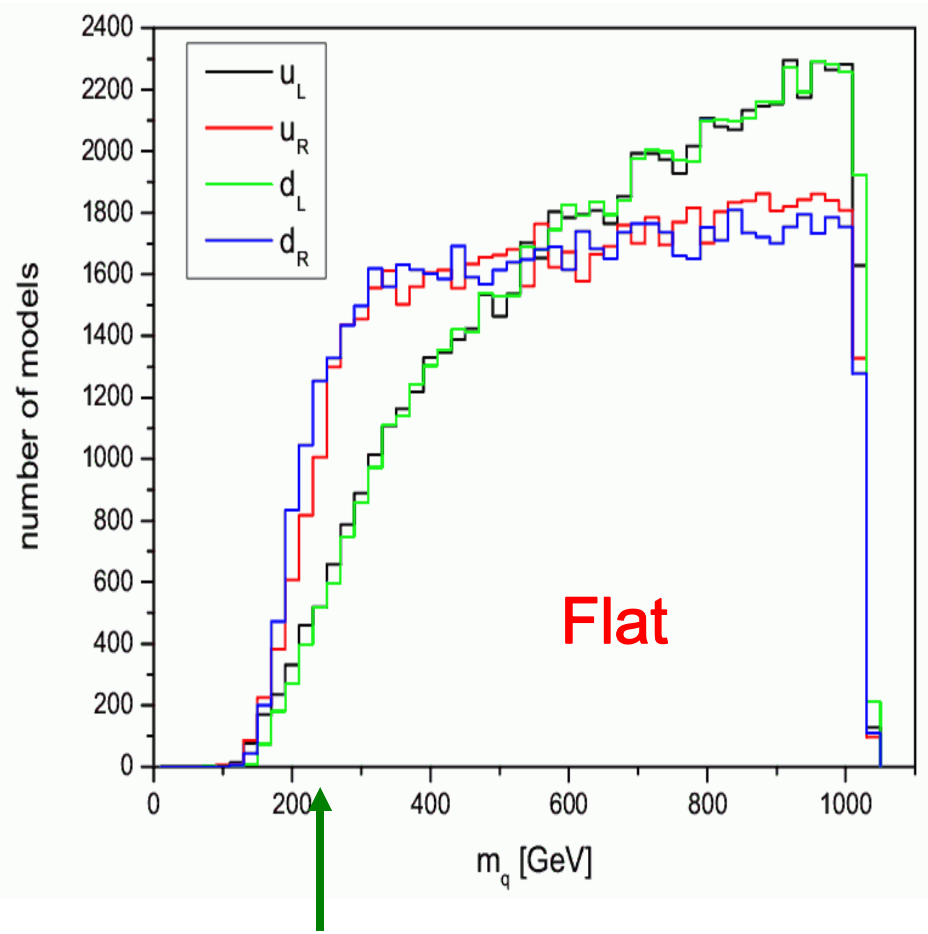
Gluino Can Be Light !!

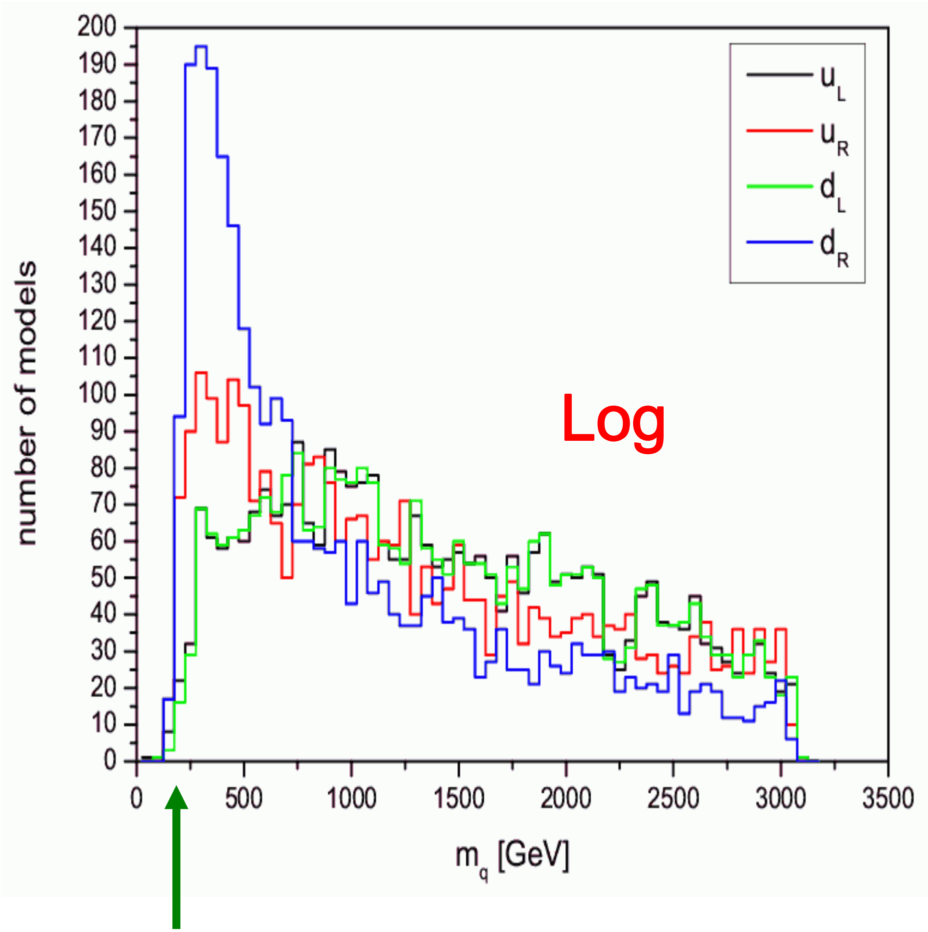






Squarks CAN Be Light !!!





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

Model 14

```
  1000001     9.80298920E+02   # ~d_L
  2000001     2.57943062E+02   # ~d_R
  1000002     9.77231862E+02   # ~u_L
  2000002     7.77002940E+02   # ~u_R
  1000003     9.80298920E+02   # ~s_L
  2000003     2.57943062E+02   # ~s_R
  1000004     9.77231862E+02   # ~c_L
  2000004     7.77002940E+02   # ~c_R
  1000005     2.01330637E+02   # ~b_1
  2000005     2.86522190E+02   # ~b_2
  1000006     2.07460974E+02   # ~t_1
  2000006     7.31867798E+02   # ~t_2
  1000011     2.26662521E+02   # ~e_L
  2000011     1.25189385E+02   # ~e_R
  1000012     2.13138122E+02   # ~nu_eL
  1000013     2.26662521E+02   # ~mu_L
  2000013     1.25189385E+02   # ~mu_R
  1000014     2.13138122E+02   # ~nu_muL
  1000015     5.86349059E+02   # ~tau_1
  2000015     8.48959329E+02   # ~tau_2
  1000016     8.45390948E+02   # ~nu_tauL
  1000021     4.99749643E+02   # ~g
  1000022    -1.19058559E+02   # ~chi_10
  1000023     5.32512753E+02   # ~chi_20
  1000025    -5.89662461E+02   # ~chi_30
  1000035     6.59450859E+02   # ~chi_40
```

```
 1.14889198E-01    2     1000006        -6   # BR(~g -> ~t_1  tb)
 1.14889198E-01    2    -1000006         6   # BR(~g -> ~t_1* t )
```

```
#         PDG            Width
DECAY   1000006     2.59765837E-09   # stop1 decays
#         BR         NDA      ID1       ID2
     9.88438468E-02    2     1000022         4   # BR(~t_1 -> ~chi_10 c )
     7.62056071E-04    2     1000022         2   # BR(~t_1 -> ~chi_10 u )
#         BR         NDA      ID1       ID2       ID3
     4.44596712E-01    3     1000022         5        24   # BR(~t_1 -> ~chi_10  b  W+)
     1.57699355E-01    3     1000005        -1         2   # BR(~t_1 -> ~b_1     db u)
     1.57699355E-01    3     1000005        -3         4   # BR(~t_1 -> ~b_1     sb c)
     3.52657727E-02    3     1000005       -15        16   # BR(~t_1 -> ~b_1     tau+ nu_tau)
     5.25664516E-02    3     1000005       -11        12   # BR(~t_1 -> ~b_1     e+   nu_e)
     5.25664516E-02    3     1000005       -13        14   # BR(~t_1 -> ~b_1     mu+  nu_mu)
```

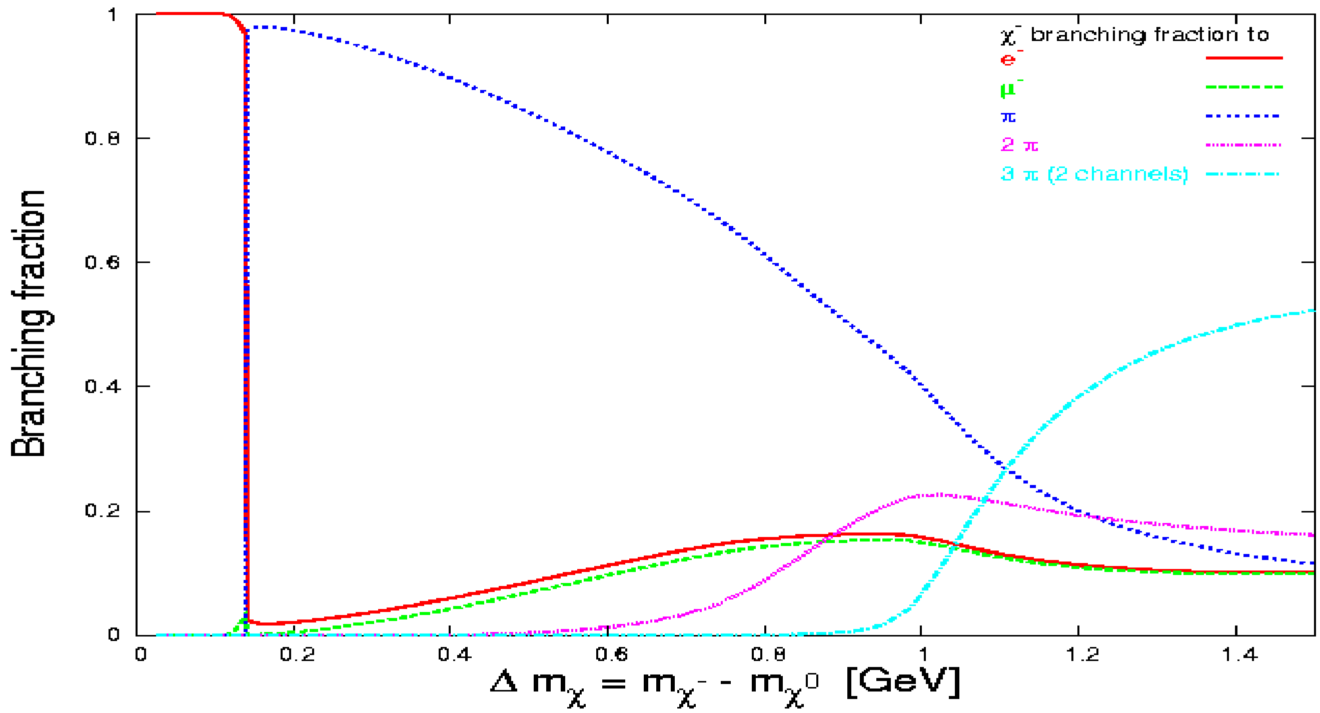
First two generation of squarks are heavy; gluinos -> stop + top
The stop hadronizes first & then decays as: stop-> bW+ LSP
w/ Q=4 GeV so b-jet is soft & MET is small

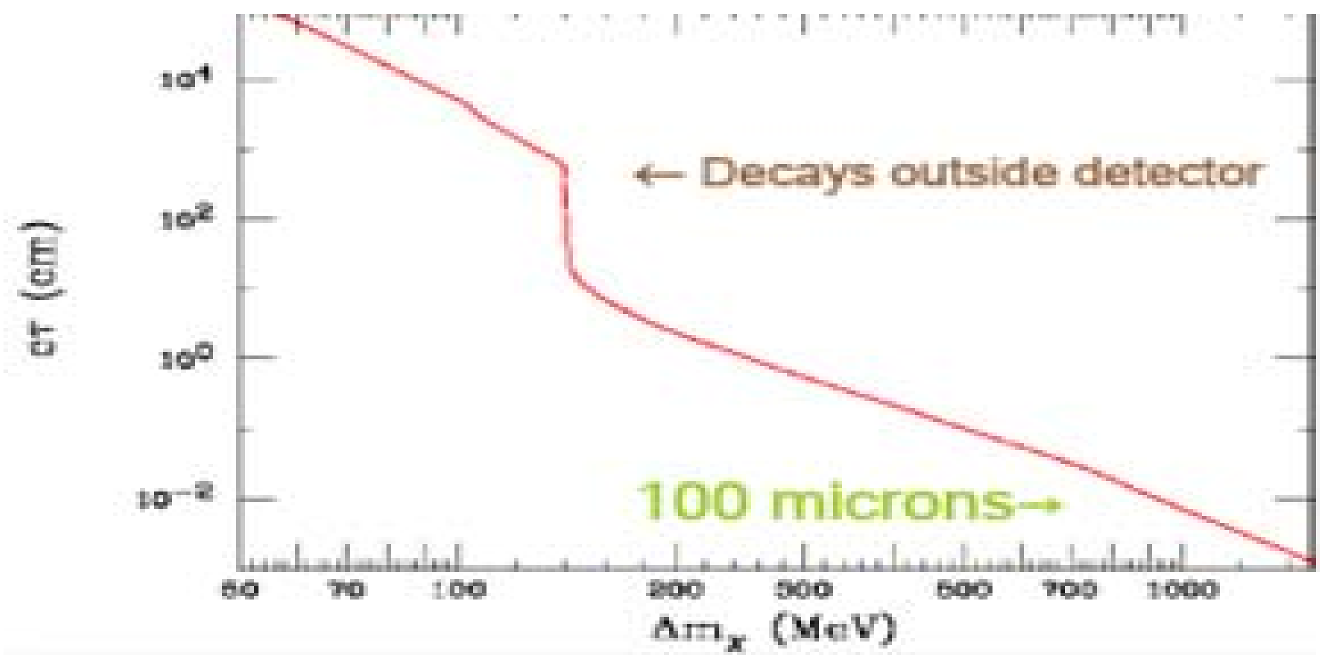
Model 12

This case is even more unusual as it didn't even show up in any of the histograms ! Here sbottom_1 is the nLSP with a mass splitting of only ~1.5 GeV so we get lots of soft jets + MET only. The other squarks are rather heavy:

```
 1000001     7.37649653E+02   # ~d_L
 2000001     4.59324254E+02   # ~d_R
 1000002     7.33455141E+02   # ~u_L
 2000002     5.28189568E+02   # ~u_R
 1000003     7.37649653E+02   # ~s_L
 2000003     4.59324254E+02   # ~s_R
 1000004     7.33455141E+02   # ~c_L
 2000004     5.28189568E+02   # ~c_R
 1000005     3.44737366E+02   # ~b_1
 2000005     1.00524409E+03   # ~b_2
 1000006     7.75478606E+02   # ~t_1
 2000006     1.01984798E+03   # ~t_2
 1000011     6.01150570E+02   # ~e_L
 2000011     4.11594957E+02   # ~e_R
 1000012     5.96024416E+02   # ~nu_eL
 1000013     6.01150570E+02   # ~mu_L
 2000013     4.11594957E+02   # ~mu_R
 1000014     5.96024416E+02   # ~nu_muL
 1000015     4.38994670E+02   # ~tau_1
 2000015     9.85606108E+02   # ~tau_2
 1000016     4.32152441E+02   # ~nu_tauL
 1000021     4.68031460E+02   # ~g
 1000022    -3.43176430E+02   # ~chi_10
 1000023     3.53977818E+02   # ~chi_20
 1000025    -8.52903614E+02   # ~chi_30
 1000035    -8.86985561E+02   # ~chi_40
 1000024     3.47535948E+02   # ~chi_1+
 1000037     8.53599295E+02   # ~chi_2+
```

Note that SDECAY treats the sbottom in this case as stable but really an R-hadron forms which then undergoes a 4-body decay or a 1-loop suppressed decay with a $c\tau$ ~10-100 μm


χ⁻ branching fraction to
e⁻
μ⁻
π
2 π
3 π (2 channels)
Branching fraction
Δ m_χ = m_χ⁻ - m_χ⁰ [GeV]


← Decays outside detector
100 microns→
cτ (cm)
Δm_χ (MeV)