too much
SUSY Without^Prejudice

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The MSSM has many nice features but is very difficult to study in any model-independent manner due to the large number of soft SUSY breaking parameters (~120).

To circumvent this issue, authors generally limit their analyses to a specific SUSY breaking scenario(s) such as mSUGRA, GMSB, AMSB,… which then determines the sparticle masses, couplings & signatures in terms of only a 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*? S*ome* set of assumptions are necessary to make any such study practical. But what? All sorts of choices are possible…

FEATURE Analysis Assumptions :

- The most general, CP-conserving MSSM
- Minimal Flavor Violation
- 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.

This leaves us with the pMSSM:

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

What are they??


M_A
$\tilde{M}_{Q1}$
$\tilde{M}_{Q3}$
$\tilde{M}_{L1}$
$\tilde{M}_{L3}$
$\tilde{M}_{u1}$
$\tilde{M}_{d1}$
$\tilde{M}_{e1}$
$\tilde{M}_{u3}$
$\tilde{M}_{d3}$
$\tilde{M}_{e3}$
A_t
A_b
A_τ
μ
M_1
M_2
M_3
$\tan\beta$

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.
- 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?
- Do physics analyses with these models for LHC, GLAST, PAMELA, ILC/CLIC, etc. etc. – all your favorites!

→ Such a general analysis allows us to study the MSSM at the electroweak/TeV scale without any reference to the nature of the UV completion: GUTs? New intermediate mass scales? Messenger scales?

How?

We have performed 2 large scans (& two smaller scans)

i) 10^7 points with *flat* priors for masses:

- 100 GeV $\leq \tilde{M}_{sfermions} \leq$ 1 TeV
- 50 GeV $\leq |M_1, M_2, \mu| \leq$ 1 TeV, 100 GeV $\leq M_3 \leq$ 1 TeV
- ~0.5 $M_Z \leq M_A \leq$ 1 TeV , $1 \leq \tan\beta \leq 50$
- $|A_{t\,b\,\tau}| \leq$ 1 TeV

These are Lagrangian parameters evaluated at the SUSY scale.

Absolute value signs account for possible 'phases' (i.e., signs) :
only Arg $(M_i\,\mu)$ and Arg $(A_f\,\mu)$ are physical…we take $M_3 > 0$

ii) 2 x10^6 points with *log* priors for masses:

- 100 GeV $\leq \tilde{M}_{sfermions} \leq$ 3 TeV
- 10 GeV $\leq | M_1, M_2, \mu | \leq$ 3 TeV, 100 GeV $\leq M_3 \leq$ 3 TeV
- ~0.5 $M_Z \leq M_A \leq$ 3 TeV , 1 $\leq \tan\beta \leq$ 60
- 10 GeV $\leq | A_{t\,b\,\tau} | \leq$ 3 TeV

While scan (i) emphasizes sparticles with moderate masses, scan (ii) emphasizes light sparticles BUT also extends to higher masses simultaneously

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.

What constraints and experimental data do we employ?


Successful models
WMAP & Direct Detection
Direct searches at LEP & Tevatron
g-2
Precision data
Spectrum requirements
Rare decays and flavor constraints

Constraints

- $-0.0007 < \Delta\rho < 0.0026$ (PDG'08)
- $b \to s\,\gamma$: B = (2.5 – 4.1) x 10^{-4} ; (HFAG) + Misiak etal. & Becher & Neubert
- $\Delta(g\text{-}2)_\mu$??? $(30.2 \pm 8.8) \times 10^{-10}$ (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 to 40) x 10^{-10} to be conservative..

- $\Gamma(Z\to$ invisible) < 2.0 MeV (LEPEWWG)
  This removes Z decays to LSPs w/ large Higgsino content
- Meson-Antimeson Mixing : Constrains 1st/3rd sfermion mass ratios to be < 5 and > 0.2 in MFV context

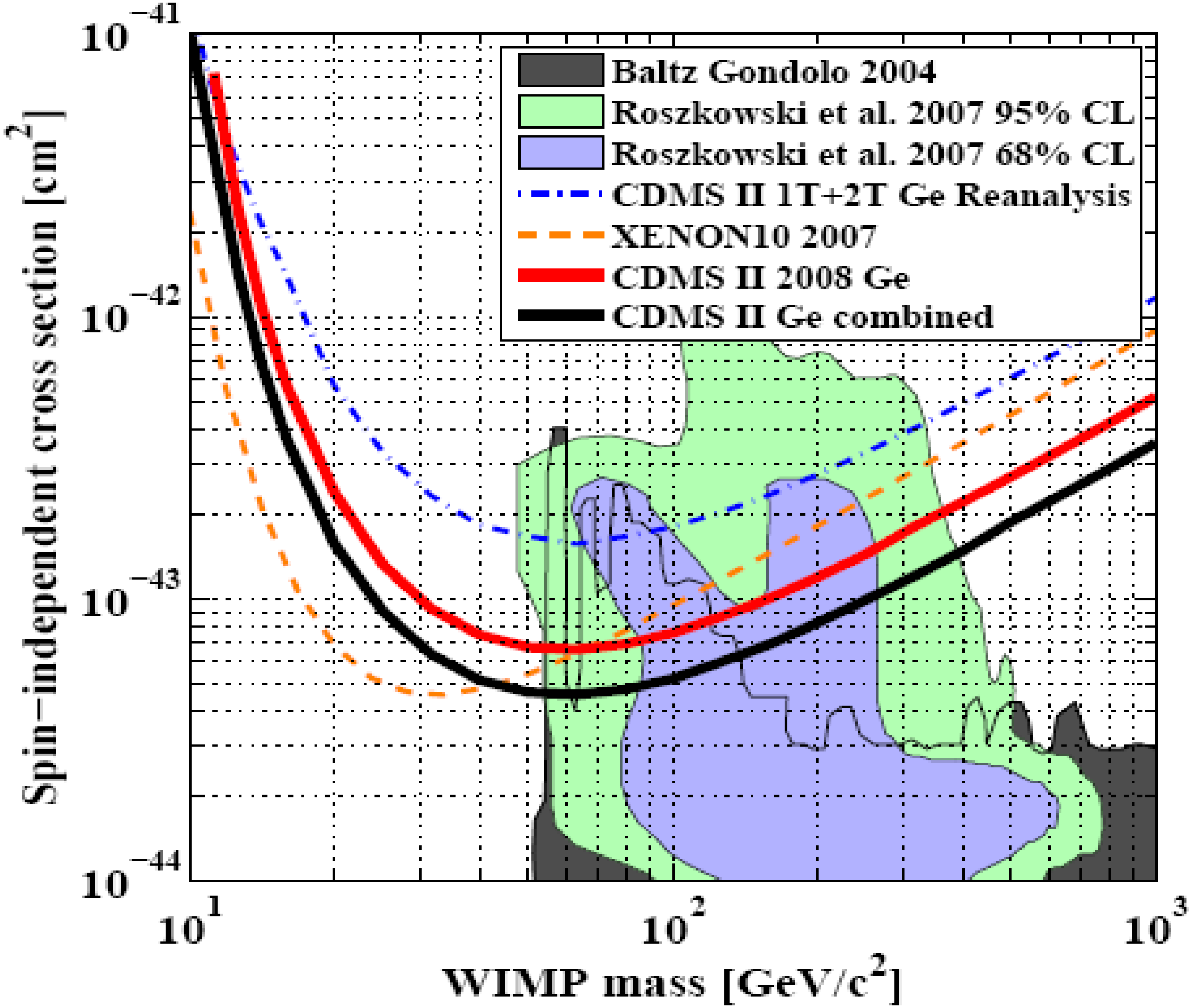
Constraints (cont)

- $B \to \tau\nu$:   HFAG + Isidori & Paradisi, hep-ph/0605012 & Erikson etal., 0808.3551 for loop corrections

  → $B = (55 \text{ to } 227) \times 10^{-6}$

- $B_s \to \mu\mu$: CDF/ D0 combined limit $B < 4.5 \times 10^{-8}$ @95% CL

Dark Matter: Direct Searches for WIMPs



Constraints (cont.)

- CDMS, XENON10, DAMA, CRESST-I,… → We find a factor of ~ 4 uncertainty in the nuclear matrix elements obtained from studying several benchmark points in detail & so we allow cross sections 4x larger than the usually quoted limits. Spin-independent limits are completely dominant here.

- 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.

- LEP and Tevatron Direct Higgs & SUSY searches : there are *many* of these searches but they are very complicated with many caveats…. CAREFUL!

Zh, h-> bb, ττ

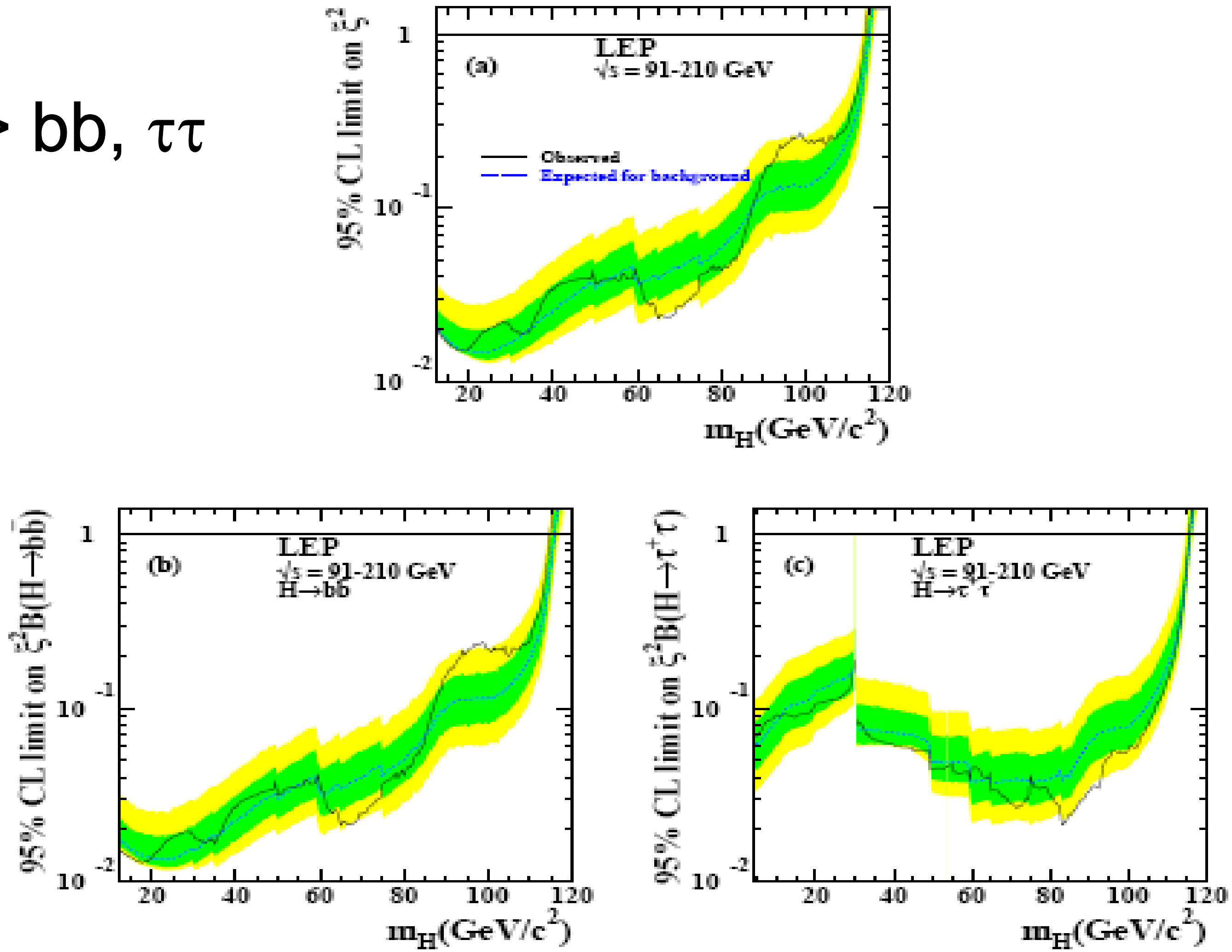


Figure 1: *The 95% c.l. upper bound on the coupling ratio* $\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$ *(see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling.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

$Z \to hA \to 4b/2b2\tau/4\tau$

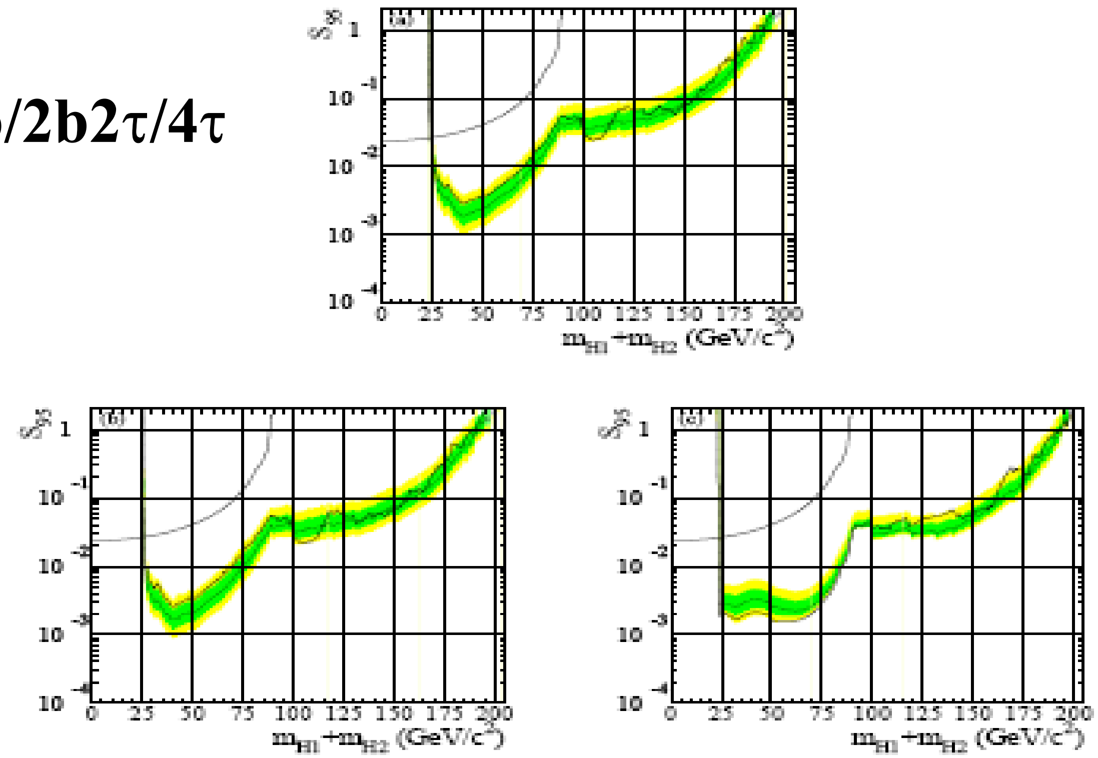
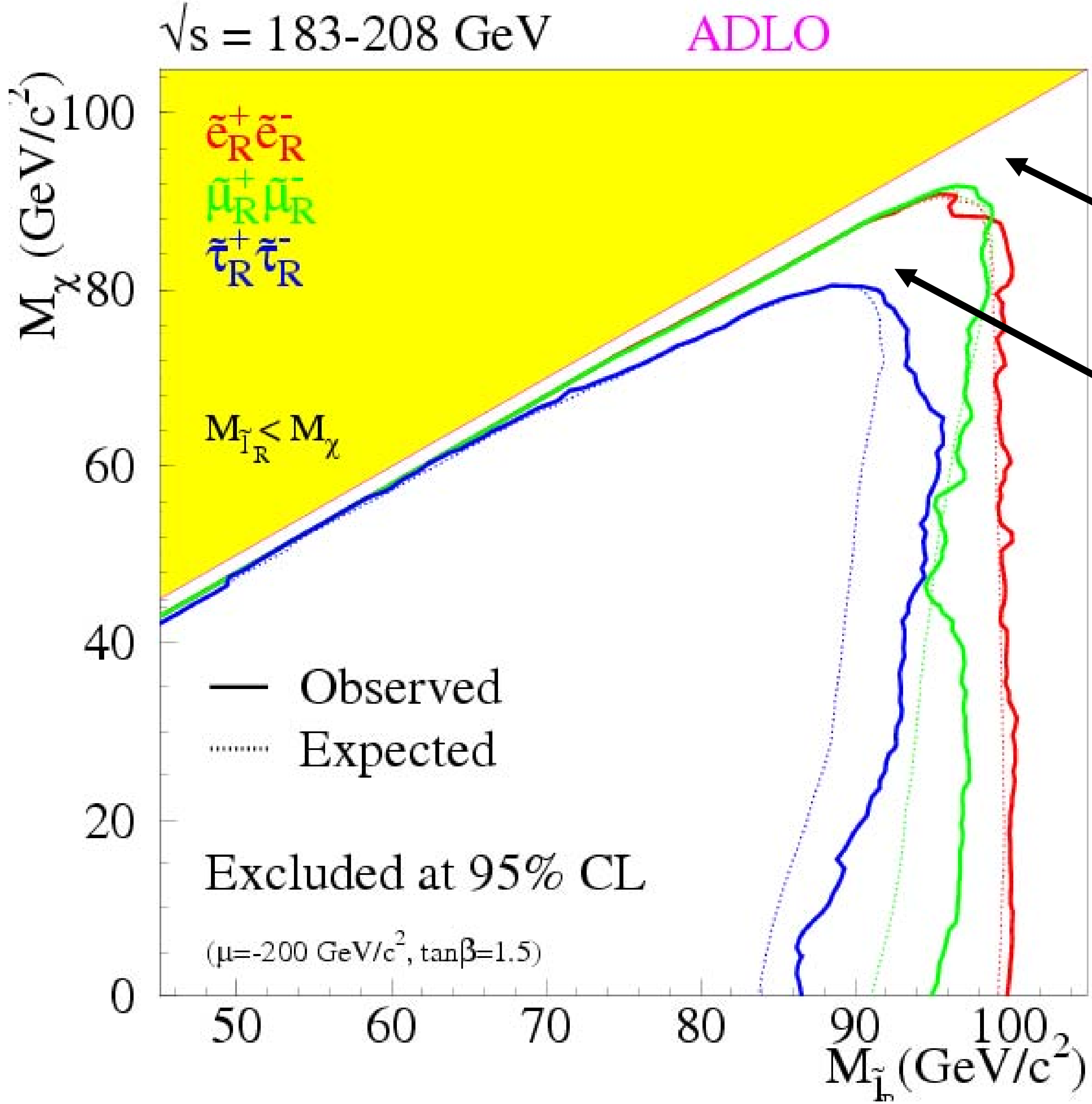


Figure 3: Model-independent 95% c.l. upper bounds, S_{95}, for various topological cross sections motivated by the pair-production process $e^+e^- \to \mathcal{H}_2\mathcal{H}_1$, for the particular case where $m_{\mathcal{H}_2}$ and $m_{\mathcal{H}_1}$ are approximately equal. Such is the case, for 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% $\mathcal{H}_1 \to b\bar{b}$, 6% $\mathcal{H}_1 \to \tau^+\tau^-$, 92% $\mathcal{H}_2 \to b\bar{b}$ and 8% $\mathcal{H}_2 \to \tau^+\tau^-$; 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 other cases when soft guys are possible..light sparticles may slip through!

Tevatron Constraints : I   Squark & Gluino Search

- 2,3,4 Jets + Missing Energy Analyses (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 so we expect squarks & gluinos far below the usual limits here....

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 ± 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

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

Tevatron III: D0 Stable Particle (= Chargino) Search

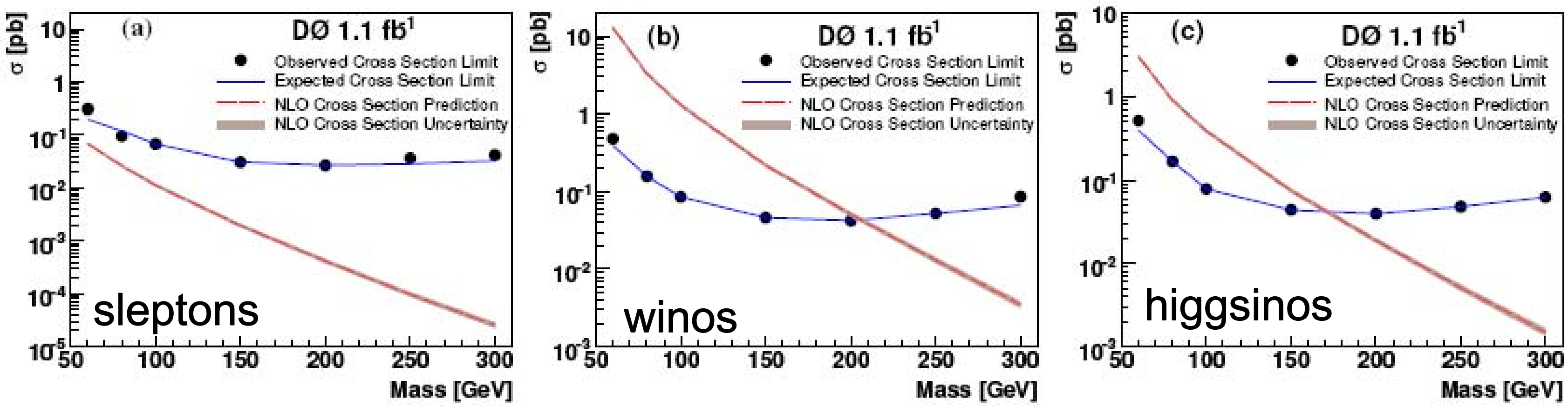


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos,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

SOME RESULTS

Survival Rates

•Flat Priors :

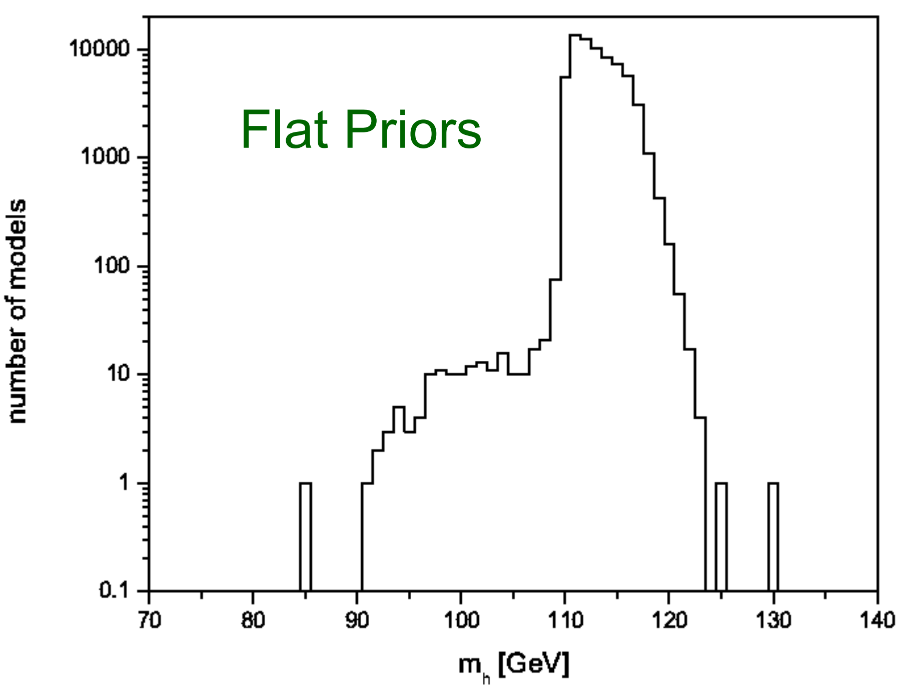
- 10^7 models scanned
- 68.5 K (0.68%) survived

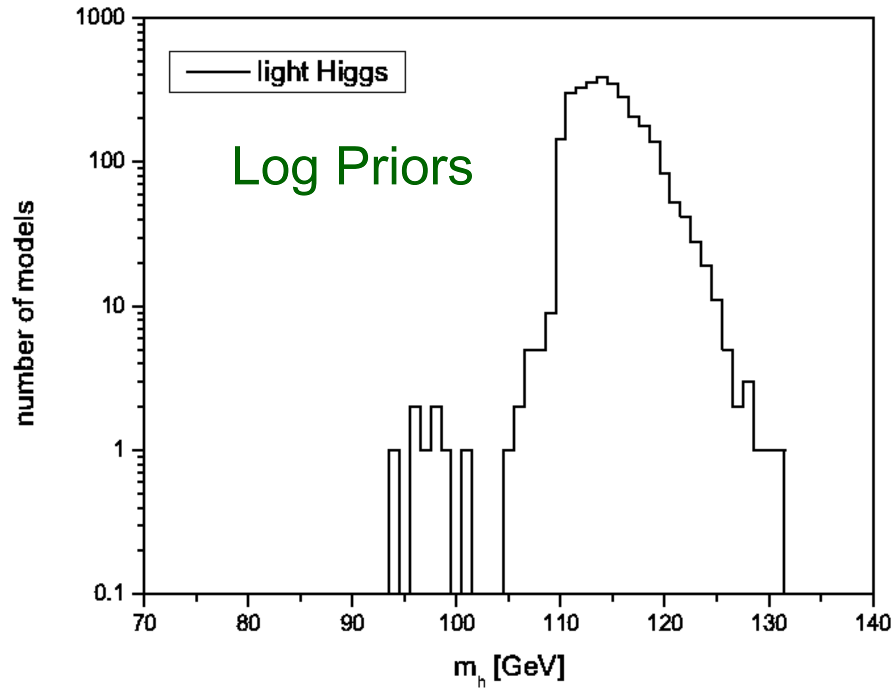
• Log Priors :

- $2x10^6$ models scanned
- 3.0 K (0.15%) survived

9999039	slha-okay.txt
7729165	error-okay.txt
3270330	lsp-okay.txt
3261059	deltaRho-okay.txt
2168599	gMinus2-okay.txt
617413	b2sGamma-okay.txt
594803	Bs2MuMu-okay.txt
592195	vacuum-okay.txt
582787	Bu2TauNu-okay.txt
471786	LEP-sparticle-okay.txt
471455	invisibleWidth-okay.txt
468539	susyhitProb-okay.txt
418503	stableParticle-okay.txt
418503	chargedHiggs-okay.txt
132877	directDetection-okay.txt
83662	neutralHiggs-okay.txt
73868	omega-okay.txt
73575	Bs2MuMu-2-okay.txt
72168	stableChargino-2-okay.txt
71976	triLepton-okay.txt
69518	jetMissing-okay.txt
68494	final-okay.txt

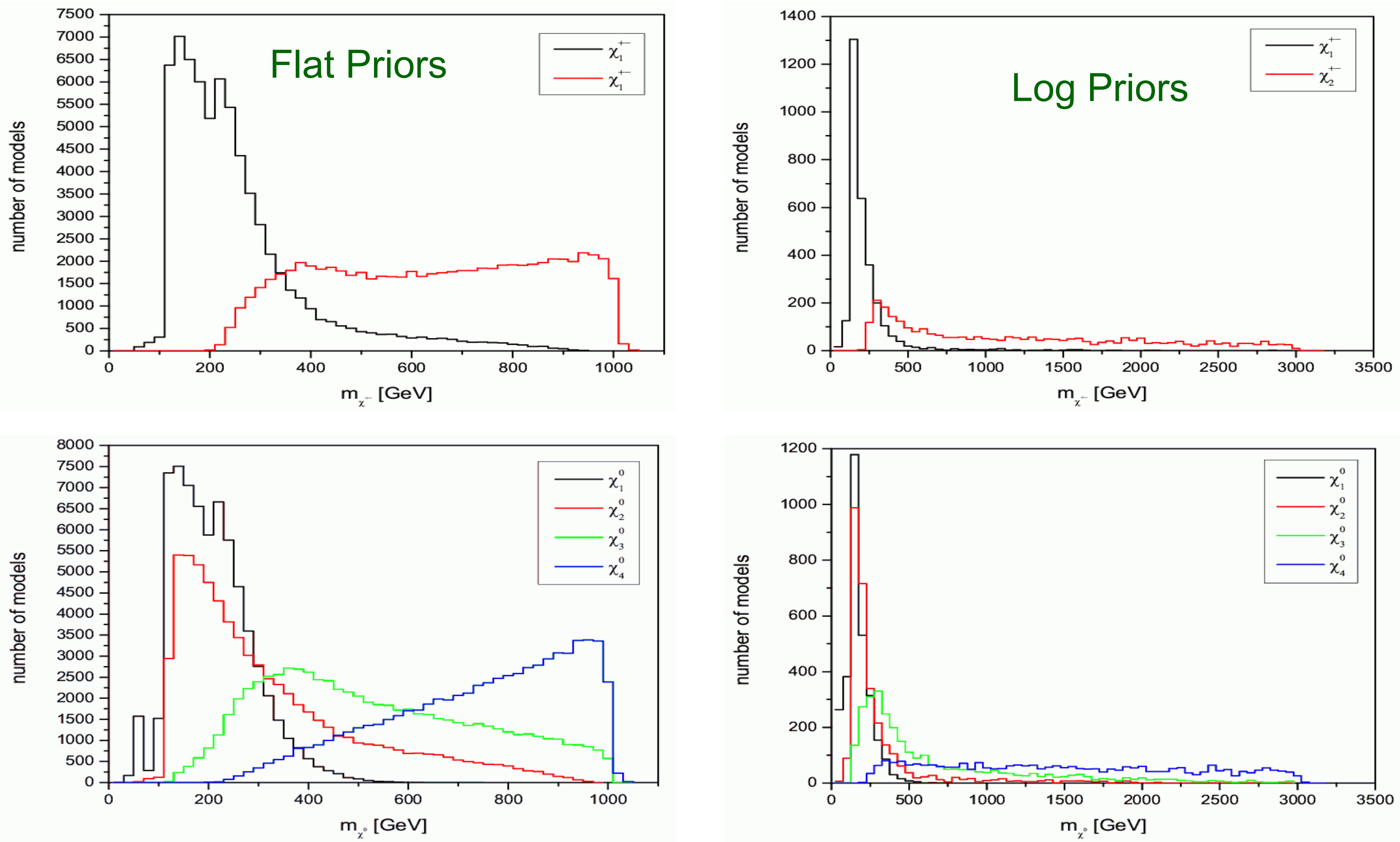
Light Higgs Mass Predictions





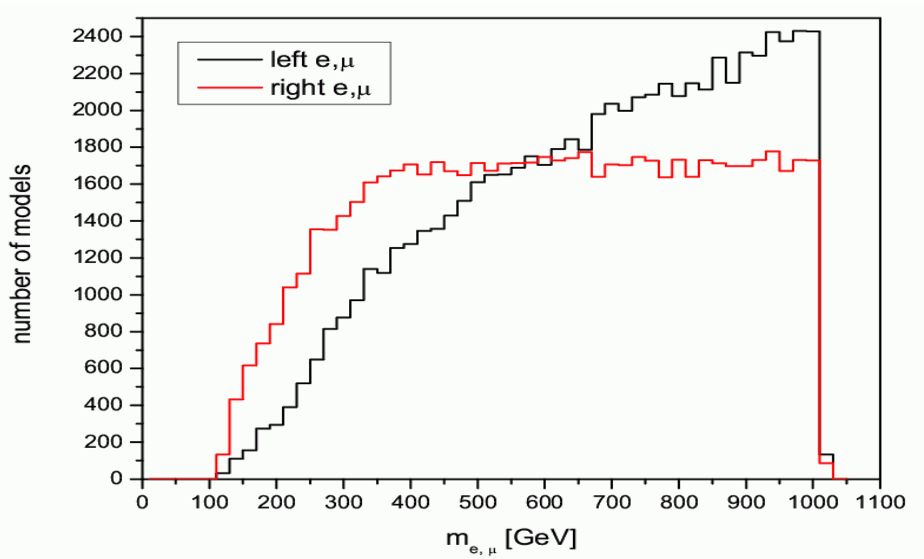
LEP Higgs mass constraints avoided by either reducing the ZZh coupling and/or reducing the, e.g., $Z \rightarrow \bar{b}b$ branching fraction by decays to LSP pairs. We have both of these in our final model sets.

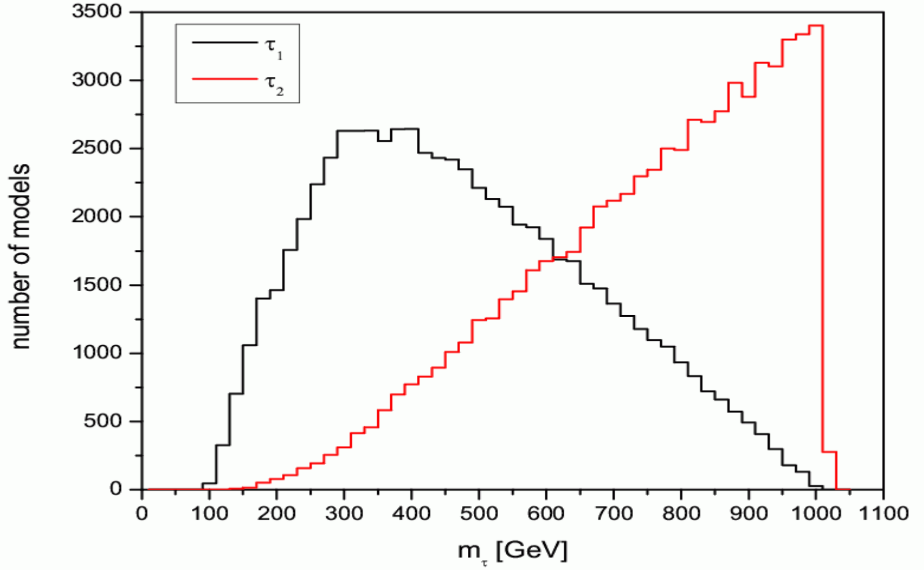
Distribution of Sparticle Masses By Species



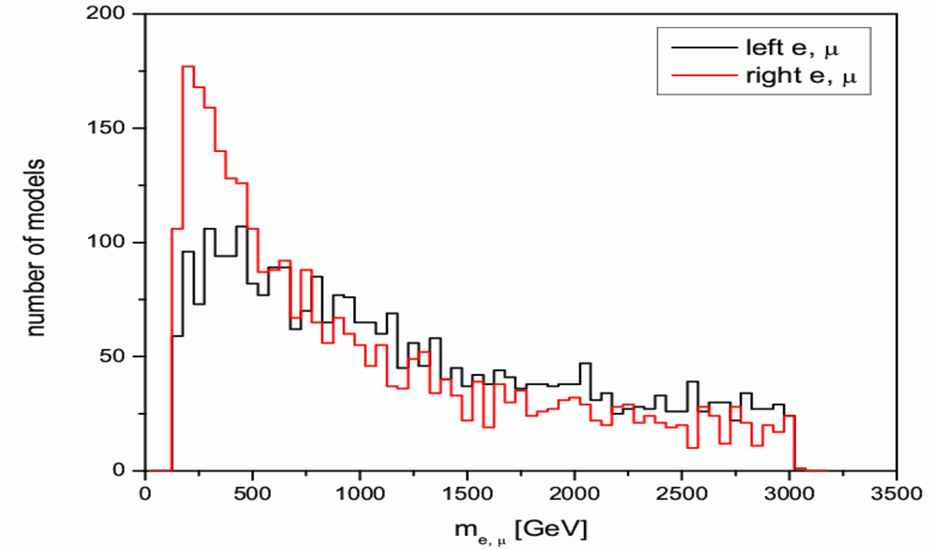
Distribution of Sparticle Masses By Species

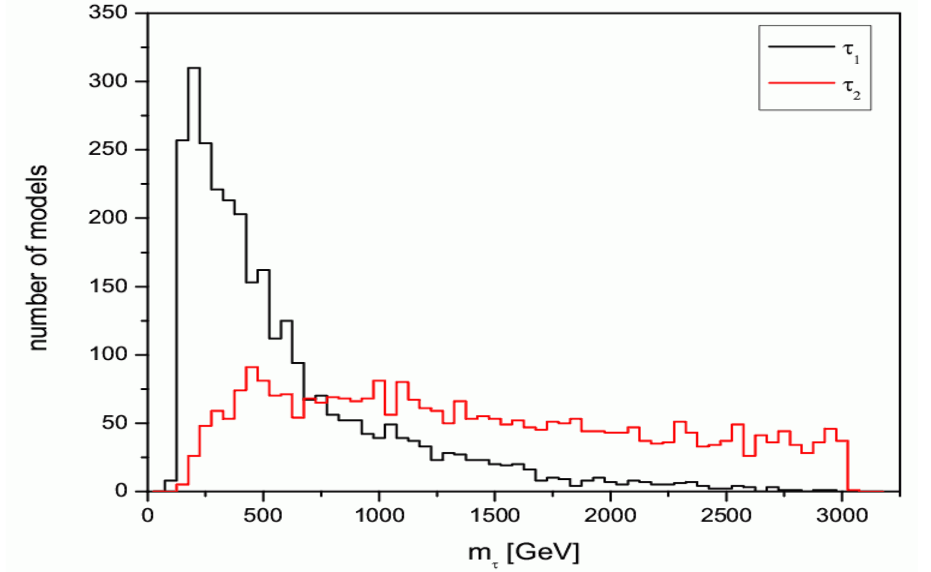
Flat Priors



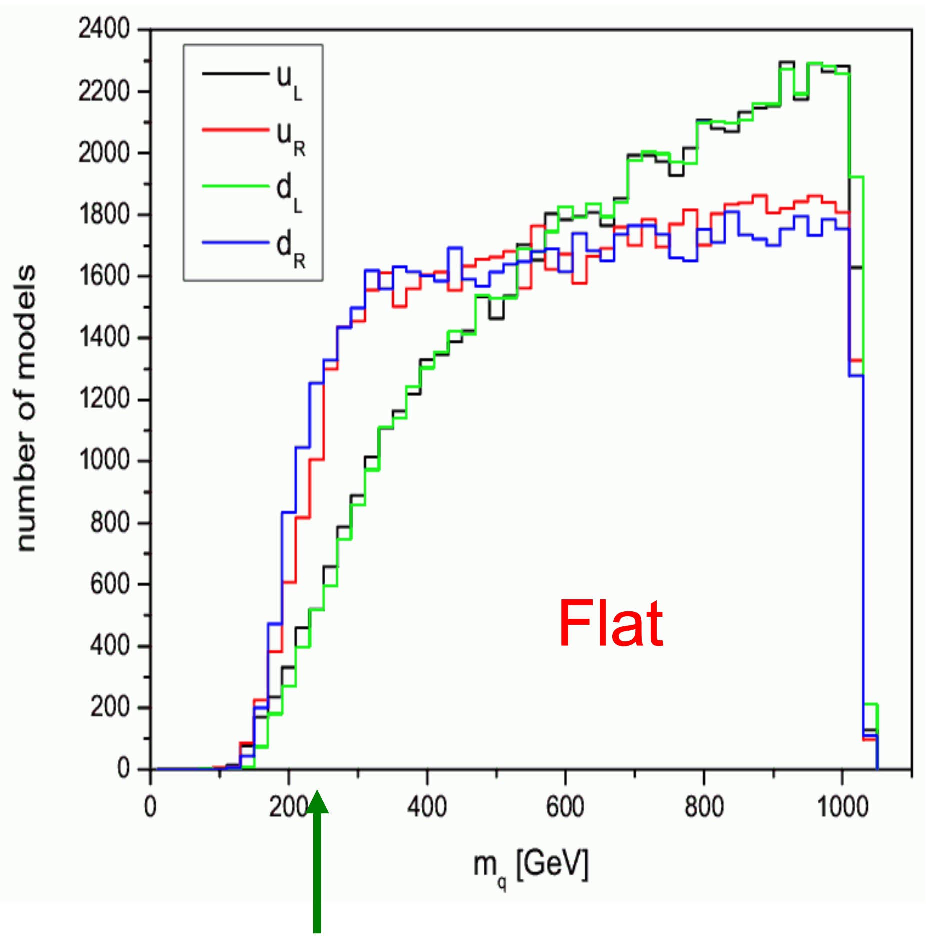


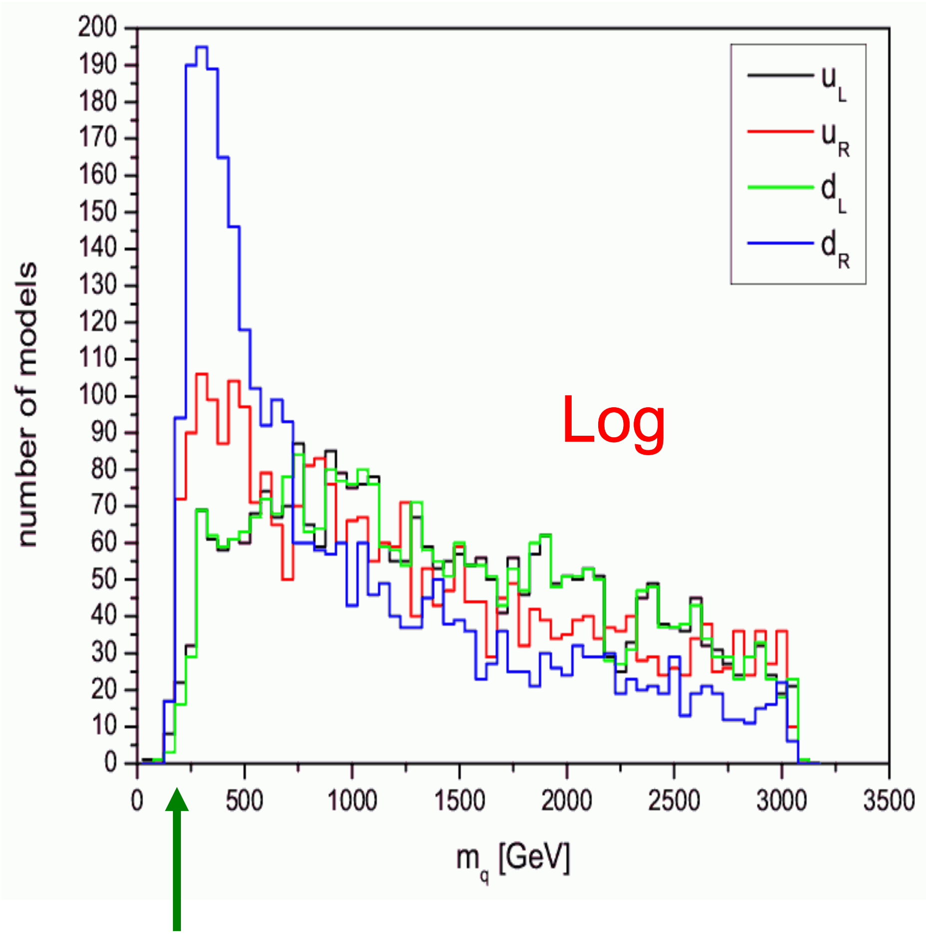
Log Priors





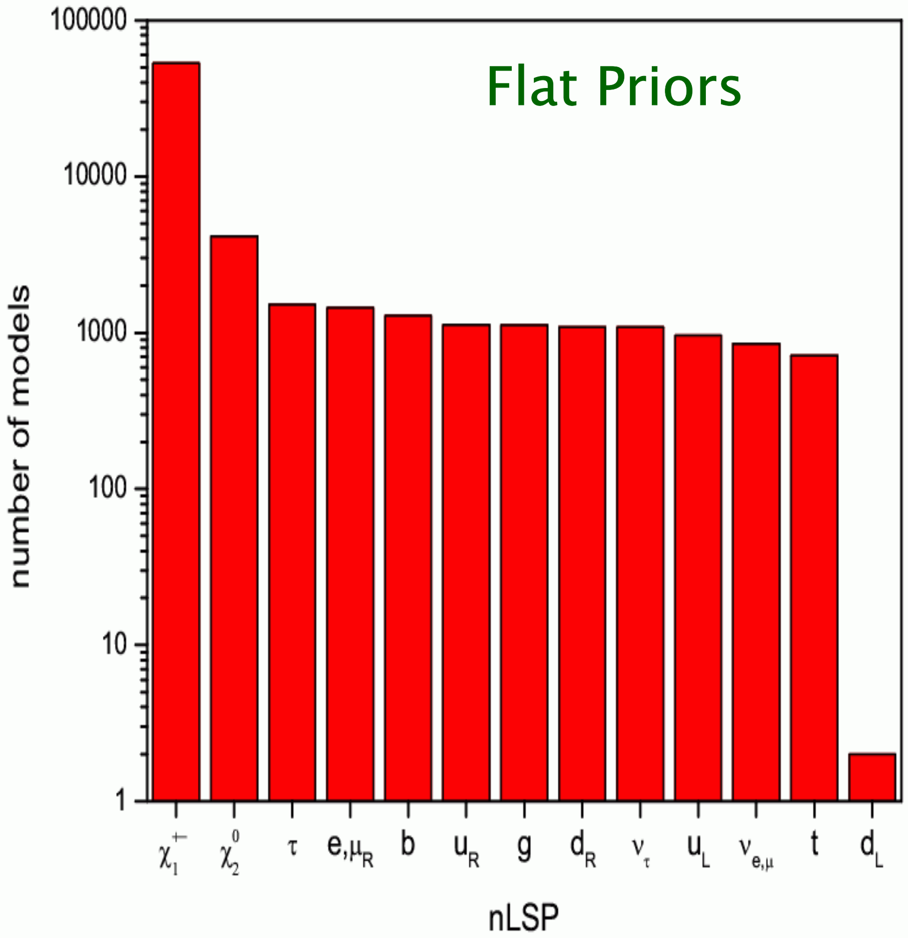
Sometimes Squarks CAN Be Light !!!

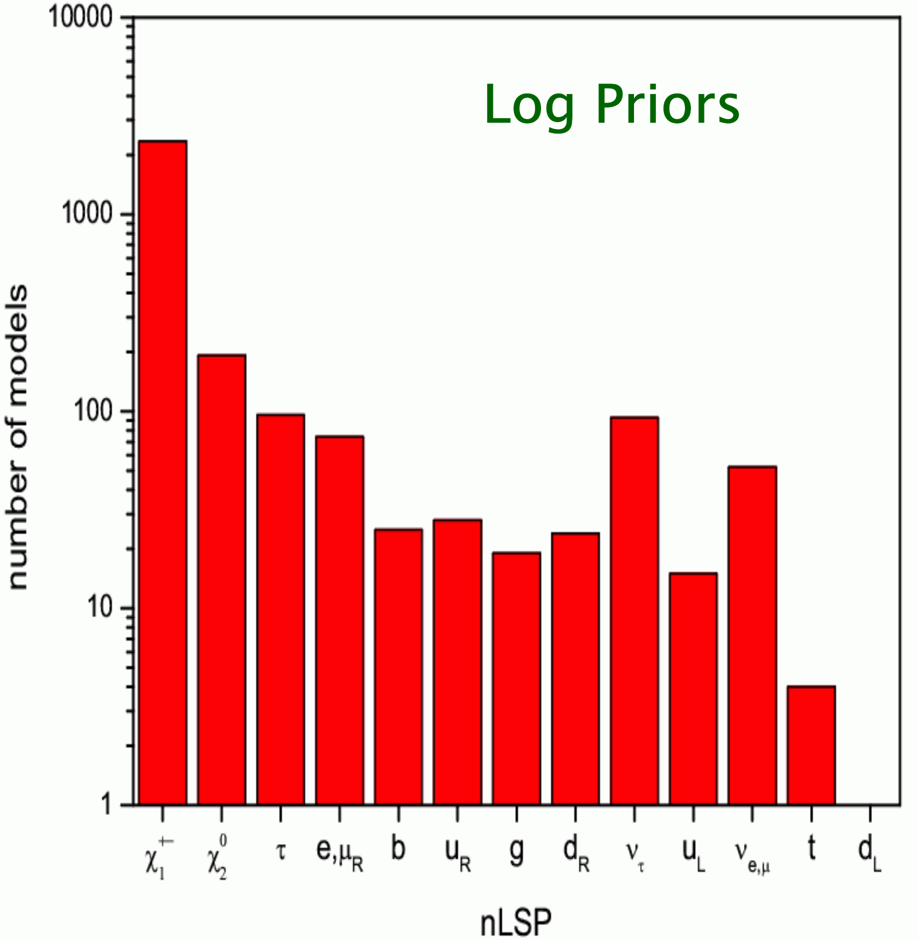




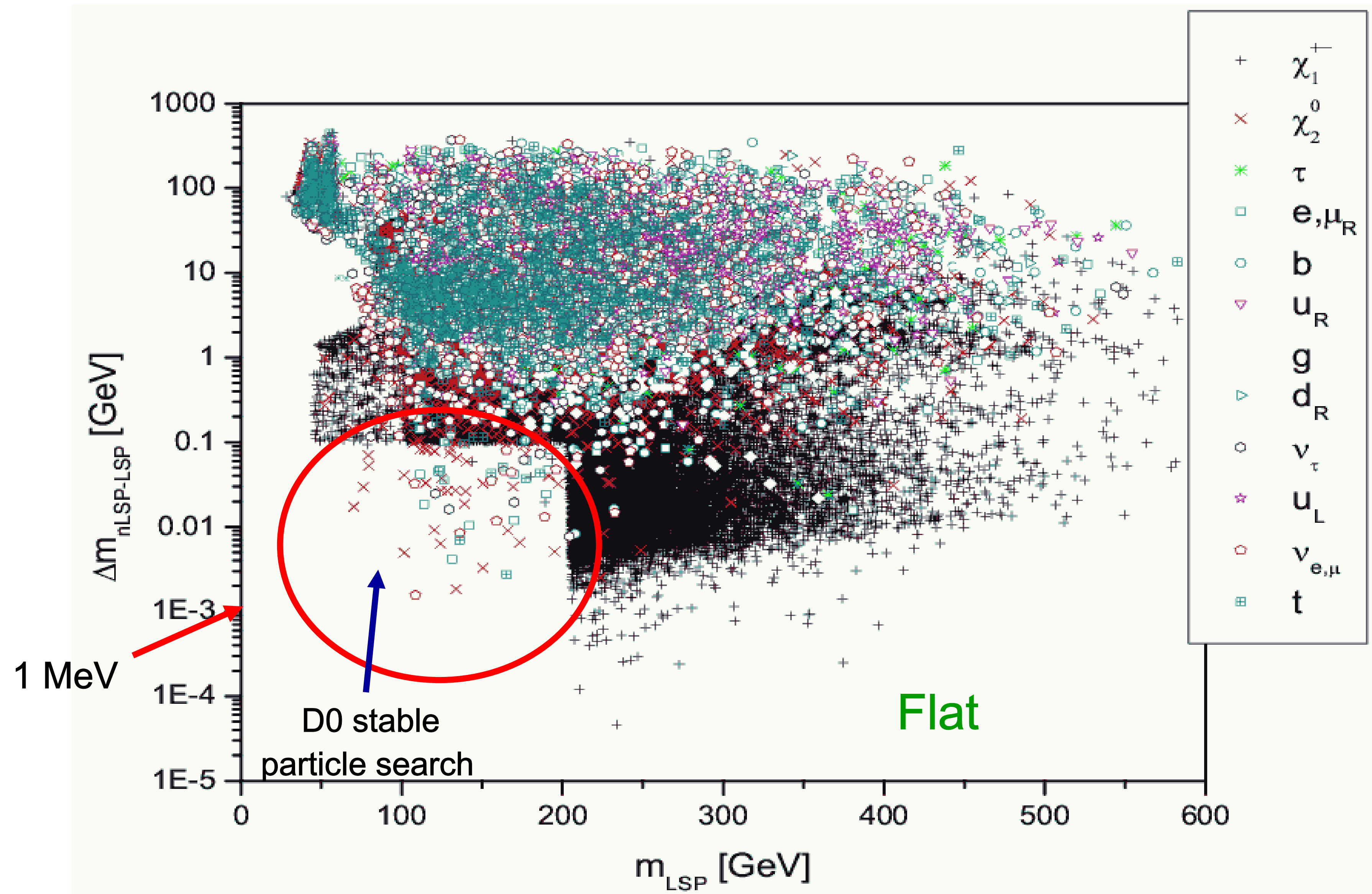
Light squarks can be missed by Tevatron searches for numerous reasons..

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

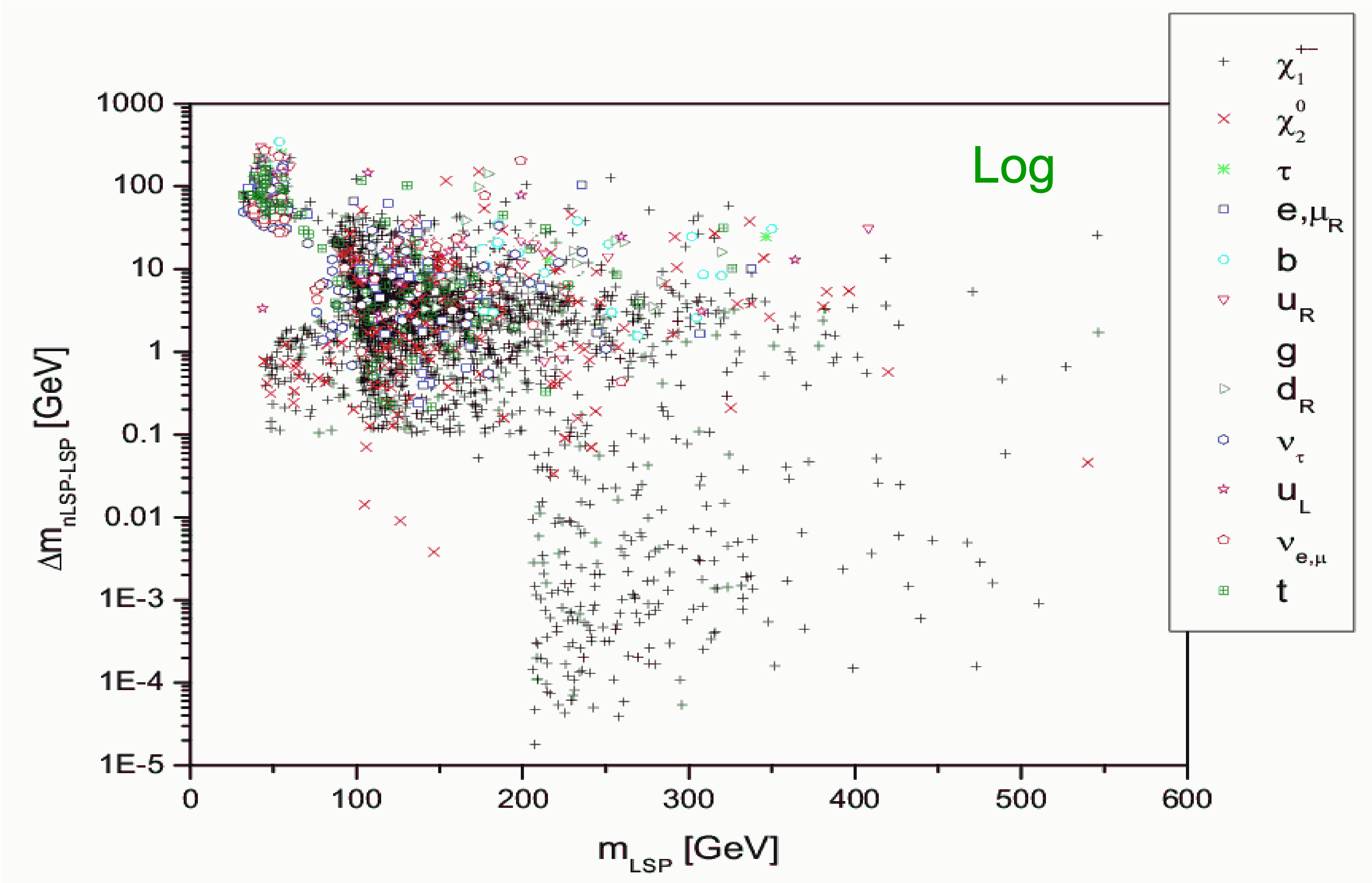




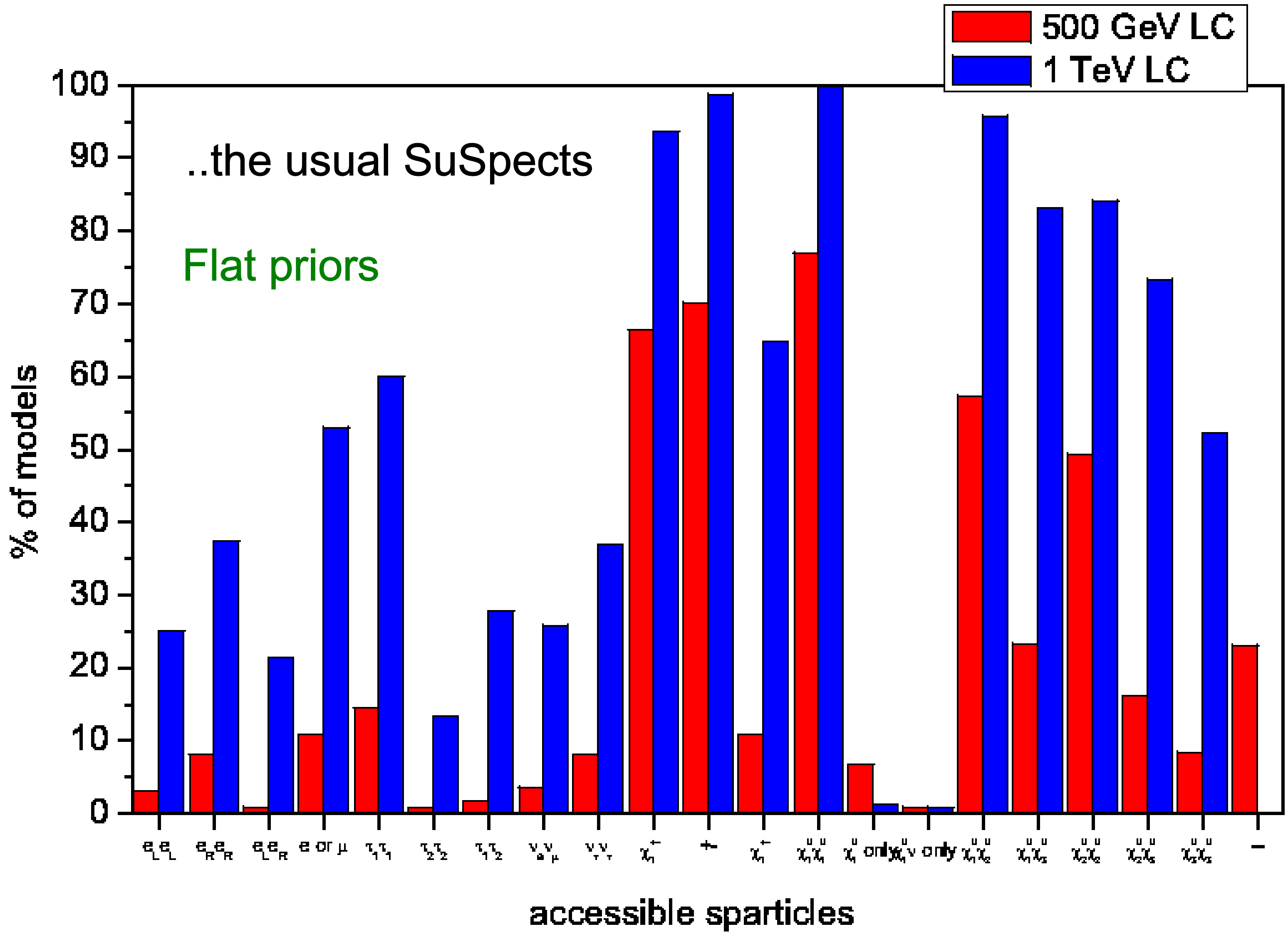
nLSP-LSP Mass Difference



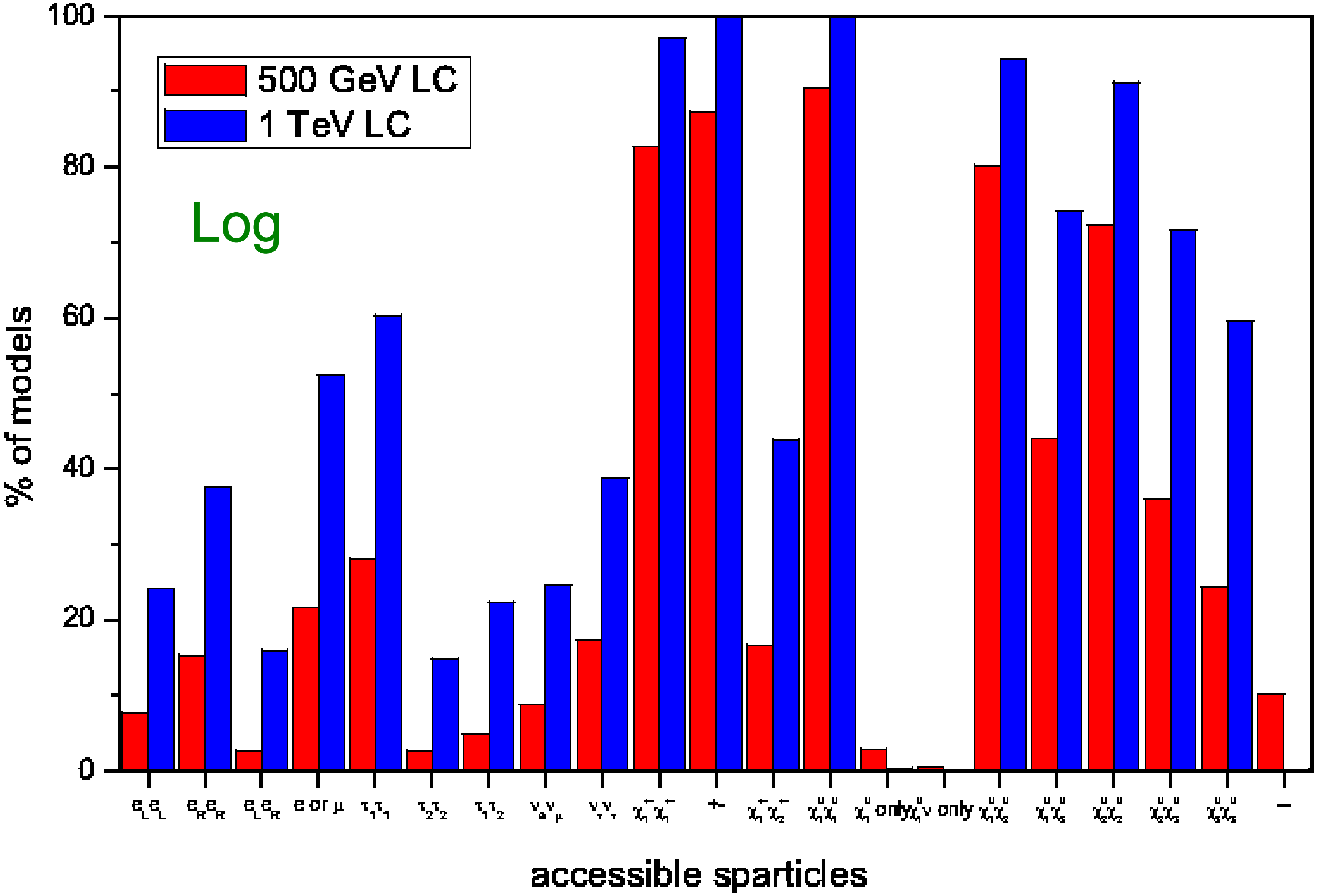
nLSP-LSP Mass Difference



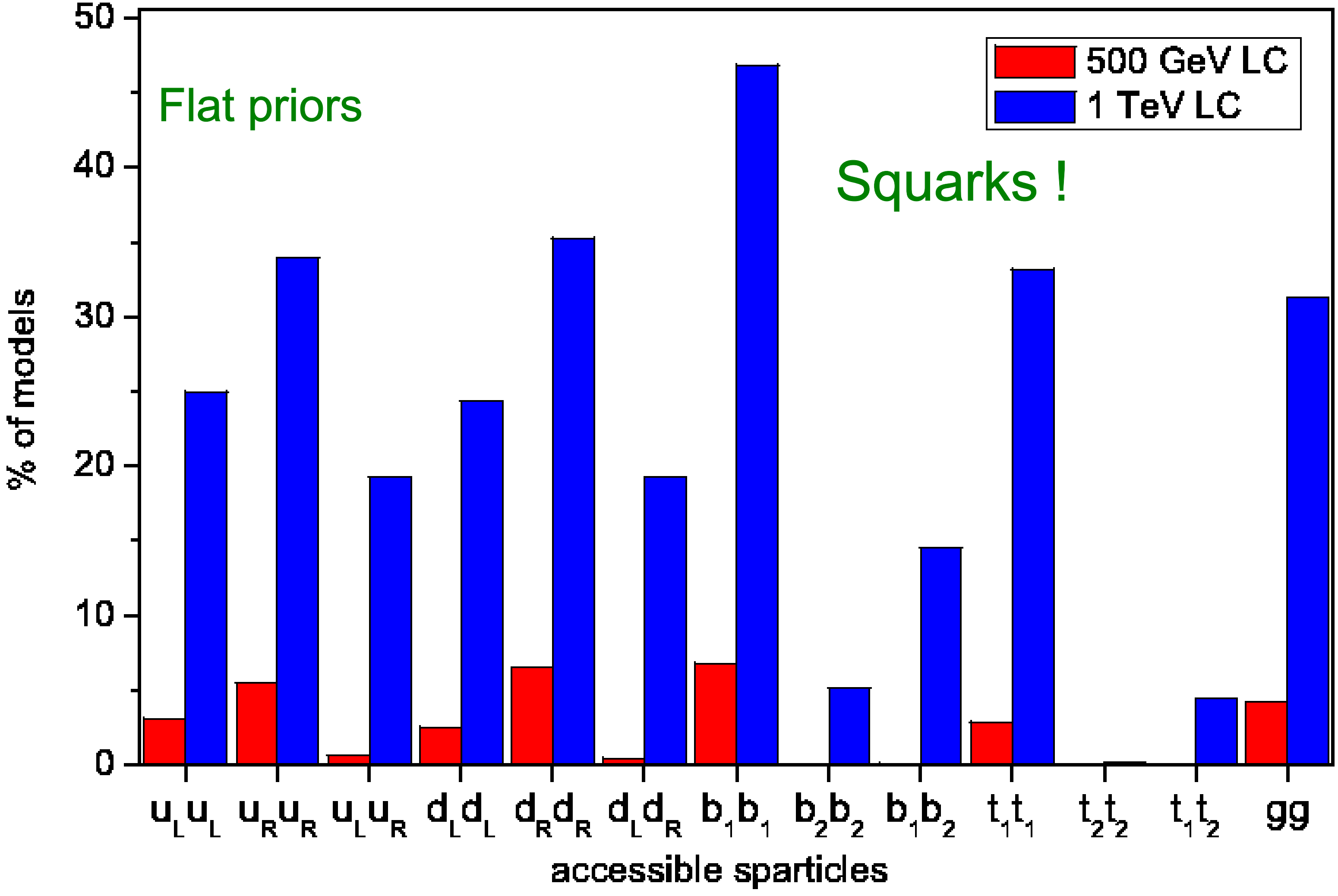
Kinematic Accessibility at the ILC : I



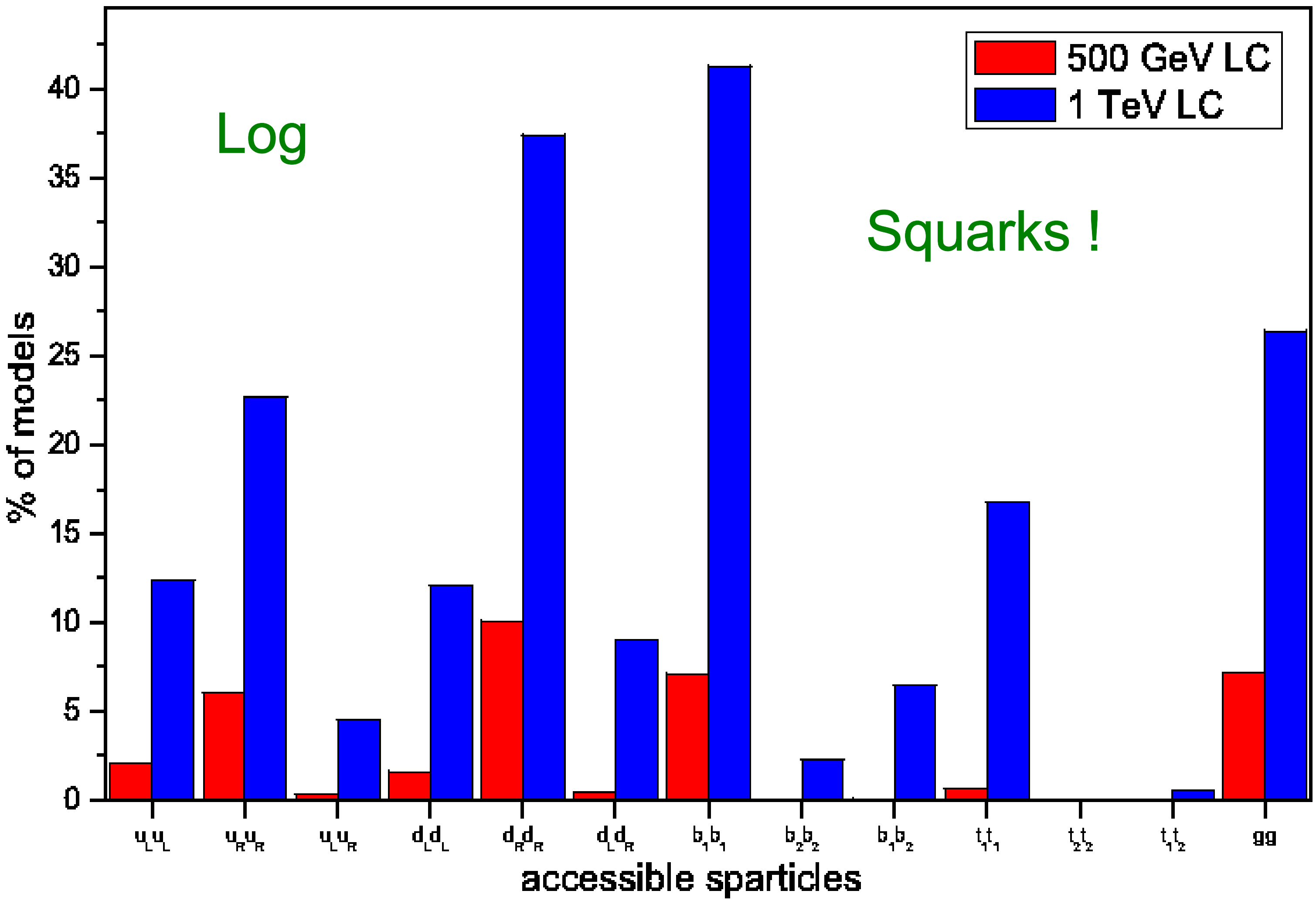
Kinematic Accessibility at the ILC : II



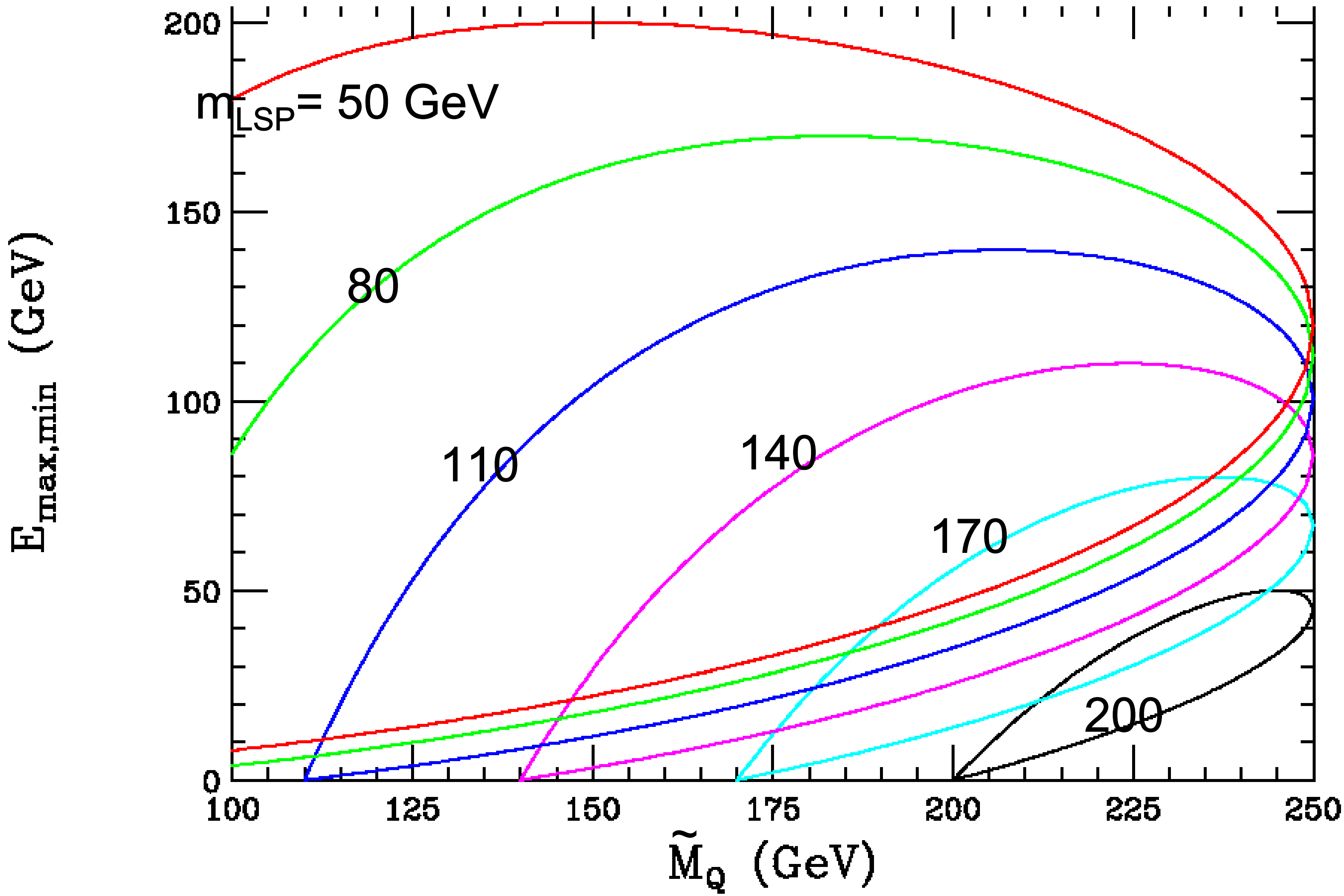
Kinematic Accessibility at the ILC : III



Kinematic Accessibility at the ILC : IV



Jet Energies from Squark Pair Production at √s=500 GeV



More Results?????

See JoAnne's talk

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 almost any sparticle!

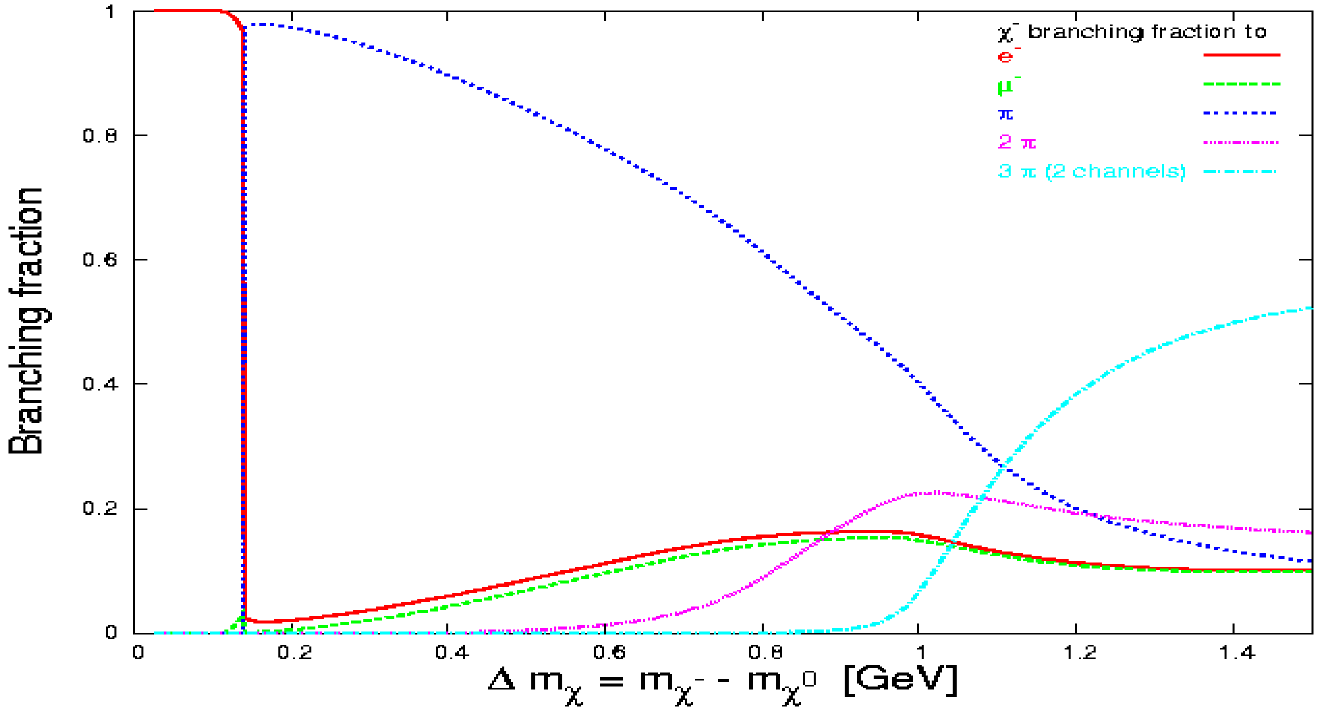
- Light partners may exist which have avoided LEP & Tevatron constraints and may be difficult to observe at the LHC due to rather common small mass differences

- Light squarks may be accessible at a 500 GeV ILC but have not been well-studied there

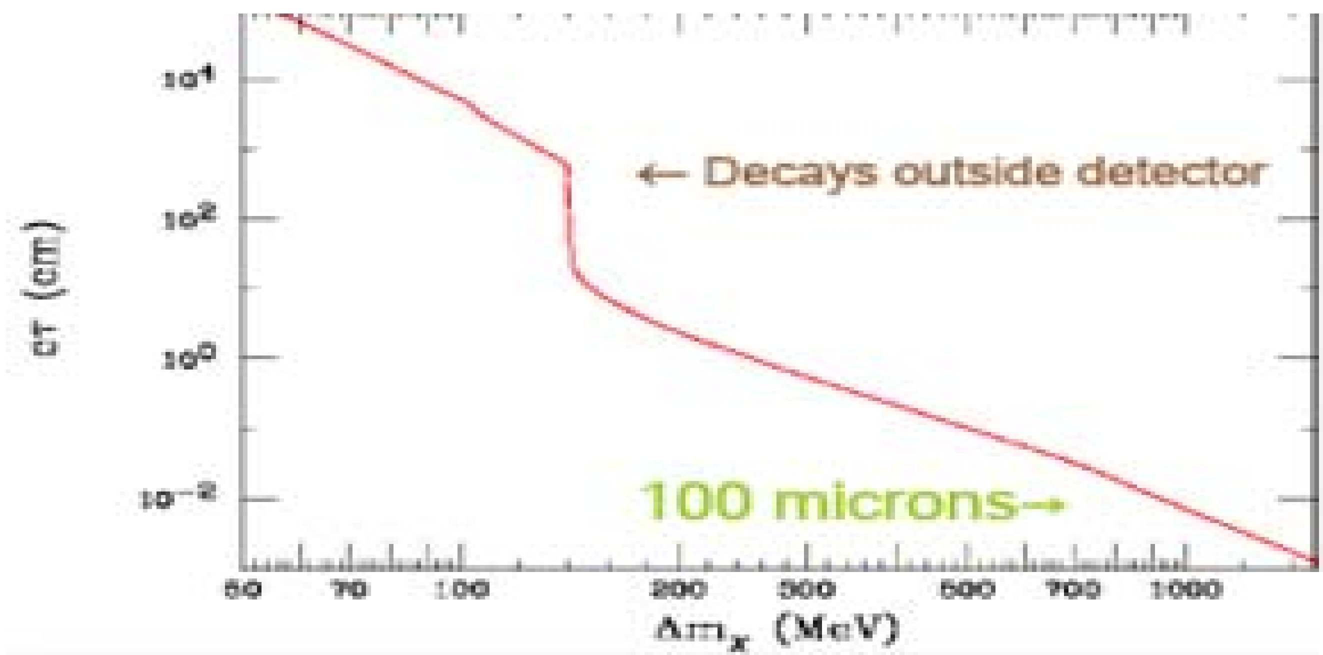
- With the WMAP constraint employed as a bound the LSP is not likely to be the dominant source of DM…but can be.

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

BACKUP SLIDES

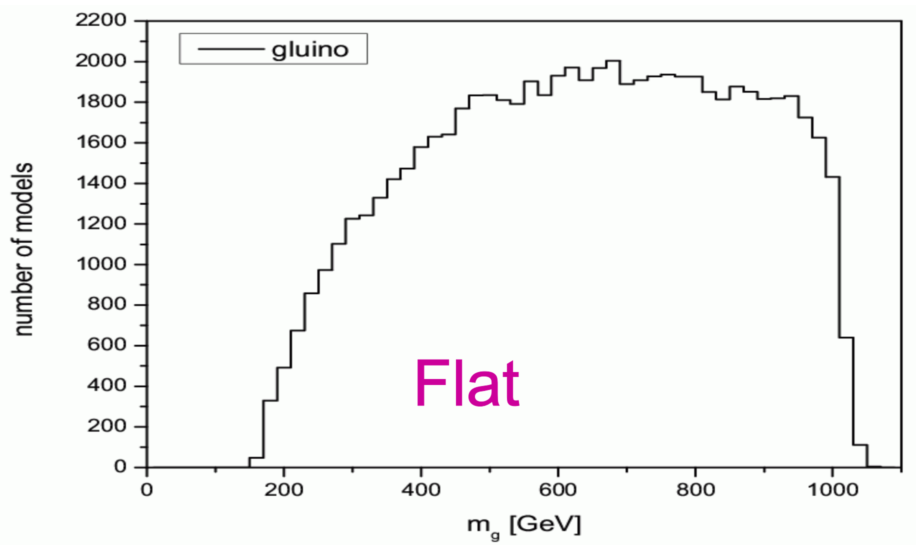


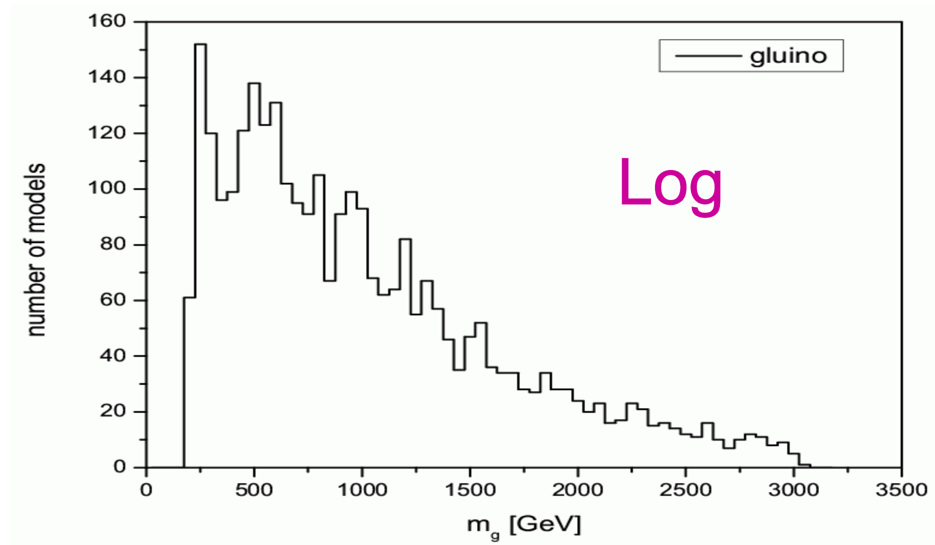
Branching fraction
χ^- branching fraction to
e^-
μ^-
π
2π
3π (2 channels)
$\Delta m_\chi = m_{\chi^-} - m_{\chi^0}$ [GeV]

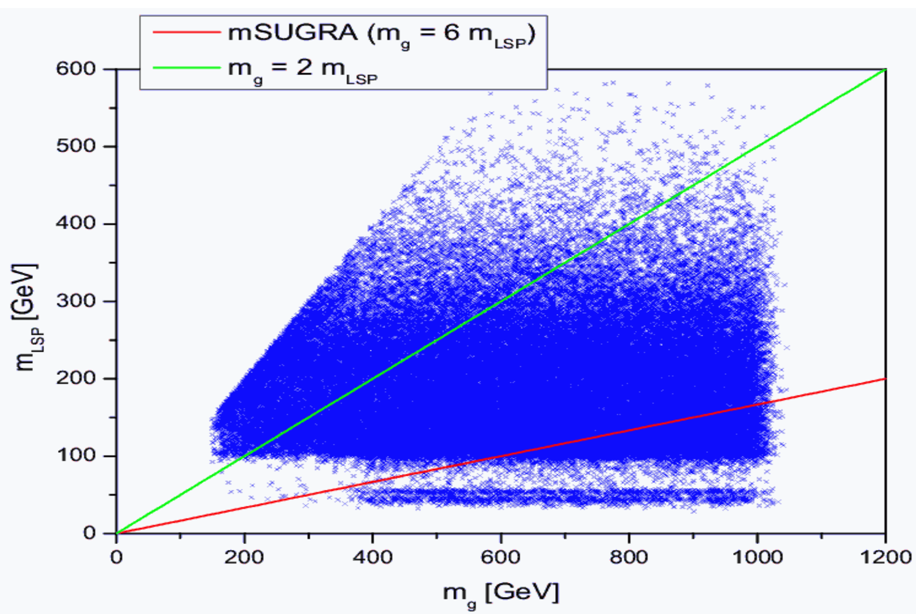


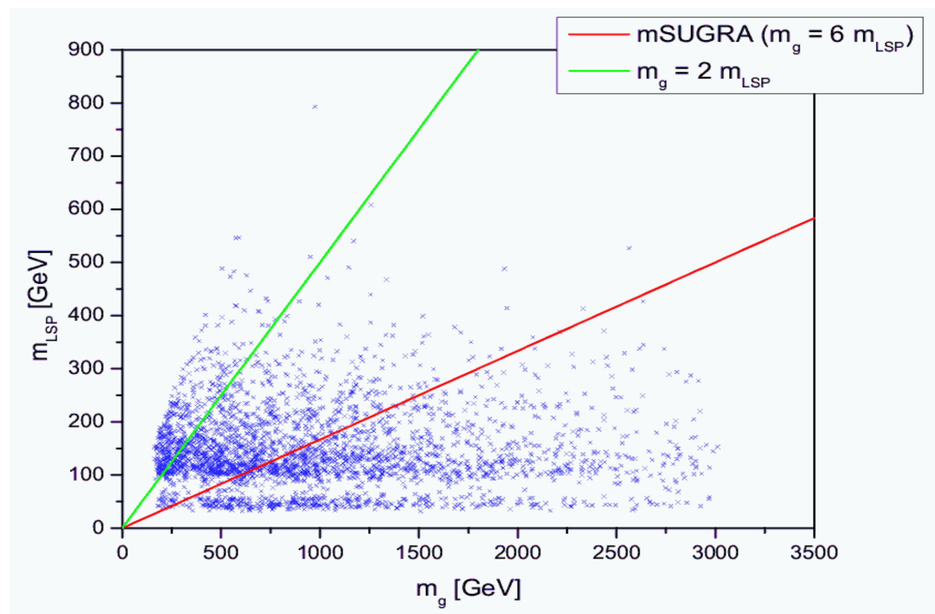
← Decays outside detector
100 microns→
cτ (cm)
Δm_χ (MeV)

Gluino Masses

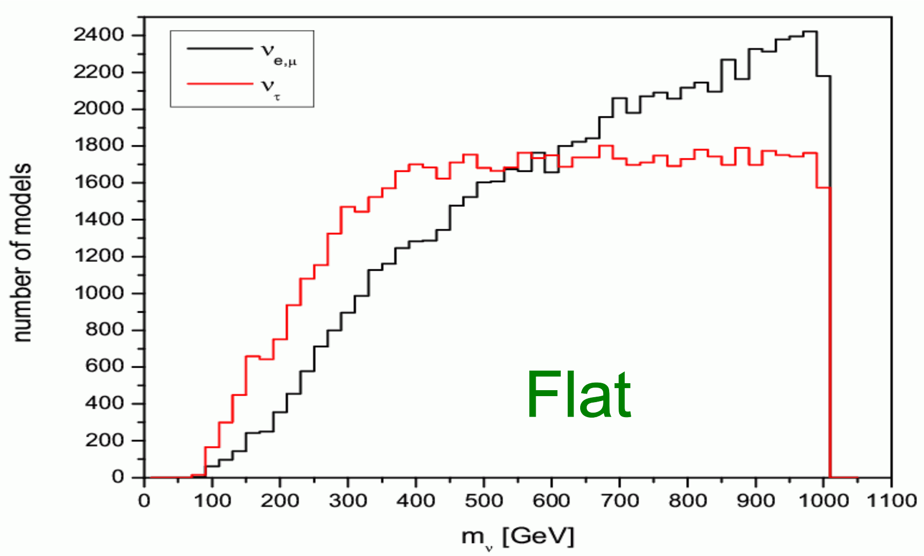


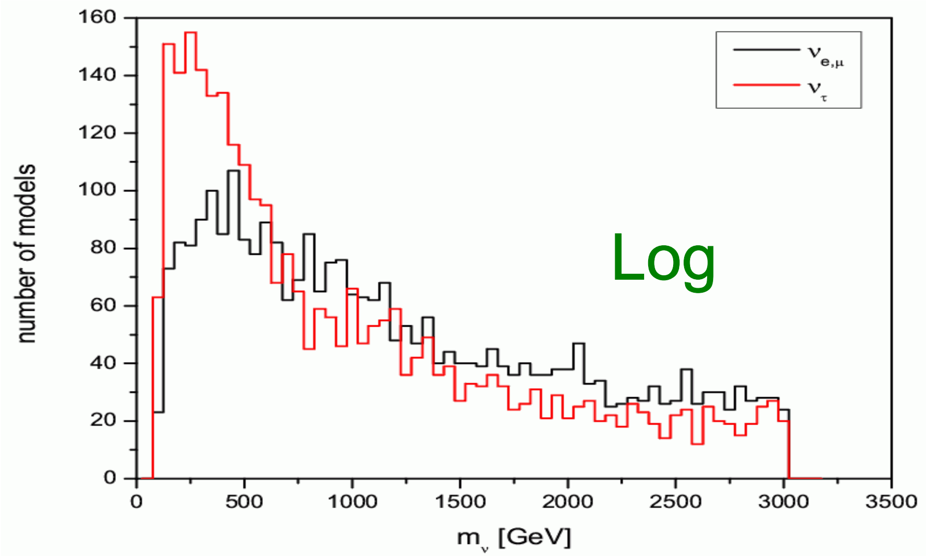


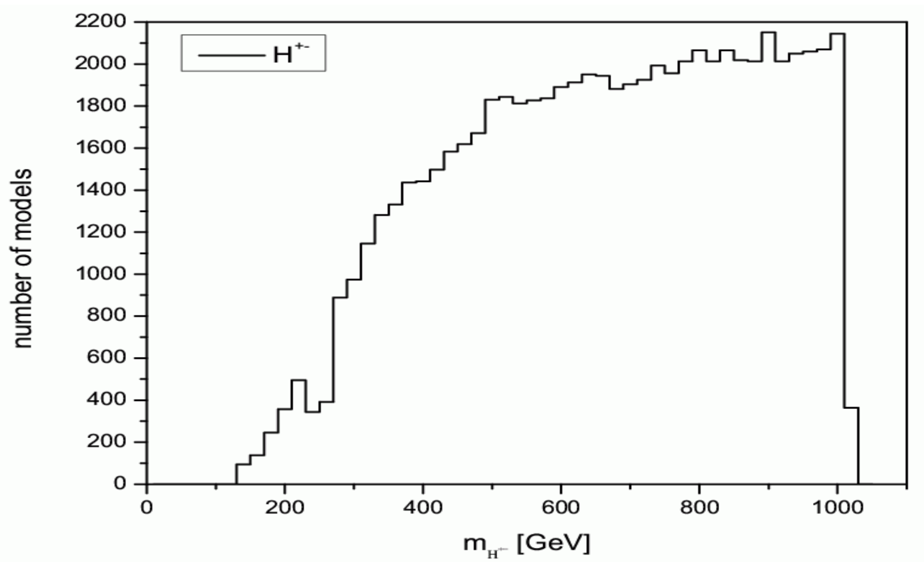


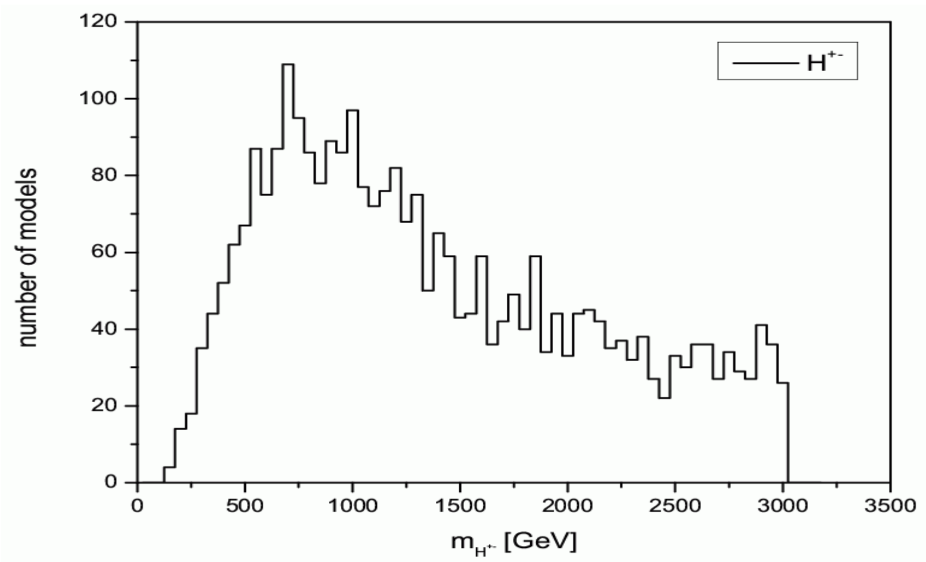


Distribution of Sparticle Masses By Species

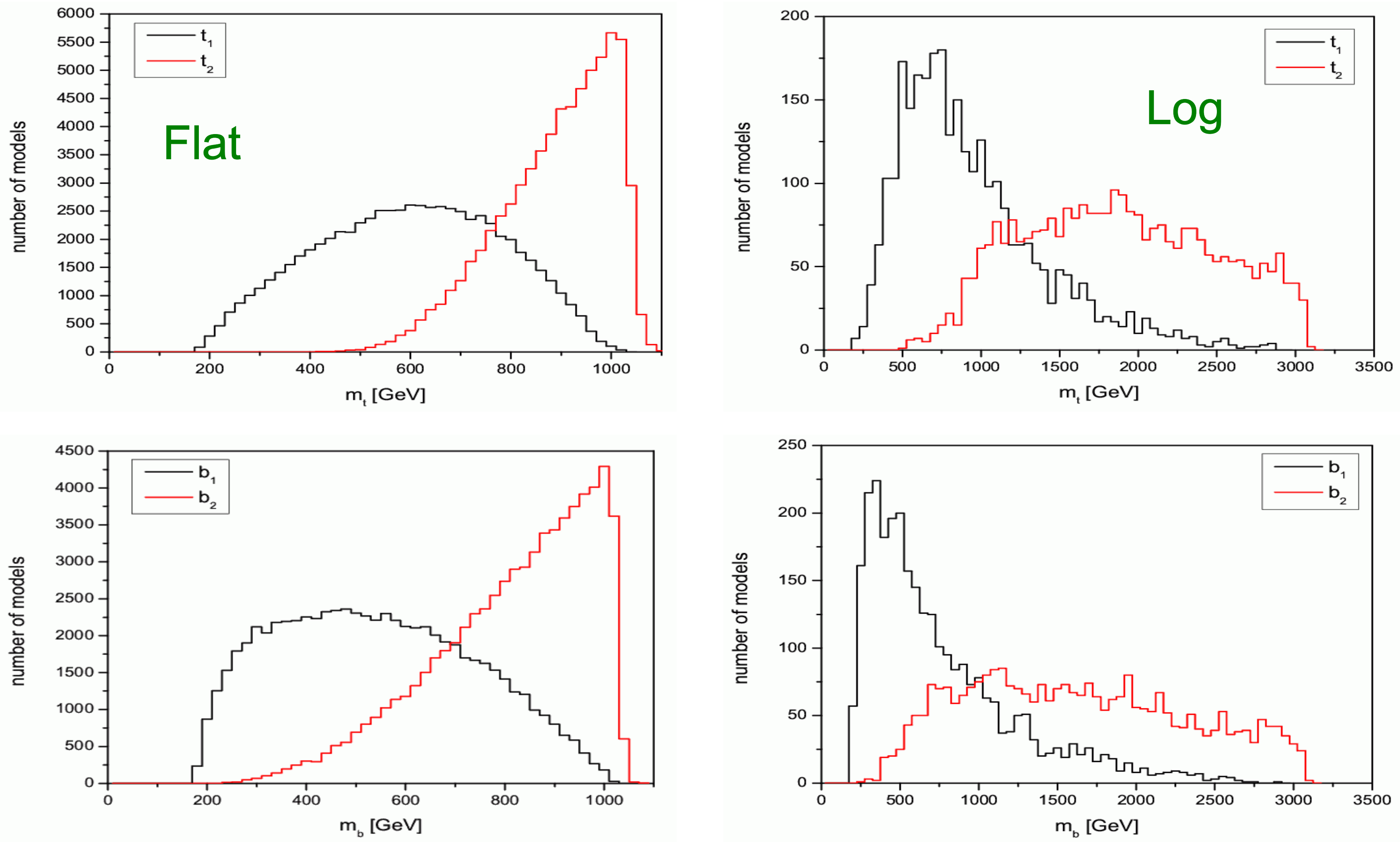




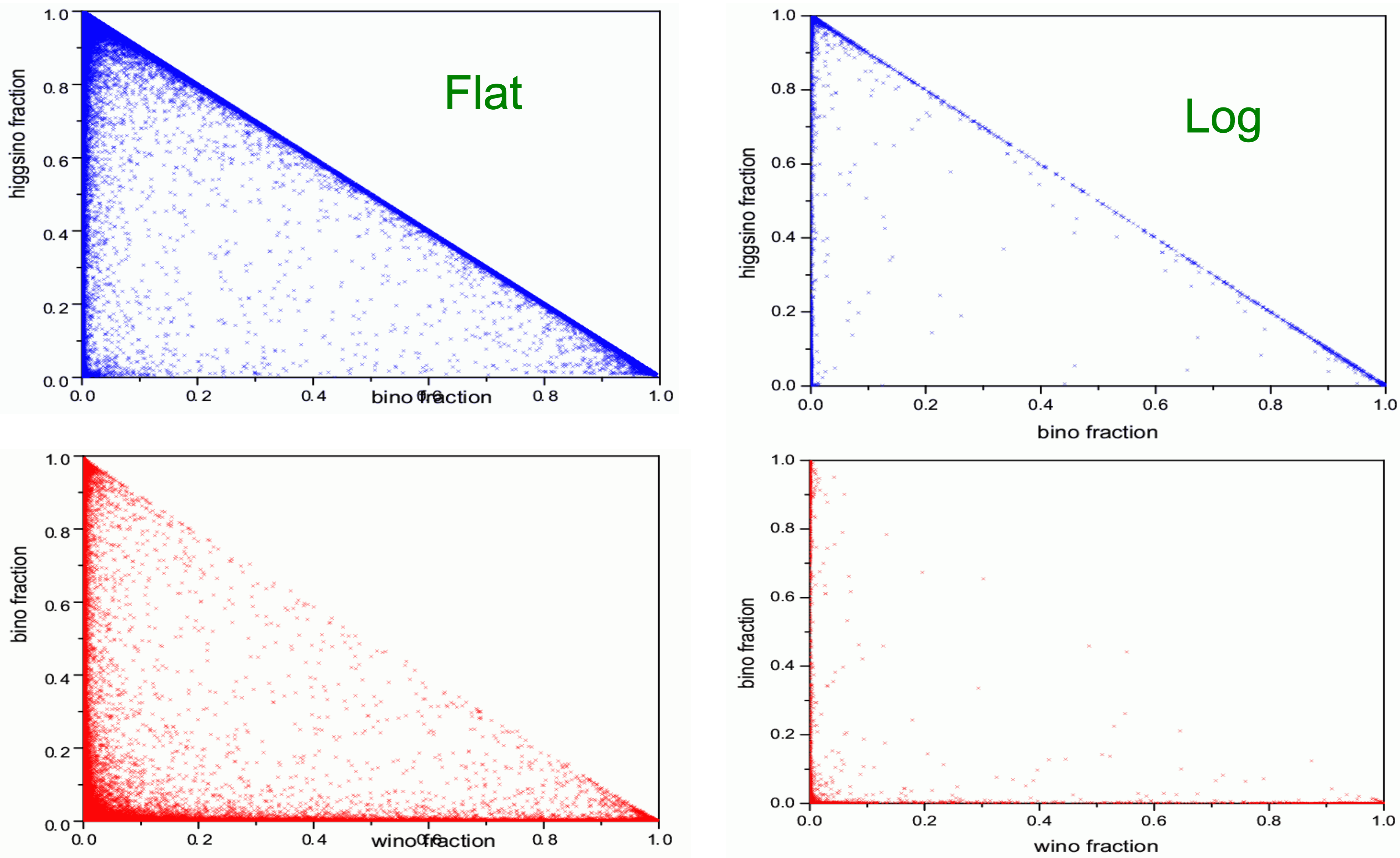




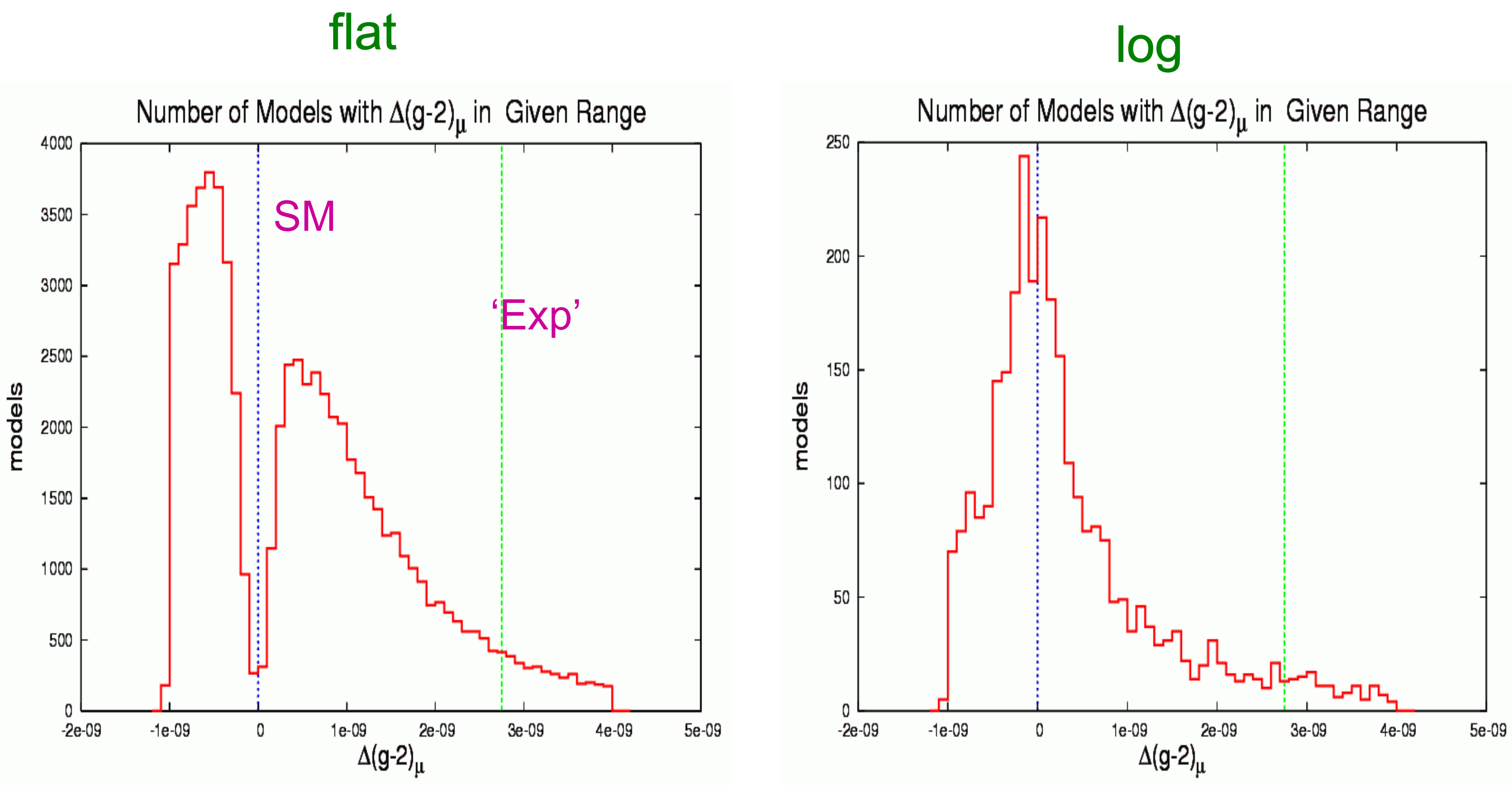
Distribution of Sparticle Masses By Species

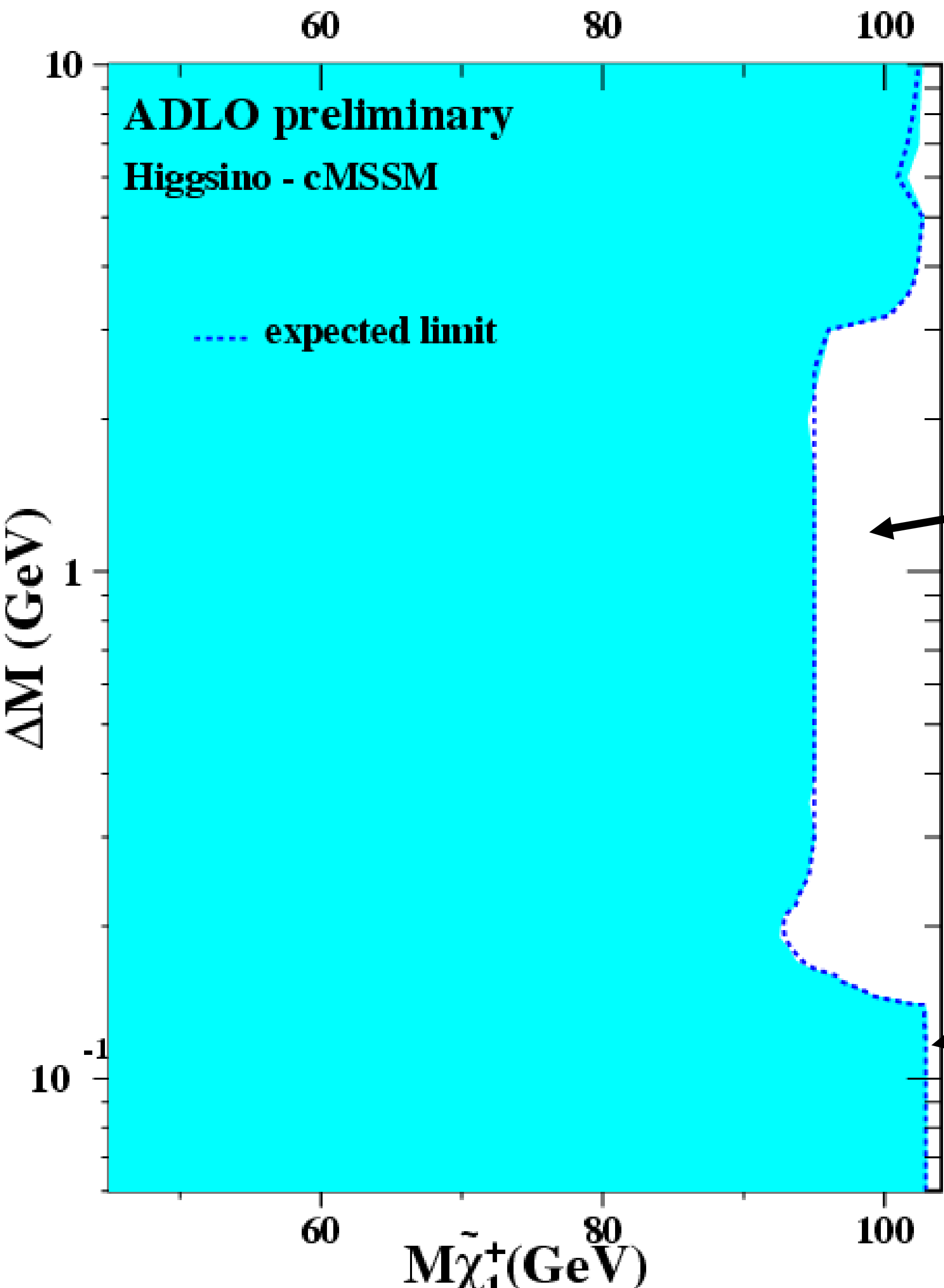


LSP Composition



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





'conventional' search

Soft final state particles

Stable particle search