too much
SUSY Without^Prejudice

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arXiv: 0812.0980

12/18/2008

The MSSM has many nice features but is very difficult to study in any detailed, model-independent manner due to the very 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,… with new ones coming along all the time. This choice then determines the sparticle masses, couplings & signatures in terms of only a few parameters.

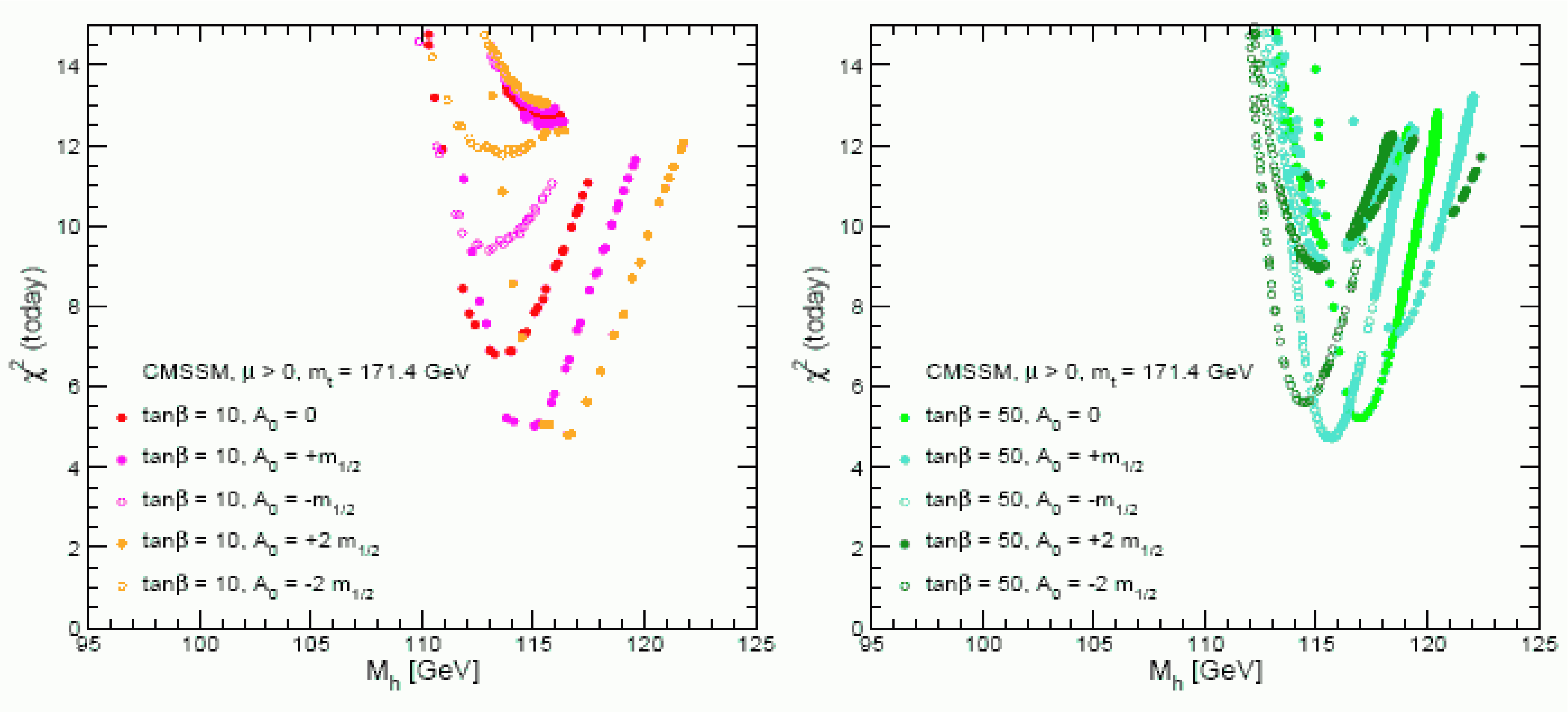
But how well do any or all of these reflect the true breadth of the MSSM?? Do we really know the MSSM as well as we think??

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

Most Analyses Assume mSUGRA/CMSSM Framework

- **CMSSM: m_0, $m_{1/2}$, A_0, tanβ, sign μ**
- **χ^2 fit to some global data set**

Prediction for Lightest Higgs Mass
Fit to EW precision, B-physics observables, & WMAP

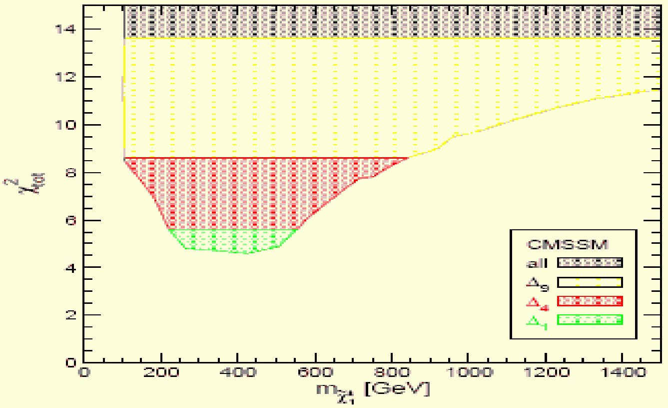


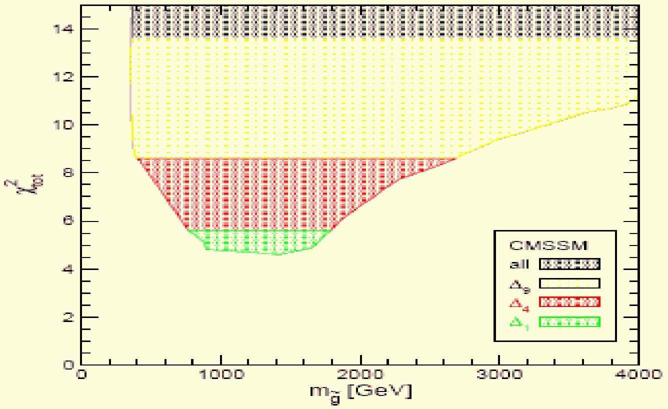
Ellis etal arXiv:0706.0652

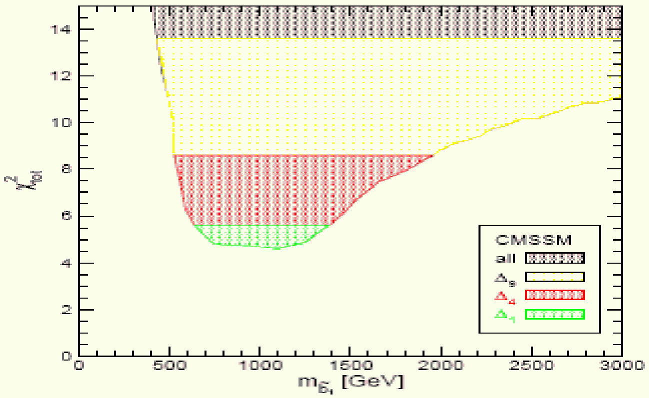
Comparison of CMSSM to GMSB & AMSB

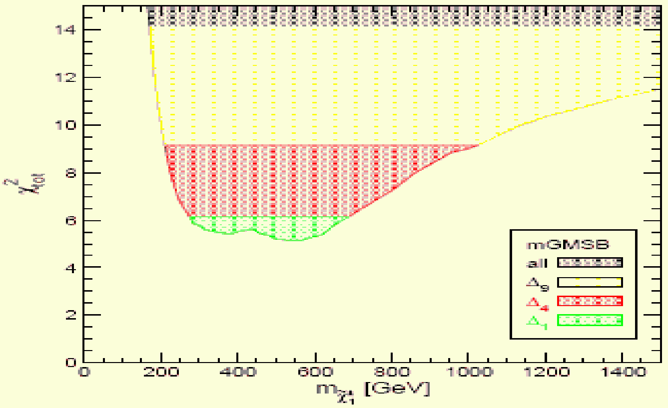
Heinemeyer etal arXiv:0805.2359

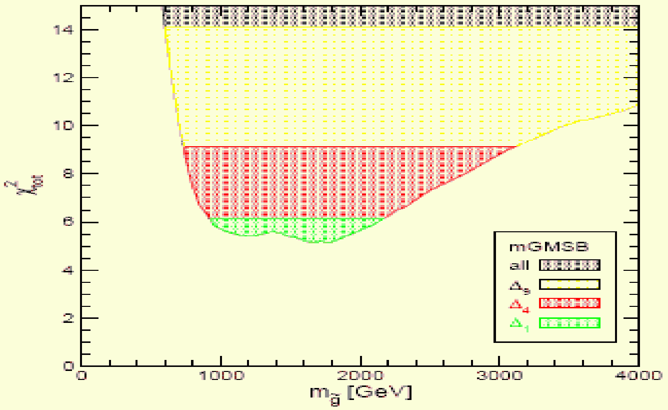
Lightest Chargino Gluino Lightest Sbottom

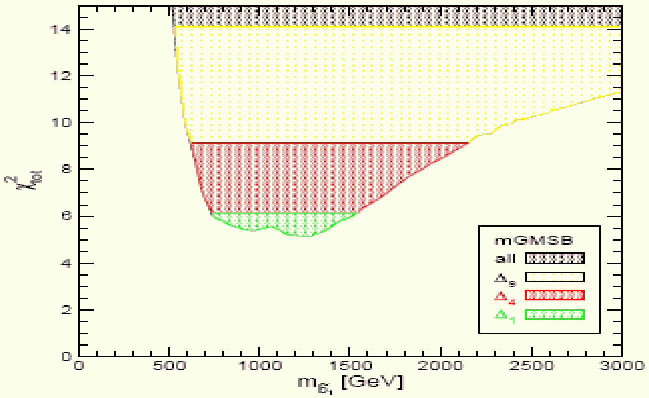


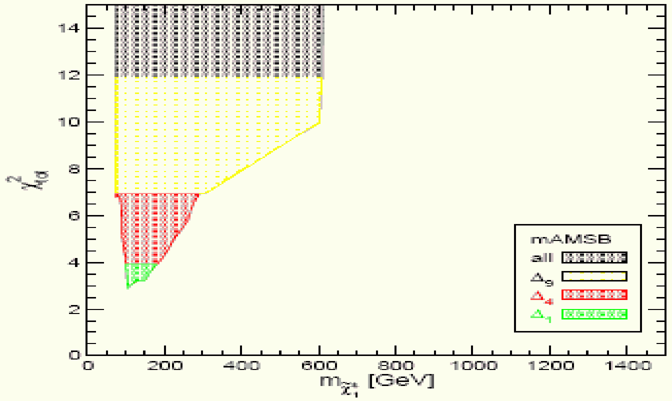


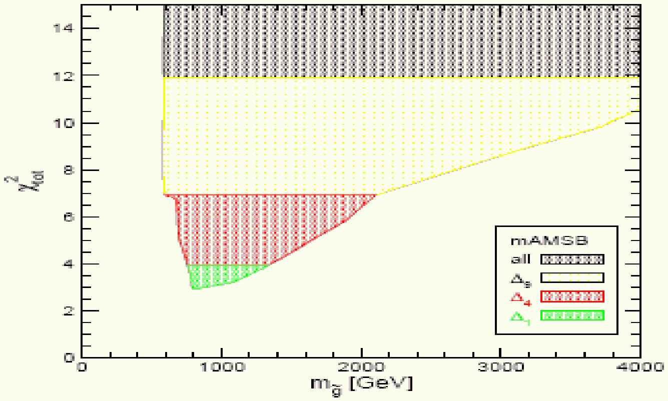


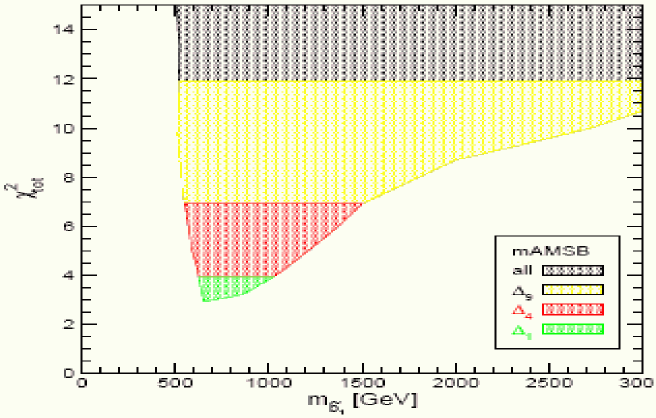












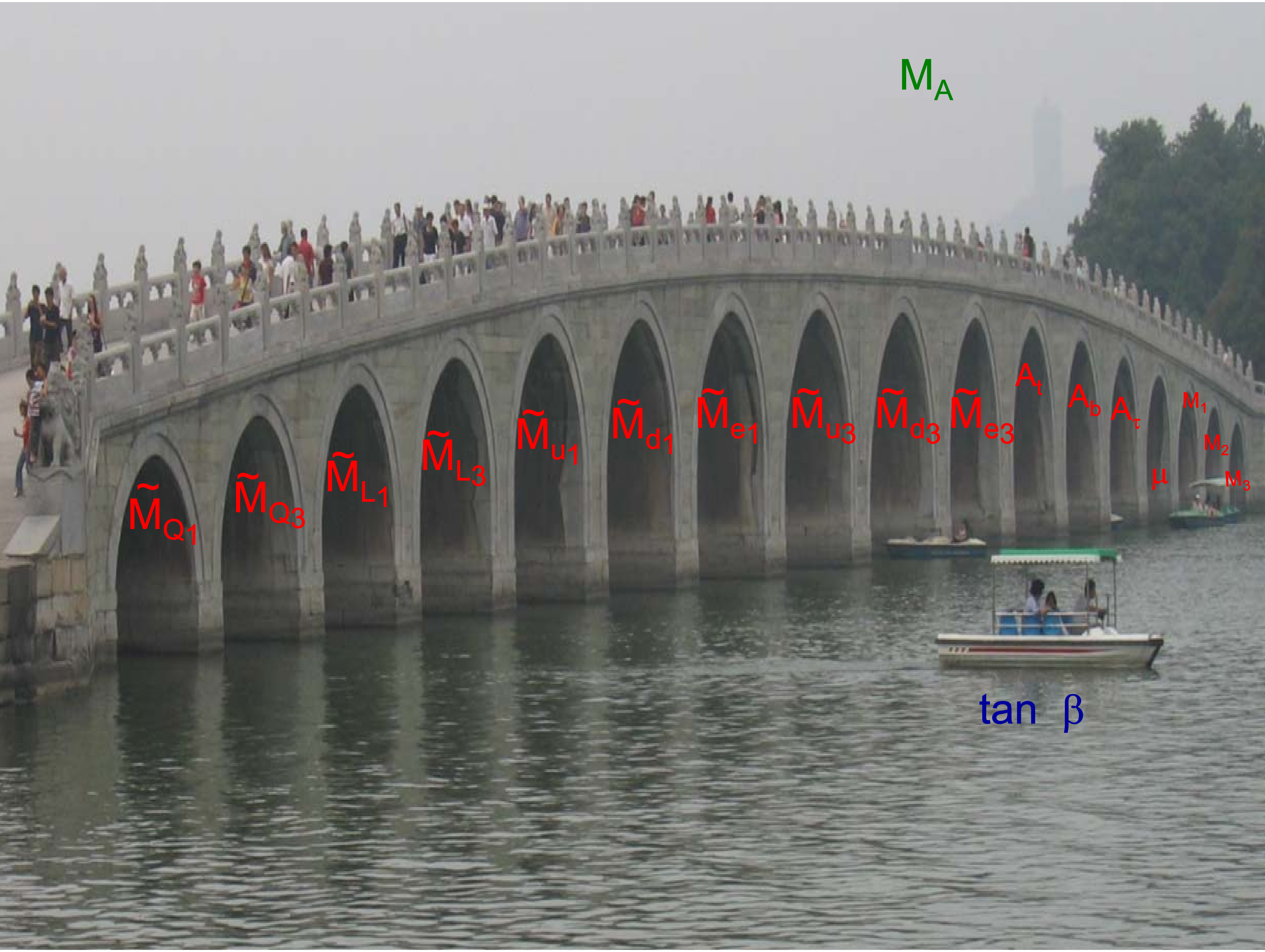
FEATURE Analysis Assumptions :

- The most general, CP-conserving MSSM with R-parity
- 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.
- No assumptions about SUSY-breaking or GUT

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, ILC/CLIC, Fermi, PAMELA/ATIC, 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 (& several smaller scans)

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

- 100 GeV $\leq \tilde{M}_{\text{sfermions}} \leq$ 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 $M_3 > 0$

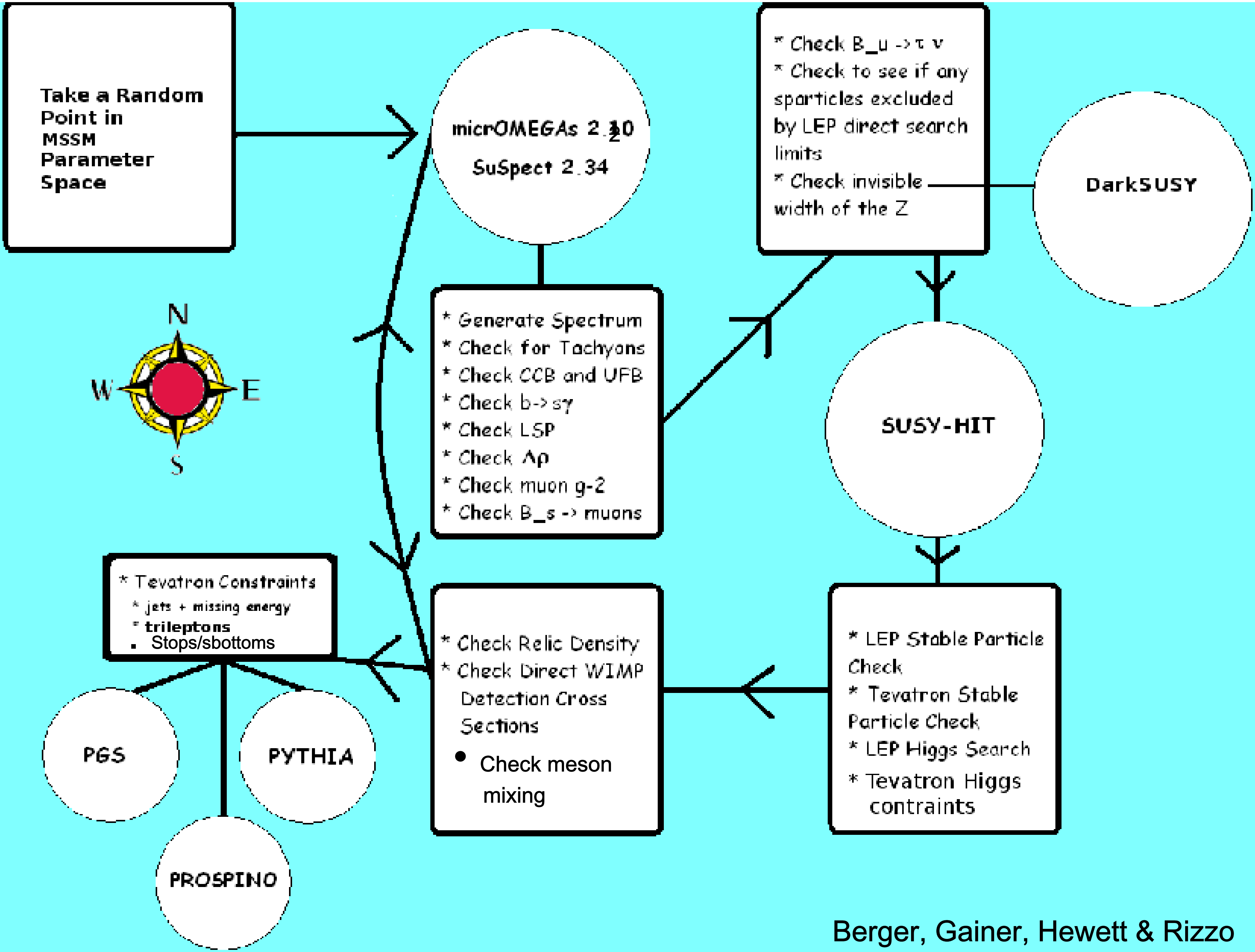
ii) 2 x10^6 points with log priors for masses:

- 100 GeV $\leq \tilde{M}_{\text{sfermions}} \leq$ 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?



Take a Random Point in MSSM Parameter Space

micrOMEGAs 2.10 2

SuSpect 2.34

- Generate Spectrum
- Check for Tachyons
- Check CCB and UFB
- Check b-> sγ
- Check LSP
- Check Δρ
- Check muon g-2
- Check B_s -> muons

- Check B_u -> τ ν
- Check to see if any sparticles excluded by LEP direct search limits
- Check invisible width of the Z

DarkSUSY

SUSY-HIT

- LEP Stable Particle Check
- Tevatron Stable Particle Check
- LEP Higgs Search
- Tevatron Higgs contraints

- Check Relic Density
- Check Direct WIMP Detection Cross Sections
- Check meson mixing

- Tevatron Constraints
  - jets + missing energy
  - **trileptons**
  - Stops/sbottoms

PGS

PYTHIA

PROSPINO

Berger, Gainer, Hewett & Rizzo

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]

→ $(-10 \text{ to } 40) \times 10^{-10}$ to be conservative..

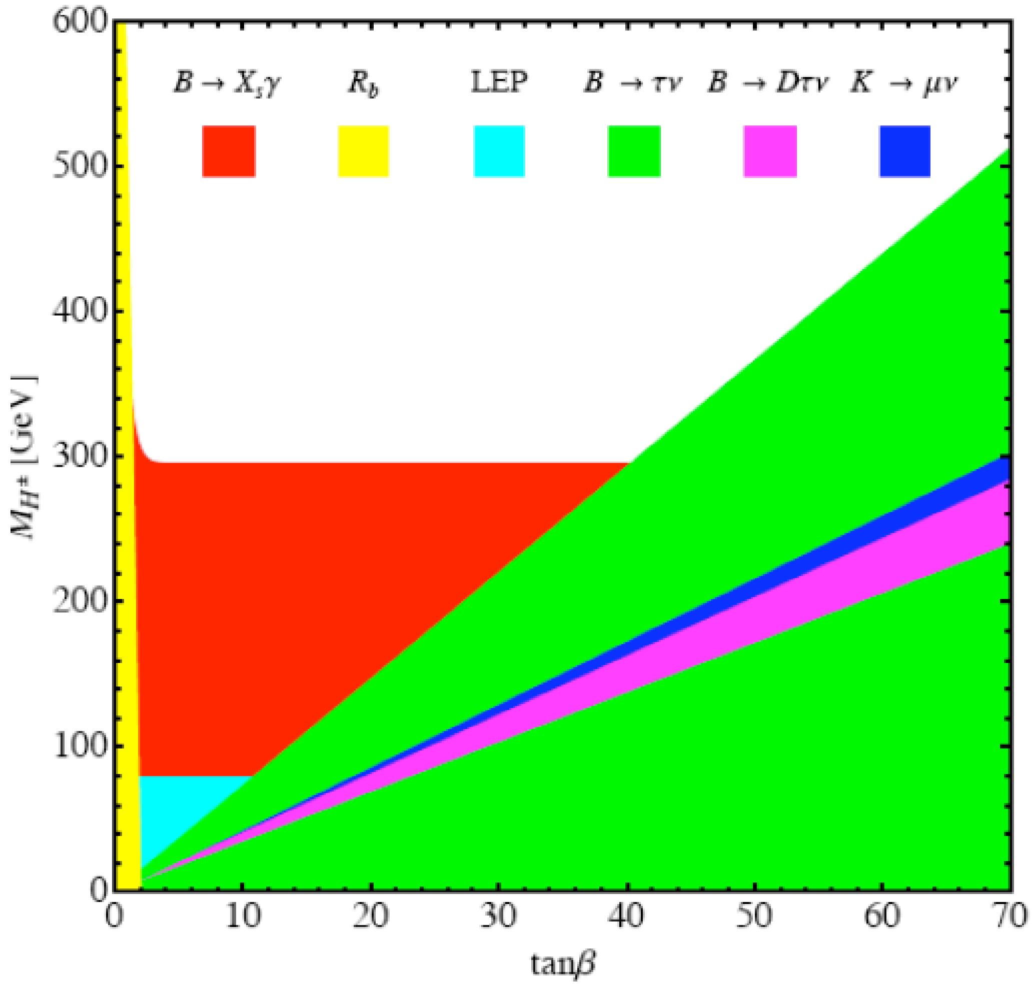
- $\Gamma(Z \to \text{invisible}) < 2.0$ MeV (LEPEWWG)
  This removes Z decays to LSPs w/ large Higgsino content
- Meson-Antimeson Mixing : Constrains 1st/3rd sfermion mass ratios to be in the range $0.2 < R < 5$ in MFV context

B→τν

Isidori & Paradisi, hep-ph/0605012 &
Erikson etal., 0808.3551 for loop corrections

Bounds on NP by rare decays: example of Two-Higgs-Doublet Model

Haisch,arXiv:0805.2141



New data from Babar and Belle

talks by Baracchini, Hara

* New bounds: $B \to K\nu\bar{\nu}, B \to \mu\nu$

* New HFAG for $B \to \tau\nu$

$BR(B \to \tau\nu) = (1.51 \pm 0.33)\, 10^{-4}$

SM: $\propto |V_{ub}|^2\, f_B^2$

$BR(B \to \tau\nu) = (0.80 \pm 0.12)\, 10^{-4}$

UTfit,2008

$\tan\beta$ suppression expected
in THDM/MSSM

Super-B ($\succeq 50 ab^{-1}$) sensitivity

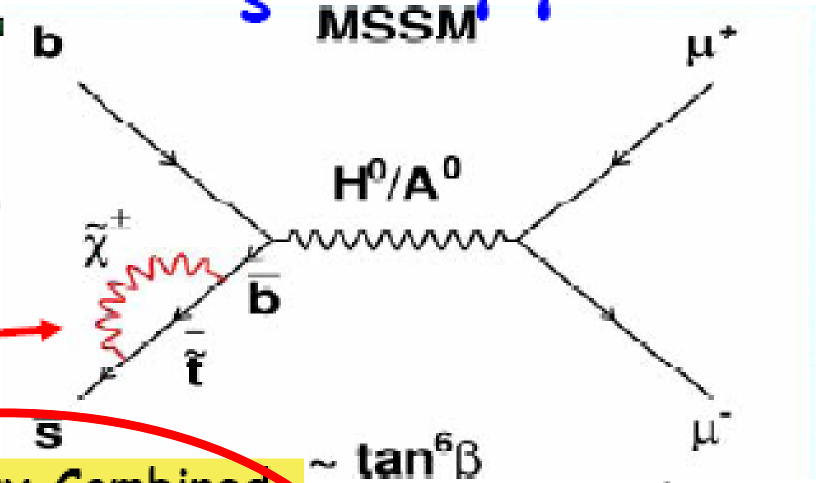
$3-4\%$ Stocchi et al.,arXiv:0710.3799

→ B = (55 to 227) x 10^{-6}

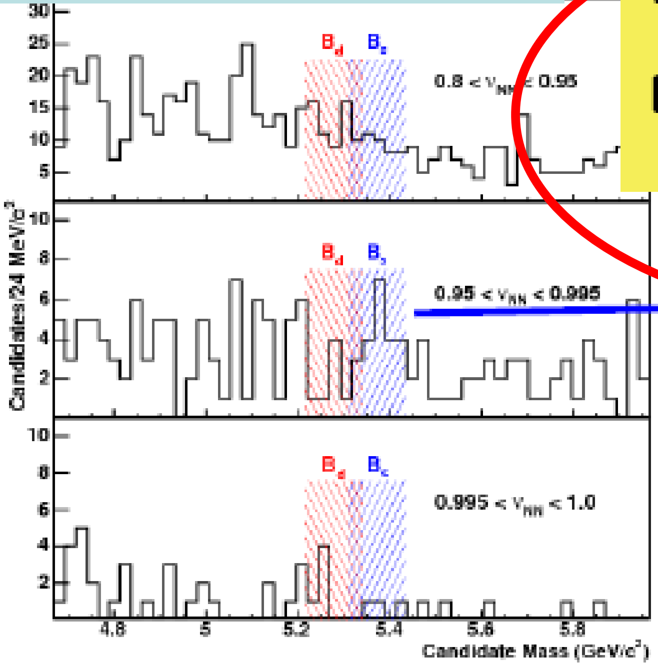
Indirect Search: $B_s \rightarrow \mu\mu$

The search for $B_s \rightarrow \mu\mu$ is perhaps the most sensitive to SUSY since sparticles show up in loops

Especially sensitive at high $\tan\beta$ ($\propto \tan\beta^6$)



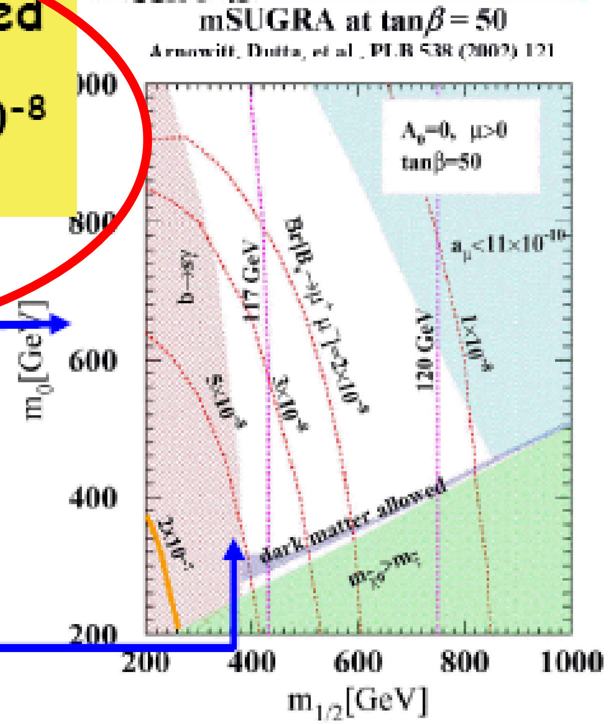
CDF, PRL 100, 101802 (2008)



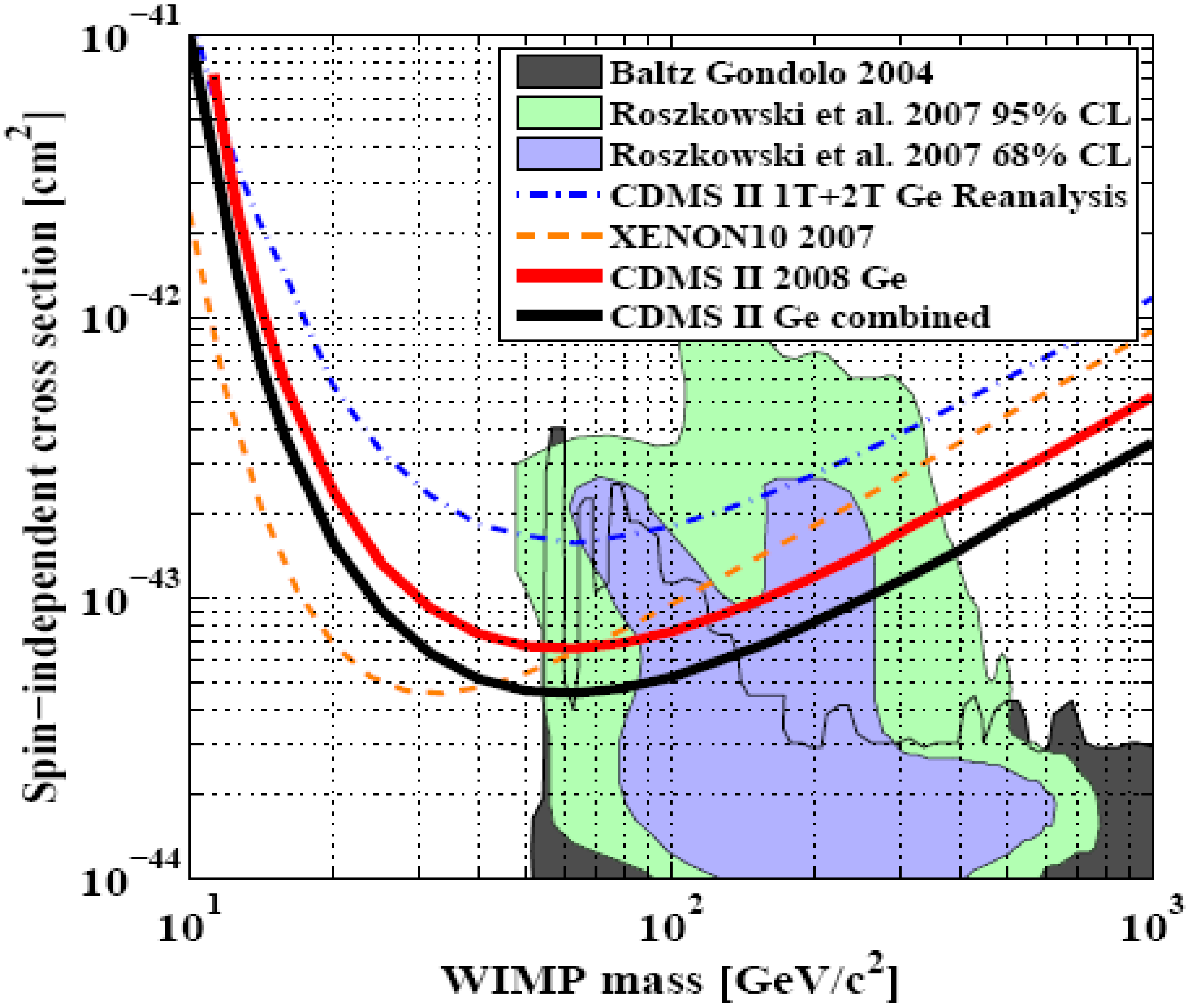
Preliminary Combined CDF/DØ

$BR(B_s \rightarrow \mu\mu) < 4.5\times10^{-8}$ @95%

$BR_{SM} = 3.5\times10^{-9}$



Dark Matter: Direct Searches for WIMPs



- CDMS, XENON10, DAMA, CRESST-I,… → We find a factor of ~ 4 uncertainty in the nuclear matrix elements. This factor was 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 here

- 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

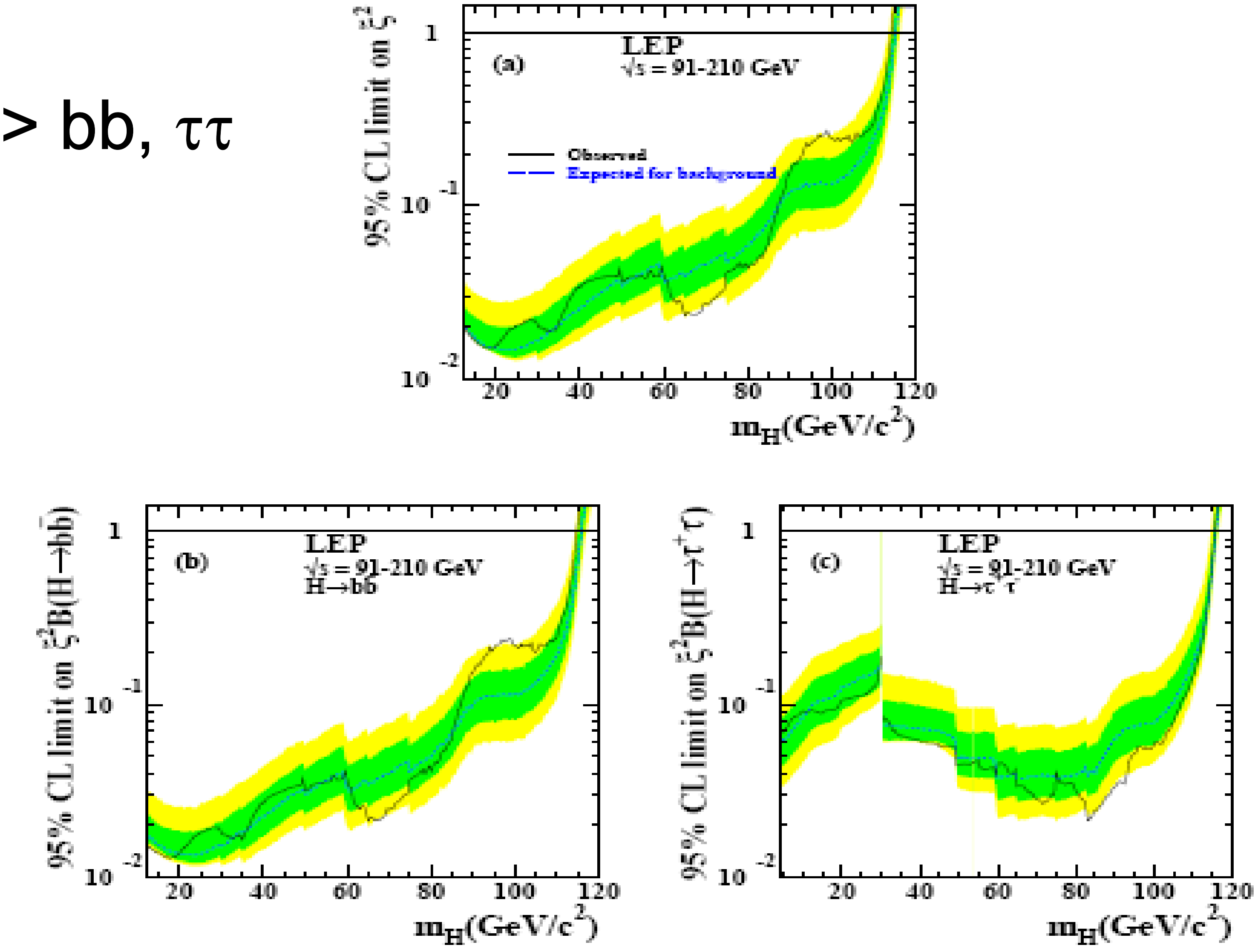


Figure 1: *The 95% c.l. upper bound on the coupling ratio* $\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$ *(see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling. (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→ hA →**4b,2b2τ,4τ**

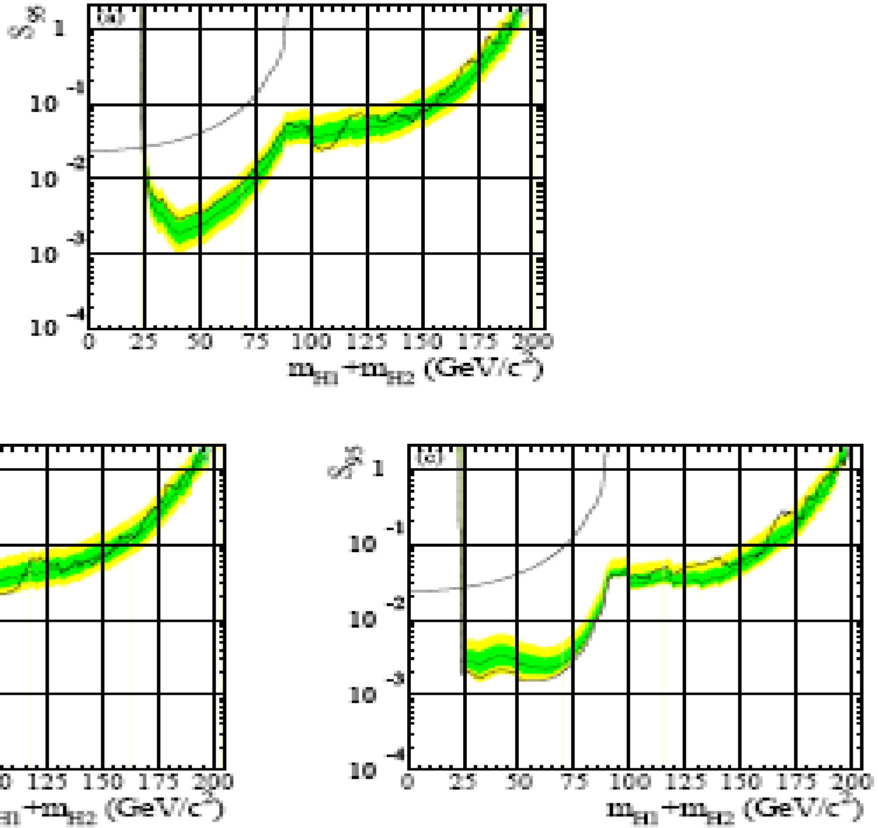
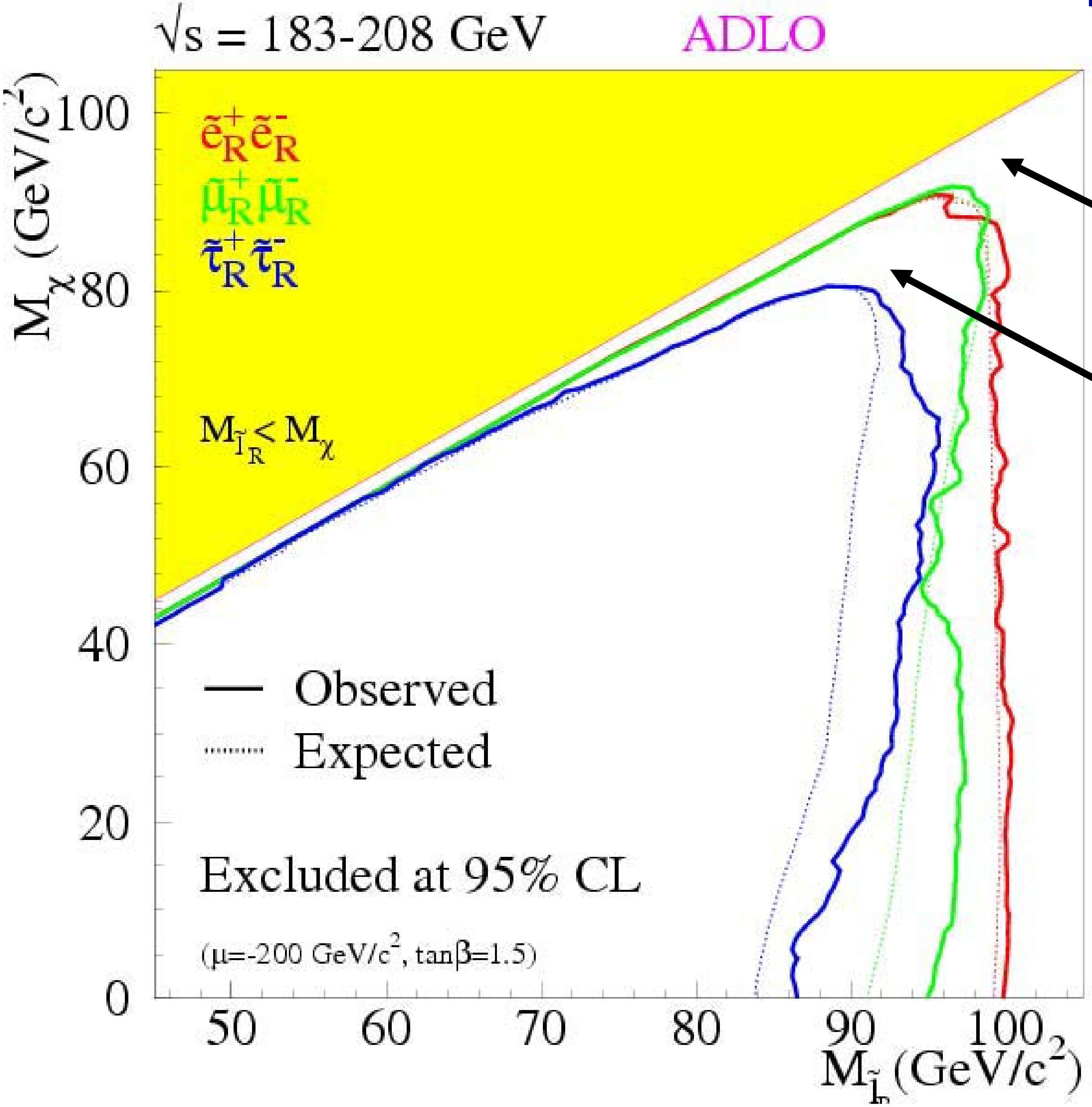


Figure 3: *Model-independent 95% c.l. upper bounds, S_{95}, for various topological cross sections motivated by the pair-production process $e^+e^- \to \mathcal{H}_2\mathcal{H}_1$, for the particular case where $m_{\mathcal{H}_1}$ and $m_{\mathcal{H}_2}$ are approximately equal. Such is the case, for 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% $\mathcal{H}_1\to$bb, 6% $\mathcal{H}_1\to\tau^+\tau^-$, 92% $\mathcal{H}_2\to$bb and 8% $\mathcal{H}_2\to\tau^+\tau^-$; lower left: both Higgs bosons are assumed to decay exclusively to bb; lower right: the Higgs bosons are assumed to decay, one into bb 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.*

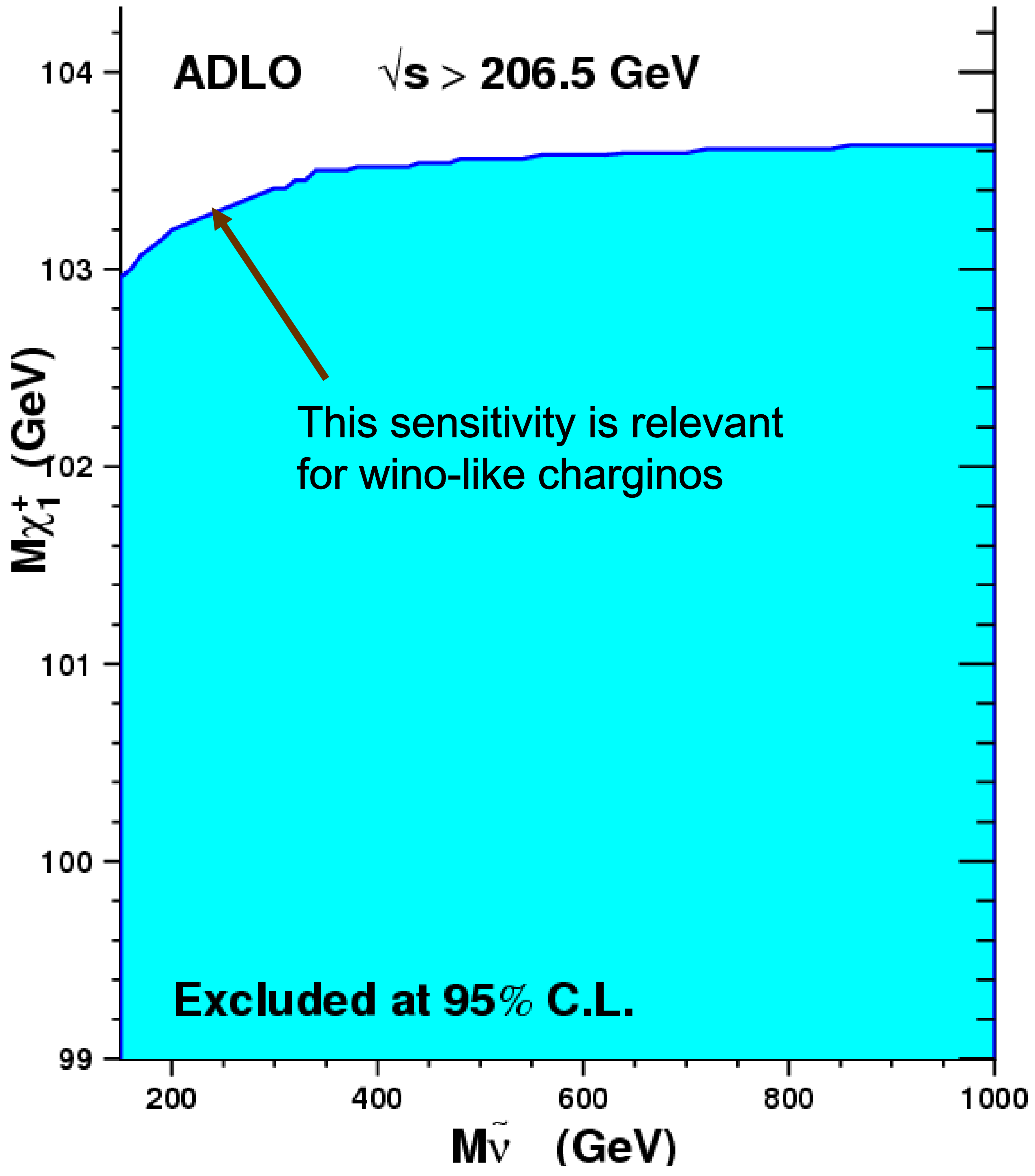
RH Sleptons



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

Large mass gap chargino search



This sensitivity is relevant for wino-like charginos

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

Tevatron Constraints : I Squark & Gluino Search

- This is the first SUSY analysis to include these constraints
- 2,3,4 Jets + Missing Energy (D0)

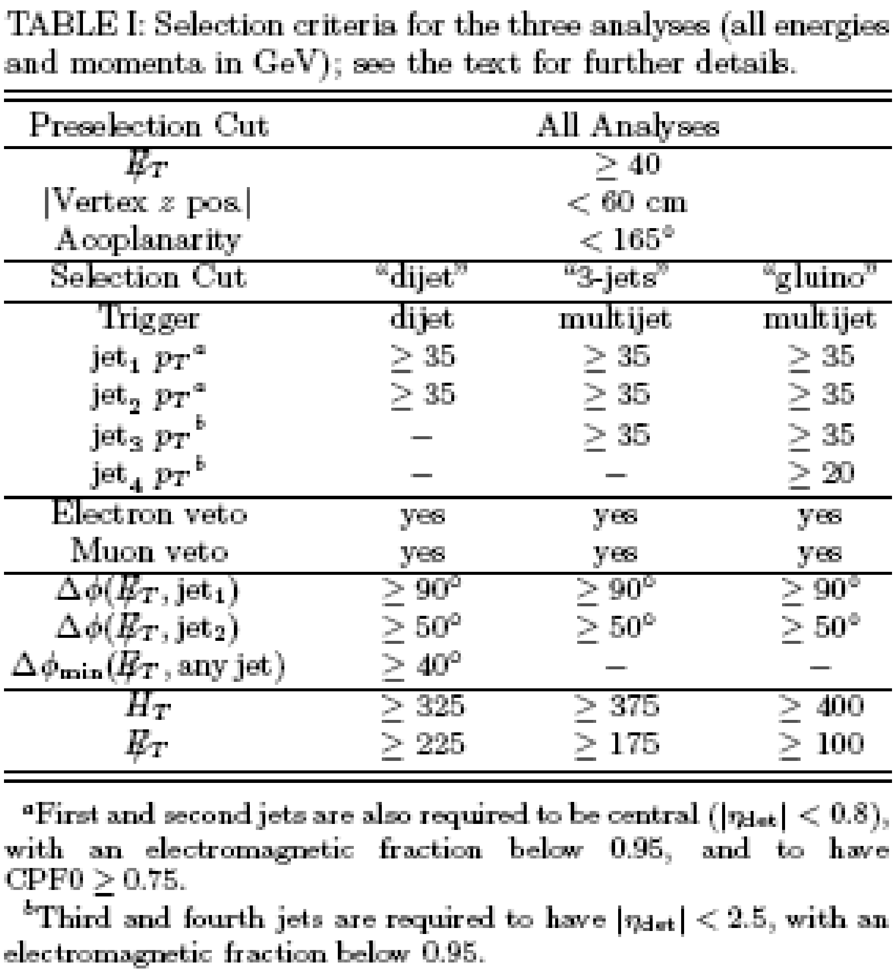


TABLE I: Selection criteria for the three analyses (all energies and momenta in GeV); see the text for further details.

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

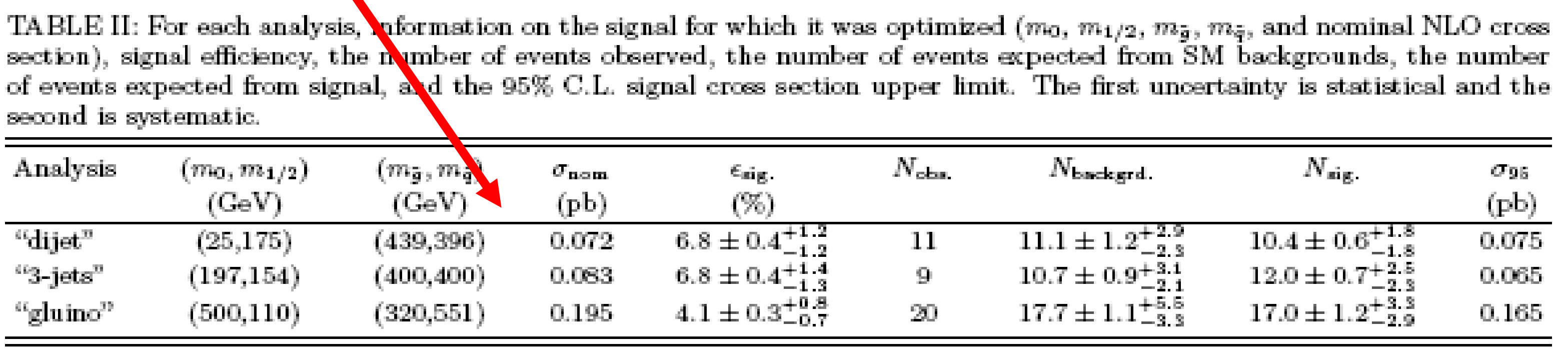


TABLE II: For each analysis, information on the signal for which it was optimized (m_0, $m_{1/2}$, $m_{\tilde{g}}$, $m_{\tilde{q}}$, and nominal NLO cross section), signal efficiency, the number of events observed, the number of events expected from SM backgrounds, the number of events expected from 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)	σ_{nom} (pb)	$\epsilon_{\text{sig.}}$ (%)	$N_{\text{obs.}}$	$N_{\text{backgrd.}}$	$N_{\text{sig.}}$	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

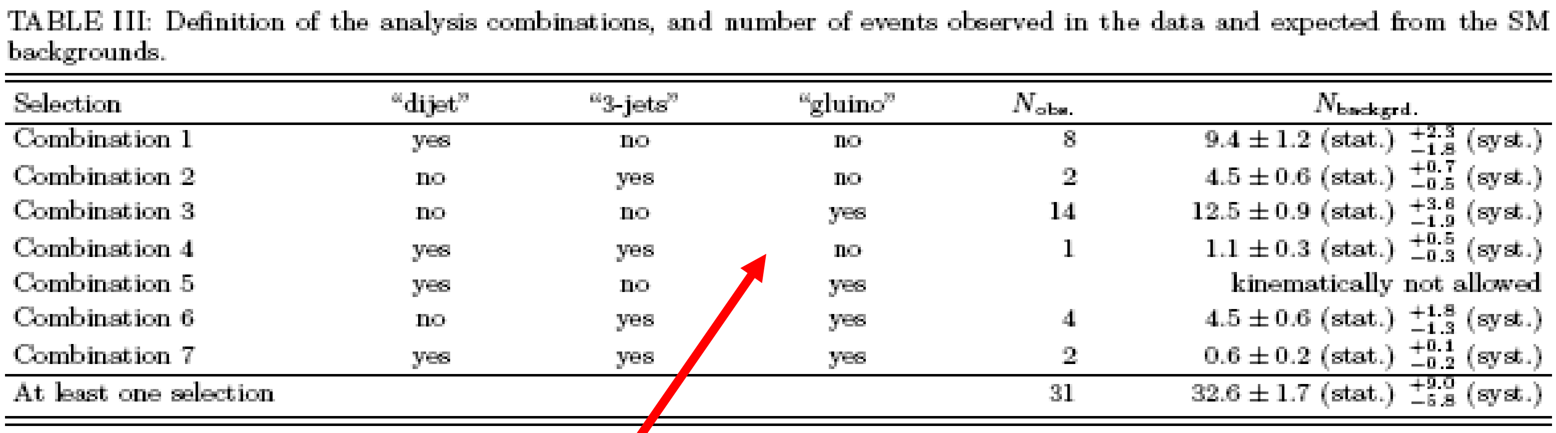


TABLE III: Definition of the analysis combinations, and number of events observed in the data and expected from the SM backgrounds.

Selection	"dijet"	"3-jets"	"gluino"	$N_{\text{obs.}}$	$N_{\text{backgrd.}}$
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.)

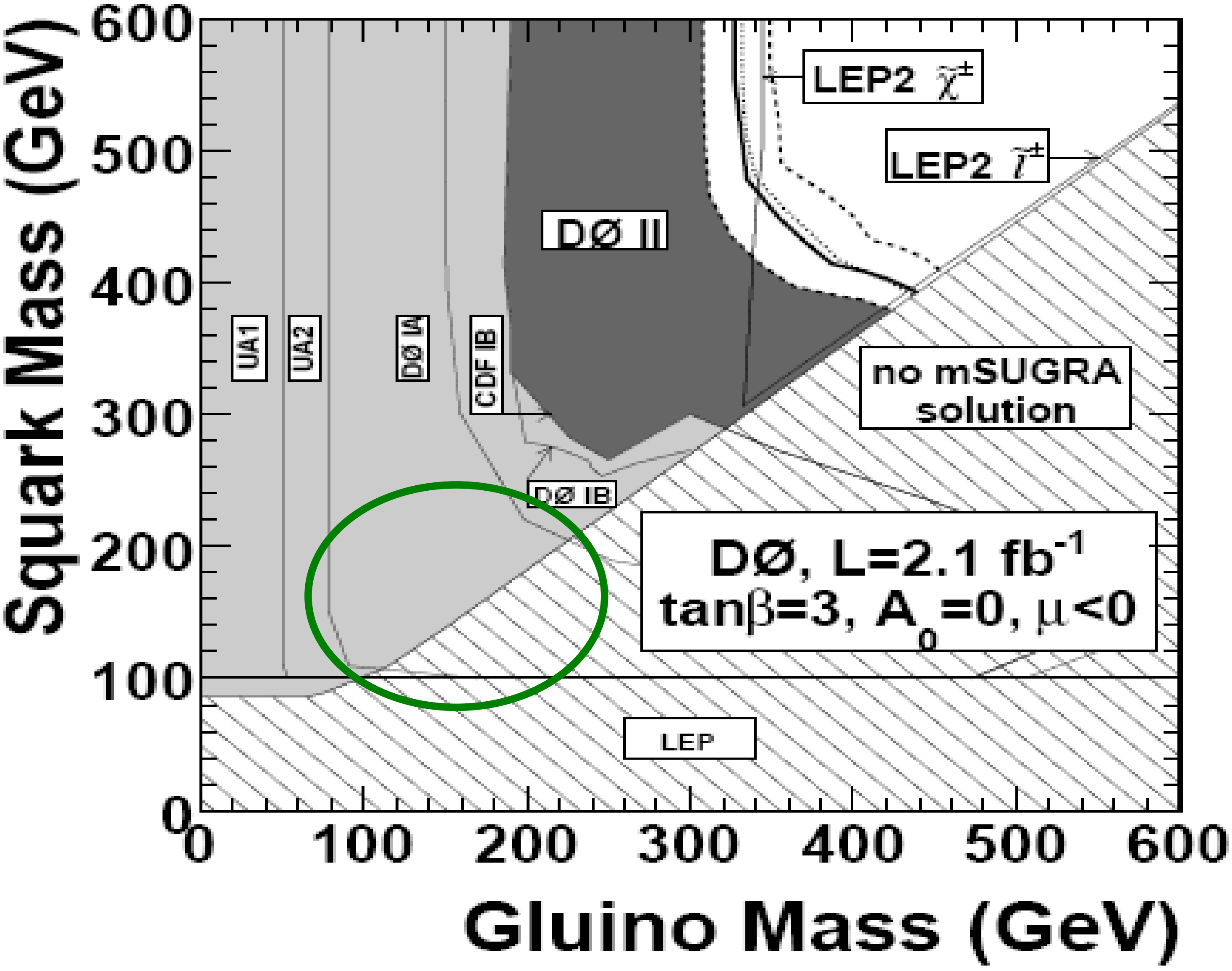
Combos of the 3 analyses

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

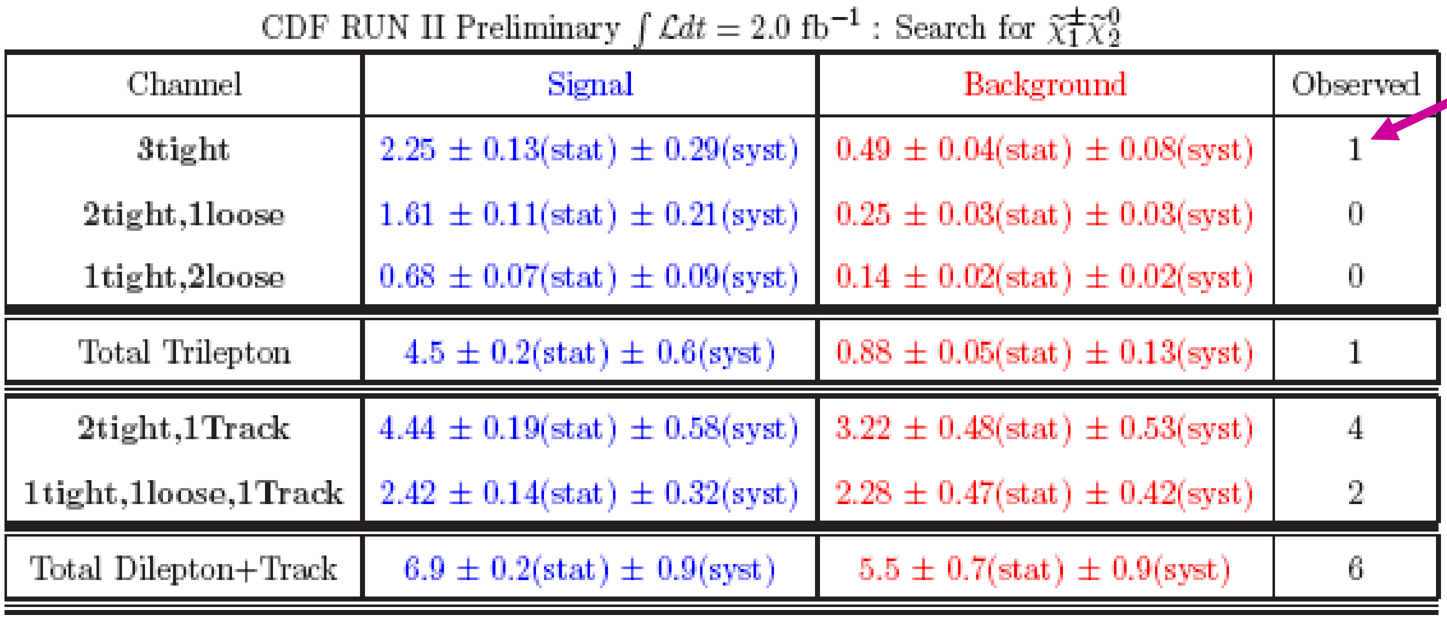
SuSpect -> SUSY-Hit -> PROSPINO -> PYTHIA -> D0-tuned PGS4 fast simulation (to reproduce the benchmark points)…

redo this analysis ~ 10^5 times !

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 !!



Tevatron II: CDF Tri-lepton Analysis



CDF RUN II Preliminary $\int \mathcal{L}dt = 2.0\ \mathrm{fb}^{-1}$: 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

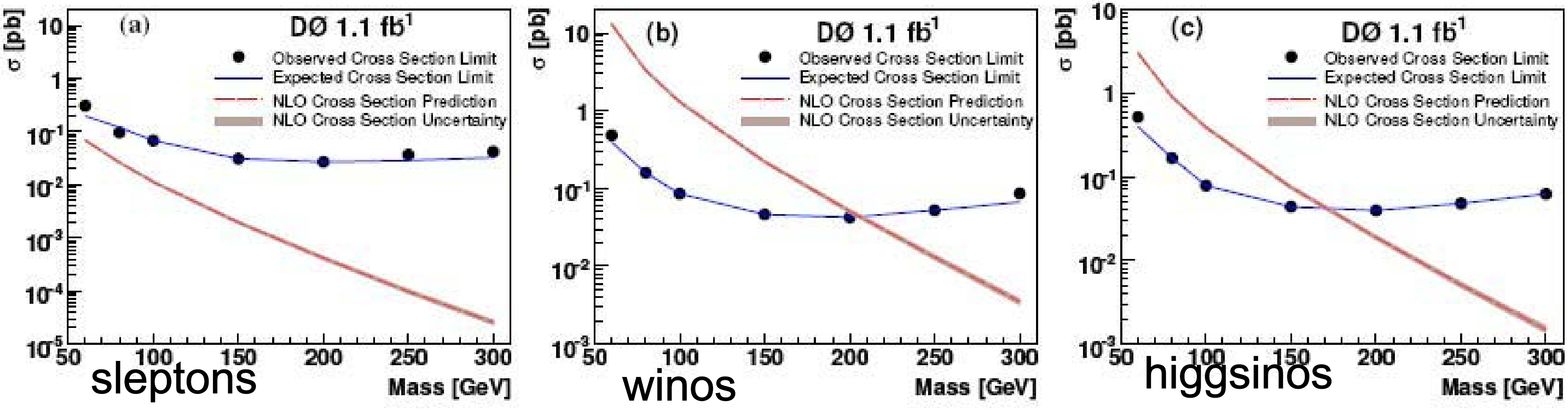


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos,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

SOME RESULTS

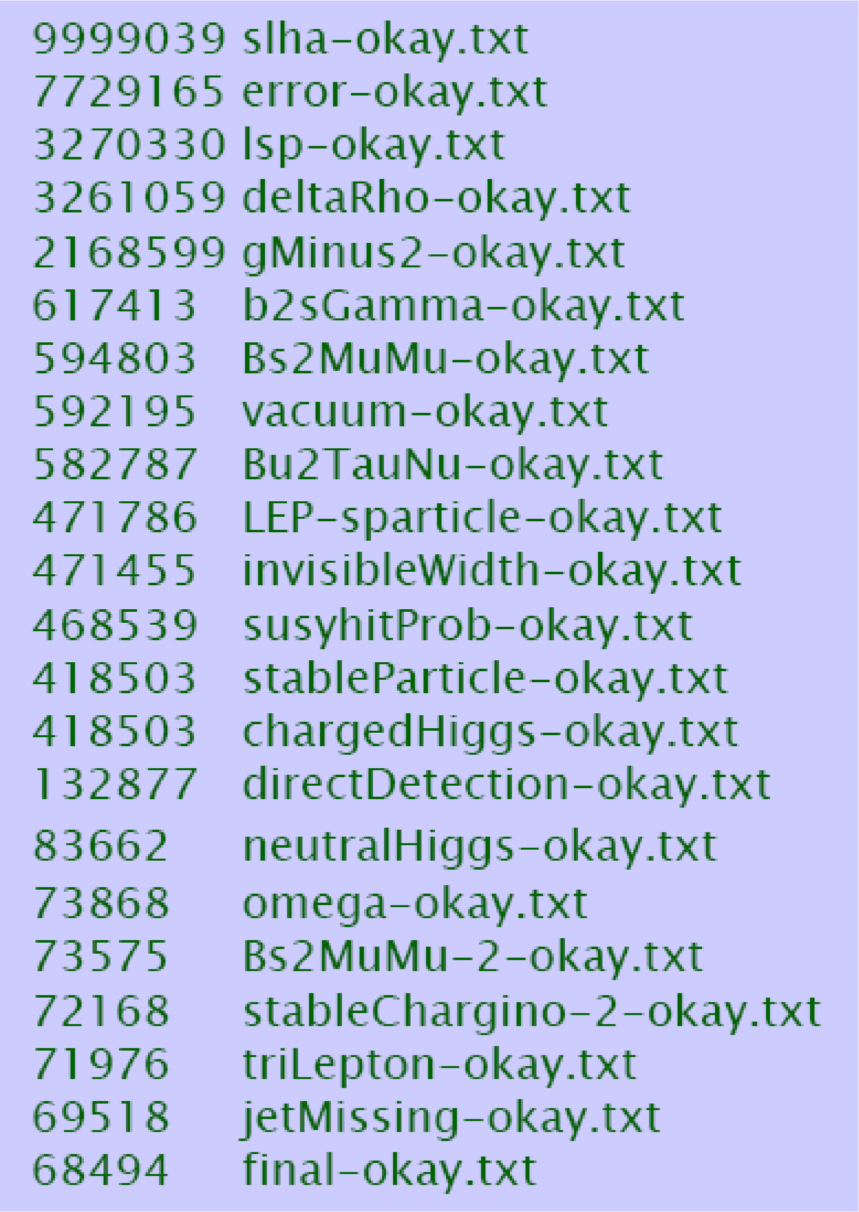
Survival Rates

- Flat Priors :

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

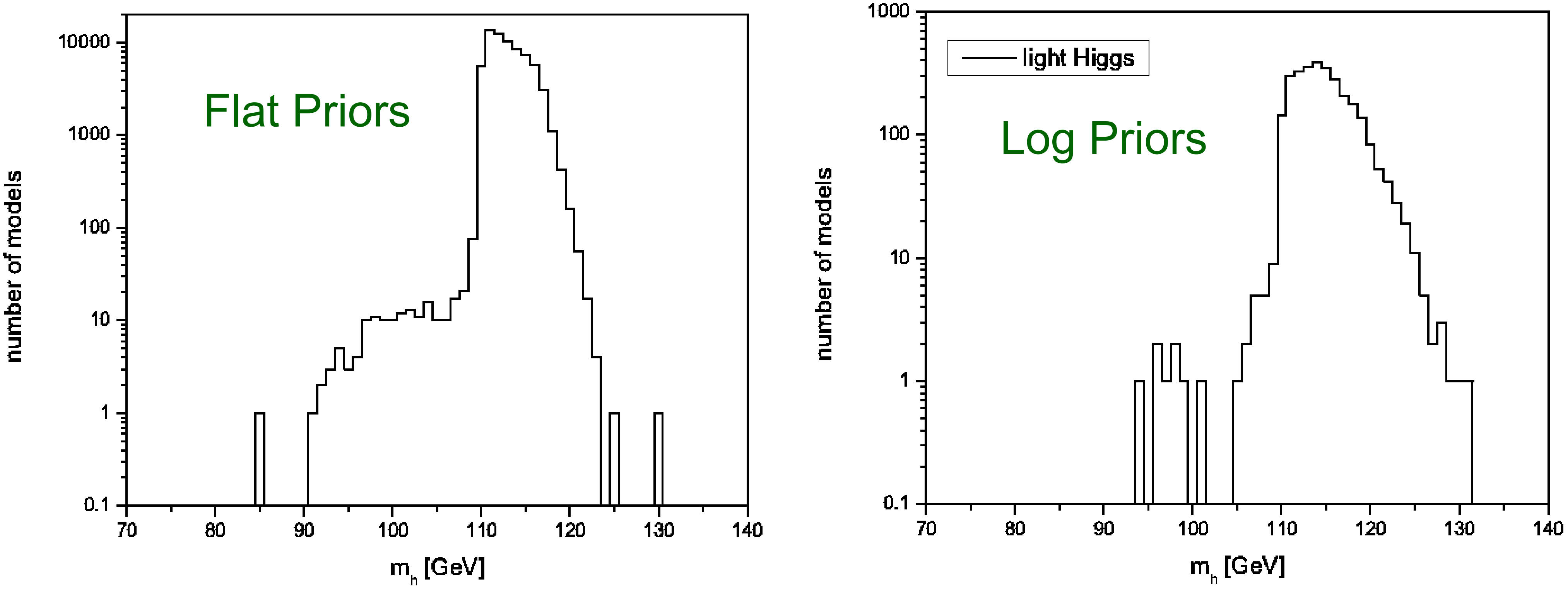
- Log Priors :

  - 2×10^6 models scanned
  - 3.0 K (0.15%) survive



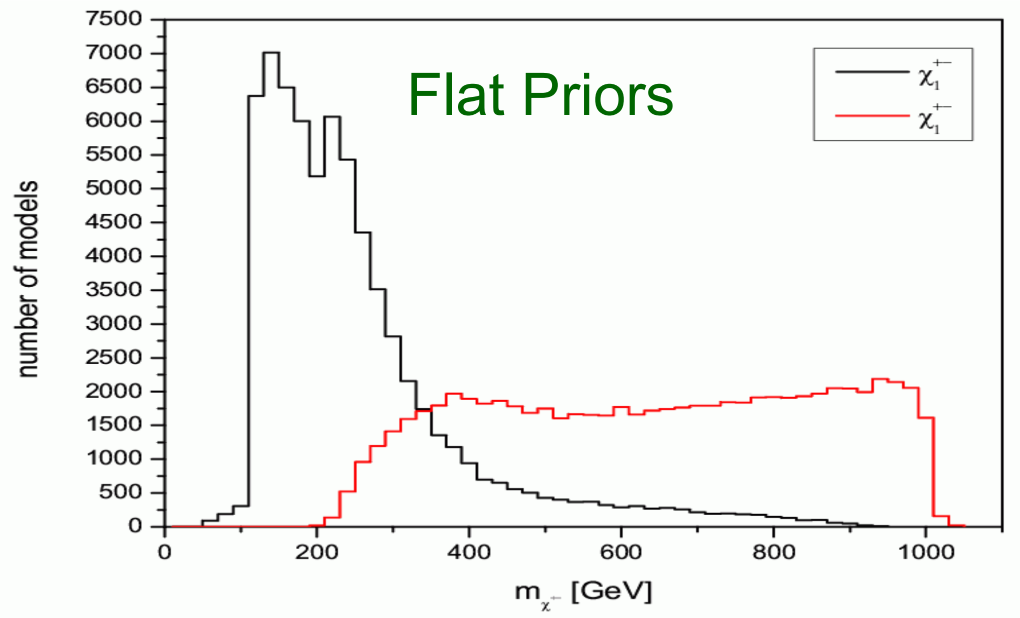
```
9999039 slha-okay.txt
7729165 error-okay.txt
3270330 lsp-okay.txt
3261059 deltaRho-okay.txt
2168599 gMinus2-okay.txt
617413   b2sGamma-okay.txt
594803   Bs2MuMu-okay.txt
592195   vacuum-okay.txt
582787   Bu2TauNu-okay.txt
471786   LEP-sparticle-okay.txt
471455   invisibleWidth-okay.txt
468539   susyhitProb-okay.txt
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
```

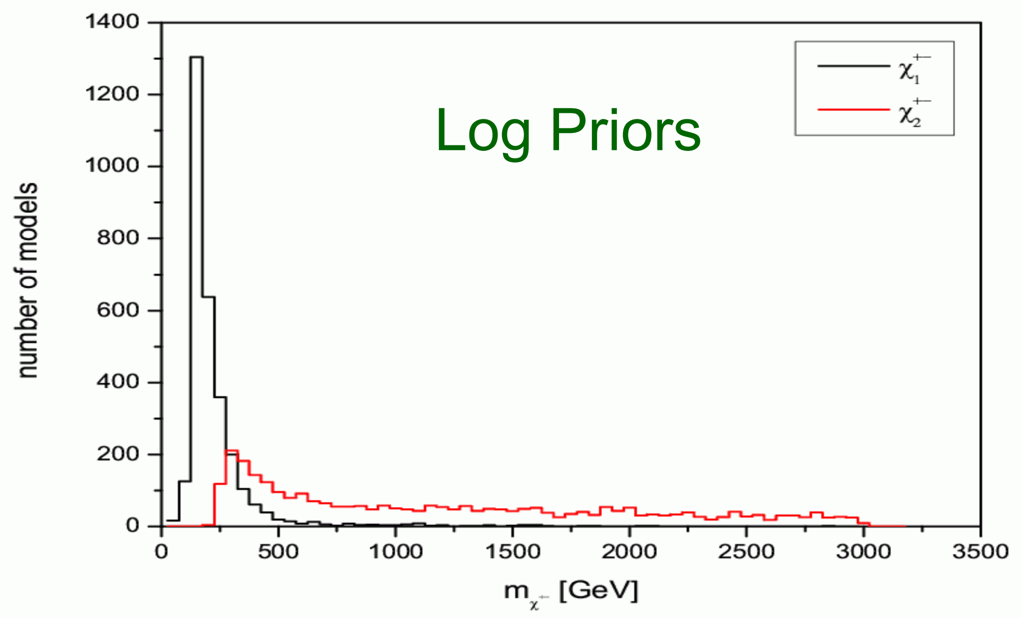
Light Higgs Mass Predictions

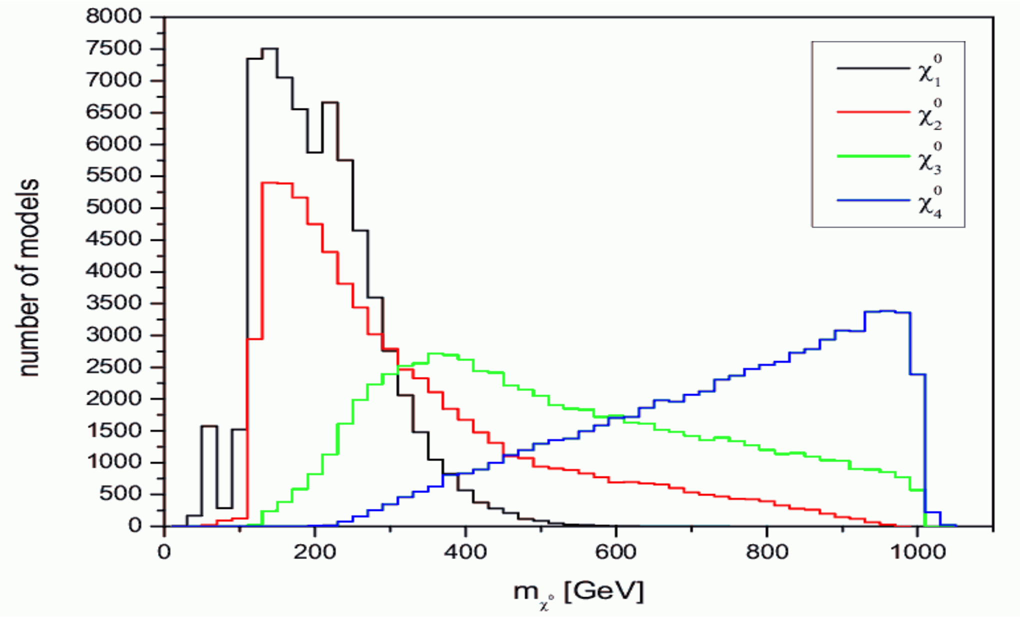


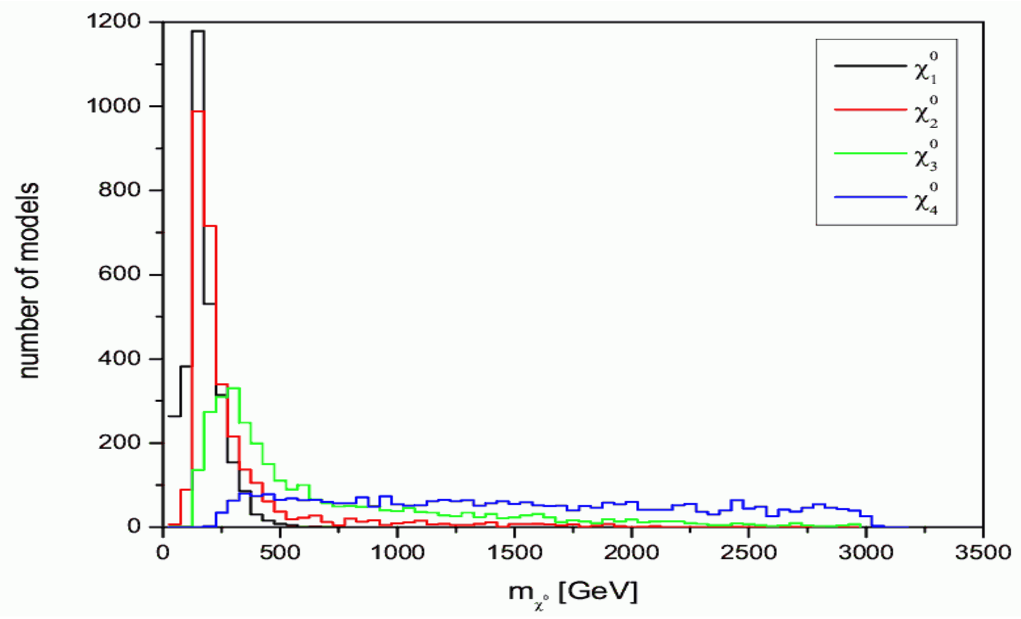
LEP Higgs mass constraints avoided by either reducing the ZZh coupling and/or reducing the, e.g., $h \to \bar{b}b$ branching fraction by decays to LSP pairs. We have both of these cases in our final model sets.

Distribution of Sparticle Masses By Species



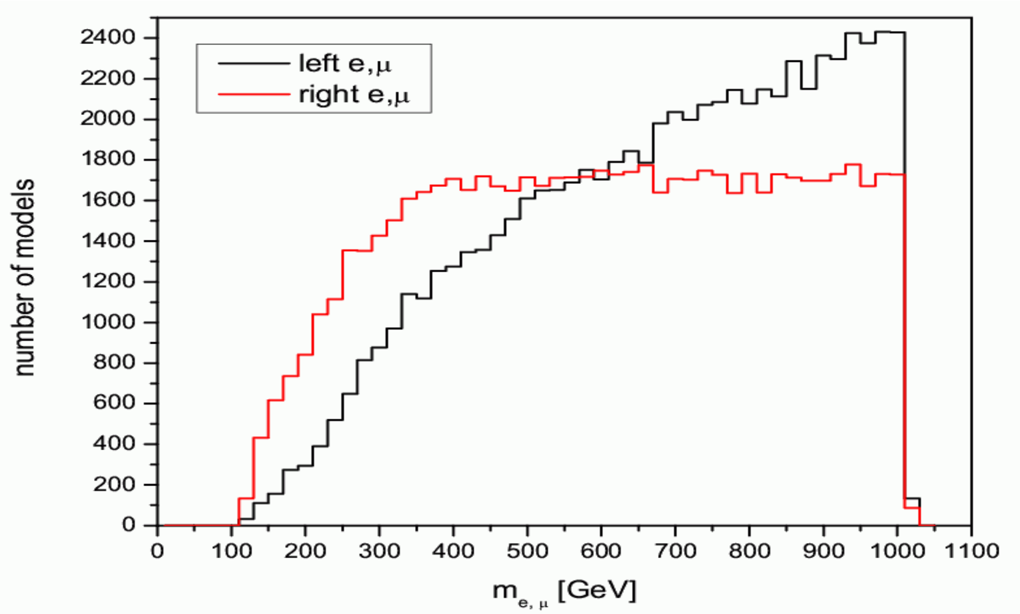


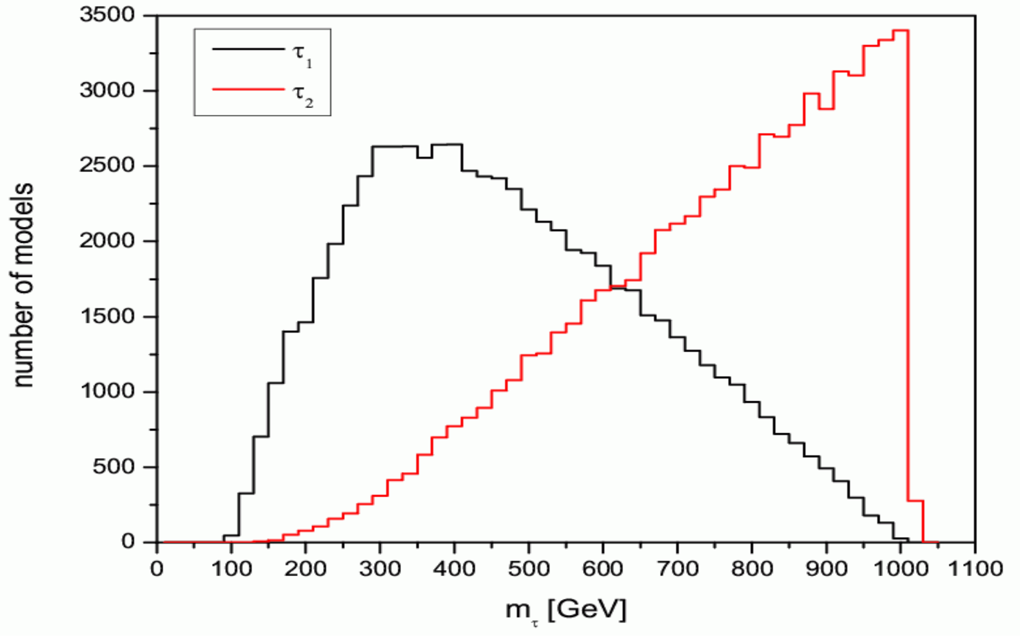




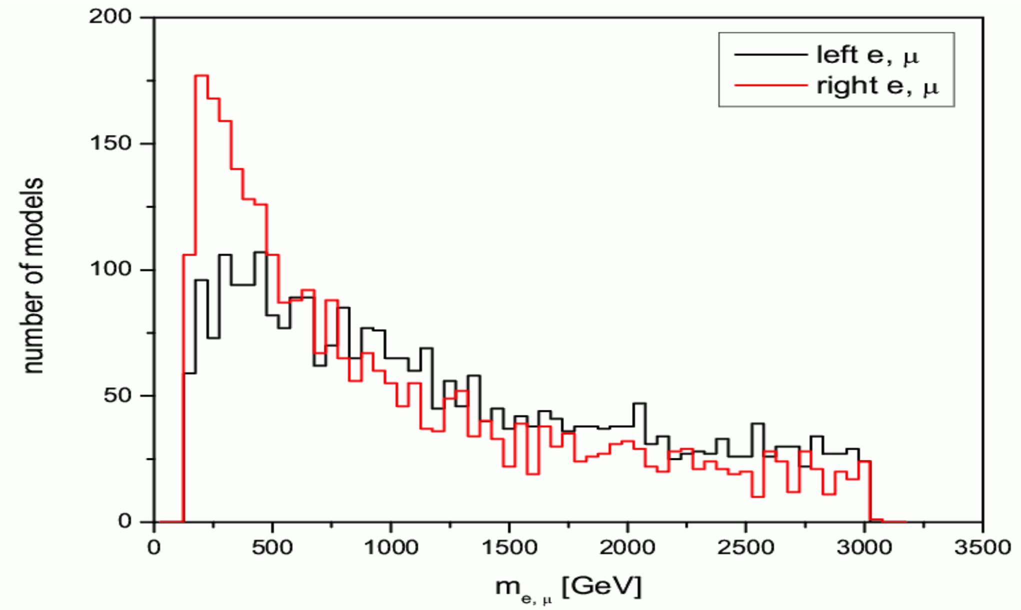
Distribution of Sparticle Masses By Species

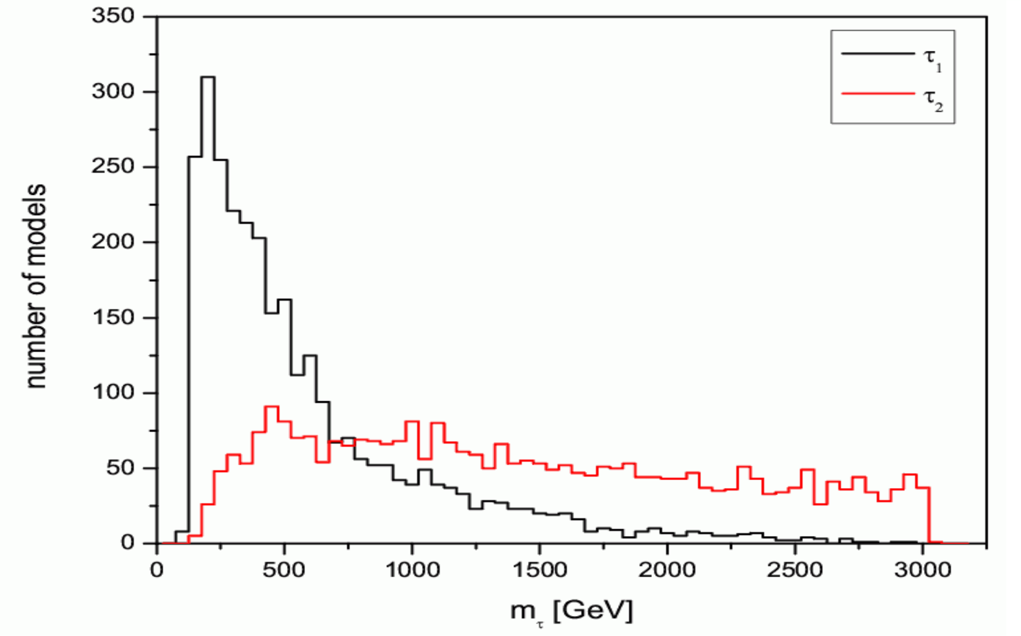
Flat Priors



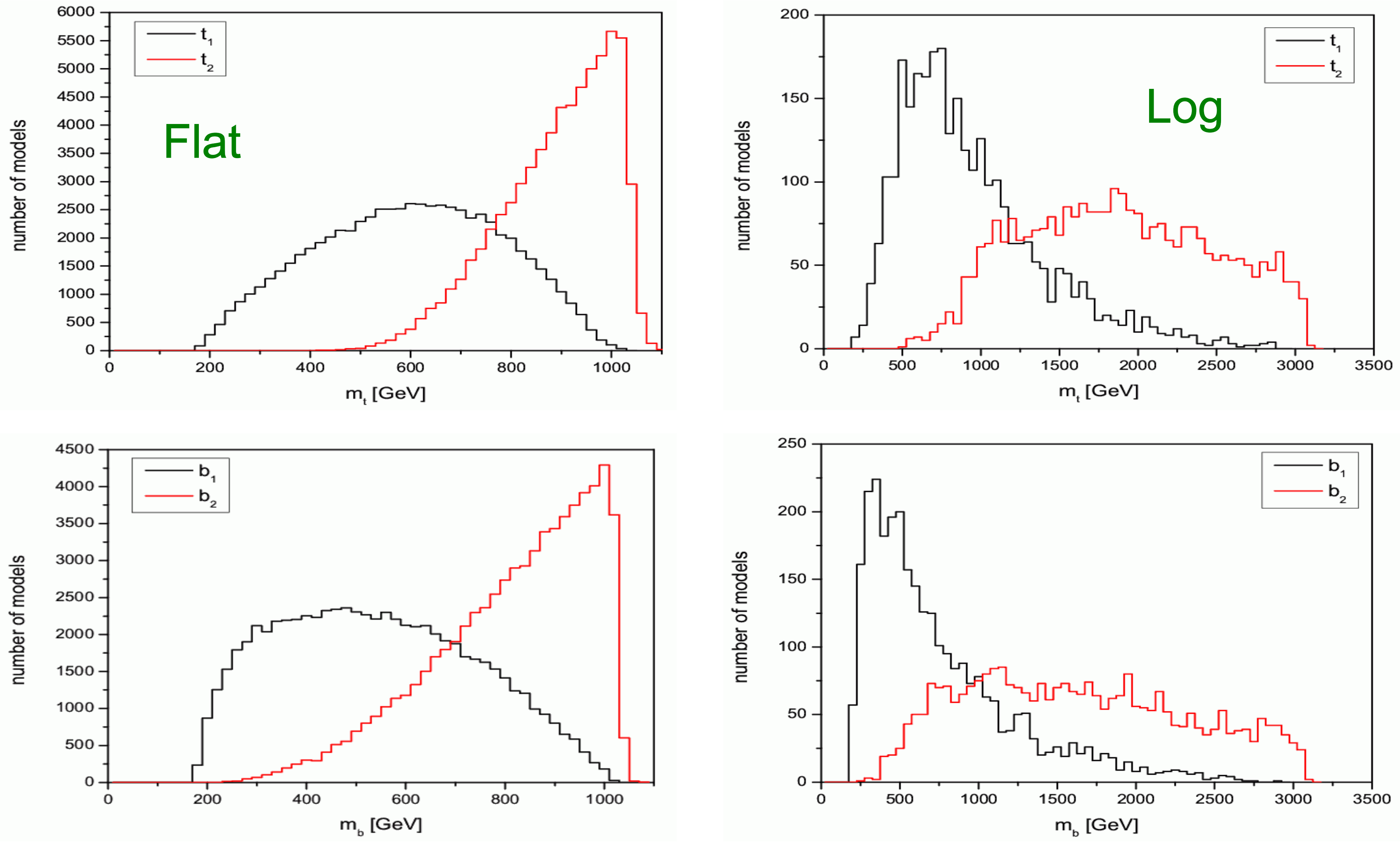


Log Priors

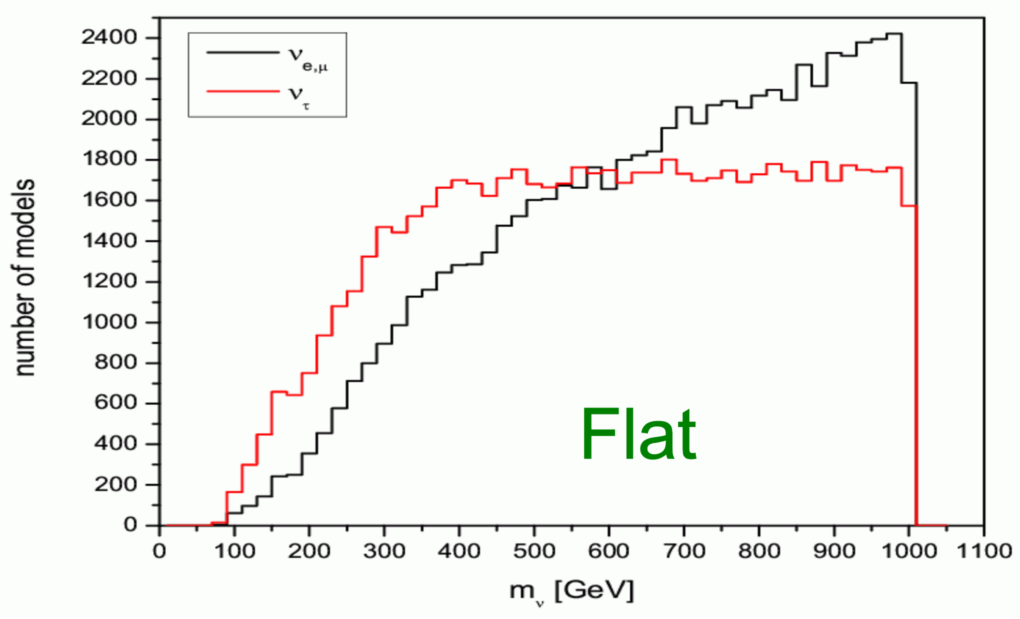


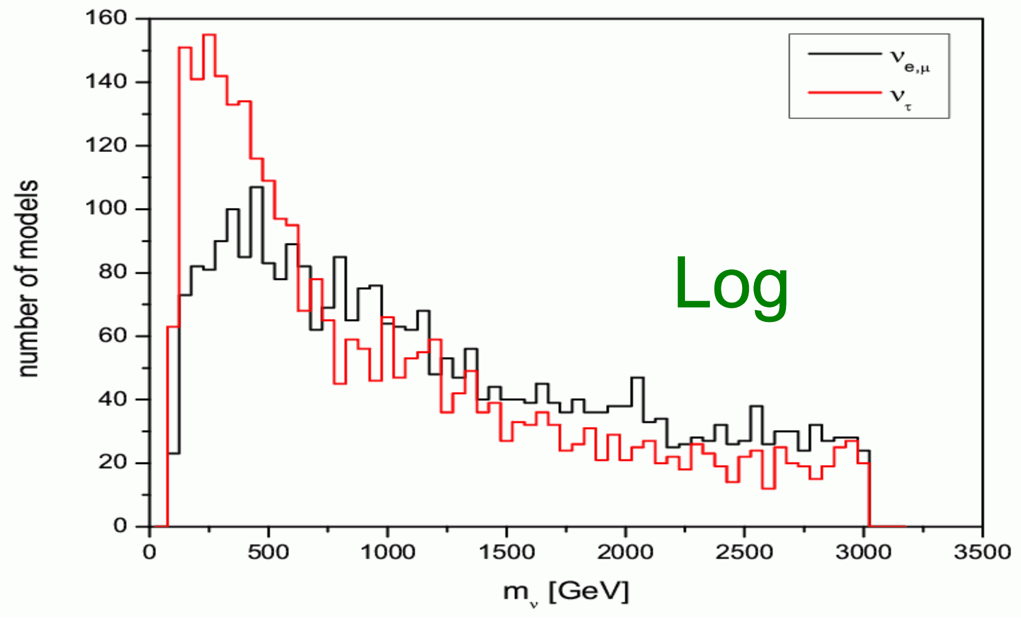


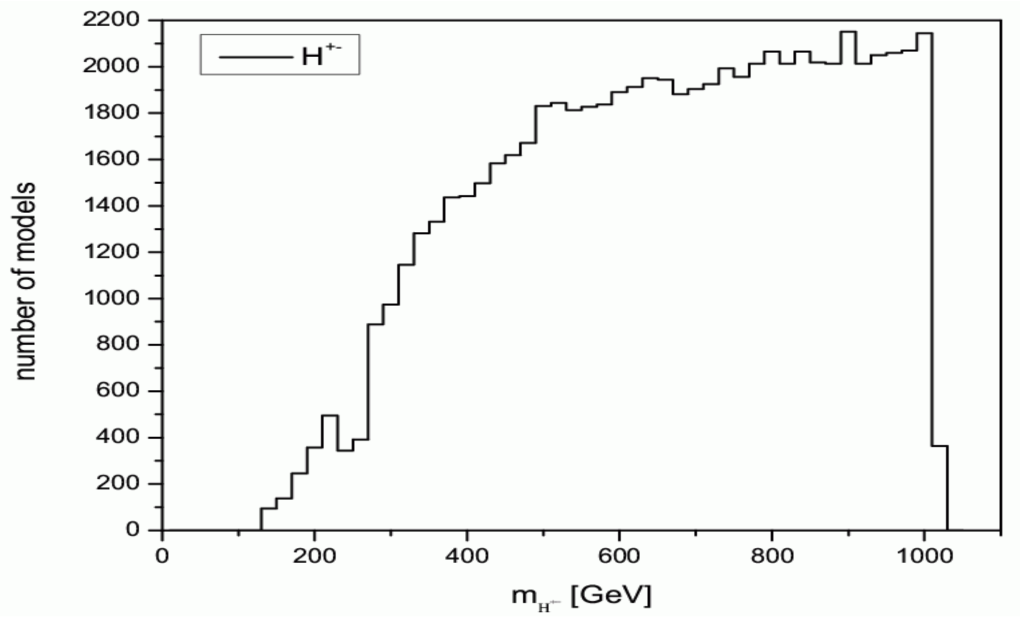
Distribution of Sparticle Masses By Species

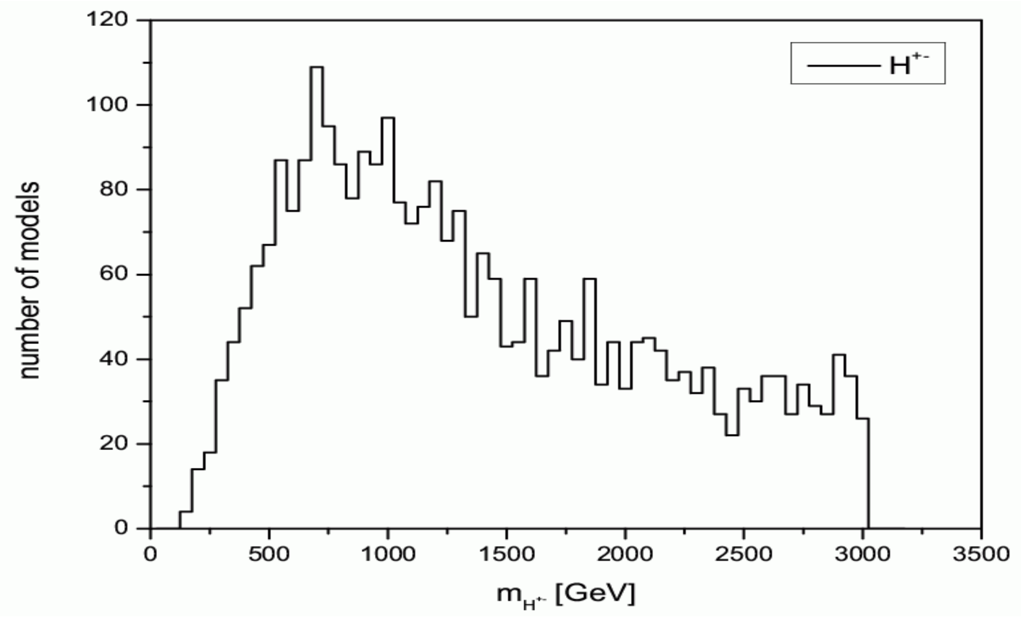


Distribution of Sparticle Masses By Species

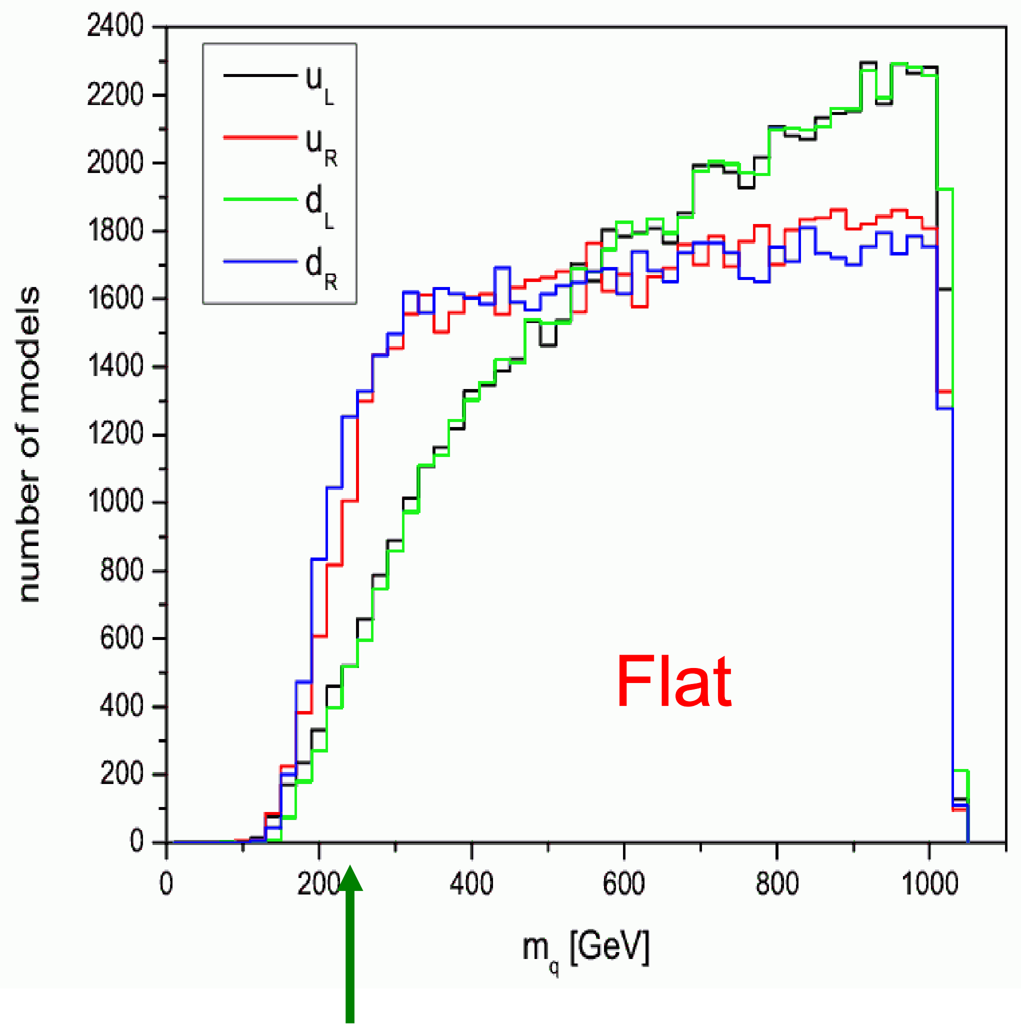


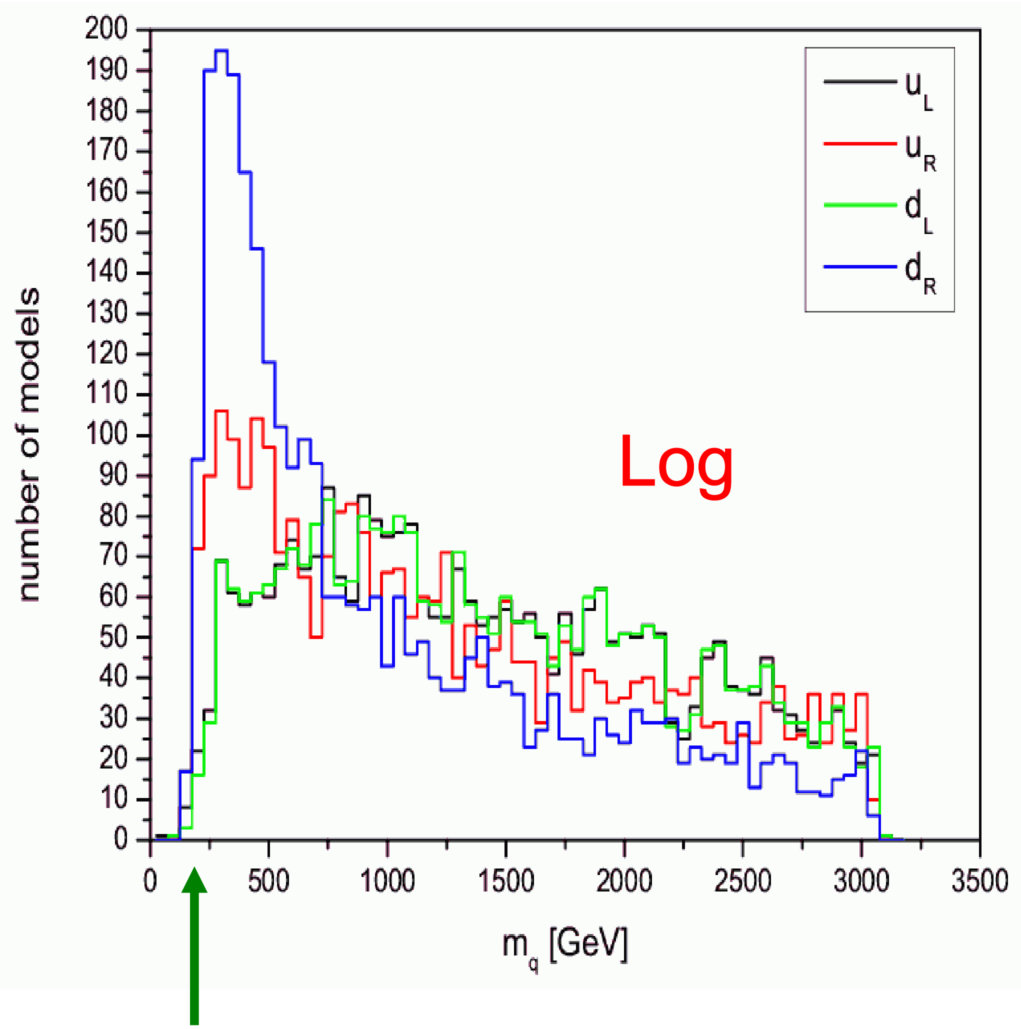






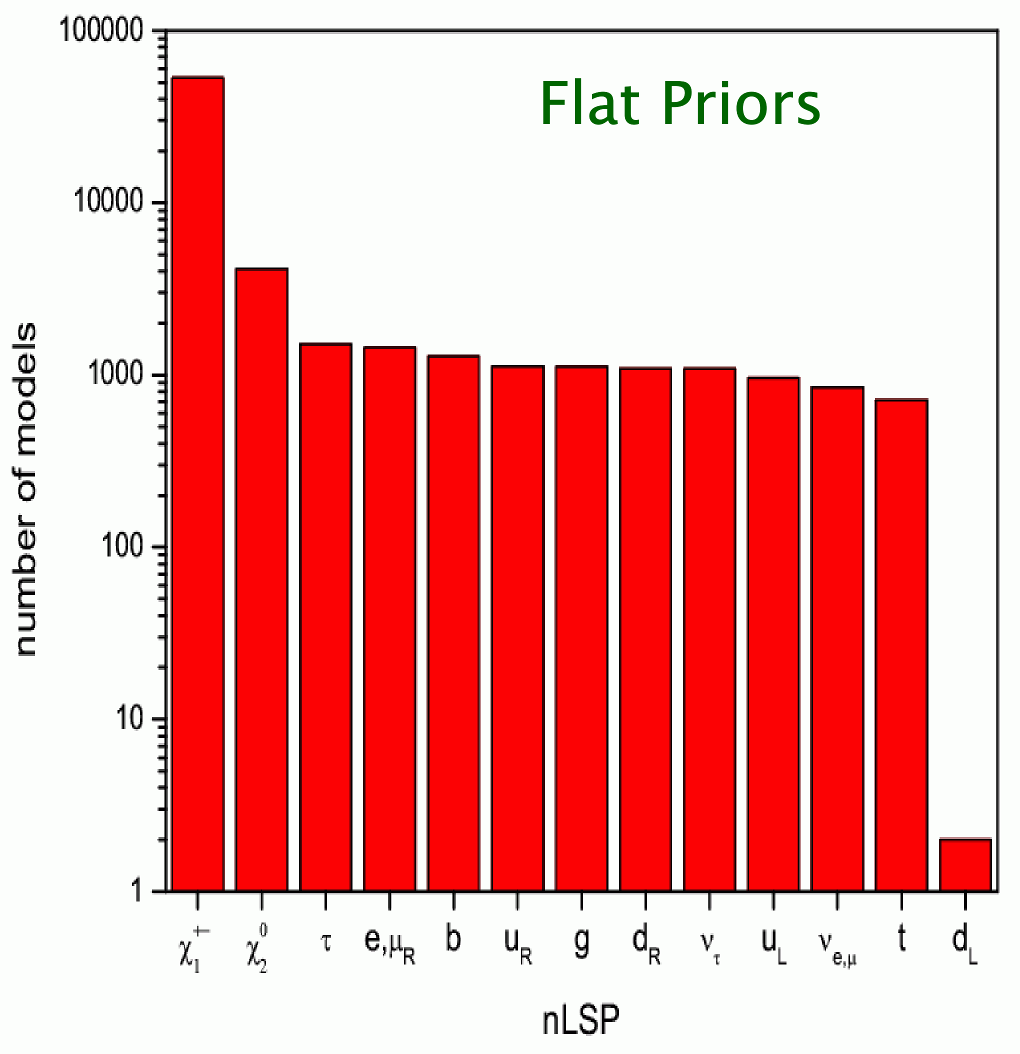
Squarks CAN Be Light !!!

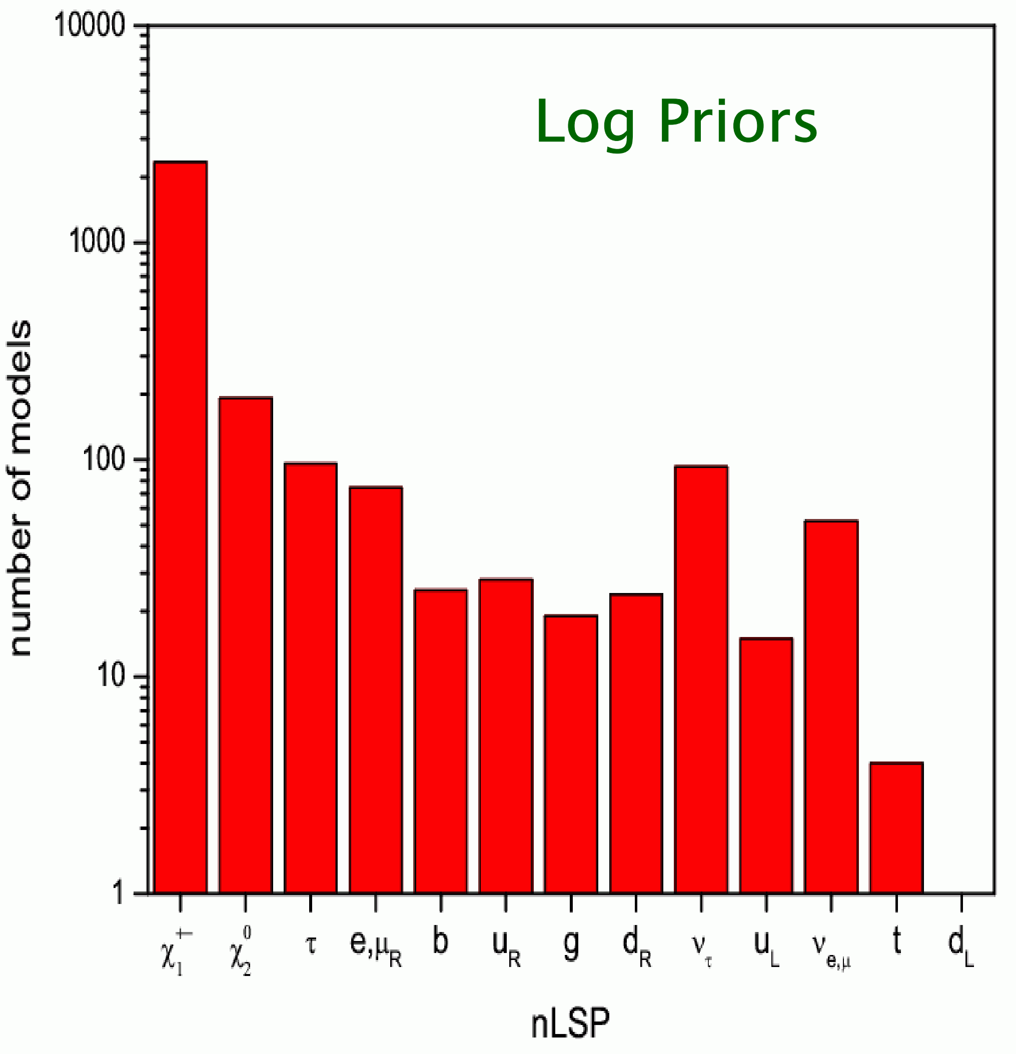




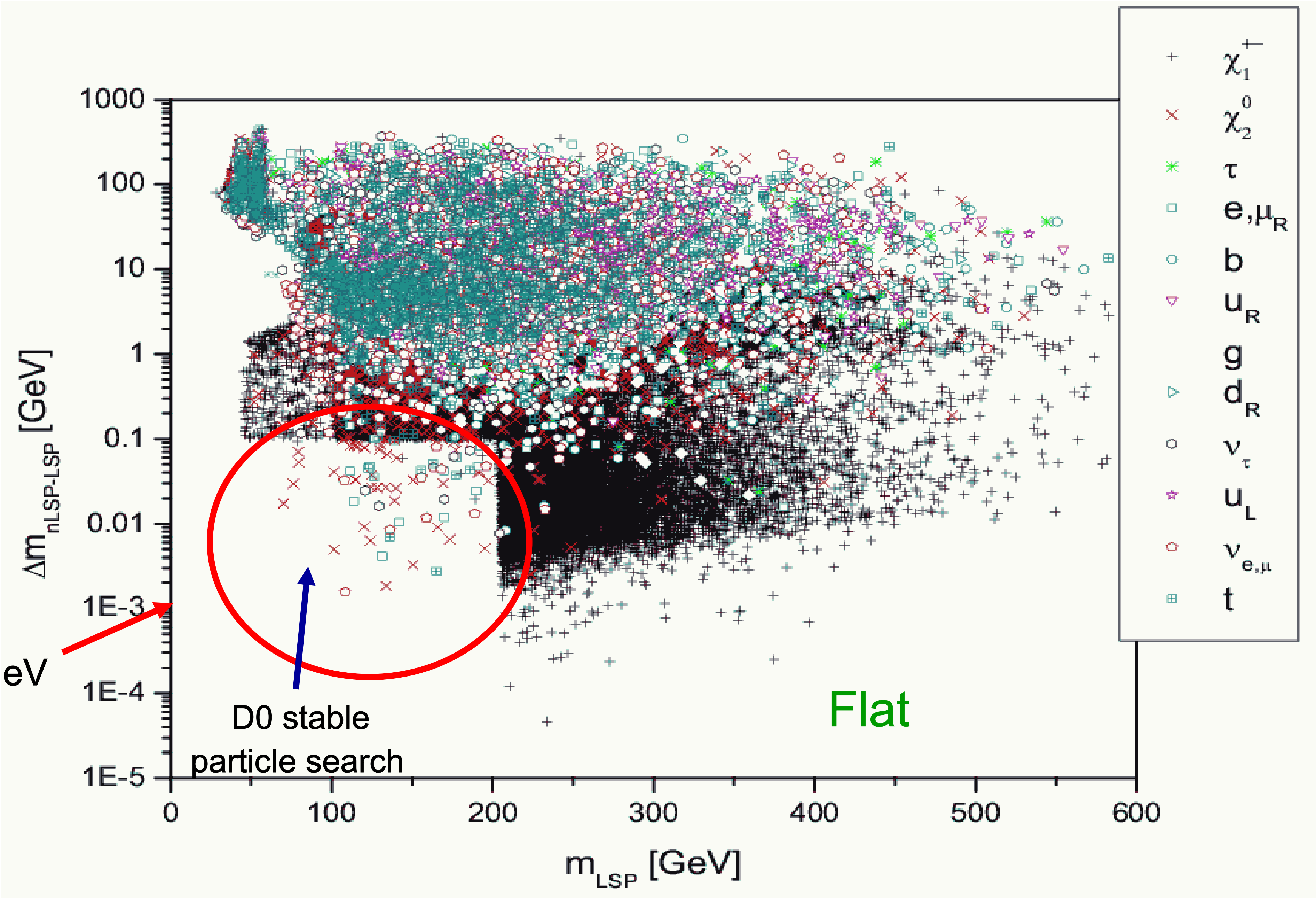
Light squarks can be missed by Tevatron searches for numerous reasons..

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

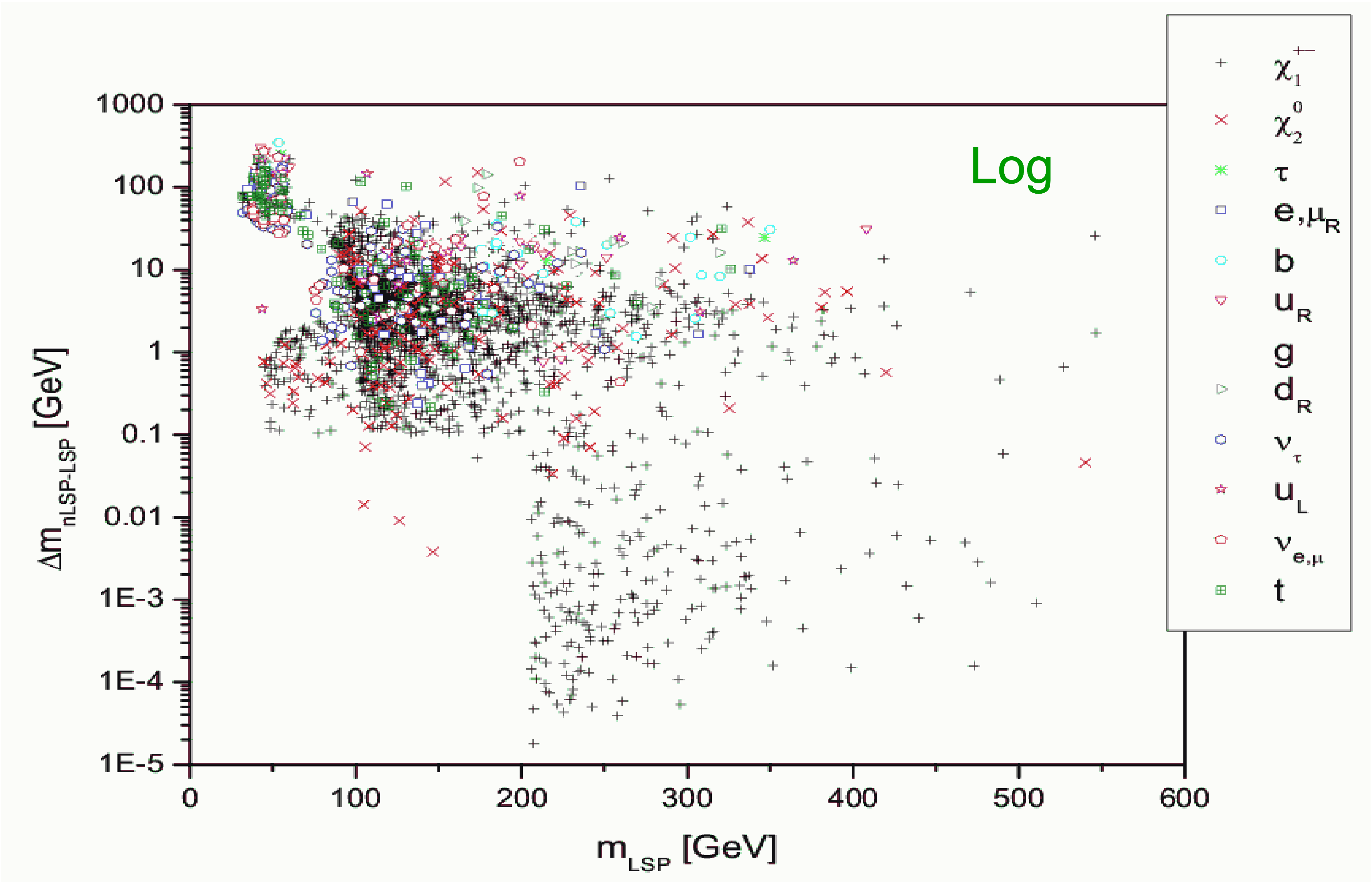


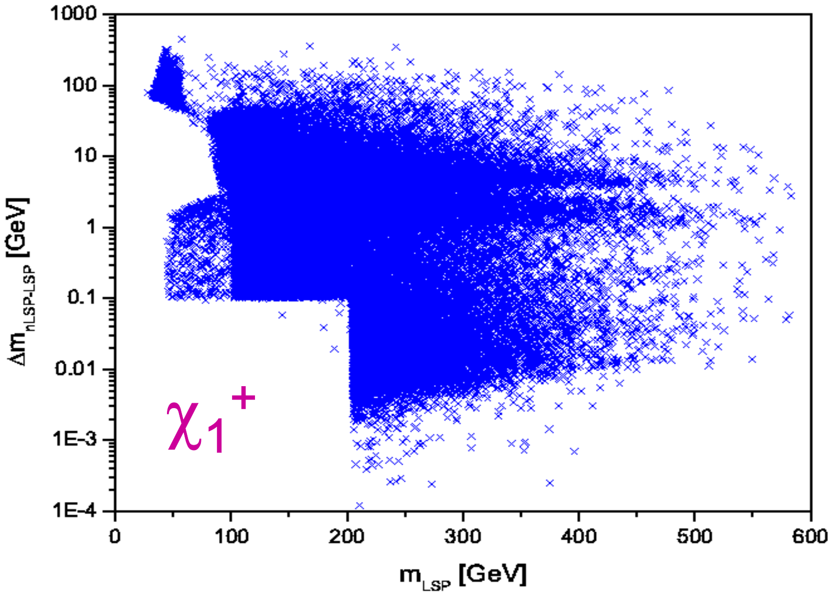
1 MeV

D0 stable particle search

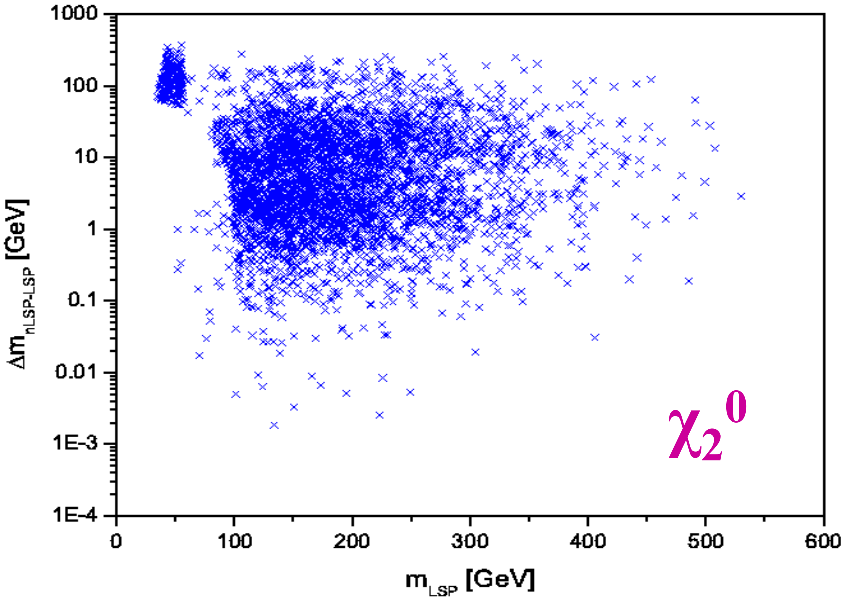
Flat

nLSP-LSP Mass Difference

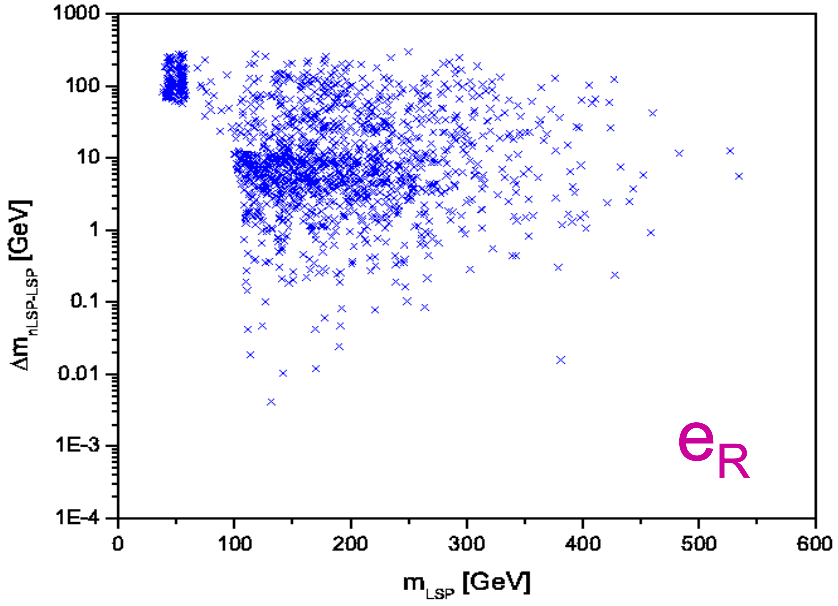




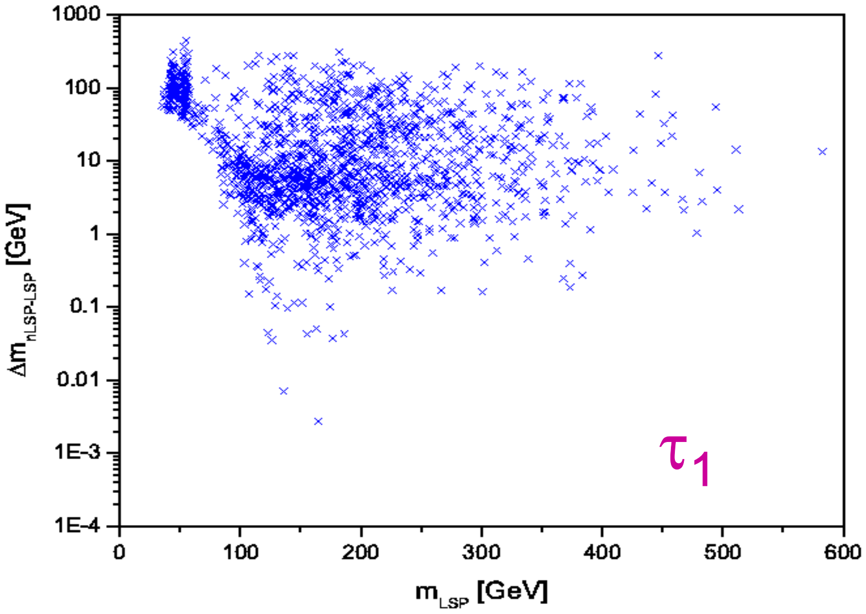
χ_1^+
$\Delta m_{\text{nLSP-LSP}}$ [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
m_{LSP} [GeV]



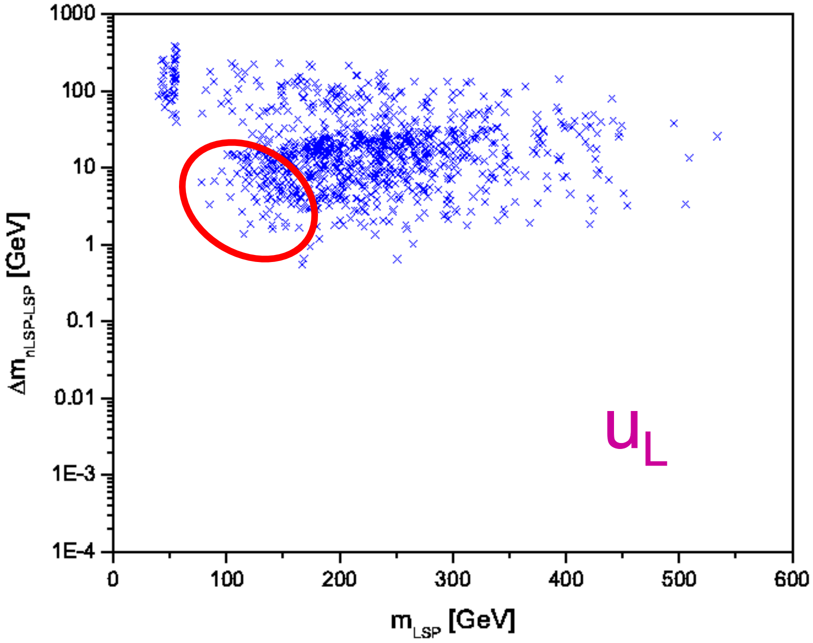
χ_2^0
$\Delta m_{\text{nLSP-LSP}}$ [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
m_{LSP} [GeV]

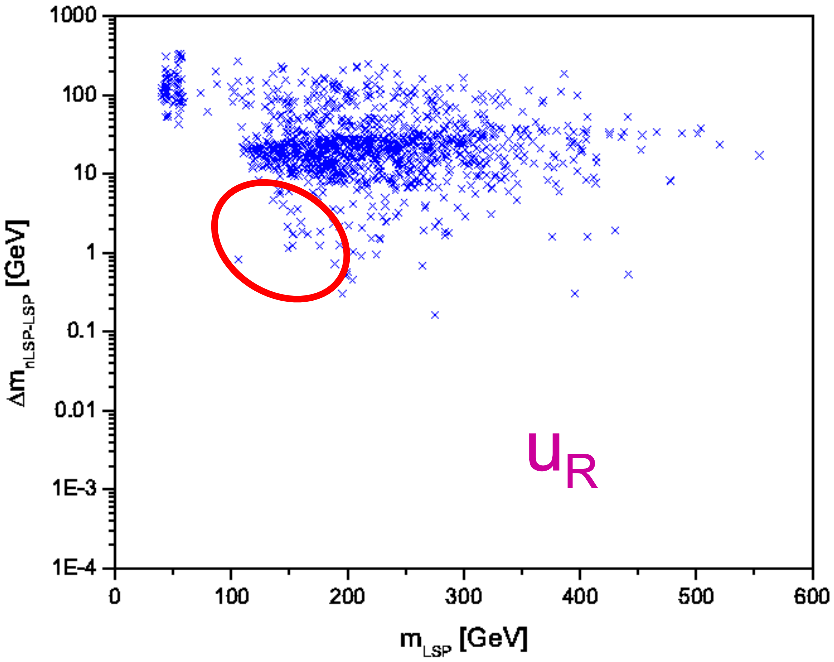


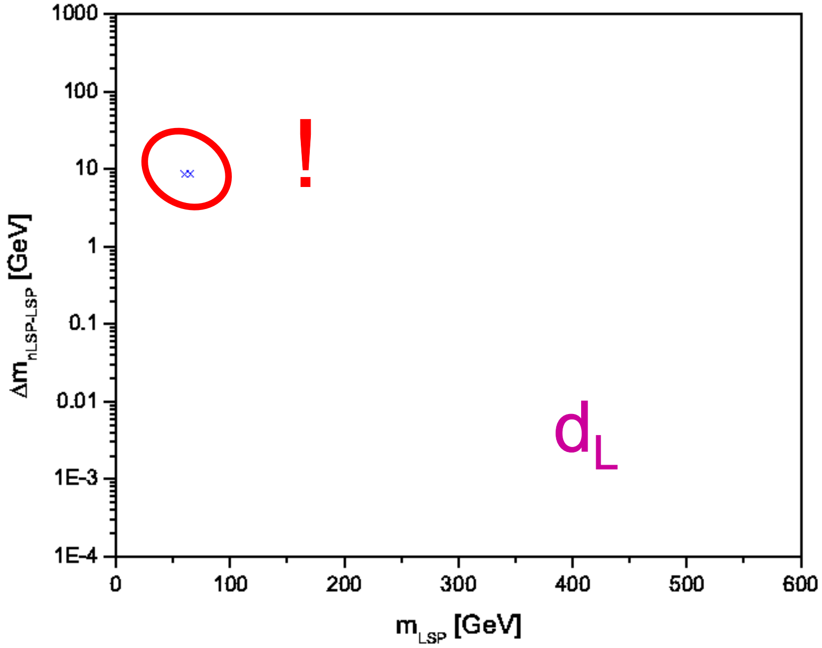
e_R
$\Delta m_{\text{nLSP-LSP}}$ [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
m_{LSP} [GeV]

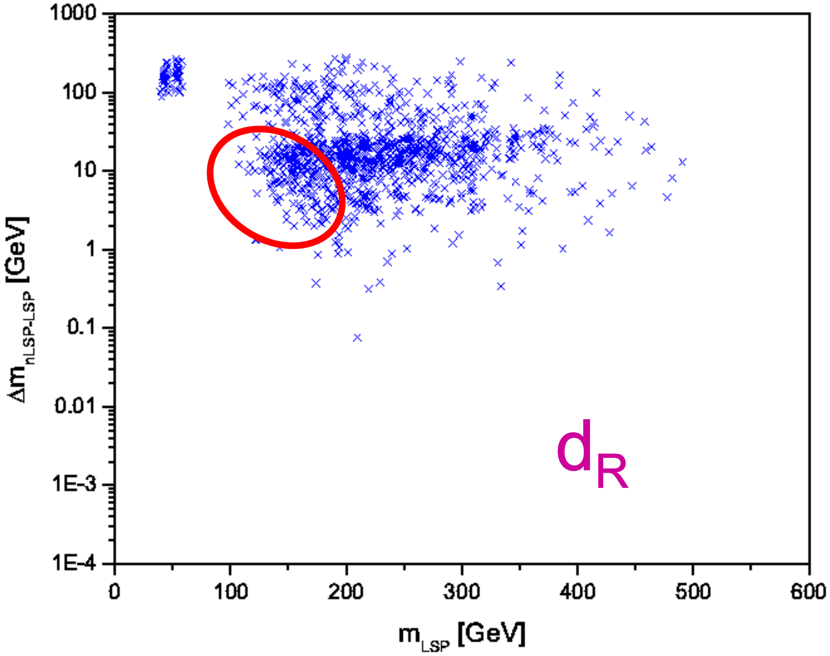


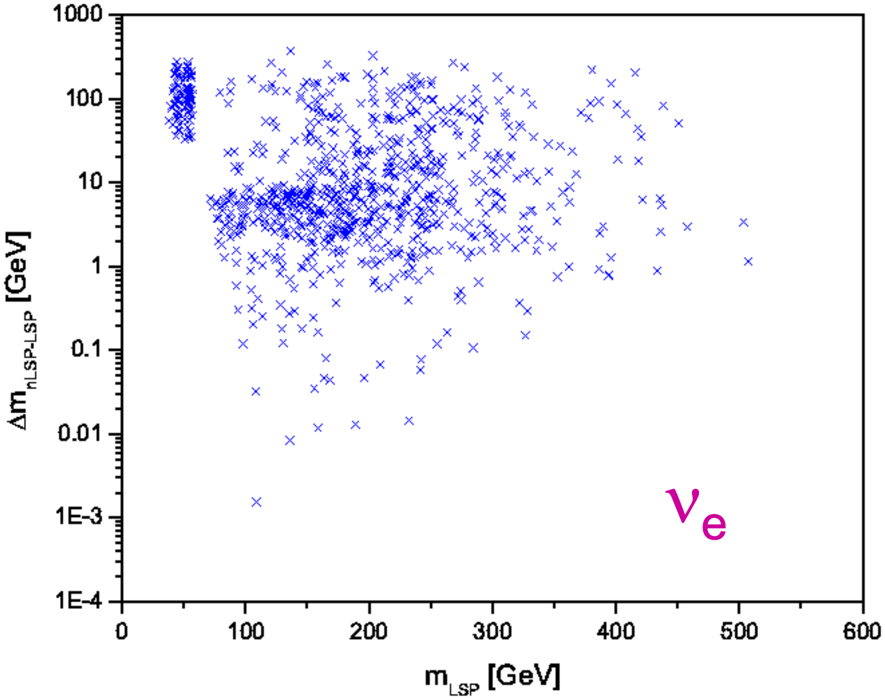
τ_1
$\Delta m_{\text{nLSP-LSP}}$ [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
m_{LSP} [GeV]

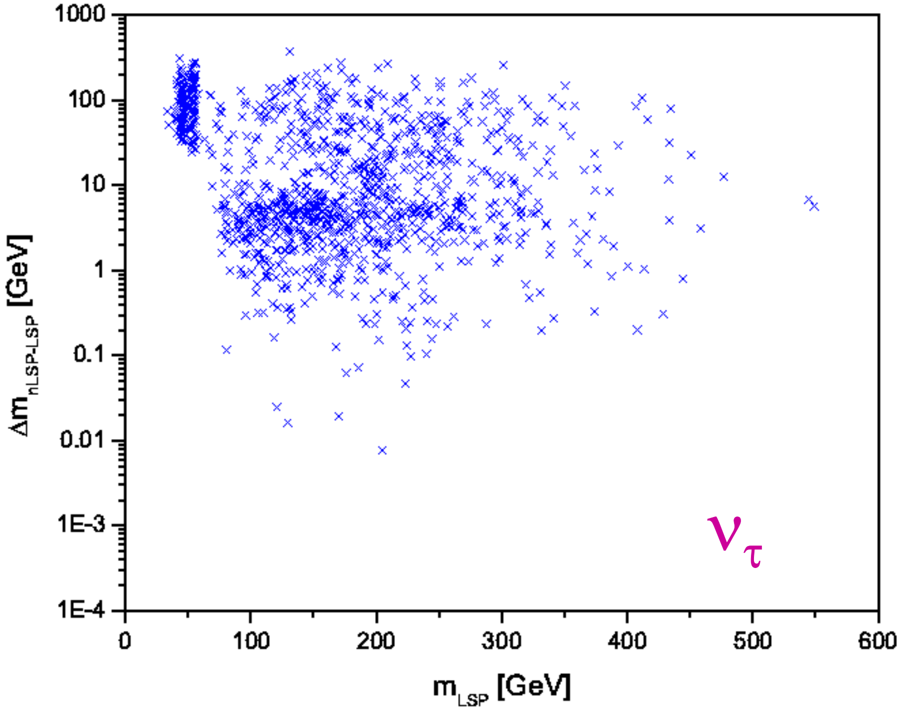

1000
100
10
1
0.1
0.01
1E-3
1E-4
$\Delta m_{nLSP-LSP}$ [GeV]
0
100
200
300
400
500
600
m_{LSP} [GeV]
u_L

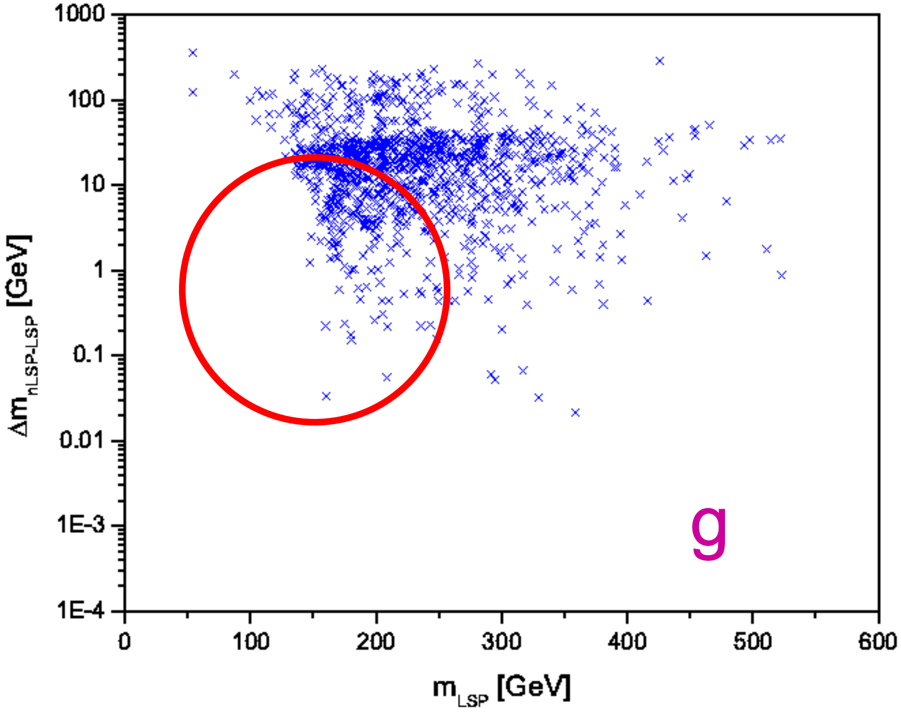

1000
100
10
1
0.1
0.01
1E-3
1E-4
$\Delta m_{nLSP-LSP}$ [GeV]
0
100
200
300
400
500
600
m_{LSP} [GeV]
u_R

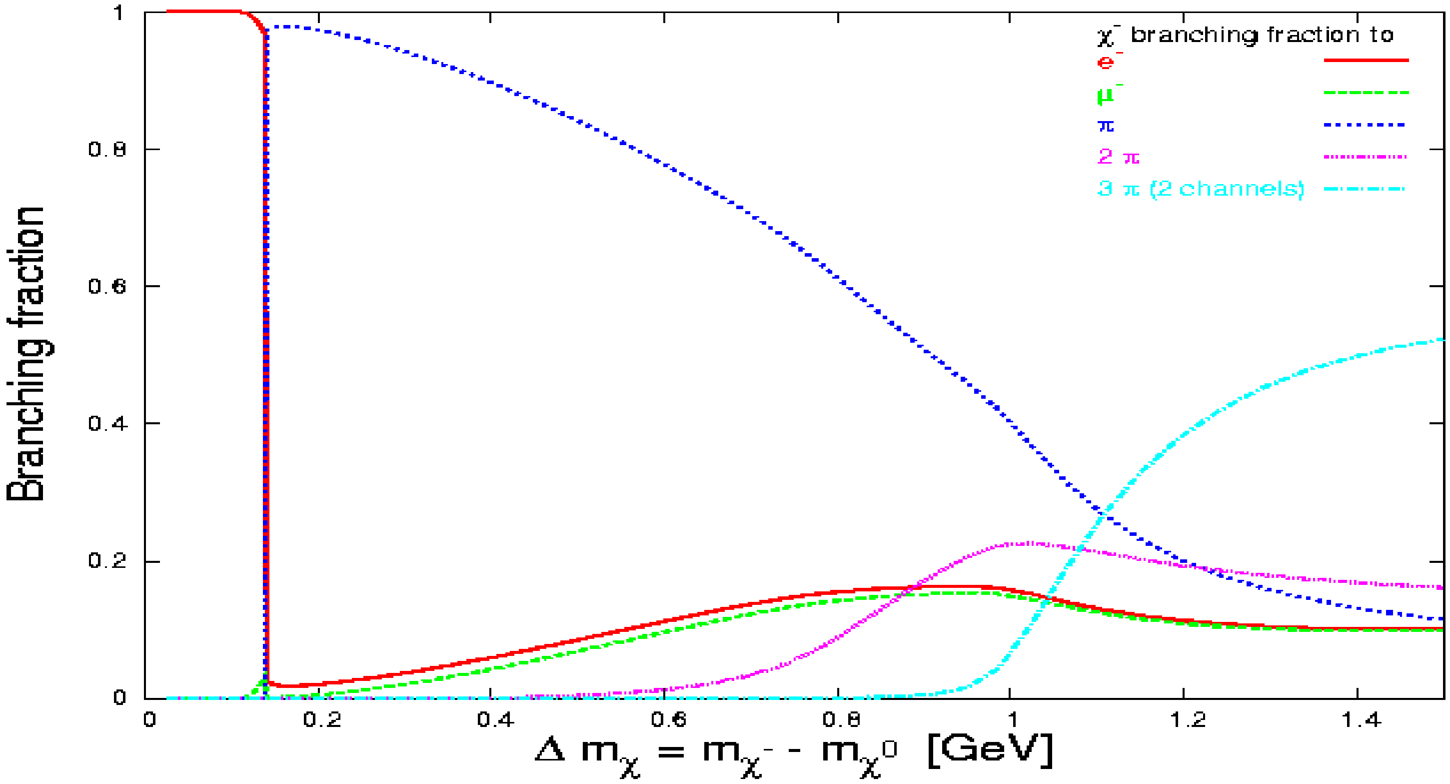

1000
100
10
1
0.1
0.01
1E-3
1E-4
$\Delta m_{nLSP-LSP}$ [GeV]
0
100
200
300
400
500
600
m_{LSP} [GeV]
!
d_L

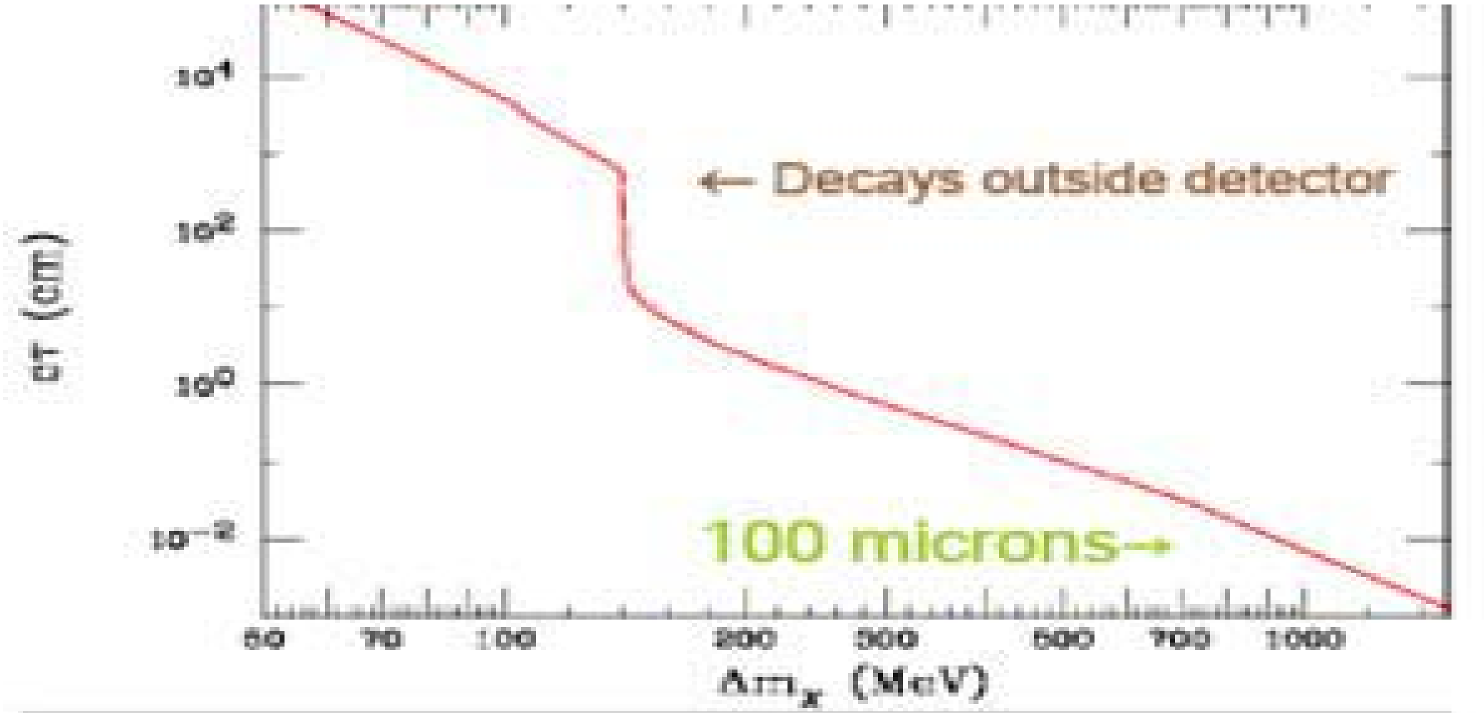

1000
100
10
1
0.1
0.01
1E-3
1E-4
$\Delta m_{nLSP-LSP}$ [GeV]
0
100
200
300
400
500
600
m_{LSP} [GeV]
d_R


1000
100
10
1
0.1
0.01
1E-3
1E-4
$\Delta m_{nLSP-LSP}$ [GeV]
0
100
200
300
400
500
600
m_{LSP} [GeV]
ν_e


1000
100
10
1
0.1
0.01
1E-3
1E-4
$\Delta m_{nLSP-LSP}$ [GeV]
0
100
200
300
400
500
600
m_{LSP} [GeV]
ν_τ

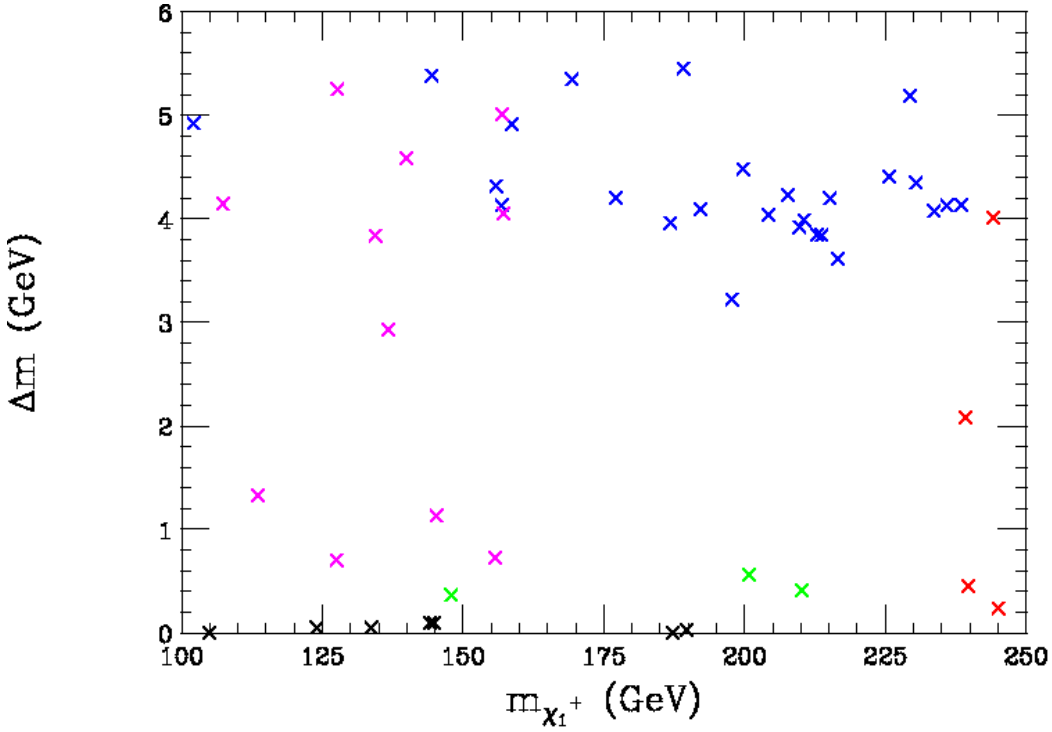

1000
100
10
1
0.1
0.01
1E-3
1E-4
$\Delta m_{nLSP-LSP}$ [GeV]
0
100
200
300
400
500
600
m_{LSP} [GeV]
g


Branching fraction
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$\Delta m_\chi = m_{\chi^-} - m_{\chi^0}$ [GeV]
χ^- branching fraction to
e^-
μ^-
π
$2\ \pi$
$3\ \pi$ (2 channels)


cτ (cm)
10^4
10^2
10^0
10^{-2}
50
70
100
200
300
500
700
1000
Δm_χ (MeV)
← Decays outside detector
100 microns→

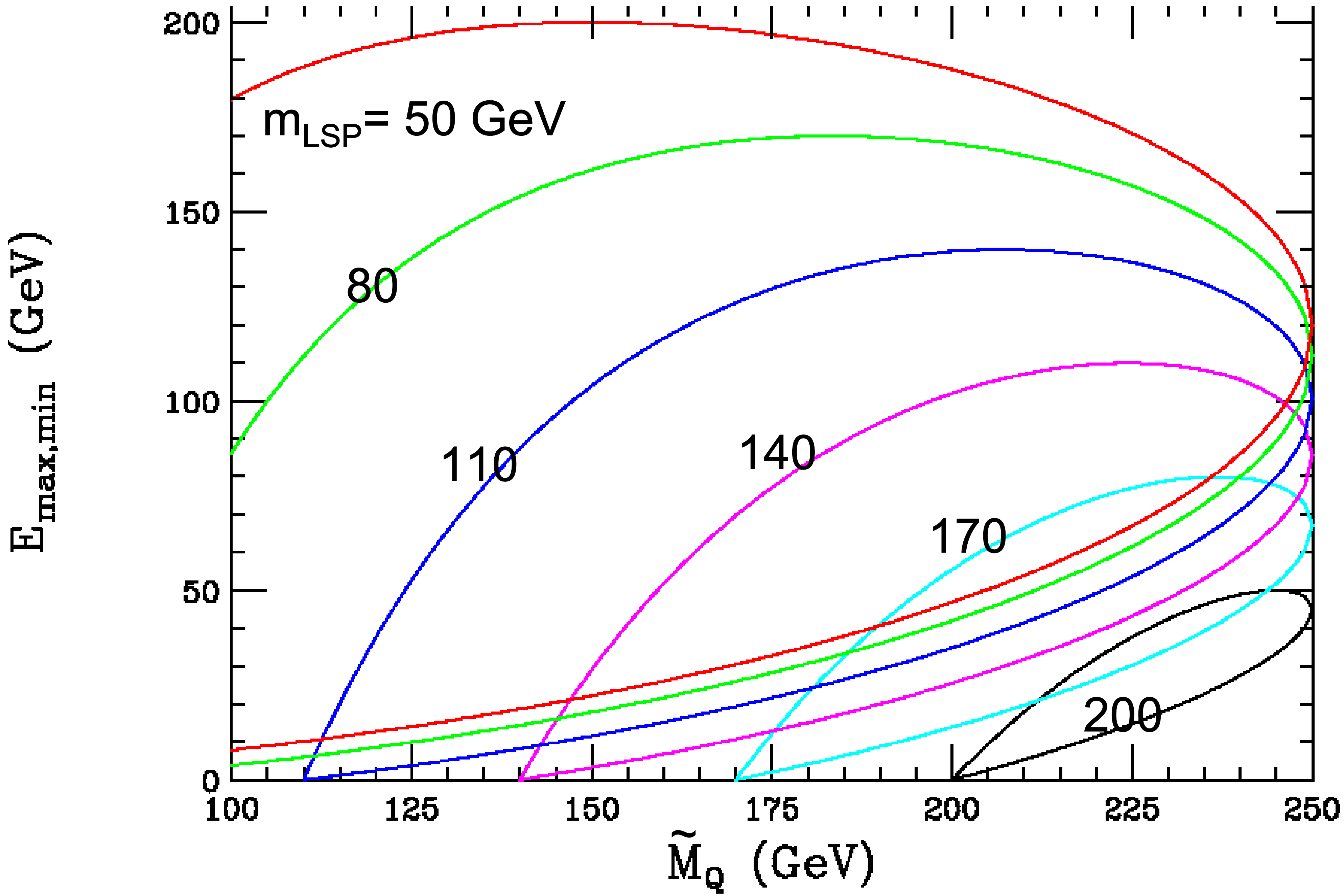
As is well-known the observation of close mass objects is generally difficult at all colliders, even in e^+e^- collisions.

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 as seen below.

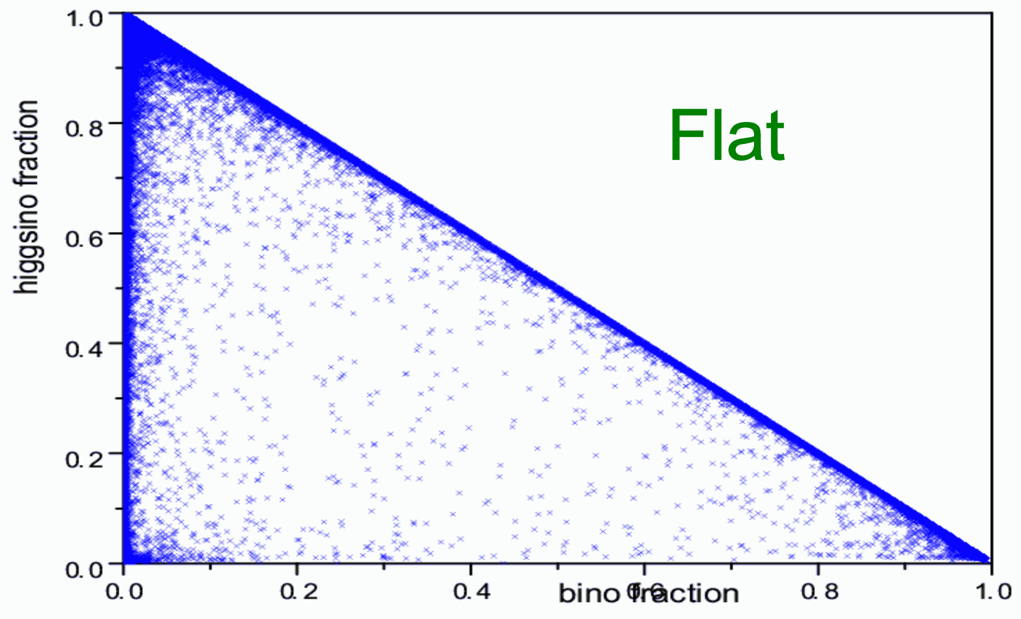


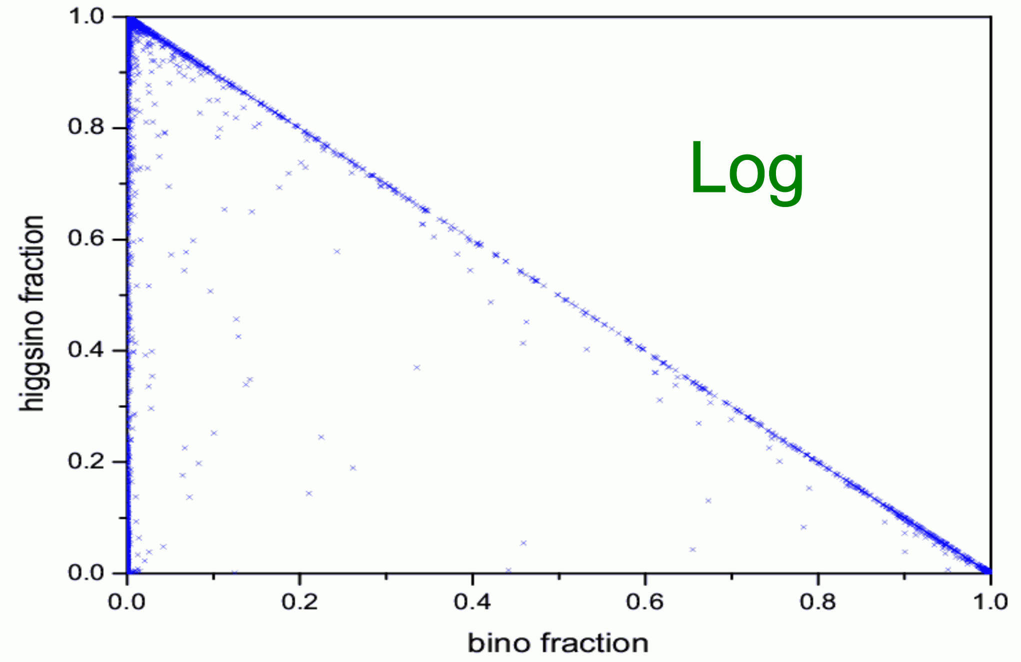
We have MANY close mass possibilities in our two model samples. Can γγ colliders possibly do any better??? For example, in the case of smuons (squarks) 1-2(1-9) GeV heavier than the LSP??

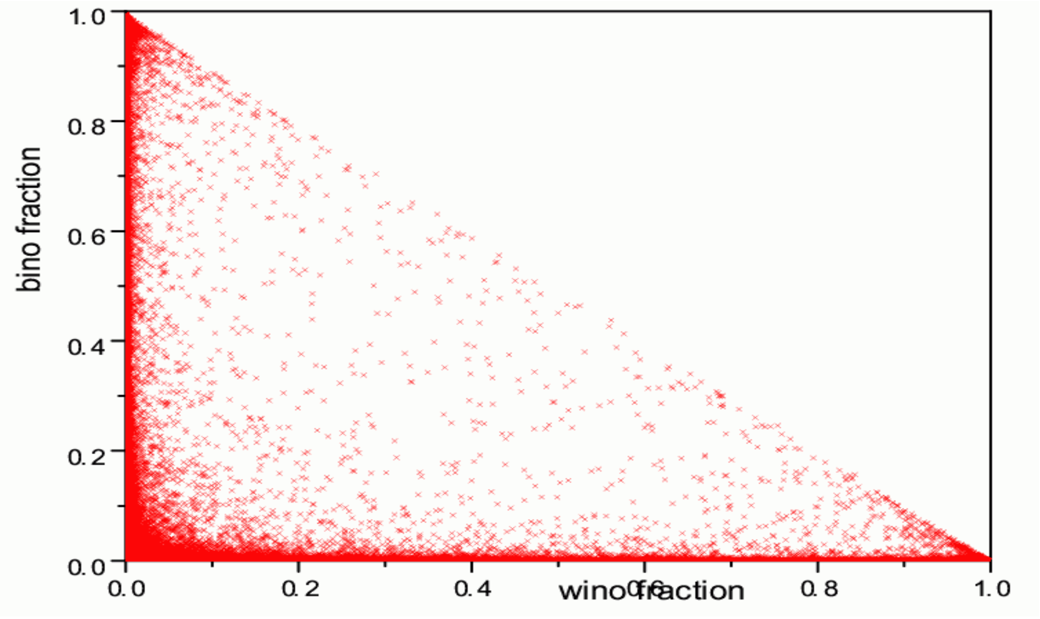
Jet Energies from Squark Pair Production at √s=500 GeV

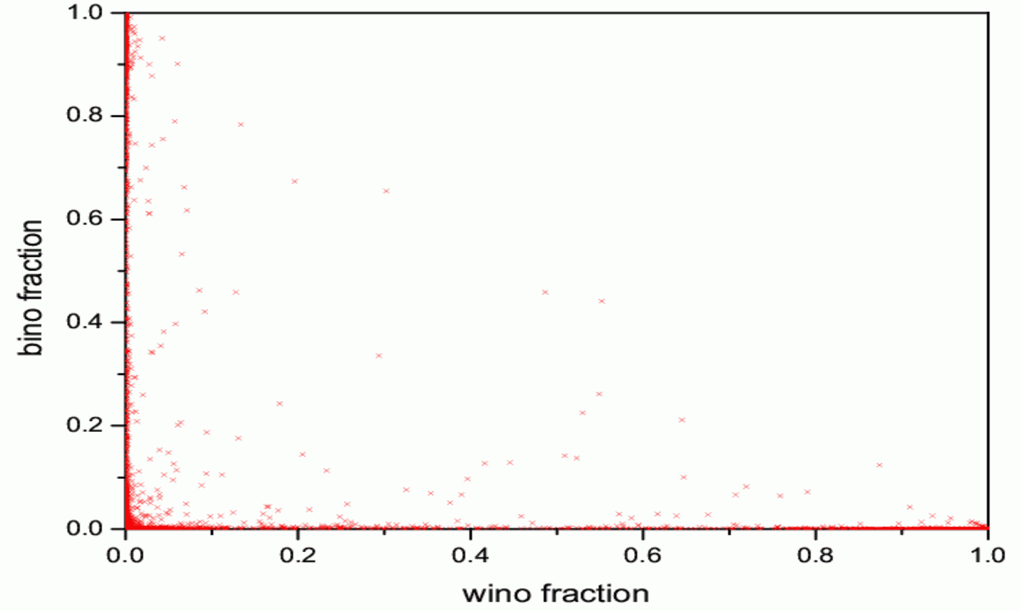


LSP Composition





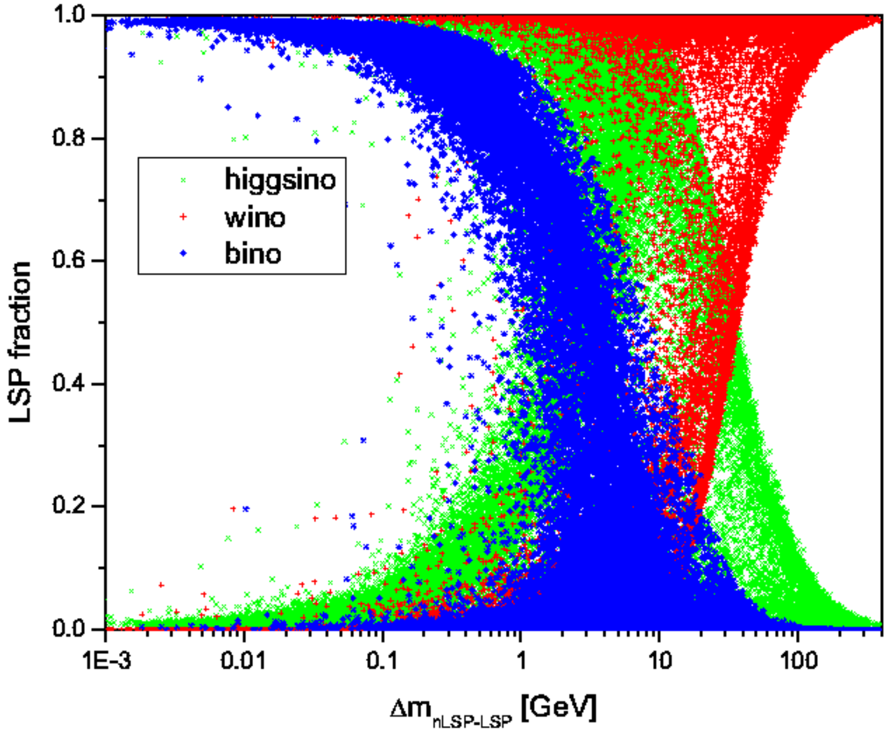




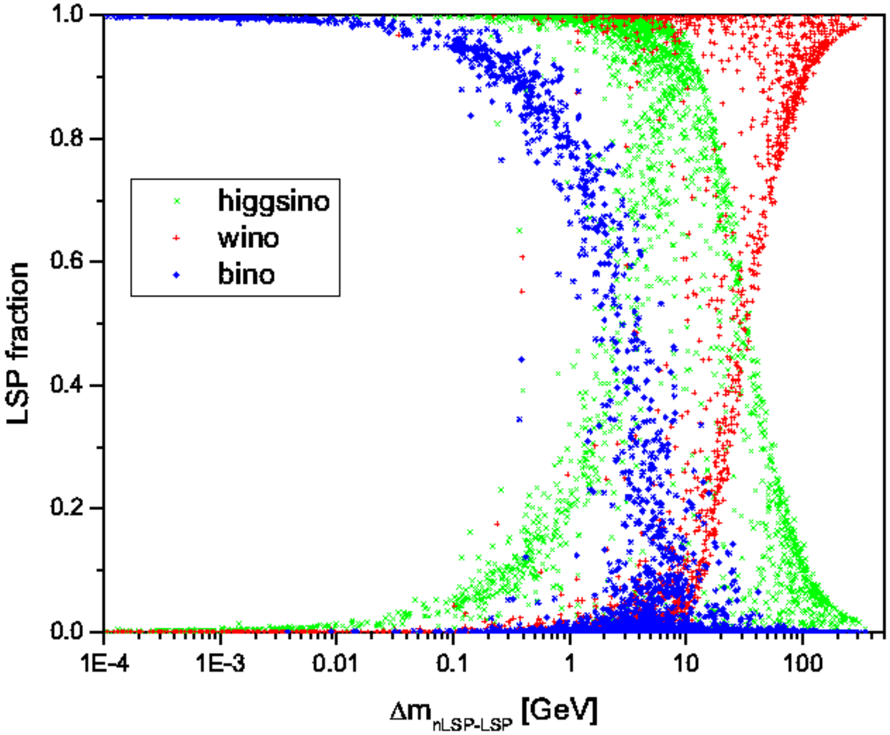
LSP Composition

The LSP composition is found to be both mass dependent as well as (no surprise) sensitive to the nLSP-LSP mass splitting…models with large mass splittings have LSPs which are wino-like but VERY small mass splittings produce bino-like LSPs.

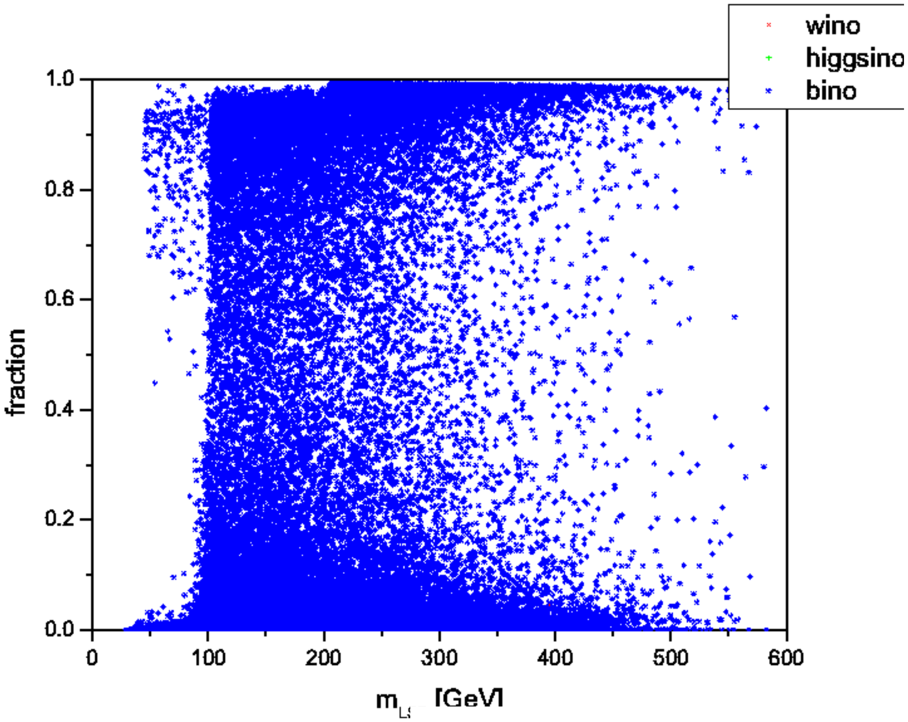
Flat

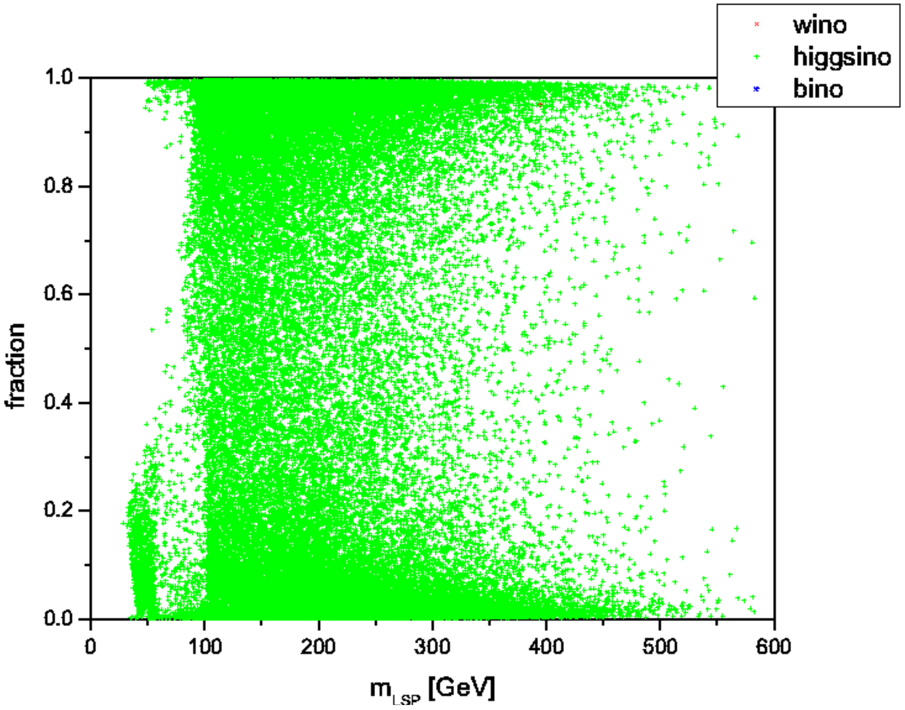


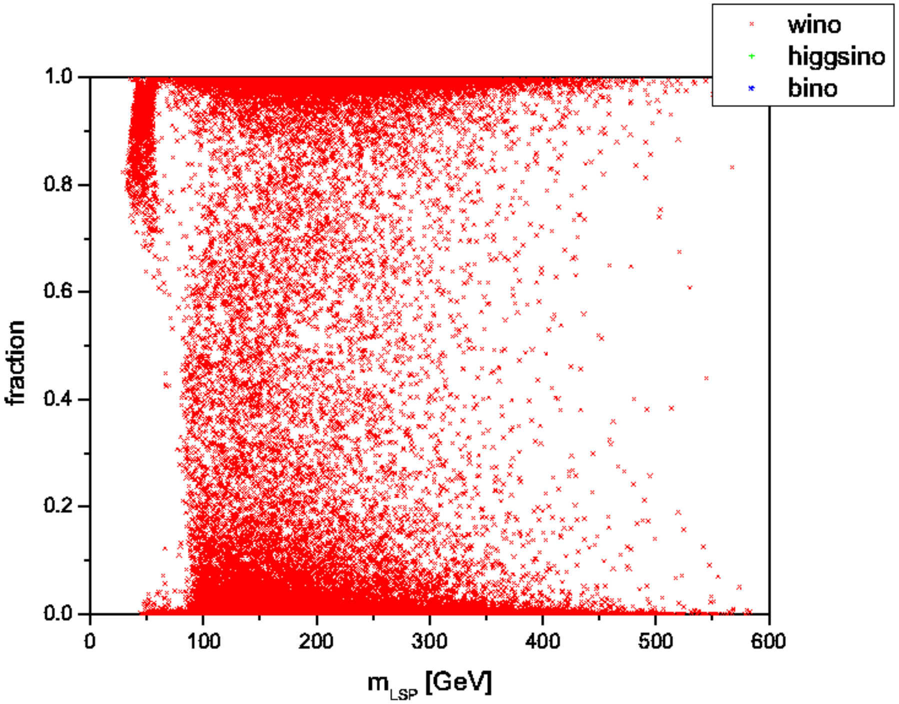
Log



LSP Composition

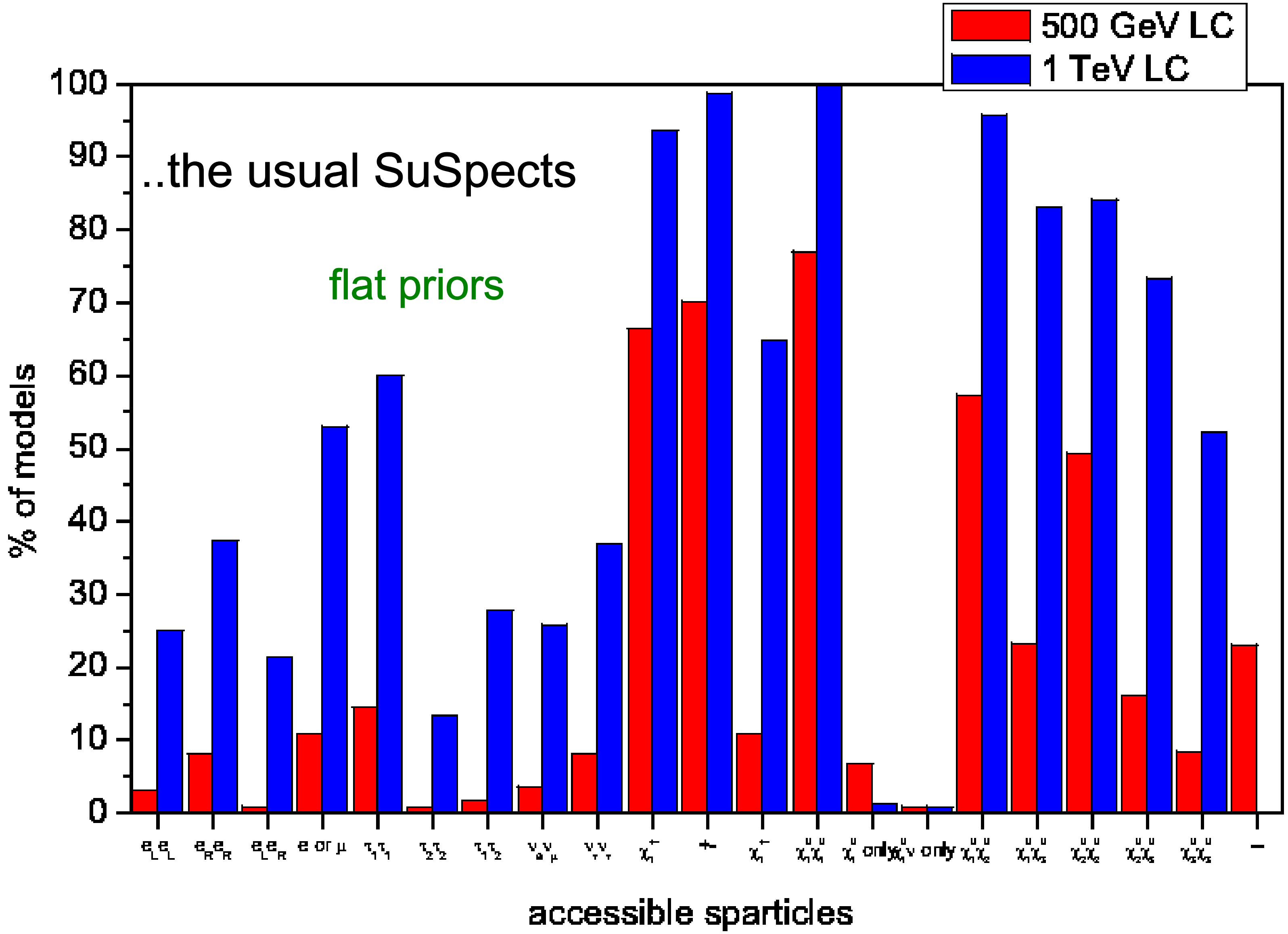






Flat Priors

Kinematic Accessibility at the ILC : I

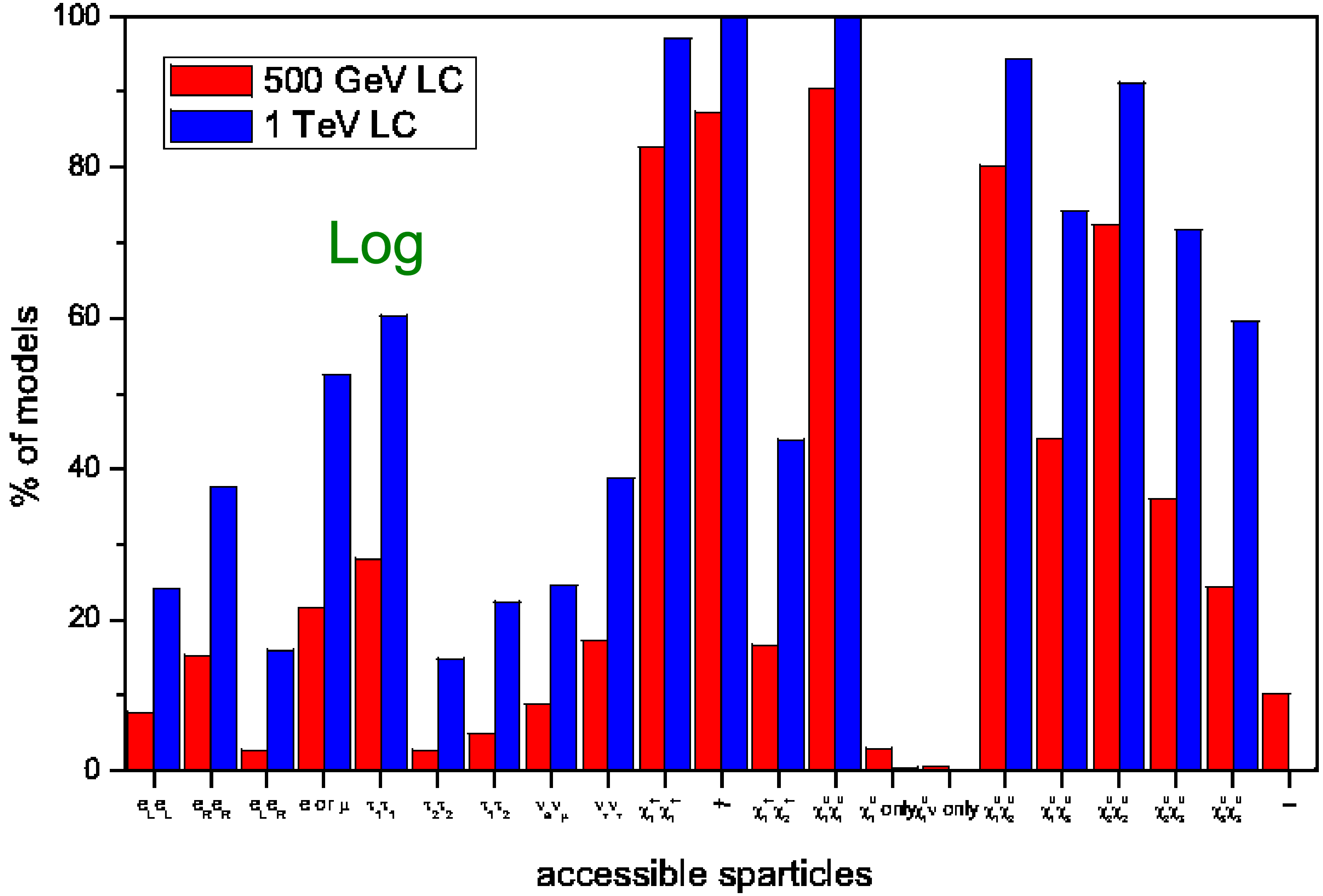


..the usual SuSpects

flat priors

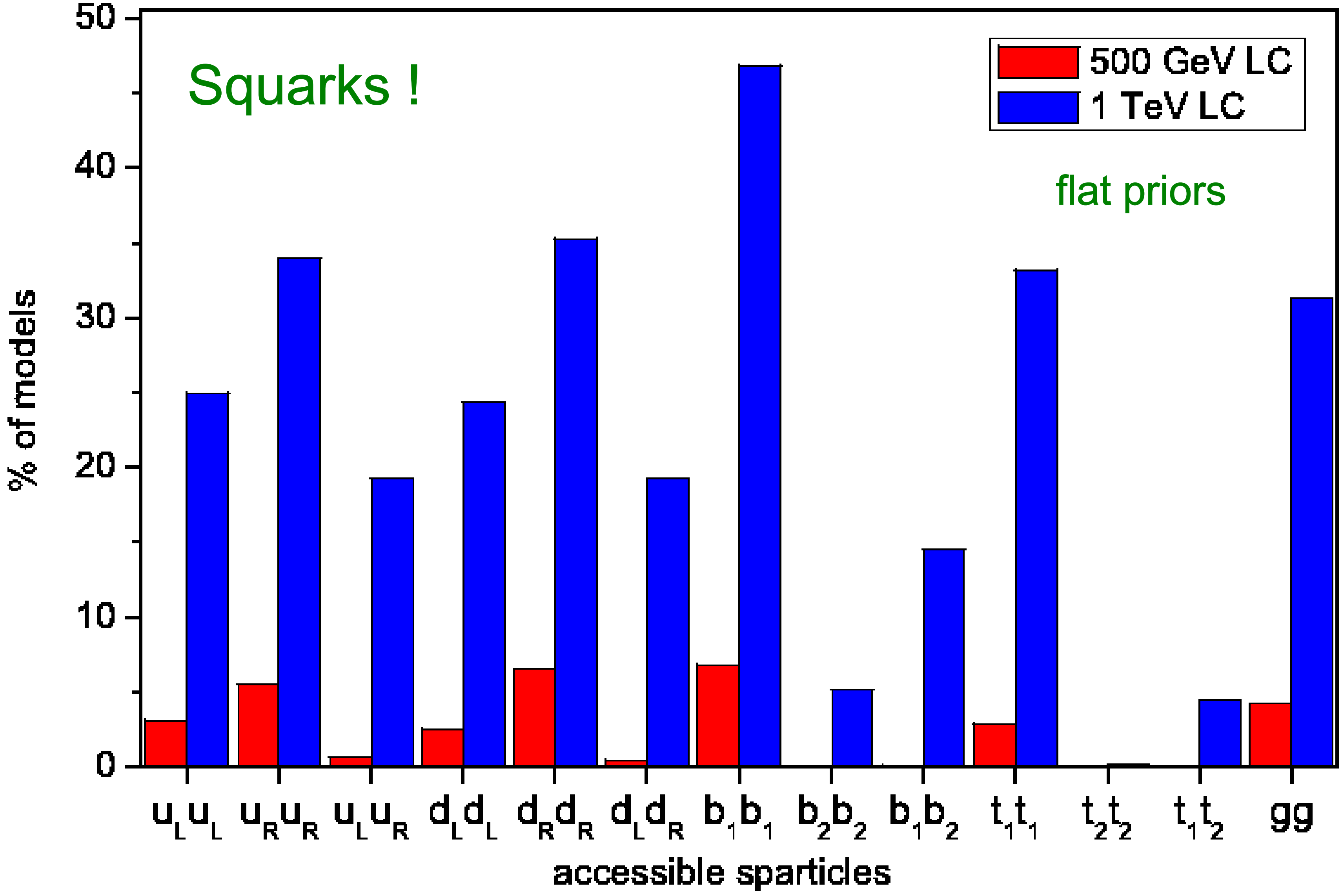
Final State
$\tilde{e}_L^+ \tilde{e}_L^-$
$\tilde{e}_R^+ \tilde{e}_R^-$
$\tilde{e}_L^\pm \tilde{e}_R^\mp$
$\tilde{\mu}_L^+ \tilde{\mu}_L^-$
$\tilde{\mu}_R^+ \tilde{\mu}_R^-$
Any selectron or smuon
$\tilde{\tau}_1^+ \tilde{\tau}_1^-$
$\tilde{\tau}_2^+ \tilde{\tau}_2^-$
$\tilde{\tau}_1^\pm \tilde{\tau}_2^\mp$
$\tilde{\nu}_{e\mu} \tilde{\nu}_{e\mu}^*$
$\tilde{\nu}_\tau \tilde{\nu}_\tau^*$
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$
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 : II

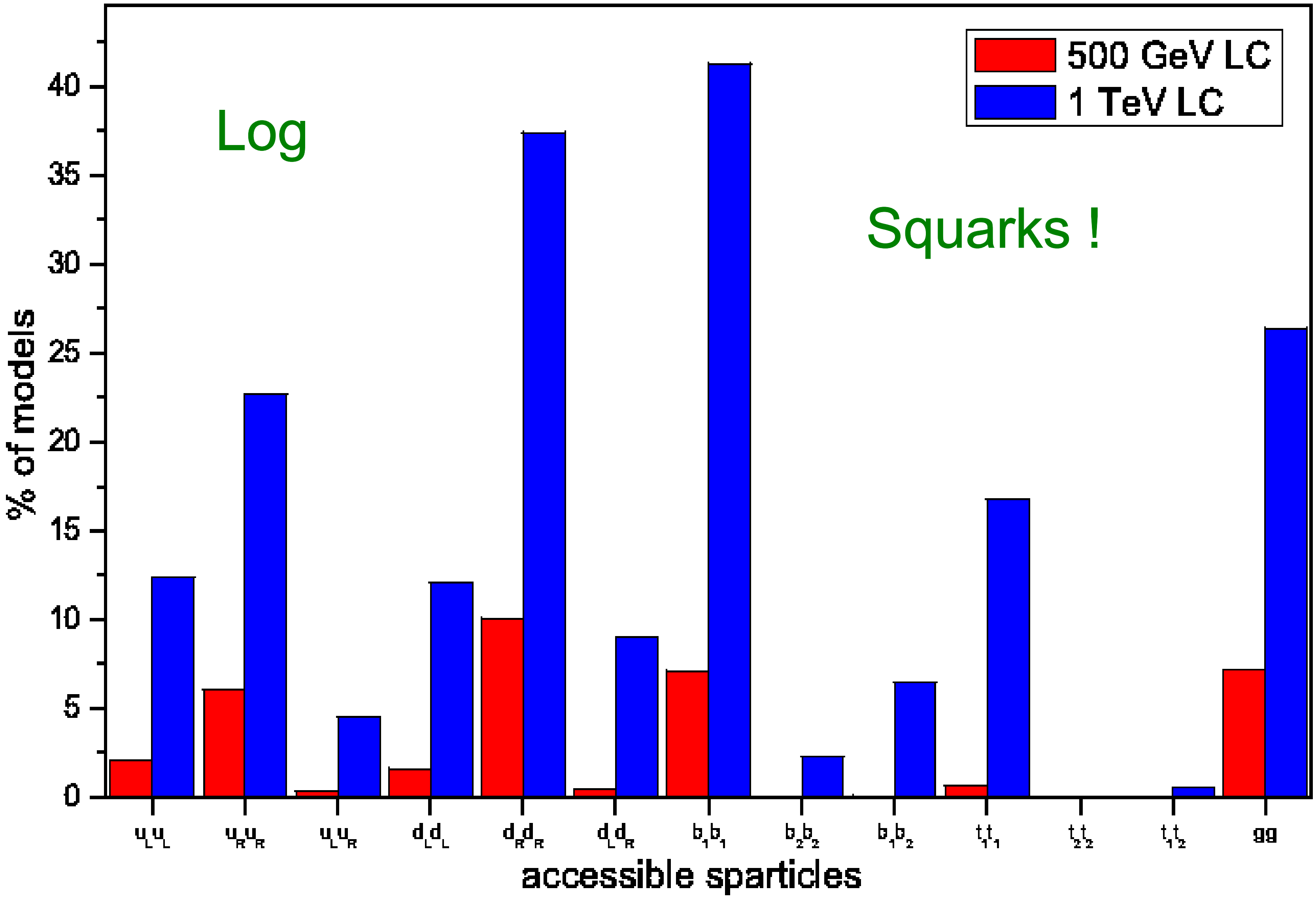


Final State
$\tilde{e}_L^+\tilde{e}_L^-$
$\tilde{e}_R^+\tilde{e}_R^-$
$\tilde{e}_L^\pm\tilde{e}_R^\mp$
$\tilde{\mu}_L^+\tilde{\mu}_L^-$
$\tilde{\mu}_R^+\tilde{\mu}_R^-$
Any selectron or smuon
$\tilde{\tau}_1^+\tilde{\tau}_1^-$
$\tilde{\tau}_2^+\tilde{\tau}_2^-$
$\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$
$\tilde{\nu}_{e\mu}\tilde{\nu}_{e\mu}^*$
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$
$\tilde{\chi}_1^+\tilde{\chi}_1^-$
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 : III



Kinematic Accessibility at the ILC : IV

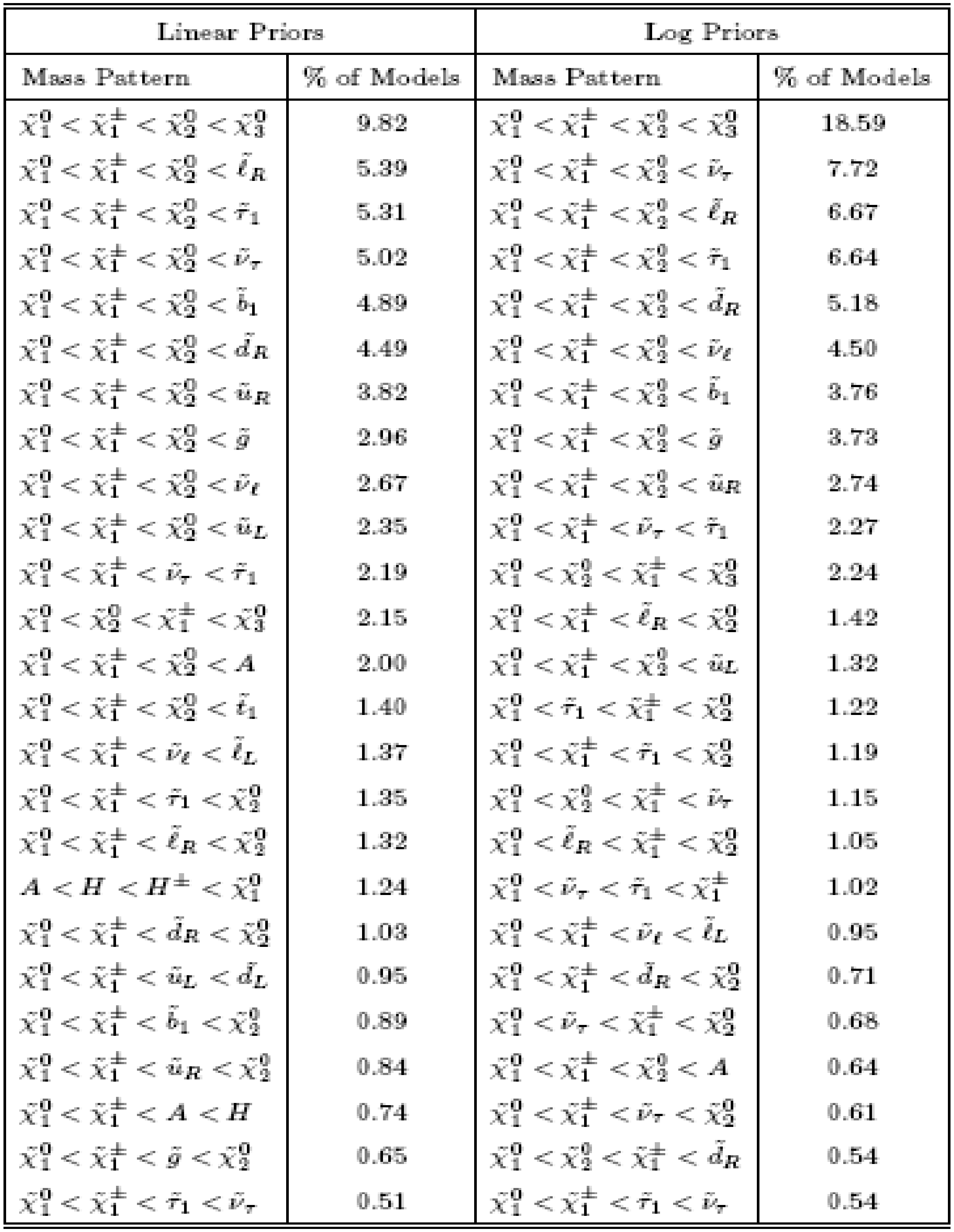


Log

Squarks !

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.

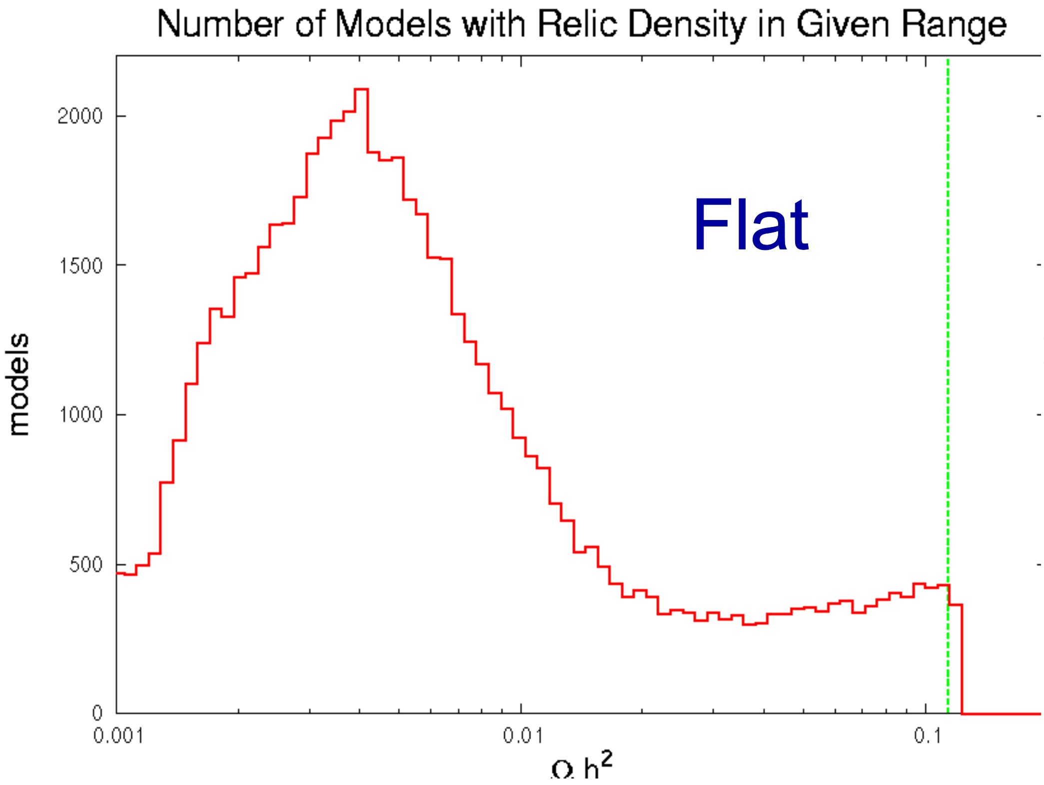
Top 25 most common mass patterns for the 4 lightest SUSY & heavy Higgs particles.

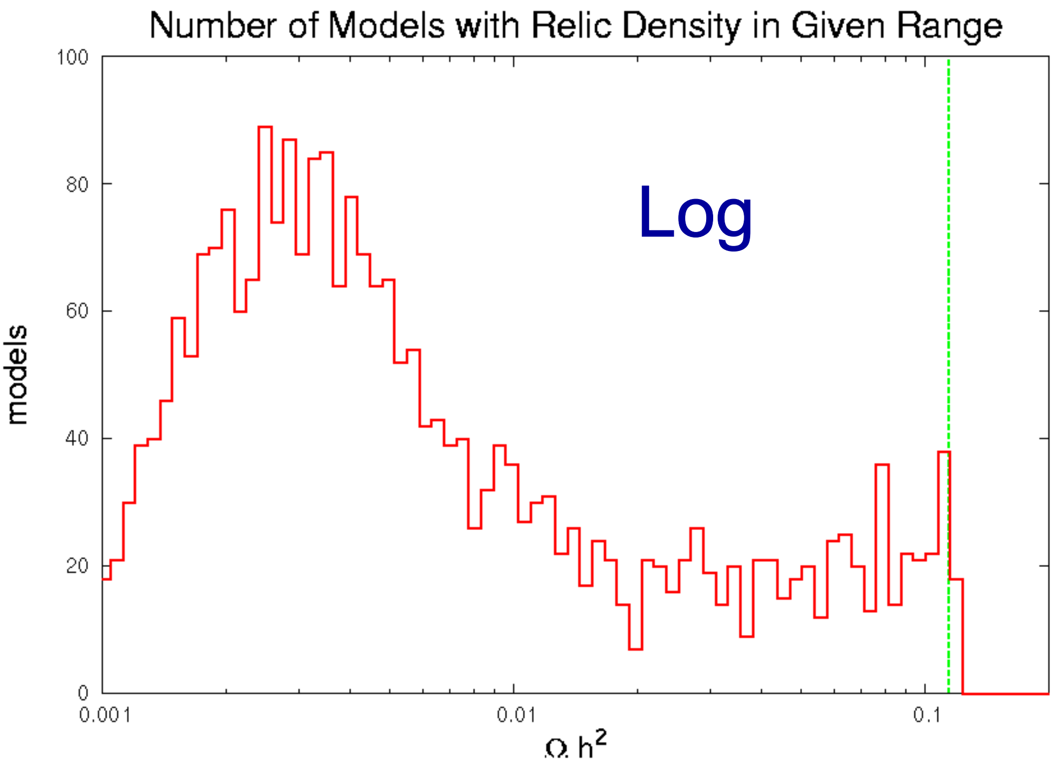
There were 1109 (267) such patterns found for the case of flat (log) priors

Only ~20 are found to occur in mSUGRA!!

Predicted Dark Matter Density : Ωh^2

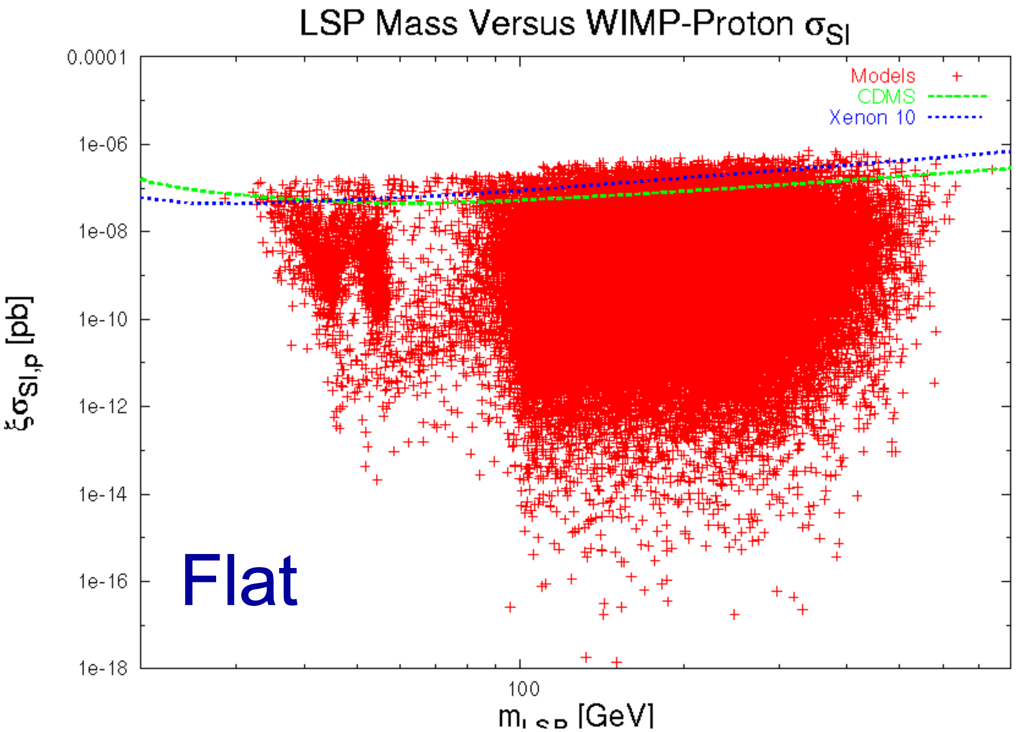
It is not likely that the LSP is the dominant component of dark matter in ‘conventional’ cosmology…but it can be in some model cases..

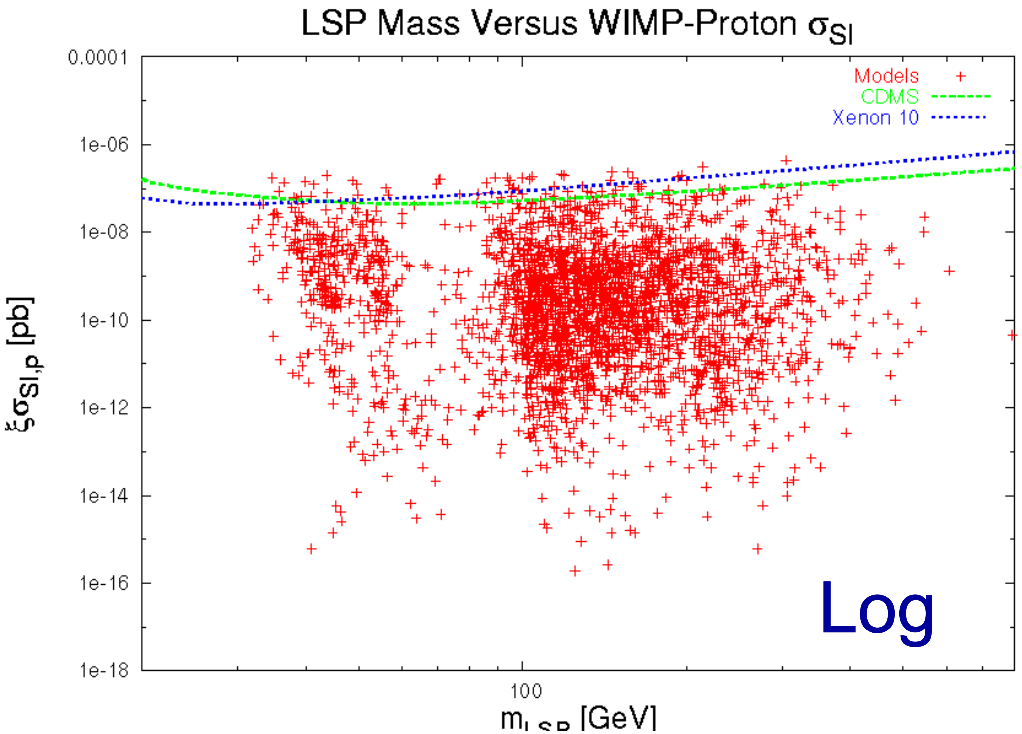




Direct Detection Expectations

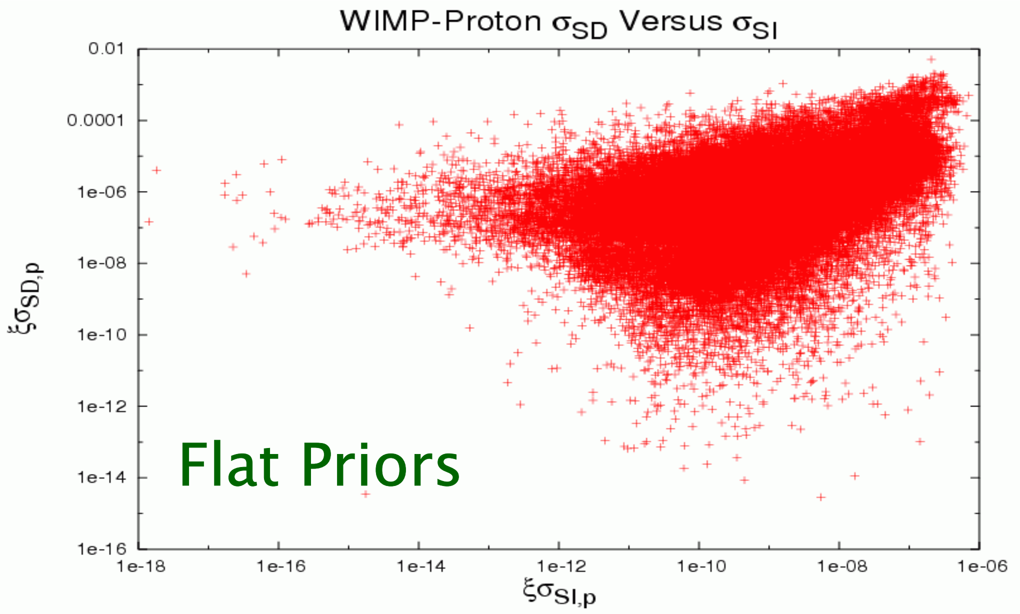
Extremely small cross sections are possible in either the flat or log prior cases…far smaller than expected in, e.g., mSUGRA….

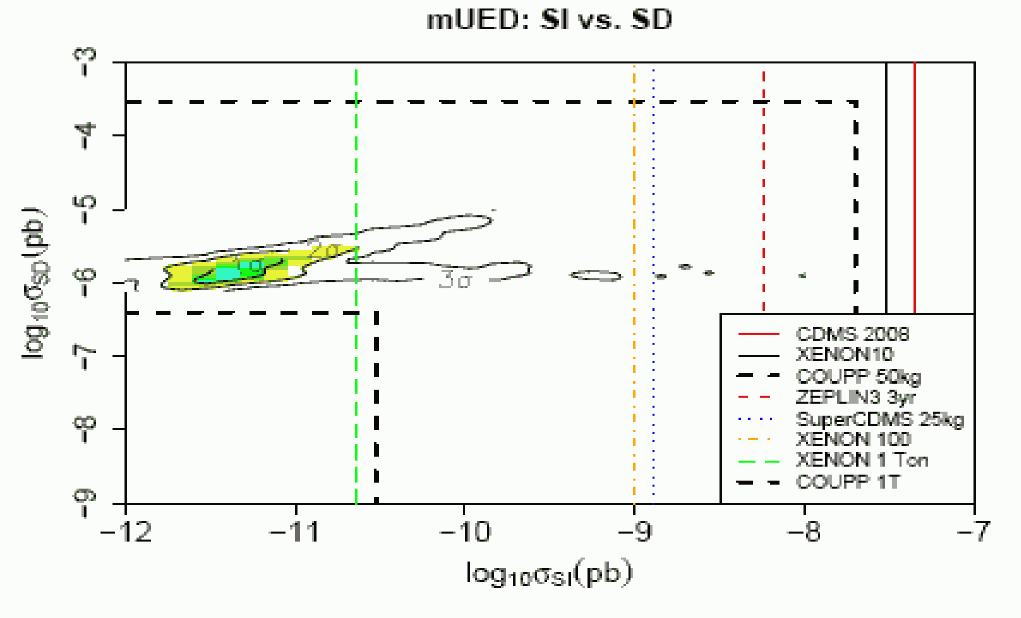


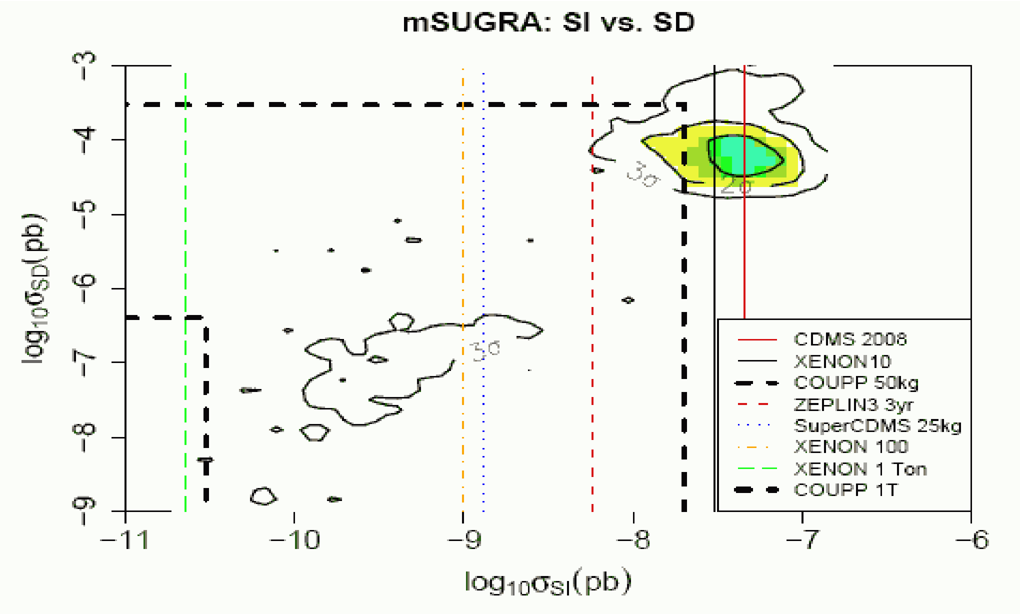


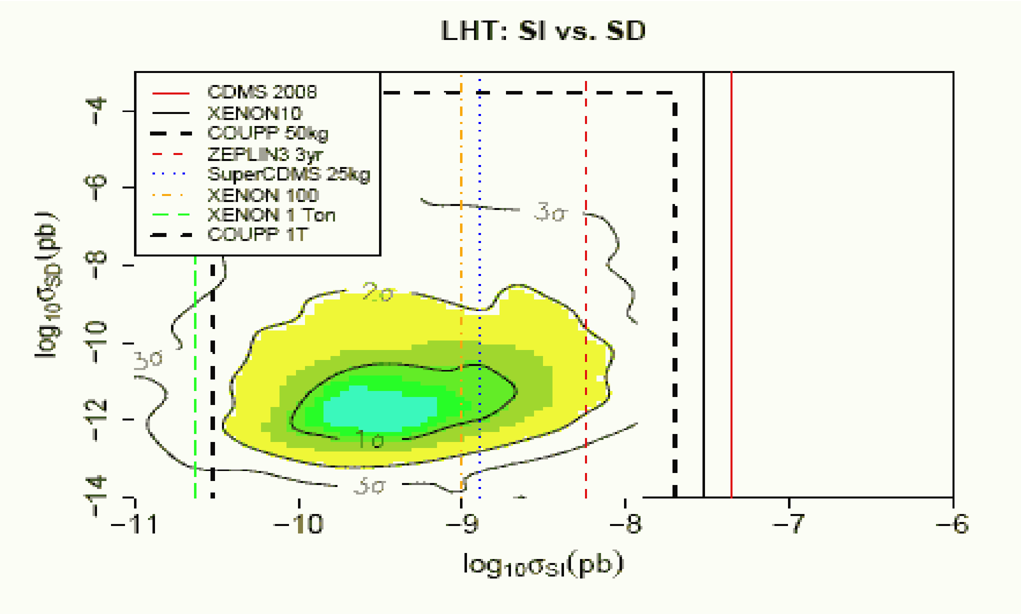
Distinguishing Dark Matter Models

Barger etal


WIMP-Proton σ_{SD} Versus σ_{SI}

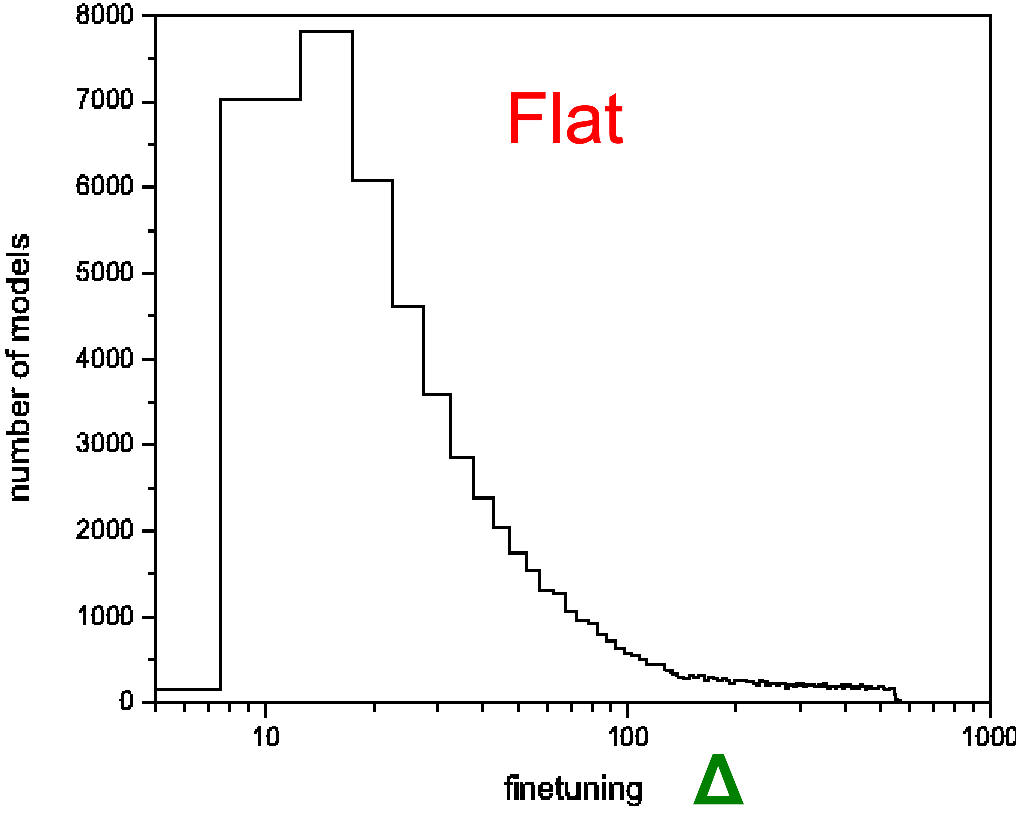

mUED: SI vs. SD

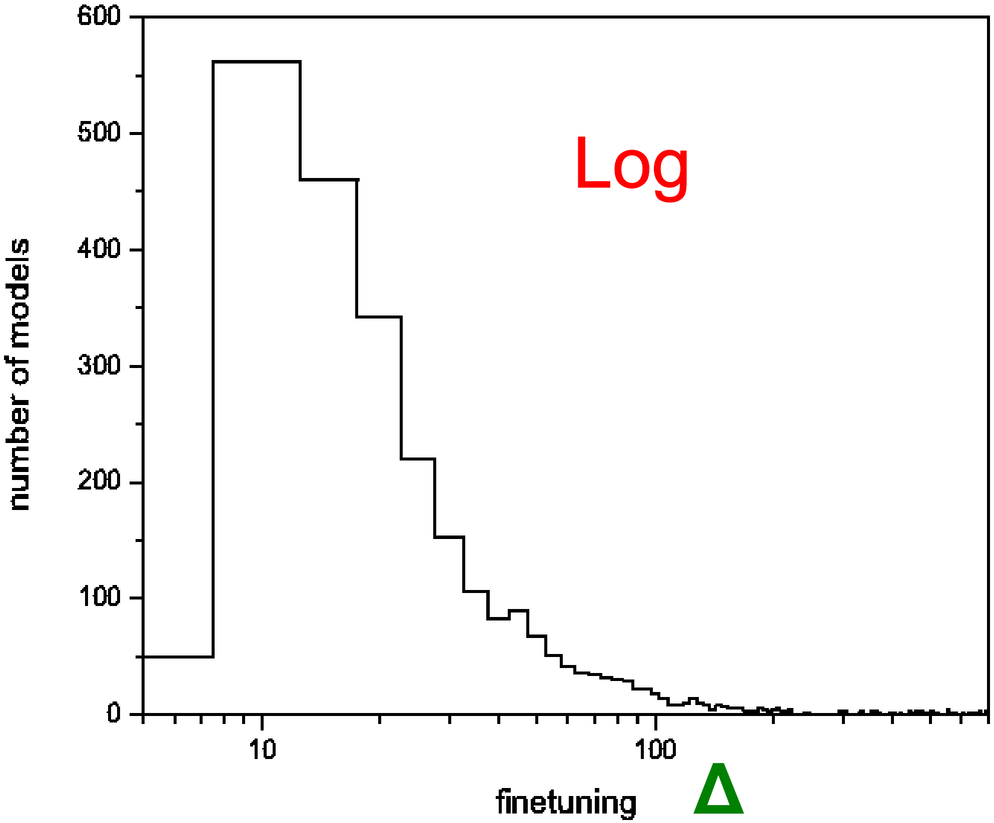

mSUGRA: SI vs. SD


LHT: SI vs. SD

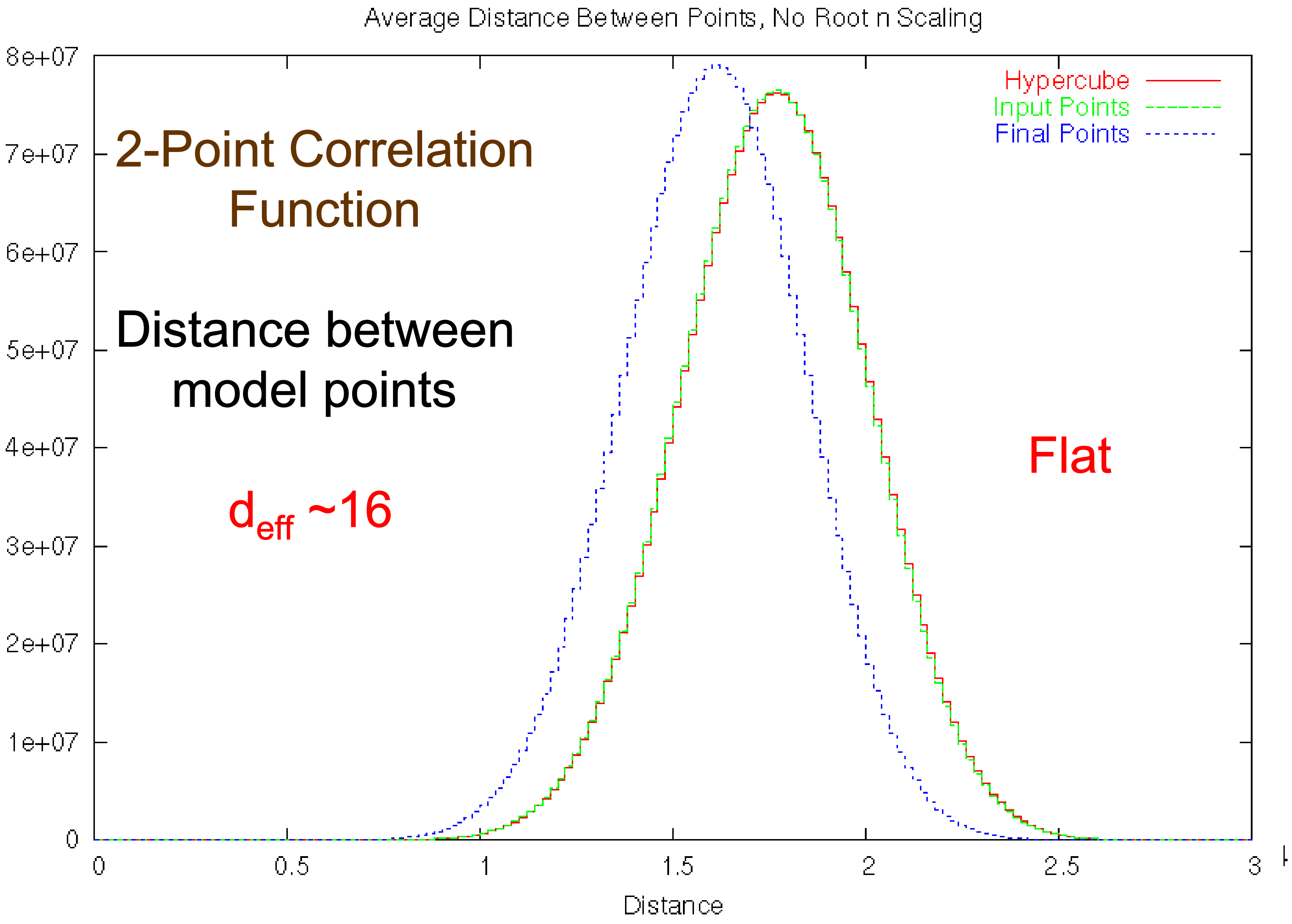
‘Fine-Tuning’ or Naturalness Criterion

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





Clustering of Model Points in 19-Dimensional Space



2-Point Correlation Function

Distance between model points

d_{eff} ~16

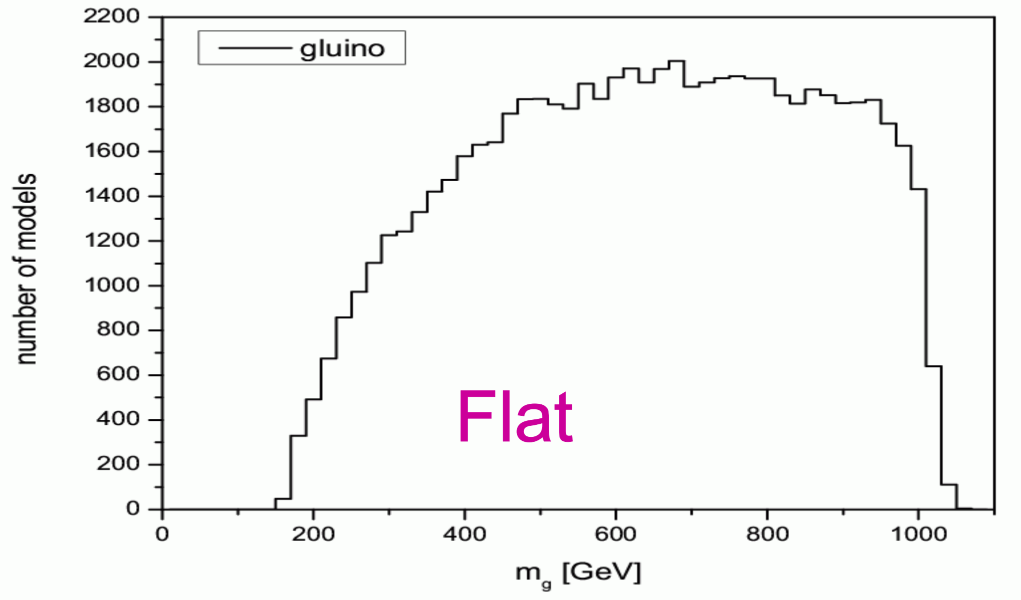
Flat

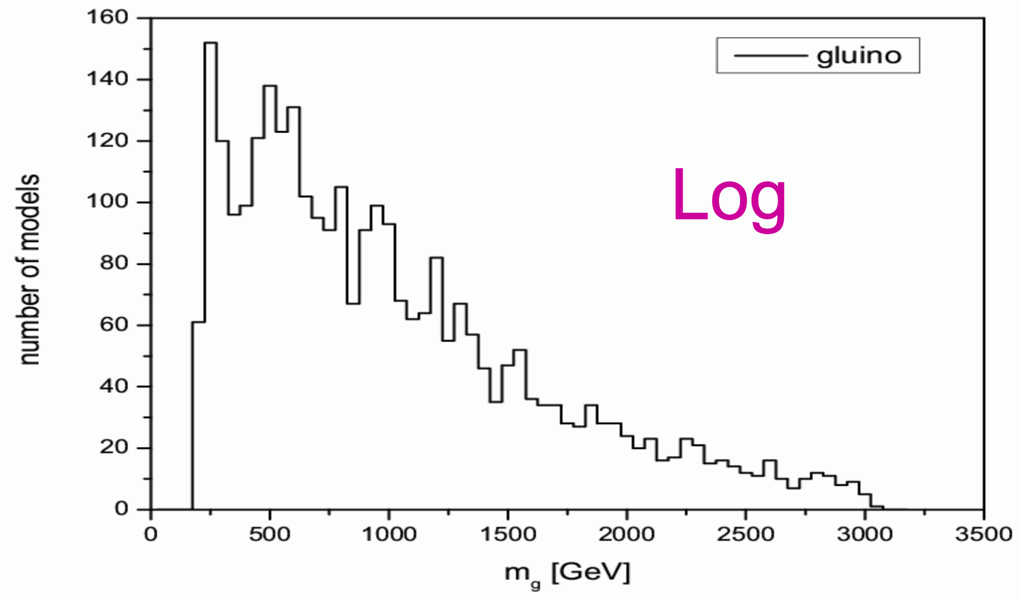
Summary

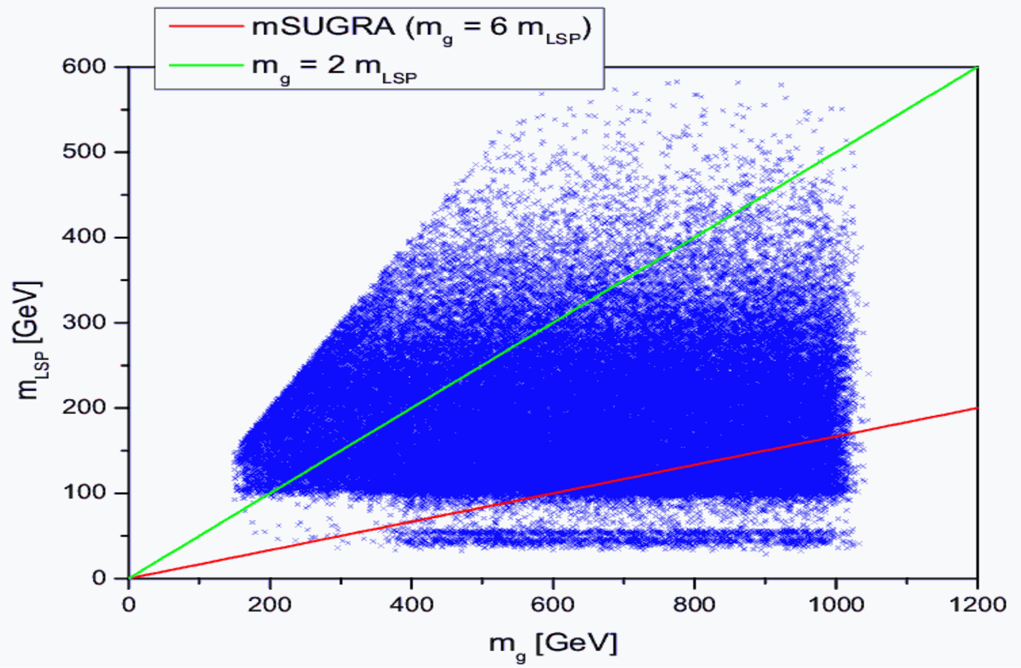
- The pMSSM has a far richer phenomenology than any of the conventional SUSY breaking scenarios. The sparticle properties can be vastly different, e.g., the nLSP can be almost any sparticle!
- Light partners may exist which have avoided LEP & Tevatron constraints and may be difficult to observe at the 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..

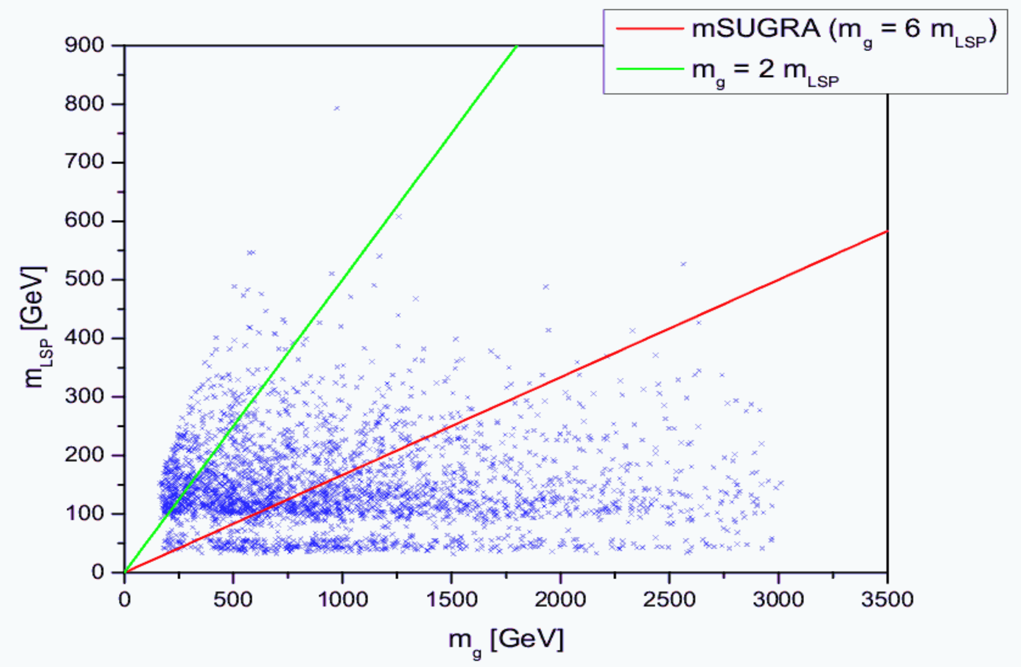
BACKUP SLIDES

Gluino Masses



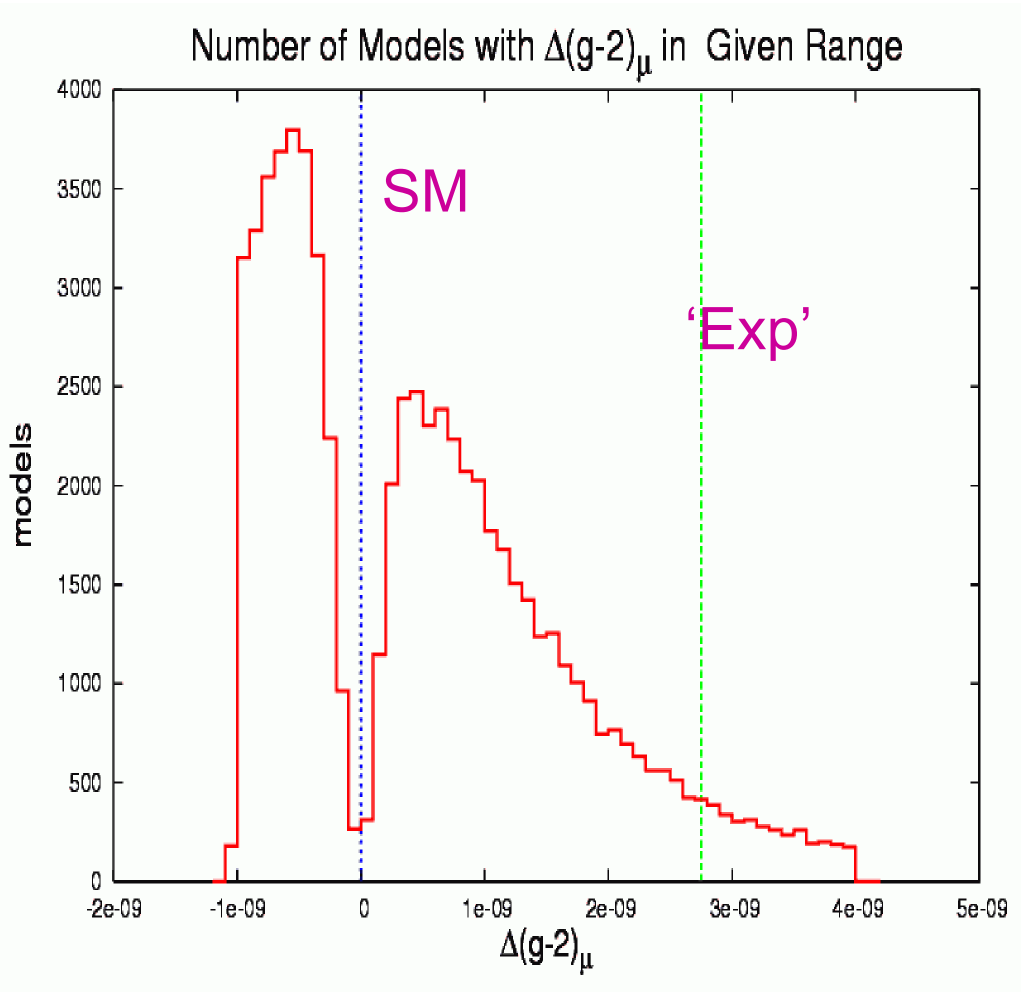




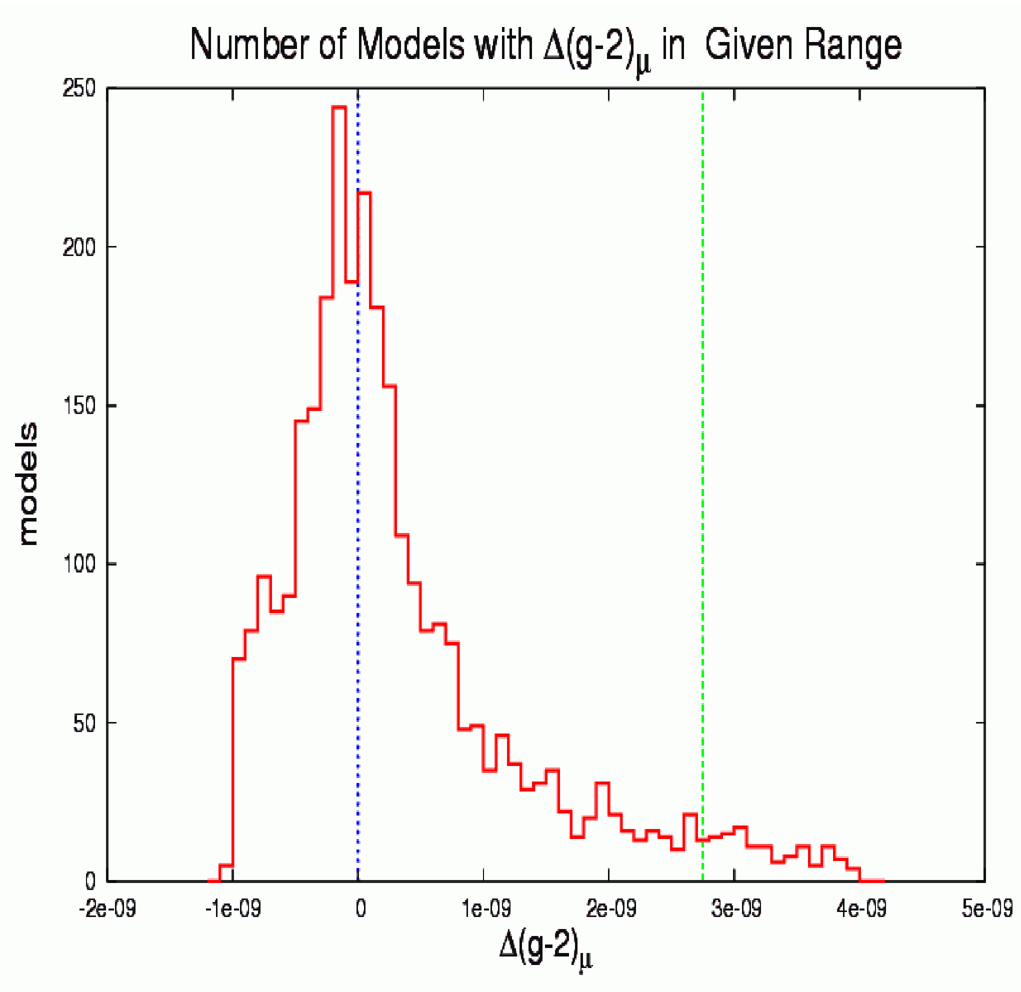


Predictions for $\Delta(g\text{-}2)_\mu$

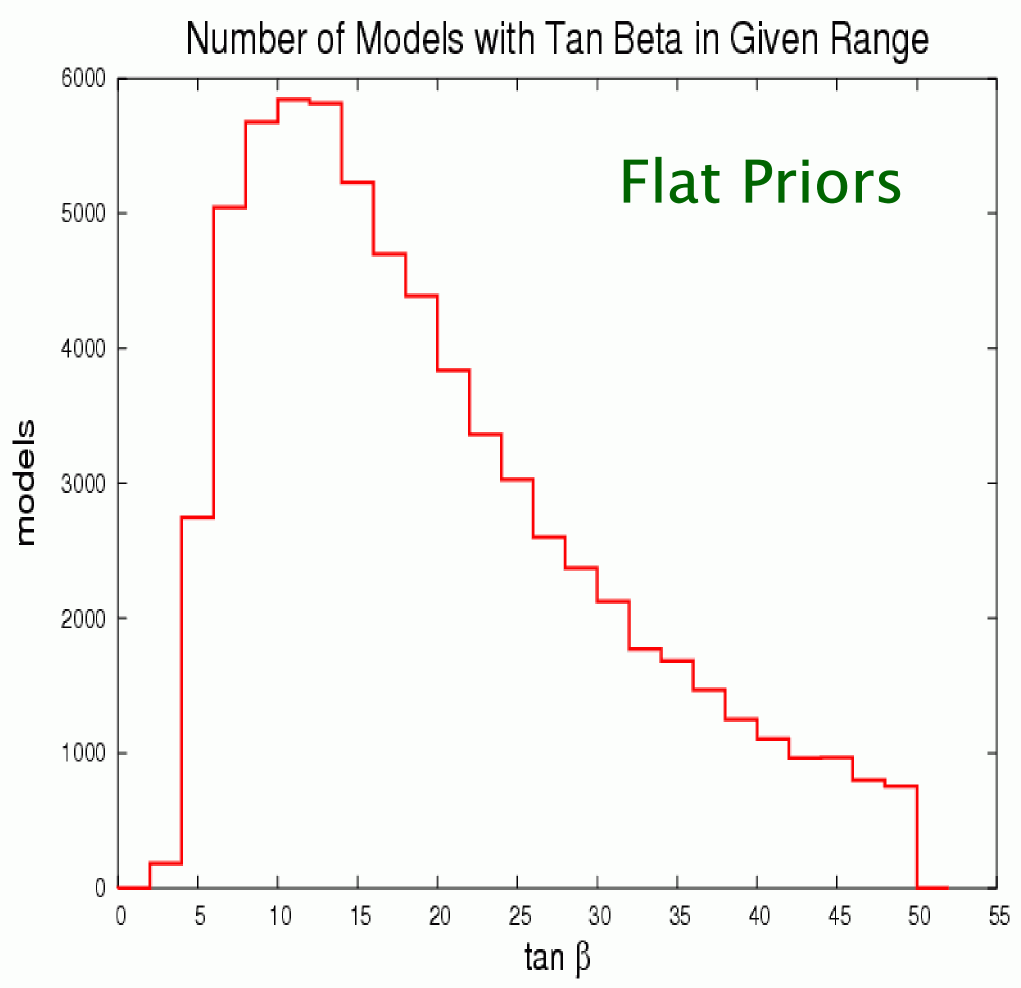
flat

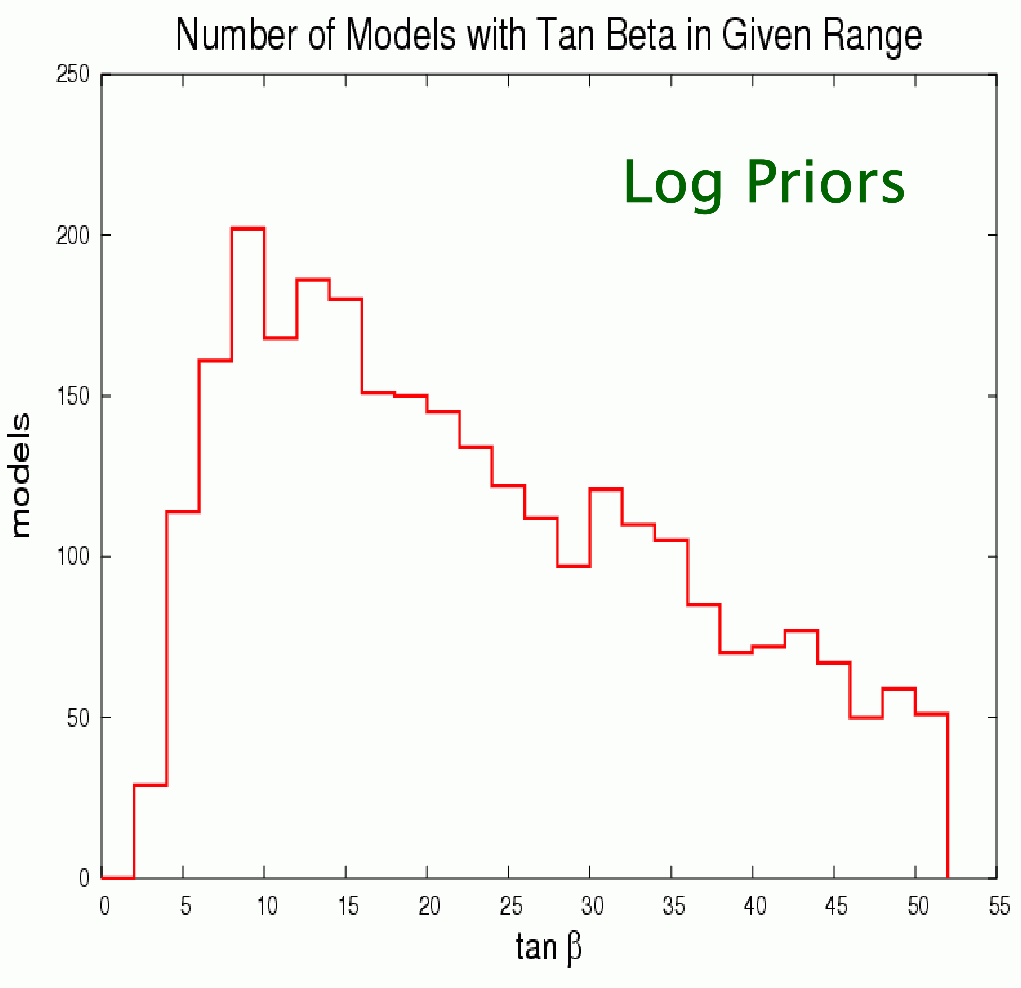


log



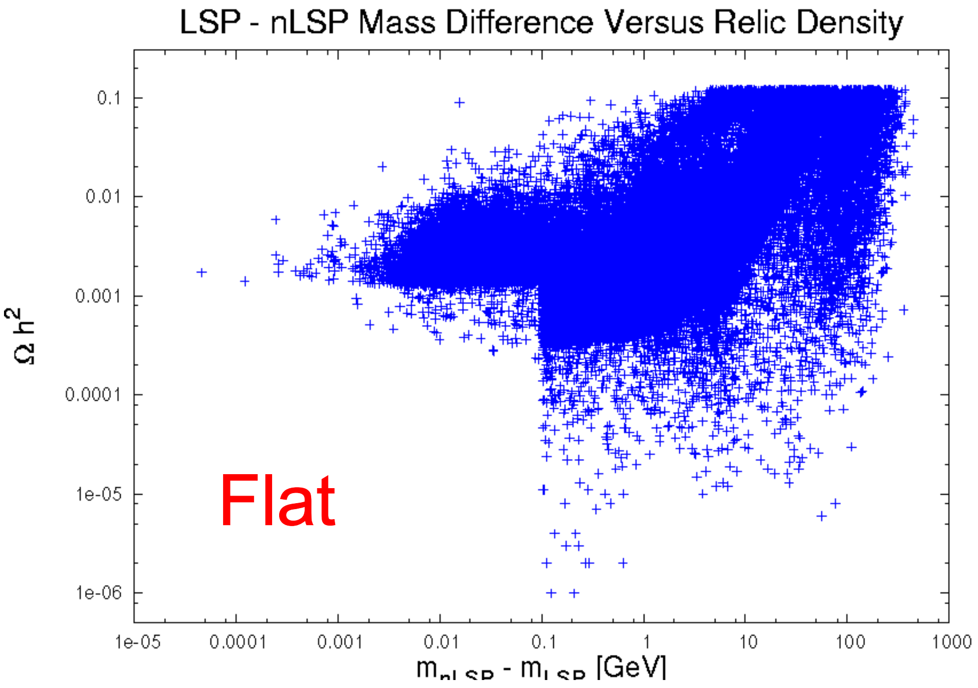
Distribution for tan beta

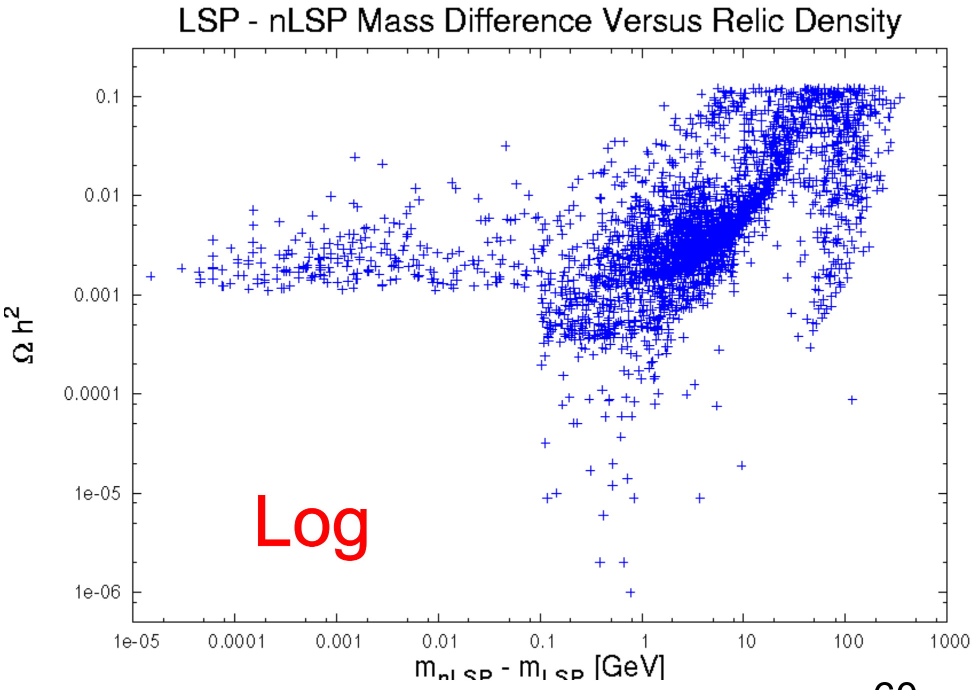




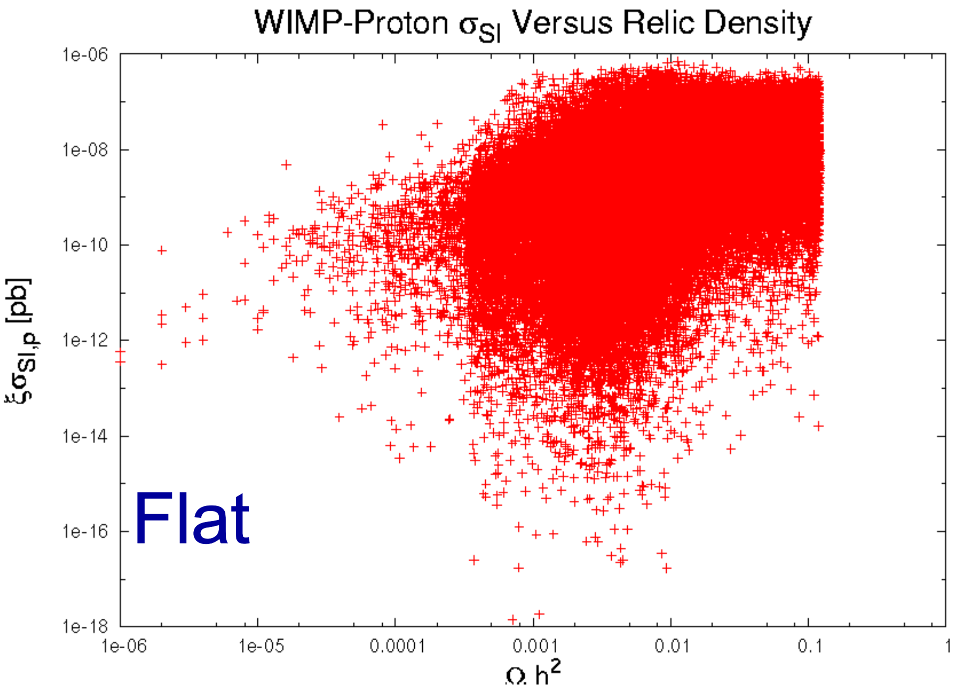
Correlation Between Dark Matter Density & the LSP-nLSP Mass Splitting

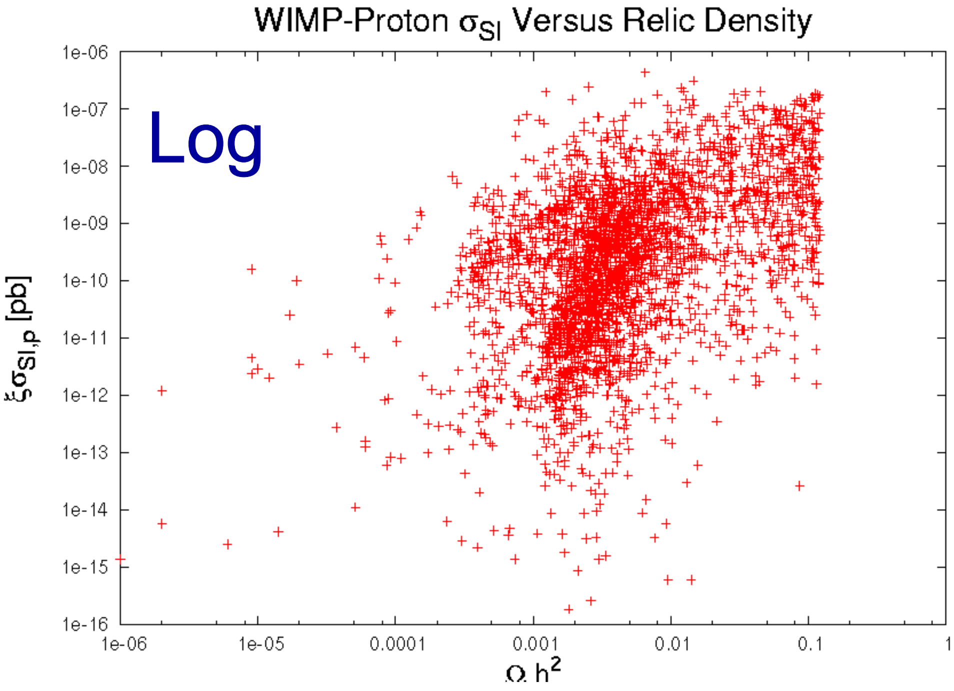
Small mass differences can lead to rapid co-annihilations reducing the dark matter density….





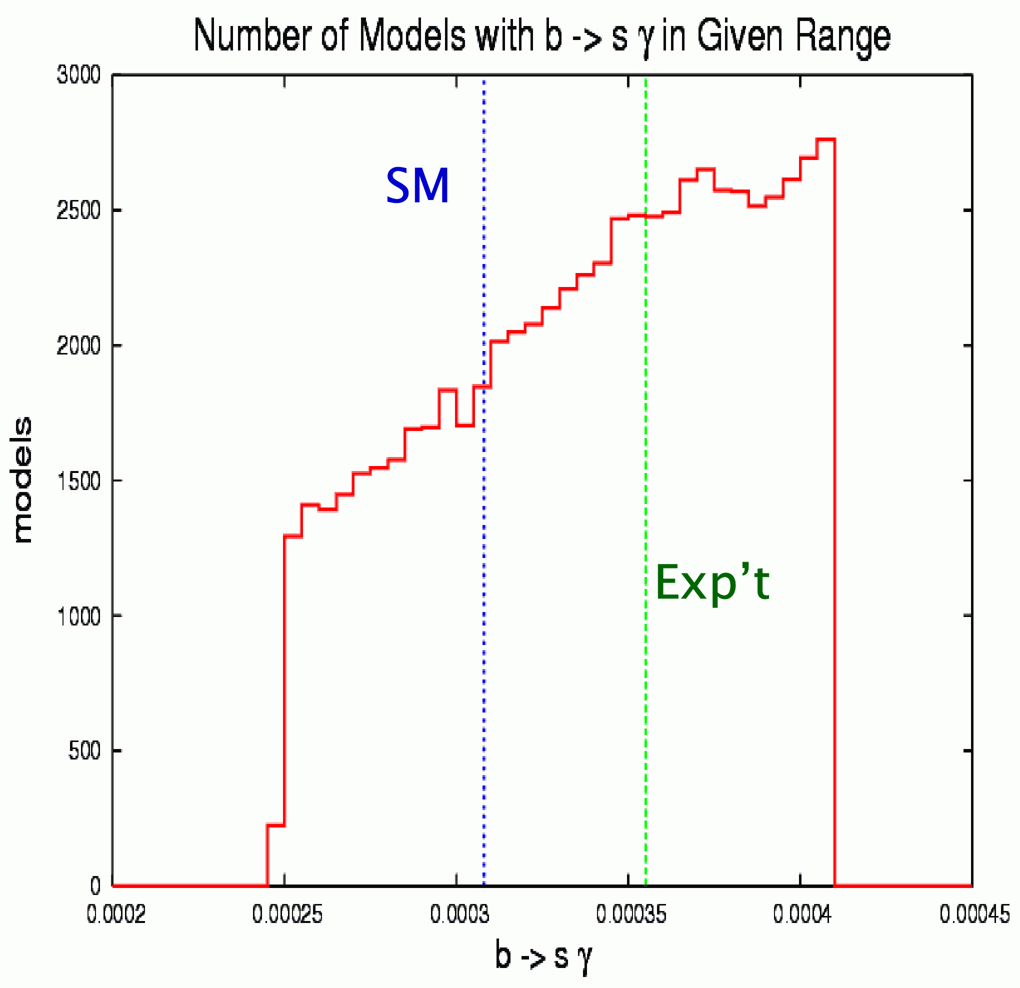
Dark Matter Density Correlation with the Direct Search Cross Section



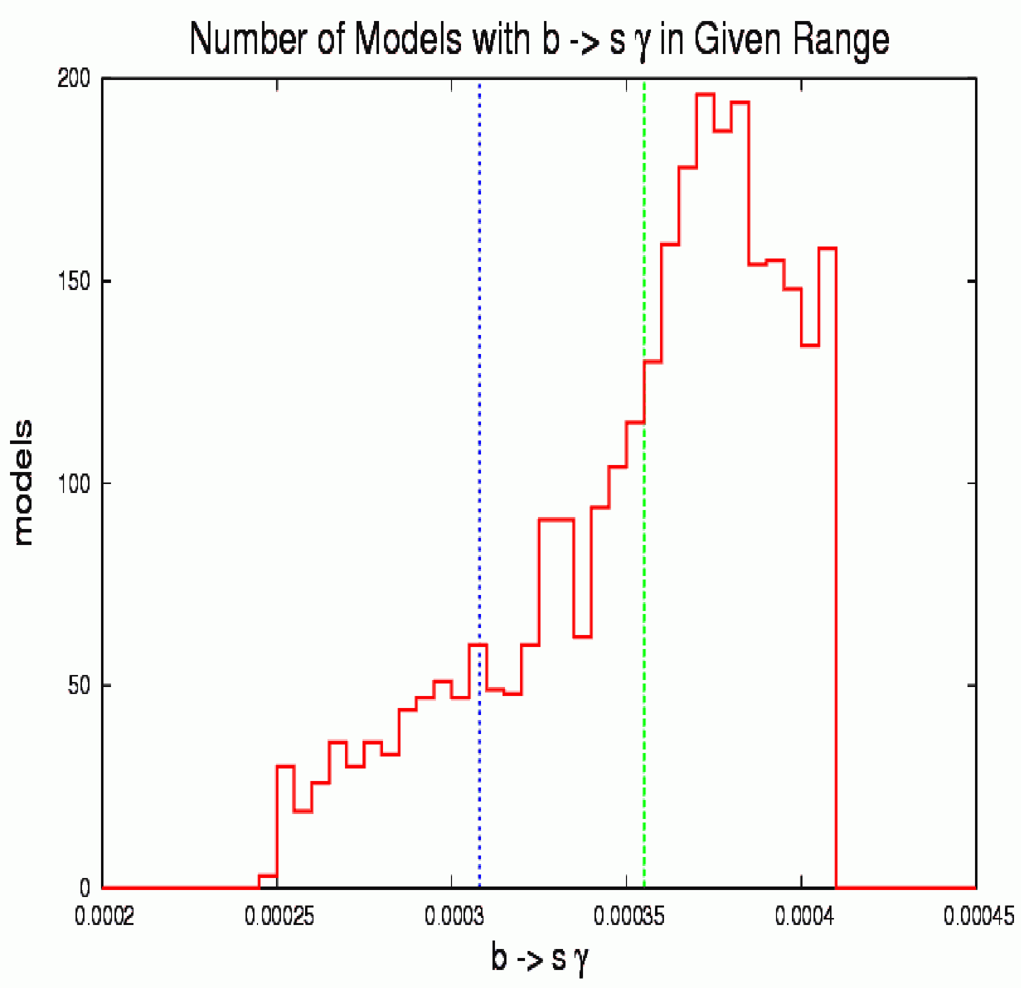


Predictions for b→sγ

Flat Priors

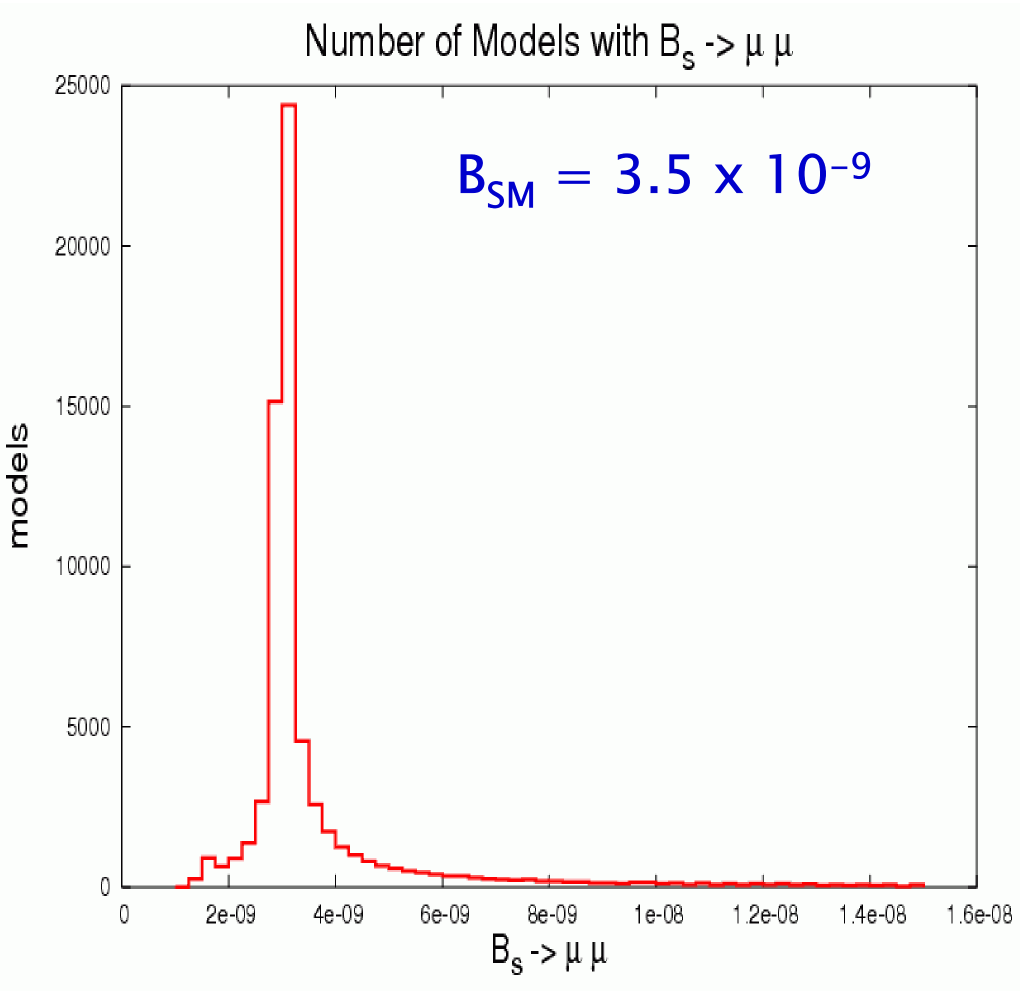


Log Priors



Predictions for $B_s \rightarrow \mu\mu$

Flat Priors



$B_{SM} = 3.5 \times 10^{-9}$

Log Priors