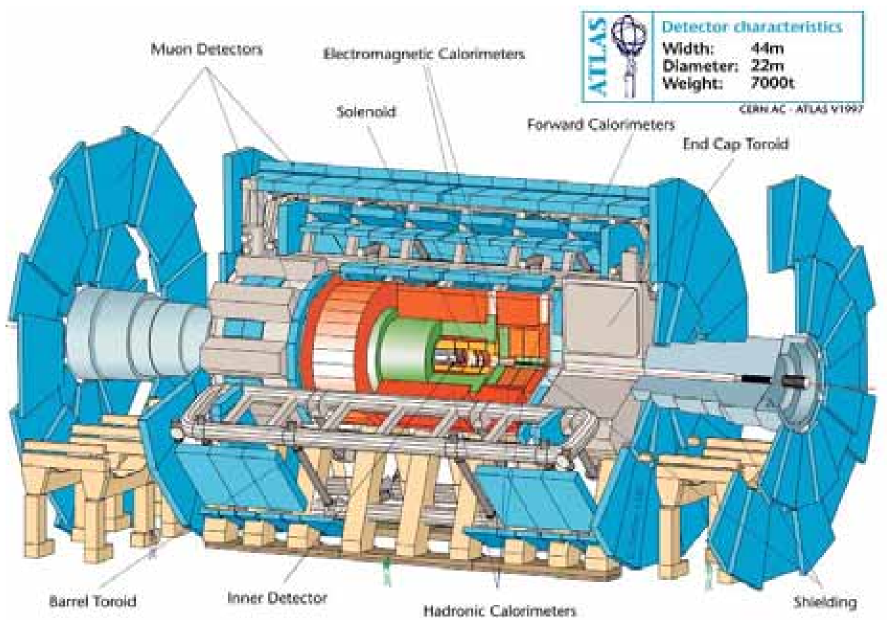
General SUSY Study: Beyond CMSSM/mSUGRA



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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 specifics of 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

How? Perform 2 Random Scans

Linear Priors

10^7 points – emphasize moderate masses

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

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

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

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

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

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

Log Priors

$2\text{x}10^6$ points – emphasize lower masses but extend to higher masses too

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

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

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

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

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

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

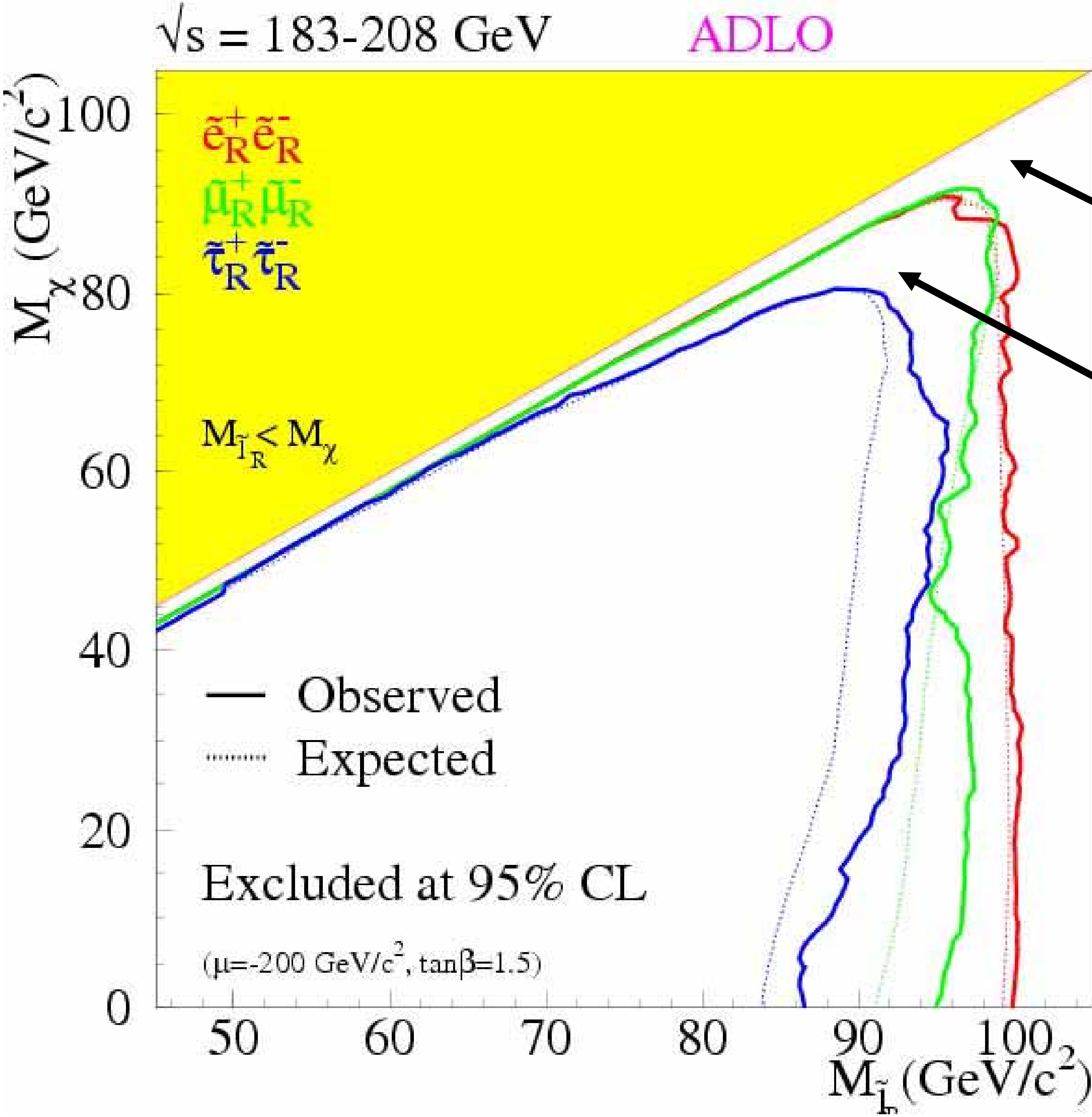
→Comparison of these two scans will show the prior sensitivity.

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

Constraints

- $\Delta\rho$
- $b \to s\ \gamma$
- $B \to \tau\nu$
- $B_S \to \mu\mu$
- $\Delta(g-2)_\mu$??? → (-10 to 40) x 10^{-10} to be conservative..
- $\Gamma(Z \to$ invisible)
- Meson-Antimeson mixing
- CDMS, XENON10, DAMA, CRESST-I.. Direct DM Searches
- Dark Matter density: $\Omega h^2 < 0.121$ → 5yr WMAP data
- LEP and Tevatron Direct Higgs & SUSY searches

RH Sleptons



Note the holes where the leptons are too soft…

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

Tevatron Constraints : I Squark & Gluino Search

- This is the first SUSY analysis to include these constraints

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

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

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

[a]First and second jets are also required to be central ($|\eta_{det}| < 0.8$), 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 an 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)	$\epsilon_{sig.}$ (%)	$N_{obs.}$	$N_{backgrd.}$	$N_{sig.}$	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.)

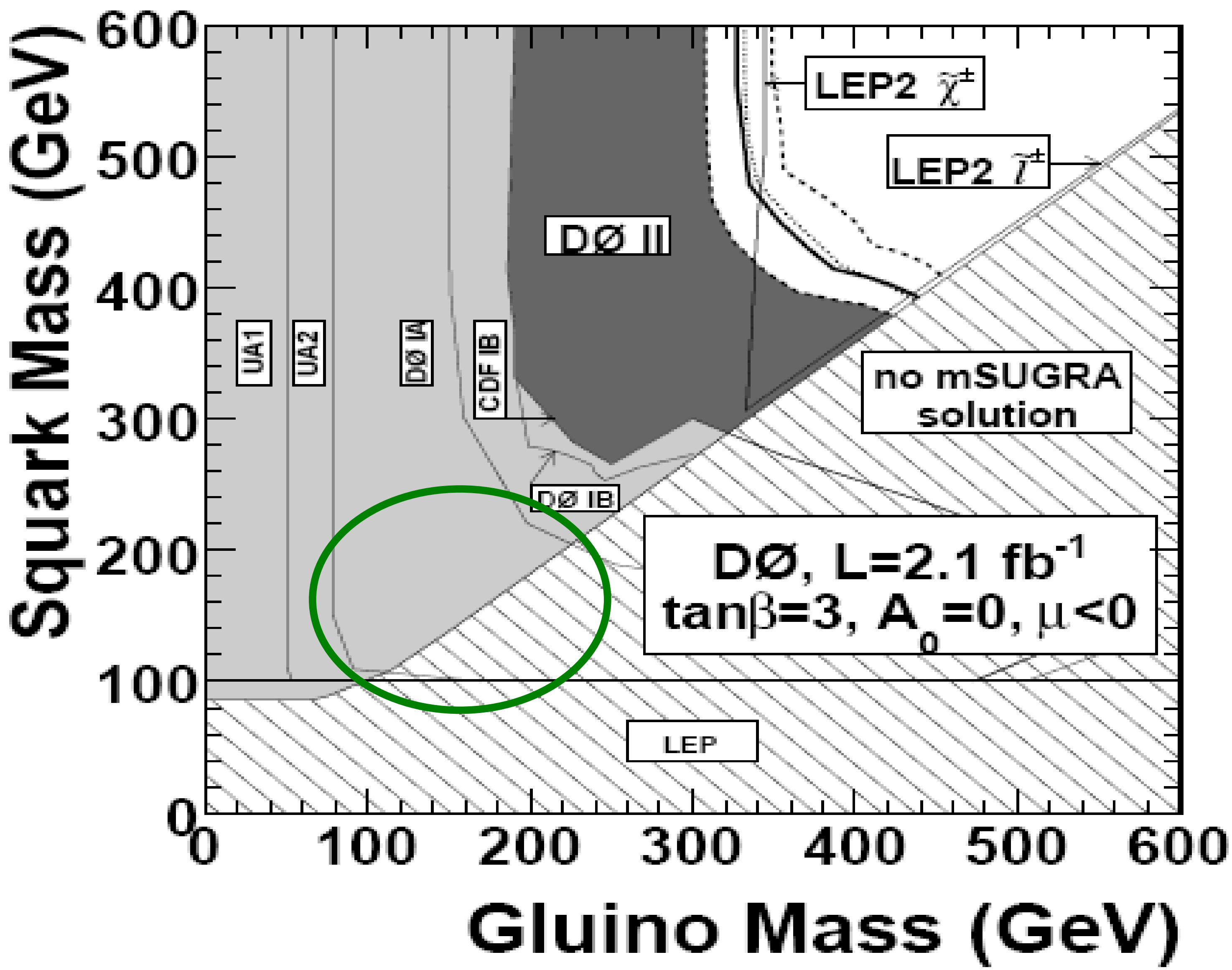
Combos of the 3 analyses

→ 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 !

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

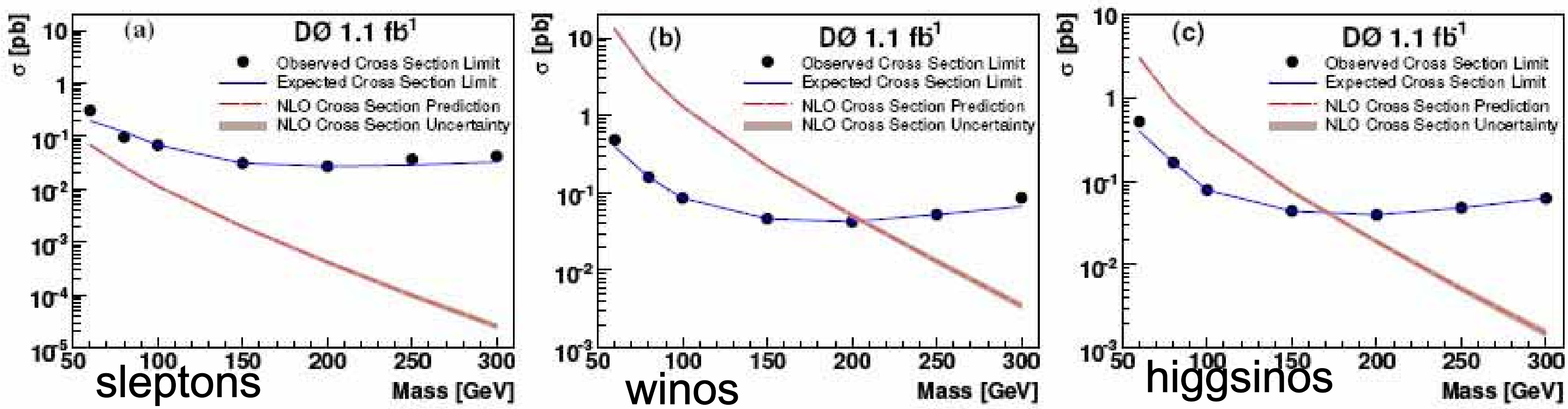


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos,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

Survival Rates

- Flat Priors :

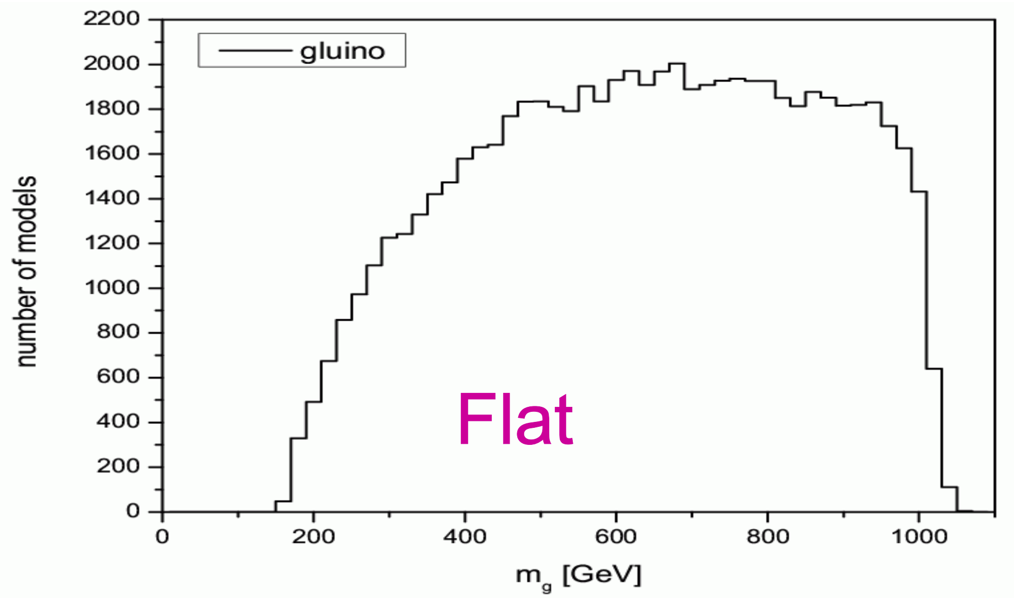
  - 10^7 models scanned
  - 68.5 K (0.68%) survive

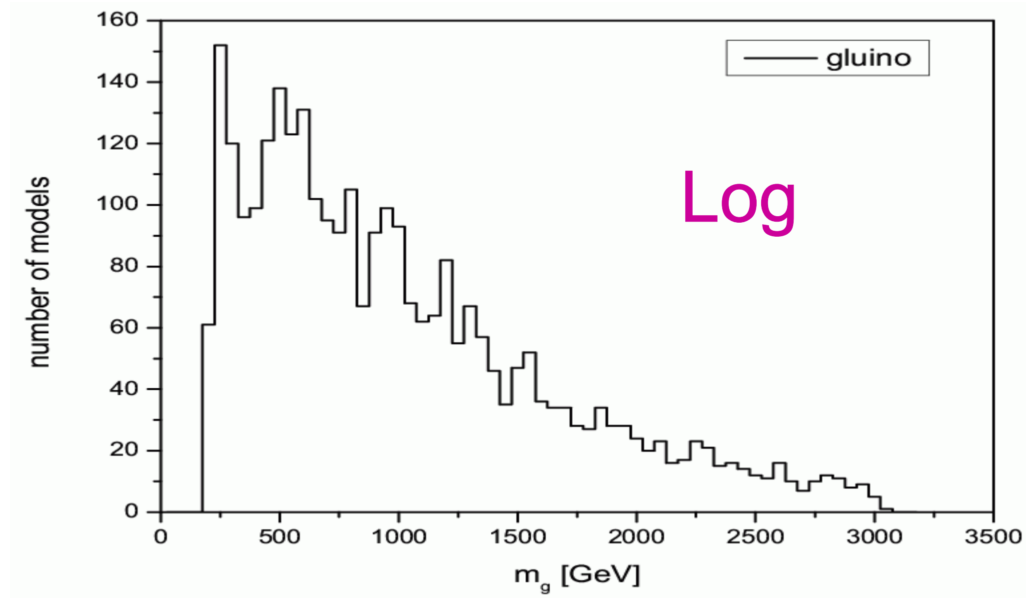
- Log Priors :

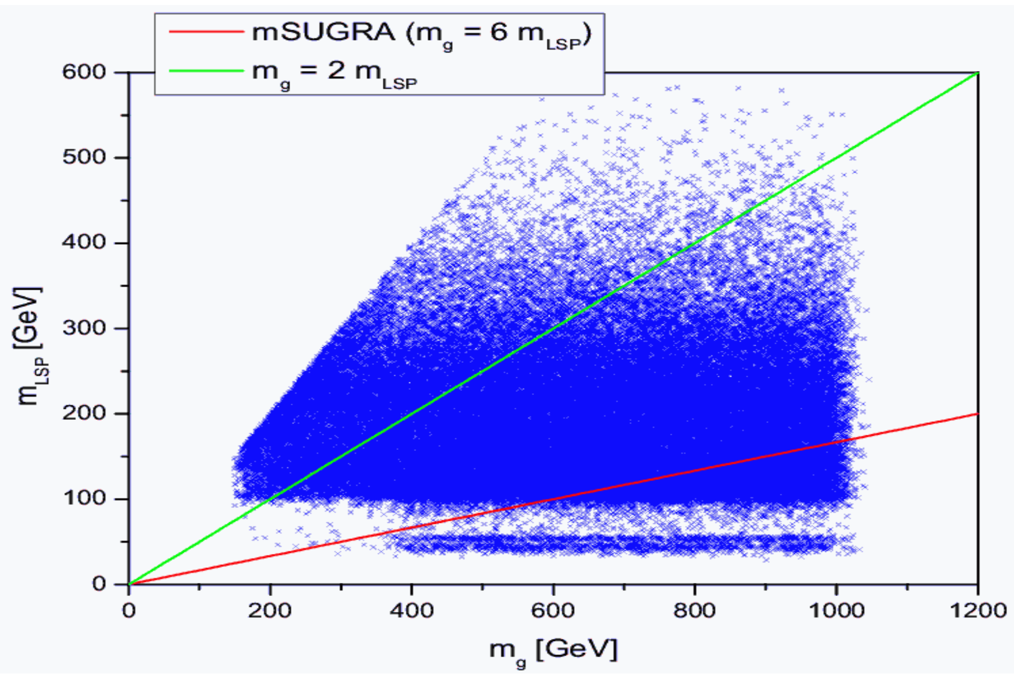
  - $2x10^6$ models scanned
  - 3.0 K (0.15%) survive

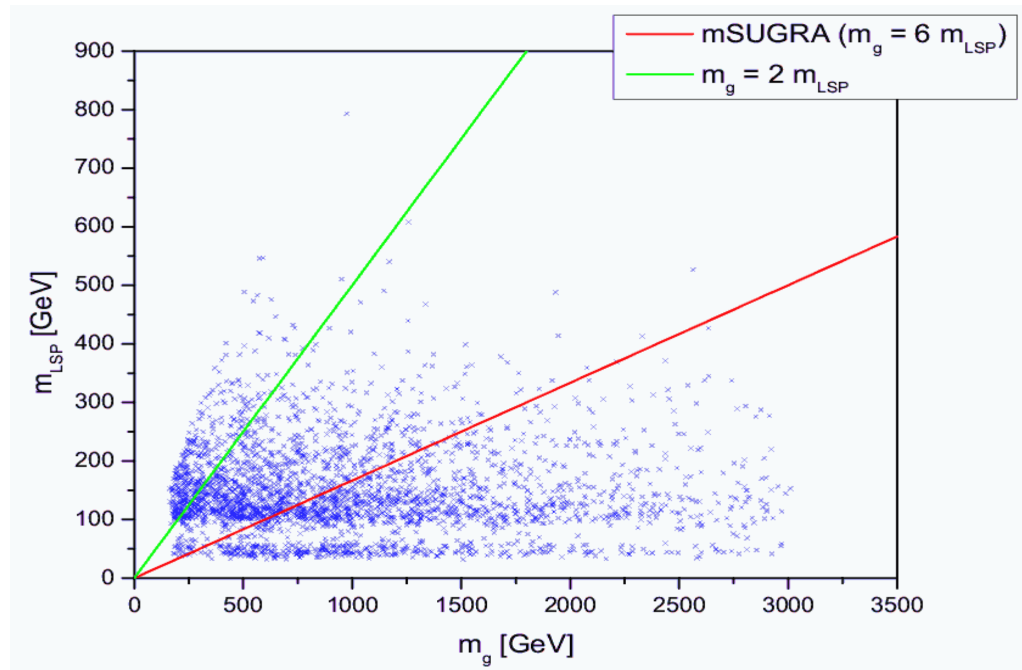
9999039	slha-okay.txt
7729165	error-okay.txt
3270330	lsp-okay.txt
3261059	deltaRho-okay.txt
2168599	gMinus2-okay.txt
617413	b2sGamma-okay.txt
594803	Bs2MuMu-okay.txt
592195	vacuum-okay.txt
582787	Bu2TauNu-okay.txt
471786	LEP-sparticle-okay.txt
471455	invisibleWidth-okay.txt
468539	susyhitProb-okay.txt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

Gluinos Can Be Light !

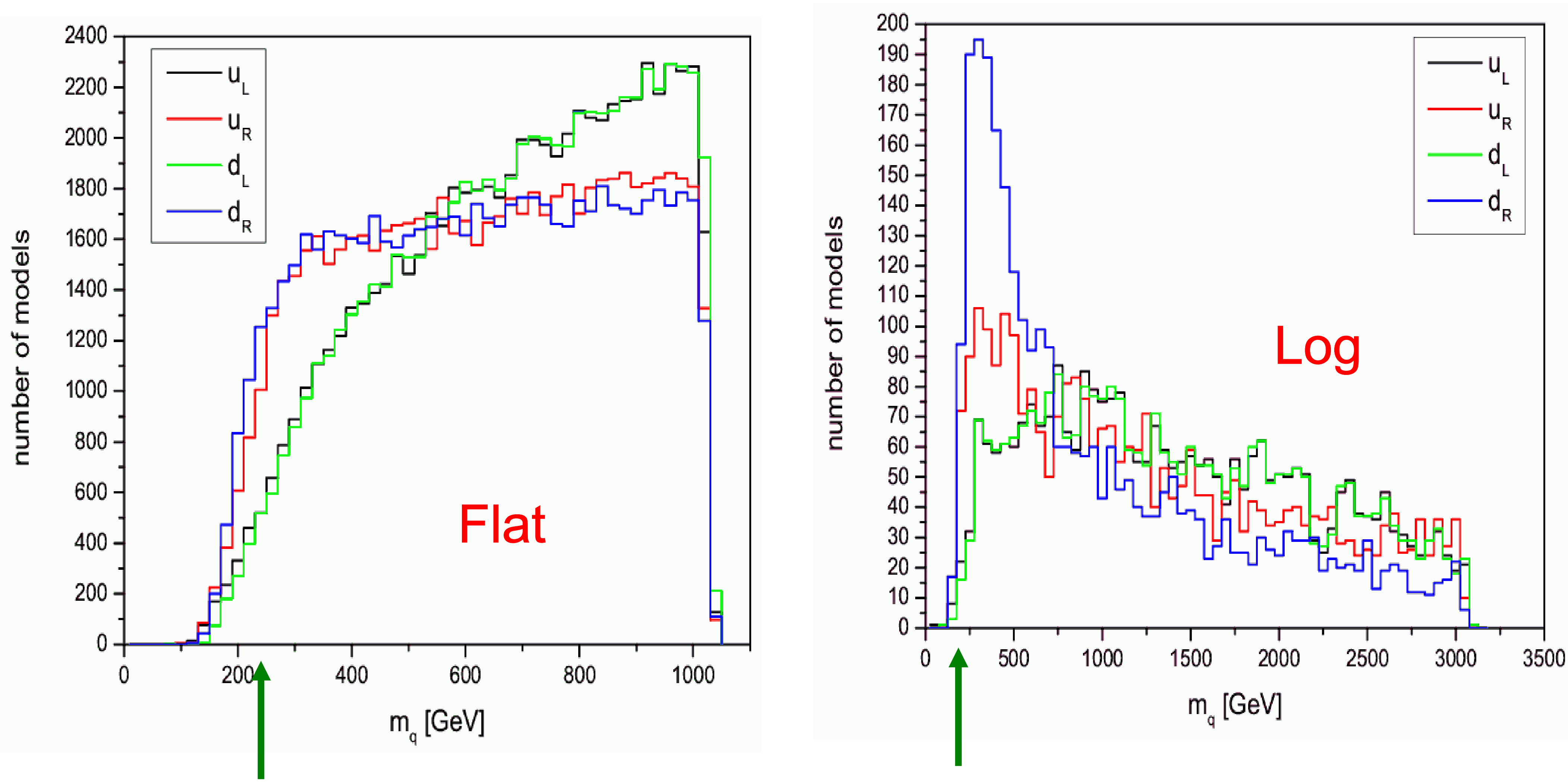






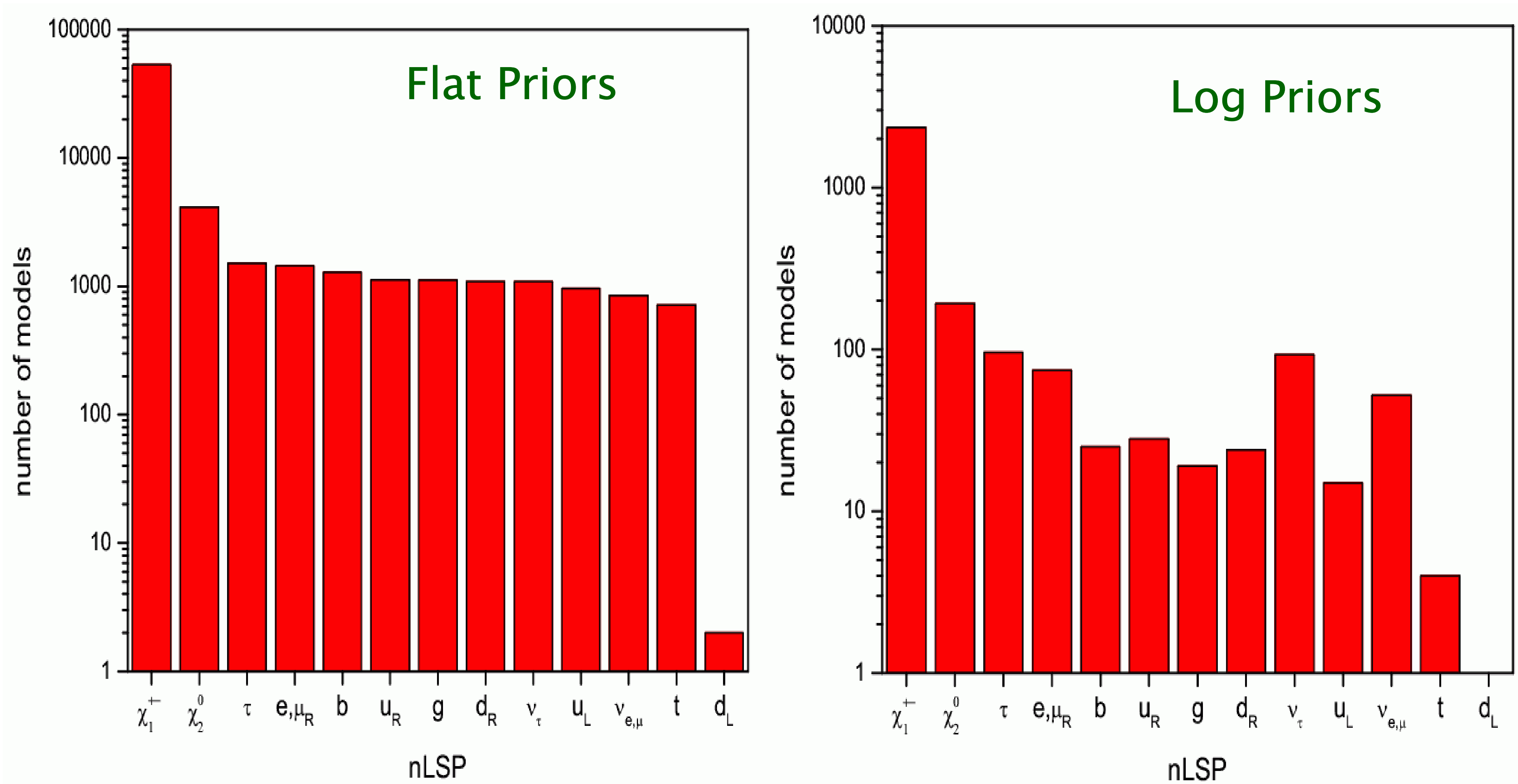


Squarks Can Be Light !!!

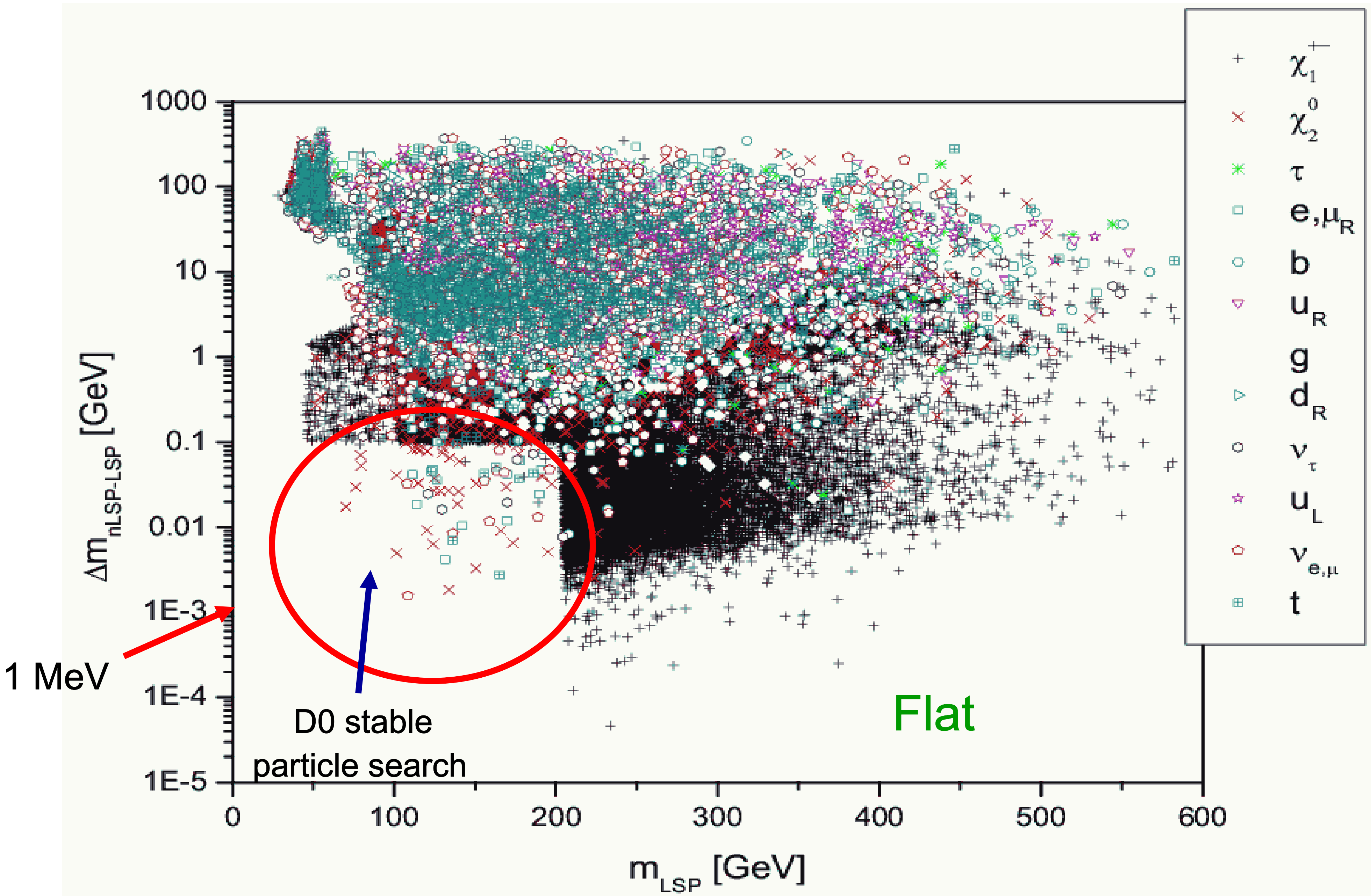


Many models survive due to the high jet E_T & MET cuts for gluinos/squarks close in mass to the LSP

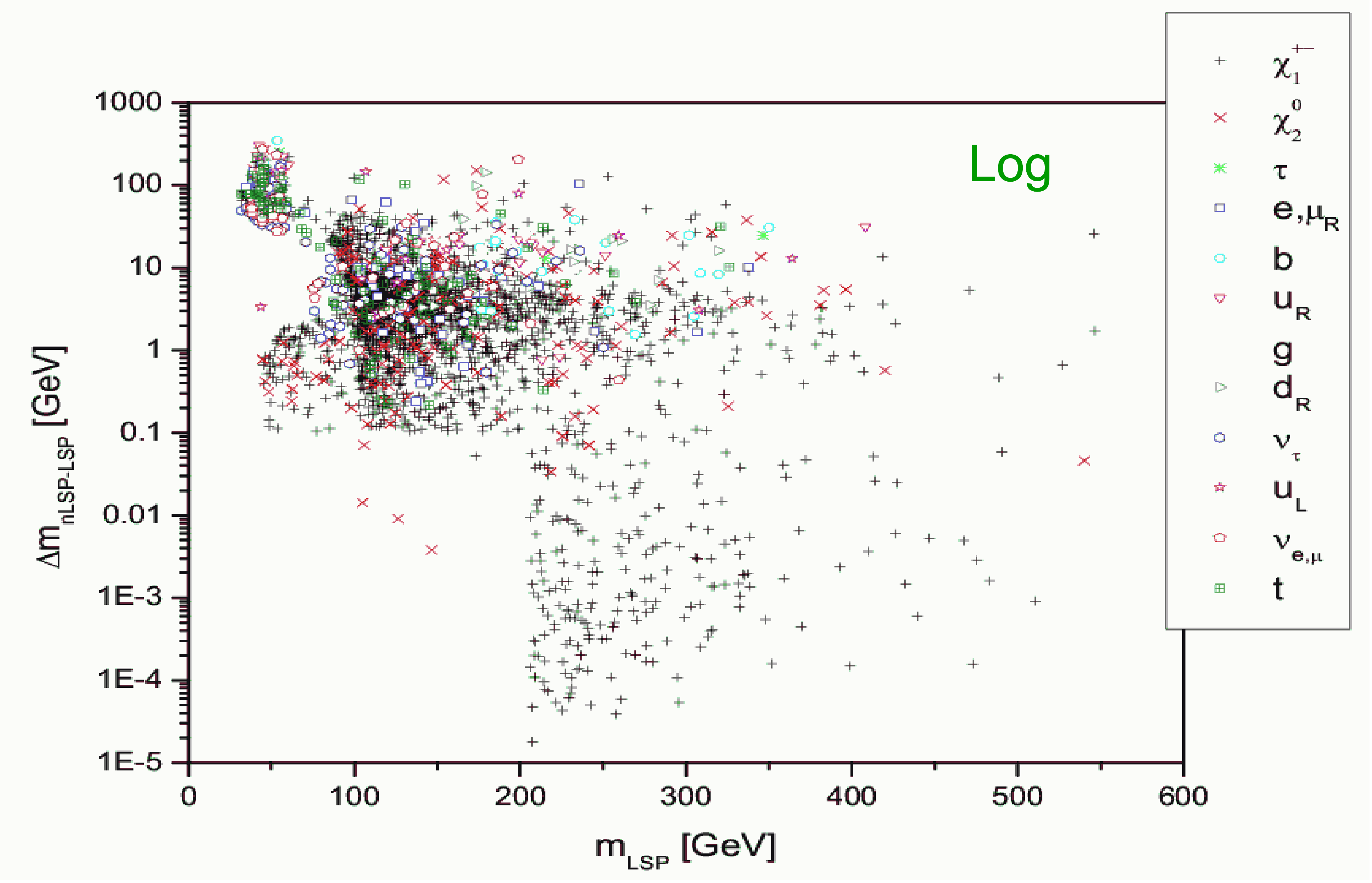
The identity of the nLSP is a critical factor in looking for SUSY signatures..who can play that role here????? Just about ANYBODY !!!

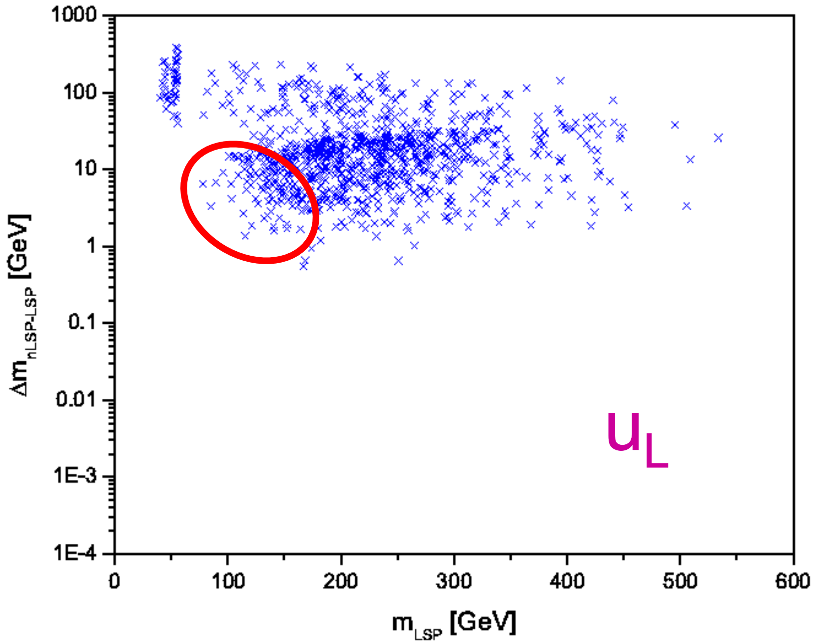


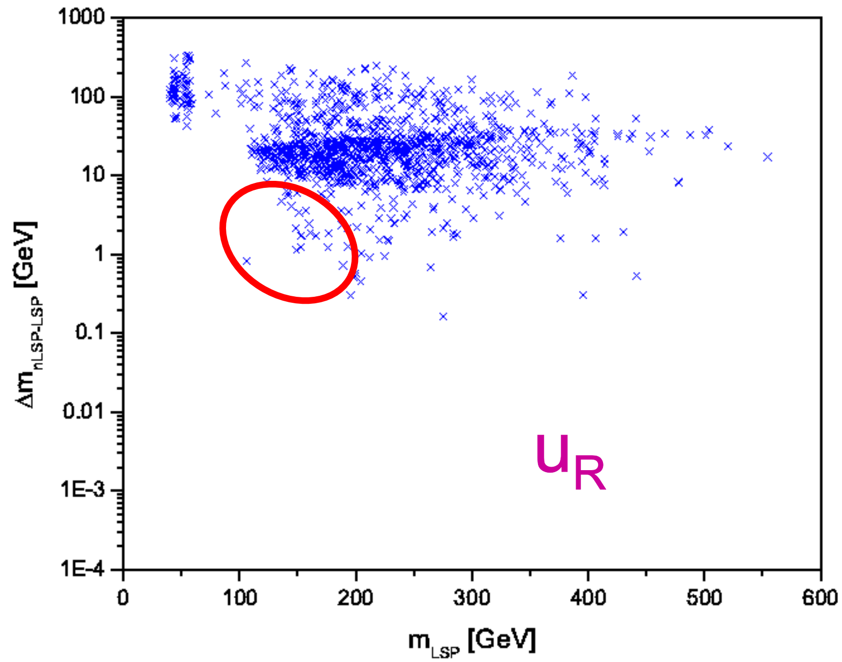
nLSP-LSP Mass Difference



nLSP-LSP Mass Difference




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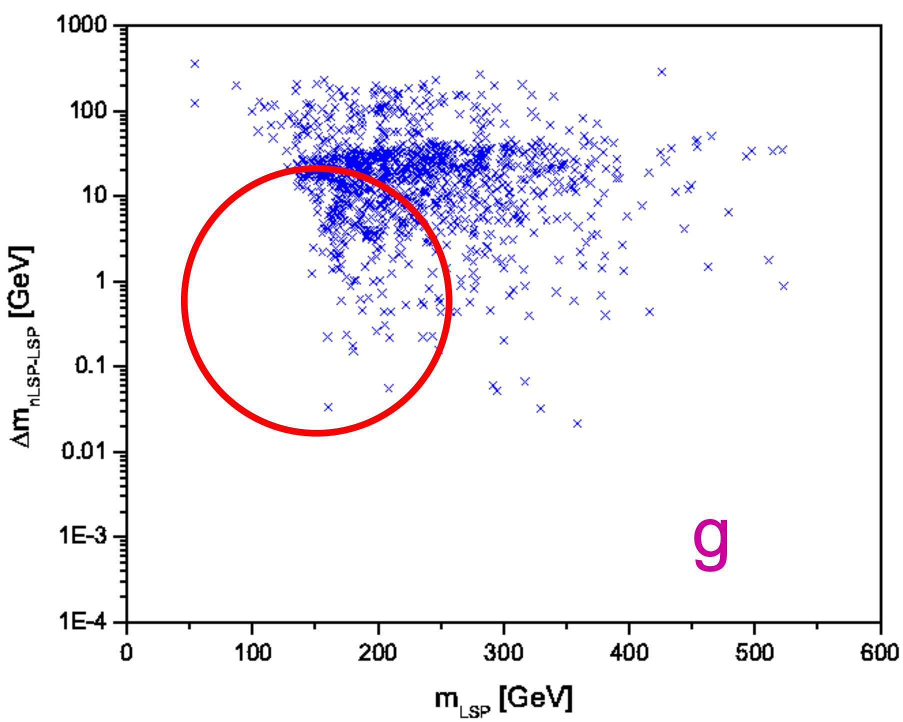
0.1
0.01
1E-3
1E-4
$\Delta m_{nLSP-LSP}$ [GeV]
0
100
200
300
400
500
600
m_{LSP} [GeV]
u_R


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]
g

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!!

Cascade Failure: Typical Analyses May Require Changes

$$\tilde{g} \rightarrow q'\bar{q}\tilde{\chi}_1^{\pm}, \quad \tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0 \rightarrow l^{\pm}\nu\tilde{\chi}_1^0$$

This is a typical mSUGRA cascade leading to 2l+4j+MET from gluino pair production. But in many of our models the W will be far off-shell & the resulting lepton will be too soft. This will then appear as 4j+MET unless the chargino is long-lived in which case we observe 4j +2 long-lived charged particles with no MET.

Something similar happens when the 2^{nd} neutralino is close in mass to the LSP as the 2^{nd} neutralino decay products may all be missed since they can be very soft; this looks like 4j+MET

$$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0, \quad \tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0 \rightarrow l^+l^-\nu\tilde{\chi}_1^0$$

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! Results are ~prior-independent.
- 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
- Things to keep in mind for LHC analyses
  - MSSM ≠ mSUGRA: a more general analysis is required
  - Stable charged particle searches are very important
  - Many models can lead to soft particles + MET; the mono-jet search is important
- A more detailed LHC study using the ATLAS ‘book’ SUSY study is now underway

BACKUP

ATLAS: SU1, SU2, SU3, SU4, SU8

CMS: LM1–LM10, HM2, HM3, HM4

SU1	OK
SU2	killed by LEP
SU3	killed by Ωh^2
SU4	killed by $b \to s\gamma$
SU8	killed by g-2
LM1	killed by Higgs
LM2	killed by g-2
LM3	killed by $b \to s\gamma$
LM4	killed by Ωh^2
LM5	killed by Ωh^2
LM6	OK
LM7	killed by LEP
LM8	killed by Ωh^2
LM9	killed by LEP
LM10	OK
HM2	killed by Ωh^2
HM3	killed by Ωh^2
HM4	killed by Ωh^2

For the curious:

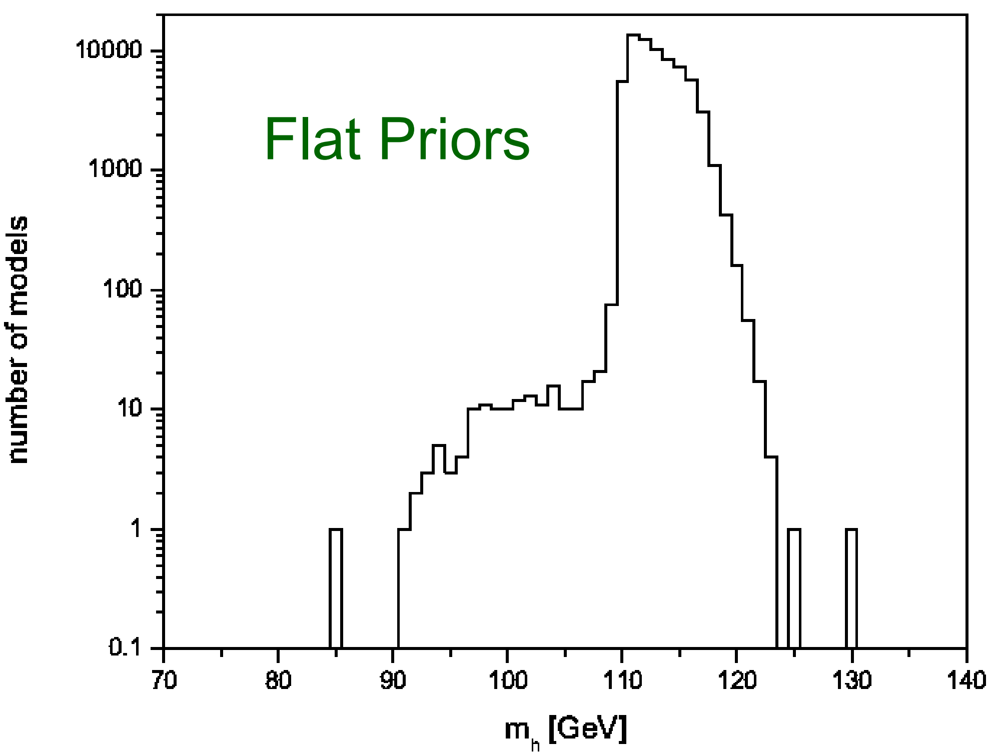
Most well-studied models do not survive confrontation with the latest data.

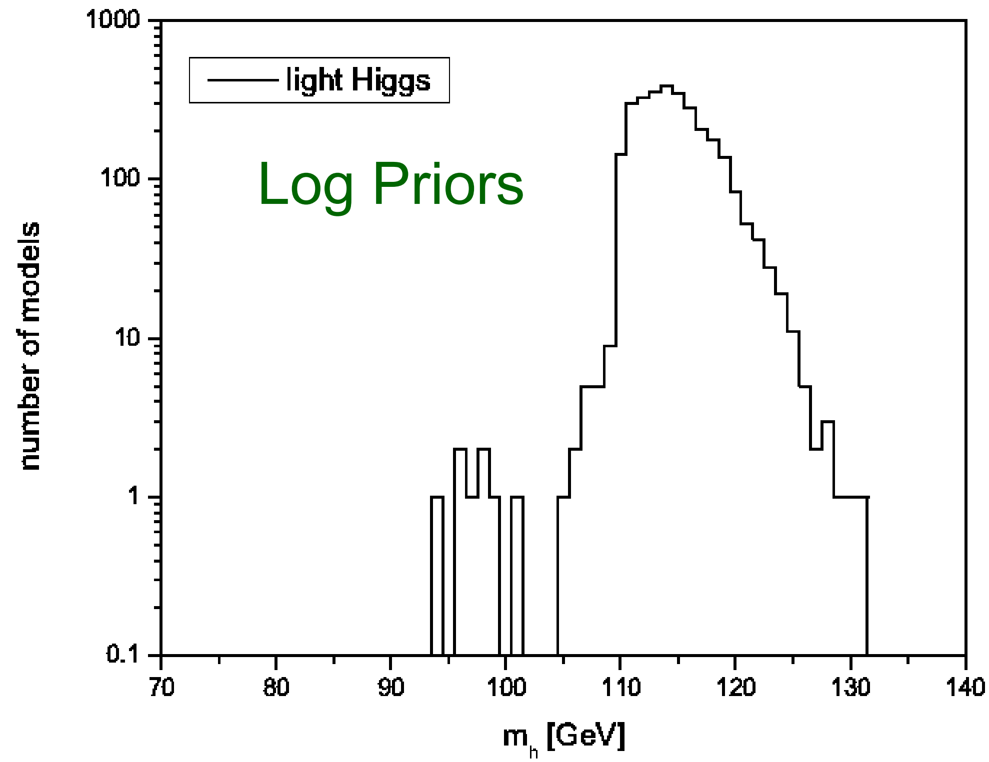
For many models this is not the unique source of failure

Similarly for the SPS Points

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

Light Higgs Mass Predictions



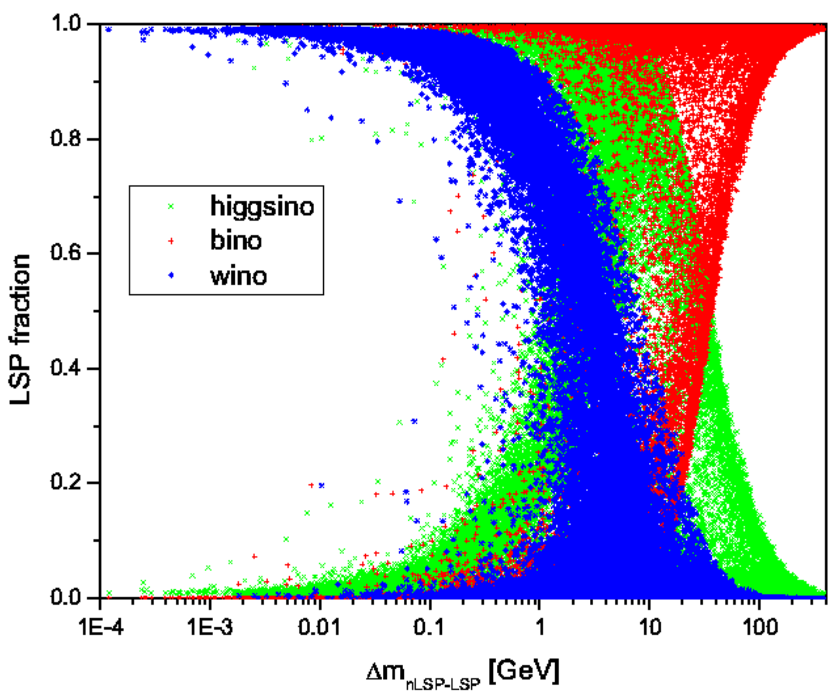


LEP Higgs mass constraints avoided by either reducing the ZZh coupling and/or reducing the, e.g., $h \rightarrow \bar{b}b$ branching fraction by decays to LSP pairs. We have both of these cases in our final model sets.

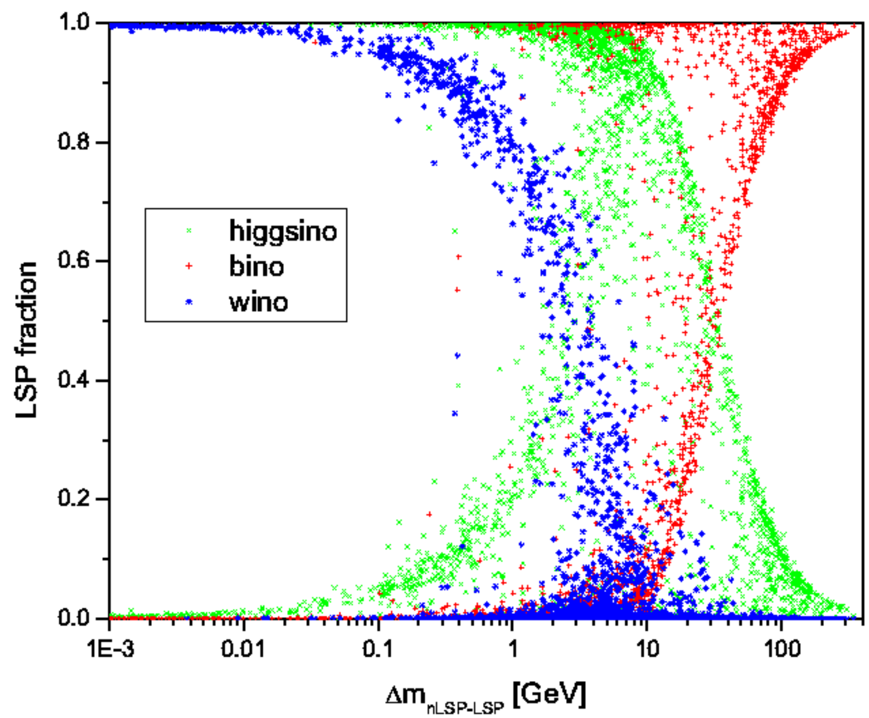
LSP Composition

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 bino-like but VERY small mass splittings produce wino-like LSPs. Higgsino-like LSPs have ‘intermediate’ splittings.

Flat



Log



Zh, h-> bb, ττ

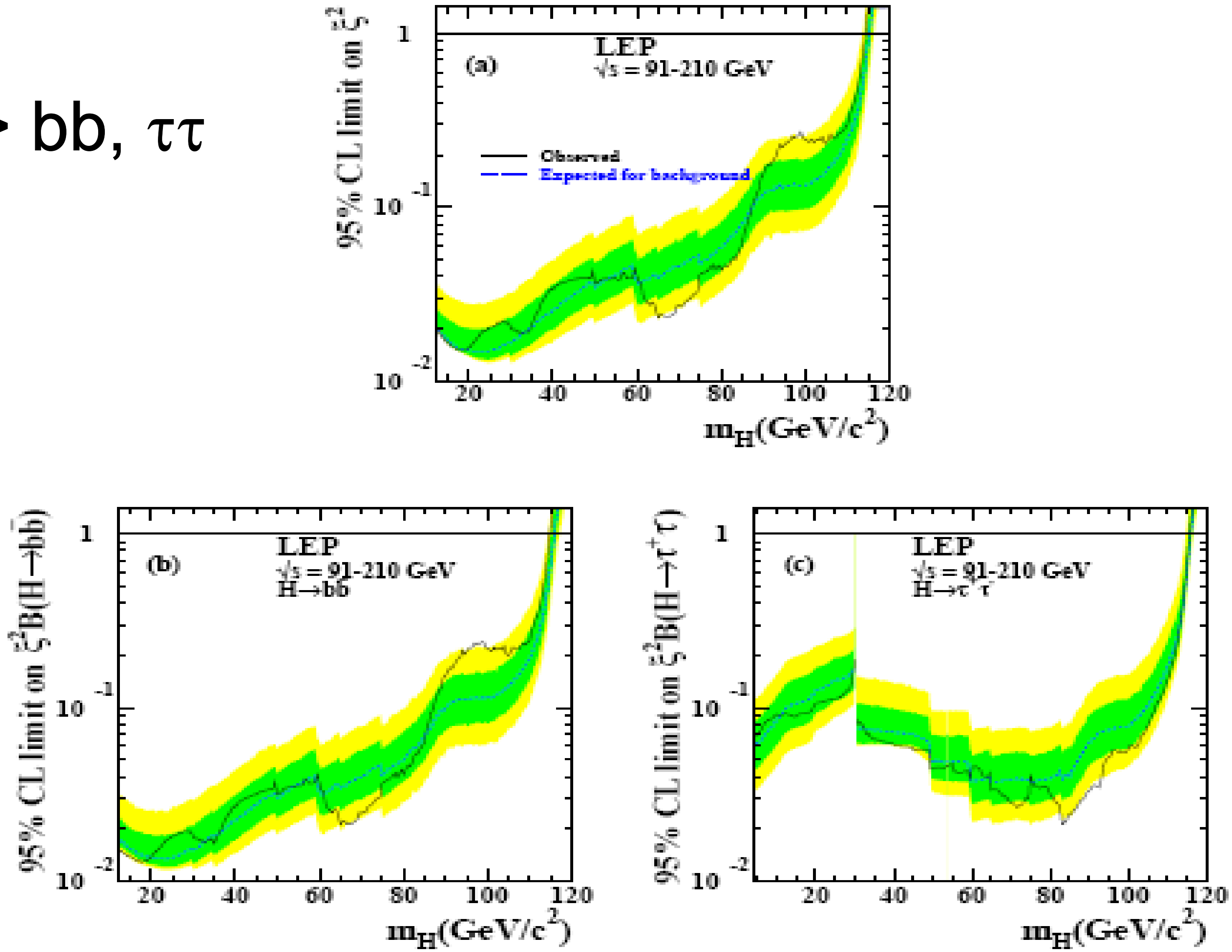


Figure 1: *The 95% c.l. upper bound on the coupling ratio* $\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$ *(see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling.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