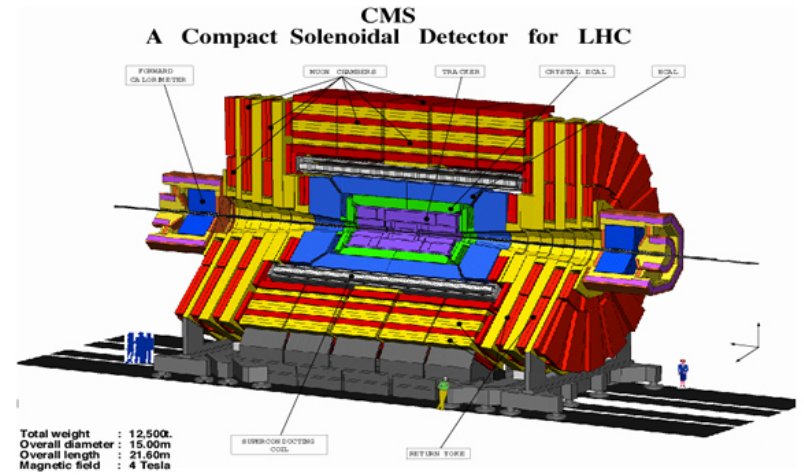
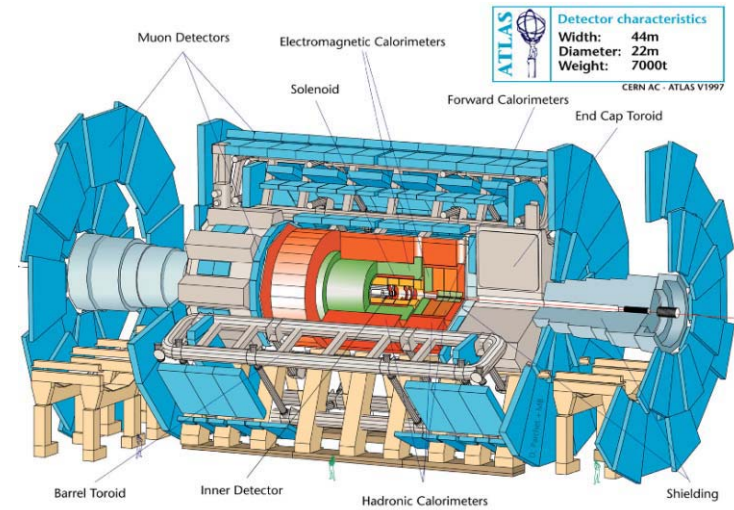


# Supersymmetry Without Prejudice



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

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 ( $\sim 100$ ).

To circumvent this issue, authors generally limit their analyses to a specific SUSY breaking scenario(s) such as mSUGRA, GMSB, AMSB,... which determines the sparticle (e.g., the LSP's) couplings & signatures in terms of 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.**

## 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, 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:  $A_b, A_t, A_\tau$

Higgs/Higgsino:  $\mu, M_A, \tan\beta$

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, Fermi/GLAST, PAMELA/ATIC, etc. etc. – all your favorites! (In progress)
- 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? 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

$2 \times 10^6$  points – emphasize lower masses but extend to higher masses

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

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

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

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

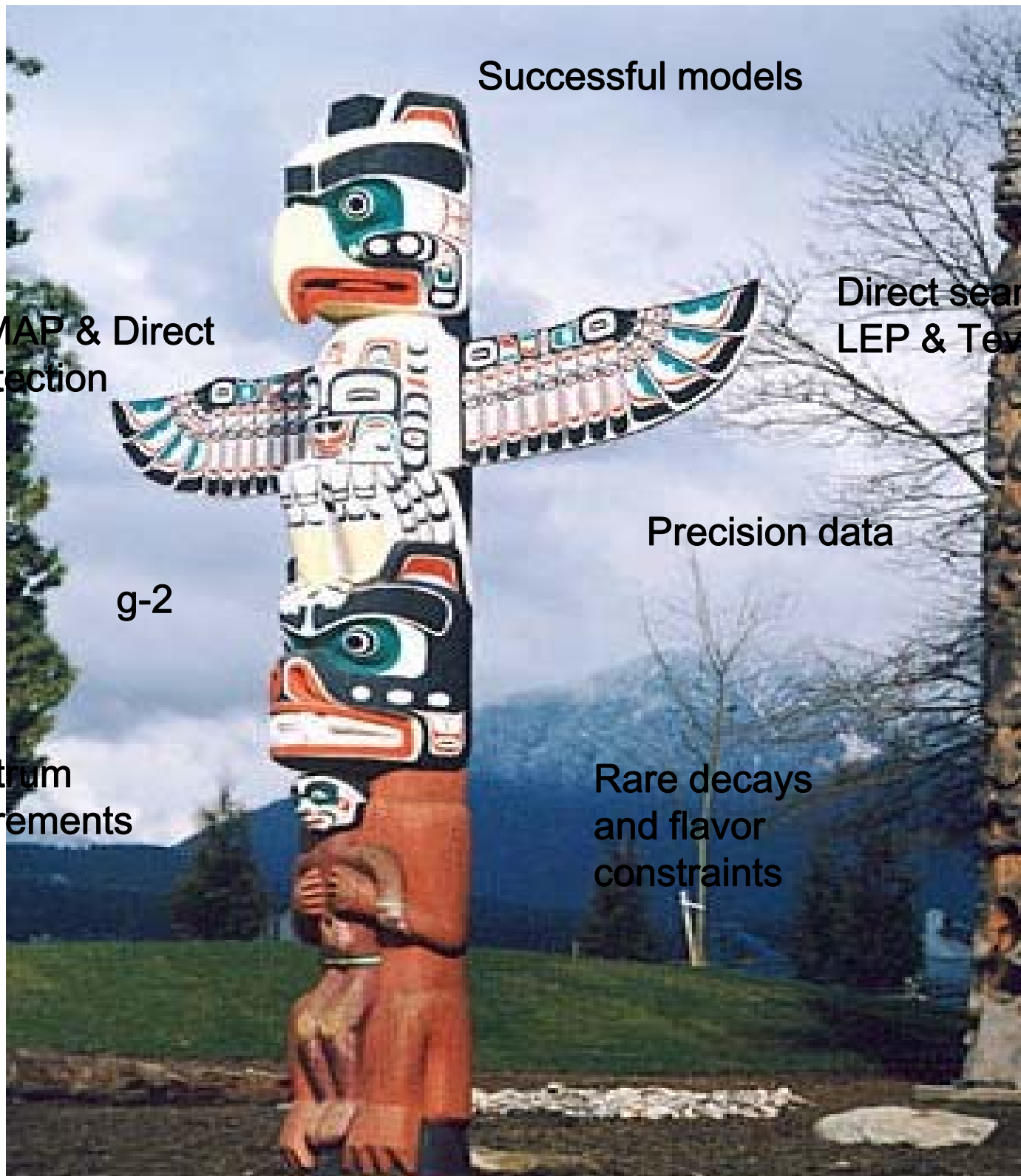
$$1 \leq \tan\beta \leq 60$$

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

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

→ This analysis required  $\sim 1$  processor-century of CPU time.

this is the real limitation of this study.



Successful models

WMAP & Direct  
Detection

Direct searches at  
LEP & Tevatron

Precision data

$g-2$

Spectrum  
requirements

Rare decays  
and flavor  
constraints

# Constraints

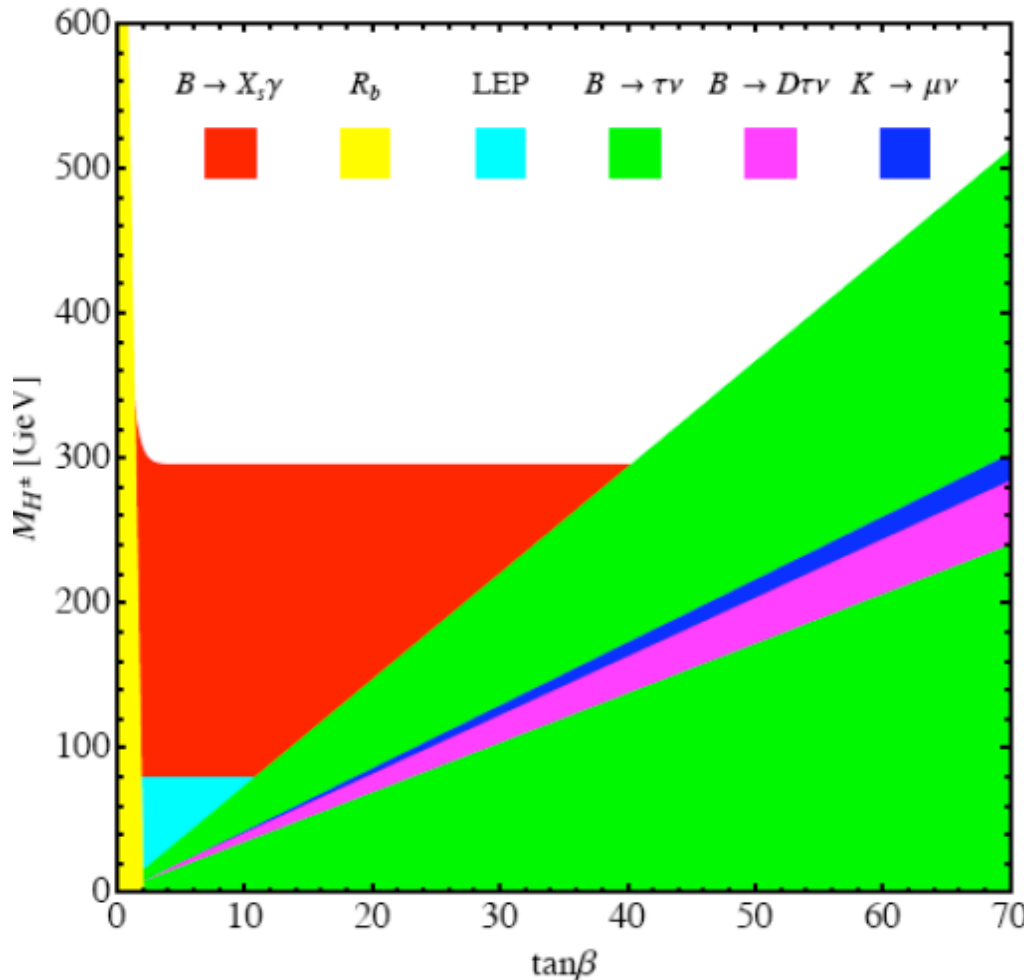
- $-0.0007 < \Delta\rho < 0.0026$  (PDG'08)
  - $b \rightarrow s \gamma : B = (2.5 - 4.1) \times 10^{-4}$  ; (HFAG) + Misiak etal. & Becher & Neubert
  - $\Delta(g-2)_\mu$  ???  $(30.2 \pm 8.8) \times 10^{-10}$  (0809.4062)  
 $(29.5 \pm 7.9) \times 10^{-10}$  (0809.3085)  
 $[\sim 14.0 \pm 8.4] \times 10^{-10}$  [Davier/BaBar-Tau08]
- $(-10 \text{ to } 40) \times 10^{-10}$  to be conservative..
- $\Gamma(Z \rightarrow \text{invisible}) < 2.0 \text{ MeV}$  (LEPEWWG)  
 This removes Z decays to LSPs w/ large Higgsino content
  - **Meson-Antimeson Mixing** : Constrains 1<sup>st</sup>/3<sup>rd</sup> sfermion mass ratios to be in the range  $0.2 < R < 5$  in MFV context

# $B \rightarrow \tau \nu$

Isidori & Paradisi, hep-ph/0605012 & Erikson et al., 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:  $B \rightarrow K \nu \bar{\nu}, B \rightarrow \mu \nu$

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

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

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

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

UTfit, 2008

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

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

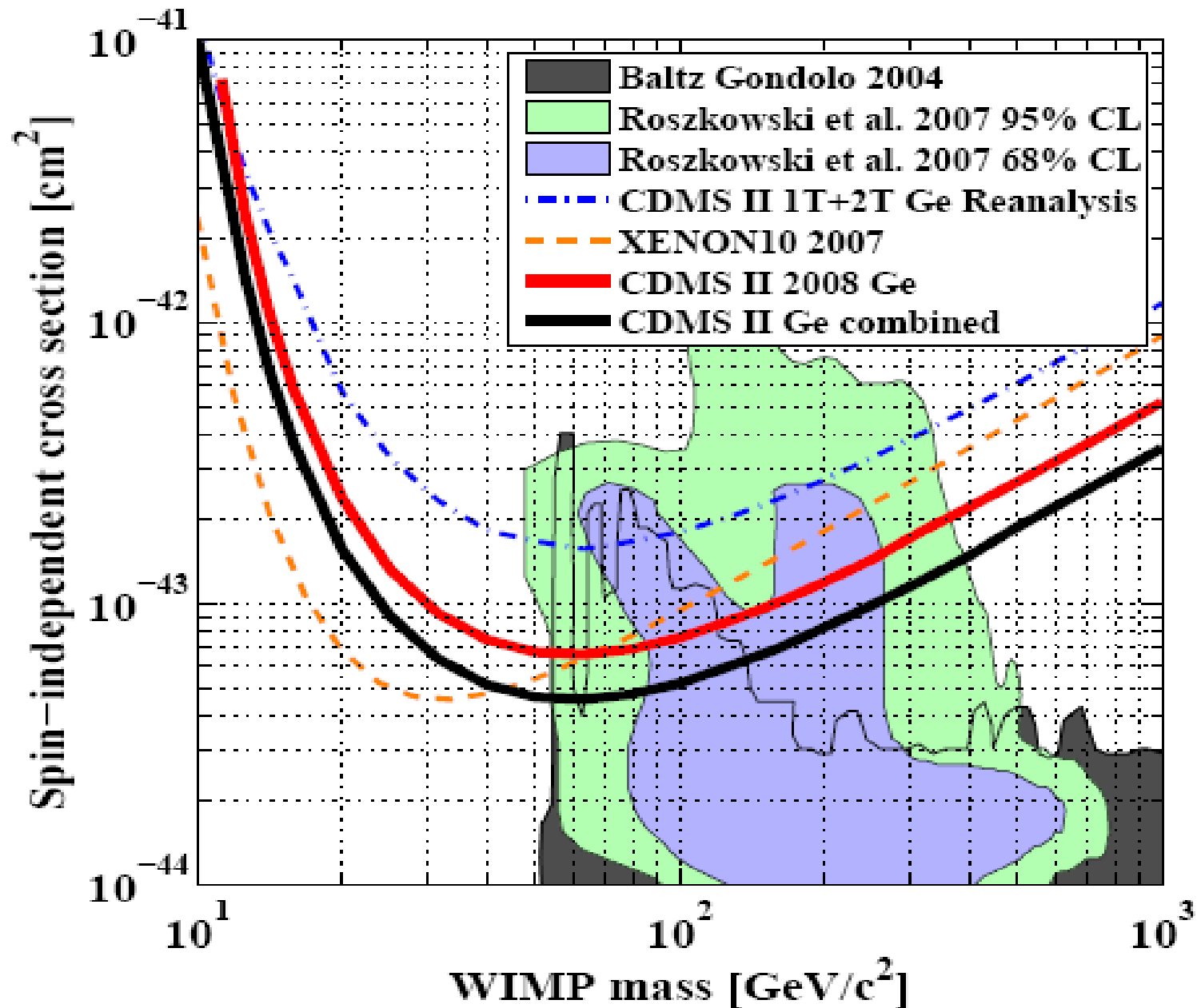
3 – 4% Stocchi et al., arXiv:0710.3799

Heavy Flavour Theory, Tobias Hurth (CERN, SLAC)



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

# Dark Matter: Direct Searches for WIMPs



- CDMS, XENON10, DAMA, CRESST-I,... → We find a factor of  $\sim 4$  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 & 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.... CAREFUL!

Zh, h- $\rightarrow$  bb,  $\tau\tau$

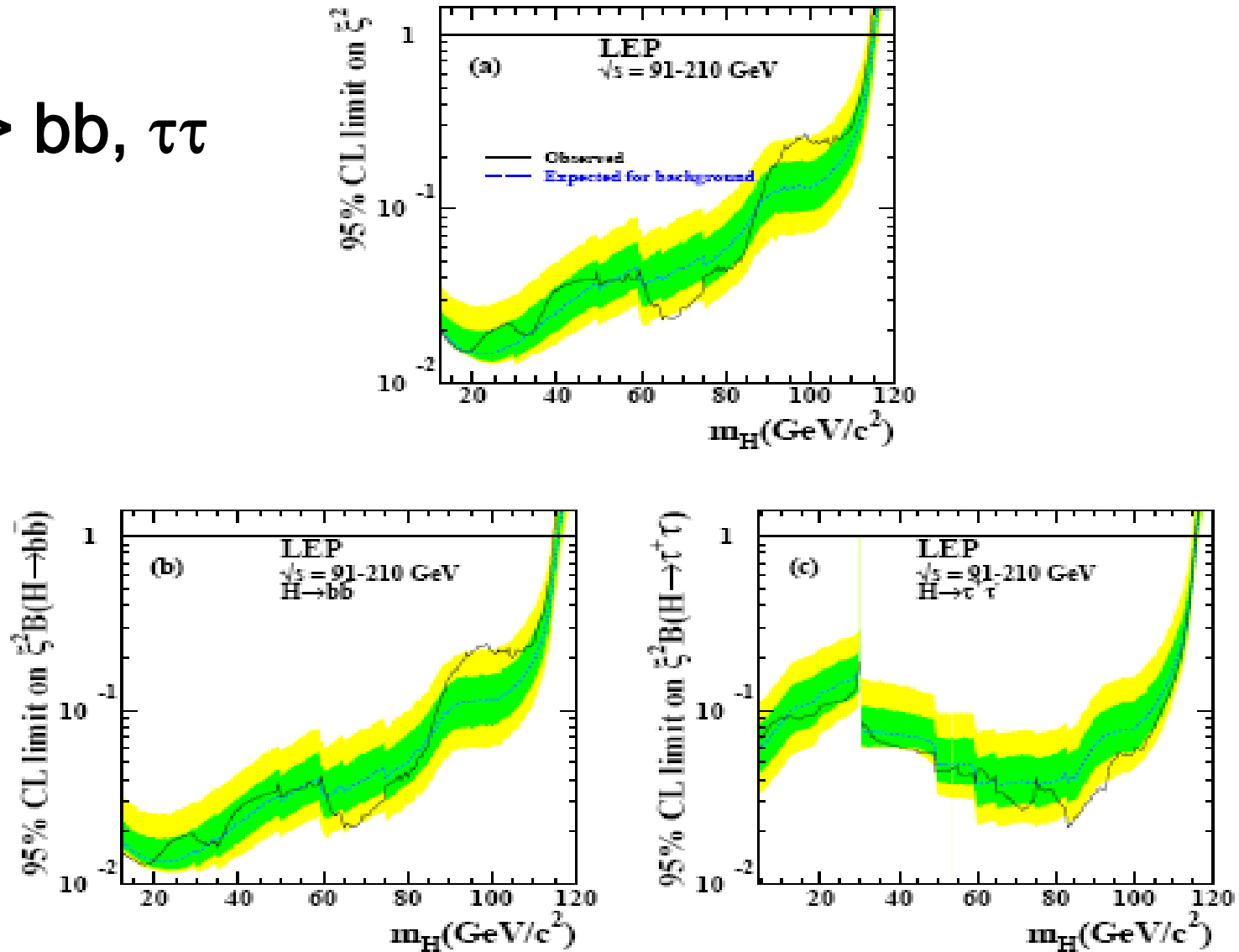
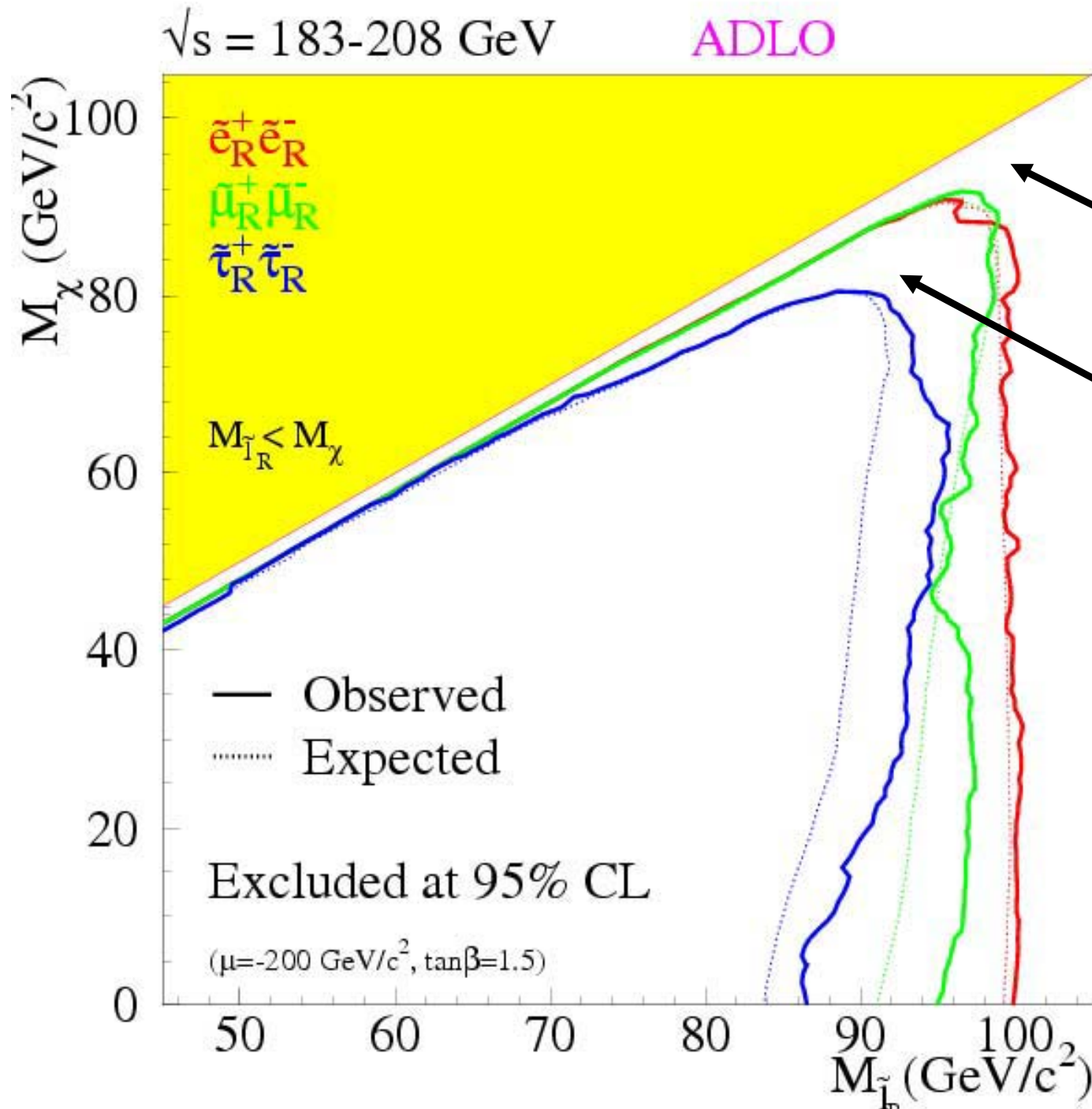


Figure 1: The 95% c.l. upper bound on the coupling ratio  $\xi^2 = (g_{HZZ}/g_{HZZ}^{\text{SM}})^2$  (see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling.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

# 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		
$\cancel{E}_T$	$\geq 40$		
Vertex $z$ pos.	$< 60$ cm		
A coplanarity	$< 165^\circ$		
Selection Cut	"dijet"	"3-jets"	"gluino"
Trigger	dijet	multijet	multijet
jet <sub>1</sub> $p_T^a$	$\geq 35$	$\geq 35$	$\geq 35$
jet <sub>2</sub> $p_T^a$	$\geq 35$	$\geq 35$	$\geq 35$
jet <sub>3</sub> $p_T^b$	–	$\geq 35$	$\geq 35$
jet <sub>4</sub> $p_T^b$	–	–	$\geq 20$
Electron veto	yes	yes	yes
Muon veto	yes	yes	yes
$\Delta\phi(\cancel{E}_T, \text{jet}_1)$	$\geq 90^\circ$	$\geq 90^\circ$	$\geq 90^\circ$
$\Delta\phi(\cancel{E}_T, \text{jet}_2)$	$\geq 50^\circ$	$\geq 50^\circ$	$\geq 50^\circ$
$\Delta\phi_{\min}(\cancel{E}_T, \text{any jet})$	$\geq 40^\circ$	–	–
$H_T$	$\geq 325$	$\geq 375$	$\geq 400$
$\cancel{E}_T$	$\geq 225$	$\geq 175$	$\geq 100$

<sup>a</sup>First and second jets are also required to be central ( $|\eta_{\text{jet}}| < 0.8$ ), with an electromagnetic fraction below 0.95, and to have  $\text{CPF0} \geq 0.75$ .

<sup>b</sup>Third and fourth jets are required to have  $|\eta_{\text{jet}}| < 2.5$ , with an electromagnetic fraction below 0.95.

Multiple analyses keyed to look for:

Squarks  $\rightarrow$  jet + MET

Gluinos  $\rightarrow$  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)	$\sigma_{\text{nom}}$ (pb)	$\epsilon_{\text{sig.}}$ (%)	$N_{\text{obs.}}$	$N_{\text{backgrd.}}$	$N_{\text{sig.}}$	$\sigma_{95}$ (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	$9.4 \pm 1.2$ (stat.) $^{+2.3}_{-1.8}$ (syst.)
Combination 2	no	yes	no	2	$4.5 \pm 0.6$ (stat.) $^{+0.7}_{-0.5}$ (syst.)
Combination 3	no	no	yes	14	$12.5 \pm 0.9$ (stat.) $^{+3.8}_{-1.9}$ (syst.)
Combination 4	yes	yes	no	1	$1.1 \pm 0.3$ (stat.) $^{+0.5}_{-0.3}$ (syst.)
Combination 5	yes	no	yes		kinematically not allowed
Combination 6	no	yes	yes	4	$4.5 \pm 0.6$ (stat.) $^{+1.8}_{-1.3}$ (syst.)
Combination 7	yes	yes	yes	2	$0.6 \pm 0.2$ (stat.) $^{+0.1}_{-0.2}$ (syst.)
At least one selection				31	$32.6 \pm 1.7$ (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  $\sim 10^5$  times !

# Tevatron II: CDF Tri-lepton Analysis

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

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

We need to perform the 3 tight lepton analysis  $\sim 10^5$  times

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

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

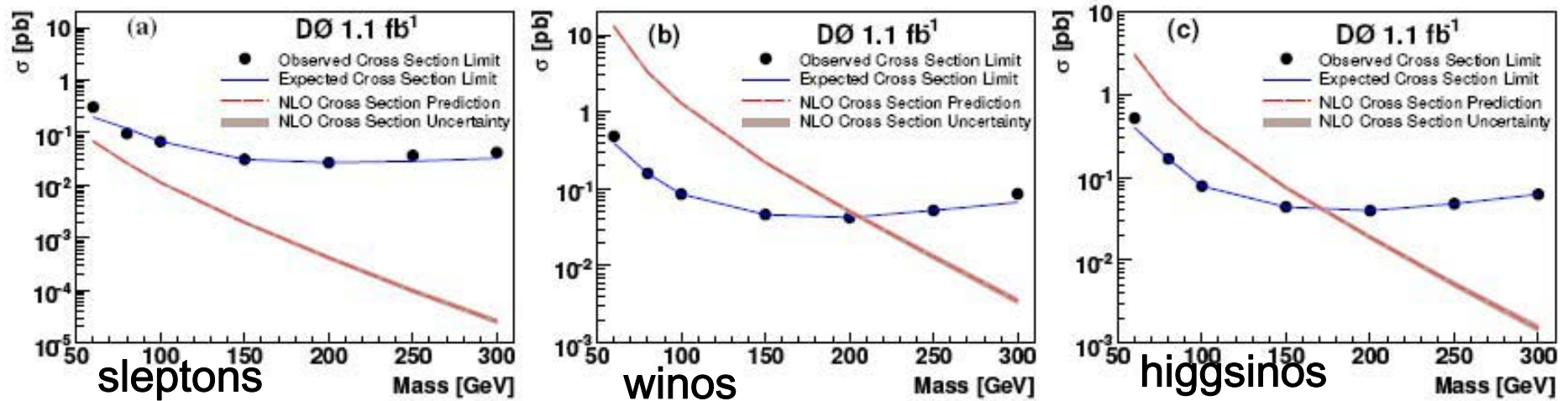


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos,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

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

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 <sup>17</sup>

# Survival Rates

- Flat Priors :

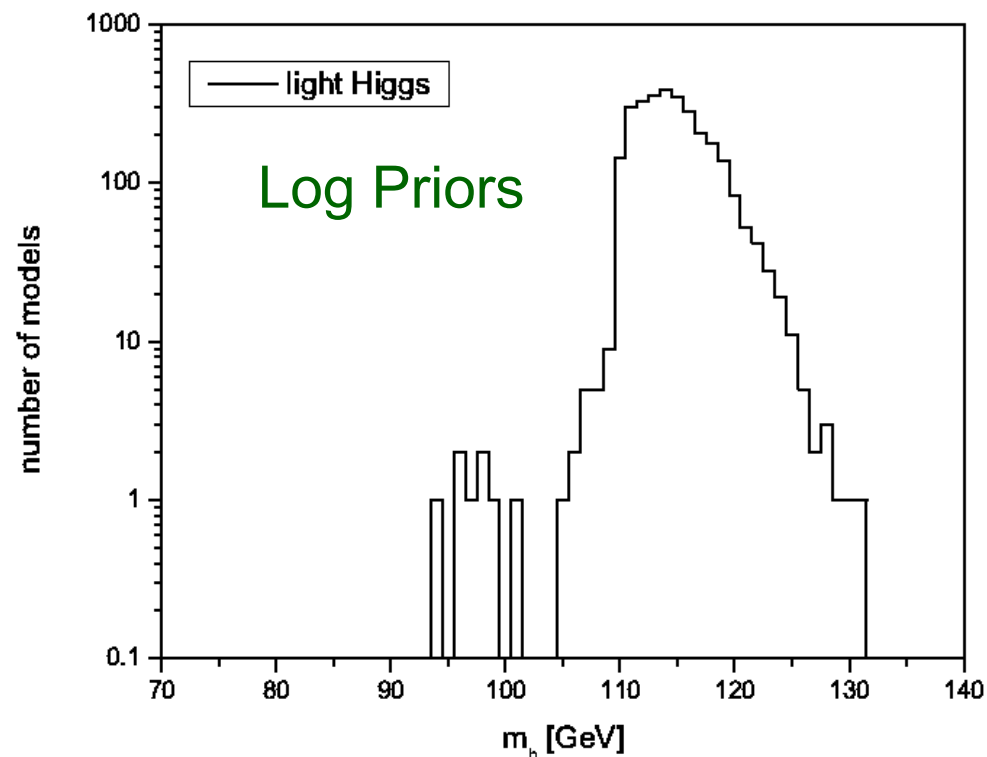
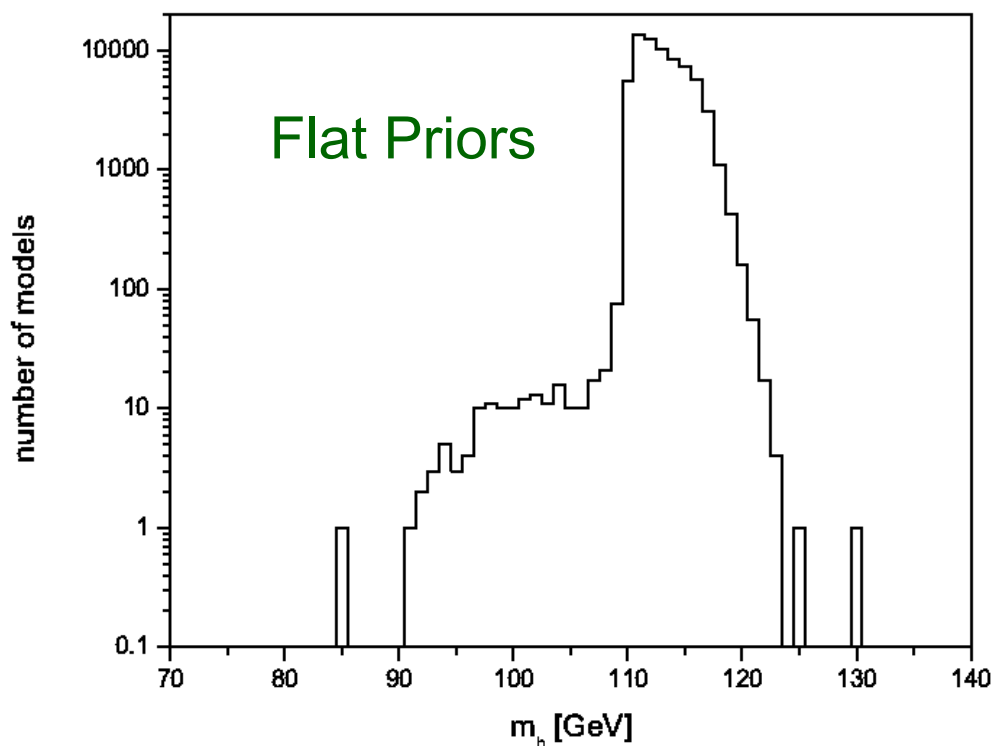
- $10^7$  models scanned
- 68.5 K (0.68%) survive

- Log Priors :

- $2 \times 10^6$  models scanned
- 3.0 K (0.15%) survive

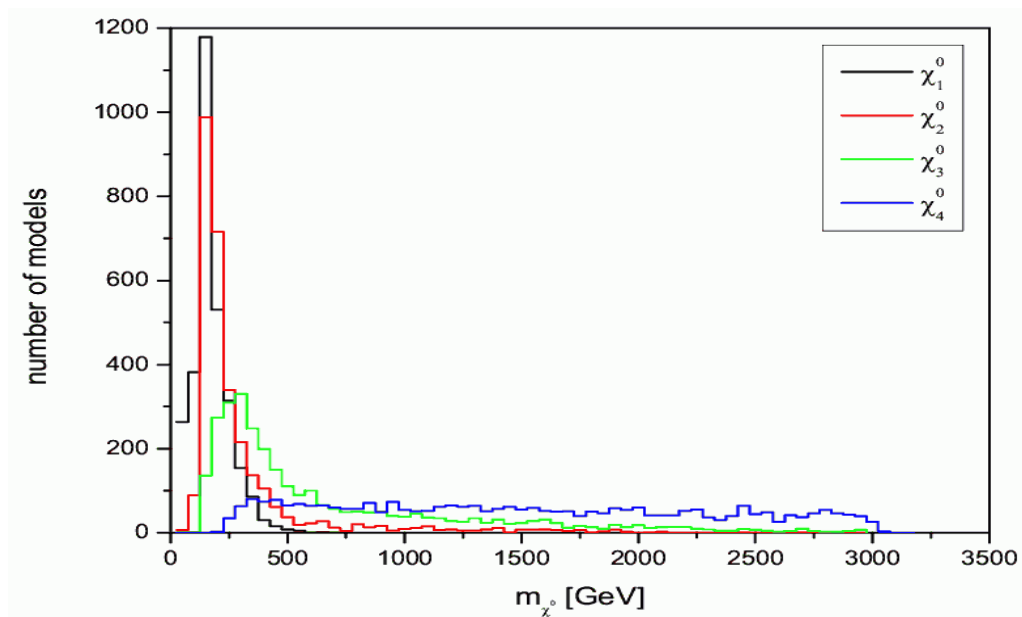
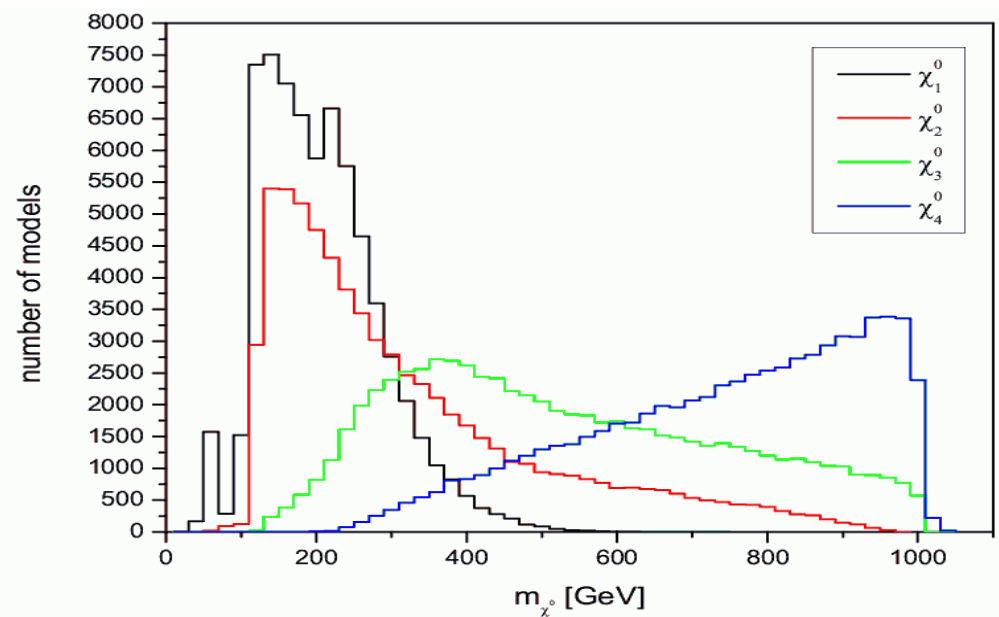
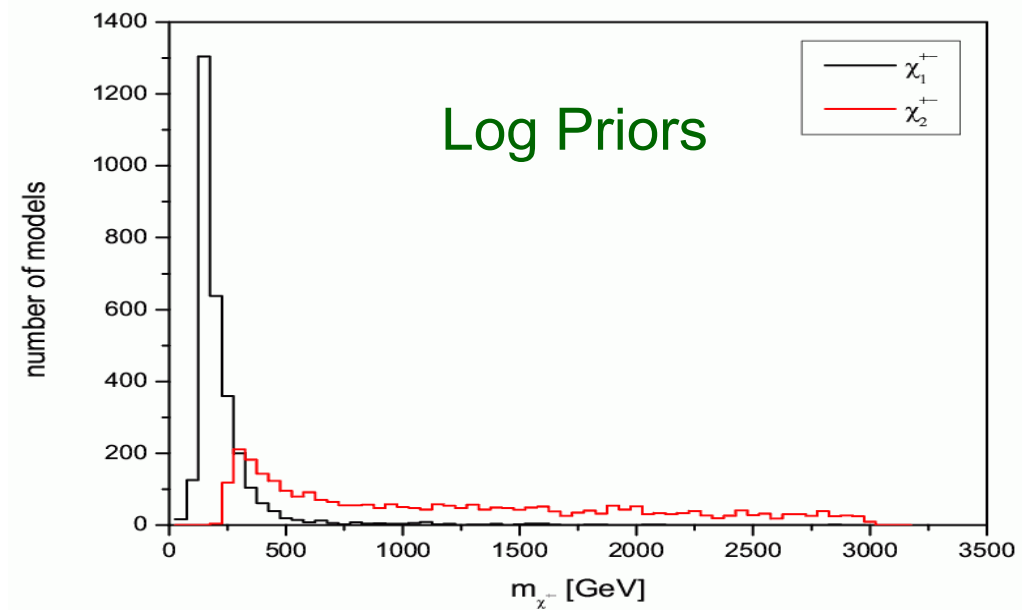
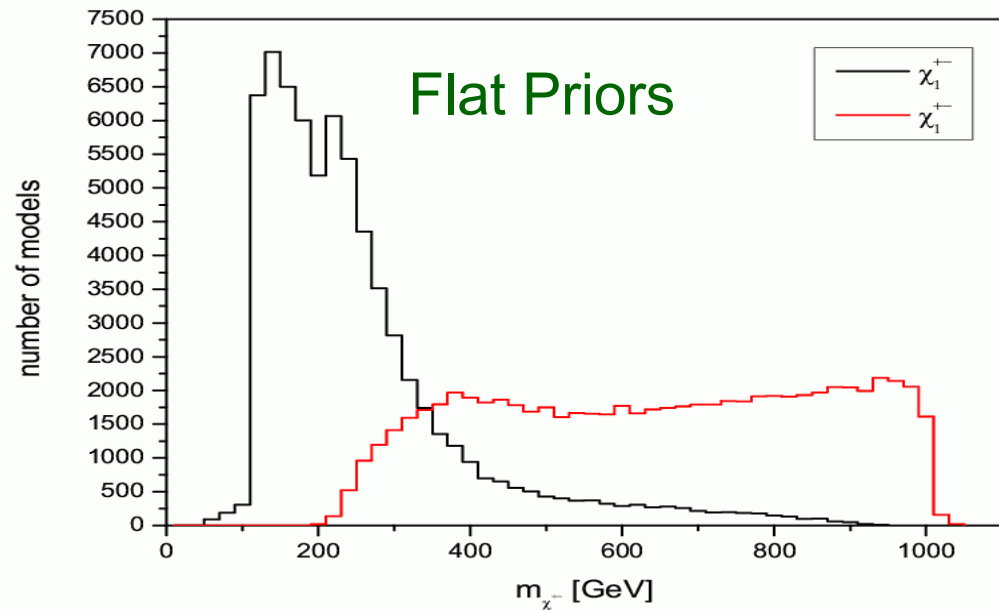
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# Light Higgs Mass Predictions



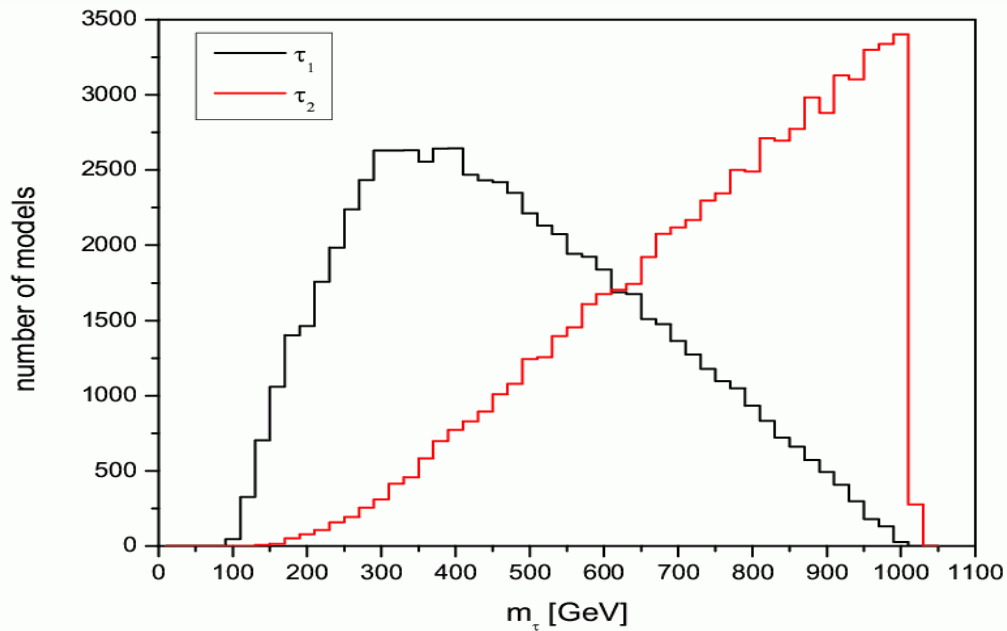
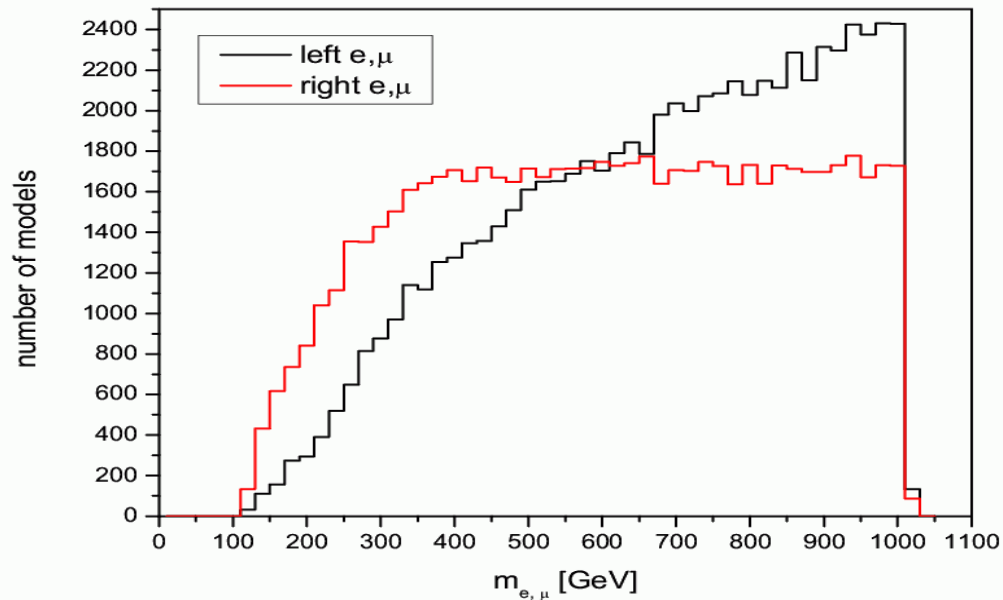
LEP Higgs mass constraints **avoided** by either **reducing** the ZZh coupling and/or **reducing** the, e.g.,  $h \rightarrow \bar{b}b$  branching fraction by decays to LSP pairs. We have **both** of these cases in our final model sets.

# Distribution of Sparticle Masses By Species

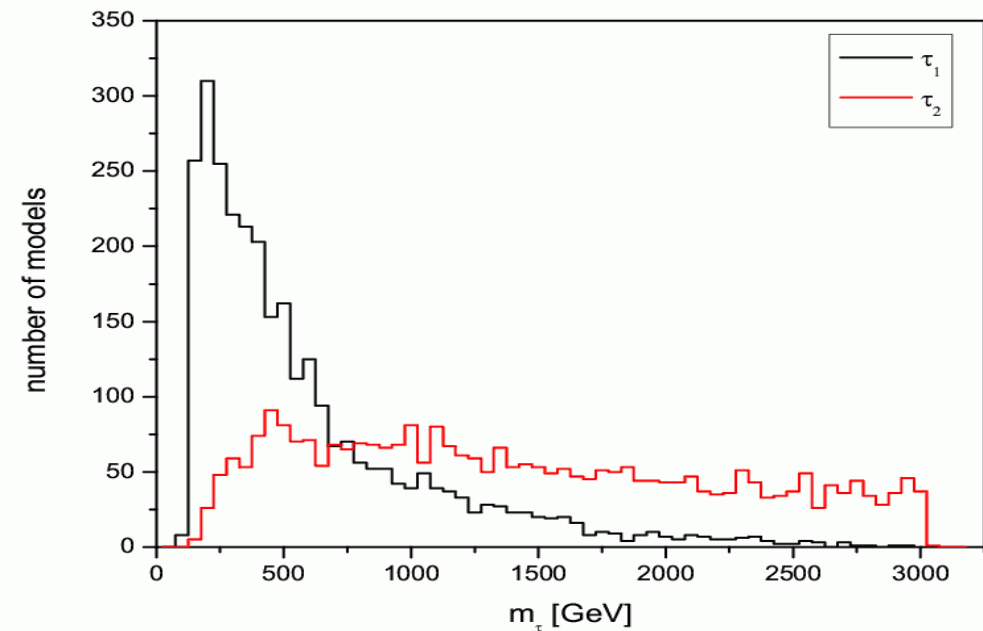
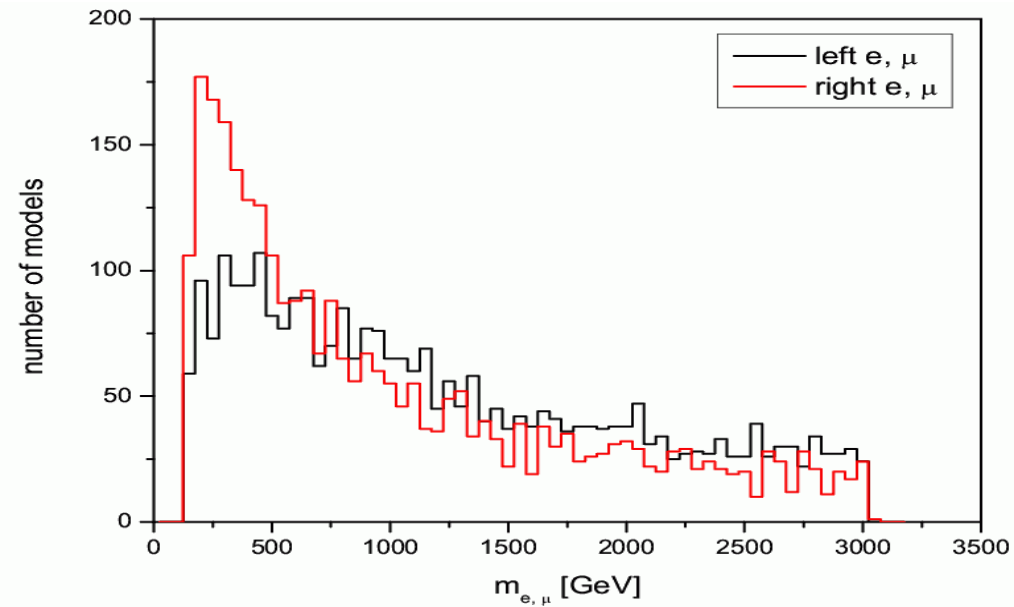


# Distribution of Sparticle Masses By Species

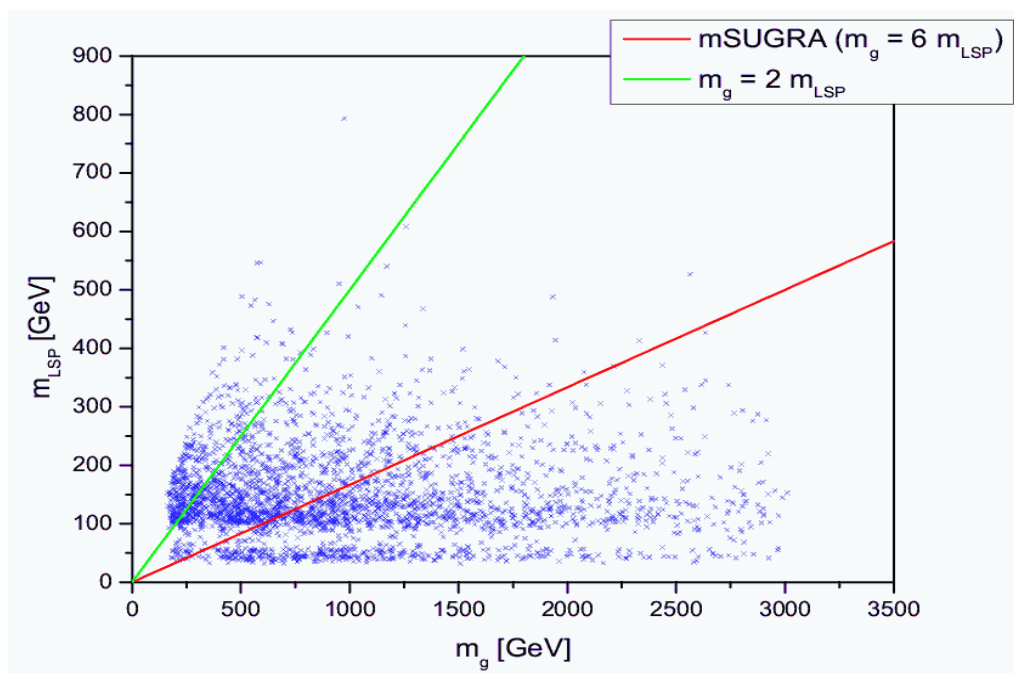
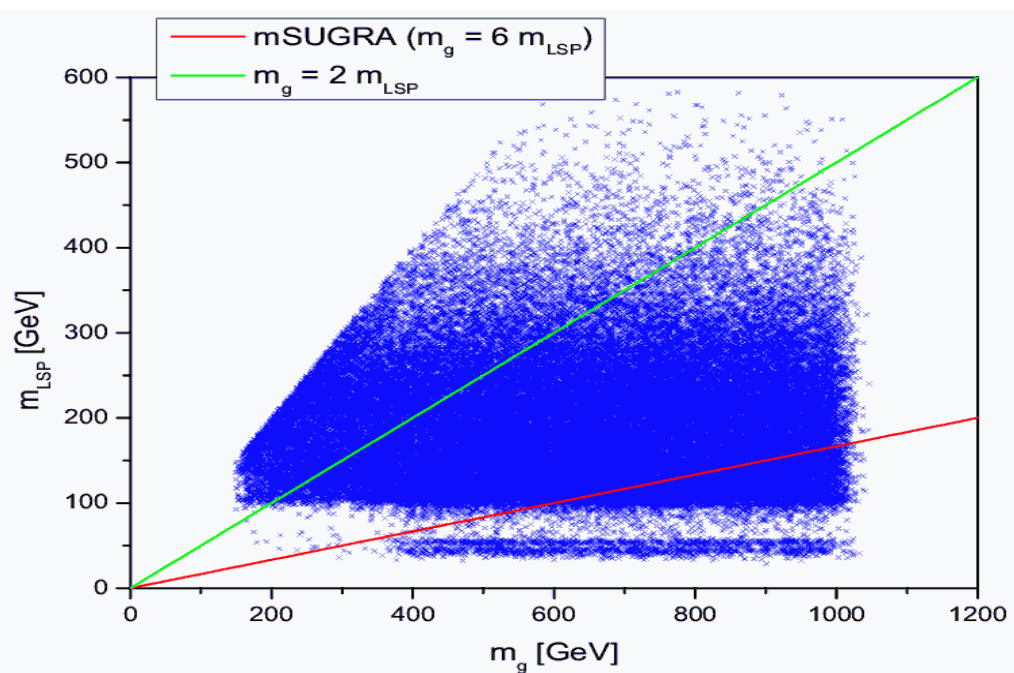
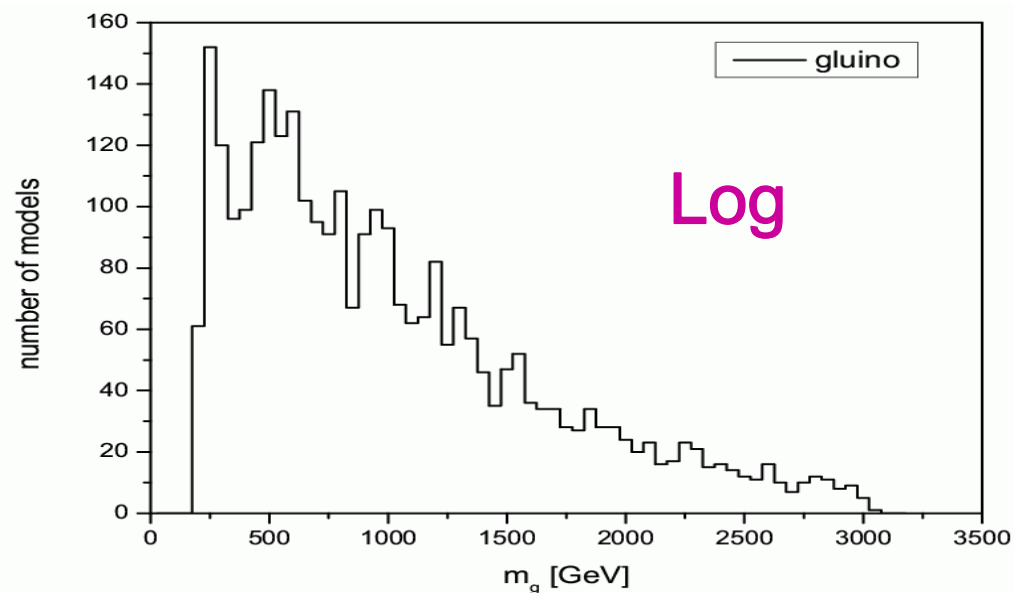
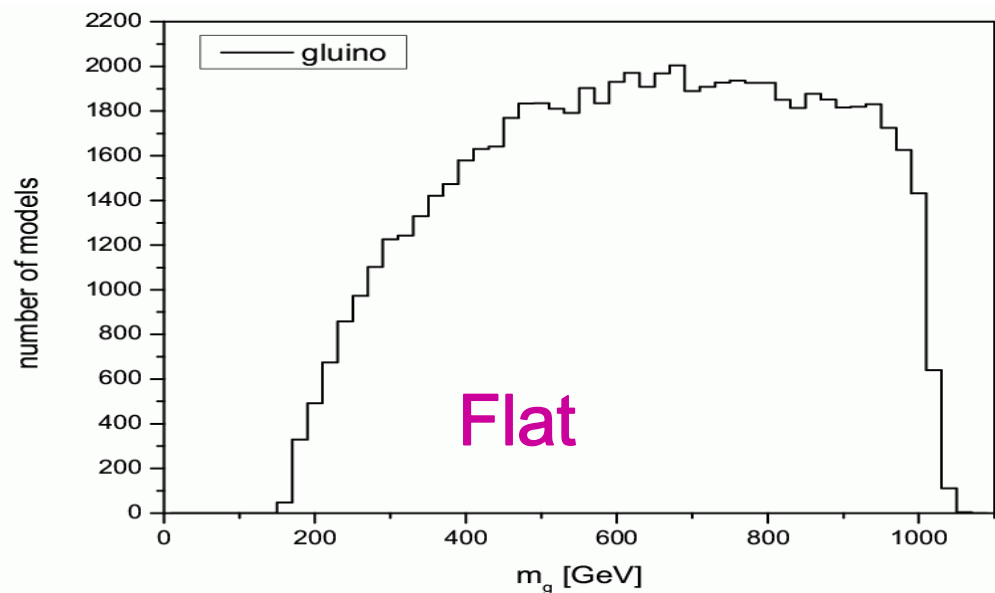
Flat Priors



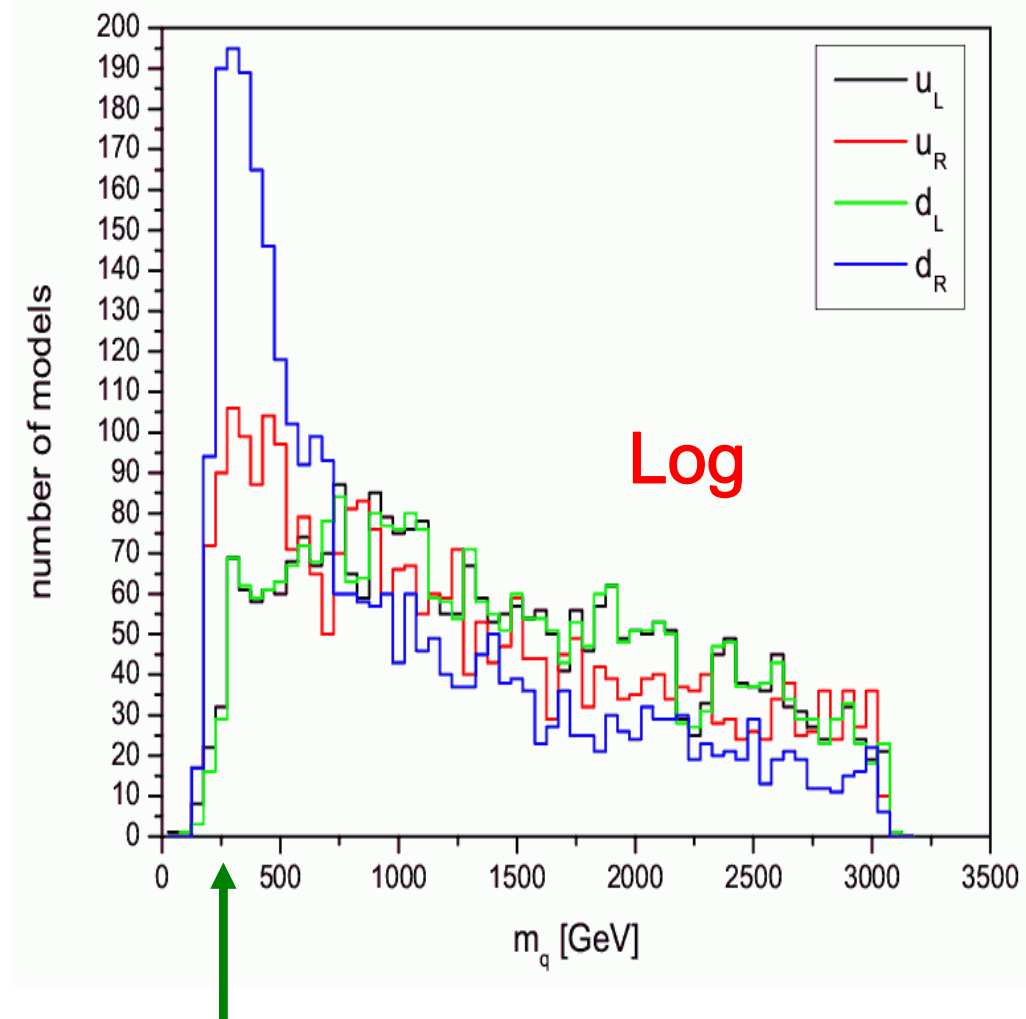
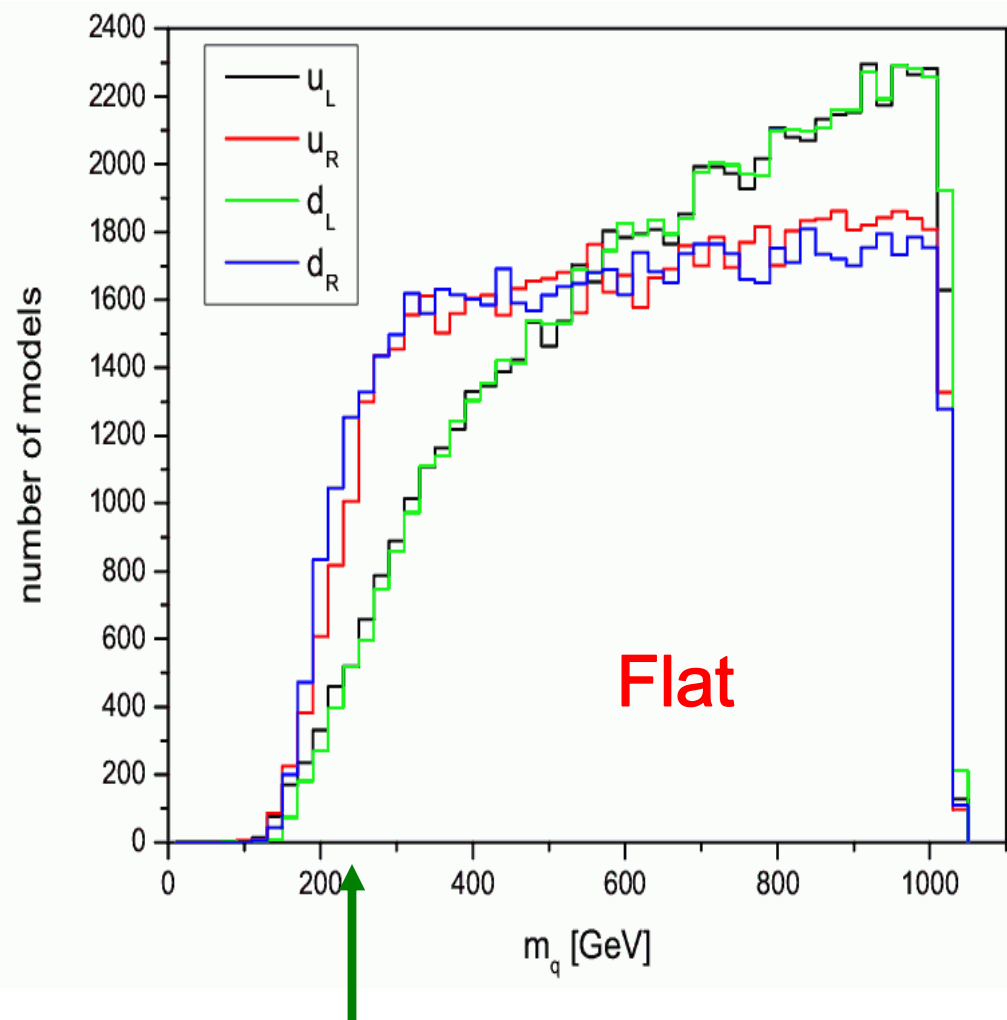
Log Priors



# Glauino Masses

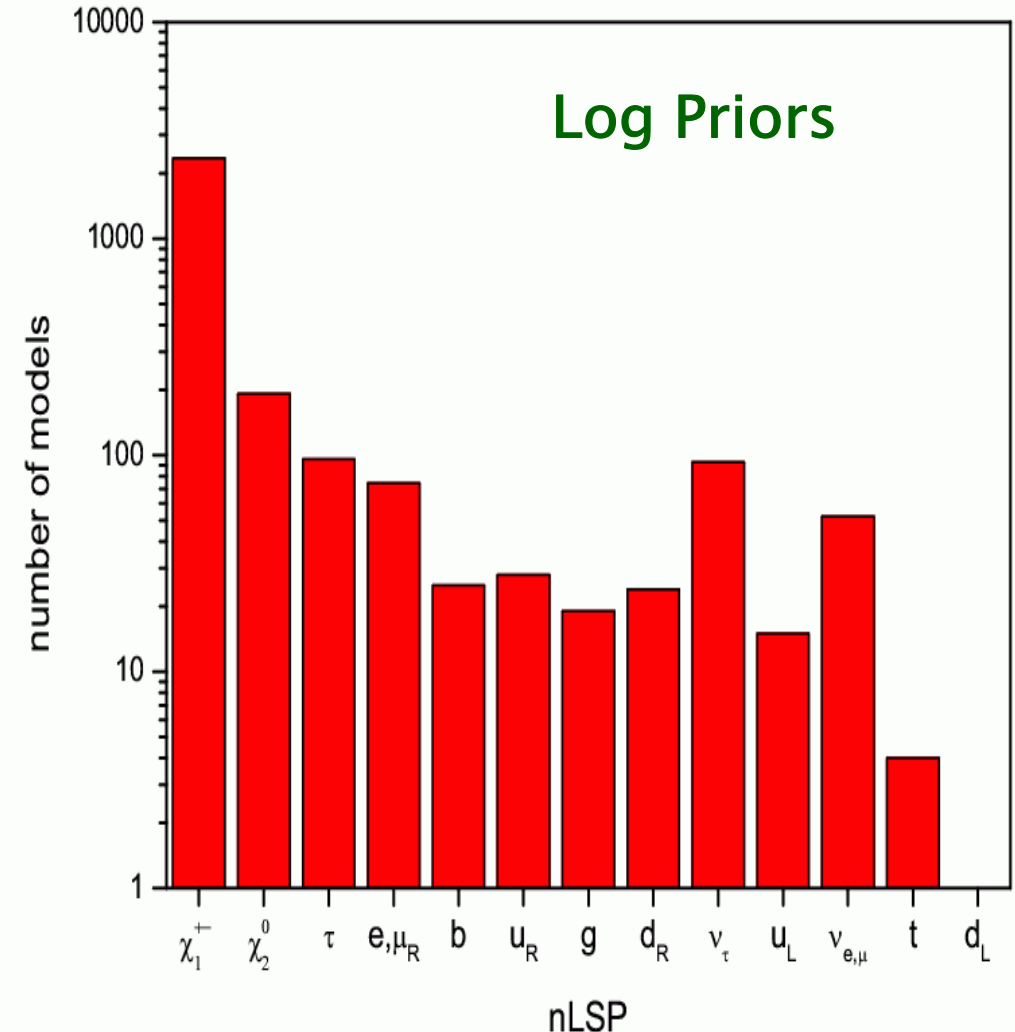
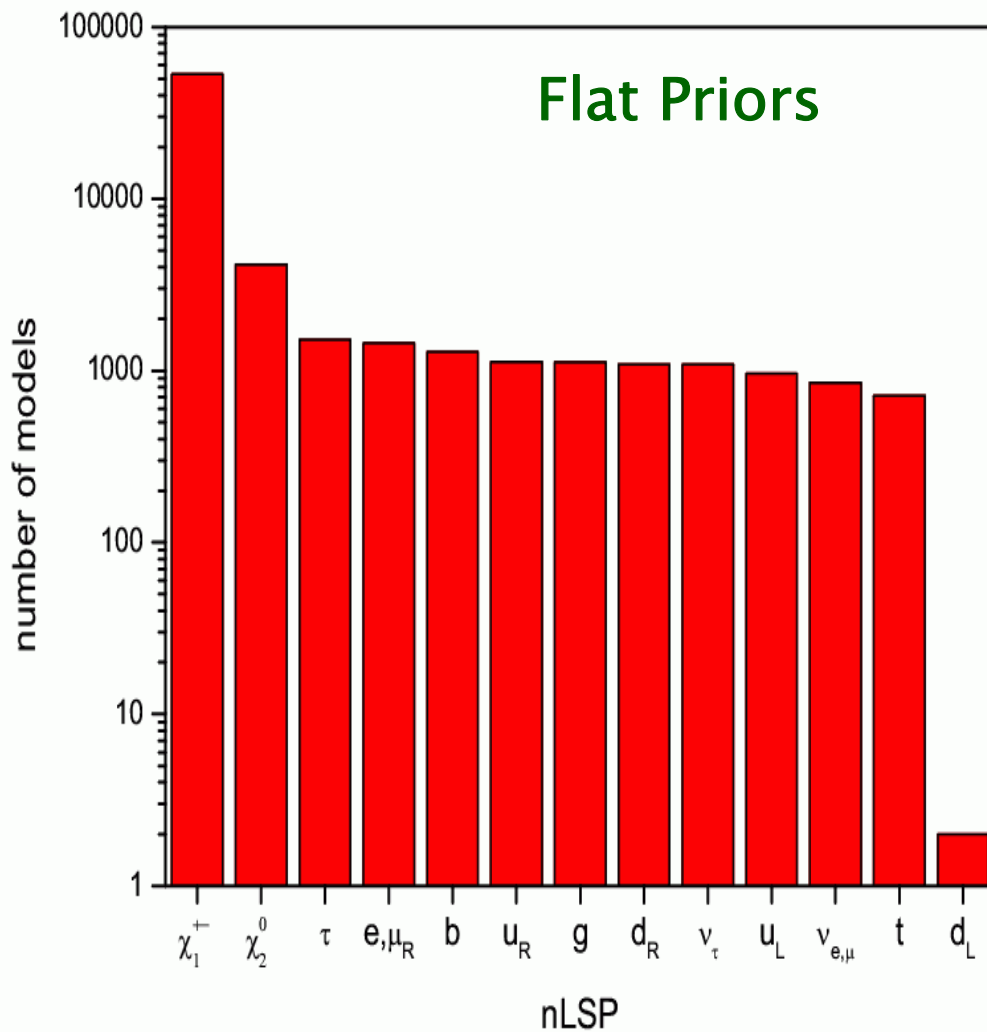


# Squarks CAN Be Light !!!

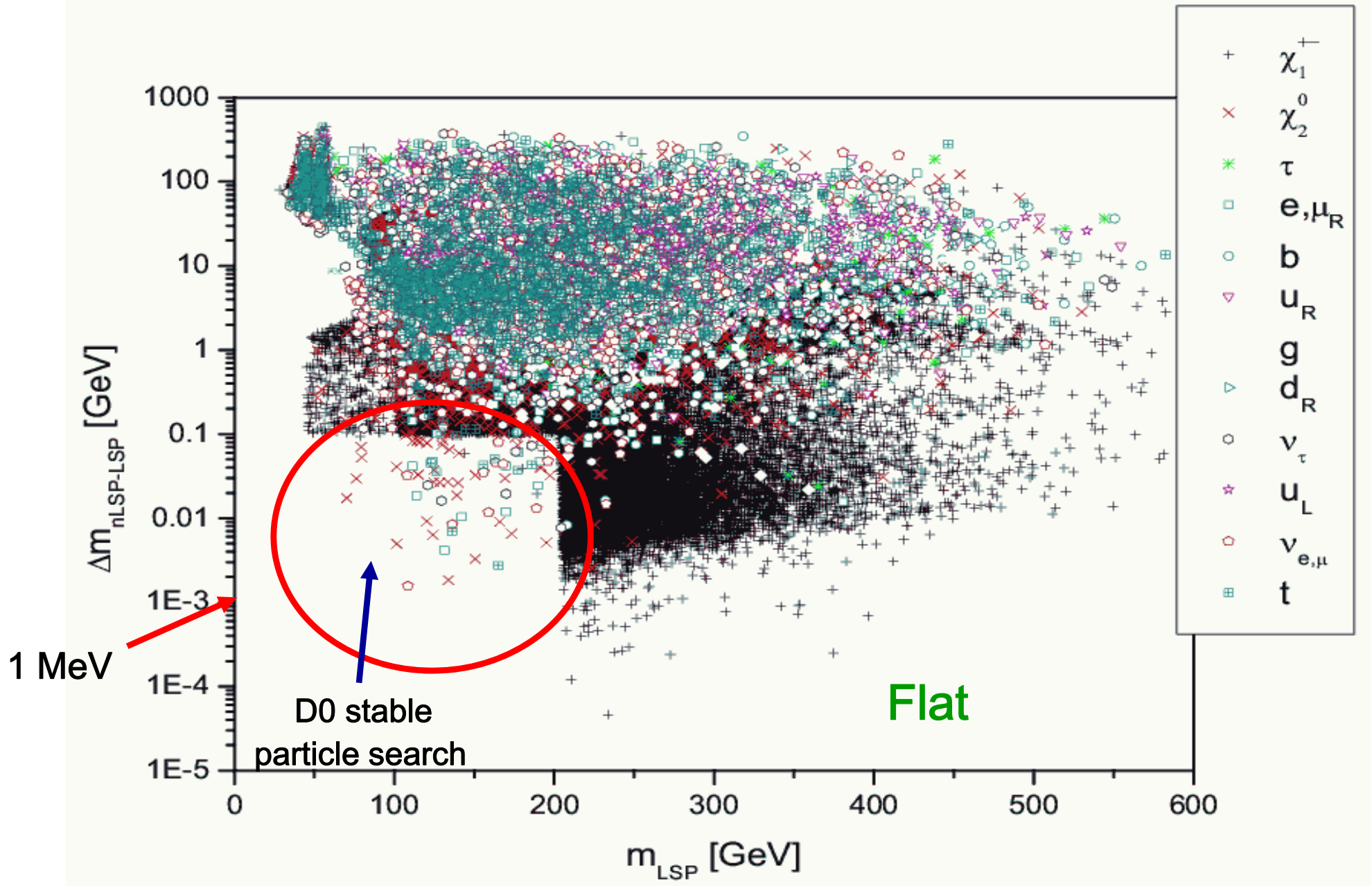


Light squarks can be missed by Tevatron searches for numerous reasons..

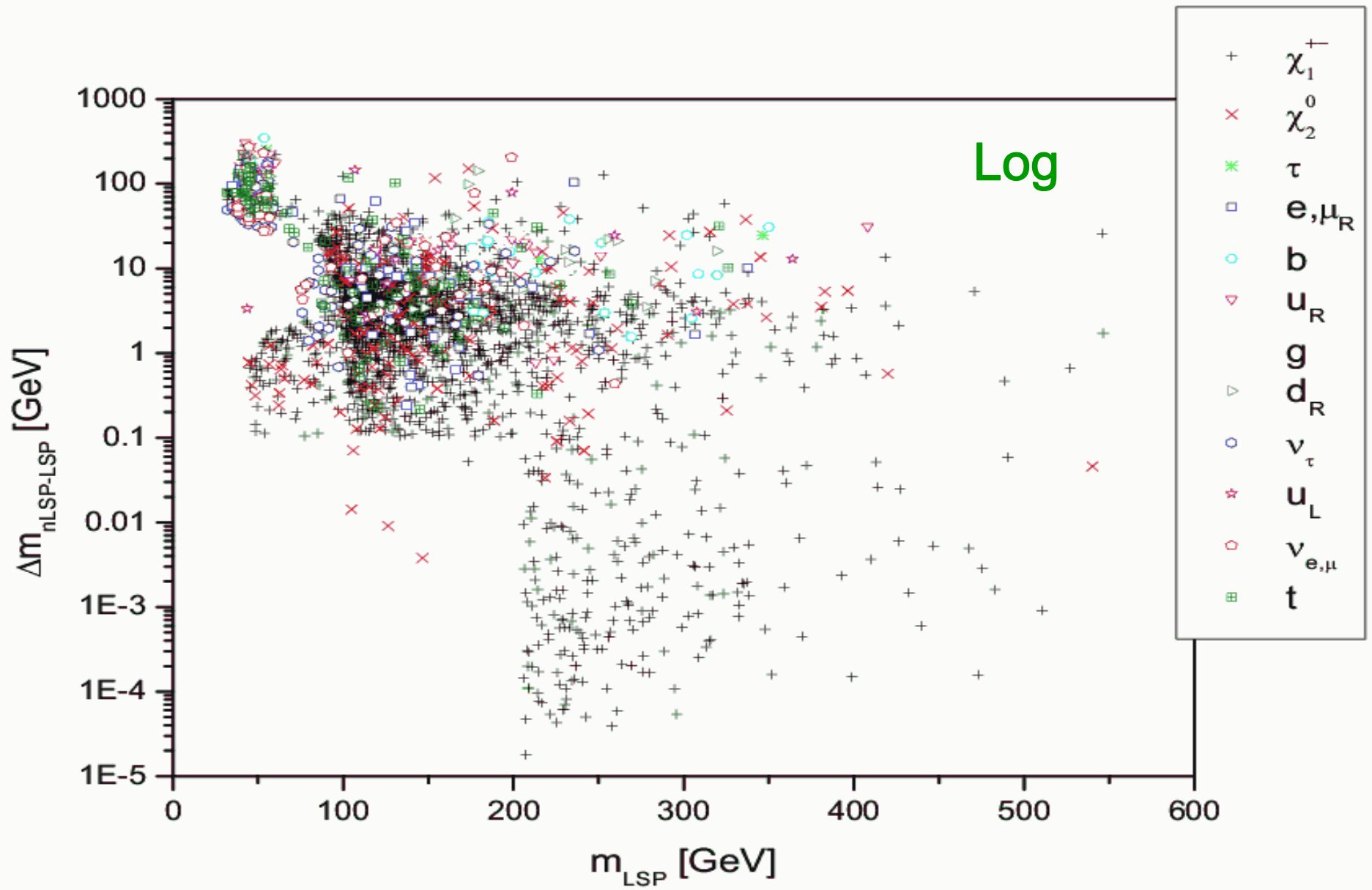
The identity of the **nLSP** is a critical factor in looking for SUSY signatures..**who** can play that role here???? Just about **ANYBODY !!!**

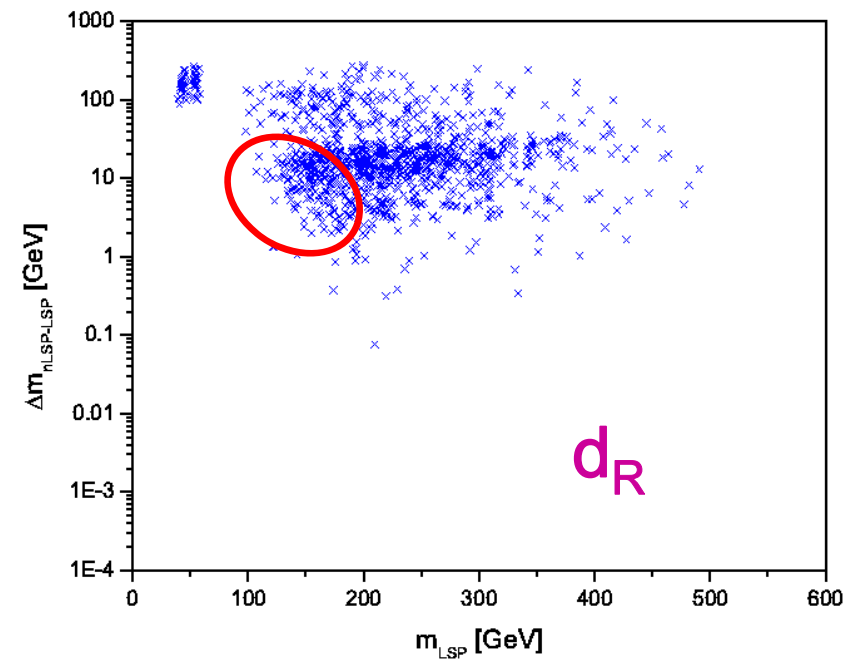
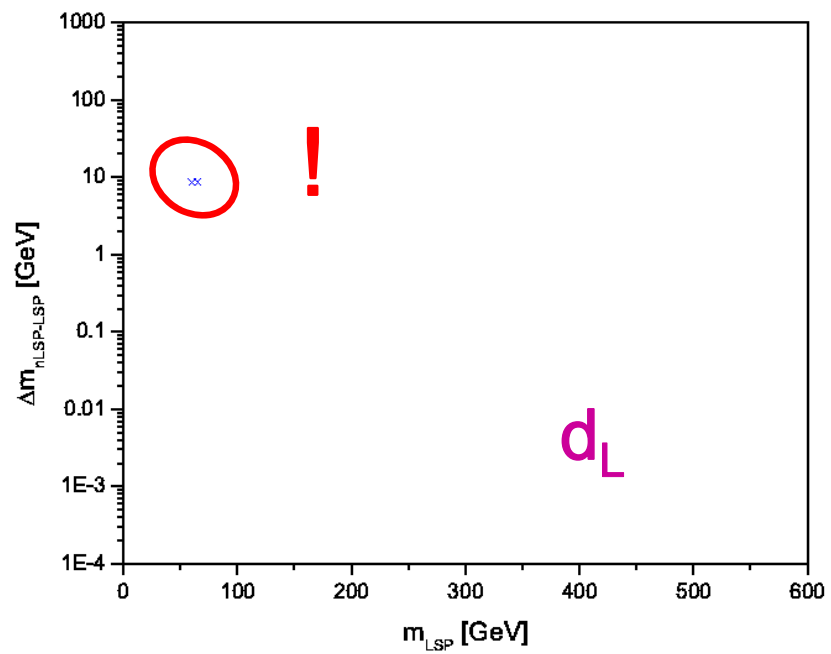
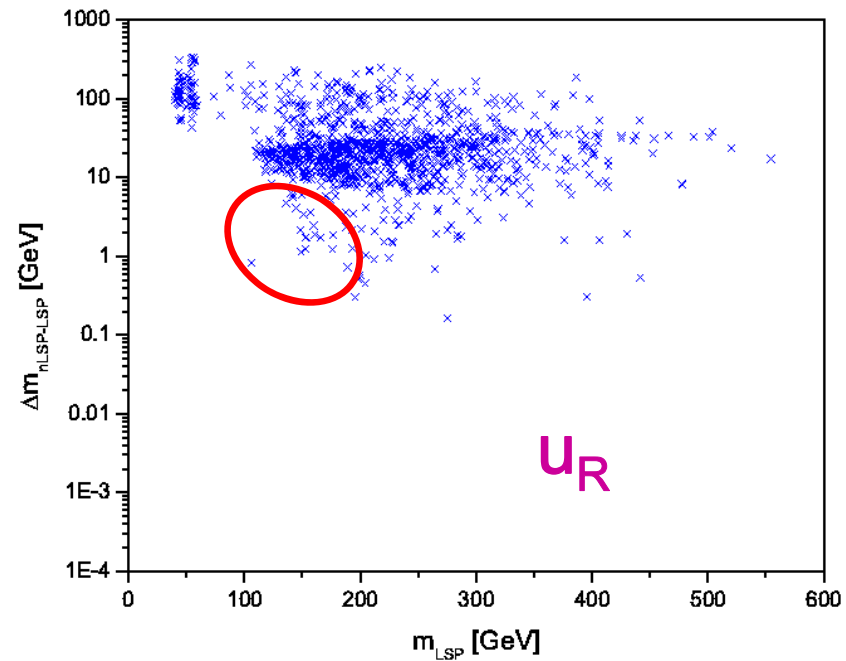
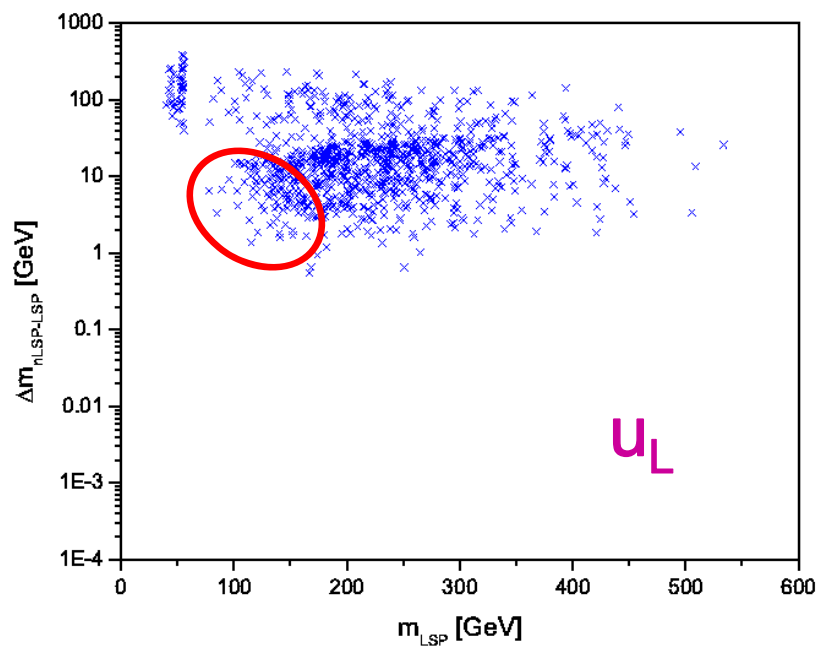


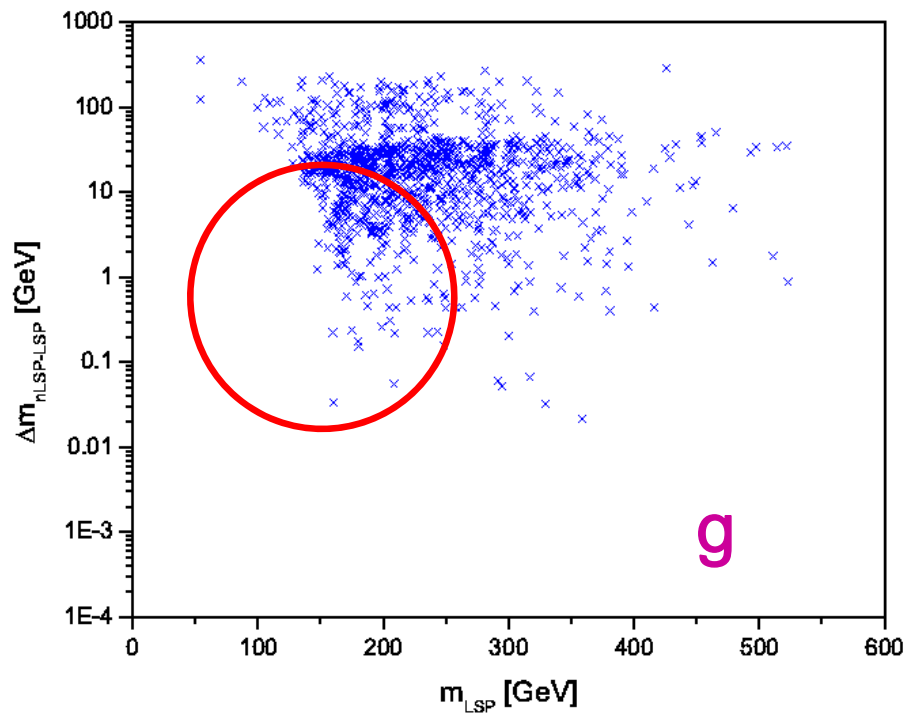
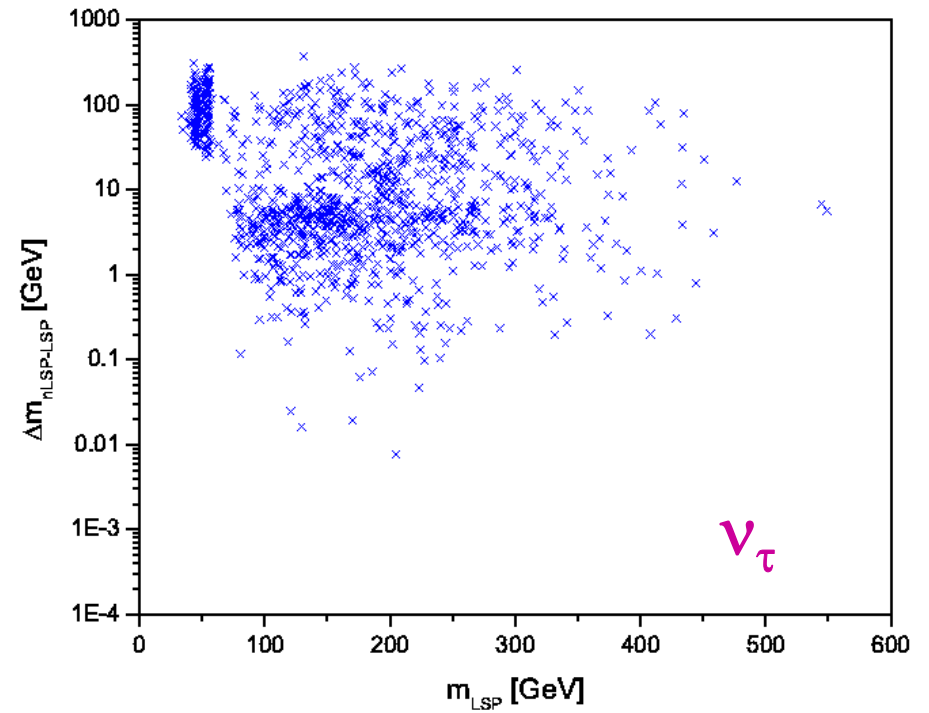
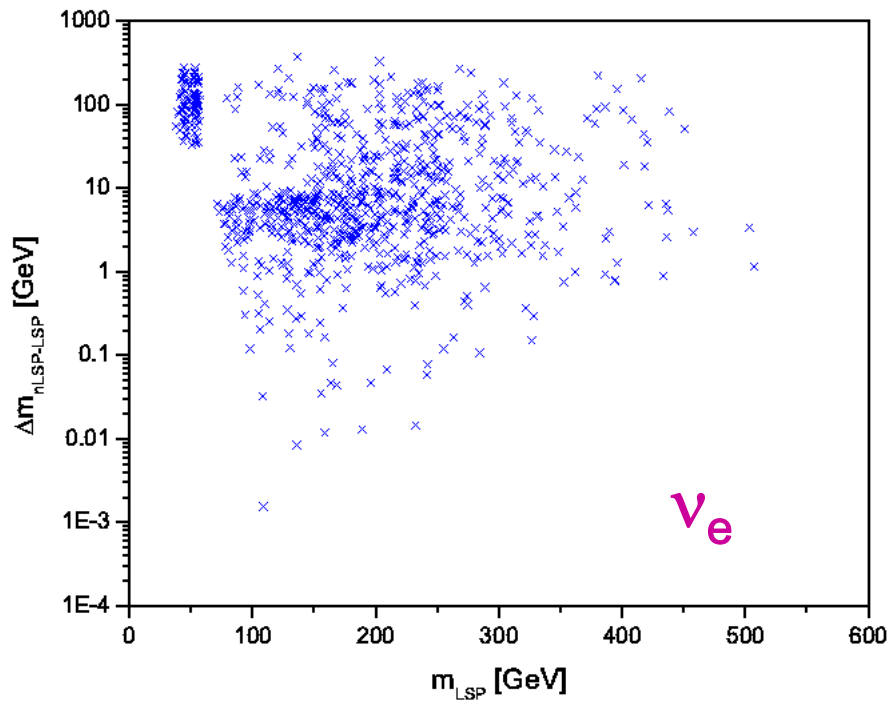
# nLSP-LSP Mass Difference



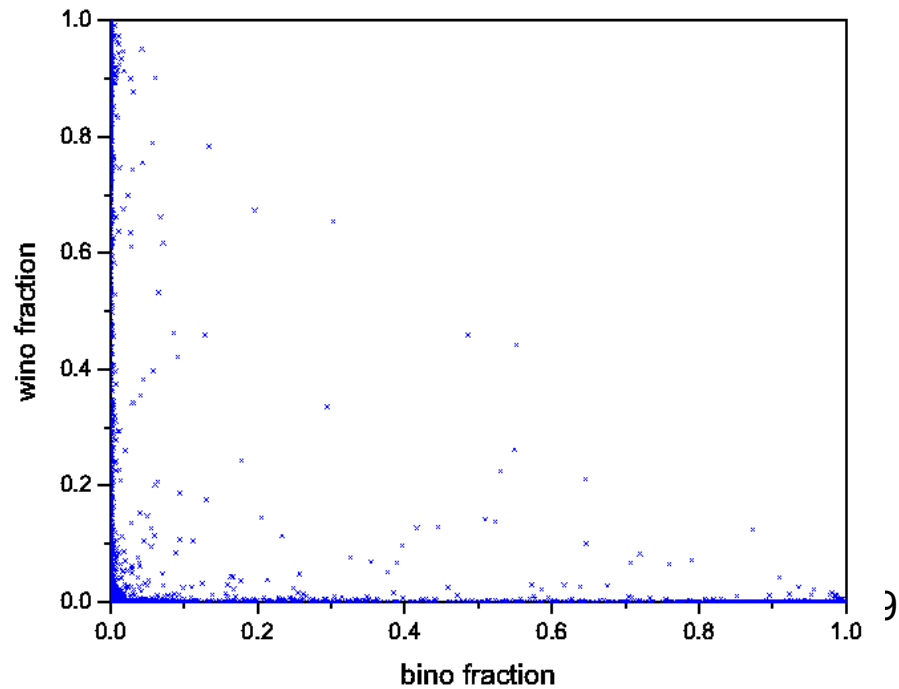
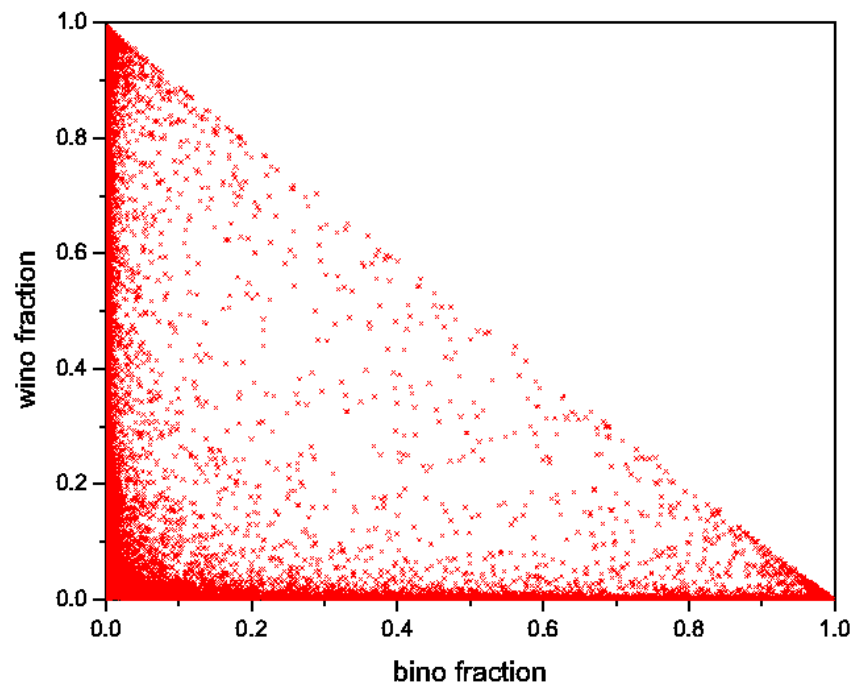
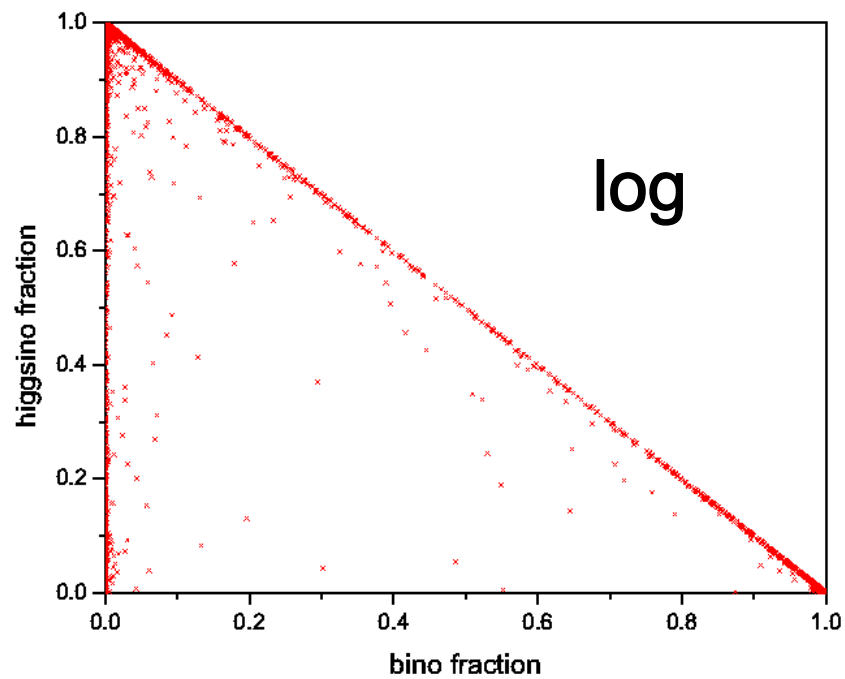
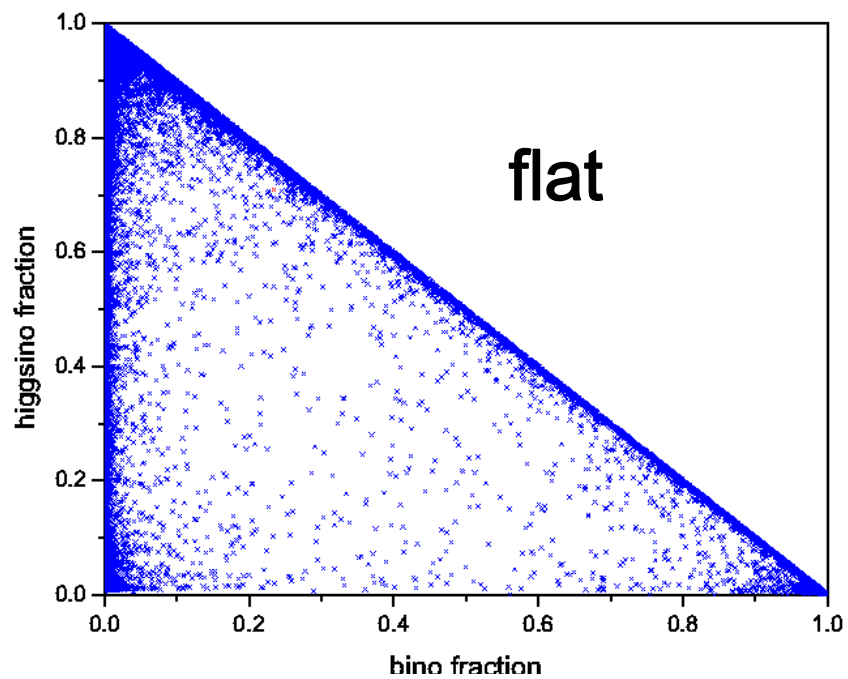
# nLSP-LSP Mass Difference







# LSP Composition

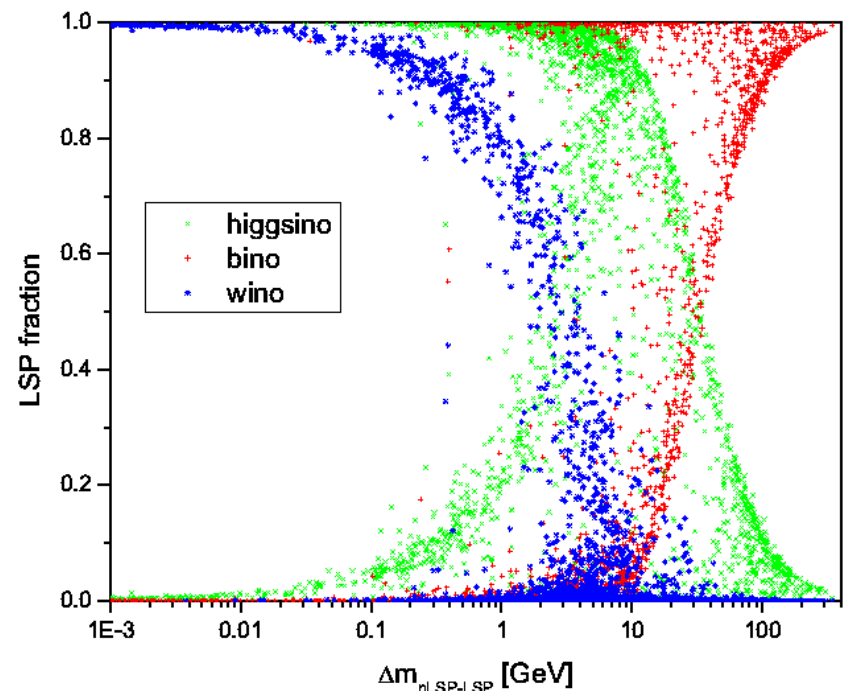
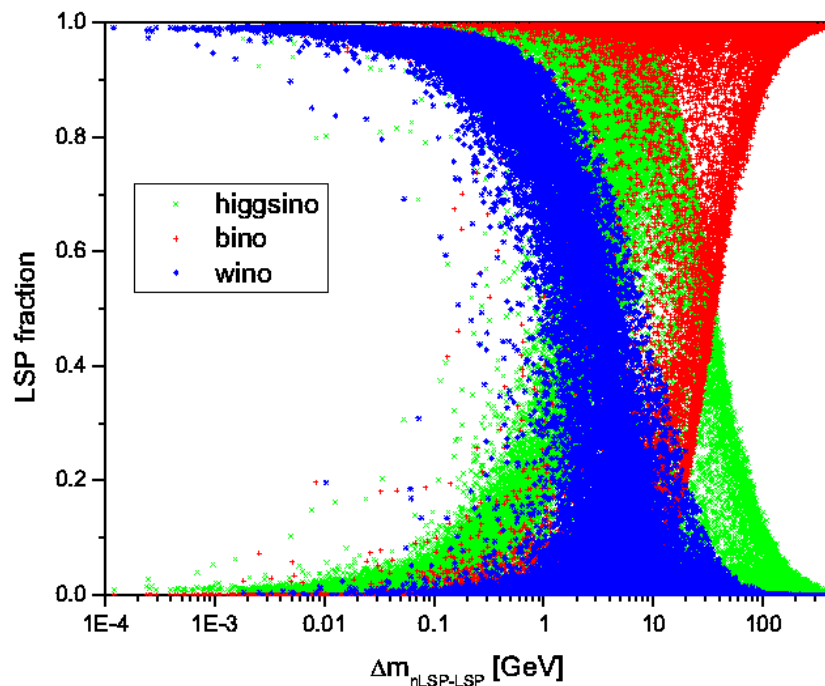


# LSP Composition

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 **bino-like** but VERY small mass splittings produce **wino-like** LSPs. **Higgsino-like** LSPs have 'intermediate' splittings.

Flat

Log

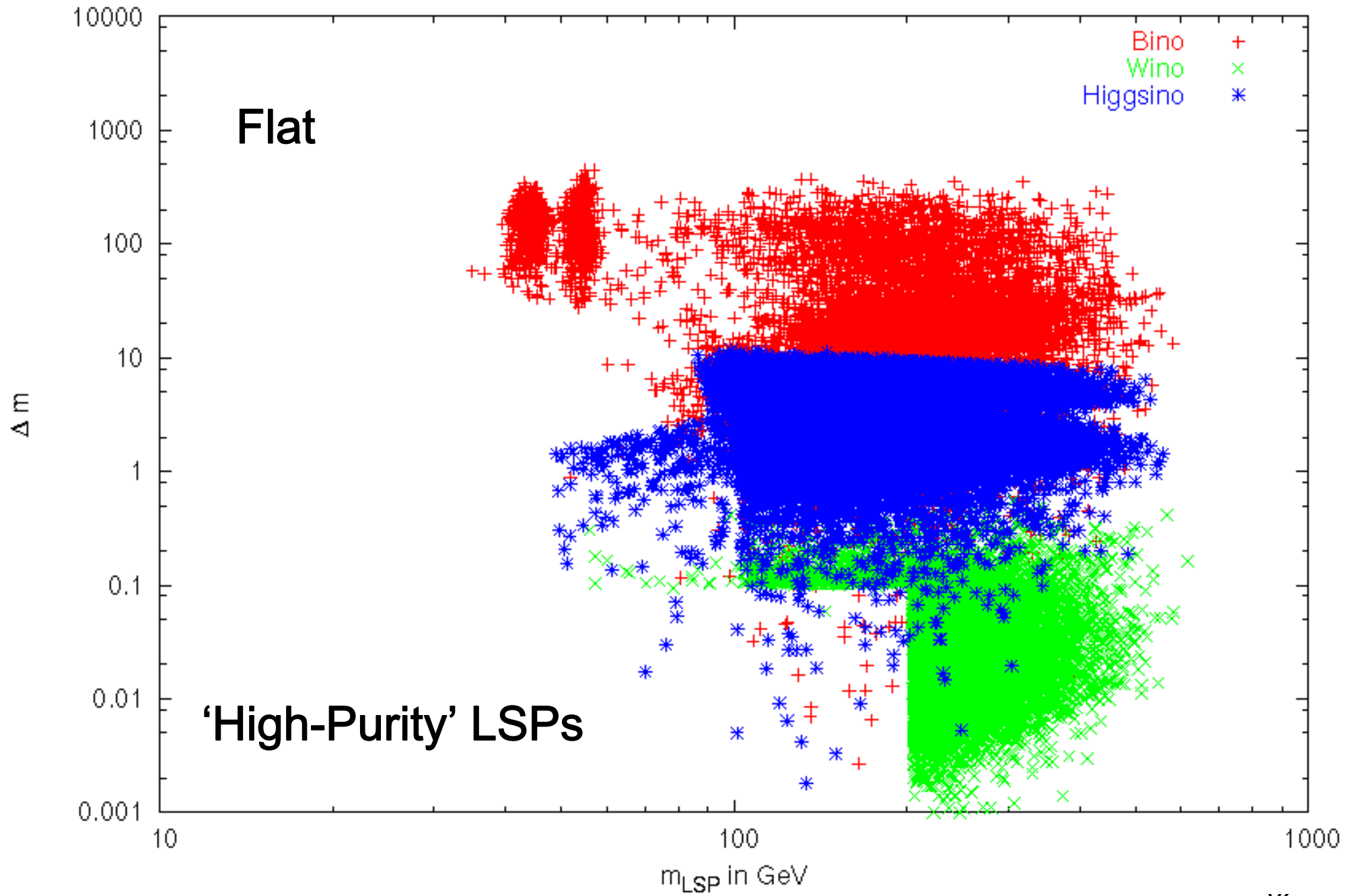


Another way to see this is to just count states with various constrained admixtures of the three weak eigenstates...

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

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

LSP Mass Versus LSP-nLSP Mass Splitting



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<sup>nd</sup> neutralino is close in mass to the LSP as the 2<sup>nd</sup> neutralino decay products may all be missed since they can be very soft; this looks like 4j+MET

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

# ATLAS SUSY Analyses w/ a Large Model Set

- We are running our ~70k MSSM models through the ATLAS SUSY analysis suite , essentially designed for mSUGRA , to explore its sensitivity to this far broader class of SUSY models
- We first need to verify that we can approximately reproduce the ATLAS results for their benchmark mSUGRA models with our analysis techniques
- We have begun our study with the multi-jet + MET analyses
- By necessity there are some differences between the two analyses.....
- This is extremely CPU intensive !

# ATLAS

ISASUGRA generates spectrum  
& sparticle decays

NLO cross section using  
PROSPINO & CTEQ6M

Herwig for fragmentation &  
hadronization

GEANT4 for full detector sim

# FEATURE

SuSpect generates spectra  
with SUSY-HIT for decays

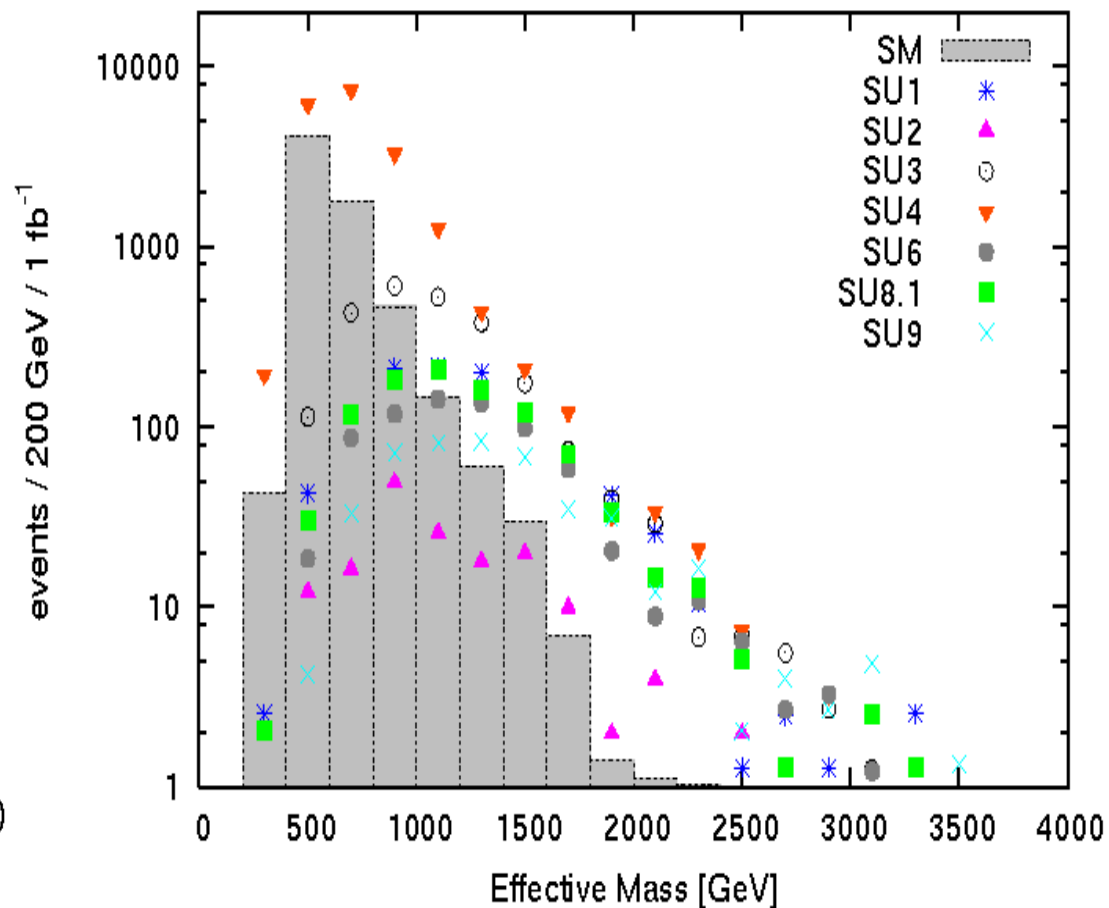
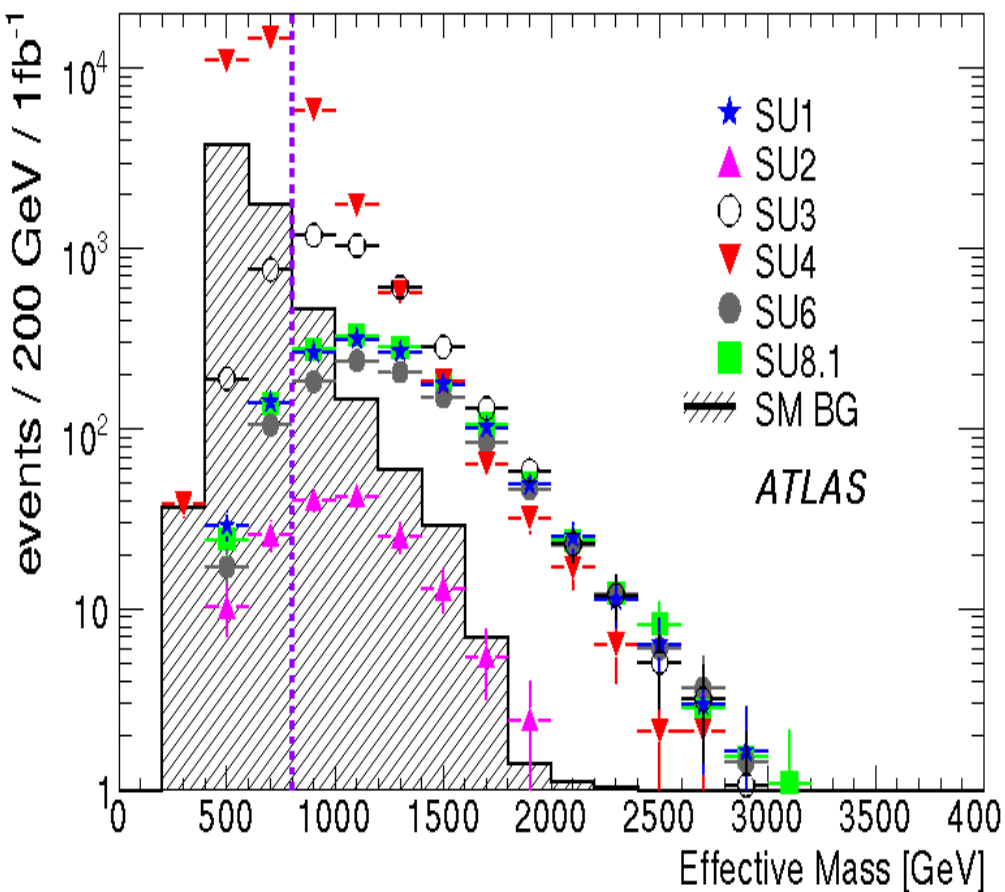
NLO cross section for ~85  
processes using PROSPINO\*\*  
& CTEQ6.6M

PYTHIA for fragmentation &  
hadronization

PGS4-ATLAS for fast detector  
sim

\*\* version w/ negative K-factor errors corrected

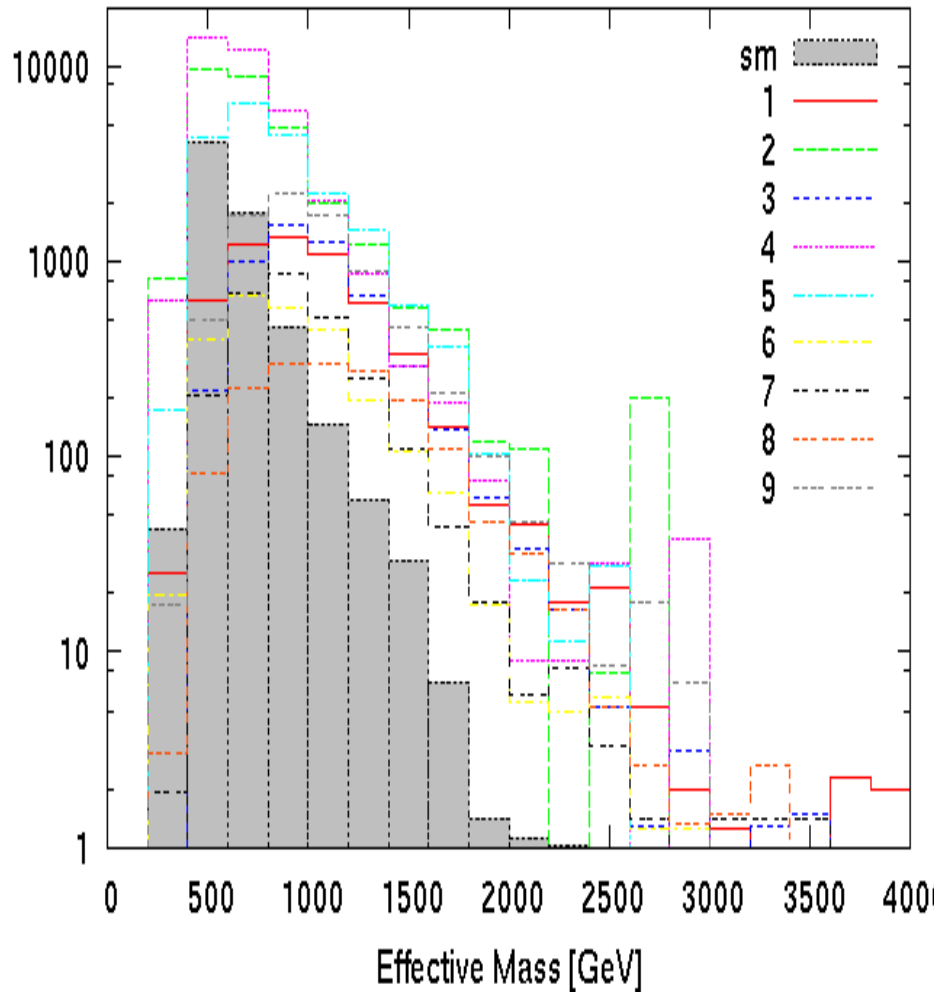
# 4-jet +MET



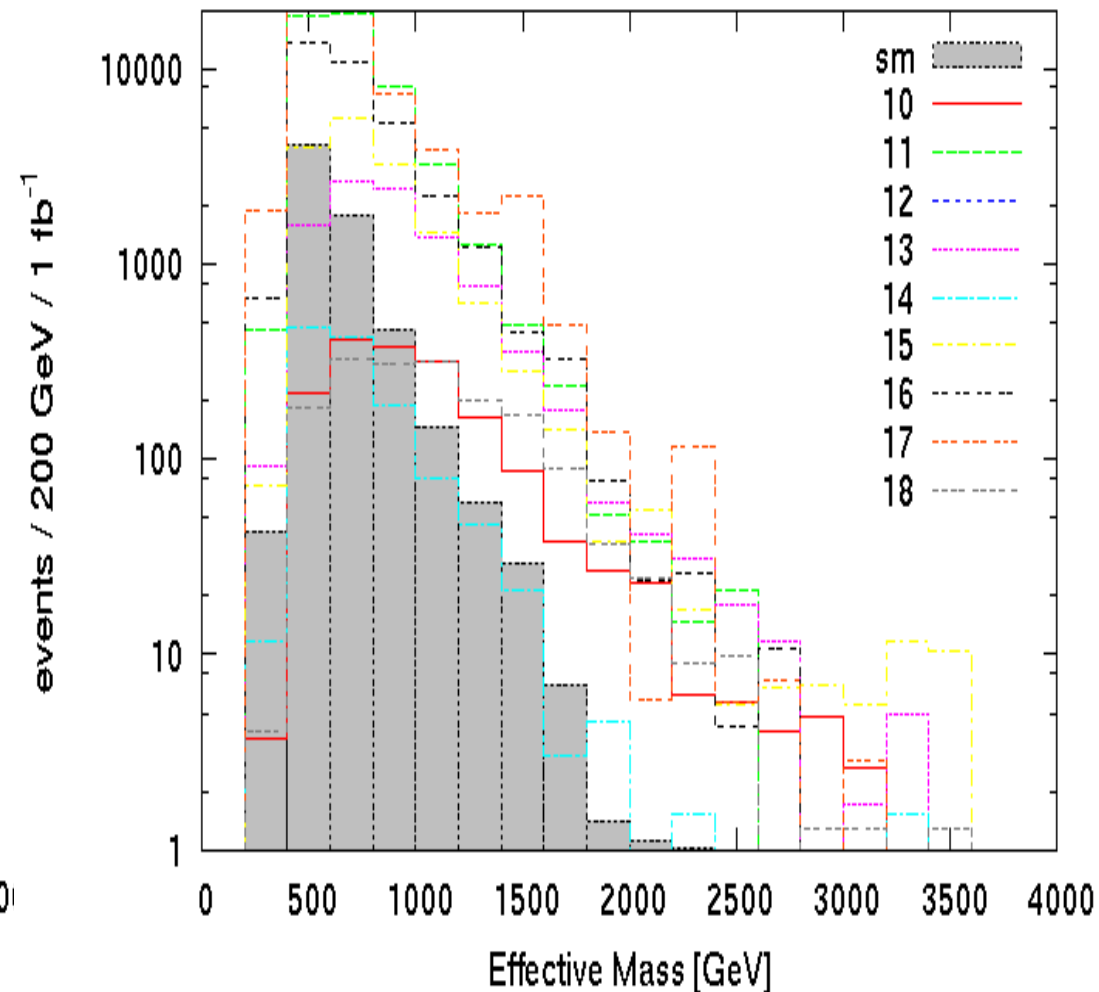
We do a good job at reproducing the mSUGRA benchmarks in this channel . If anything, our rates are a bit **LOWER** than are those obtained by ATLAS.

# Sample Model Results

4 jet, 0 lepton analysis

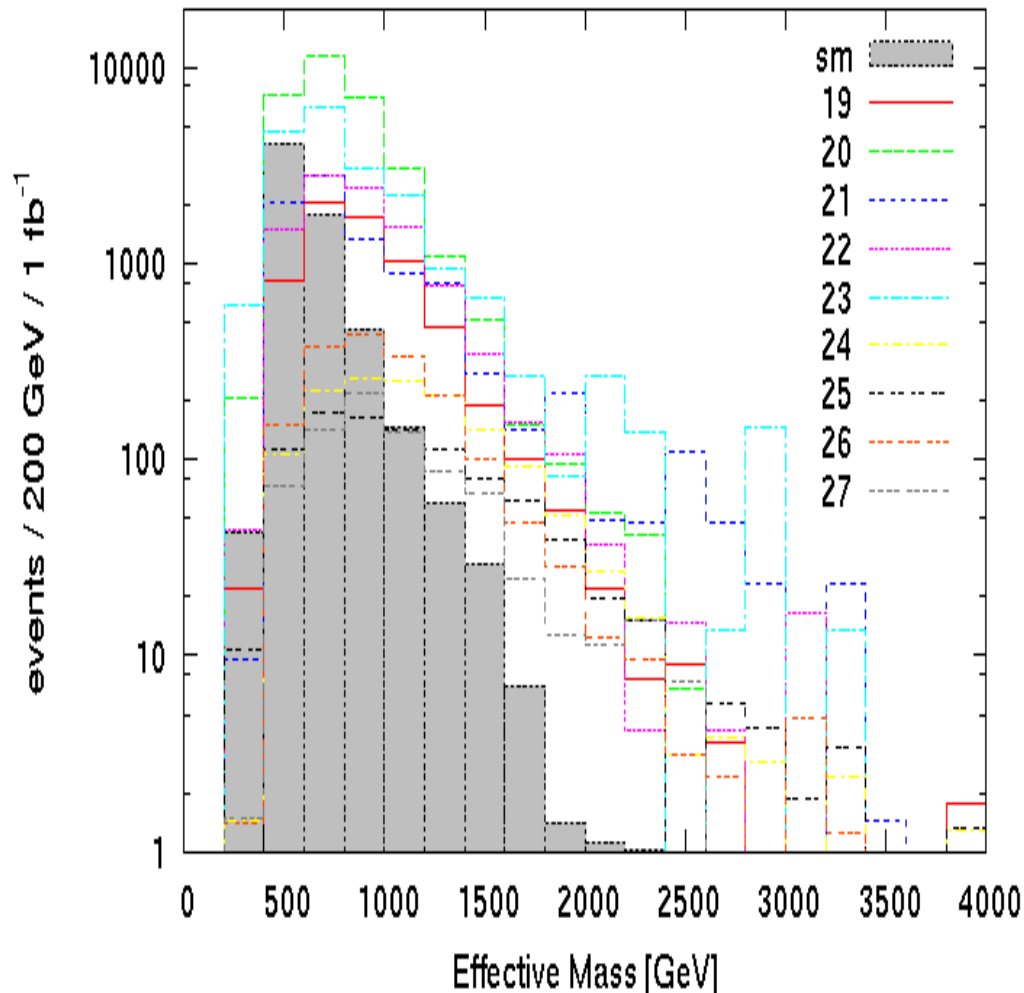


4 jet, 0 lepton analysis

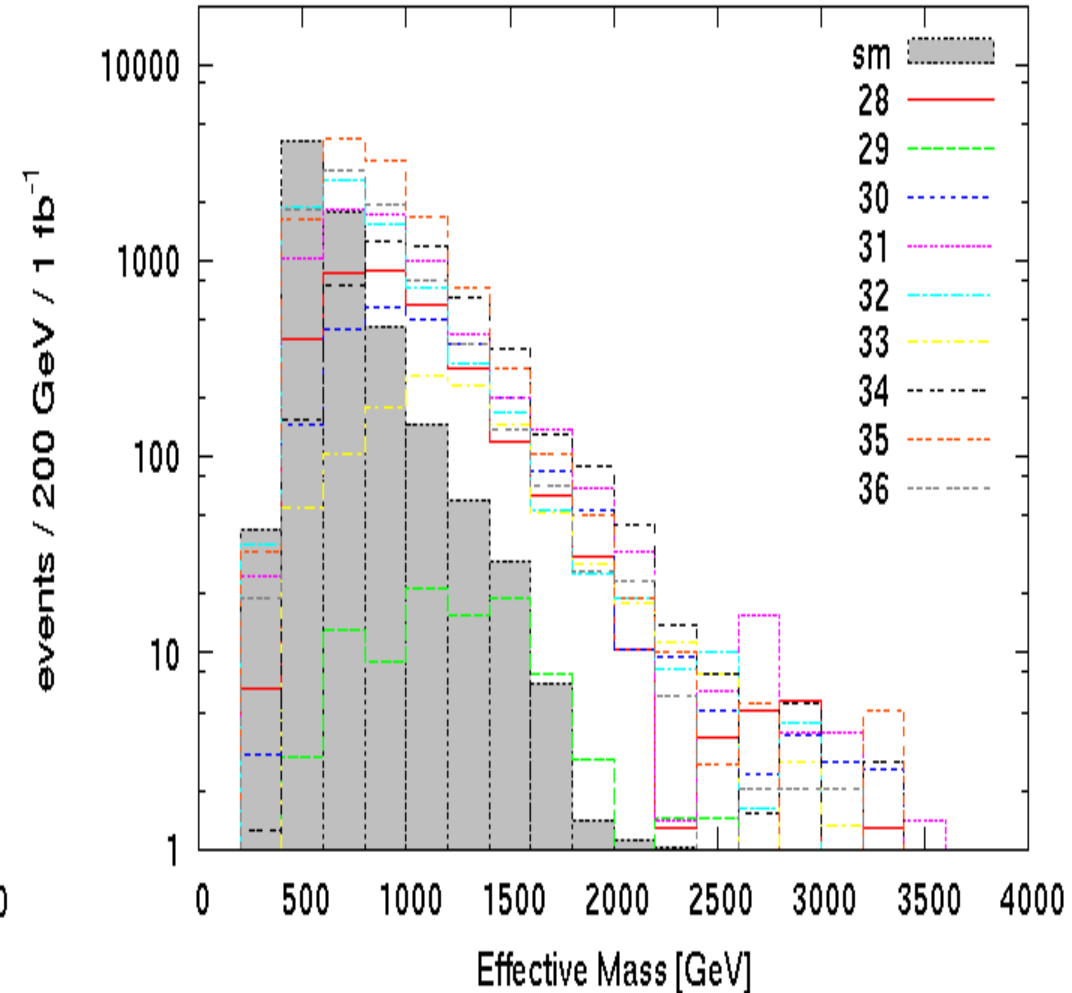


# Sample Model Results (cont.)

4 jet, 0 lepton analysis

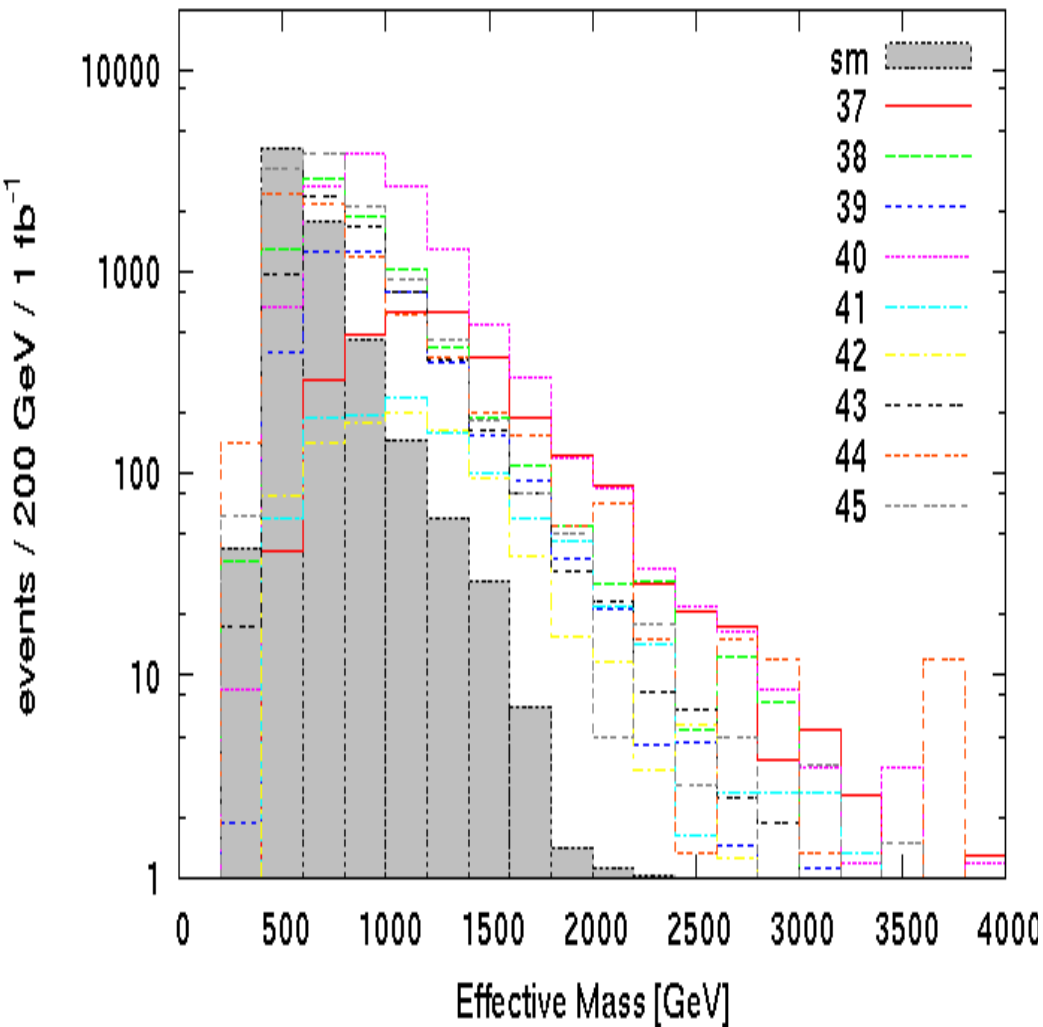


4 jet, 0 lepton analysis

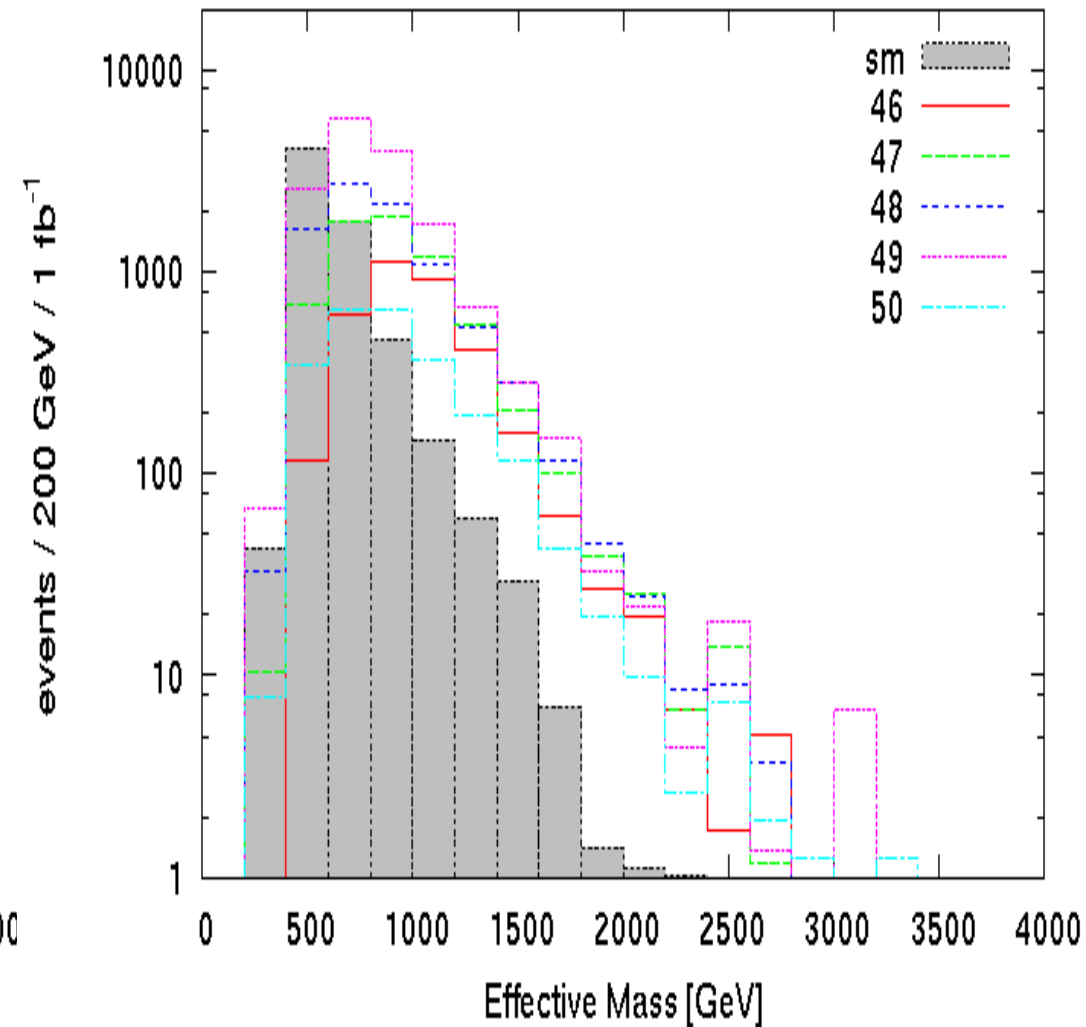


# Sample Model Results (cont.)

4 jet, 0 lepton analysis



4 jet, 0 lepton analysis

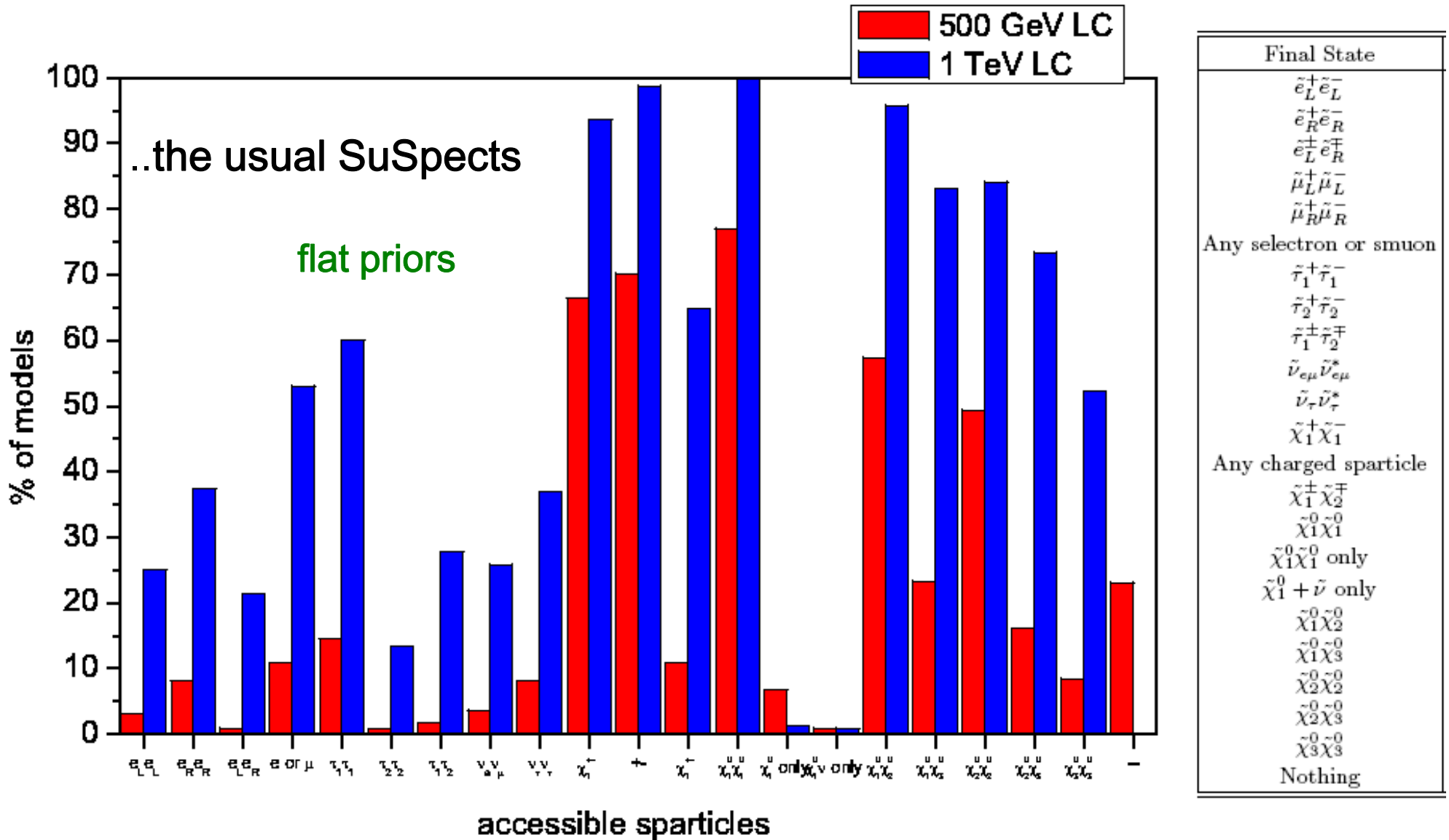


# What can we conclude from this ???

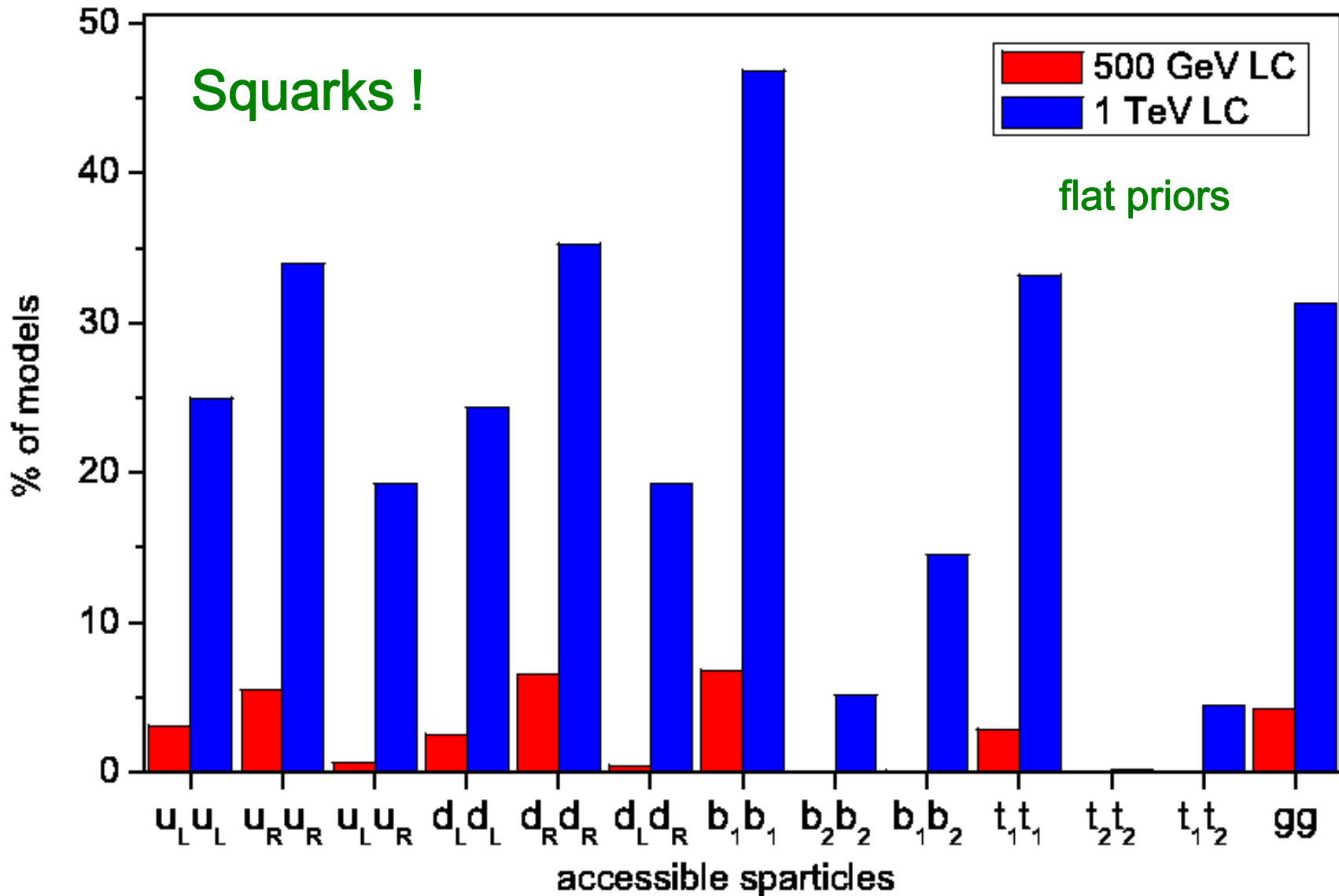
There are many models which will show a respectable signal in this channel.. But this is a VERY SMALL set to base any conclusions on..After all, it's only ~0.07% of all of our models !!!

More work is needed in this channel and all the others ...code is running on hundreds of processors right now !!!!

# Kinematic Accessibility at the ILC : I



# Kinematic Accessibility at the ILC : III



# 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 it can be.
- The study of these complex models is still at early stage..

# BACKUP SLIDES

# Dark Matter Challenge



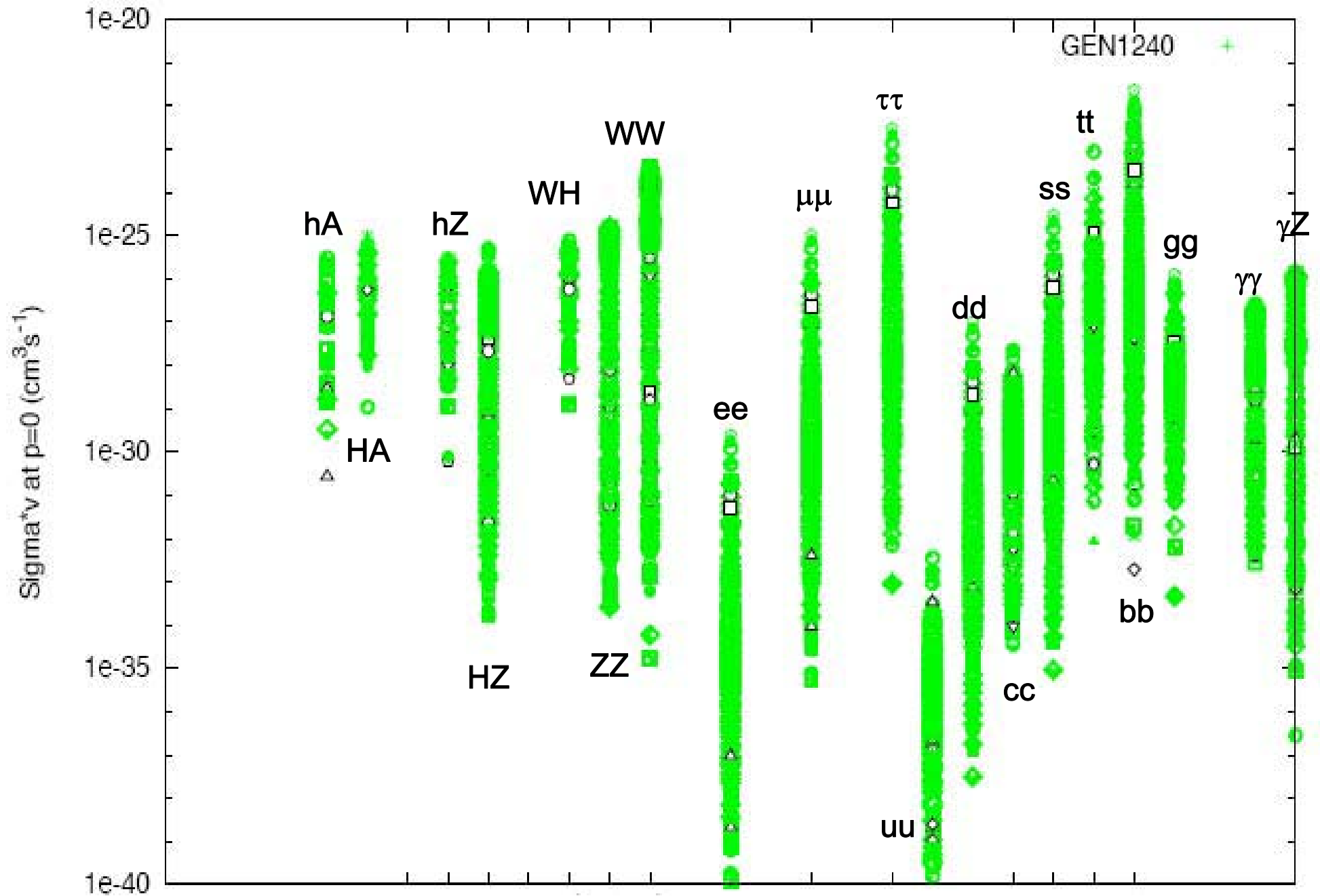
Can we find models (out of our ~70k model sample) that ALSO

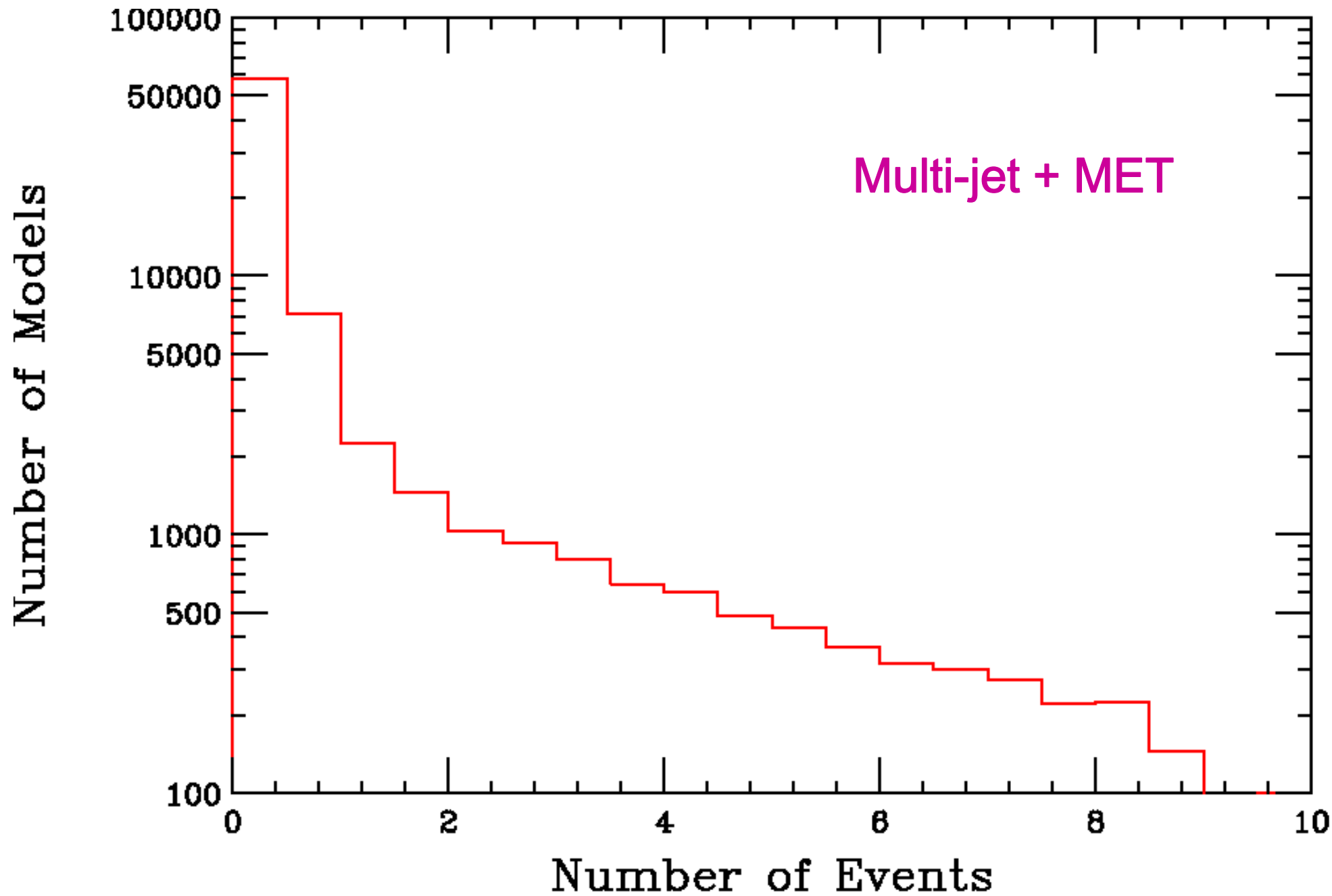
- saturate the WMAP dark matter constraint (~ 1300 models)
- can reproduce the positron flux seen at PAMELA with 'low'  $\chi^2$  & a 'small' boost factor
- can avoid the PAMELA anti-proton constraints with the *same* boost factor (though this need not be the case!)

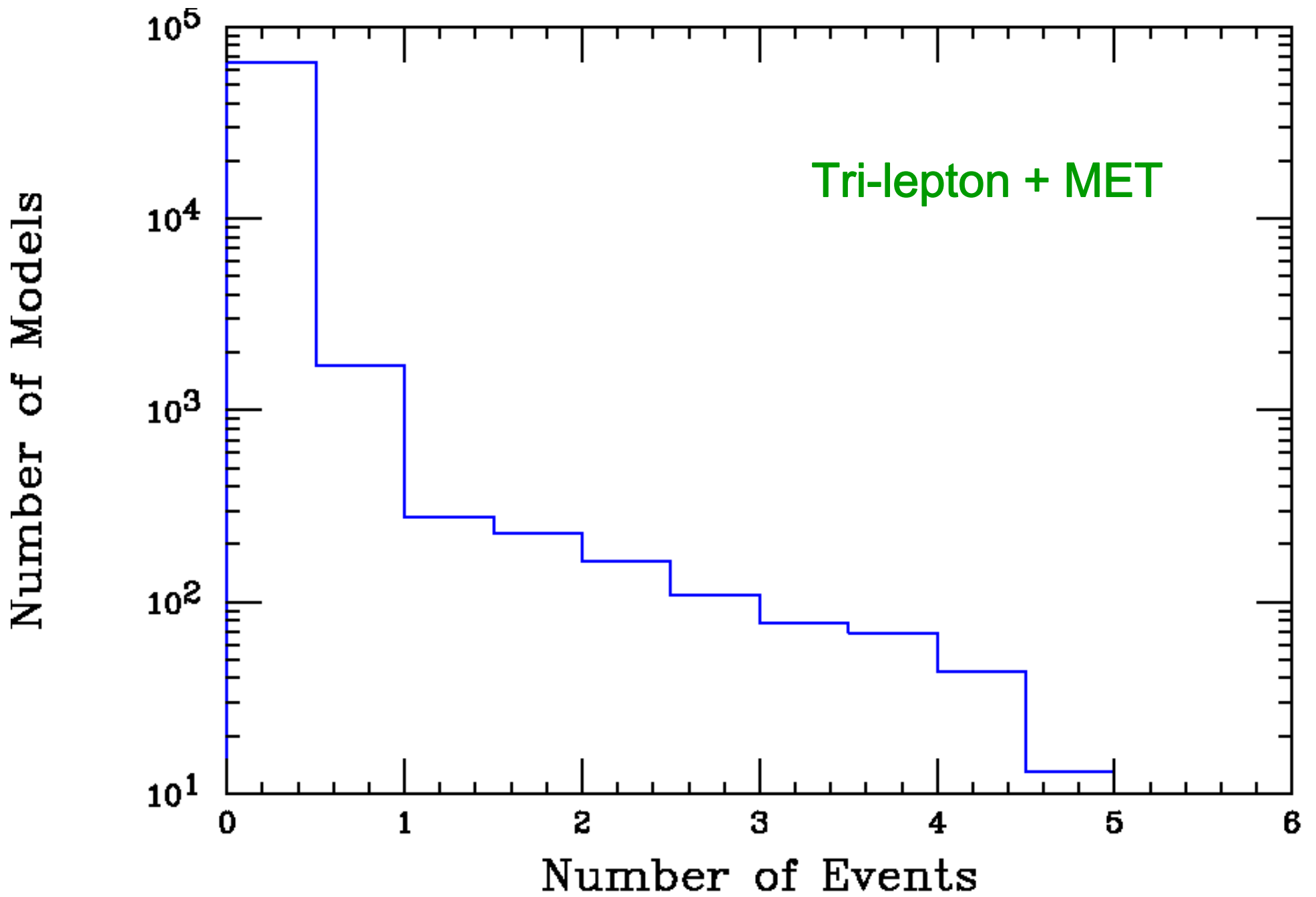
as we might hope since we have such a large parameter space?

**YES !!**

# Annihilation Cross Sections for ~1200 Random Models

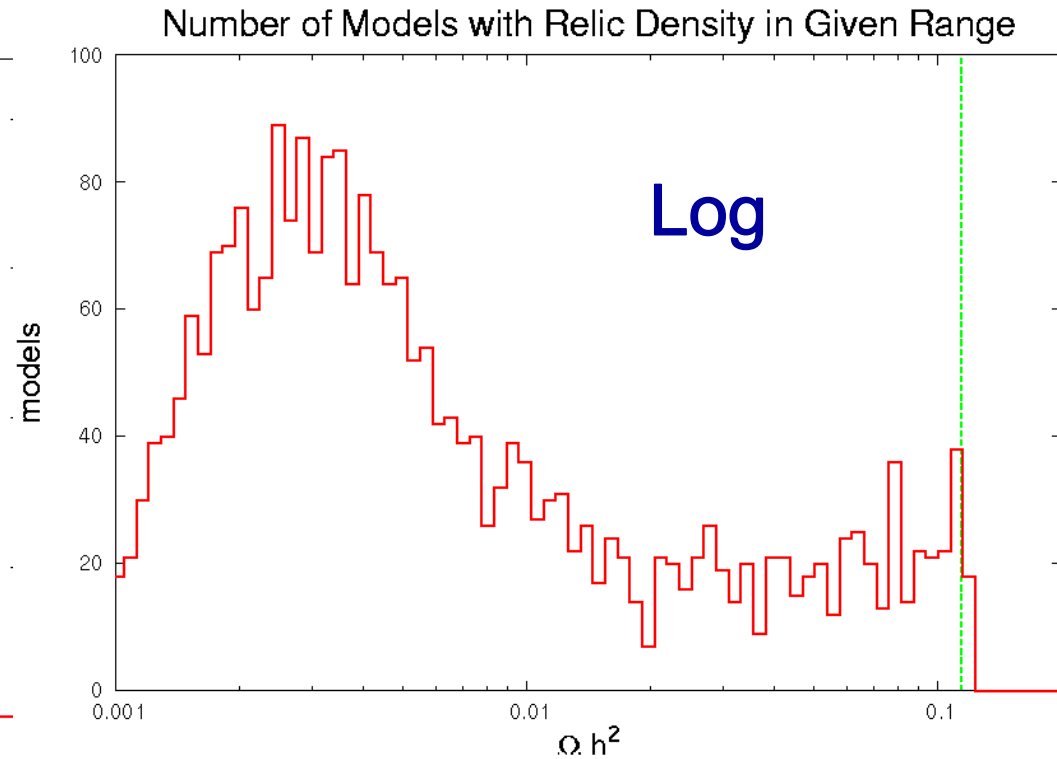
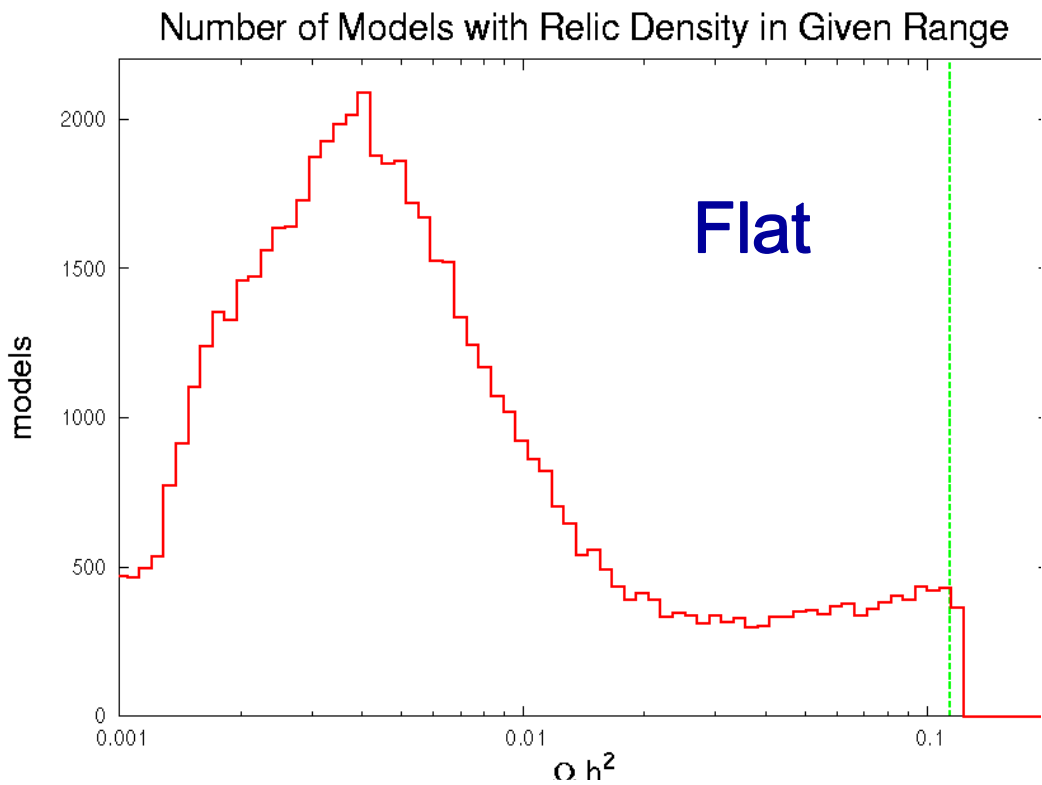






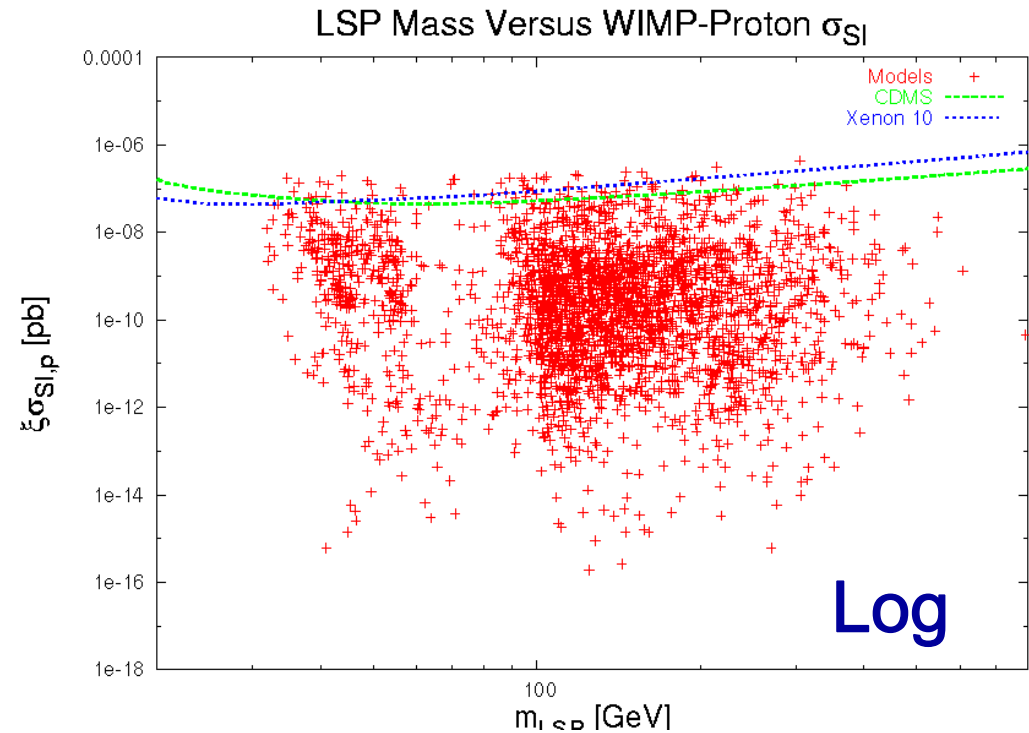
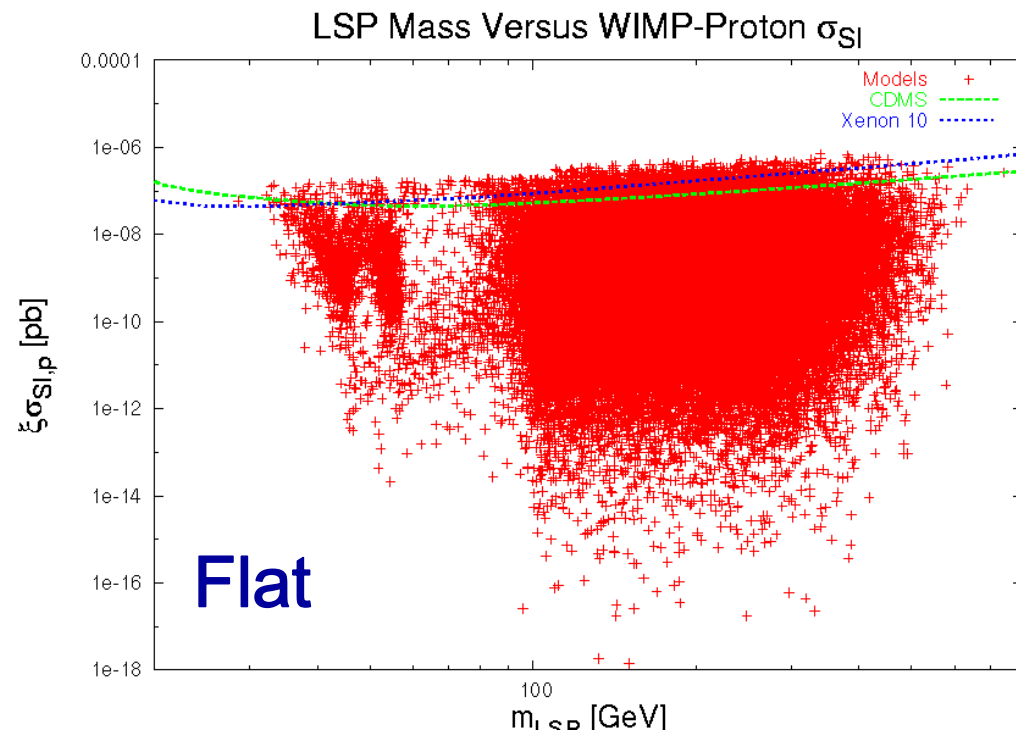
# Predicted Dark Matter Density : $\Omega h^2$

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..



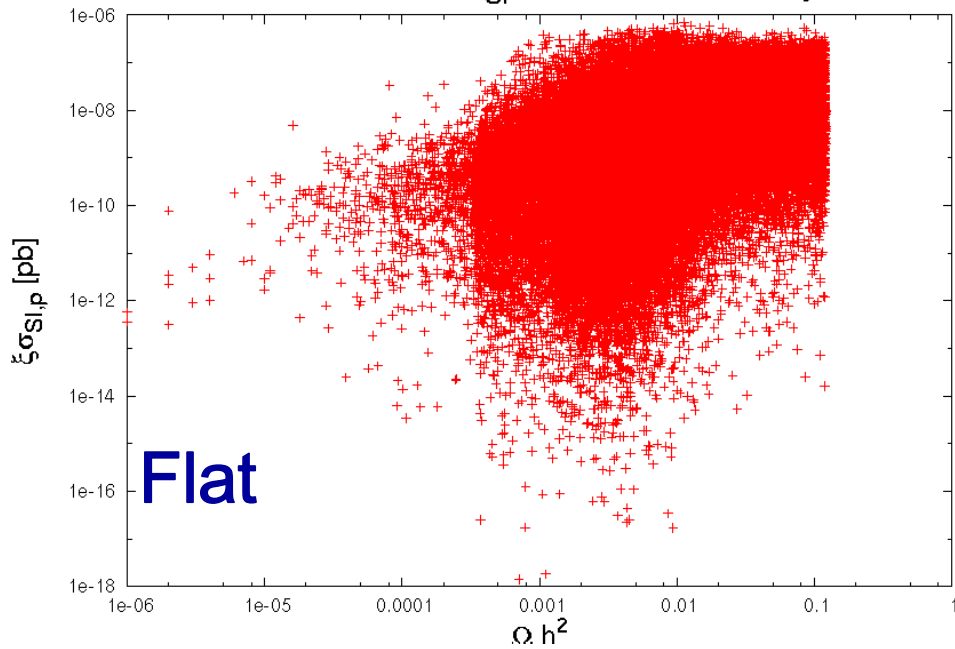
# Direct Detection Expectations

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

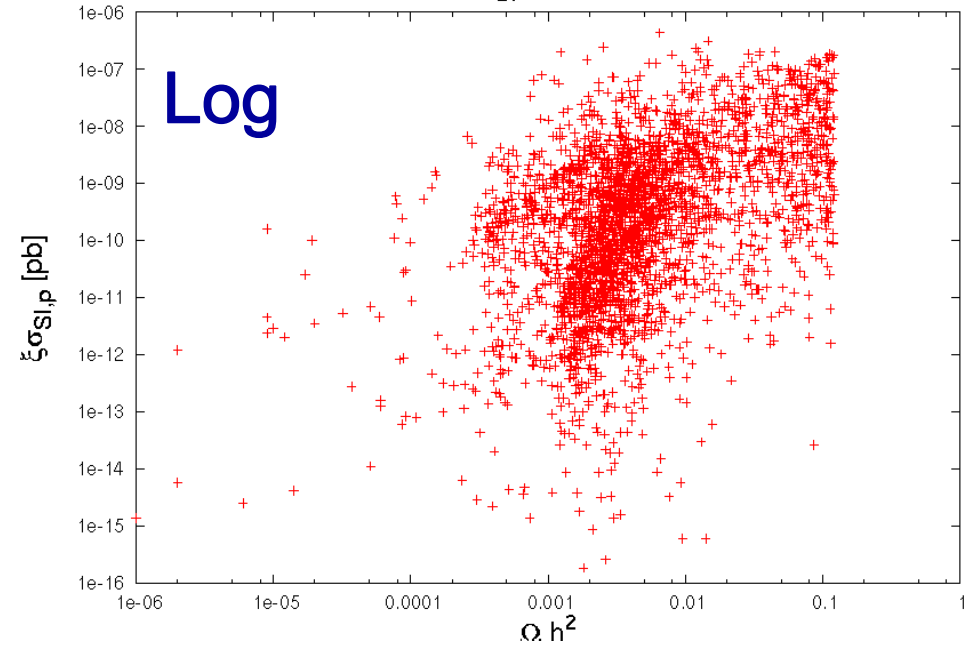


# Dark Matter Density Correlation with the Direct Search Cross Section

WIMP-Proton  $\sigma_{SI}$  Versus Relic Density



WIMP-Proton  $\sigma_{SI}$  Versus Relic Density



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

**For the curious:**

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

For many models this is not the unique source of failure

# Similarly for the SPS Points

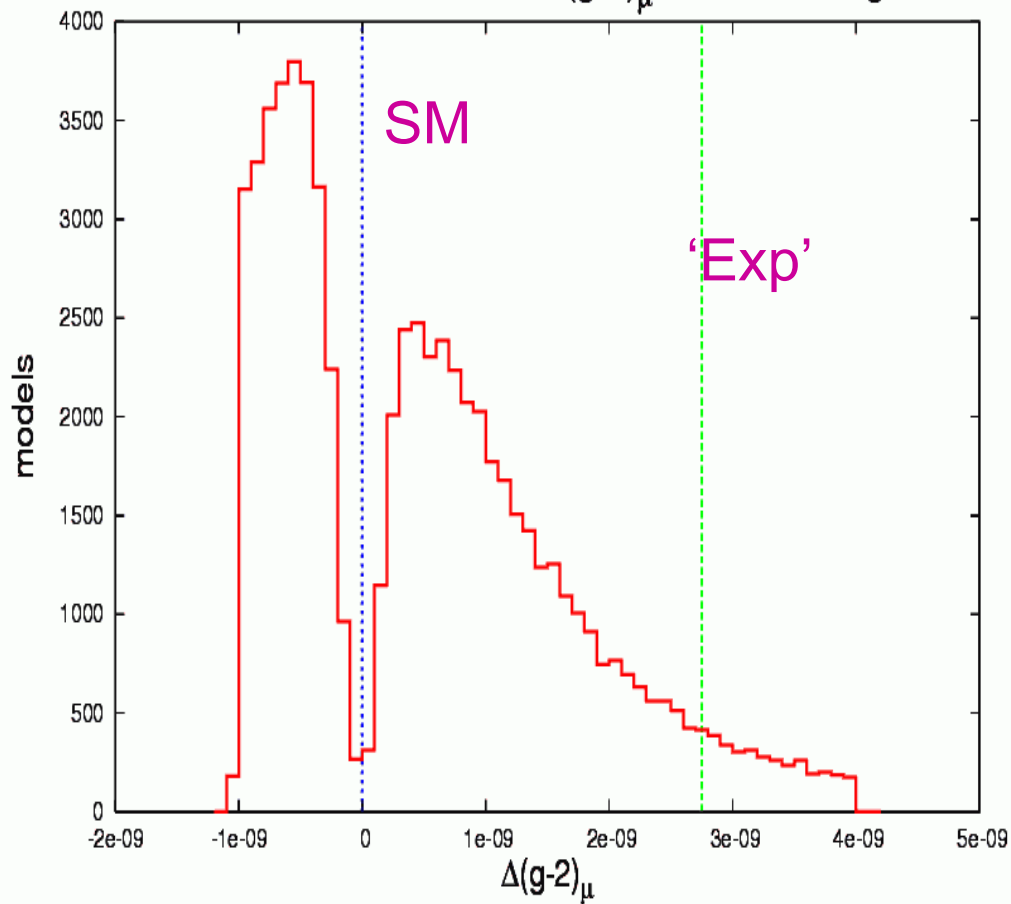
SPS1a	killed by $b \rightarrow s\gamma$
SPS1a'	OK
SPS1b	killed by $b \rightarrow s\gamma$
SPS2	killed by $\Omega h^2$ (GUT) / OK(low)
SPS3	killed by $\Omega h^2$ (low) / OK(GUT)
SPS4	killed by $g-2$
SPS5	killed by $\Omega h^2$
SPS6	OK
SPS9	killed by Tevatron stable chargino

# Predictions for $\Delta(g-2)_\mu$

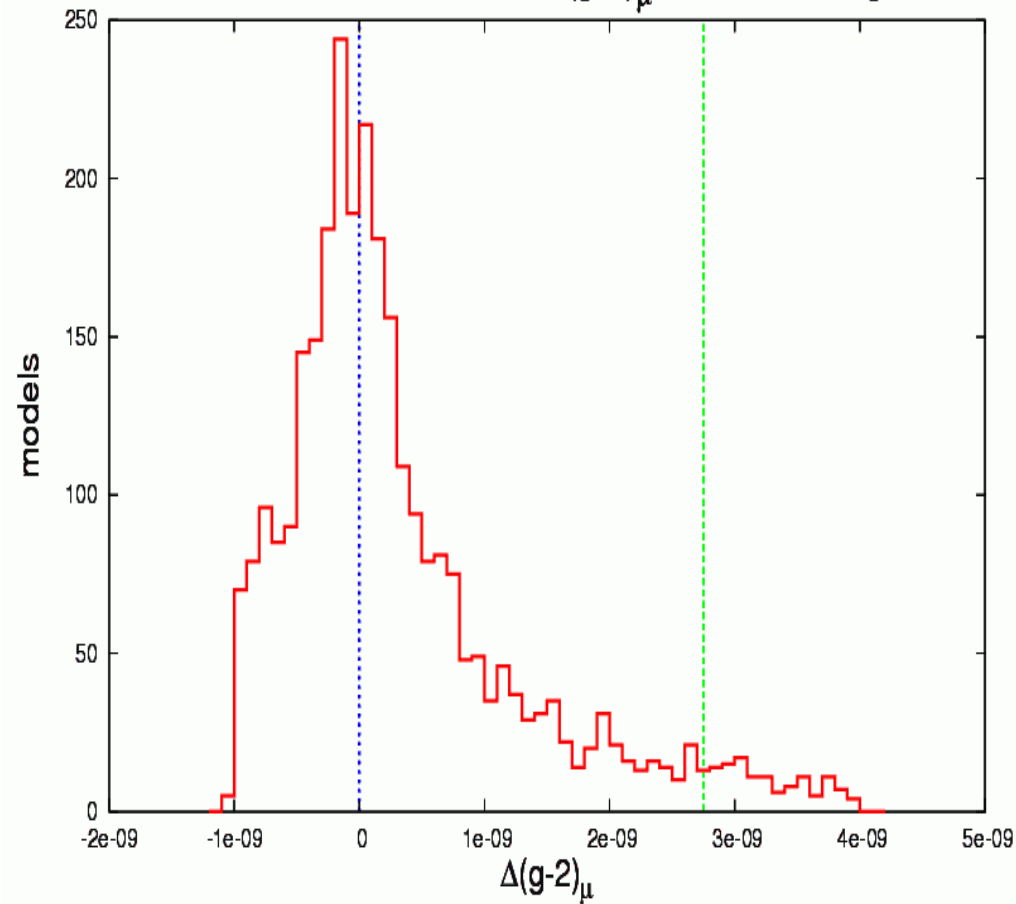
flat

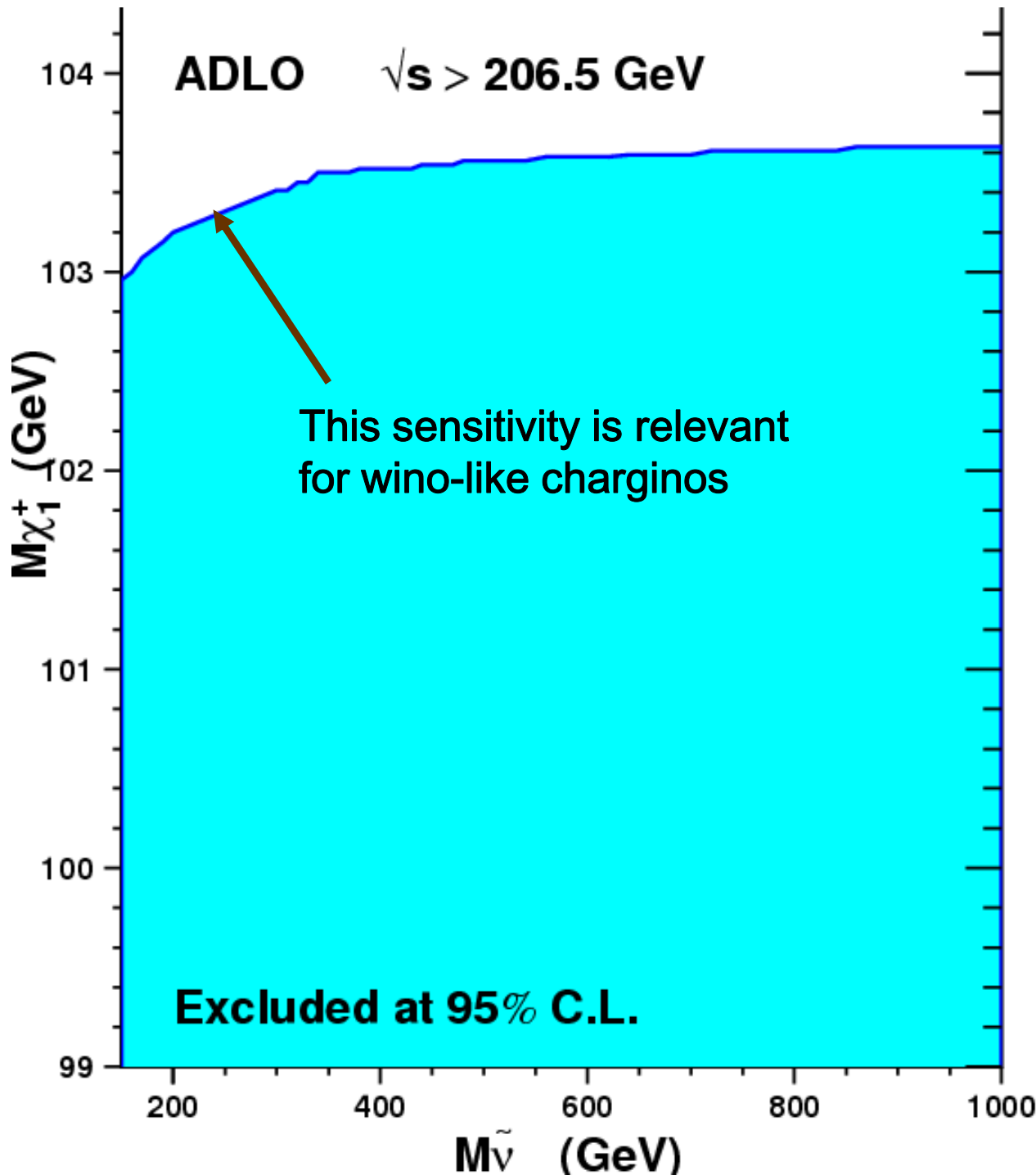
log

Number of Models with  $\Delta(g-2)_\mu$  in Given Range



Number of Models with  $\Delta(g-2)_\mu$  in Given Range



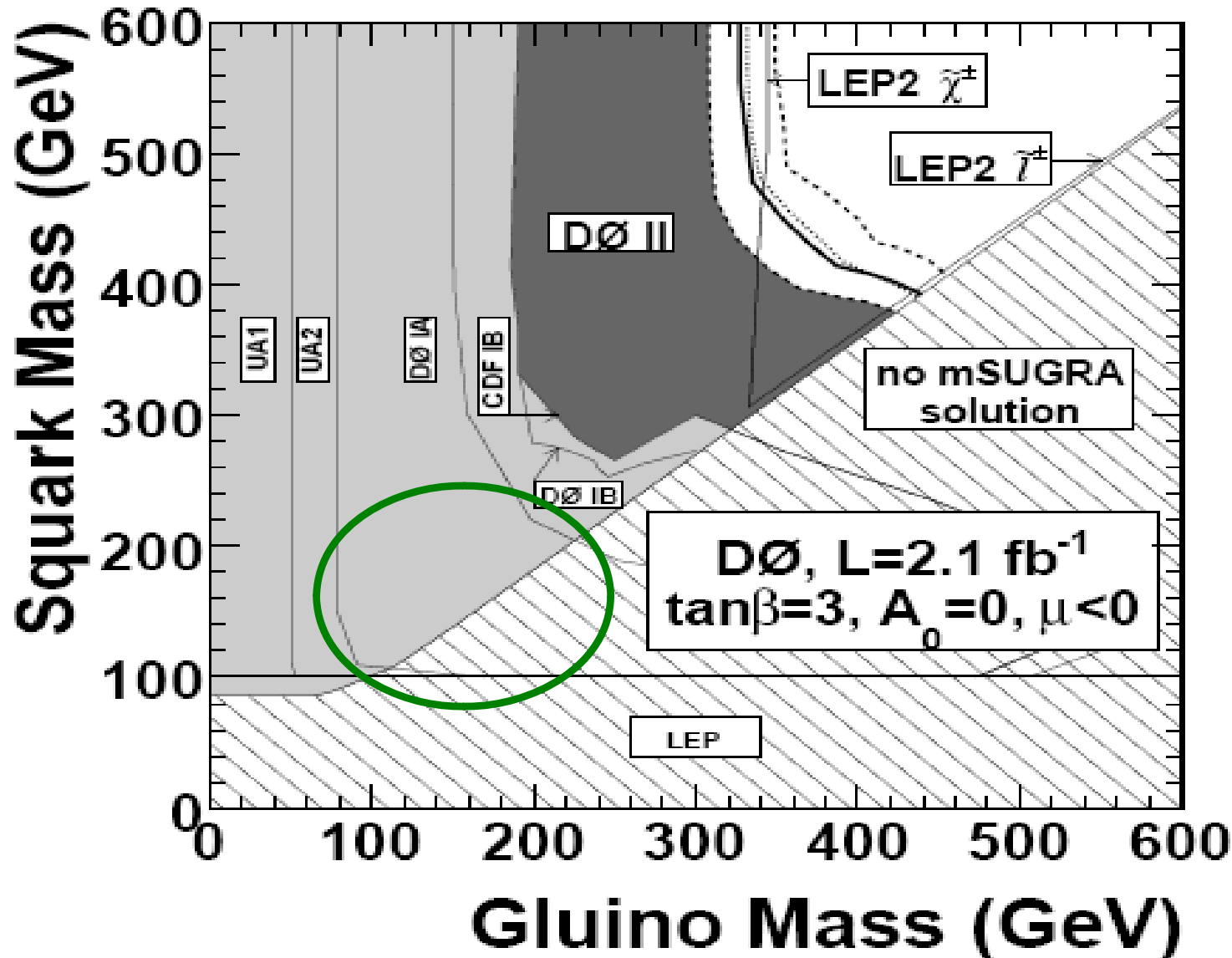


Large mass gap chargino search

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

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

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



# LEP II: Associated Higgs Production

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

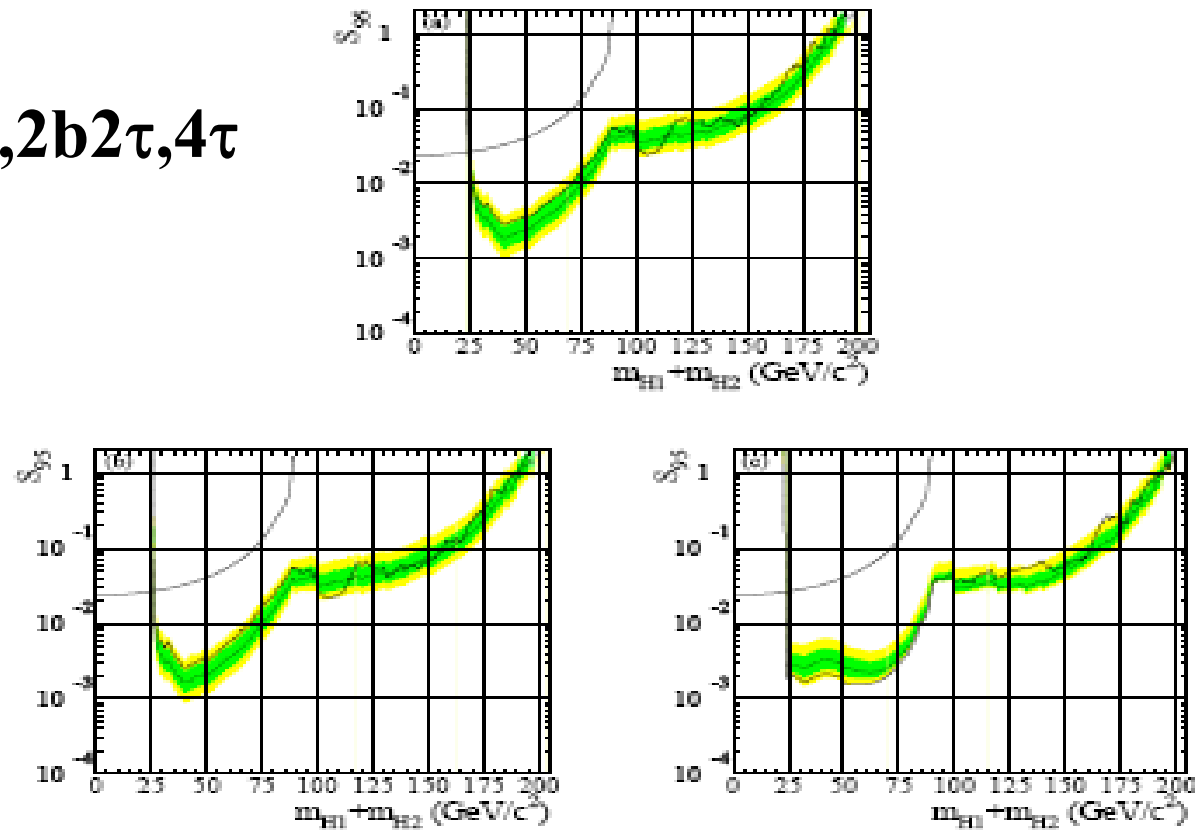
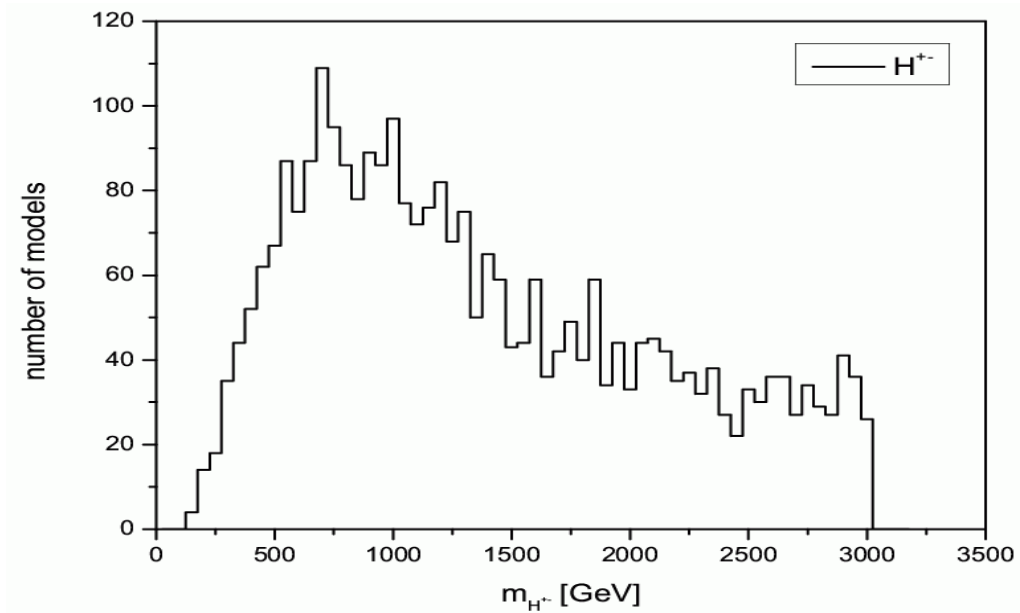
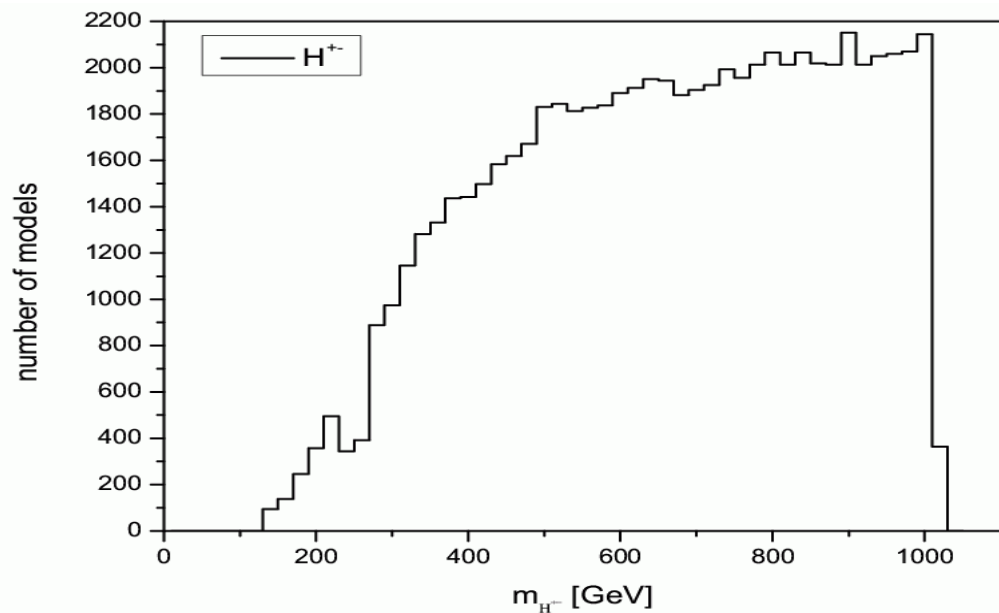
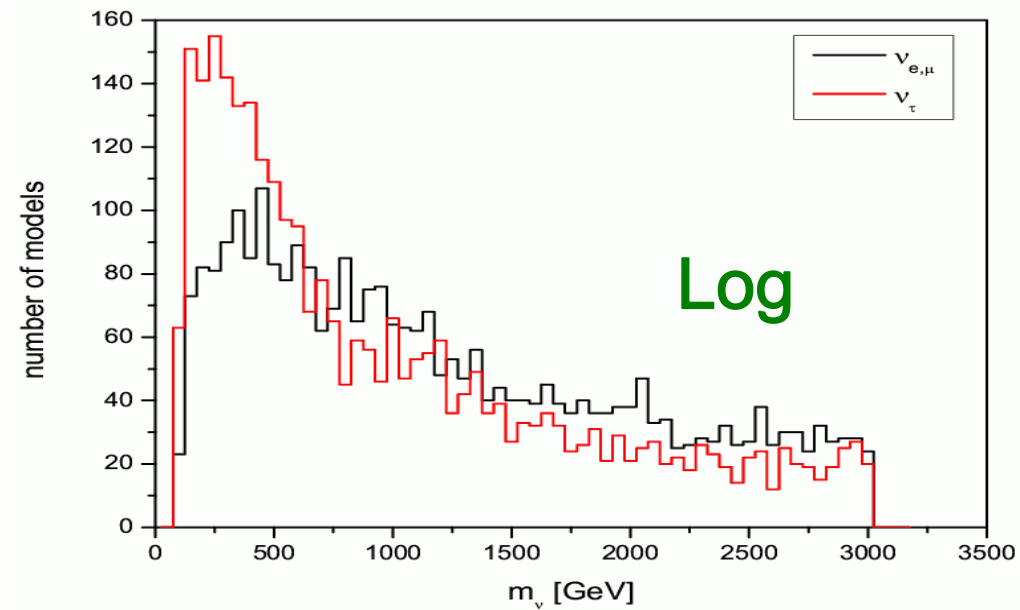
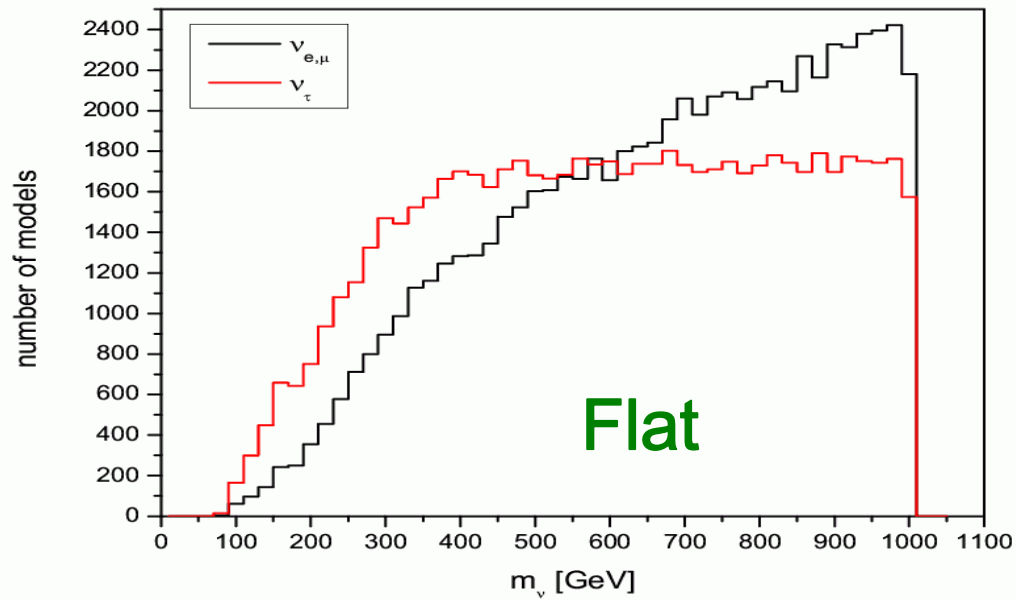


Figure 3: Model-independent 95% c.l. upper bounds,  $S_{95}$ , for various topological cross sections motivated by the pair-production process  $e^+e^- \rightarrow H_2 H_1$ , for the particular case where  $m_{H_1}$  and  $m_{H_2}$  are approximately equal. Such is the case, for example, in the CP-conserving 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%  $H_1 \rightarrow bb$ , 6%  $H_1 \rightarrow \tau^+\tau^-$ , 92%  $H_2 \rightarrow bb$  and 8%  $H_2 \rightarrow \tau^+\tau^-$ ; 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.

# Distribution of Sparticle Masses By Species



# Distribution of Sparticle Masses By Species

