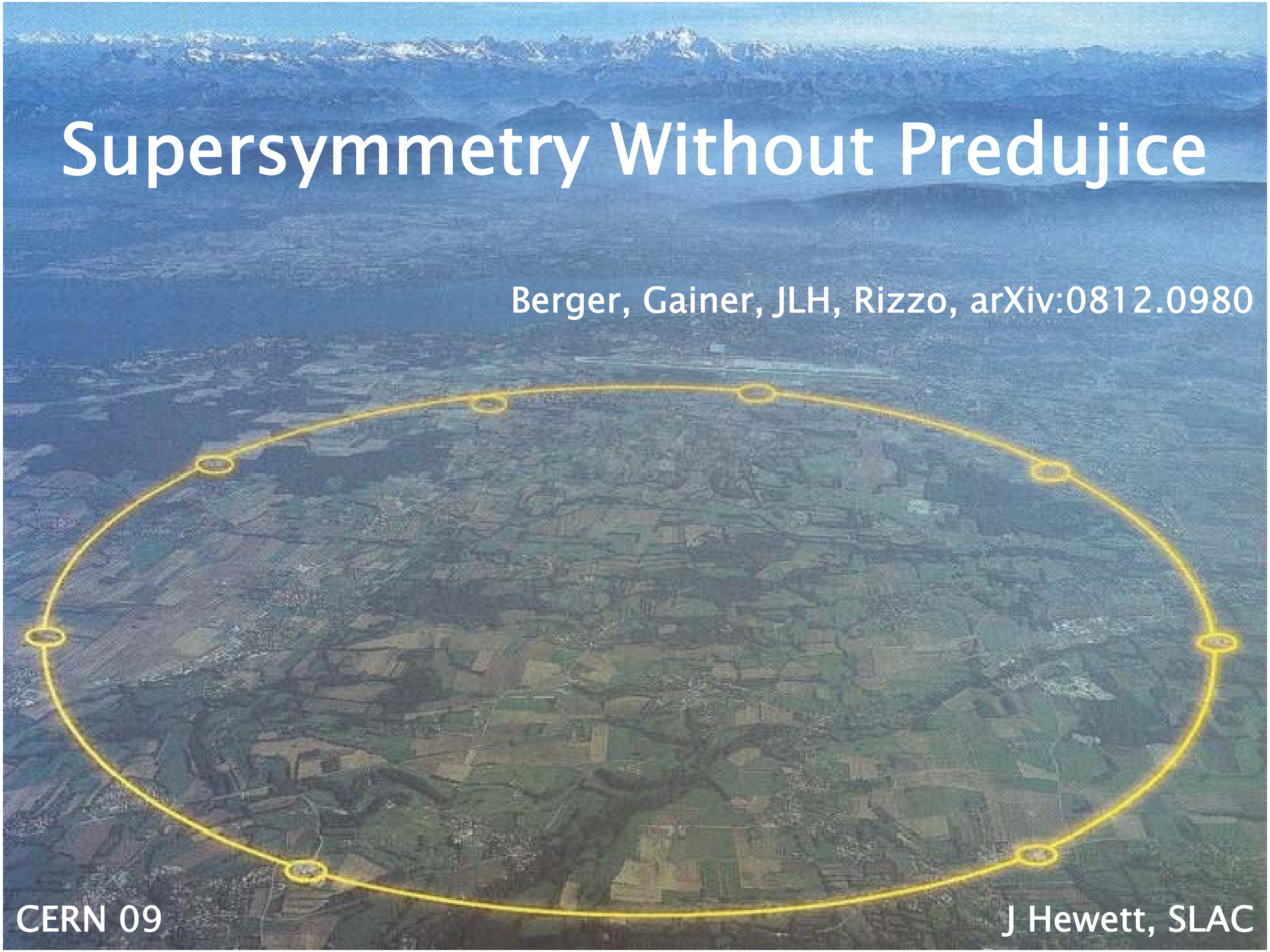


Supersymmetry Without Predujice

Berger, Gainer, JLH, Rizzo, arXiv:0812.0980

CERN 09

J Hewett, SLAC

Supersymmetry With or Without Prejudice?

- The Minimal Supersymmetric Standard Model has ~120 parameters
- Studies/Searches incorporate simplified versions
  - Theoretical assumptions @ GUT scale
  - Assume specific SUSY breaking scenarios (mSUGRA, GMSB, AMSB)
  - Small number of well-studied benchmark points
- Studies incorporate various data sets

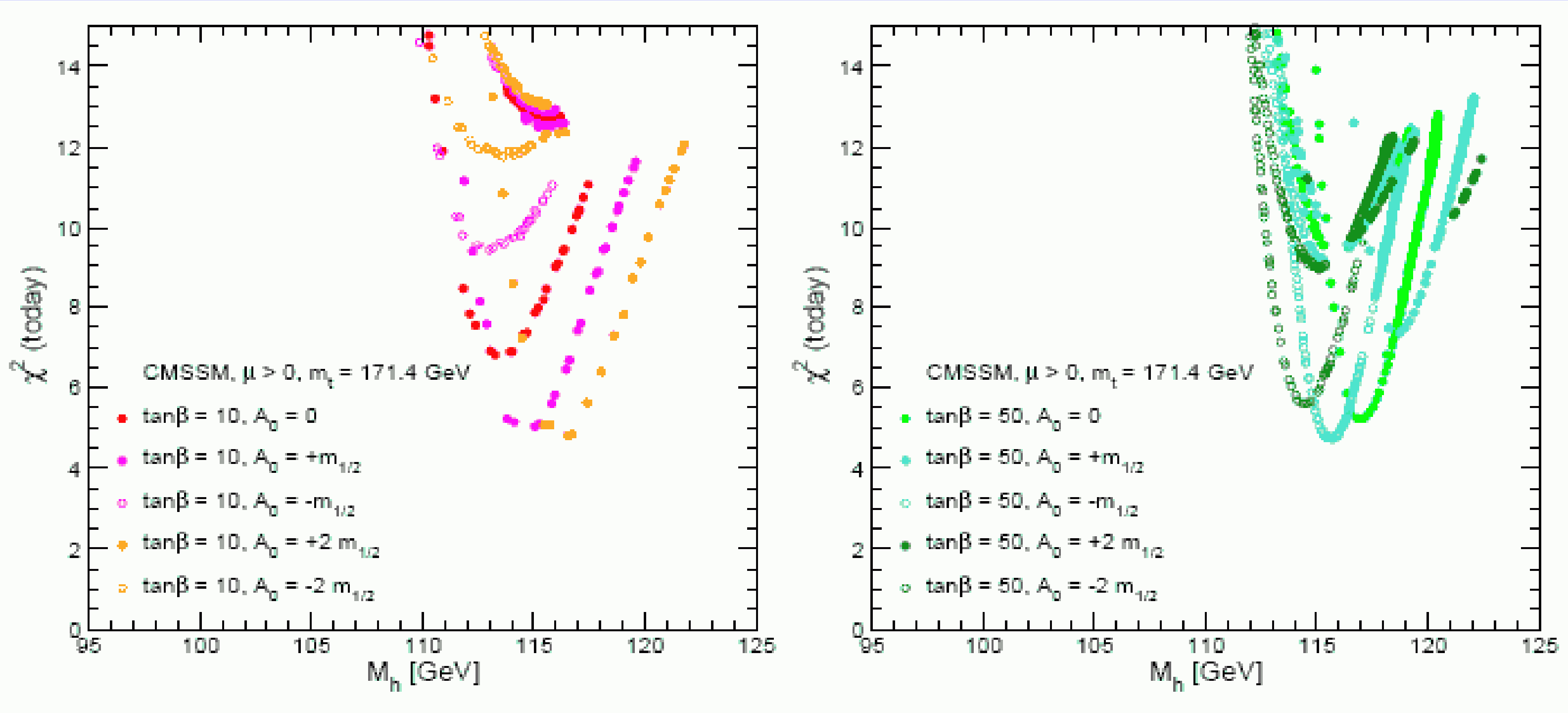
- Does this adequately describe the true breadth of the MSSM and all its possible signatures?

- The LHC is turning on, era of speculation will end, and we need to be ready for all possible signals

Most Analyses Assume CMSSM Framework

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

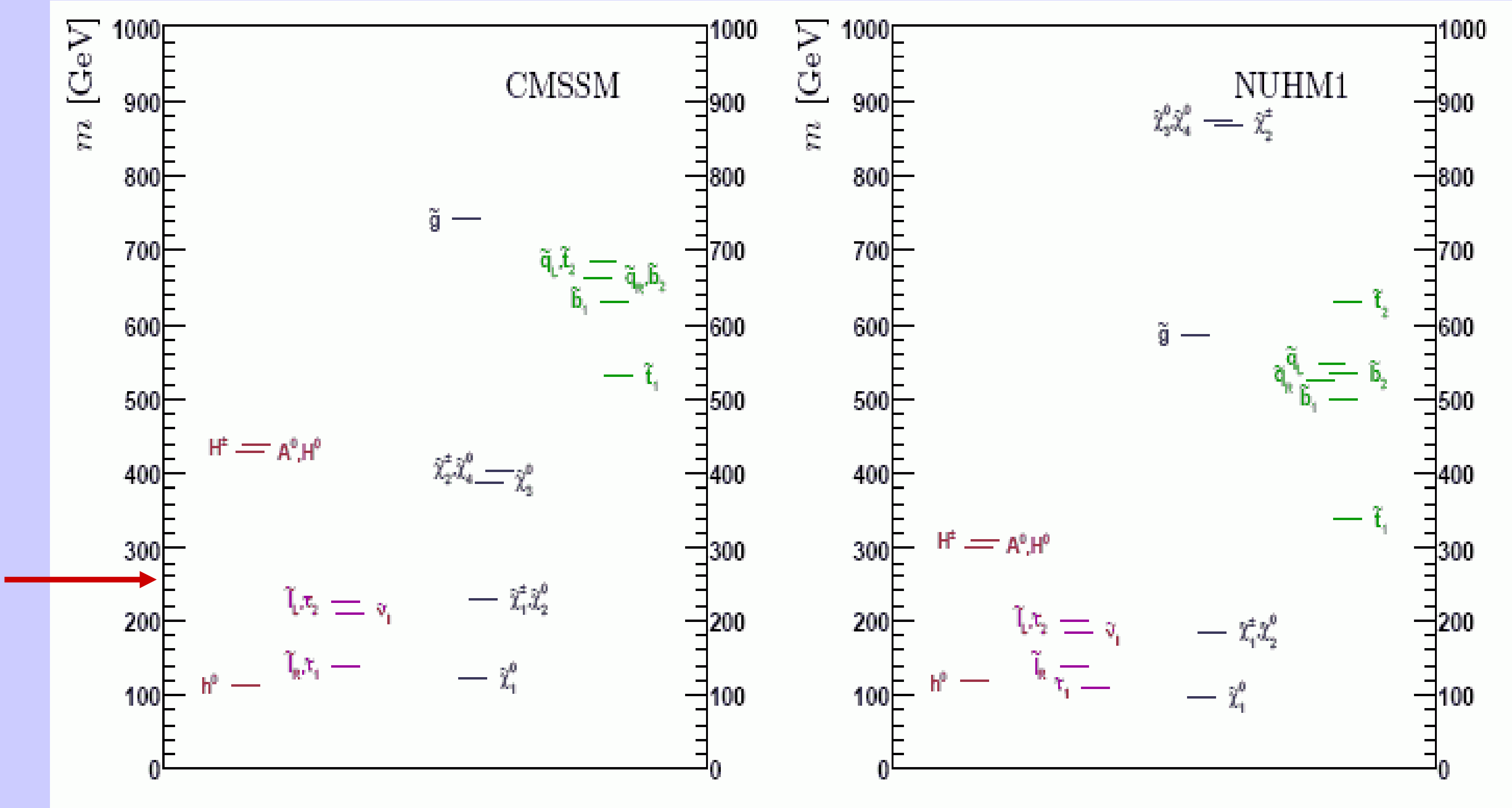
Prediction for Lightest Higgs Mass
Fit to EW precision, B-physics observables, & WMAP



Ellis etal arXiv:0706.0652

Spectrum for Best Fit CMSSM/NUHM Point

NUHM includes two more parameters: M_A, μ

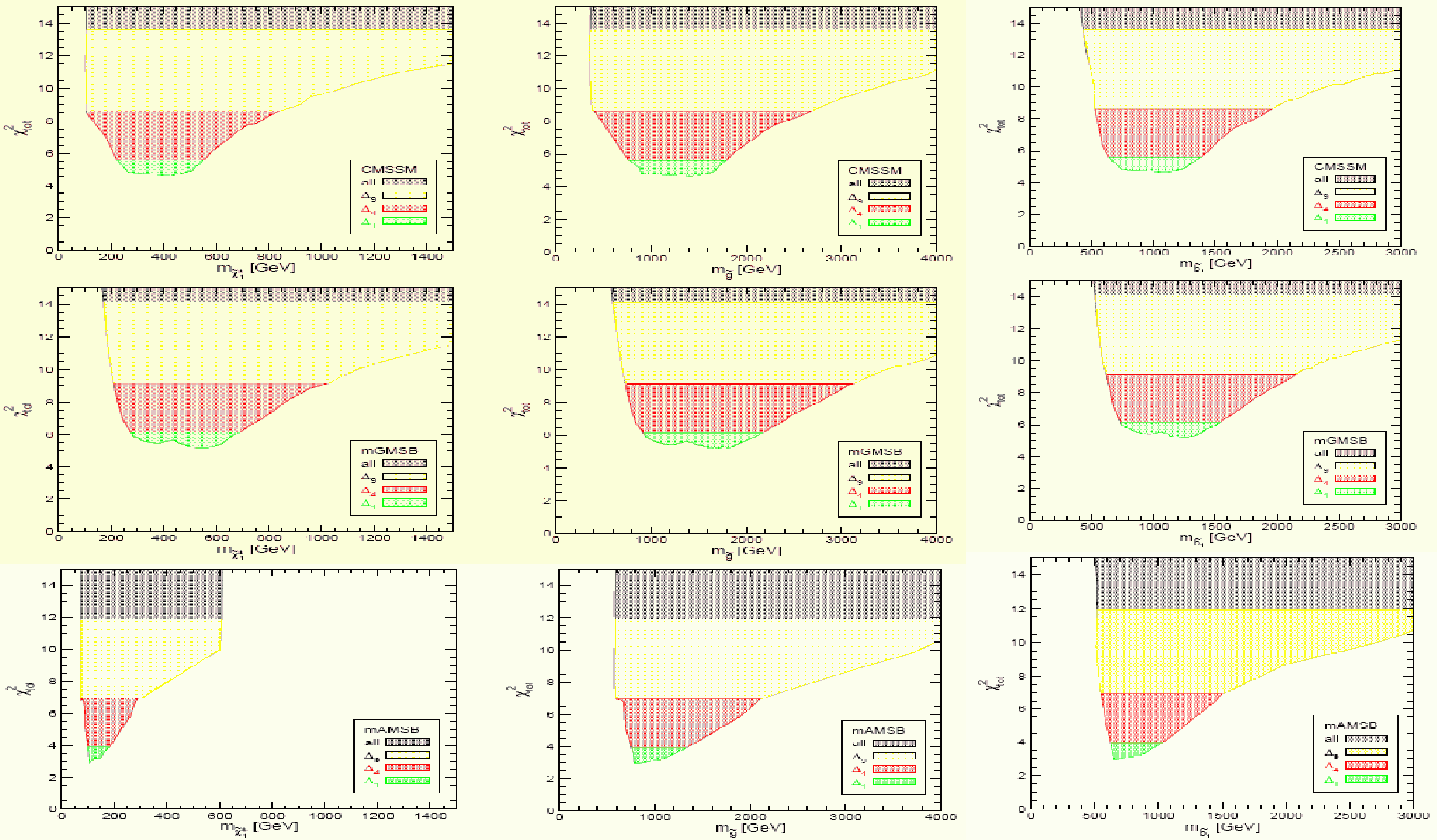


Buchmuller etal arXiv:0808.4128

Comparison of CMSSM to GMSB & AMSB

Heinemeyer etal arXiv:0805.2359

Lightest Chargino **Gluino** **Lightest Sbottom**



More Comprehensive MSSM Analysis

Berger, Gainer, JLH, Rizzo, arXiv:0812.0980

- Study Most general CP-conserving MSSM
  - Minimal Flavor Violation
  - Lightest neutralino is the LSP
  - First 2 sfermion generations are degenerate w/ negligible Yukawas
  - No GUT, SUSY-breaking assumptions

- ⇒ pMSSM: 19 real, weak-scale parameters

  scalars:

  $m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}$

  gauginos: M_1, M_2, M_3

  tri-linear couplings: A_b, A_t, A_τ

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

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, FERMI, PAMELA/ATIC, ILC/CLIC, 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?

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 and extend to higher masses

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

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

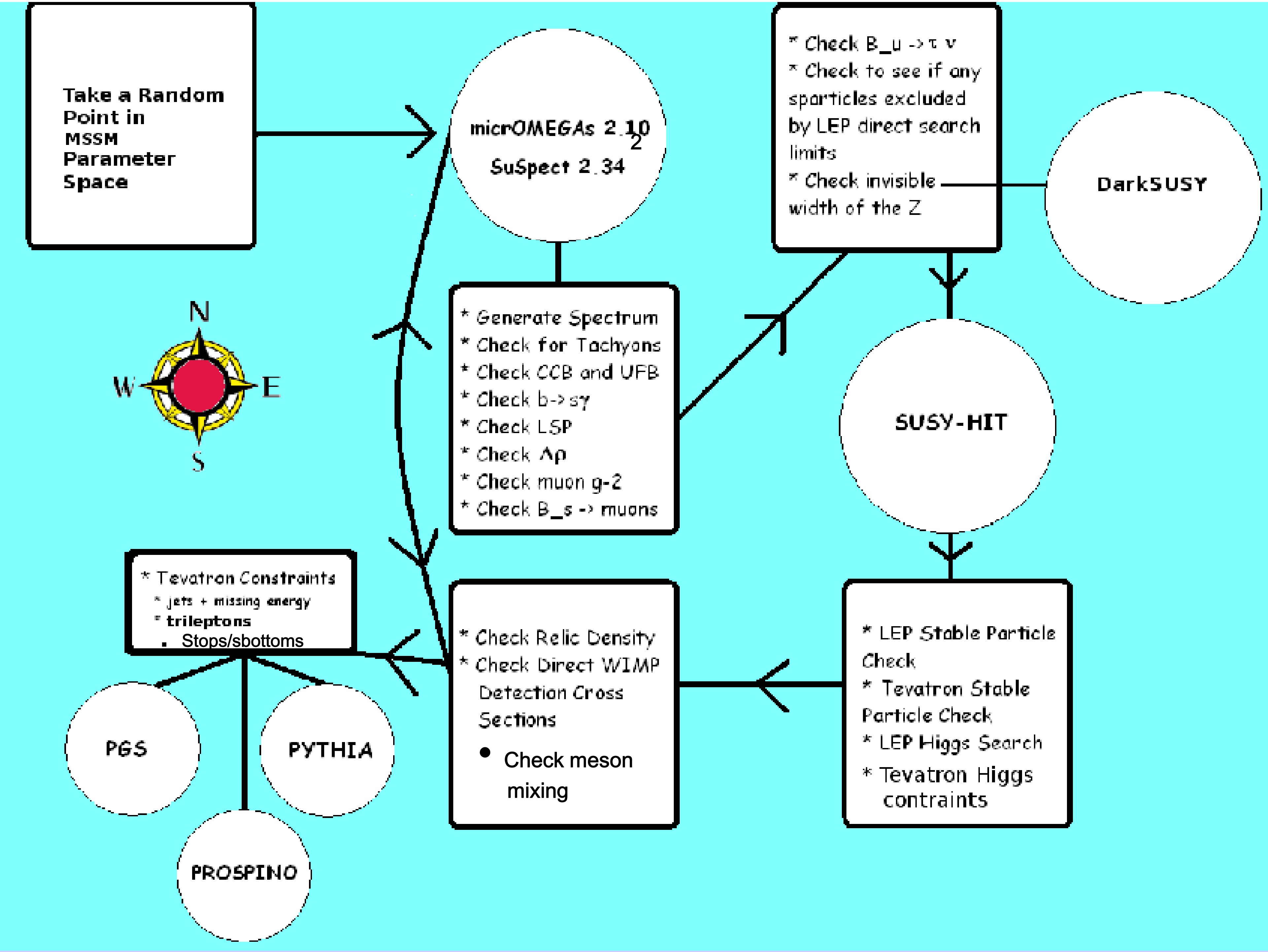
$100 \text{ GeV} \leq M_3 \leq 3 \text{ TeV}$

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

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

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

Absolute values account for possible phases
only Arg ($M_i\, \mu$) and Arg ($A_f\, \mu$) are physical



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

Set of Experimental Constraints I

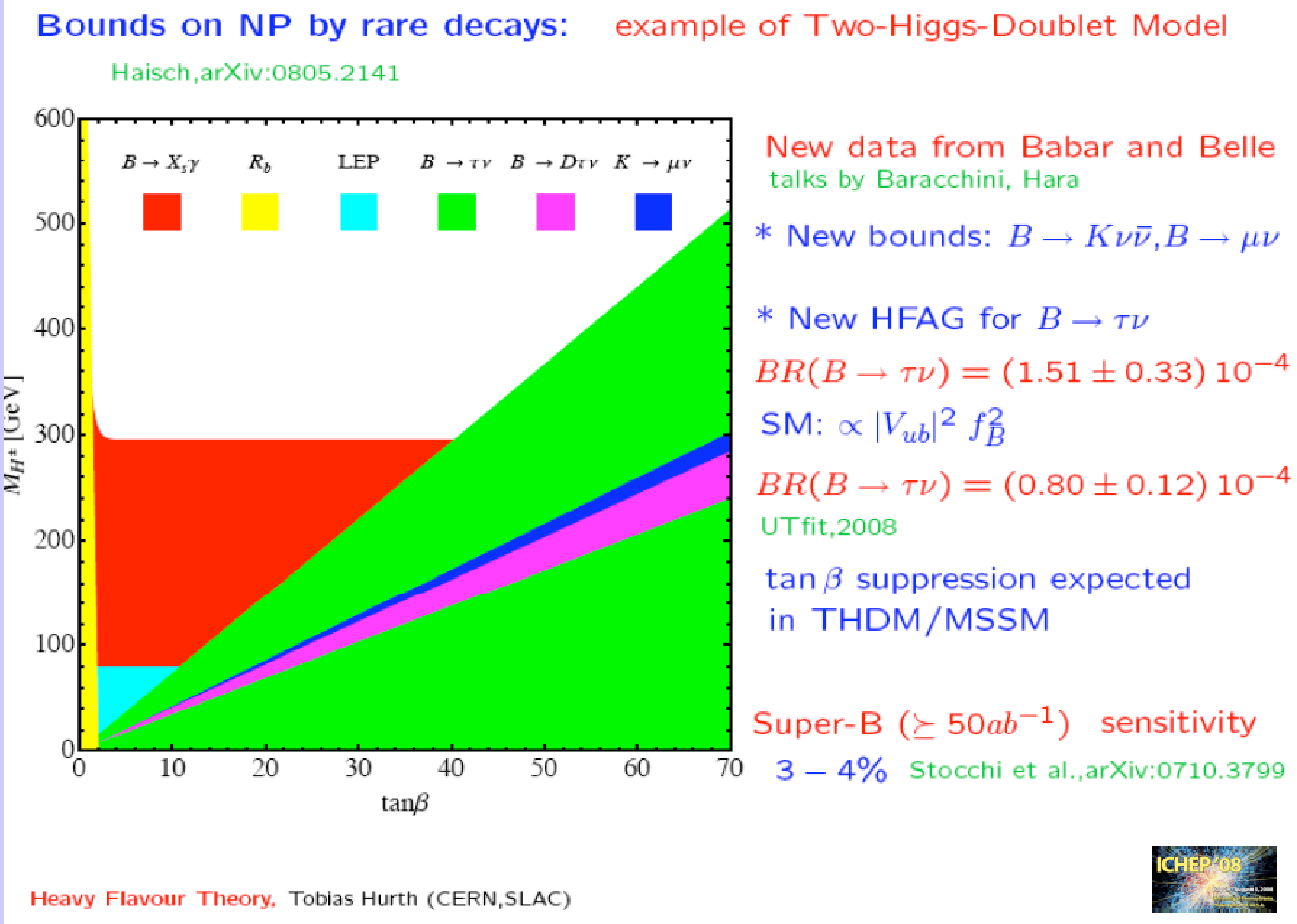
- Theoretical spectrum Requirements (no tachyons, etc)
- Precision measurements:
  - $\Delta\rho$, $\Gamma(Z \to$ invisible)
  - $\Delta(g-2)_\mu$??? $(30.2 \pm 8.8) \times 10^{-10}$ (0809.4062)

    $(29.5 \pm 7.9) \times 10^{-10}$ (0809.3085)

    $(\sim 14.0 \pm 8.4) \times 10-10$ (Davier/BaBar-Tau08)

    → $(-10$ to $40) \times 10^{-10}$ to be conservative..
- Flavor Physics
  - $b \to s\,\gamma$, $B \to \tau\nu$, $B_s \to \mu\mu$
  - Meson-Antimeson Mixing : Constrains 1st/3rd sfermion mass ratios to be < 5 in MFV context

B → τν: Provides an Important Constraint



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 β suppression expected
in THDM/MSSM

Super-B ($\succeq 50 ab^{-1}$) sensitivity
$3 - 4\%$ Stocchi et al.,arXiv:0710.3799

Heavy Flavour Theory, Tobias Hurth (CERN,SLAC)

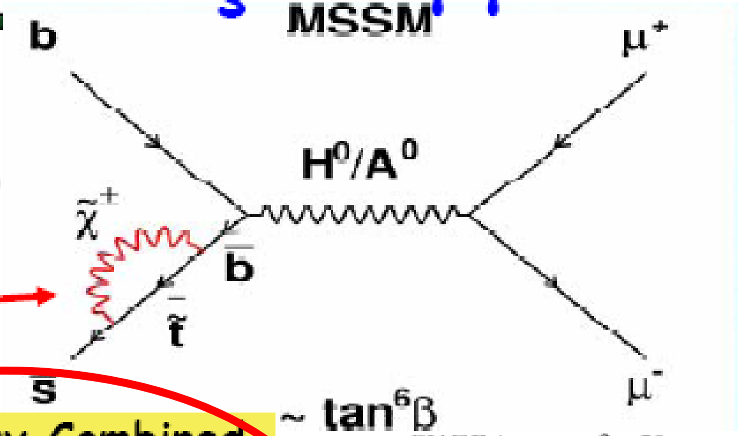
→ B = (55 to 227) x 10^{-6}

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

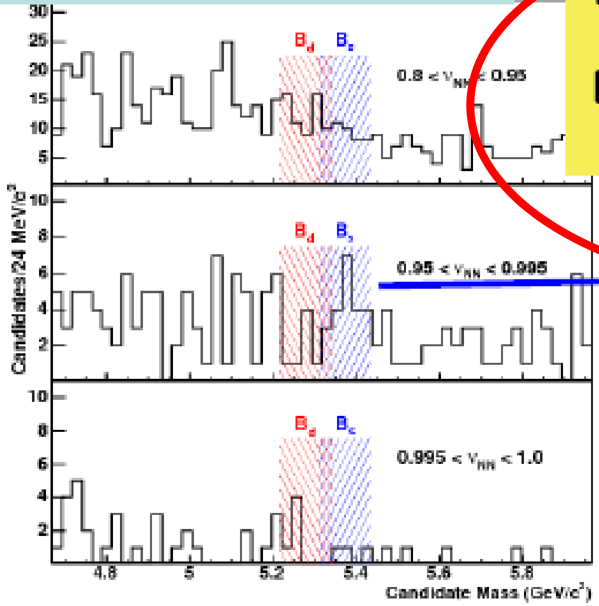
Indirect Search: $B_s \rightarrow \mu\mu$

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)



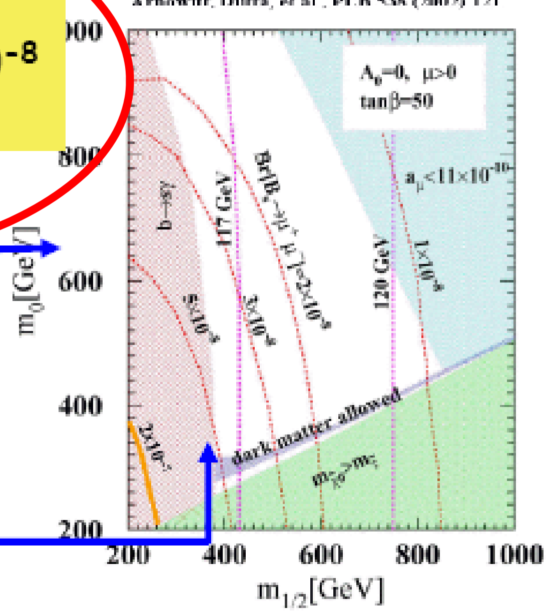
Preliminary Combined CDF/DØ

$BR(B_s \rightarrow \mu\mu) < 4.5 \times 10^{-8}$ @95%

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

mSUGRA at $\tan\beta = 50$

Arnowitt, Dutta, et al., PLB 538 (2002) 121



Set of Experimental Constraints II

- Dark Matter
  - Direct Searches: CDMS, XENON10, DAMA, CRESST I
  - Relic density: $\Omega h2 < 0.1210$ → 5yr WMAP data

- Collider Searches: complicated with many caveats!
  - LEPII: Neutral & Charged Higgs searches
    Sparticle production
    Stable charged particles
  - Tevatron: Squark & gluino searches
    Trilepton search
    Stable charged particles
    BSM Higgs searches

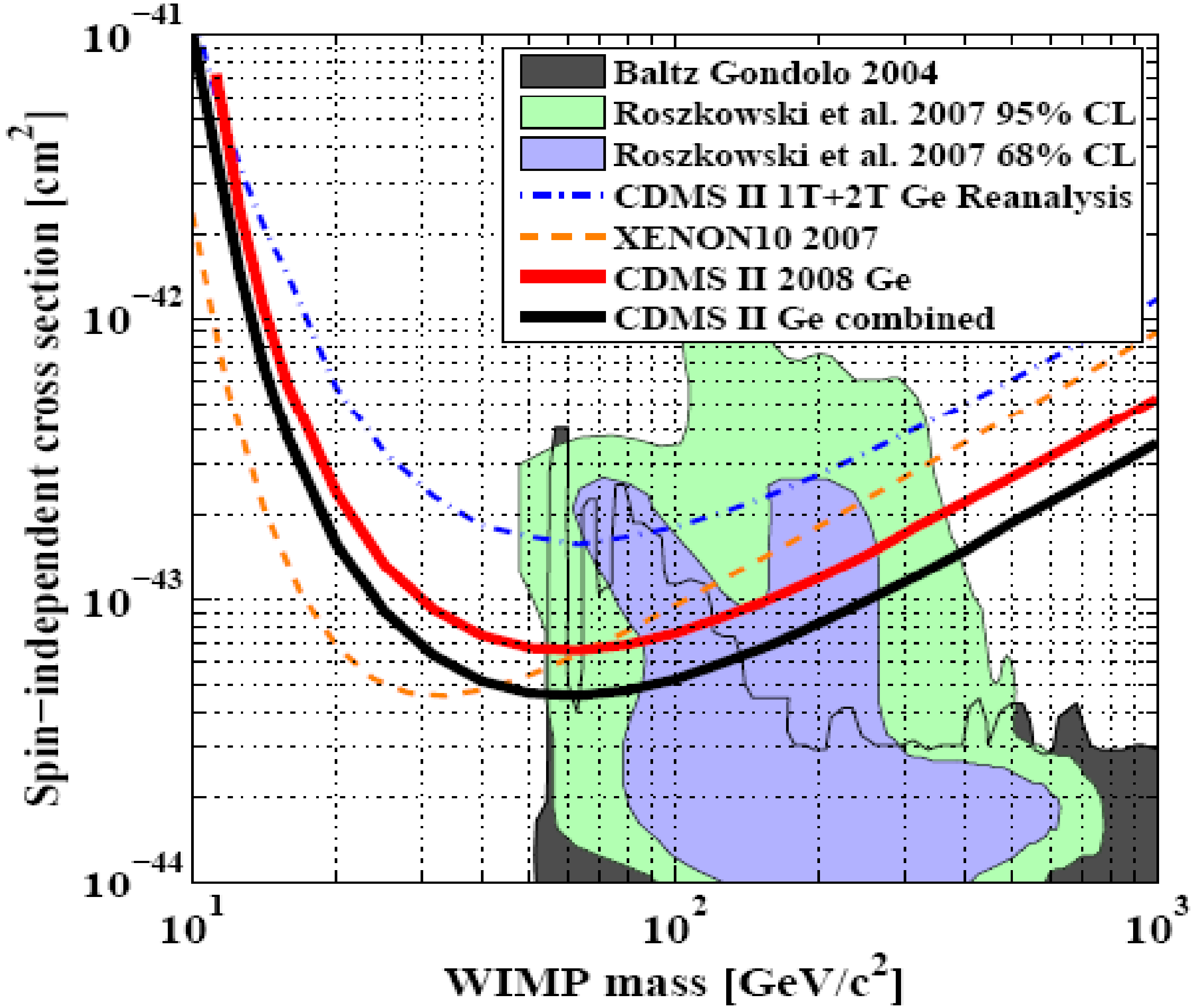
- CDMS, XENON10, DAMA, CRESST-I,…

  We find a factor of ~ 4 uncertainty in the nuclear matrix elements from studying several benchmark points in detail. Thus we allow cross sections 4x larger than the usually quoted limits.
  Spin-independent limits are completely dominant here.

- Dark Matter density:

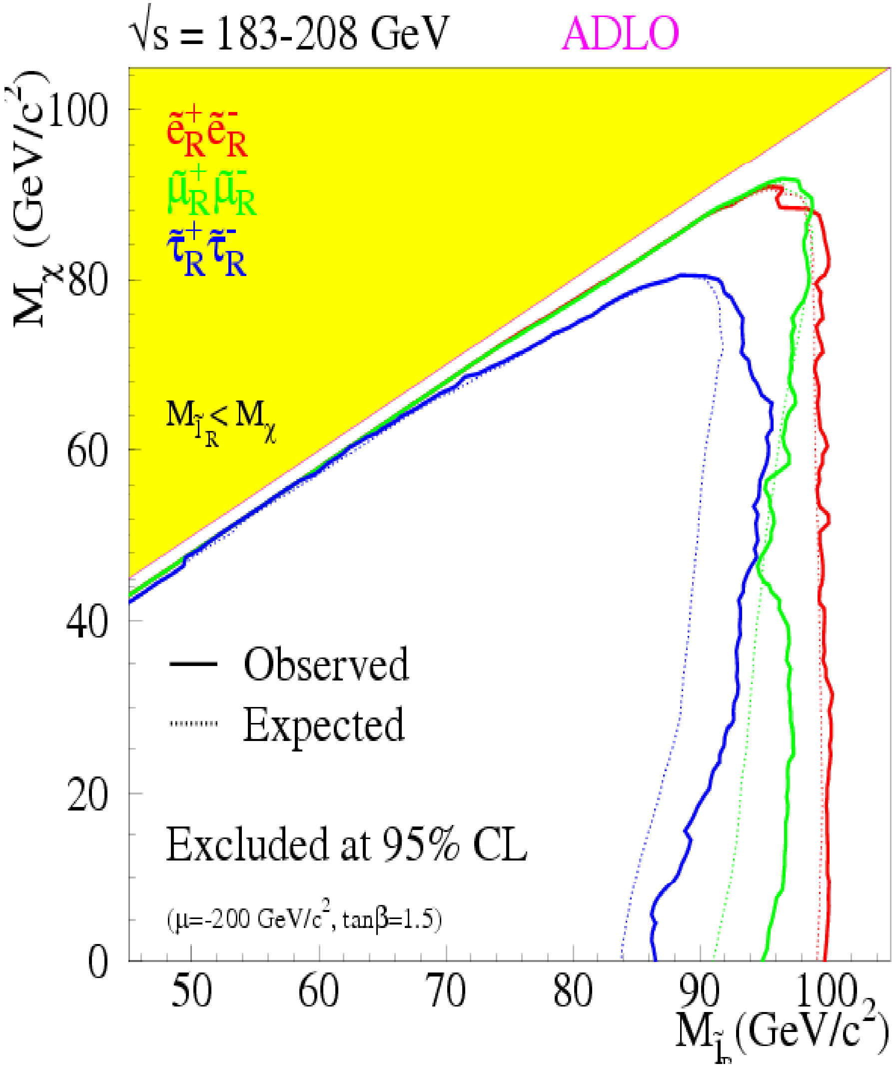
  $\Omega h^2 < 0.1210 \rightarrow$ 5yr WMAP data +
  We treat this only as an upper bound on the LSP DM density to allow for multi-component DM
  Recall the lightest neutralino is the LSP here and is a thermal relic

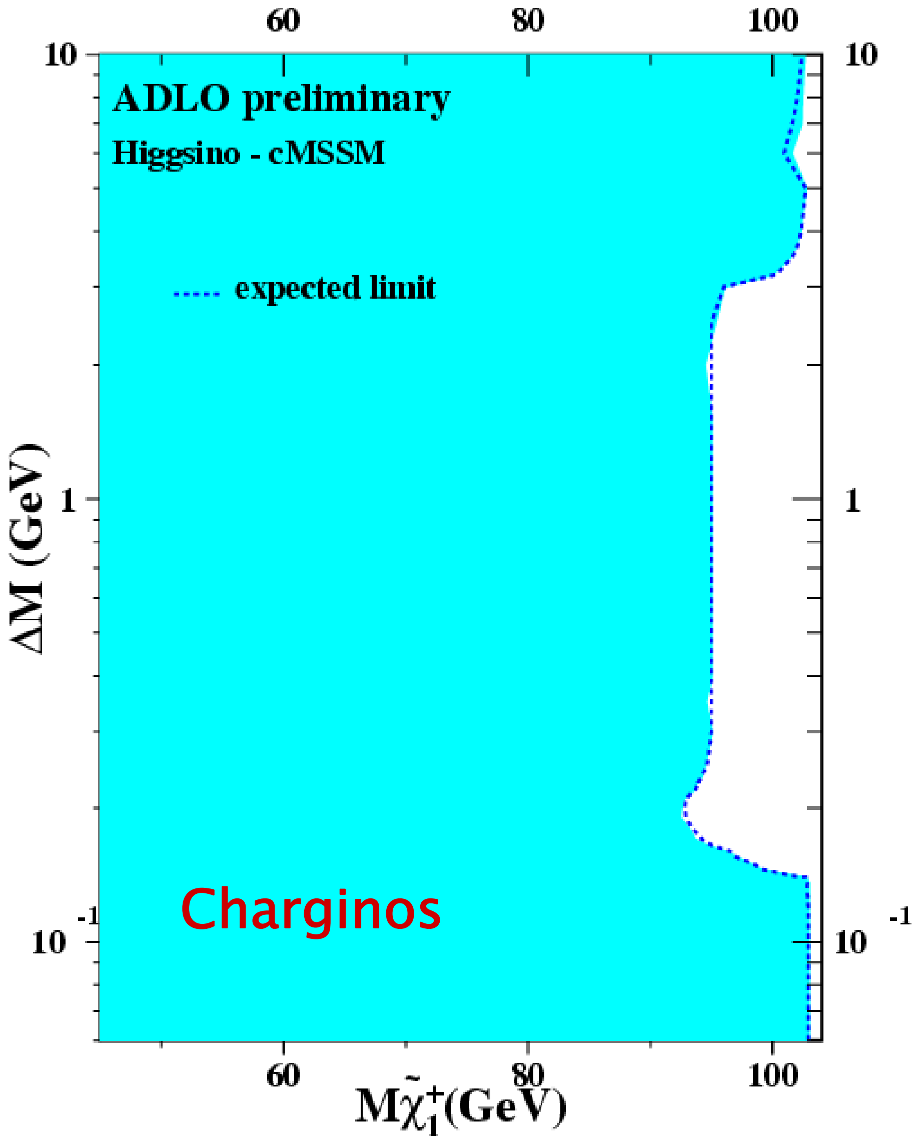
Dark Matter: Direct Searches for WIMPs



Slepton & Chargino Searches at LEPII

Sleptons





Charginos

LEP II: Zh production, h-> bb, ττ

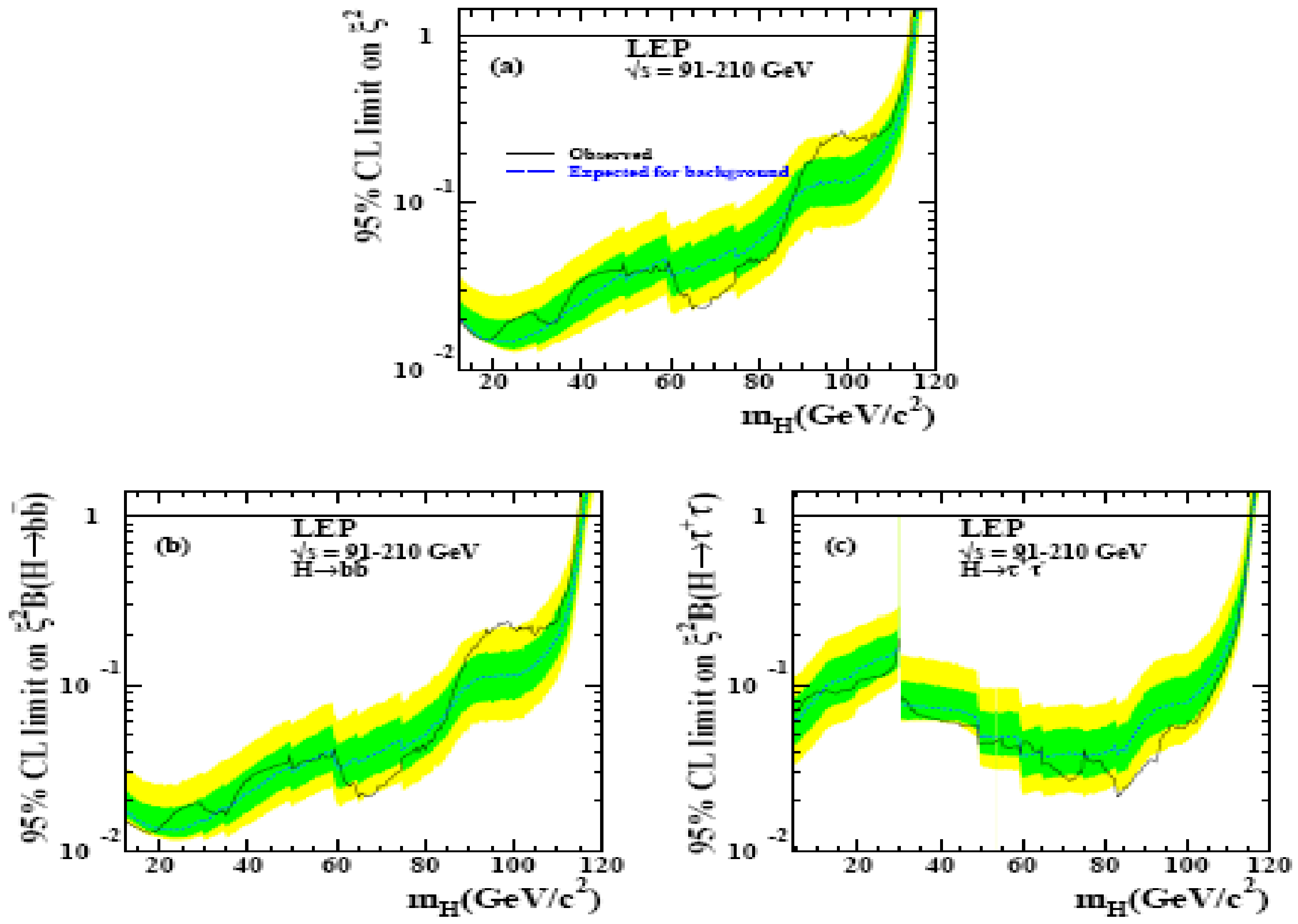


Figure 1: *The 95% c.l. upper bound on the coupling ratio* $\xi^2 = (g_{\rm HZZ}/g^{\rm SM}_{\rm HZZ})^2$ *(see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling. (a): For Higgs boson decays predicted by the Standard Model; (b): for the Higgs boson decaying exclusively into* $\rm b\bar{b}$ *and (c): into* $\tau^+\tau^-$ *pairs.*

LEP II: Associated Higgs Production

Z→ hA →4b,2b2τ,4τ

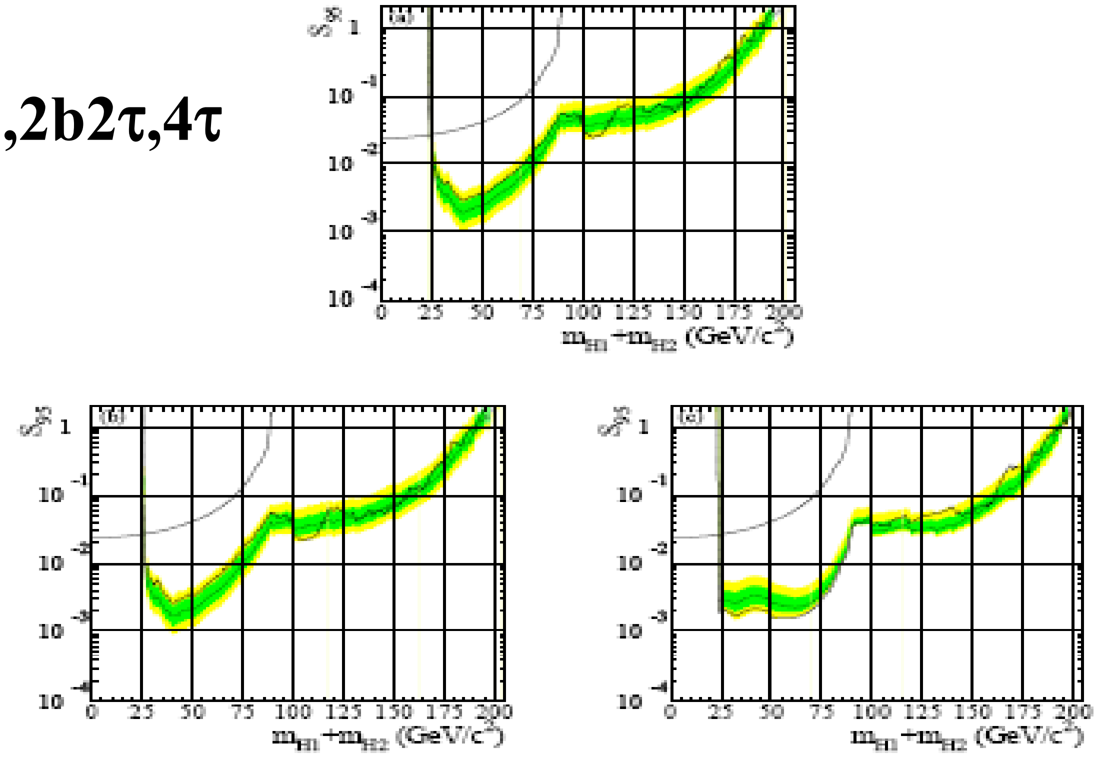


Figure 3: *Model-independent 95% c.l. upper bounds, S_{95}, for various topological cross sections motivated by the pair-production process $e^+e^- \rightarrow \mathcal{H}_2\mathcal{H}_1$, for the particular case where $m_{\mathcal{H}_2}$ and $m_{\mathcal{H}_1}$ are approximately equal. Such is the case, for example, in the CP-conserving MSSM scenarios for $\tan\beta$ greater than 10. The abscissa represents the sum of the two Higgs boson masses. The full line represents the observed limit. The dark (green) and light (yellow) shaded bands around the median expectation (dashed line) correspond to the 68% and 95% probability bands. The curves which complete the exclusion at low masses are obtained using the constraint from the measured decay width of the Z boson, see Section 3.2. Upper plot: the Higgs boson decay branching ratios correspond to the m_h-max benchmark scenario with $\tan\beta$=10, namely 94% $\mathcal{H}_1 \rightarrow b\bar{b}$, 6% $\mathcal{H}_1 \rightarrow \tau^+\tau^-$, 92% $\mathcal{H}_2 \rightarrow b\bar{b}$ and 8% $\mathcal{H}_2 \rightarrow \tau^+\tau^-$; lower left: both Higgs bosons are assumed to decay exclusively to $b\bar{b}$; lower right: the Higgs bosons are assumed to decay, one into $b\bar{b}$ only and the other one into $\tau^+\tau^-$ only. For the case where both Higgs bosons decay to $\tau^+\tau^-$, the corresponding upper bound can be found in Ref. [31], Figure 15.*

Tevatron Squark & Gluino Search

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

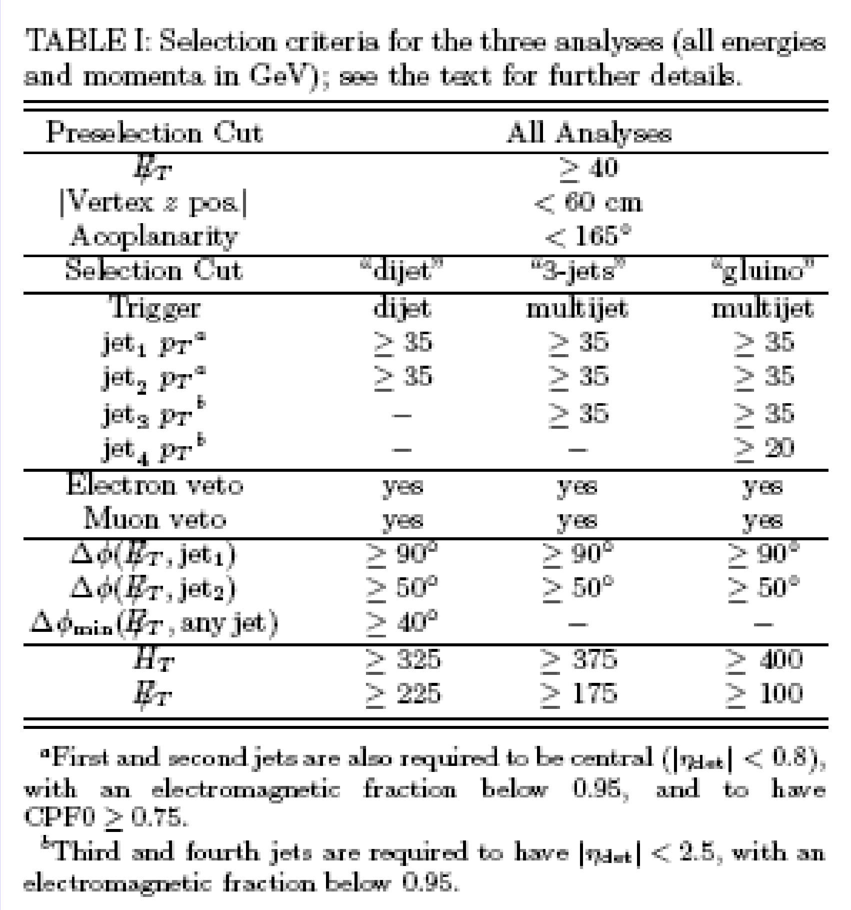


TABLE I: Selection criteria for the three analyses (all energies and momenta in GeV); see the text for further details.

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

[a] First and second jets are also required to be central ($|\eta_{\mathrm{det}}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.

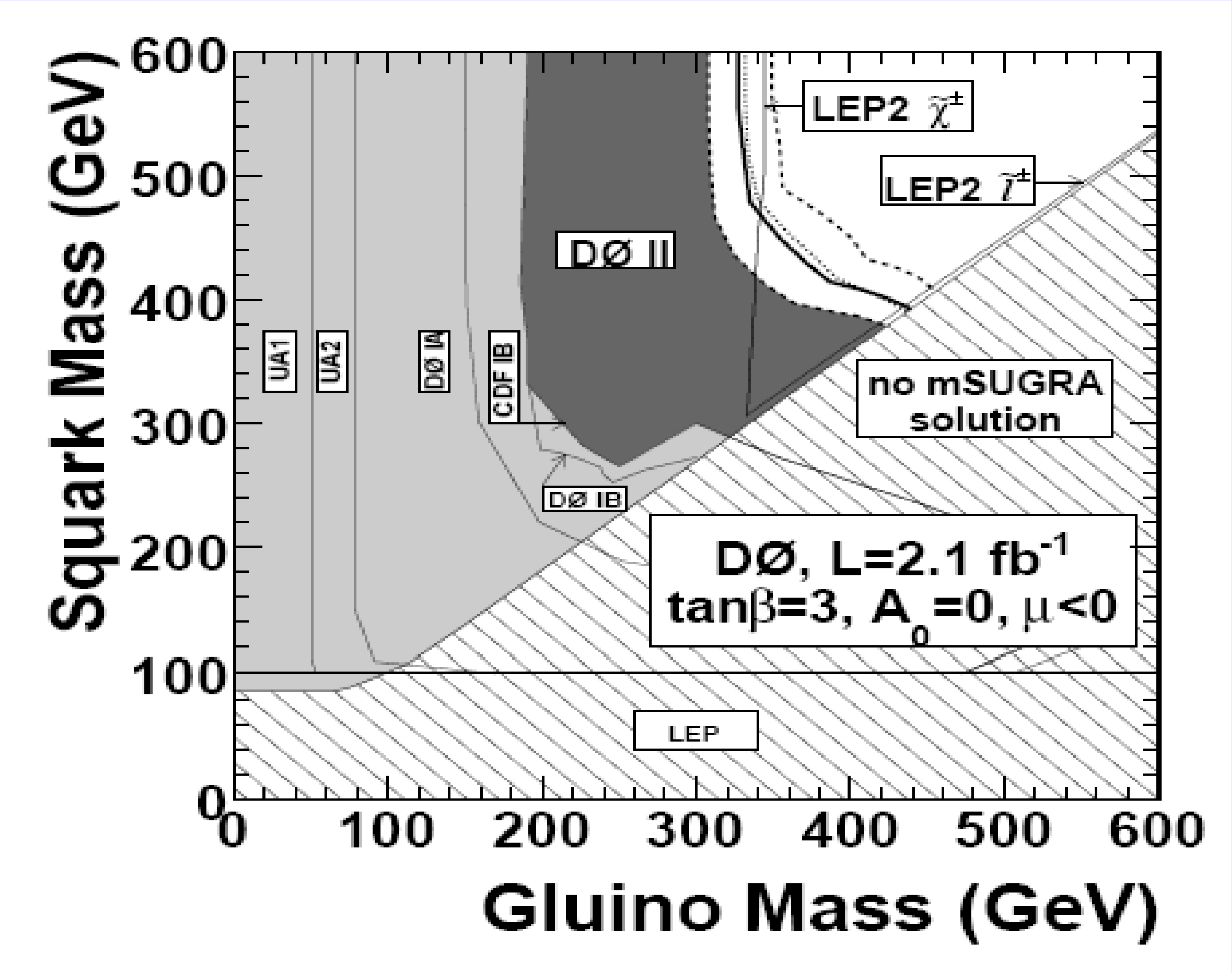
[b] Third and fourth jets are required to have $|\eta_{\mathrm{det}}| < 2.5$, with an electromagnetic fraction below 0.95.

Multiple analyses keyed to look for:
Squarks-> jet +MET
Gluinos -> 2 j + MET

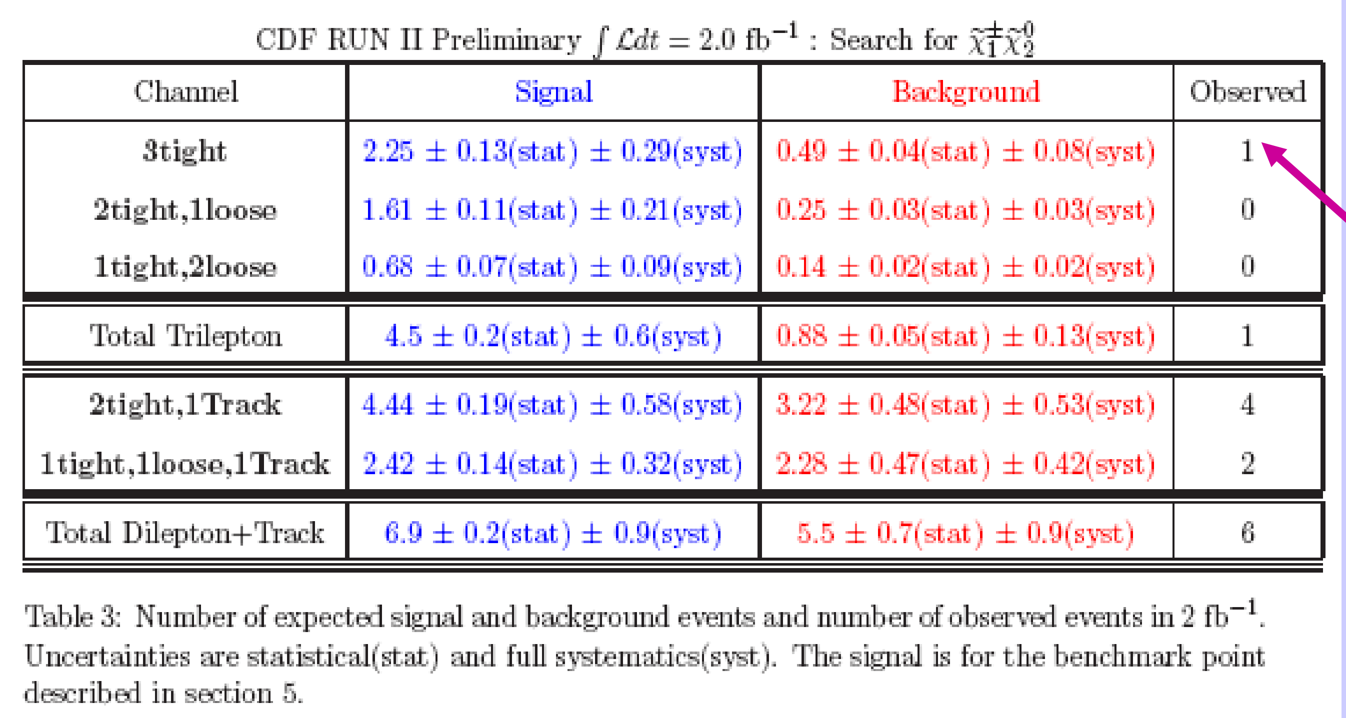
Feldman-Cousins 95% CL
Signal limit: 8.34 events

For each model in our scan we run SuSpect -> SUSY-Hit -> PROSPINO -> PYTHIA -> D0-tuned PGS4 fast simulation and compare to the data

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

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

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

We need to perform the 3 tight lepton analysis ~ 10^5 times

We perform this analysis using CDF-tuned PGS4, PYTHIA in LO plus a PROSPINO K-factor

→ Feldman-Cousins 95% CL Signal limit: 4.65 events

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

Tevatron: D0 Stable Particle (= Chargino) Search

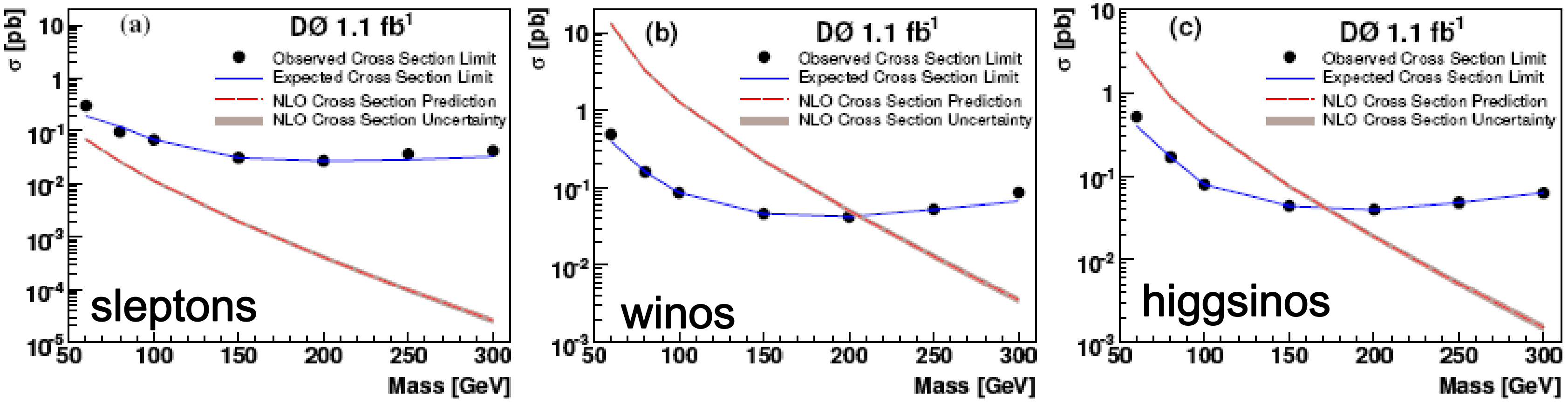


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos, 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!
- No applicable bounds on charged sleptons..the cross sections are too small.

Survival Statistics

One CPU-processor century later:

- Flat Priors:
  - 10^7 models scanned
  - 68.5K (0.68%) survive
- Log Priors:
  - 2 x10^6 models scanned
  - 3.0k (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

Fate of Benchmark Points!

ATLAS	SU1	OK
	SU2	killed by LEP
	SU3	killed by Ωh^2
	SU4	killed by $b \to s\gamma$
	SU8	killed by g-2
CMS	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

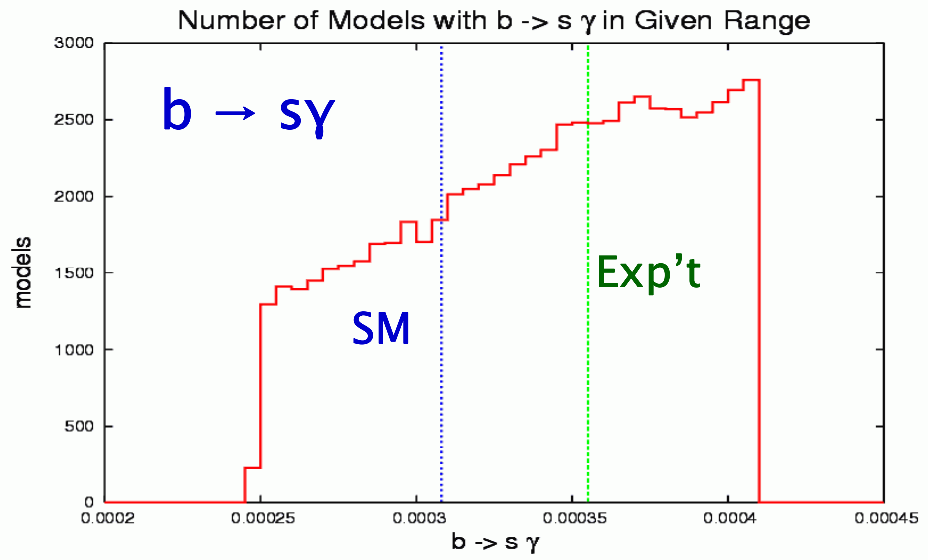
Most well-studied models do not survive confrontation with the latest data.

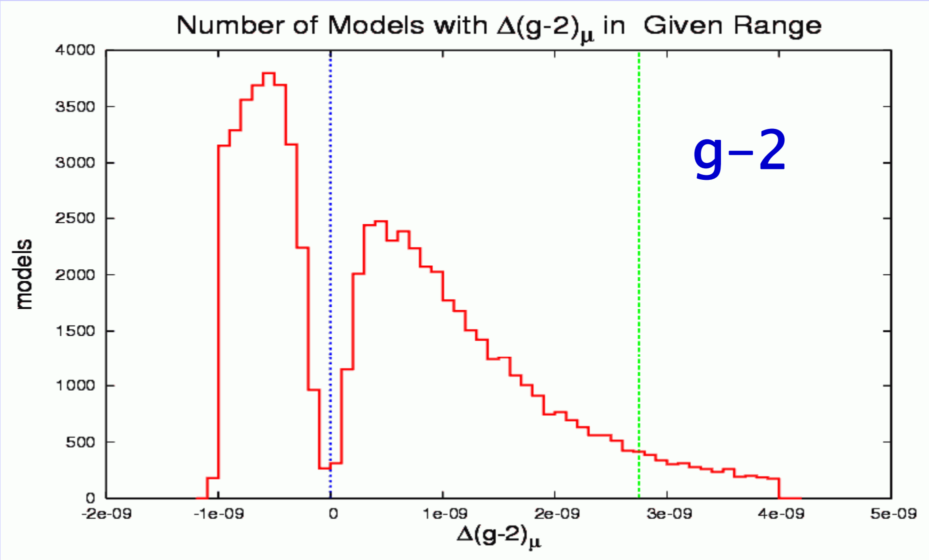
For many models this is not the unique source of failure

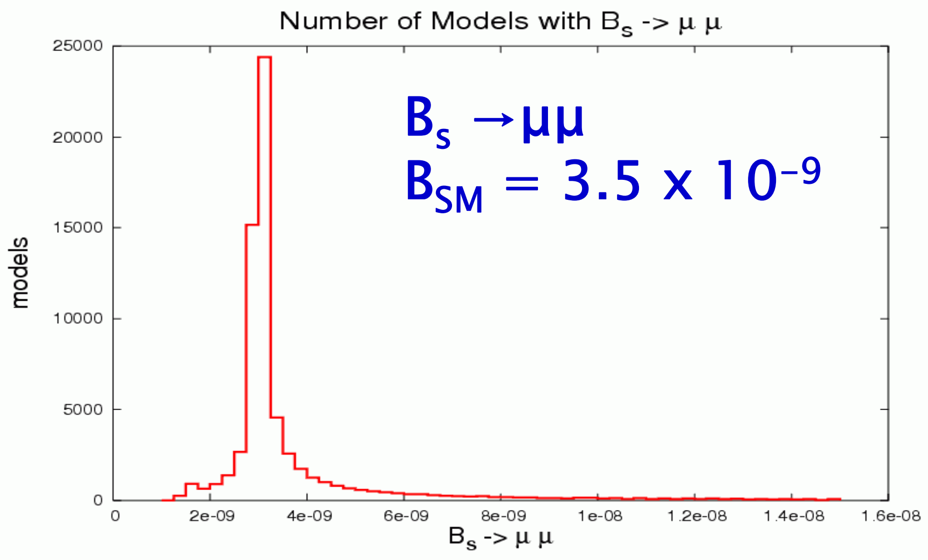
Similarly for the SPS Points

SPS1a	killed by $b \rightarrow s\gamma$
SPS1a’	OK
SPS1b	killed by $b \rightarrow s\gamma$
SPS2	killed by 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

Predictions for Observables (Flat Priors)

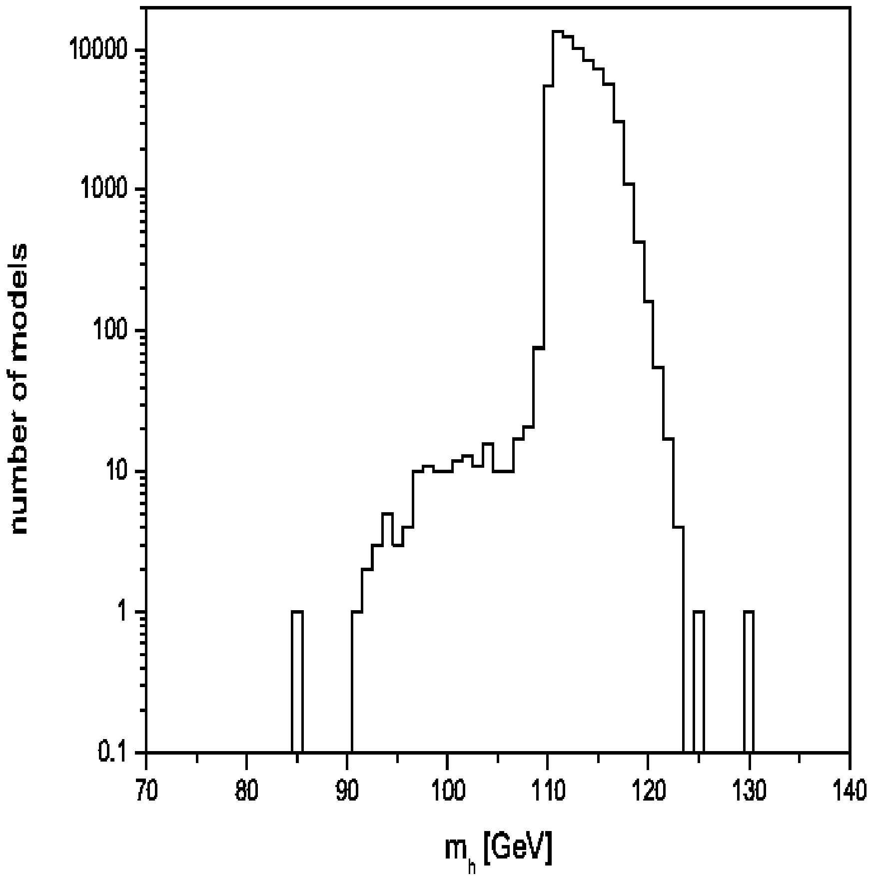




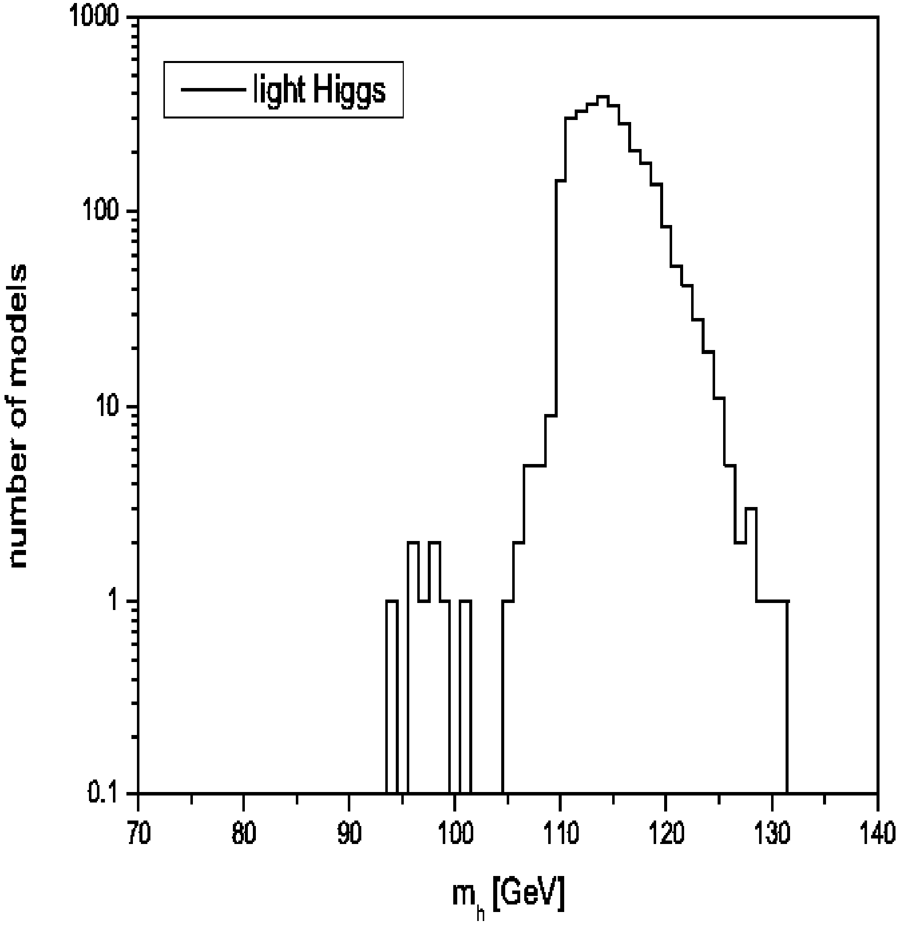


Predictions for Lightest Higgs Mass

Flat Priors



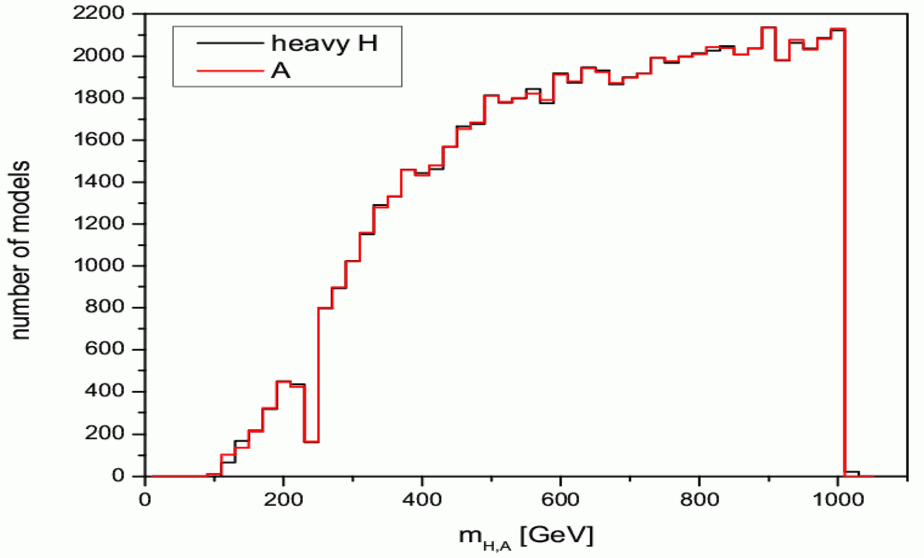
Log Priors

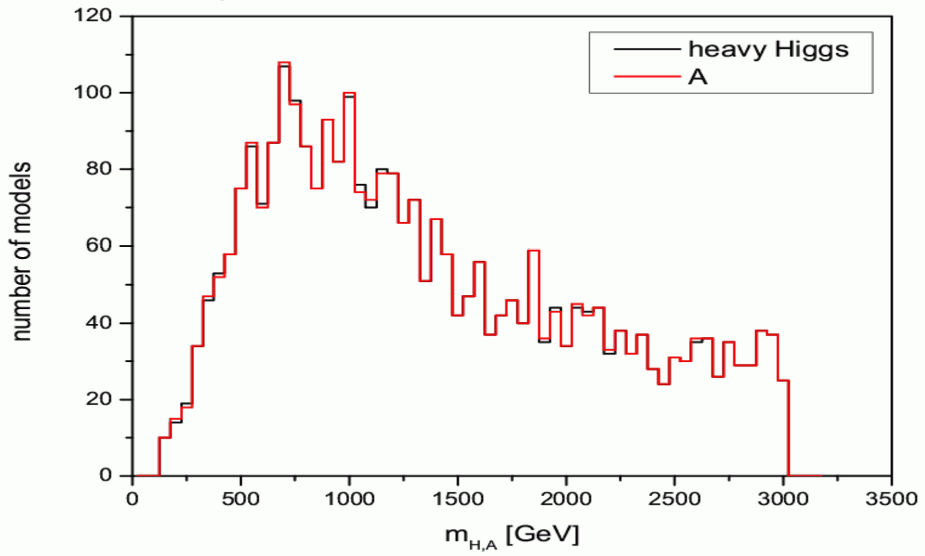


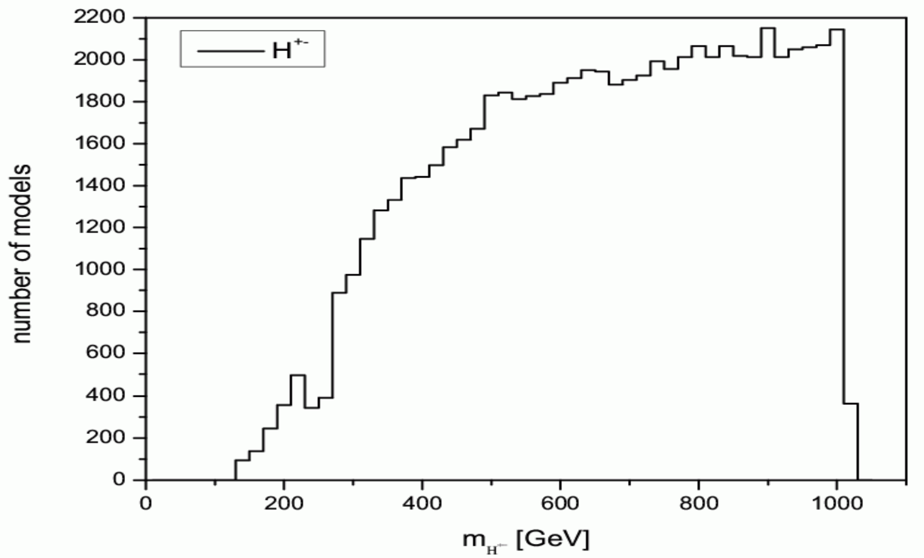
Predictions for Heavy & Charged Higgs

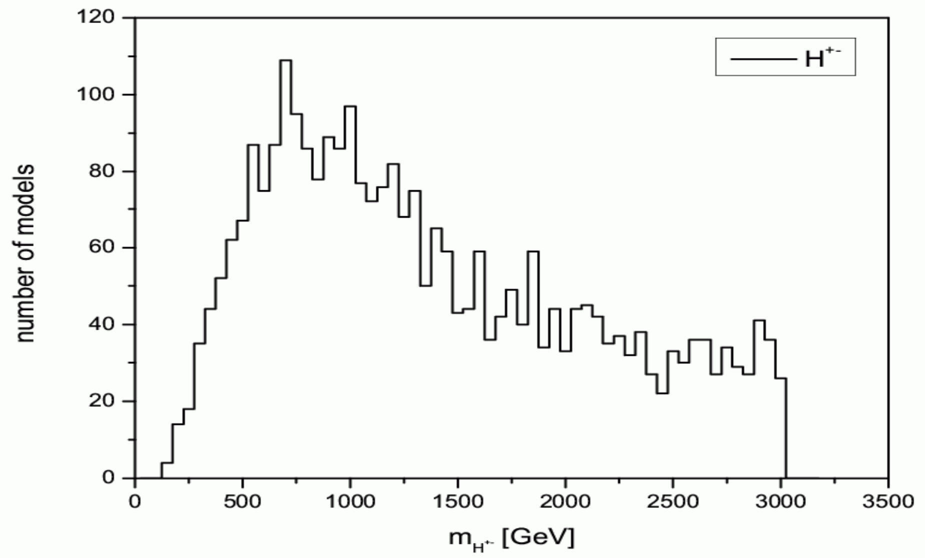
Flat Priors

Log Priors

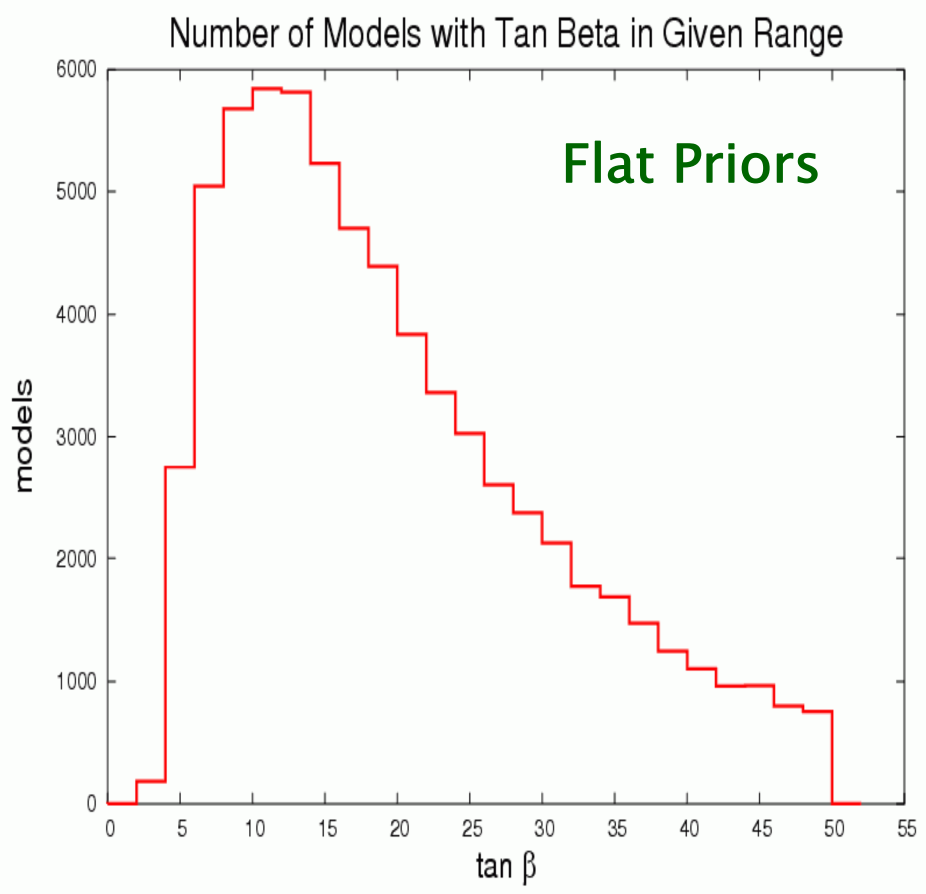


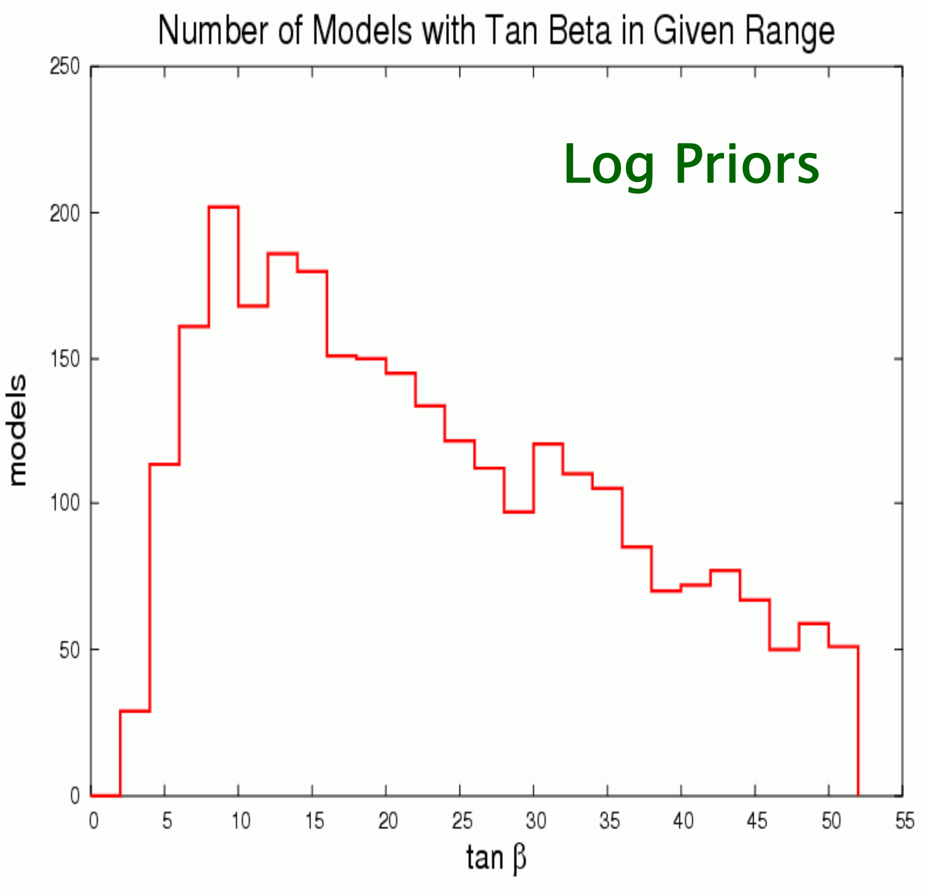






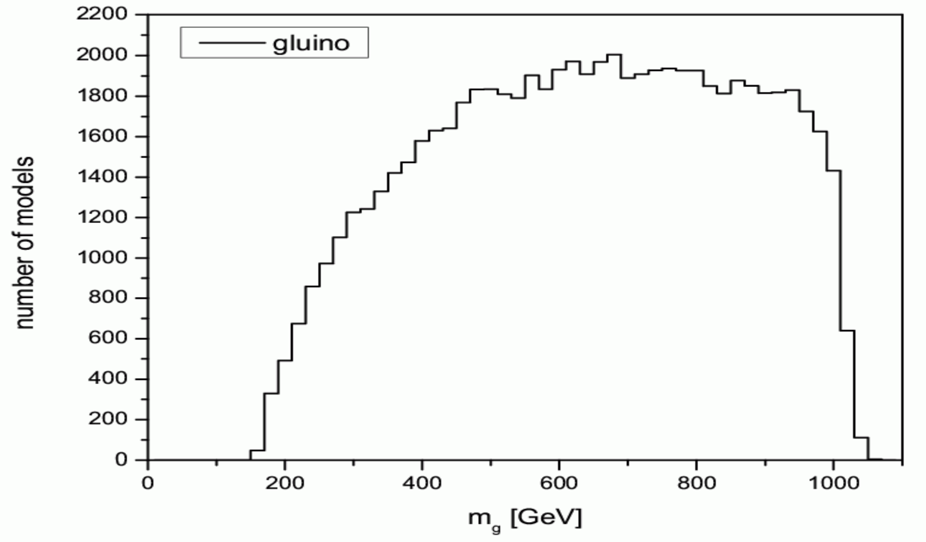
Distribution for tan beta

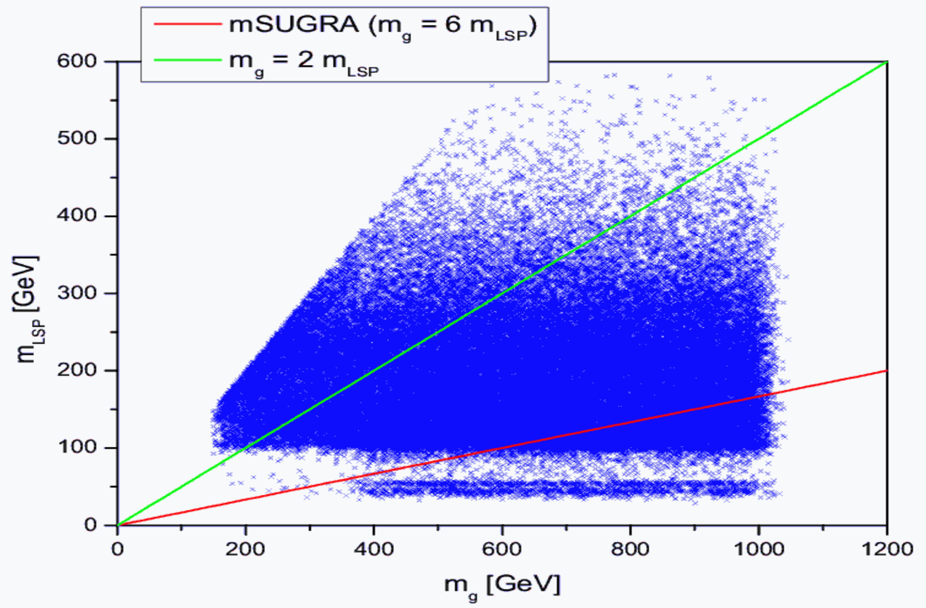




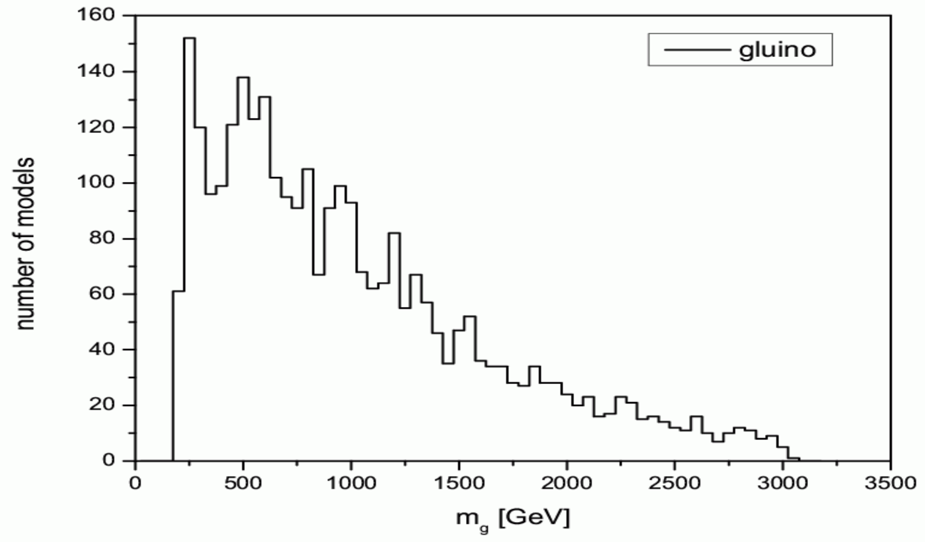
Distribution of Gluino Masses

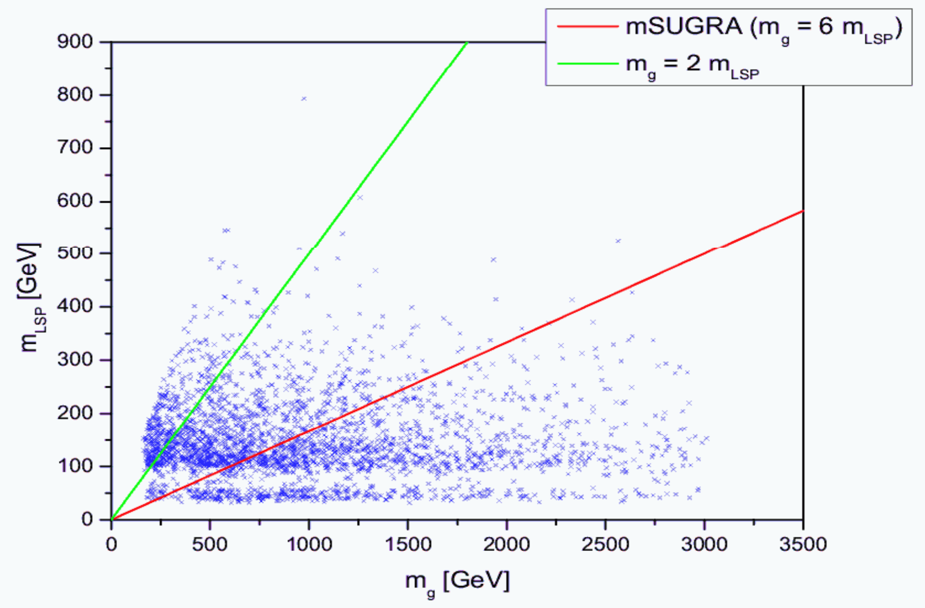
Flat Priors





Log Priors

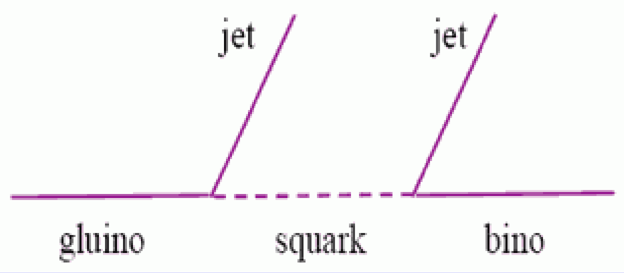




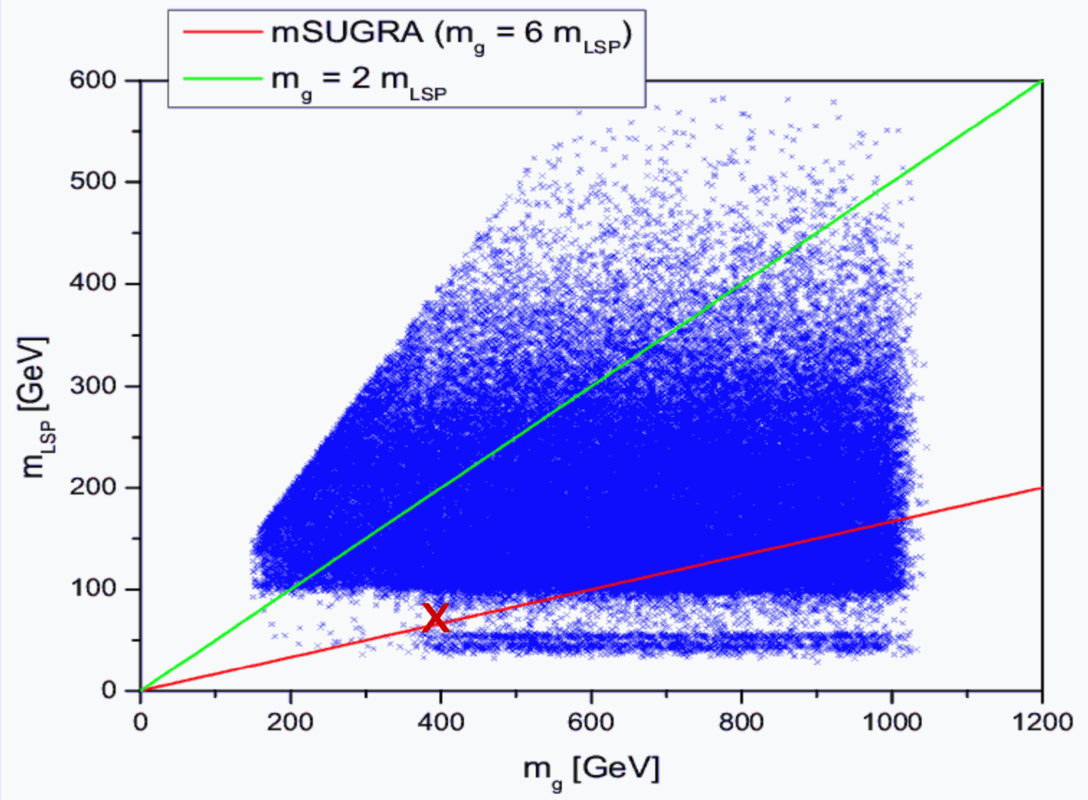
Gluinos at the Tevatron

- Tevatron gluino/squark analyses performed solely for mSUGRA – constant ratio $m_{gluino} : m_{Bino} \simeq 6 : 1$

Gluino-Bino mass ratio determines kinematics



Distribution of Gluino Masses

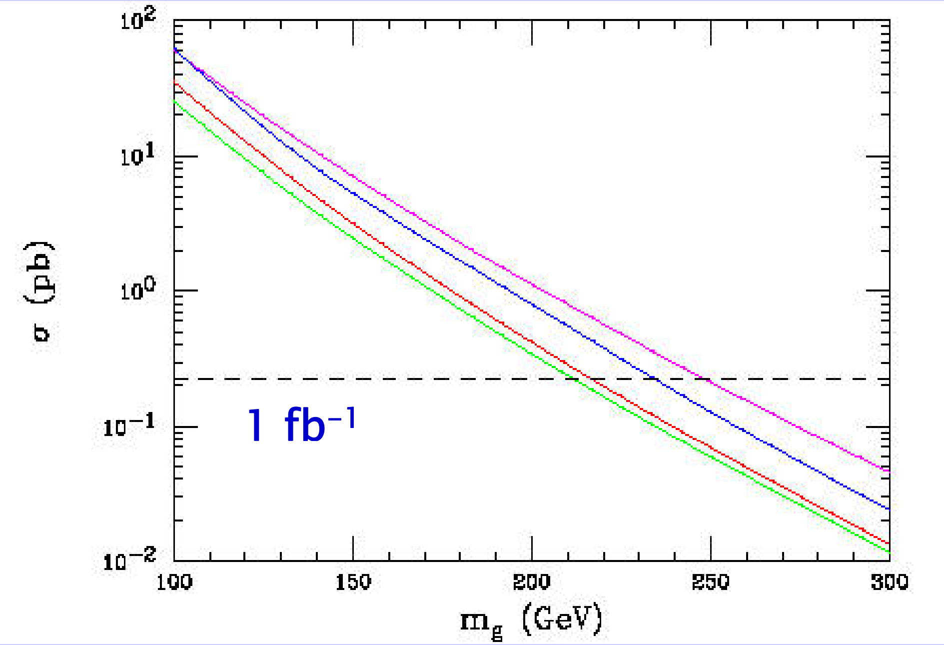


Monojet Searches are Important!

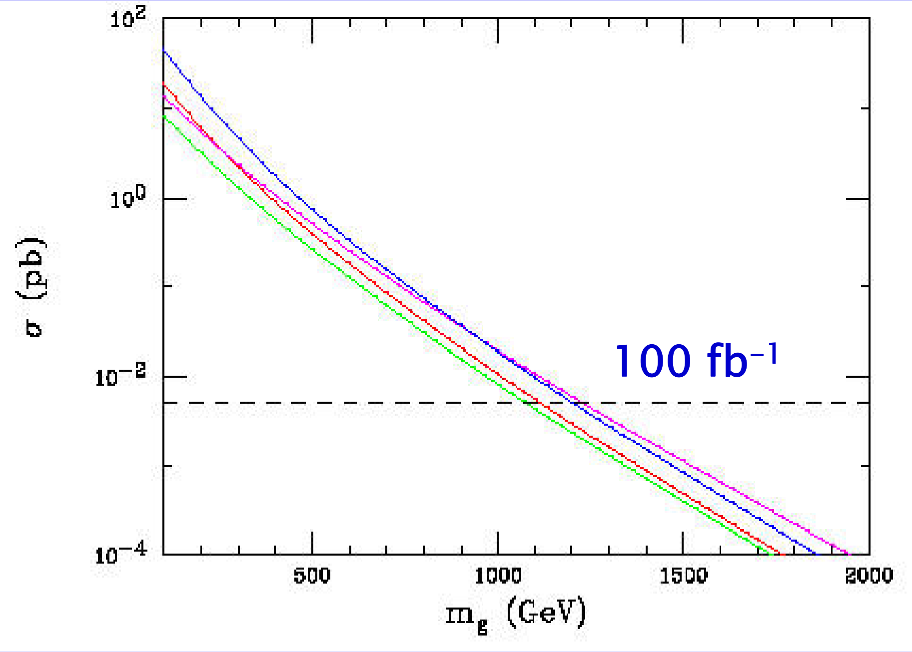
JLH, Lillie, Massip, Rizzo hep-ph/0408248

Gluino pair + jet cross section

Tevatron



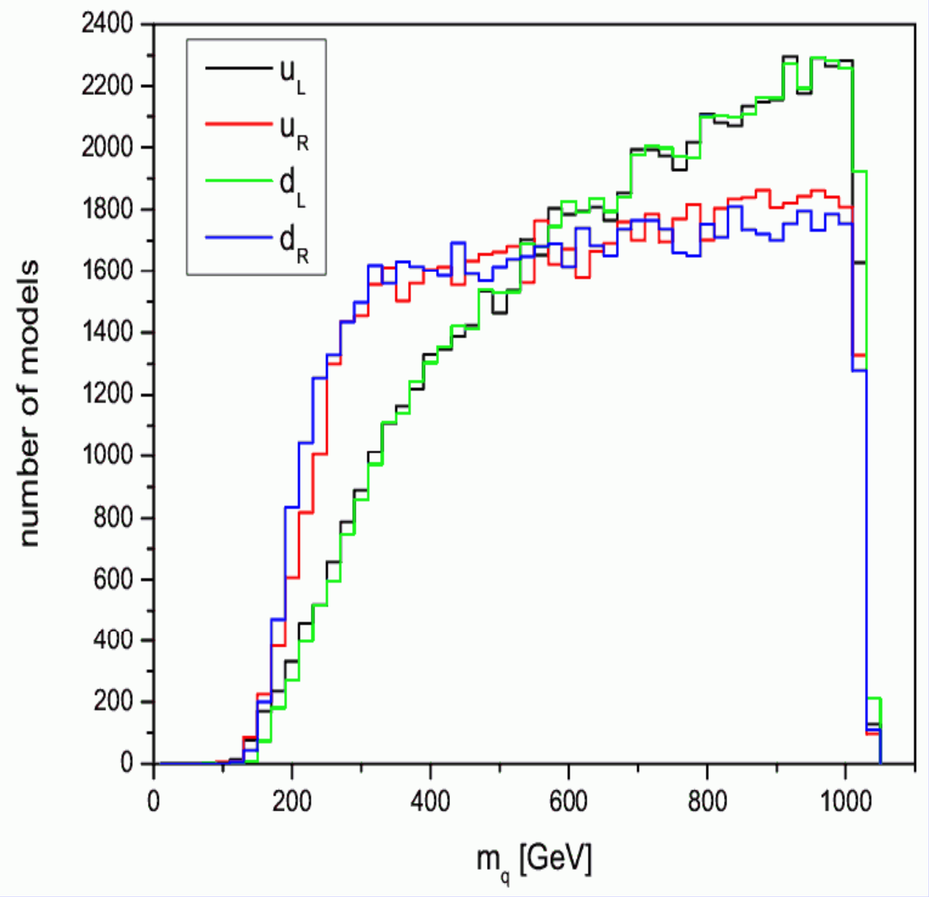
LHC



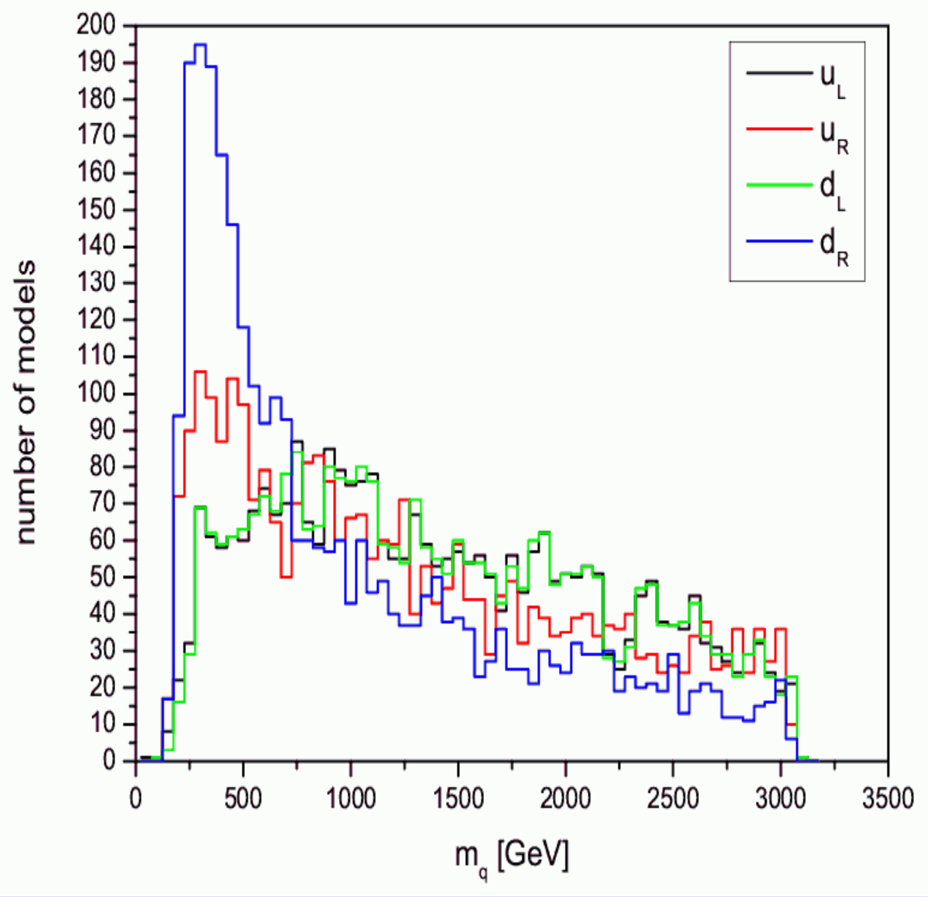
At LO with several renormalization scales

Distribution of Squark Masses

Flat Priors

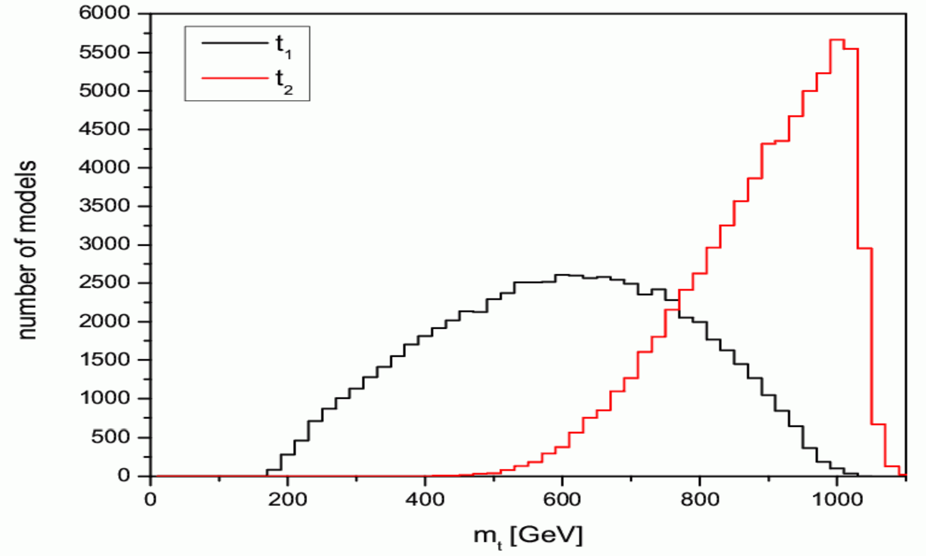


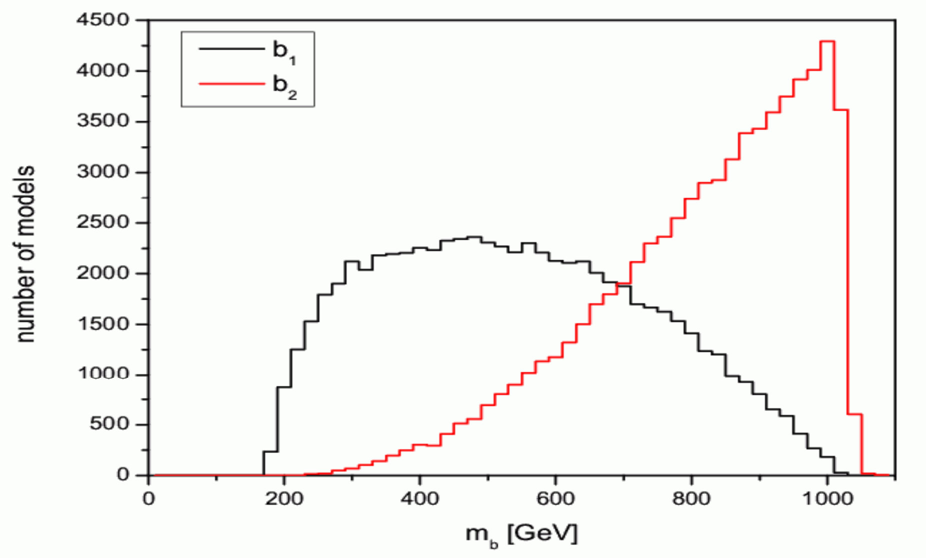
Log Priors



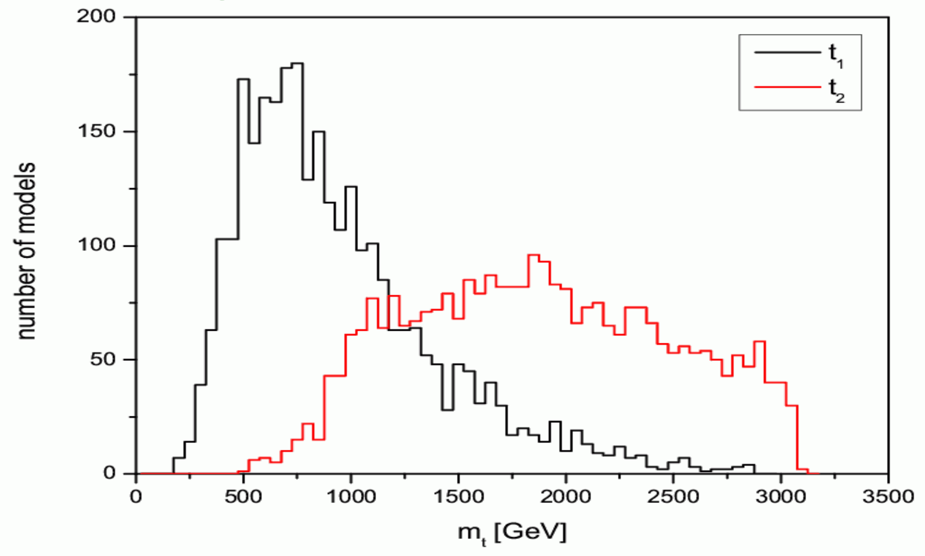
Distribution of Sbottom/Stop Masses

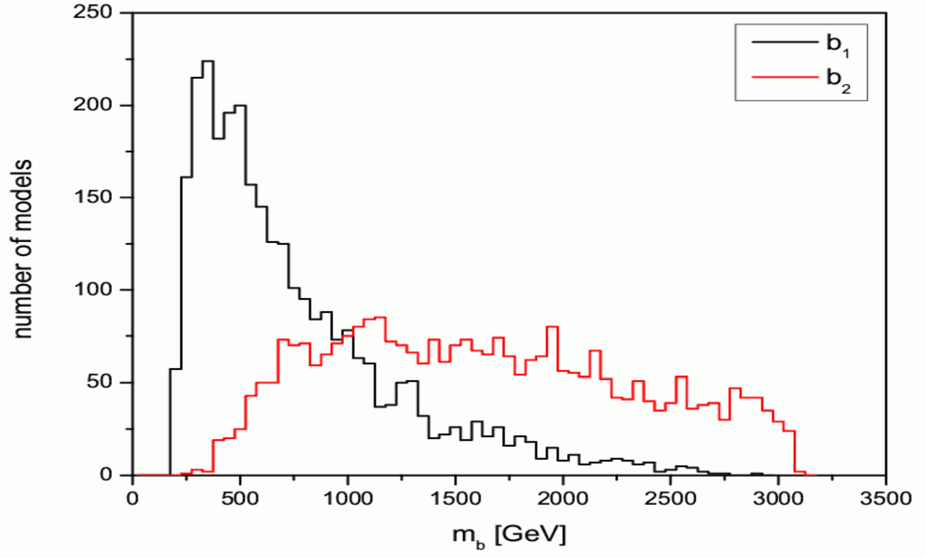
Flat Priors



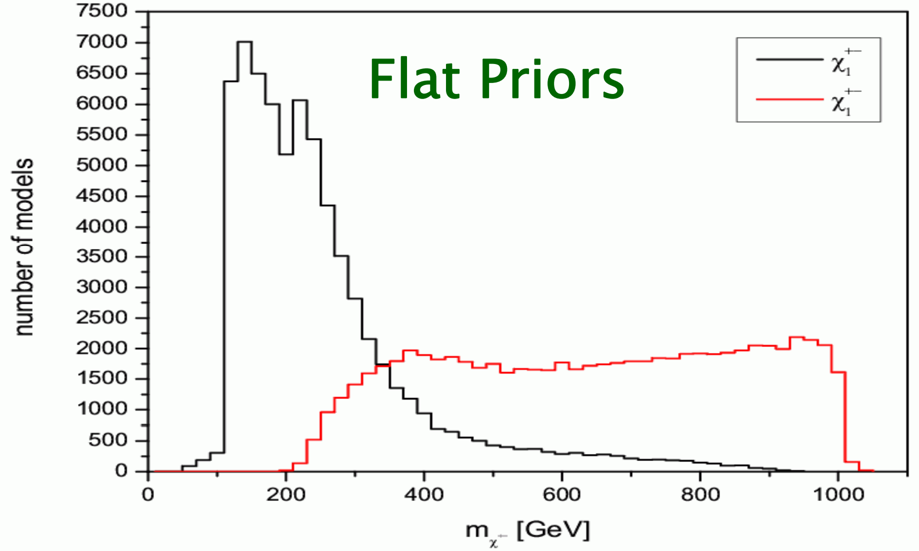


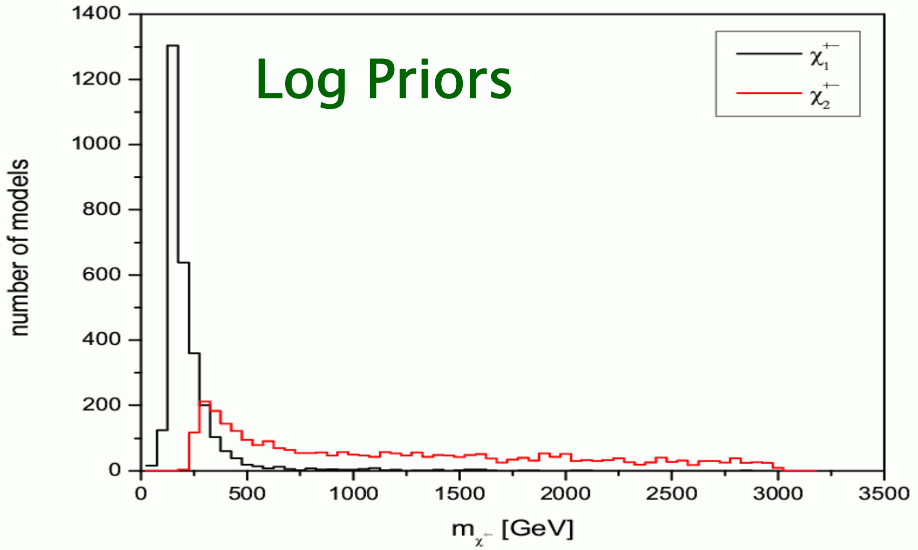
Log Priors

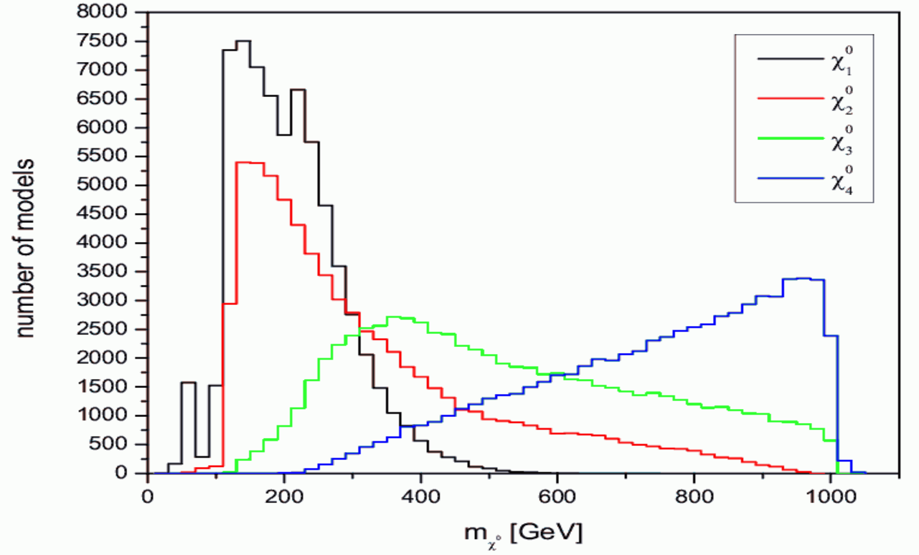


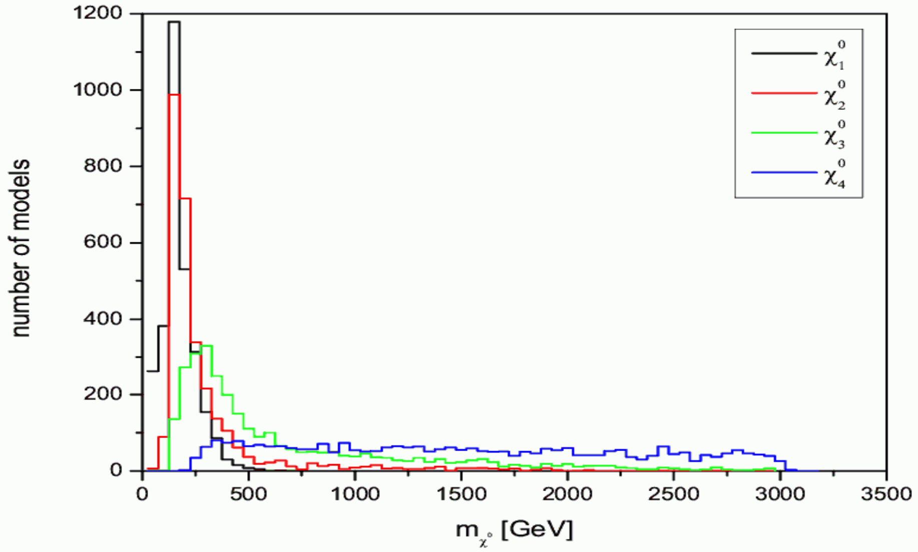


Distributions for EW Gaugino Masses


Flat Priors


Log Priors

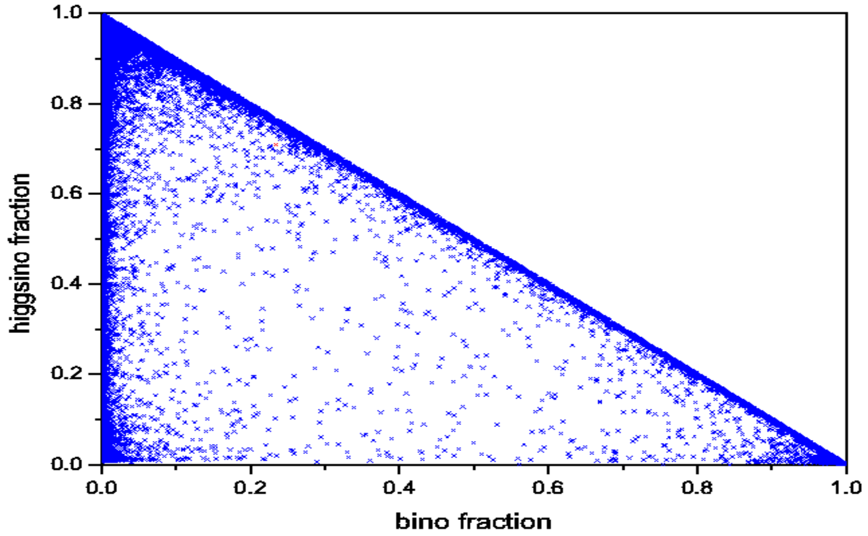


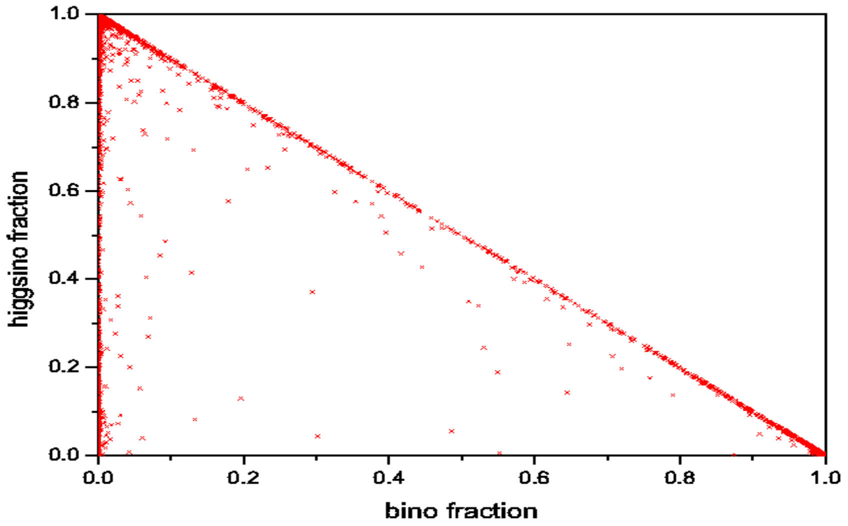


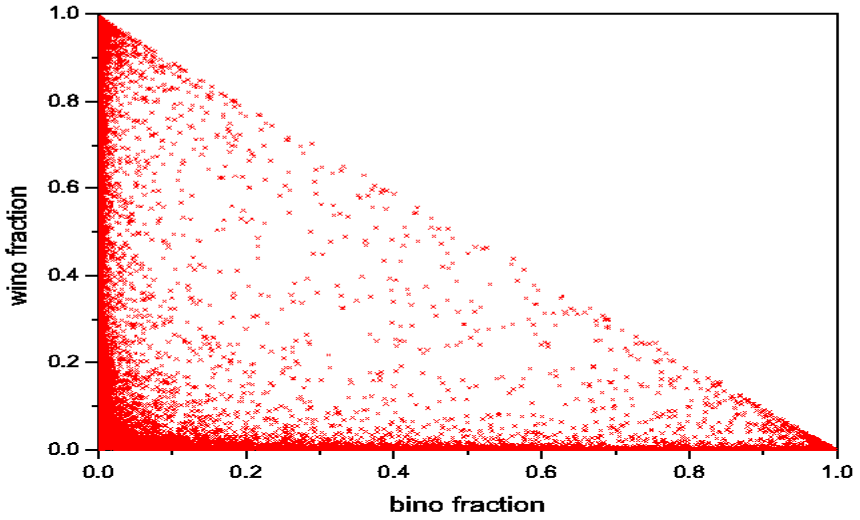
Composition of the LSP

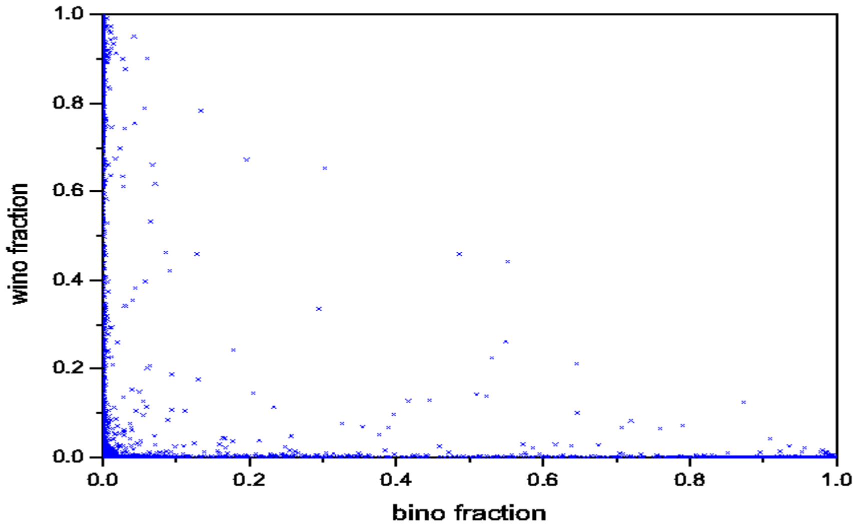
Flat Priors

Log Priors



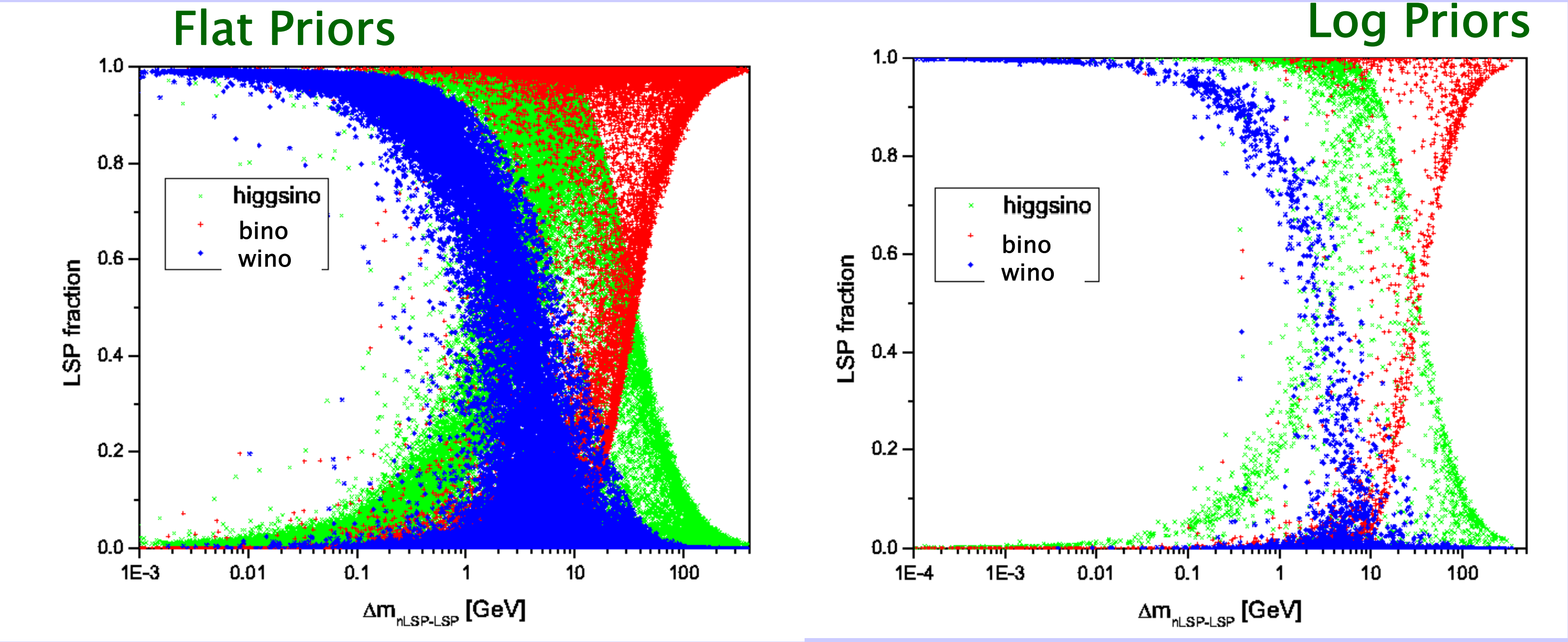






LSP Composition

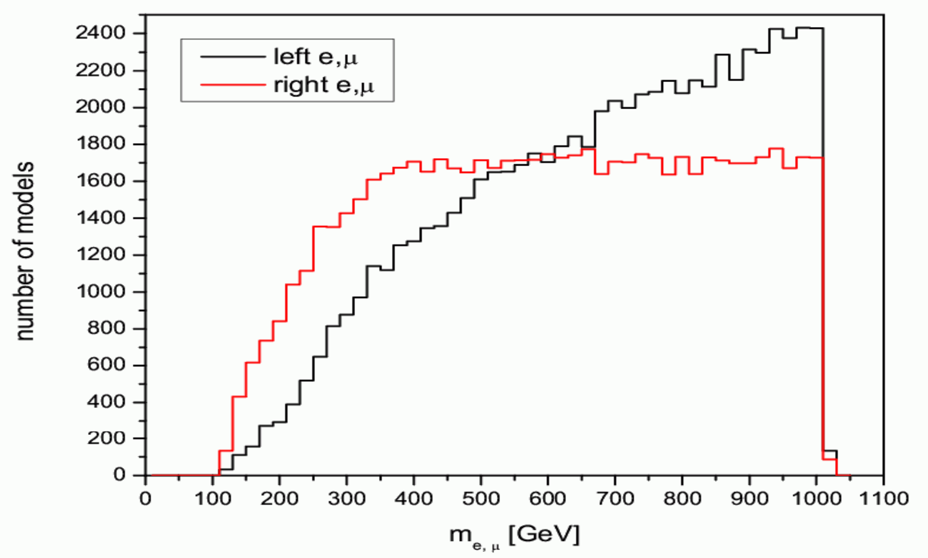
The LSP composition is found to be mass dependent as well as sensitive to the nLSP-LSP mass splitting. Models with large mass splittings have LSPs which are bino-like but VERY small mass splittings produce wino-like LSPs.

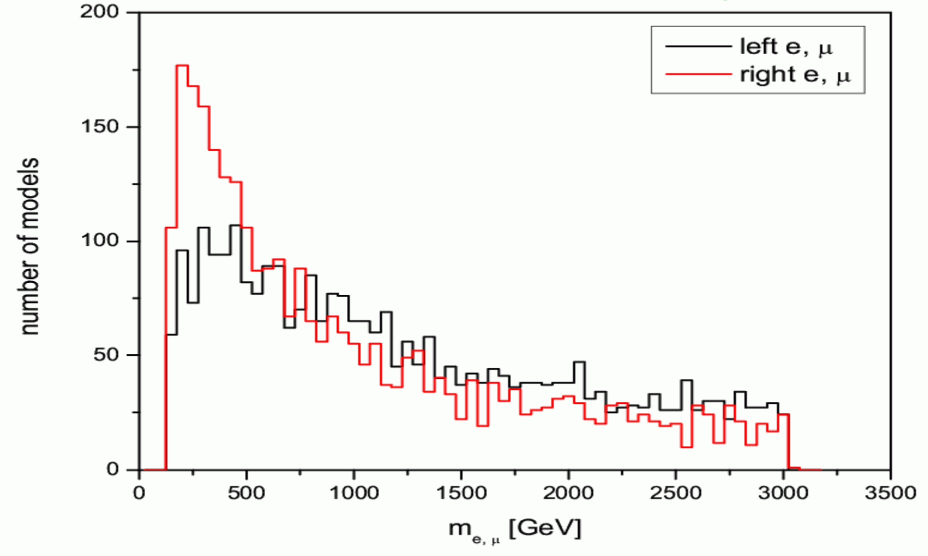


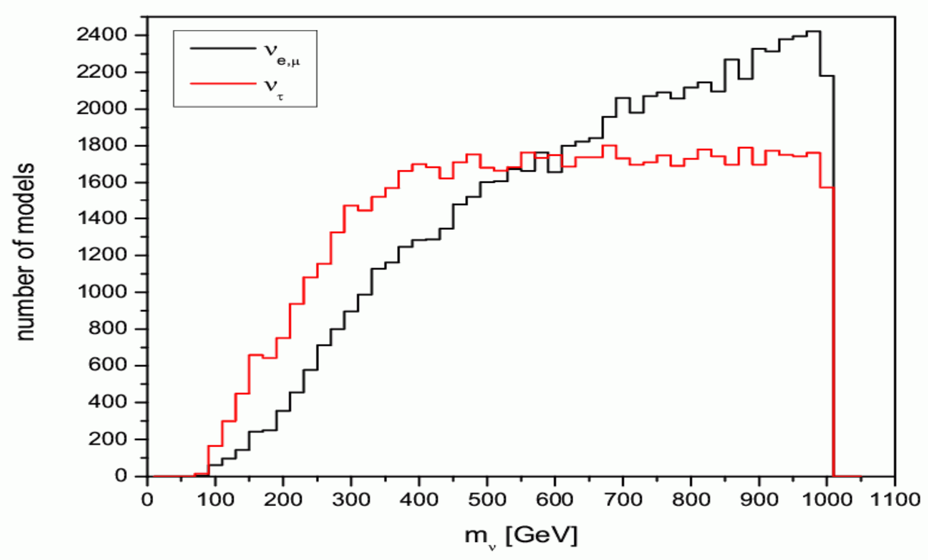
Distribution for Selectron/Sneutrino Masses

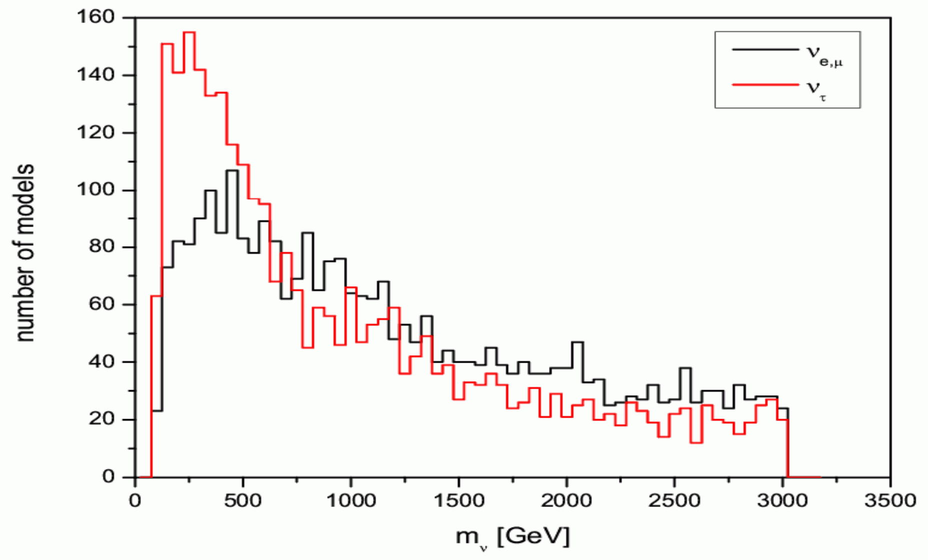
Flat Priors

Log Priors



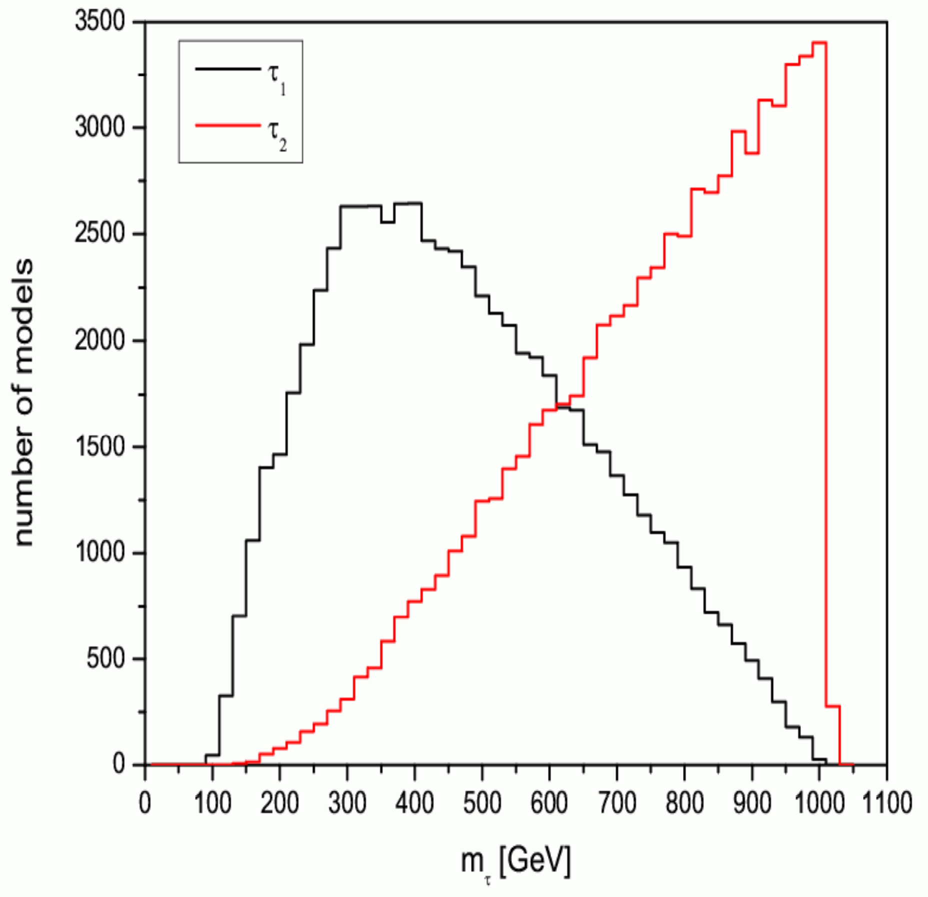




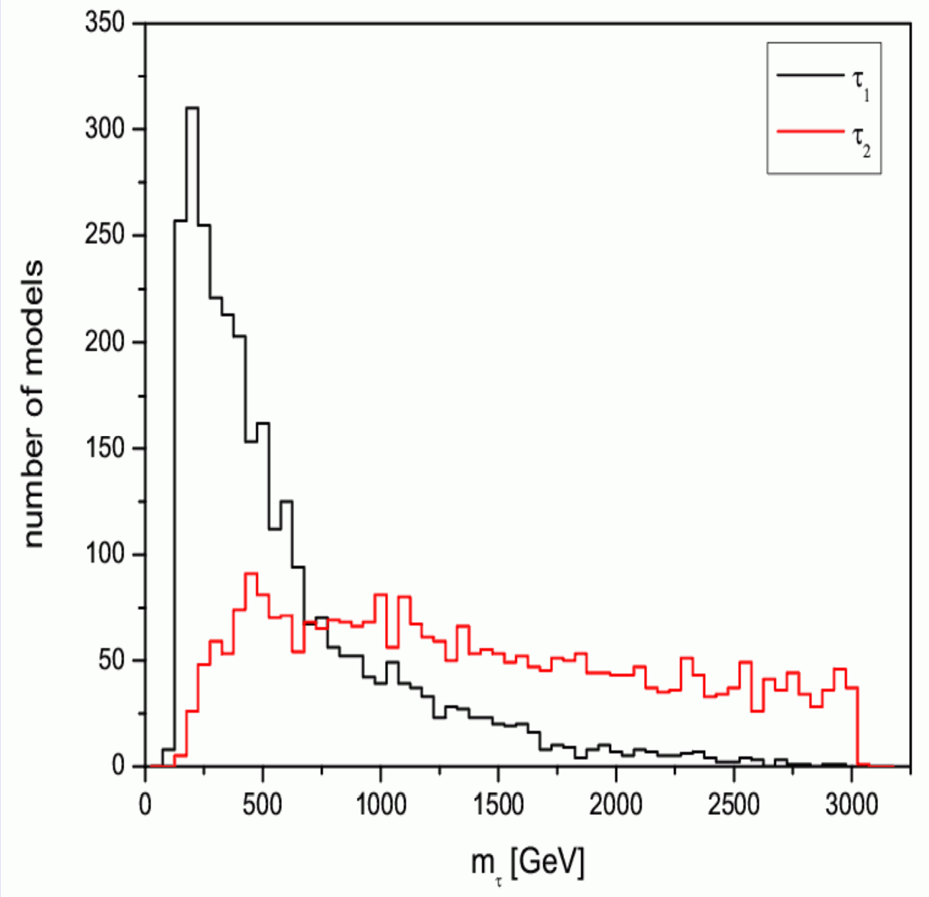


Distribution of Stau Masses

Flat Priors

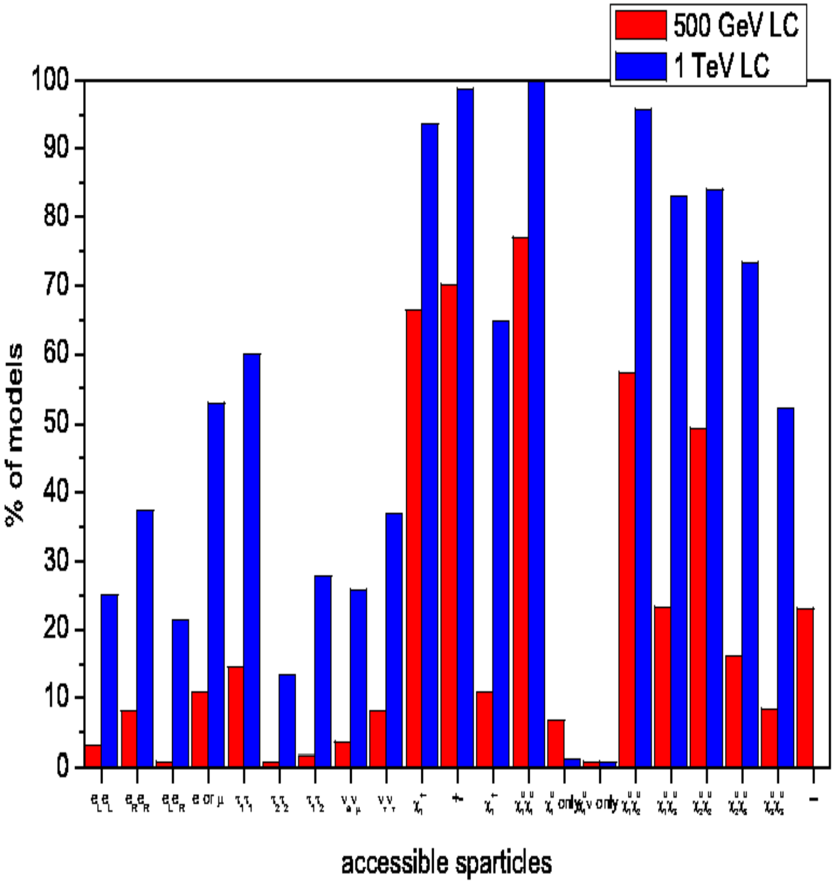


Log Priors

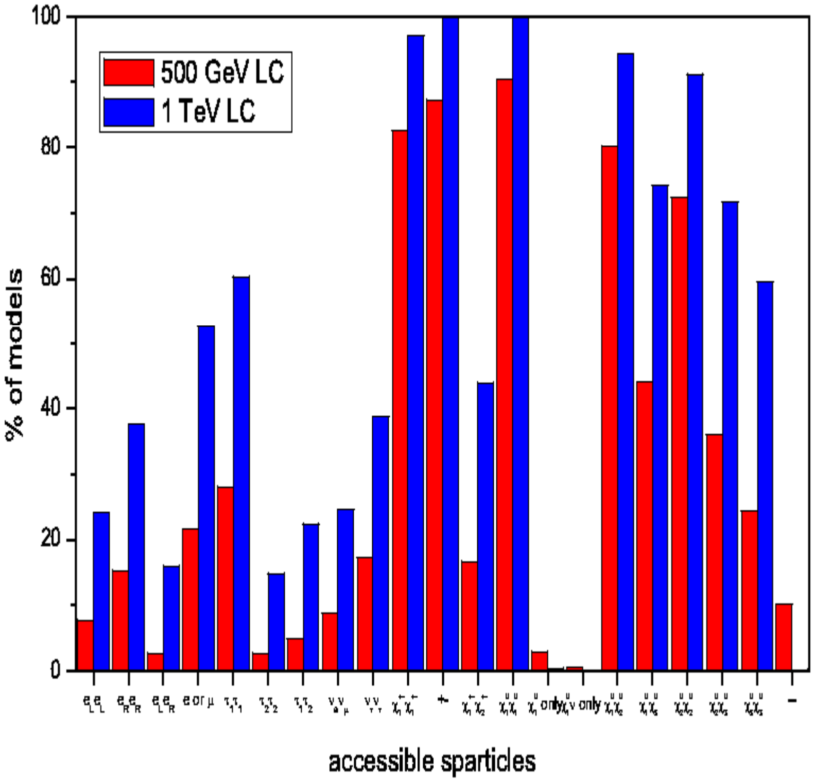


ILC Search Region: Sleptons and EW Gauginos

Flat Priors: $M_{SUSY} \leq 1$ TeV



Log Priors: $M_{SUSY} \leq 3$ TeV

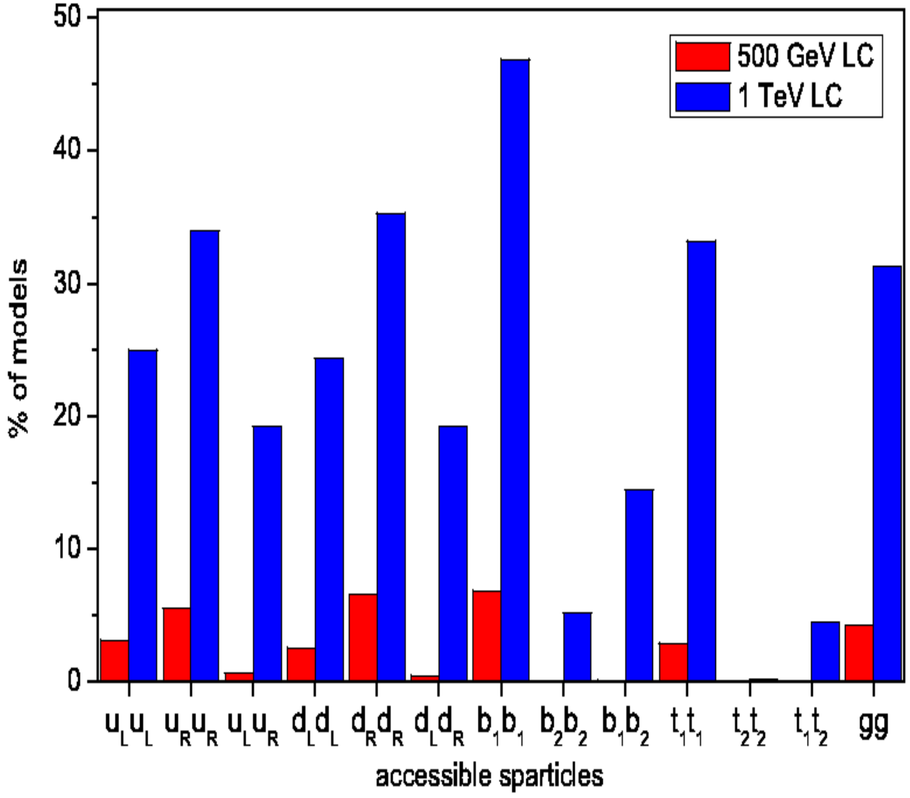


x-axis legend

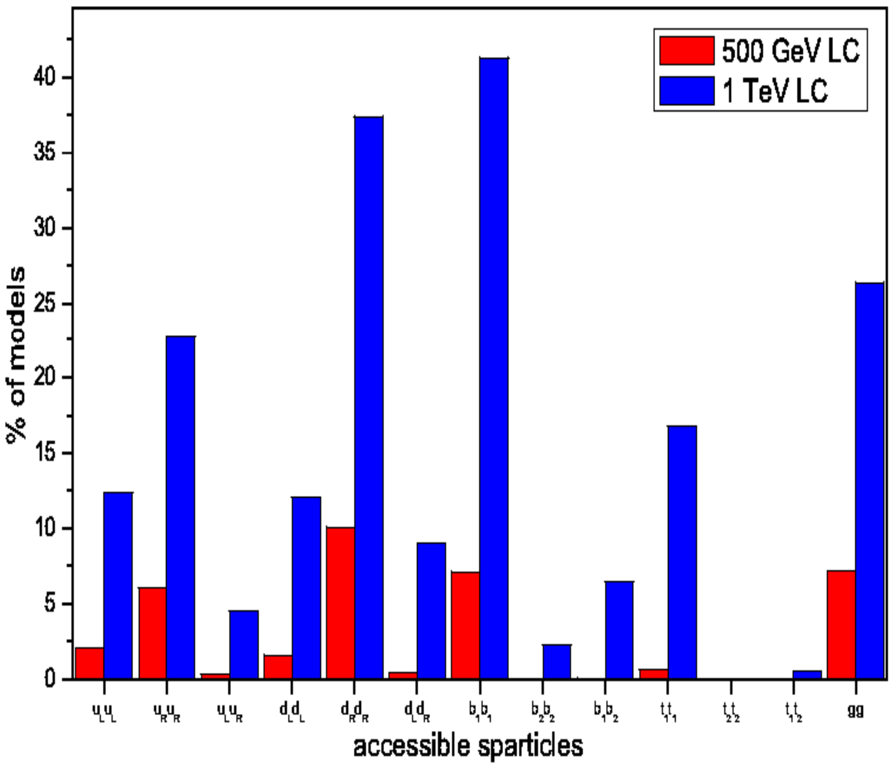
$\tilde{e}_L^+\tilde{e}_L^-$
$\tilde{e}_R^+\tilde{e}_R^-$
$\tilde{e}_L^\pm\tilde{e}_R^\mp$
$\tilde{\mu}_L^+\tilde{\mu}_L^-$
$\tilde{\mu}_R^+\tilde{\mu}_R^-$
Any selectron or smuon
$\tilde{\tau}_1^+\tilde{\tau}_1^-$
$\tilde{\tau}_2^+\tilde{\tau}_2^-$
$\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$
$\tilde{\nu}_{e\mu}\tilde{\nu}_{e\mu}^*$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

ILC Search Region: Squarks and Gluinos

Flat Priors: $M_{SUSY} \leq 1$ TeV

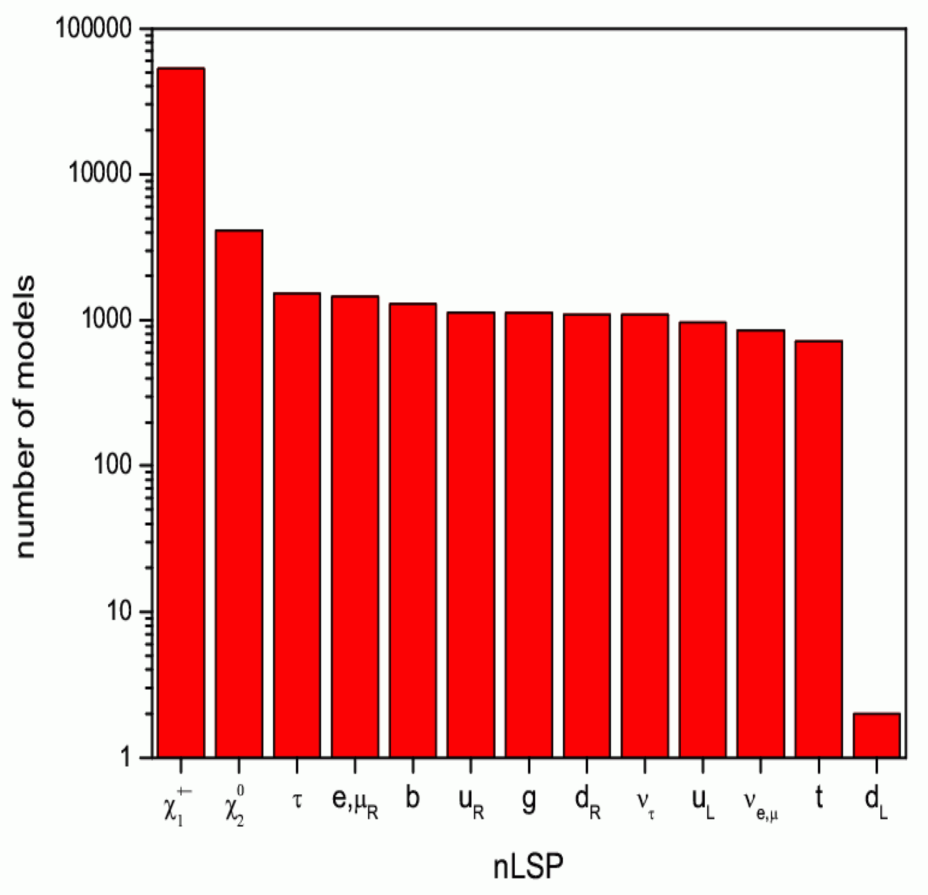


Log Priors: $M_{SUSY} \leq 3$ TeV

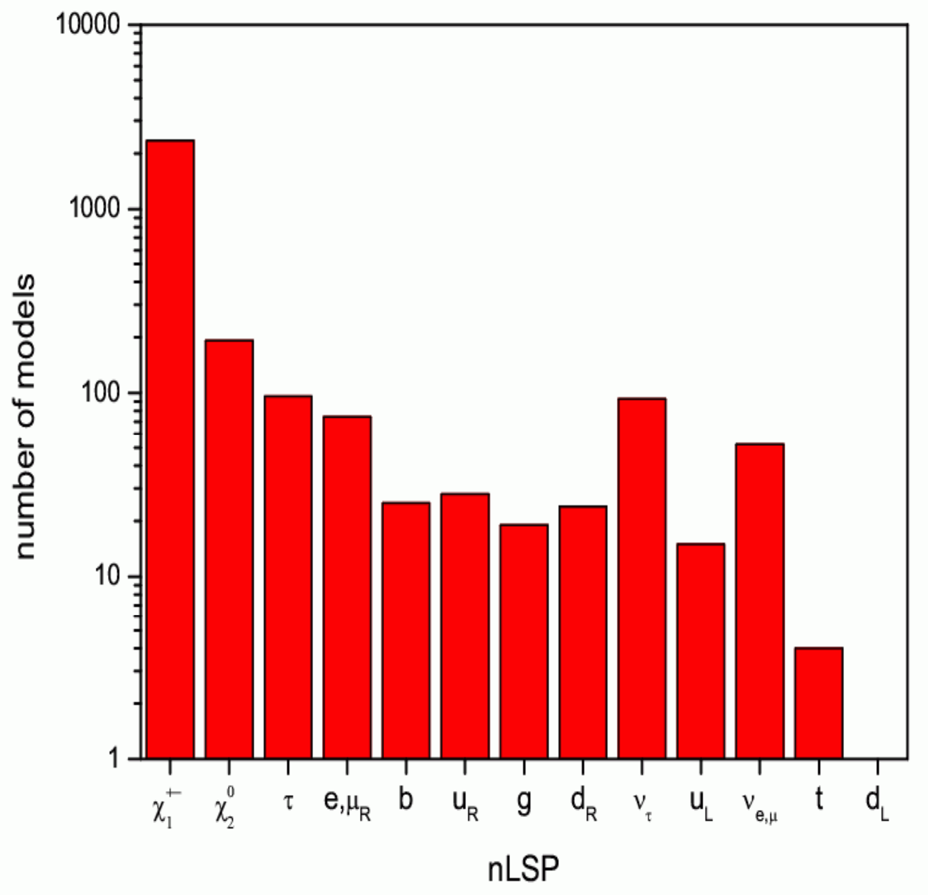


Character of the NLSP: it can be anything!

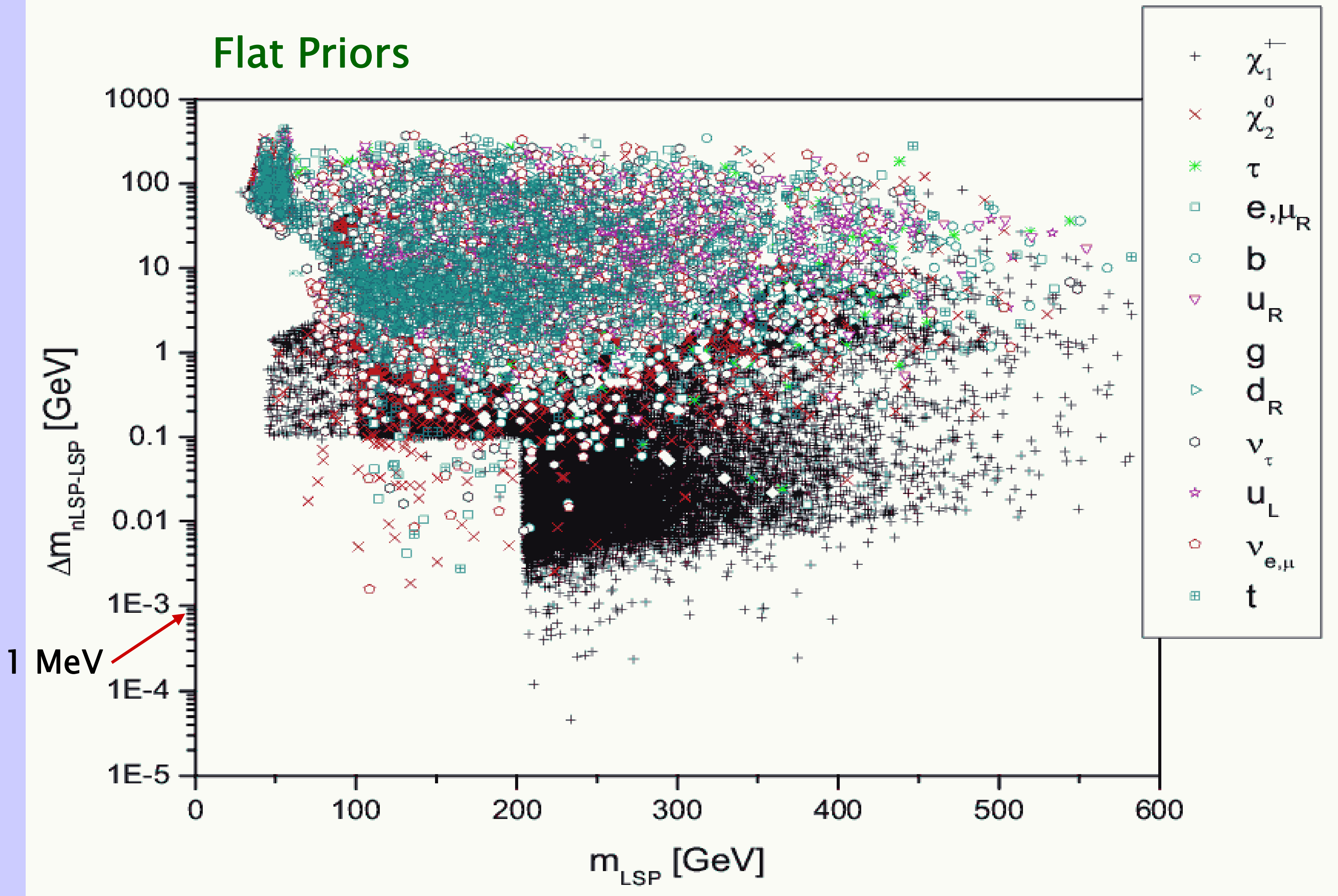
Flat Priors



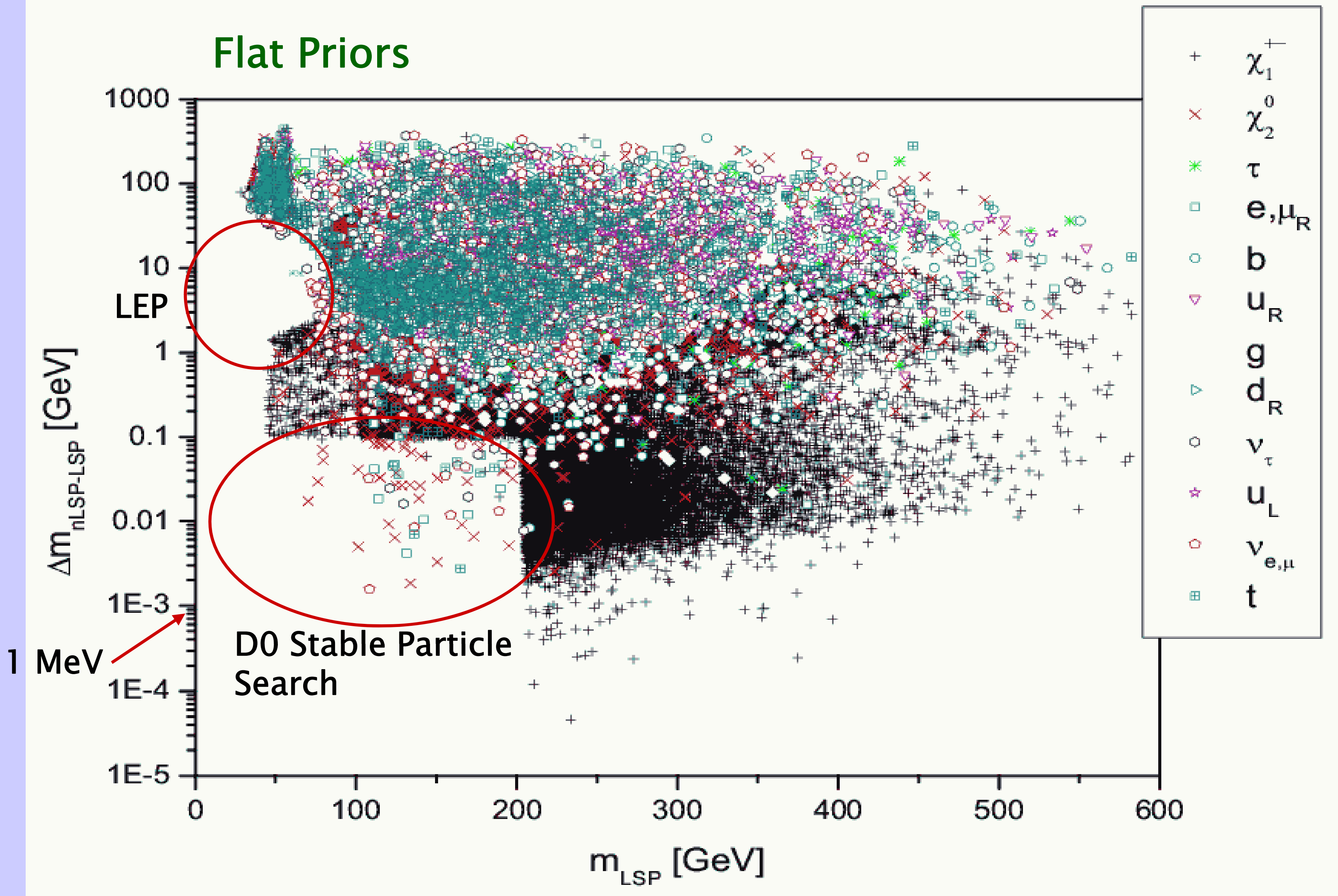
Log Priors



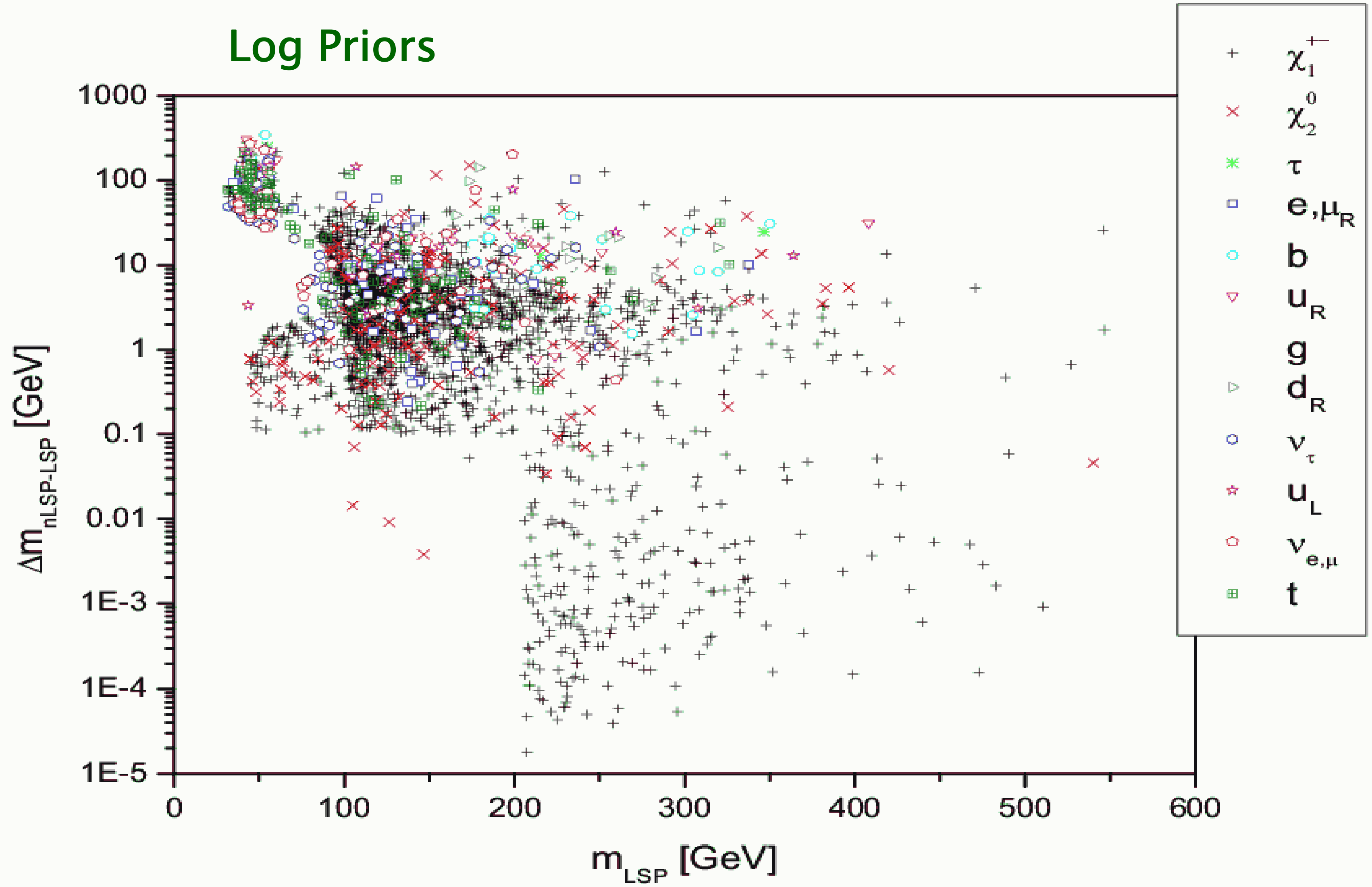
NLSP-LSP Mass Splitting



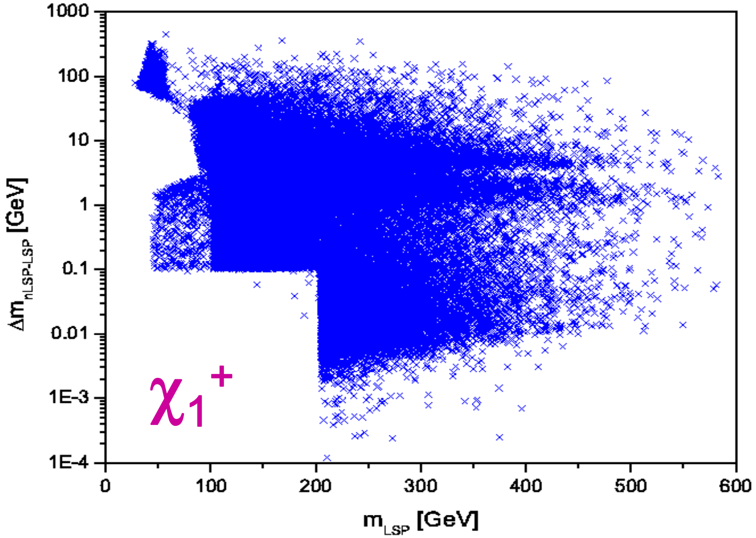
NLSP–LSP Mass Splitting

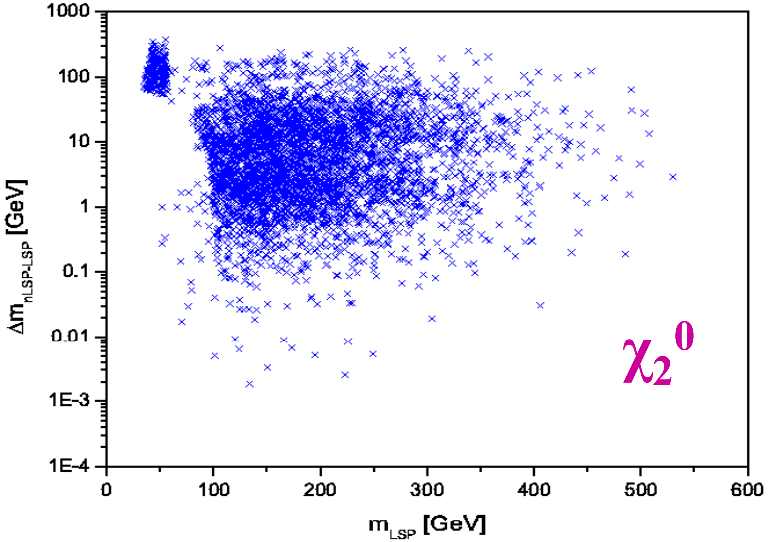


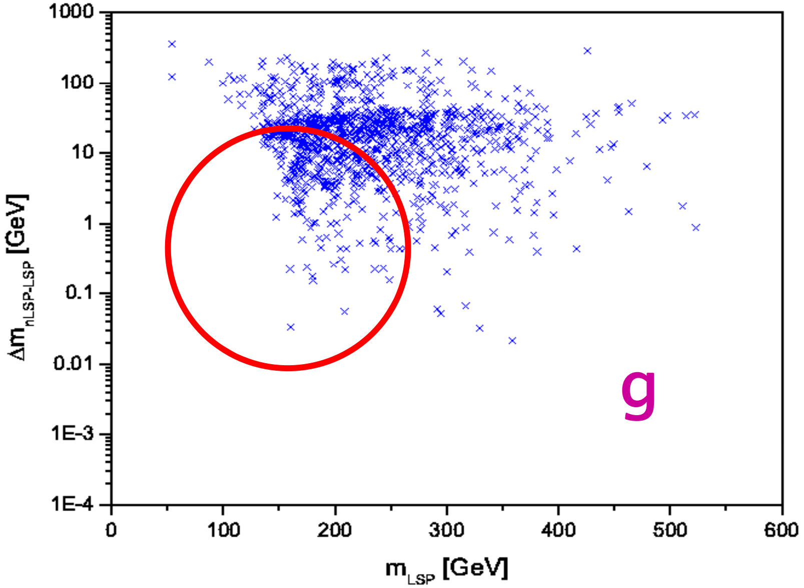
NLSP-LSP Mass Splitting

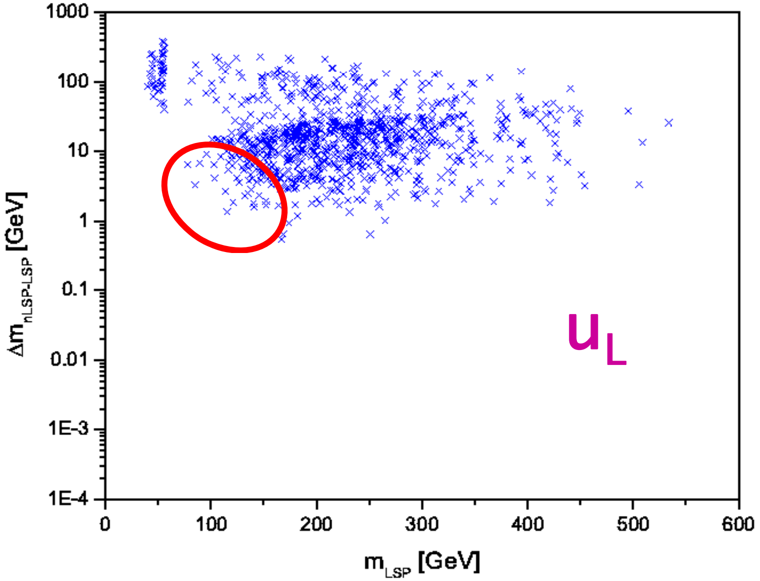


nLSP Mass Distributions By Species









Cascade Failure: Changes in Typical Analyses?

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

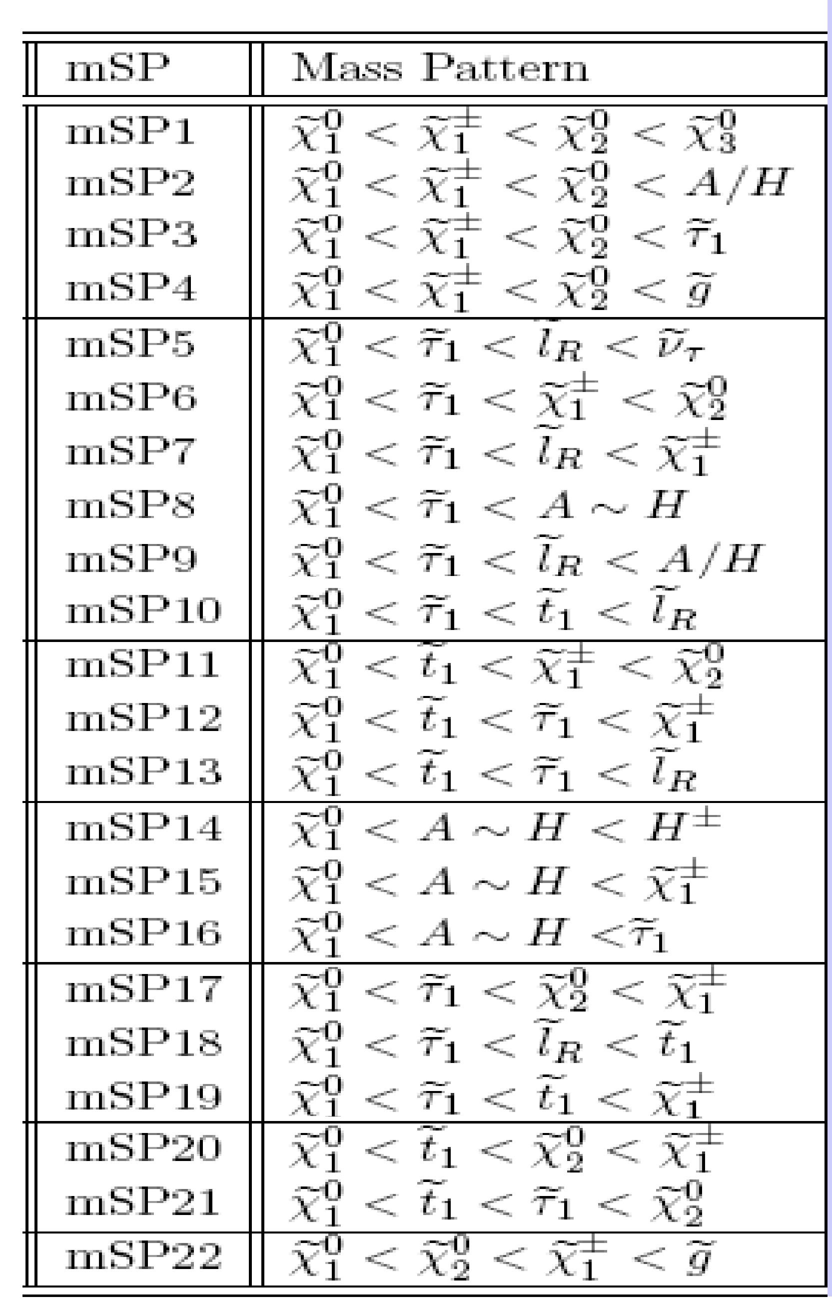
- Typical mSUGRA cascade leading to 2l+4j+MET from gluino pair production. In many of our models the W will be far off-shell & the resulting lepton will be too soft. This will then appear as 4j+MET unless the chargino is long-lived in which case we have 4j +2 long-lived charged particles with no MET.

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

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

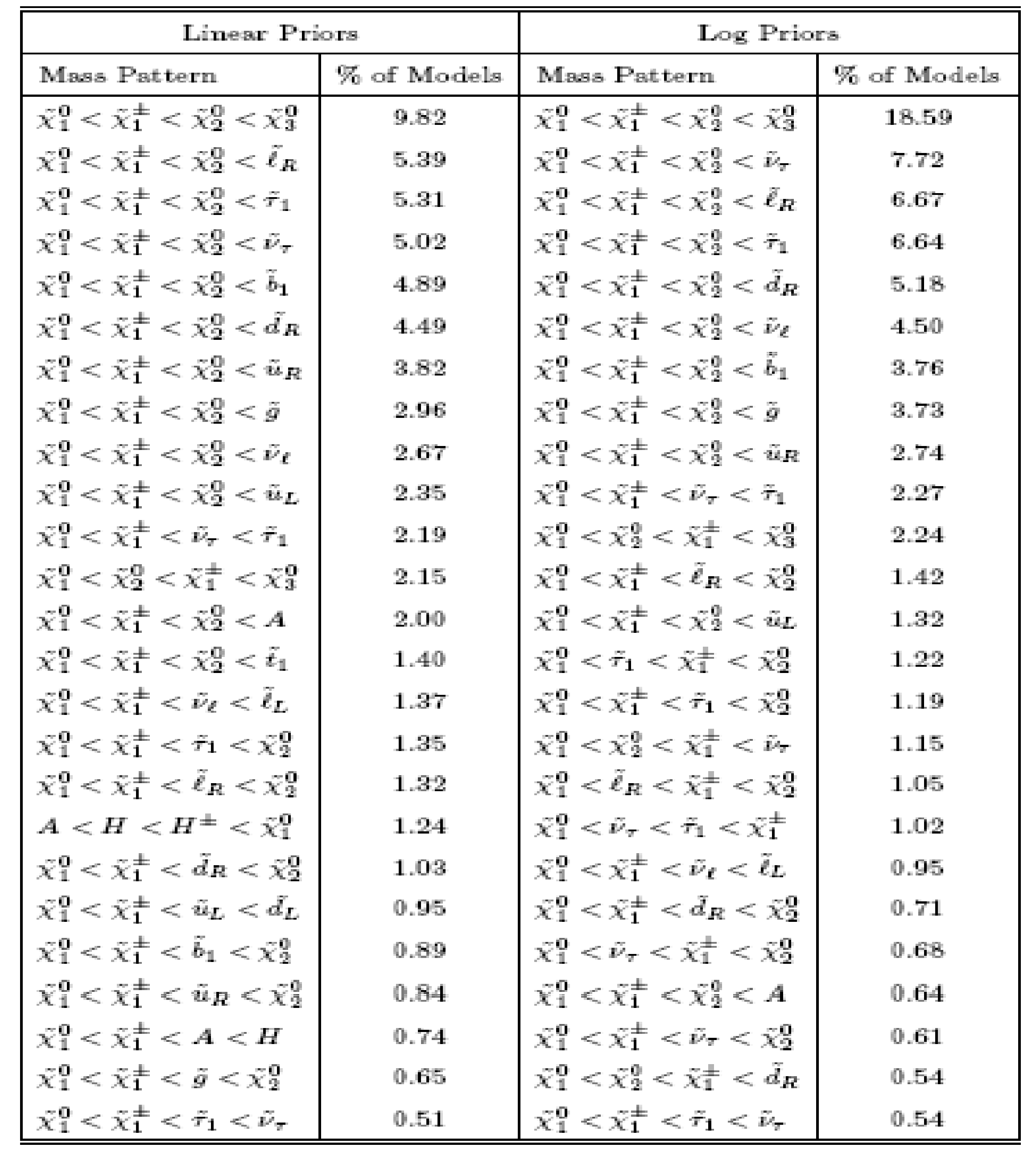
Nath etal

Mass Pattern Classification: mSUGRA



mSP	Mass Pattern	Linear	Log
mSP1	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\chi}_3^0$	9.81	18.49
mSP2	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < A/H$	2.07	0.67
mSP3	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\tau}_1$	5.31	6.60
mSP4	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{g}$	2.96	3.70
mSP5	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\tau$	0.02	0.13
mSP6	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	0.46	1.21
mSP7	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\chi}_1^\pm$	0.02	0.03
mSP8	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < A \sim H$	0.06	0.00
mSP9	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < A/H$	0.01	0.00
mSP10	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{l}_R$	0.00	0.00
mSP11	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	0.09	0.00
mSP12	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm$	0.01	0.00
mSP13	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{l}_R$	0.01	0.00
mSP14	$\widetilde{\chi}_1^0 < A \sim H < H^\pm$	0.35	0.10
mSP15	$\widetilde{\chi}_1^0 < A \sim H < \widetilde{\chi}_1^\pm$	0.01	0.03
mSP16	$\widetilde{\chi}_1^0 < A \sim H < \widetilde{\tau}_1$	0.08	0.00
mSP17	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm$	0.18	0.40
mSP18	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{t}_1$	0.01	0.00
mSP19	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm$	0.00	0.00
mSP20	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm$	0.06	0.00
mSP21	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0$	0.01	0.00
mSP22	$\widetilde{\chi}_1^0 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm < \widetilde{g}$	0.27	0.51

Flat Priors Log Priors



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

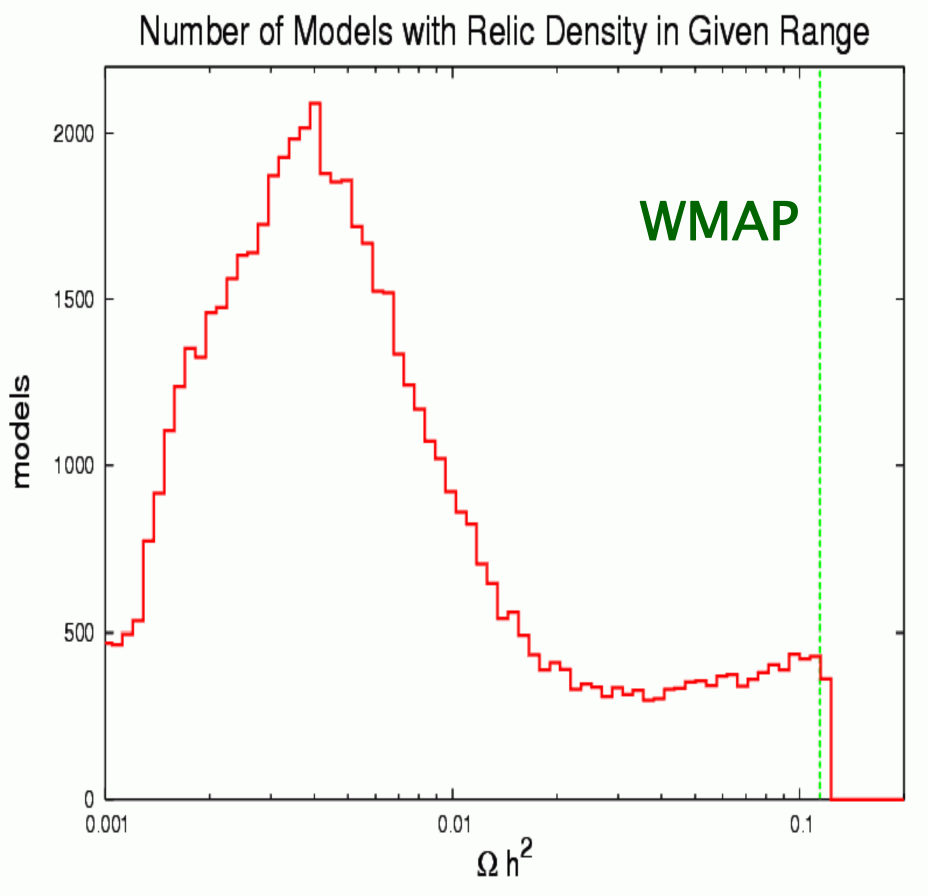
We have many more classifications!

Flat Priors:
1109 Classes

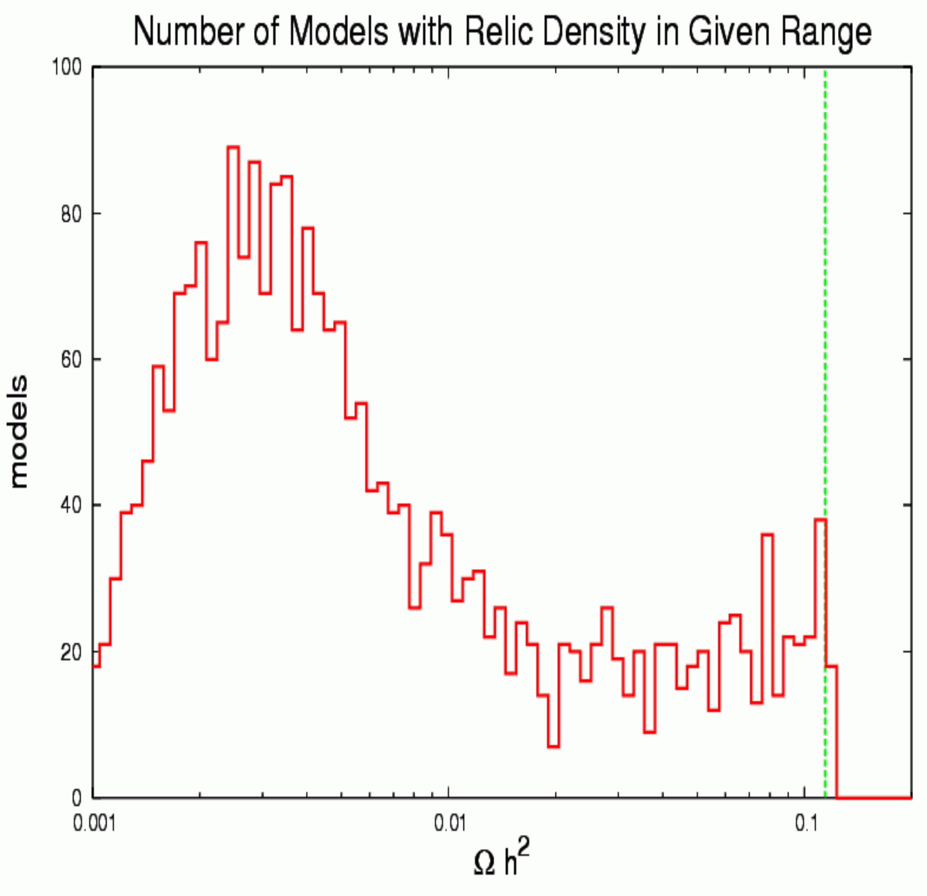
Log Priors:
267 Classes

Predictions for Relic Density

Flat Priors

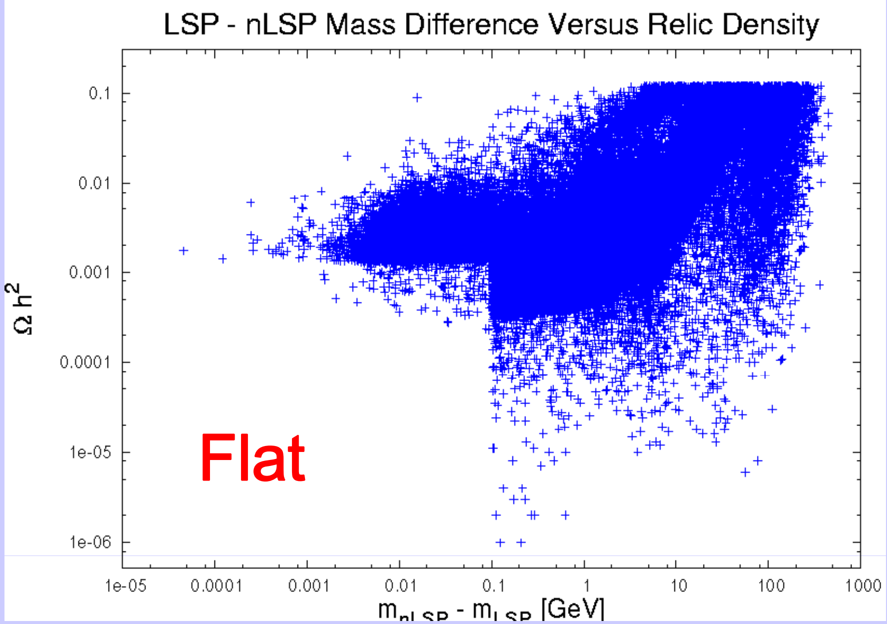


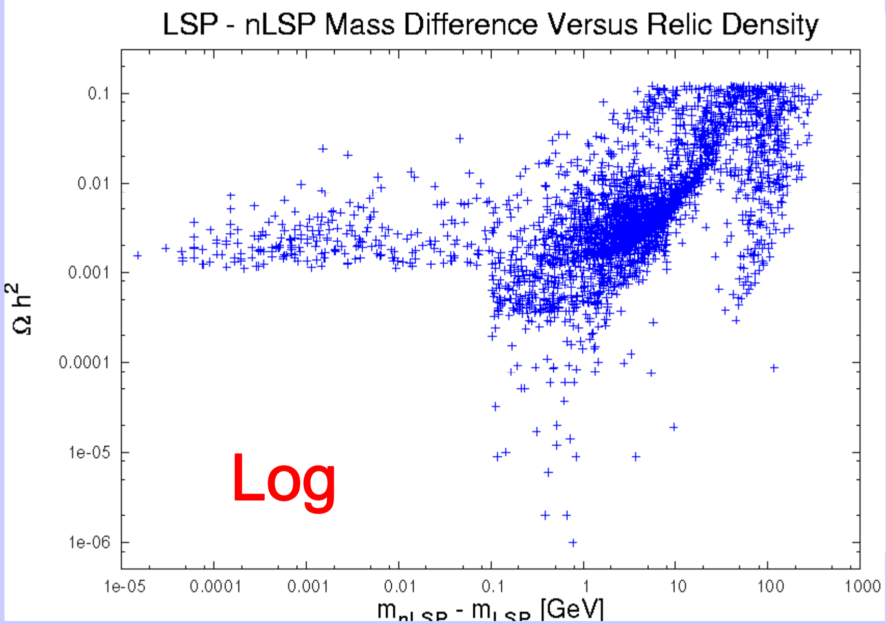
Log Priors



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

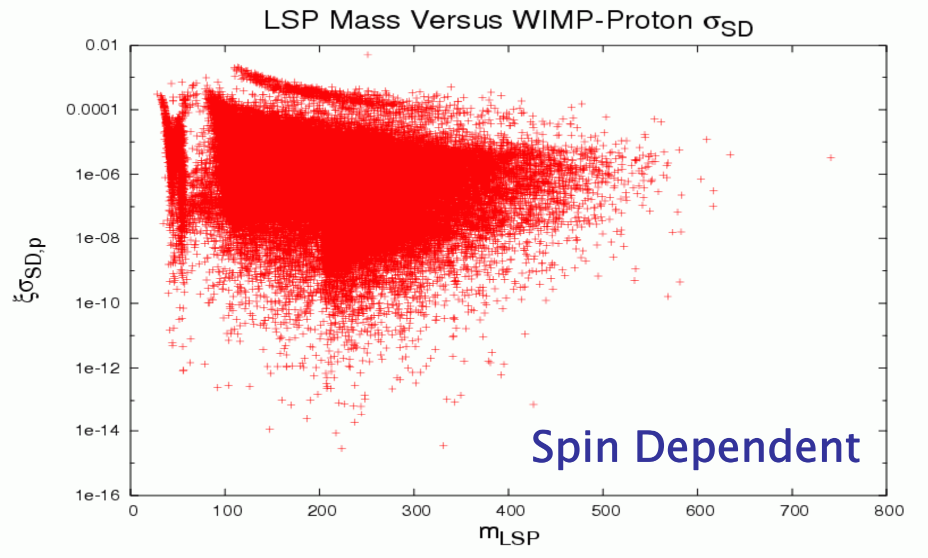
Small mass differences can lead to rapid co-annihilations reducing the dark matter density....



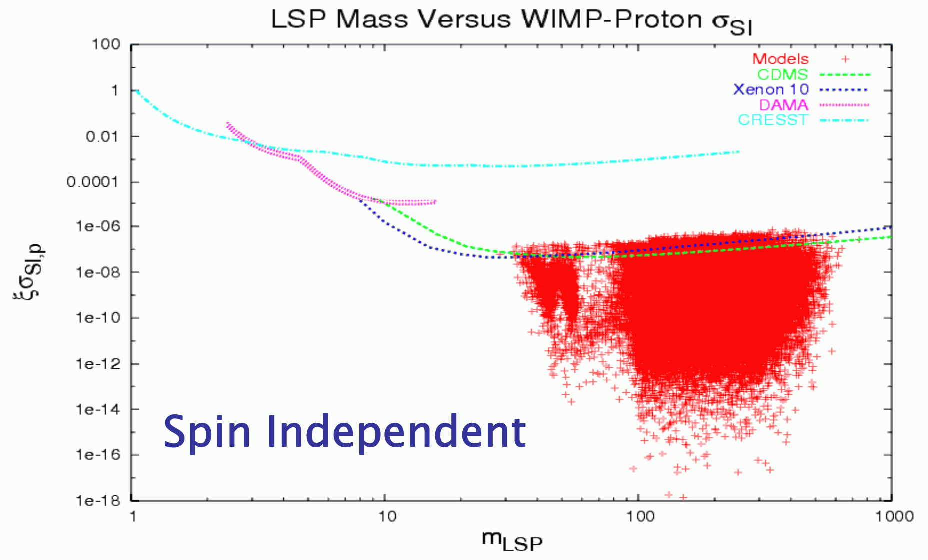


Dark Matter Direct Detection Cross Sections

Flat Priors

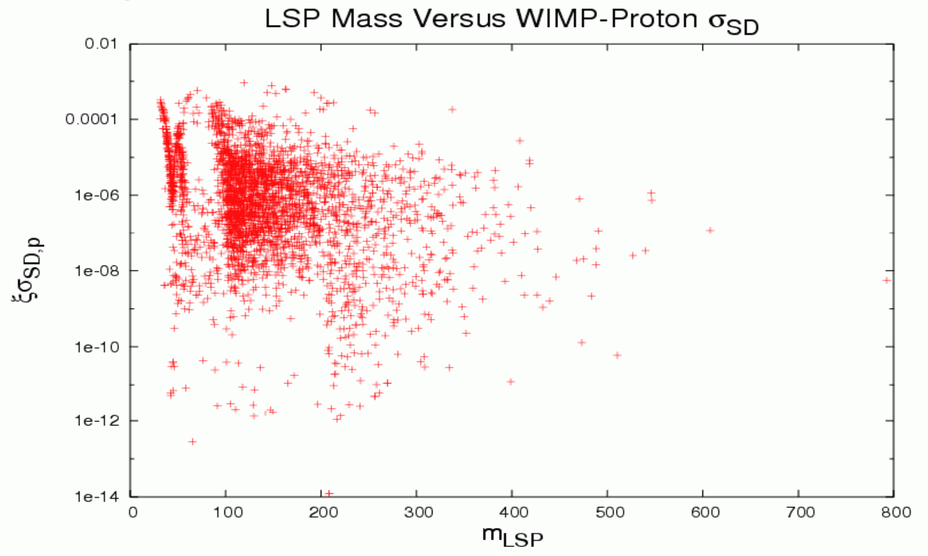


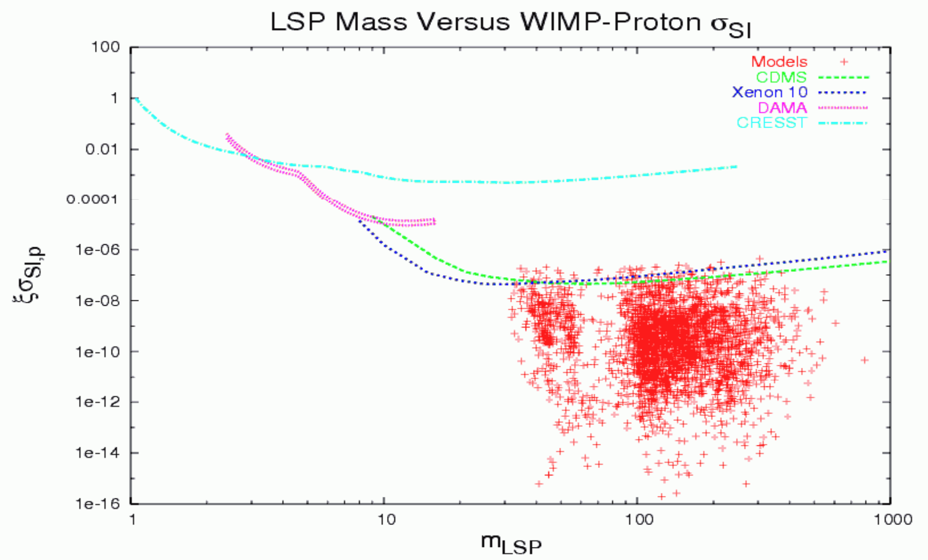
Spin Dependent



Spin Independent

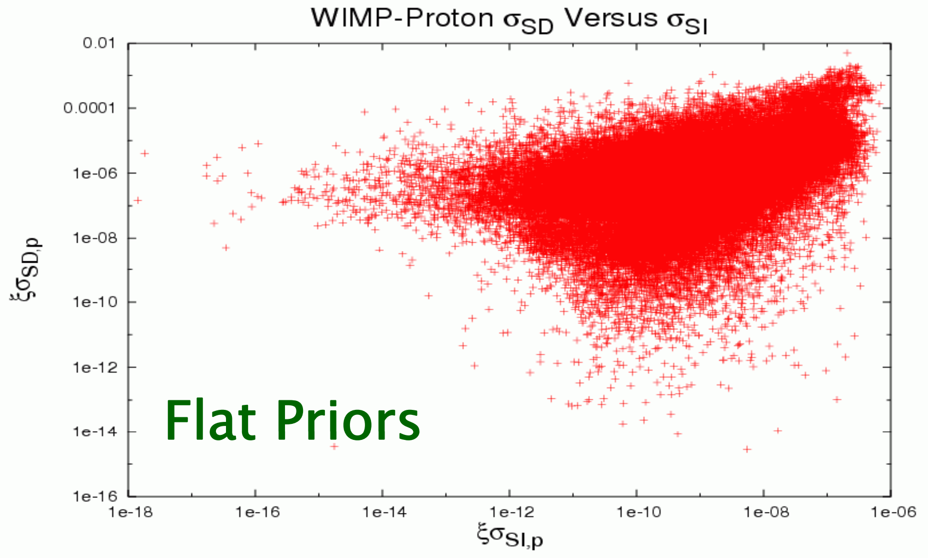
Log Priors



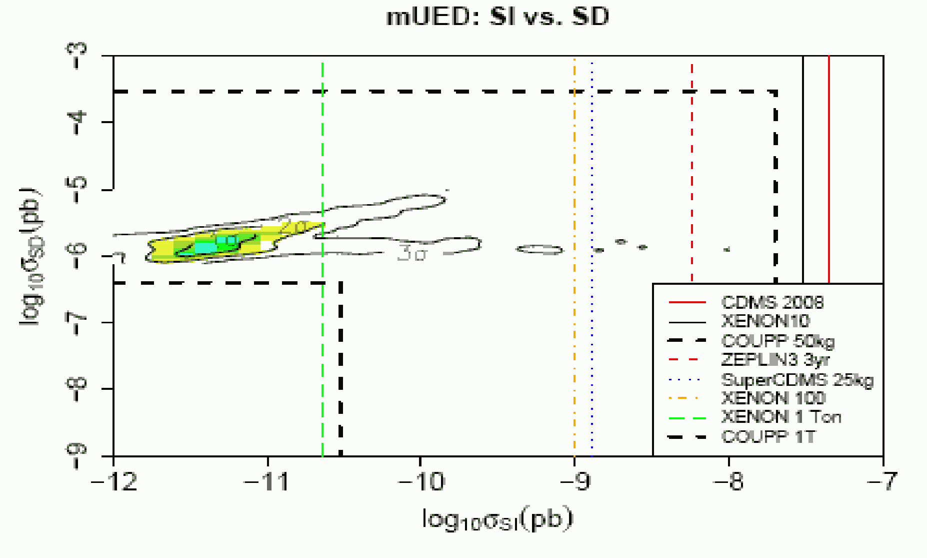


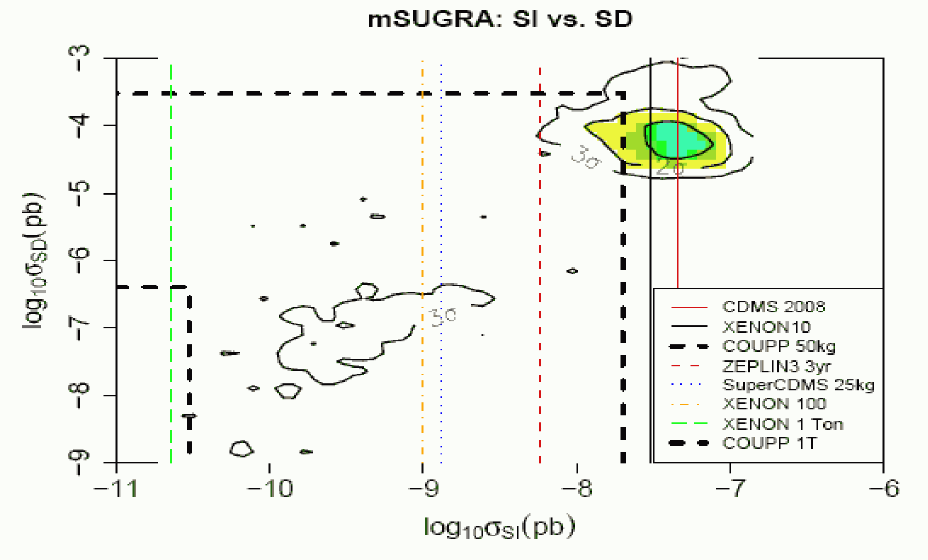
Distinguishing Dark Matter Models

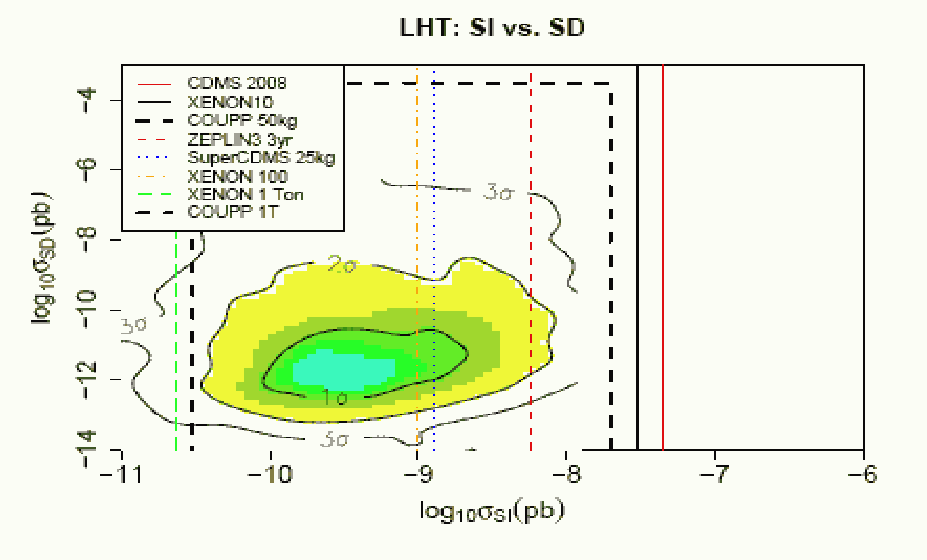
Barger etal



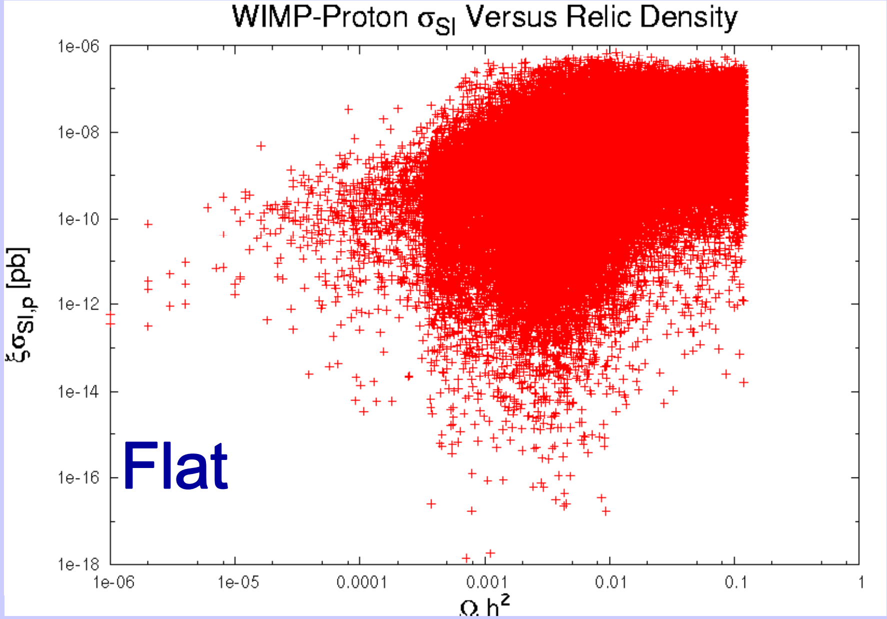
Flat Priors

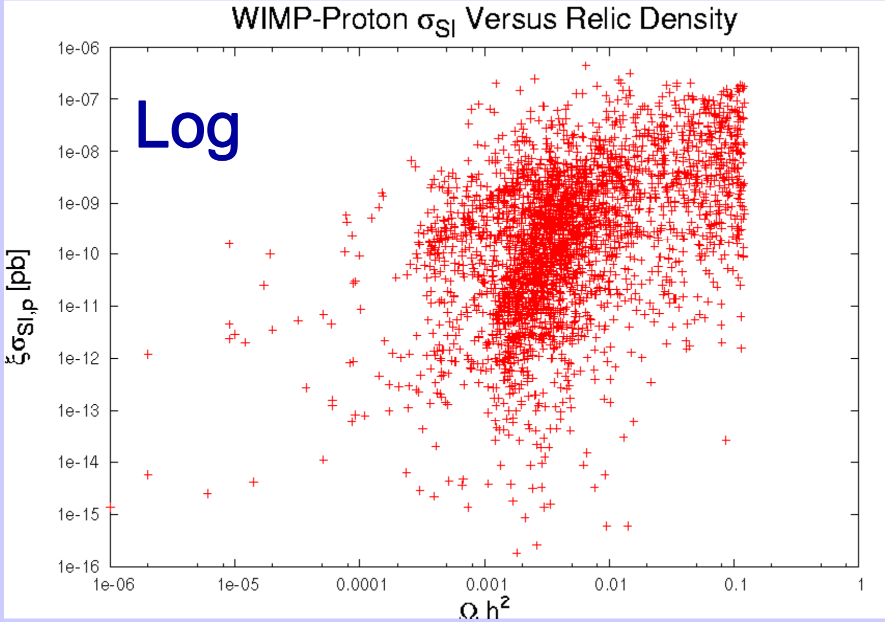






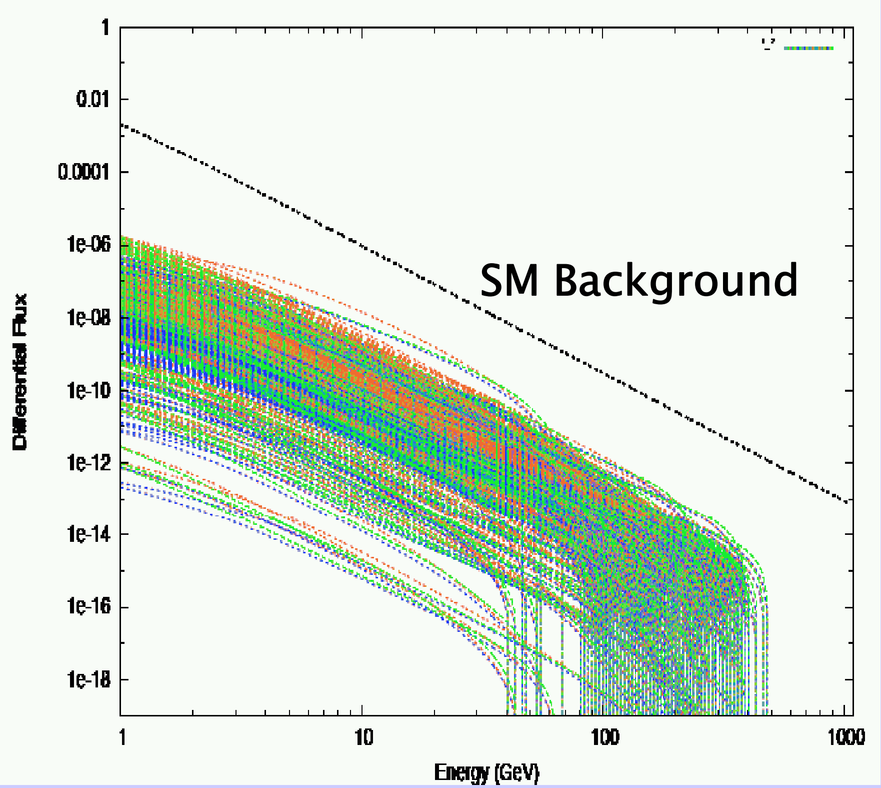
Dark Matter Density Correlation with the Direct Search Cross Section



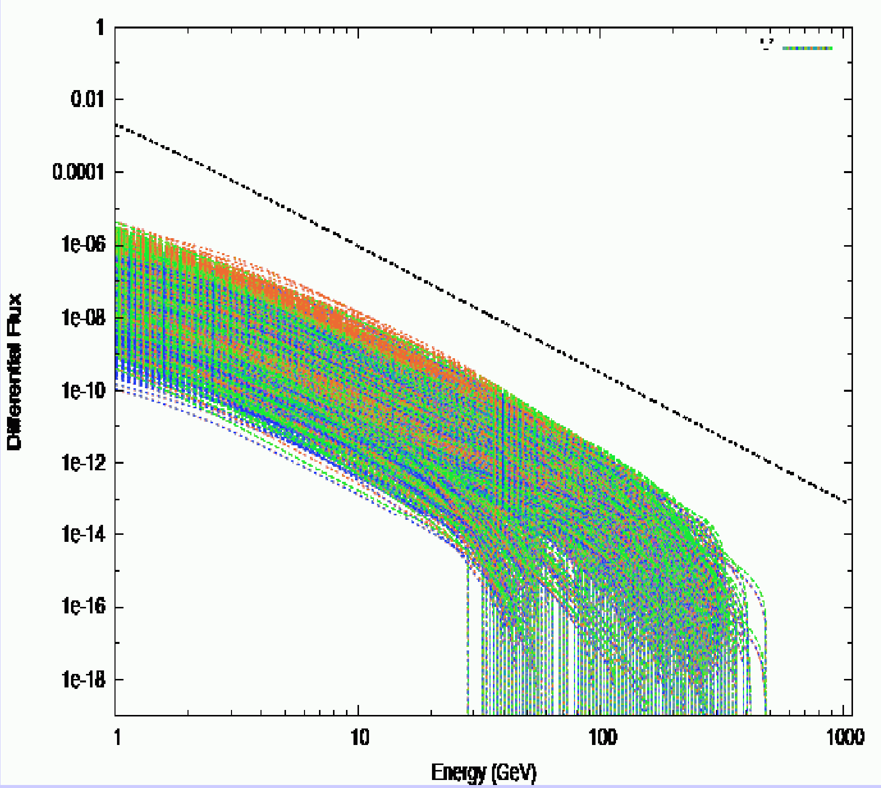


Cosmic Ray Positron Flux: No Boost

500 Random models from our data set



500 Models that saturate WMAP



Propagation Models:

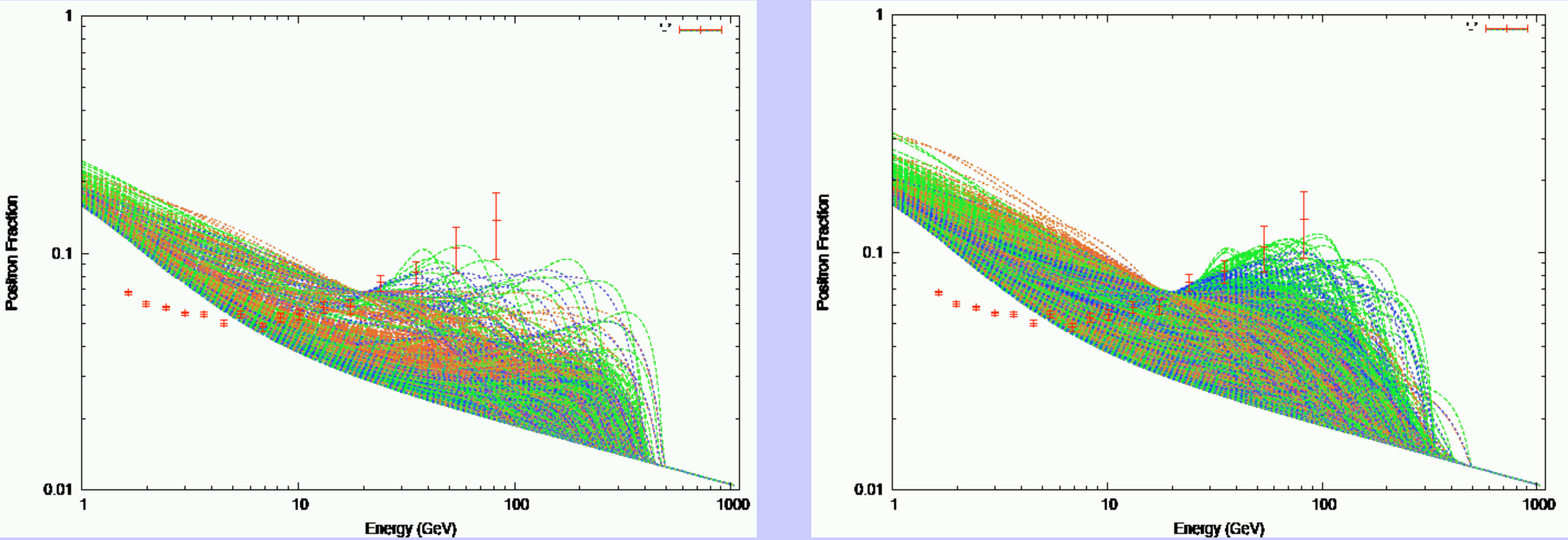
Edsjo-Baltz
Moskalenko-Strong
Kamionkowski-Turner

Cosmic Ray Positron Flux: Fit with Boost

- χ^2 fit to 5 highest energy PAMELA data points
- Vary boost for best fit (take Boost $\leq$ 2000)

500 Random models from our data set

500 Models that saturate WMAP



Propagation Models:

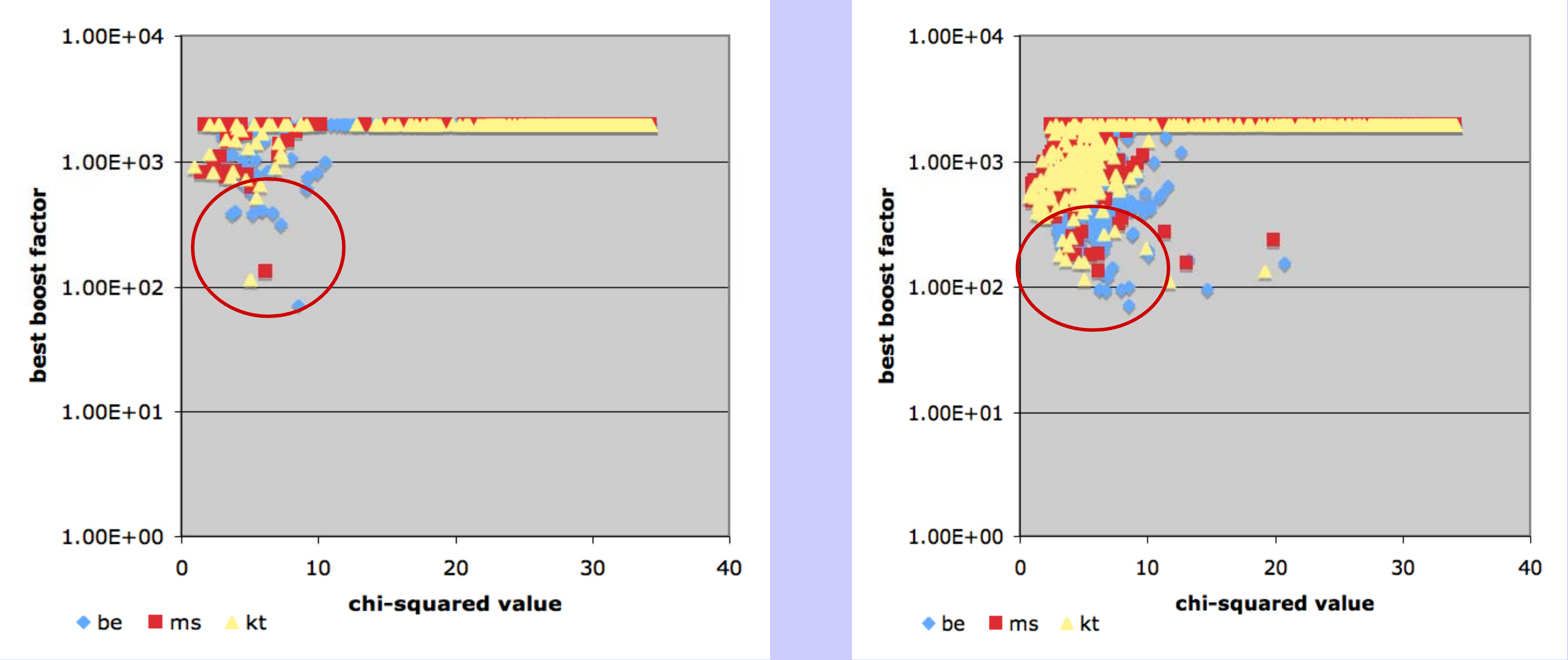
Edsjo-Baltz
Moskalenko-Strong
Kamionkowski-Turner

Best Fit Boost Factor

- χ^2 fit to 5 highest energy PAMELA data points
- Vary boost for best fit (take Boost $\leq$ 2000)

500 Random models from our data set

500 Models that saturate WMAP



mSUGRA fits need boost factor of ~ 100,000!

Naturalness Criterion

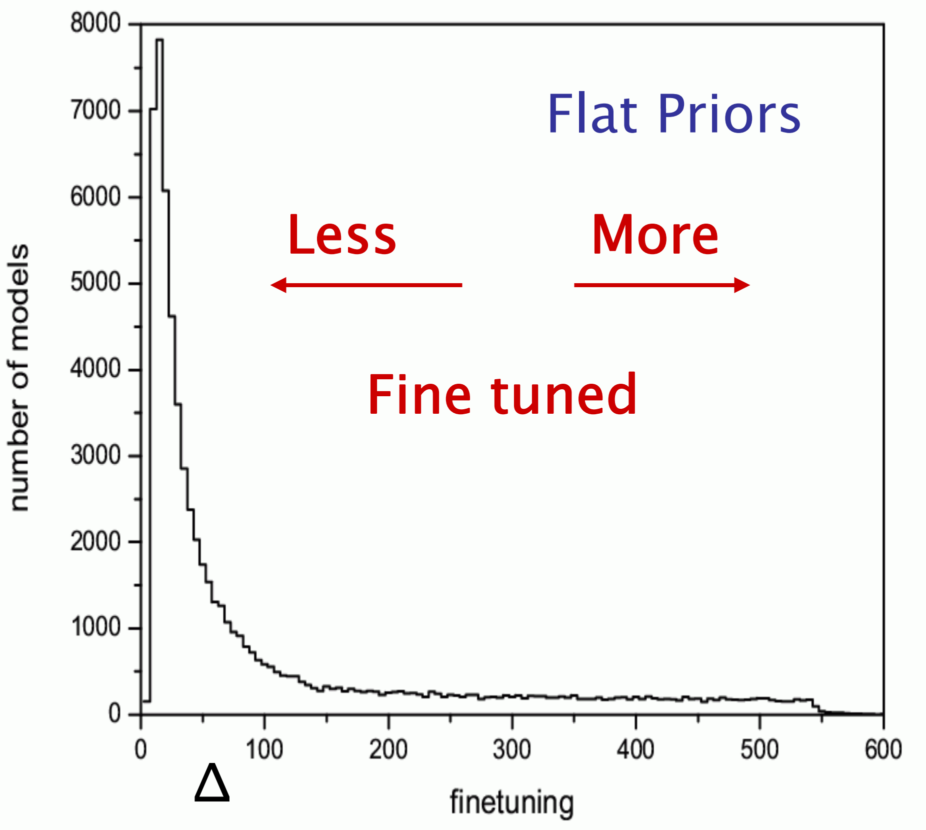
Barbieri, Giudice
Kasahara, Freese, Gondolo

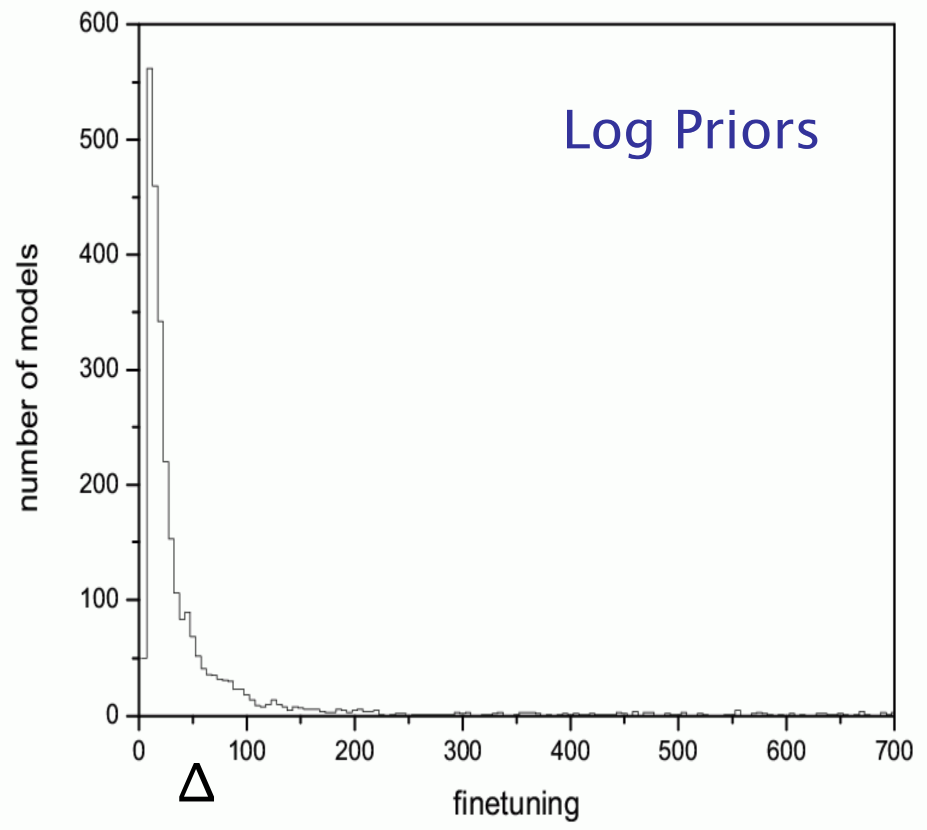
$$m_Z^2 = -m_u^2\left(1-\frac{1}{\cos 2\beta}\right) - m_d^2\left(1+\frac{1}{\cos 2\beta}\right) - 2|\mu|^2,$$

$$\sin 2\beta = \frac{2b}{m_u^2+m_d^2+2|\mu|^2}.$$

$$A(\xi) = \left|\frac{\partial \log m_Z^2}{\partial \log \xi}\right|$$

$$\begin{aligned}
A(\mu) &= \frac{4\mu^2}{m_Z^2}\left(1+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right),\\
A(b) &= \left(1+\frac{m_A^2}{m_Z^2}\right)\tan^2 2\beta,\\
A(m_u^2) &= \left|\frac{1}{2}\cos 2\beta+\frac{m_A^2}{m_Z^2}\cos^2\beta-\frac{\mu^2}{m_Z^2}\right| \times \left(1-\frac{1}{\cos 2\beta}+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right),\\
A(m_d^2) &= \left|-\frac{1}{2}\cos 2\beta+\frac{m_A^2}{m_Z^2}\sin^2\beta-\frac{\mu^2}{m_Z^2}\right| \times \left|1+\frac{1}{\cos 2\beta}+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right|,
\end{aligned}$$





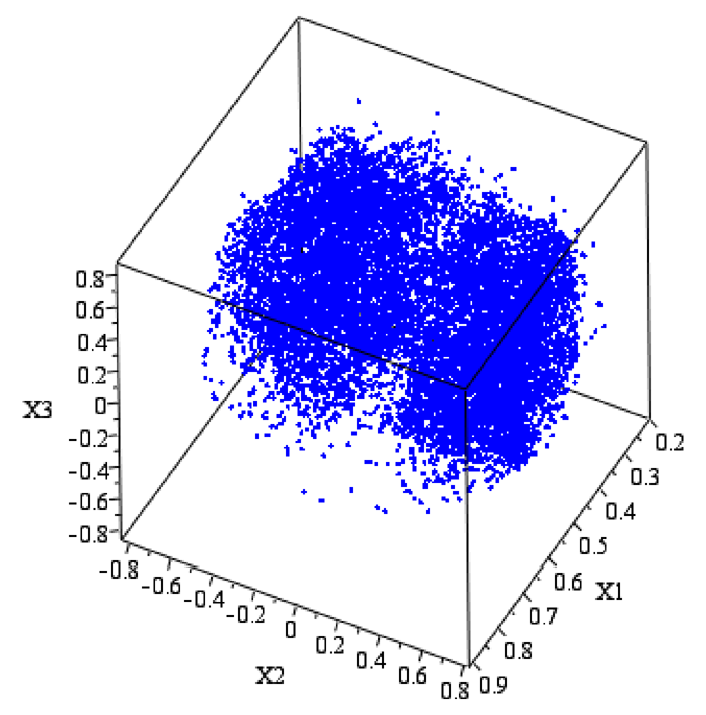
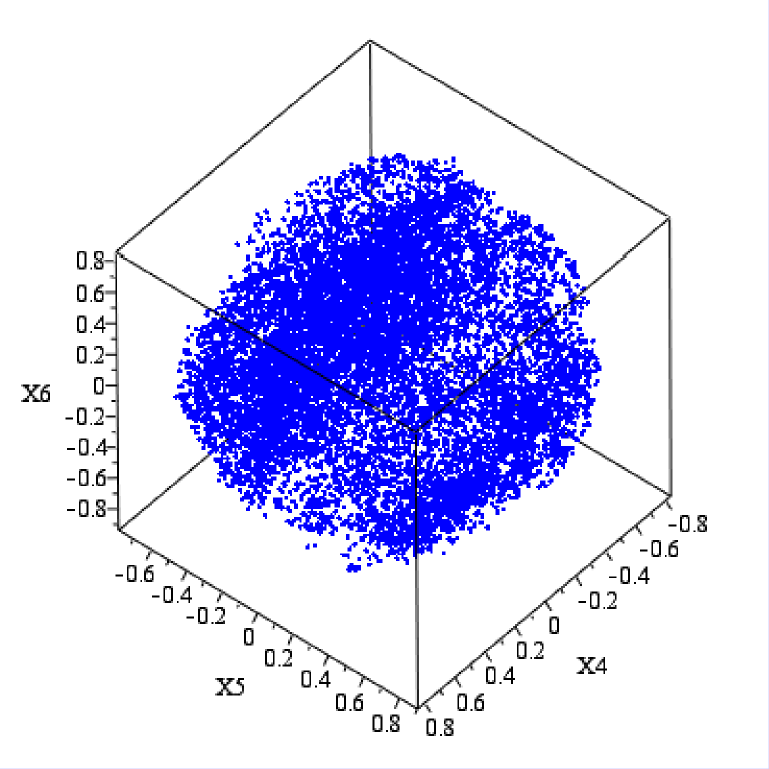
Do the Model Points Cluster in the 19-Dimensional Parameter Space?

- New data mining procedure based on Gaussian potentials

M. Weinstein

- Full Model Set before constraints is random – no clustering

Clustering of Models (12000 Points)

Dimensions 1,2,3	Dimensions 4,5,6
	

Gainer, JLH, Rizzo, Weinstein, in progress

Summary

- Studied the pMSSM, without GUT & SUSY breaking assumptions, subject to experimental constraints

- We have found a wide variety of model properties not found in mSUGRA/CMSSM
  - Colored sparticles can be very light
  - NLSP can be basically any sparticle
  - NLSP-LSP mass difference can be very small

- Wider variety of SUSY predictions for Dark Matter & Collider Signatures than previously thought

- 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
  - Mono-jet search is important