Supersymmetry Without Prejudice at the LHC

James Gainer

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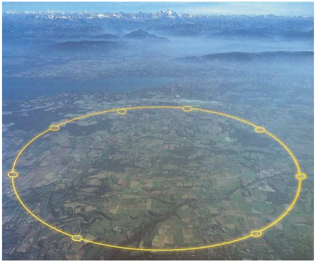


SUSY Without Prejudice at the LHC

This talk is based on

- JHEP 0902:023,2009/ arXiv:0812.0980 [hep-ph].
- LHC signature study in progress.

There are also related studies of dark matter signatures:

- arXiv:0903.4409 [hep-ph].
- Indirect detection study in progress.

Work by C. F. Berger, R. C. Cotta, J. G. Cogan, JSG, J. L. Hewett, T. G. Rizzo

Motivation

- Even the R-parity conserving MSSM has over 100 parameters.
- Raises the question of how well have we explored the MSSM.
- Generally, to avoid this issue one limits one's analyses to a specific SUSY breaking scenario(s) such as mSUGRA, GMSB, AMSB, etc. This reduces the number of parameters one needs to consider.
- But how well do any of these scenarios reflect the true breadth of the MSSM??
- Do we really know the MSSM as well as we think??

The Bigger Picture

- With the turn-on (hopefully!) of the LHC this year(ish?), a generation of theories will either be confirmed or rejected.
- Important to understand the full range of predictions from established models or frameworks; can surprising data be explained by well-motivated models?
- Nature will probably surprise us; the more we can be prepared for, the better.

Procedure

- Choose random points in MSSM parameter space.
- Calculate observables for each parameter space point ("model").
- Determine whether the model is allowed by existing theoretical, observational, and experimental constraints.
- Obtain a set of models and study their predictions for, e.g., LHC and cosmic ray experiments.

Parameter Space

- Unfortunately, it is impractical to scan over 100 parameters.
- Assume
  - CP conservation
  - Minimal Flavor Violation
  - 1st and 2nd generation sfermion masses are degenerate.
  - 1st and 2nd generation trilinear couplings negligible (so can set to zero)
- End up with the **pMSSM** (phenomenological MSSM).

The pMSSM

- 19 Parameters
  - Gaugino masses: M_1, M_2, M_3
  - Sfermion masses: $m_{q1,2}, m_{u1,2}, m_{d1,2}, m_{l1,2}, m_{e1,2}, m_{q3}, m_{u3}, m_{d3}, m_{l3}, m_{e3}$.
  - 3^{rd} generation trilinears: A_t, A_b, A_τ
  - Higgs/ Higgsino parameters: $\mu, m_A, \tan\beta$
- **Notes:** All parameters specified $\sim$ the weak scale. Gauge unification is not assumed.

Parameter Ranges

Flat Priors 10^7 points

$$
\begin{aligned}
100\,\mathrm{GeV} \le m_{\tilde{f}} &\le 1\,\mathrm{TeV}\,, \\
50\,\mathrm{GeV} \le |M_{1,2}, \mu| &\le 1\,\mathrm{TeV}\,, \\
100\,\mathrm{GeV} \le M_3 &\le 1\,\mathrm{TeV}\,, \\
|A_{b,t,\tau}| &\le 1\,\mathrm{TeV}\,, \\
1 \le \tan\beta &\le 50\,, \\
43.5\,\mathrm{GeV} \le m_A &\le 1\,\mathrm{TeV}\,.
\end{aligned}
$$

Log Priors 2×10^6 points

$$
\begin{aligned}
100\,\mathrm{GeV} \le m_{\tilde{f}} &\le 3\,\mathrm{TeV}\,, \\
10\,\mathrm{GeV} \le |M_{1,2}, \mu| &\le 3\,\mathrm{TeV}\,, \\
100\,\mathrm{GeV} \le M_3 &\le 3\,\mathrm{TeV}\,, \\
10\,\mathrm{GeV} \le |A_{b,t,\tau}| &\le 3\,\mathrm{TeV}\,, \\
1 \le \tan\beta &\le 60\,, \\
43.5\,\mathrm{GeV} \le m_A &\le 3\,\mathrm{TeV}\,.
\end{aligned}
$$

We take SM parameters as given.

Spectrum Calculation

For each parameter point, we calculate the SUSY spectrum using SuSpect (as interfaced by micrOMEGAs for convenience in calculating other observables).

We then apply the following constraints...

Constraints

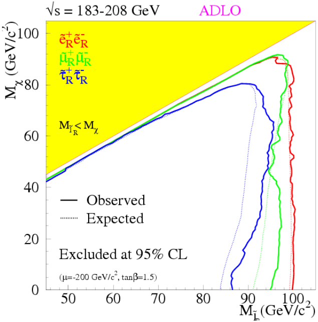
- LSP is lightest neutralino.
- No tachyons, CCB vacua.
- Higgs potential bounded from below.
- LSP relic density does not overclose universe, but we **DO NOT** demand that the LSP be the dominant component of the dark matter (e.g. axions could be dominant dark matter species).
- Contribution to invisible width of the Z less than 2 MeV (LEP).

Constraints

- $-0.0007 < \Delta\rho < 0.0026$ (PDG '08).
- $b \to s\gamma$: branching fraction in $(2.5 - 4.1) \times 10^{-4}$ (Combining results from HFAG, Misiak et al., Becher & Neubert).
- $B \to \mu\mu$: BF $\leq 4.5 \times 10^{-8}$ (CDF/ D0 combined).
- SUSY contribution to muon $g-2$: $(-10 \leq (g-2)_\mu \leq 40) \times 10^{-10}$ Wide range to accommodate current tension between theoretical and experimental values. These first 4 observables are calculated with micrOMEGAs.
- $B \to \tau\nu$: $(55 - 227) \times 10^{-6}$ (HFAG, ICHEP08). Our calculation of this quantity followed Isidori and Paradisi and Erikson, Mamoudi and Stal.
- Meson-Antimeson Mixing : Constrains 1st/3rd sfermion mass ratios to be in the range $0.2 < R < 5$ in MFV context. (We implement this constraint in choosing parameter points).

LEP Charged Sparticle Constraints

- LEP bounds on RH sleptons
- Note that very light sleptons with small mass splitting with LSP are not ruled out.
- We implement similar LEP constraints on LH sleptons, squarks.
- We also demand, following LEP, that there are no stable charged particles with mass less than 100 GeV.



LEP Higgs Constraints

Implement LEP constraints on Higgs sector by using **hdecay**, as interfaced to SUSY-HIT, to calculate cross section times branching ratio to given final states in the models, compare this with LEP bounds.

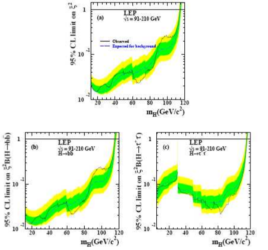


Figure 1: *The 95% c.l. upper bound on the coupling ratio* $\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$ *(see text). The dark (green) and light (yellow) shaded bands around the median expected line correspond to the 68% and 95% probability bands. The horizontal lines correspond to the Standard Model coupling.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

Figure 1 of hep-ex/0602042 from "Search for Neutral MSSM Higgs Bosons at LEP" by the LEP Working Group for Higgs Boson Searches.

Higgs Constraints

- We allow the calculated Higgs mass to be off by up to 3 GeV.
- Tevatron has ruled out some of the $M_A/\tan\beta$ plane; we also implement this Higgs sector constraint.

Stable Particles

- We implement D0 constraints on heavy charged particles that are stable on detector length scales.
- This has rules out a number of models for which the chargino is nearly degenerate with the LSP.

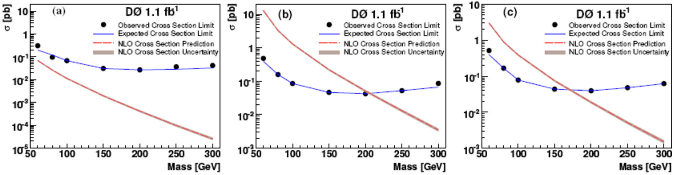
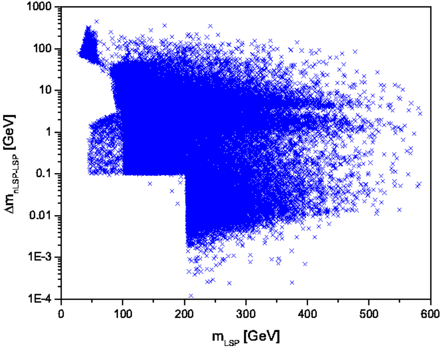


FIG. 2: The observed (dots) and expected (solid line) 95% cross section limits, the NLO production cross section (dashed line), and NLO cross section uncertainty (barely visible shaded band) as a function of (a) stau mass for stau pair production, (b) chargino mass for pair produced gaugino-like charginos,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

Stable Particles

- We implement D0 constraints on heavy charged particles, which are stable on detector length scale.
- This rules out a number of models for which the chargino is nearly degenerate with the LSP.



Jets Plus Missing Energy

- We implement the D0 jet plus missing energy constraints
- To do this we use the cuts for "2-jet", "3-jet", and "4-jet" events from the D0 analysis 0712.3805.

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
$\Delta\phi(\not{E}_T, \text{jet}_1)$	$\geq 90°$	$\geq 90°$	$\geq 90°$
$\Delta\phi(\not{E}_T, \text{jet}_2)$	$\geq 50°$	$\geq 50°$	$\geq 50°$
$\Delta\phi_{\text{min}}(\not{E}_T, \text{any jet})$	$\geq 40°$	–	–
H_T	≥ 325	≥ 375	≥ 400
$\not{E}_T$	≥ 225	≥ 175	≥ 100

[a]First and second jets are also required to be central ($|\eta_{\text{det}}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.
[b]Third and fourth jets are required to have $|\eta_{\text{det}}| < 2.5$, with an electromagnetic fraction below 0.95.

Jets Plus Missing Energy

- We use PGS for the detector simulation and SUSY-HIT for the decay table, as we generate 2.1 fb^{-1} of simulated Tevatron data (using PYTHIA as interfaced with PGS).
- We obtain K-factors from Prospino.
- We compare the total number of events which are identified as any of "2-jet", "3-jet", or "4-jet" to the 95% confidence limit on such events from D0.

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.

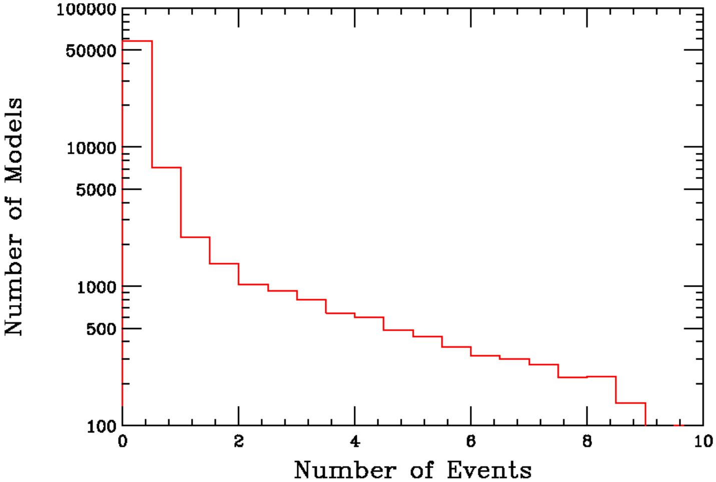
Analysis	$(m_0, m_{1/2})$ (GeV)	$(m_{\tilde{g}}, m_{\tilde{q}})$ (GeV)	$\sigma_{\rm nom}$ (pb)	$\epsilon_{\rm sig.}$ (%)	$N_{\rm obs.}$	$N_{\rm backgrd.}$	$N_{\rm sig.}$	σ_{95} (pb)
"dijet"	(25,175)	(439,396)	0.072	$6.8 \pm 0.4^{+1.2}_{-1.2}$	11	$11.1 \pm 1.2^{+2.9}_{-2.3}$	$10.4 \pm 0.6^{+1.8}_{-1.8}$	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"	$N_{\rm obs.}$	$N_{\rm backgrd.}$
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.)

Jets Plus Missing Energy

The 95% confidence limit on total number of events passing cuts for some event type is 8.34. Below is a histogram showing the distribution of total jet plus missing events for models in the flat priors model set.



Trileptons

- We implemented the Tevatron constraints on trilepton events by following a procedure analogous to the above, this time using cuts and limits from the CDF analysis 0808.2446.
- At our level of sophistication, were only able to implement the 3 tight track constraint.

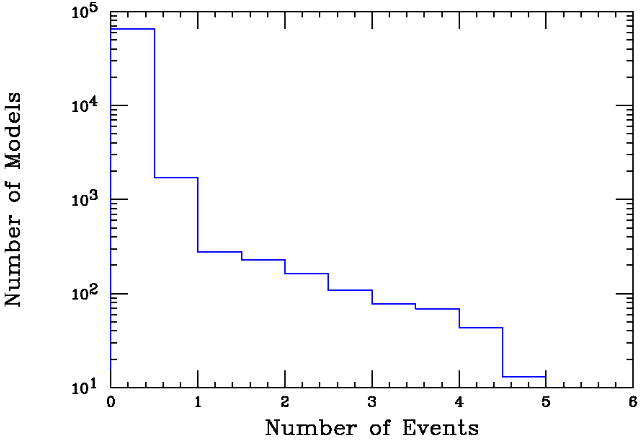
CDF RUN II Preliminary $\int \mathcal{L}dt = 2.0\ \text{fb}^{-1}$: Search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$

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

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

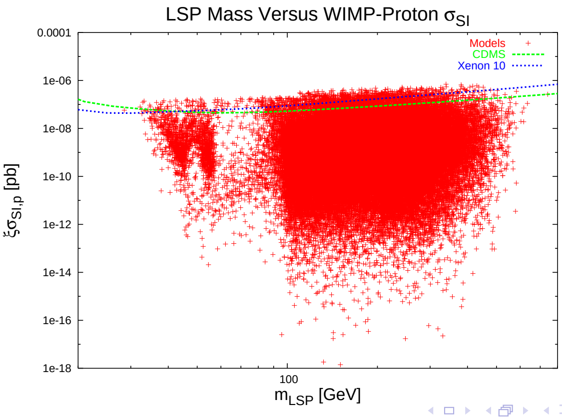
Trileptons

The 95% confidence level limit (Feldman-Cousins) is 4.65 events. Below is a histogram showing the distribution of these trilepton events for models in the flat priors model set.



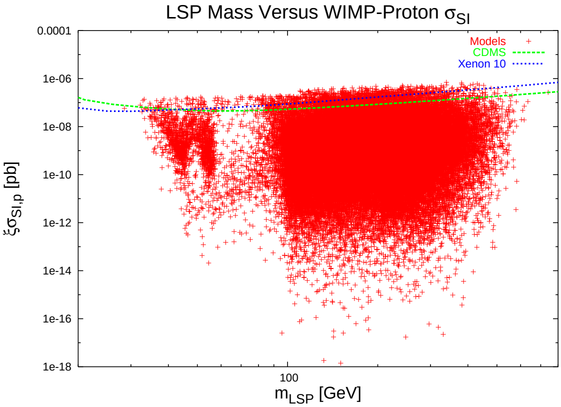
Direct Detection Constraints

We also use micrOMEGAs to calculate the spin-independent and spin-dependent WIMP-proton and WIMP-neutron cross sections and implement bounds on WIMP-nucleon cross section, in particular (for our LSP mass range) from XENON10 and CDMS.



Direct Detection Constraints

- Allowed for factor of 4 uncertainty in cross section.
- Cross section scaled to LSP fraction of DM.



Results

- We find that ∼68,000 models out of the 10,000,000 flat prior points chosen satisfy all existing constraints.
- For our logarithmic priors, ∼2000 models out of 2,000,000 satisfy all constraints.

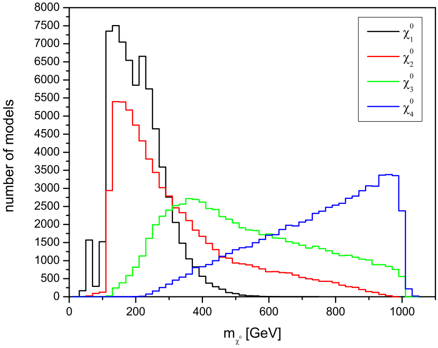
Effectiveness of Constraints

file	Description	Percent of Models Remaining
slha-okay.txt	SuSpect generates SLHA file	99.99 %
error-okay.txt	Spectrum tachyon, other error free	77.29%
lsp-okay.txt	LSP the lightest neutralino	32.70 %
deltaRho-okay.txt	$\Delta\rho$	32.61 %
gMinus2-okay.txt	$g - 2$	21.69 %
b2sGamma-okay.txt	$b \longrightarrow s\gamma$	6.17 %
Bs2MuMu-okay.txt	$B \longrightarrow \mu\mu$	5.95 %
vacuum-okay.txt	No CCB, potential not UFB	5.92 %
Bu2TauNu-okay.txt	$B \longrightarrow \tau\nu$	5.83 %
LEP-sparticle-okay.txt	LEP sfermion checks	4.72 %
invisibleWidth-okay.txt	Invisible Width of Z	4.71 %
susyhitProb-okay.txt	Heavy Higgs not problematic for SUSY-HIT	4.69 %
stableParticle-okay.txt	Tevatron stable chargino search	4.19 %
chargedHiggs-okay.txt	LEP/ Tevatron charged Higgs search	4.19 %
neutralHiggs-okay.txt	LEP neutral Higgs search	0.84 %
neutralHiggs-marginal.txt	LEP neutral Higgs search (3 GeV)	0.89 %
directDetection-okay.txt	WIMP direct detection	1.32 %
directDetection-marginal.txt	WIMP direct detection within factor of 4	0.23 %
omega-okay.txt	Ωh^2	0.74 %
Bs2MuMu-2-okay.txt	$B \longrightarrow \mu\mu$	0.74 %
stableChargino-2-okay.txt	Tevatron stable chargino search	0.72 %
triLepton-okay.txt	Tevatron trilepton	0.72 %
jetMissing-okay.txt	Tevatron jet plus missing	0.70 %
final-okay.txt	Final after cutting models with e.g. light stop, sbottoms	0.68 %

LSP Masses

The LSPs in our set are relatively light; most are between 100 and 400 GeV.

The distribution of all 4 neutralino masses for the ∼68,000 flat prior models is shown below.



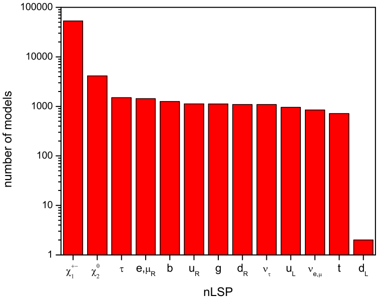
LSP Masses

A plurality of the models have an LSP which is either nearly pure Higgsino or mostly Higgsino. There are more models with LSPs which have $|Z_{12}|^2 > 0.8$ than with $|Z_{11}|^2 > 0.8$.

LSP Type	Definition	Fraction of Models
Bino	$|Z_{11}|^2 > 0.95$	0.14
Mostly Bino	$0.8 < |Z_{11}|^2 \leq 0.95$	0.03
Wino	$|Z_{12}|^2 > 0.95$	0.14
Mostly Wino	$0.8 < |Z_{12}|^2 \leq 0.95$	0.09
Higgsino	$|Z_{13}|^2 + |Z_{14}|^2 > 0.95$	0.32
Mostly Higgsino	$0.8 < |Z_{13}|^2 + |Z_{14}|^2 \leq 0.95$	0.12
All other models		0.15

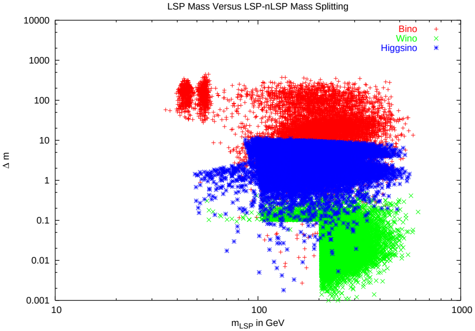
nLSP Identities

Not surprisingly, given the number of models with Higgsino or Wino LSPs, in many of the models the nLSP is a chargino or a neutralino. However, there are 11 other species of sparticles which are the nLSP in at least one of the models.



nLSP-LSP Mass Splitting

LSP type strongly correlated with nLSP-LSP mass splitting, but there are also accidental degeneracies.



Points in above plot correspond to LSPs which are nearly pure gaugino eigenstates; e.g. $|Z_{11}|^2 > 0.95$ for Bino LSPs, analagous statements hold for Wino, Higgsino LSPs.

nLSP-LSP Mass Splitting

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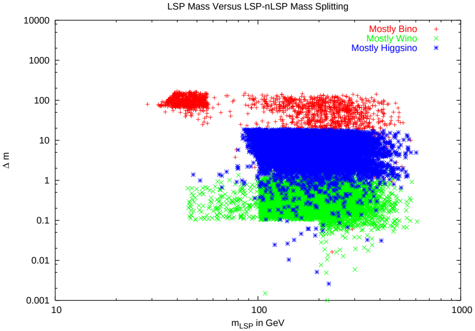
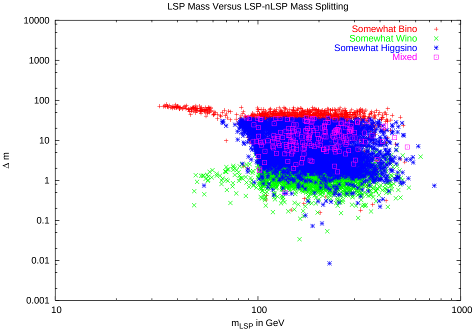


Points in above plot correspond to LSPs which are nearly pure gaugino eigenstates; e.g. $0.80 < |Z_{11}|^2 \leq 0.95$ for Bino LSPs, analagous statements hold for Wino, Higgsino LSPs.

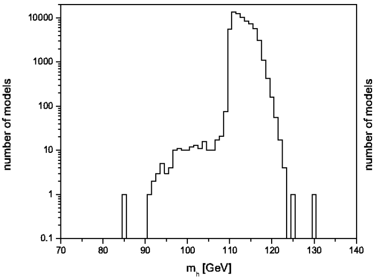
nLSP-LSP Mass Splitting

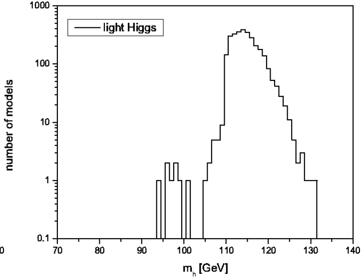
LSP type strongly correlated with nLSP-LSP mass splitting, but there are also accidental degeneracies.



Points in above plot correspond to LSPs which are not particularly pure gaugino eigenstates; i.e. do not fit into either of the categories presented in the last two plots.

Higgs Mass Ranges

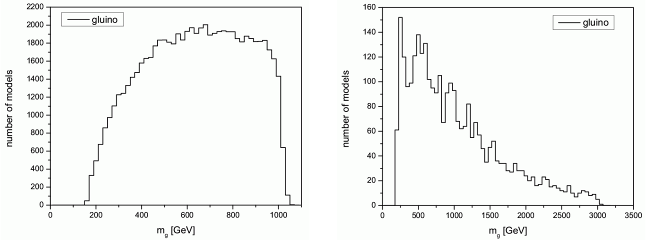




Significantly many models have light Higgs, even taking the 3 GeV uncertainty into account.

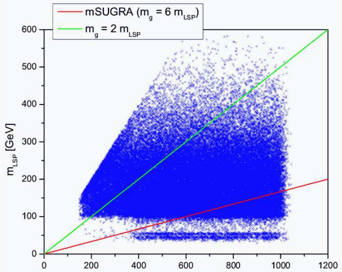
Gluino Mass Ranges

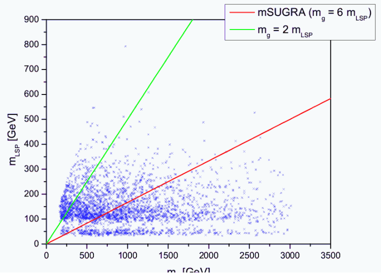
Especially in the flat prior case, there are a substantial number of models with relatively light gluinos ($\gtrsim 8\%$ are < 300 GeV).



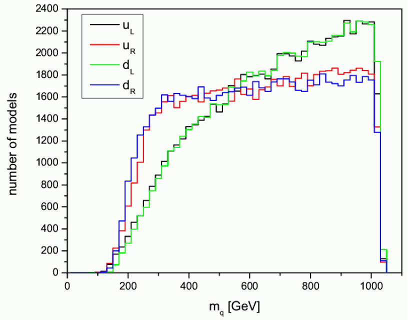
Gluino Mass Ranges

Most models have $m_{\tilde{g}}/m_{LSP} \ll 6$. Cascade decays may look very different than mSUGRA.



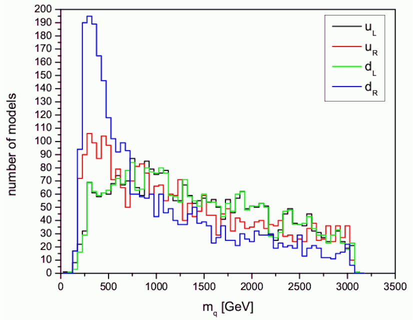


Squark Mass Ranges



Here we see a wide range of squark masses in the flat prior model set, extending from relatively low values to about a TeV (this cutoff is due to the parameter ranges).

Squark Mass Ranges



Again we see a wide range of squark masses, here for the log prior model set, though with a significant spike in the distribution for right sdowns below about 700 GeV.

New Mass Hierarchies

Feldman, Liu, and Nath (0707.1873) find $\sim$ 16 mass patterns for the 4 lightest sparticles in mSUGRA. In our flat prior case, we have 1109 such hierarchies; 269 in the log prior case.

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

New LHC Signatures?

- Models in these sets have properties which may lead to interesting LHC signatures.
  - Many models with small $m_{nLSP} - m_{LSP}$.
  - A variety of $m_{\tilde{g}}/m_{LSP}$ values, including gluinos with mass close to the LSP mass.
  - Light gluinos (sometimes).
  - Wide range of squark masses.
  - New particle mass hierarchies; different cascade (or other) decays than normally considered.

Given the imminent(!?) turn-on of LHC, and in light of the above, it might be interesting to consider the LHC signatures of models in this model set.

Comparison with ATLAS Benchmark Analyses

- Working on determining the ATLAS signatures of the models that survive constraints.
- Use analyses in SUSY chapter of “Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics” 0901.0512.
- Compare our signal to their backgrounds.

Comparison with ATLAS Benchmark Analyses

For this approach to be valid, we must be able to obtain similar predictions for SUSY in each analysis channel. They generate their signals using

- ISASUGRA to generate spectrum and decay table.
- Prospino for K - factors.
- Herwig for event generation, fragmentation, and hadronization.
- GEANT4 for full detector simulation.

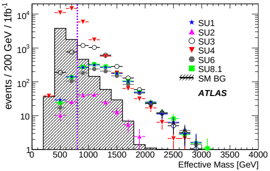
Comparison with ATLAS Benchmark Analyses

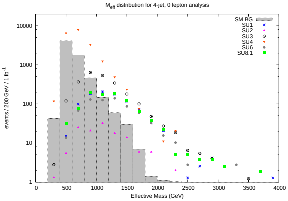
We cannot duplicate this exactly; already have spectra generated with SuSpect; GEANT4 simulation for $\sim 70,000$ models is **WAY** beyond our resources. Instead, we use

- SuSpect to generate spectra, SUSY-HIT to generate decay table.
- Prospino for K - factors.
- PYTHIA for event generation, fragmentation, and hadronization.
- PGS4 for fast detector simulation.

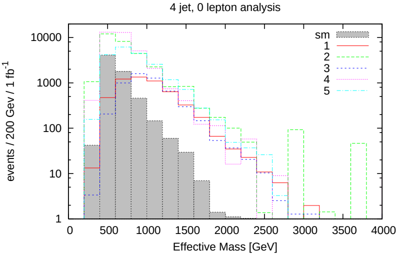
Need to verify that the results of this procedure approximate the results one obtains following the ATLAS procedure.

Four Jets, Zero Leptons



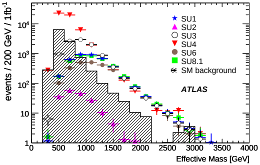


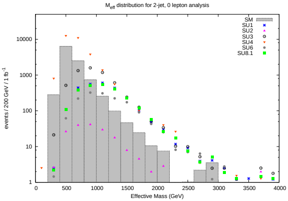
ATLAS Benchmarks (ATLAS left, us right).



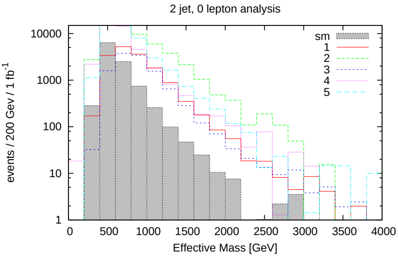
Flat prior model set models.

Two Jets, Zero Leptons.



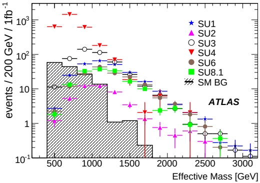


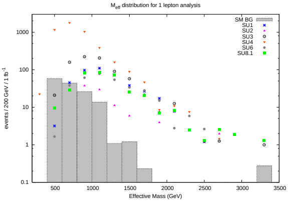
ATLAS Benchmarks (ATLAS left, us right).



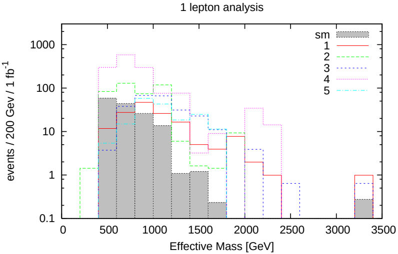
Flat prior model set models.

Four Jets, One Lepton



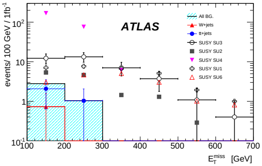


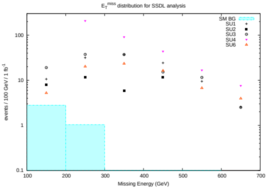
ATLAS Benchmarks (ATLAS left, us right).



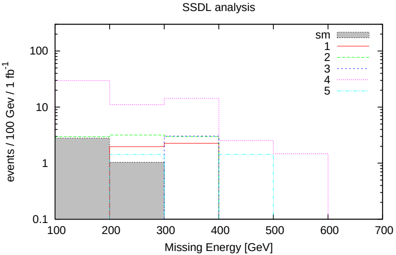
Flat prior model set models.

Same Sign Dilepton



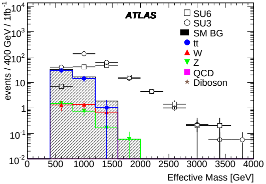


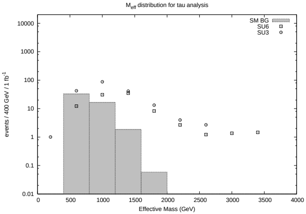
ATLAS Benchmarks (ATLAS left, us right).



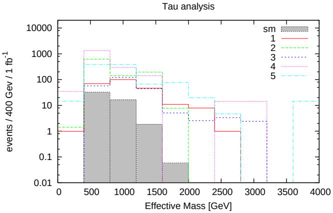
Flat prior model set models.

Four Jets, Tau



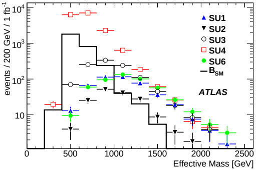


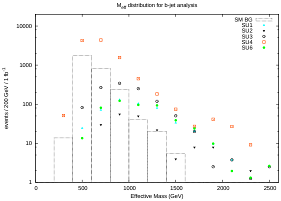
ATLAS Benchmarks (ATLAS left, us right).



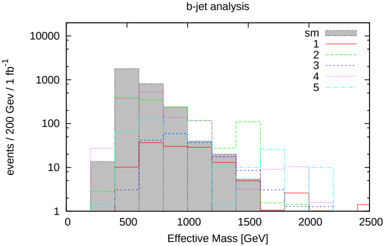
Flat prior model set models.

Four Jets, Two Bottom Tagged





ATLAS Benchmarks (ATLAS left, us right).



Flat prior model set models.

Conclusions

- A large set of models (parameter points in pMSSM space) have been generated which satisfy existing theoretical, experimental, and observational constraints.
- Models in this set have novel properties; they may have novel LHC signatures- stay tuned!

ATLAS Benchmarks

Verbatim from 0901.0512

SU1 $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.

SU2 $m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Focus point region near the boundary where $\mu^2 < 0$. This is the only region in mSUGRA where the $\tilde{\chi}_1^0$ has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to WW$.

SU3 $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan\beta = 6$, $\mu > 0$. Bulk region: LSP annihilation happens through the exchange of light sleptons.

SU4 $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan\beta = 10$, $\mu > 0$. Low mass point close to Tevatron bound.

SU6 $m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$, $\tan\beta = 50$, $\mu > 0$. The funnel region where $2m_{\tilde{\chi}_1^0} \approx m_A$. Since $\tan\beta \gg 1$, the width of the pseudoscalar Higgs boson A is large and τ decays dominate.

SU8.1 $m_0 = 210$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan\beta = 40$, $\mu > 0$. Variant of coannihilation region with $\tan\beta \gg 1$, so that only $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ is small.

SU9 $m_0 = 300$ GeV, $m_{1/2} = 425$ GeV, $A_0 = 20$, $\tan\beta = 20$, $\mu > 0$. Point in the bulk region with enhanced Higgs production

Mass spectra for each of these points are listed in Table 2

Model 1

LSP has mass 225.16 GeV.
The nLSP is ul
LSP-nLSP mass splitting = 128.18 GeV.

All masses in GeV.

Gaugino Masses (with signs)
mn1= 225.16 mn3= 745.12 mc1= 727.47
mn2= -726.46 mn4= -924.49 mc2= 924.59
mg= 751.64

Squark Masses
mul= 353.34 mur= 576.80 mdl= 362.48 mdr= 702.80
mb1= 689.59 mb2= 979.70 mt1= 570.80 mt2= 996.82

Slepton Masses
mel= 445.97 mer= 489.42 msne= 439.00
stl= 459.39 st2= 778.62 msnt= 773.16

Higgs Masses and Mixing
mhl= 111.95 mH= 464.65 mA= 464.69 mH+= 471.48

Higgs Mixing Angle alpha = -0.0458

Neutralino Mixing Matrix

0.9975	0.0018	0.0665	-0.0228
0.0299	0.2794	-0.6859	-0.6712
0.0631	-0.0351	-0.7035	0.7070
0.0082	-0.9595	-0.1738	-0.2213

Chargino Mixing Matrices

U		V	
-0.2472	0.9690	0.3147	0.9492
0.9690	0.2472	-0.9492	0.3147

Sfermion mixing matrices

stop		sbottom		stau	
0.1623	0.9867	0.0708	0.9975	0.0761	0.9971
-0.9867	0.1623	-0.9975	0.0708	-0.9971	0.0761

SUSY Contributions:

```
rho parameter: 3.0400e-05           muon g-2: -3.1100e-10

0.000 jet + missing energy events at Tevatron (2.1 fb^-1).
0.000 trilepton events at Tevatron (2.1 fb^-1).

The SUSY contribution to the invisible width of the Z is zero.

The branching fraction for B -> X_s gamma in this model is 2.8200e-04
The branching fraction for Bs -> mu mu in this model is 6.4000e-09
The branching fraction for Bu -> tau nu in this model is 1.3795e-04


Unscaled WIMP - Nucleon Cross Sections in pb
Proton Spin-Ind.  Spin-Dep.   Neutron Spin-Ind. Spin-Dep.
      3.5209e-09  1.9178e-07        3.6990e-09  1.9178e-07

Omega h^2 = 6.7002e-03

Input Parameters
MG1 = 230.36      MG2 = -925.91     MG3 = 726.97      mu = 742.82 tb = 23.45
Mq1 = 314.24      Mu1 = 544.25      Md1 = 672.18      Mel1 = 443.61     Mer1 = 487.41
Mq3 = 956.70      Mu3 = 531.31      Md3 = 660.41      Mel3 = 775.79     Mer3 = 459.74
At = -658.40      Ab = 450.20 Atau = -609.12    MH3 = 464.69

The original model serial number was 1 1
```

Model 2

LSP has mass 179.79 GeV.
The nLSP is mc1
LSP-nLSP mass splitting = 5.76 GeV.

All masses in GeV.

Gaugino Masses (with signs)
mn1= 179.79 mn3= 366.16 mc1= 185.54
mn2= -197.82 mn4= -867.52 mc2= 366.75
mg= 259.91

Squark Masses
mul= 923.37 mur= 263.47 mdl= 926.69 mdr= 221.13
mb1= 396.96 mb2= 416.54 mt1= 375.54 mt2= 567.18

Slepton Masses
mel= 575.30 mer= 375.02 msne= 570.04
stl= 279.05 st2= 546.37 msnt= 540.82

Higgs Masses and Mixing
mhl= 110.22 mH= 813.10 mA= 812.85 mH+= 817.16

Higgs Mixing Angle alpha = -0.1275

Neutralino Mixing Matrix

0.0236	0.2654	0.7107	0.6511
0.0523	0.1145	-0.6940	0.7089
0.0090	-0.9573	0.1140	0.2656
0.9983	-0.0037	0.0185	-0.0549

Chargino Mixing Matrices

U		V	
0.1676	0.9859	0.3854	-0.9227
0.9859	-0.1676	0.9227	0.3854

Sfermion mixing matrices

stop		sbottom		stau	
0.8778	-0.4790	0.8919	-0.4522	-0.0045	1.0000
0.4790	0.8778	0.4522	0.8919	-1.0000	-0.0045

SUSY Contributions:

rho parameter: 1.7100e-04 muon g-2: -7.4600e-10

1.000 jet + missing energy events at Tevatron (2.1 fb^-1).
0.000 trilepton events at Tevatron (2.1 fb^-1).

The SUSY contribution to the invisible width of the Z is zero.

The branching fraction for B -> X_s gamma in this model is 3.5000e-04
The branching fraction for Bs -> mu mu in this model is 3.0100e-09
The branching fraction for Bu -> tau nu in this model is 1.5259e-04

Unscaled WIMP - Nucleon Cross Sections in pb

Proton Spin-Ind.	Spin-Dep.	Neutron Spin-Ind.	Spin-Dep.
1.4997e-08	8.9821e-05	1.5173e-08	8.9821e-05

Omega h^2 = 5.3034e-03

Input Parameters

MG1 = -866.57	MG2 = 333.75	MG3 = 206.10	mu = -190.70	tb = 8.24
Mq1 = 915.36	Mu1 = 253.67	Md1 = 204.30	Mel1 = 573.50	Mer1 = 372.49
Mq3 = 388.79	Mu3 = 509.39	Md3 = 403.98	Mel3 = 544.47	Mer3 = 275.64

At = 509.85 Ab = 859.53 Atau = -964.44 MH3 = 812.85

The original model serial number was 1 655

Model 3

LSP has mass 233.49 GeV.
The nLSP is mc1
LSP-nLSP mass splitting = 0.015408 GeV.

All masses in GeV.

Gaugino Masses (with signs)
mn1= -233.49 mn3= 787.65 mc1= 233.51
mn2= -685.95 mn4= -796.79 mc2= 791.81
mg= 671.15

Squark Masses
mul= 673.65 mur= 548.70 mdl= 678.17 mdr= 779.85
mb1= 811.77 mb2= 881.05 mt1= 698.84 mt2= 900.09

Slepton Masses
mel= 810.20 mer= 627.48 msne= 806.39
stl= 308.46 st2= 984.08 msnt= 980.69

Higgs Masses and Mixing
mhl= 111.59 mH= 298.50 mA= 298.36 mH+= 309.32

Higgs Mixing Angle alpha = -0.0733

Neutralino Mixing Matrix

0.0018	-0.9939	0.1076	0.0258
0.9612	0.0289	0.2079	0.1788
0.0224	-0.0578	-0.7041	0.7074
0.2749	-0.0898	-0.6704	-0.6833

Chargino Mixing Matrices

U		V	
-0.9885	0.1512	0.9993	0.0362
0.1512	0.9885	-0.0362	0.9993

Sfermion mixing matrices

stop		sbottom		stau	
0.2846	0.9586	0.2379	0.9713	0.0236	0.9997
-0.9586	0.2846	-0.9713	0.2379	-0.9997	0.0236

SUSY Contributions:

```
rho parameter: 2.3000e-05           muon g-2: -5.3100e-10

0.000 jet + missing energy events at Tevatron (2.1 fb^-1).
0.000 trilepton events at Tevatron (2.1 fb^-1).

The SUSY contribution to the invisible width of the Z is zero.

The branching fraction for B -> X_s gamma in this model is 3.8900e-04
The branching fraction for Bs -> mu mu in this model is 4.2900e-09
The branching fraction for Bu -> tau nu in this model is 1.3472e-04


Unscaled WIMP - Nucleon Cross Sections in pb
Proton Spin-Ind.  Spin-Dep.   Neutron Spin-Ind. Spin-Dep.
      2.2075e-08  6.6679e-07        2.3351e-08  6.6679e-07

Omega h^2 = 1.7221e-03

Input Parameters
MG1 = -701.30     MG2 = -225.97     MG3 = 608.66      mu = 787.33 tb = 16.47
Mq1 = 648.26      Mu1 = 516.86      Md1 = 756.79      Mel1 = 808.90     Mer1 = 625.92
Mq3 = 855.83      Mu3 = 675.51      Md3 = 794.11      Mel3 = 982.76     Mer3 = 306.07
At = -496.68      Ab = 18.70  Atau = 780.49     MH3 = 298.36

The original model serial number was 1 681
```

Model 4

LSP has mass 115.13 GeV.
The nLSP is mc1
LSP-nLSP mass splitting = 7.73 GeV.

All masses in GeV.

Gaugino Masses (with signs)
mn1= -115.13 mn3= -246.92 mc1= 122.86
mn2= 142.72 mn4= 609.46 mc2= 248.91
mg= 414.69

Squark Masses
mul= 266.23 mur= 252.05 mdl= 277.77 mdr= 870.08
mb1= 835.66 mb2= 930.52 mt1= 404.16 mt2= 855.47

Slepton Masses
mel= 747.02 mer= 604.49 msne= 742.97
stl= 196.63 st2= 399.33 msnt= 180.66

Higgs Masses and Mixing
mhl= 112.42 mH= 437.83 mA= 437.07 mH+= 444.54

Higgs Mixing Angle alpha = -0.1467

Neutralino Mixing Matrix

0.0298	0.3820	-0.7149	-0.5849
0.0755	0.1747	0.6777	-0.7103
0.0185	-0.9074	-0.1702	-0.3837
0.9965	-0.0078	-0.0268	0.0784

Chargino Mixing Matrices

U		V	
-0.2589	0.9659	0.5695	0.8220
0.9659	0.2589	-0.8220	0.5695

Sfermion mixing matrices

stop		sbottom		stau	
-0.1877	0.9822	0.9999	0.0143	1.0000	0.0083
-0.9822	-0.1877	-0.0143	0.9999	-0.0083	1.0000

SUSY Contributions:

rho parameter: 5.1500e-05 muon g-2: -6.4200e-10

1.701 jet + missing energy events at Tevatron (2.1 fb^-1).
0.400 trilepton events at Tevatron (2.1 fb^-1).

The SUSY contribution to the invisible width of the Z is zero.

The branching fraction for B -> X_s gamma in this model is 2.8200e-04
The branching fraction for Bs -> mu mu in this model is 2.9400e-09
The branching fraction for Bu -> tau nu in this model is 1.5101e-04

Unscaled WIMP - Nucleon Cross Sections in pb

Proton Spin-Ind.	Spin-Dep.	Neutron Spin-Ind.	Spin-Dep.
1.2951e-09	3.6494e-04	1.6966e-09	3.6494e-04

Omega h^2 = 3.3584e-03

Input Parameters

MG1 = 614.09	MG2 = -213.47	MG3 = 371.43	mu = 132.56 tb = 7.82	
Mq1 = 243.01	Mu1 = 224.88	Md1 = 859.23	Mel1 = 745.63	Mer1 = 602.93
Mq3 = 823.13	Mu3 = 385.68	Md3 = 919.64	Mel3 = 191.29	Mer3 = 396.96

At = 757.59 Ab = 22.57 Atau = 432.77 MH3 = 437.07

The original model serial number was 1 755

Model 5

LSP has mass 158.77 GeV.
The nLSP is mc1
LSP-nLSP mass splitting = 3.27 GeV.

All masses in GeV.

Gaugino Masses (with signs)
mn1= -158.77 mn3= -398.28 mc1= 162.03
mn2= 175.31 mn4= 605.37 mc2= 398.60
mg= 387.62

Squark Masses
mul= 918.67 mur= 813.71 mdl= 922.06 mdr= 180.84
mb1= 409.80 mb2= 949.67 mt1= 777.10 mt2= 966.32

Slepton Masses
mel= 394.23 mer= 559.34 msne= 386.36
stl= 564.71 st2= 985.38 msnt= 982.22

Higgs Masses and Mixing
mhl= 113.32 mH= 435.76 mA= 435.64 mH+= 443.37

Higgs Mixing Angle alpha = -0.0535

Neutralino Mixing Matrix

0.0402	0.2477	0.7094	-0.6586
0.0699	0.0958	-0.6954	-0.7088
0.0108	-0.9641	0.1131	-0.2402
0.9967	-0.0062	0.0189	0.0789

Chargino Mixing Matrices

U		V	
0.1616	0.9869	-0.3447	-0.9387
0.9869	-0.1616	-0.9387	0.3447

Sfermion mixing matrices

stop		sbottom		stau	
-0.2487	0.9686	-0.0126	0.9999	-0.0091	1.0000
-0.9686	-0.2487	-0.9999	-0.0126	-1.0000	-0.0091

SUSY Contributions:

rho parameter: 1.3600e-05 muon g-2: 2.5300e-09

2.155 jet + missing energy events at Tevatron (2.1 fb^-1).
0.000 trilepton events at Tevatron (2.1 fb^-1).

The SUSY contribution to the invisible width of the Z is zero.

The branching fraction for B -> X_s gamma in this model is 3.9100e-04
The branching fraction for Bs -> mu mu in this model is 2.9800e-09
The branching fraction for Bu -> tau nu in this model is 1.3417e-04

Unscaled WIMP - Nucleon Cross Sections in pb

Proton Spin-Ind.	Spin-Dep.	Neutron Spin-Ind.	Spin-Dep.
5.4581e-08	6.6061e-05	5.5702e-08	6.6061e-05

Omega h^2 = 3.6995e-03

Input Parameters

MG1 = 612.06	MG2 = -369.95	MG3 = 312.37	mu = -169.87	tb = 21.45
Mq1 = 908.58	Mu1 = 802.97	Md1 = 135.74	Mel1 = 391.56	Mer1 = 557.60
Mq3 = 936.12	Mu3 = 777.81	Md3 = 389.71	Mel3 = 984.28	Mer3 = 563.03

At = 560.96 Ab = -6.32 Atau = -187.23 MH3 = 435.64

The original model serial number was 1 946