Supersymmetry Without Prejudice

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 (~ 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, dark matter, etc. etc. – all your favorites! (In progress)
How? Perform 2 Random Scans

**Linear Priors**
- 10^7 points – emphasizes moderate masses
- \(100 \text{ GeV} \leq m_{\text{sfermions}} \leq 1 \text{ TeV}\)
- \(50 \text{ GeV} \leq |M_1, M_2, \mu| \leq 1 \text{ TeV}\)
- \(100 \text{ GeV} \leq M_3 \leq 1 \text{ TeV}\)
- \(~0.5 M_Z \leq M_A \leq 1 \text{ TeV}\)
- \(1 \leq \tan \beta \leq 50\)
- \(|A_{t,b,\tau}| \leq 1 \text{ TeV}\)

**Log Priors**
- 2 \times 10^6 points – emphasizes lower masses but extends to higher masses
- \(100 \text{ GeV} \leq m_{\text{sfermions}} \leq 3 \text{ TeV}\)
- \(10 \text{ GeV} \leq |M_1, M_2, \mu| \leq 3 \text{ TeV}\)
- \(100 \text{ GeV} \leq M_3 \leq 3 \text{ TeV}\)
- \(~0.5 M_Z \leq M_A \leq 3 \text{ TeV}\)
- \(1 \leq \tan \beta \leq 60\)
- \(10 \text{ GeV} \leq |A_{t,b,\tau}| \leq 3 \text{ TeV}\)

→ Comparison of these two scans will show the prior sensitivity.
→ This analysis required \(~ 1\) processor-century of CPU time... this is the real limitation of this study.
Successful models

WMAP & Direct Detection

Direct searches at LEP & Tevatron

Rare decays and flavor constraints

Precision data

g-2

Spectrum requirements
Constraints

• $-0.0007 < \Delta \rho < 0.0026 \quad \text{(PDG’08)}$

• $b \rightarrow s \gamma : B = (2.5 - 4.1) \times 10^{-4} \quad \text{(HFAG) + Misiak etal. & Becher & Neubert}$

• $\Delta(g-2)_{\mu} \quad (30.2 \pm 8.8) \times 10^{-10} \quad \text{(0809.4062)}$
  $(29.5 \pm 7.9) \times 10^{-10} \quad \text{(0809.3085)}$
  $[-14.0 \pm 8.4] \times 10^{-10} \quad \text{[Davier/BaBar-Tau08]}$
  $\rightarrow (-10 \text{ to } 40) \times 10^{-10} \quad \text{to be conservative.}$

• $\Gamma(Z\rightarrow \text{invisible}) < 2.0 \text{ MeV} \quad \text{(LEPEWWG)}$

• Meson-Antimeson Mixing $0.2 < R_{13} < 5$

• $B \rightarrow \tau \nu \quad B = (55 \text{ to } 227) \times 10^{-6} \quad \text{Isidori & Paradisi, hep-ph/0605012 & Erikson etal., 0808.3551 for loop corrections}$

• $B_s \rightarrow \mu \mu \quad B < 4.5 \times 10^{-8} \quad \text{(CDF + D0)}$
• Direct Detection of Dark Matter → We find a factor of ~ 4 uncertainty in the nuclear matrix elements. This factor was obtained from studying several benchmark points in detail & so we allow cross sections 4x larger than the usually quoted limits. Spin-independent limits are completely dominant here.

• Dark Matter density: \( \Omega h^2 < 0.1210 \rightarrow 5 \text{yr WMAP data} \). 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…. We need to be cautious here in how the constraints are used.
Example:

Zh, h→ bb, ττ

Figure 1: The 95% c.l. upper bound on the coupling ratio \( \xi^2 = (g_{\text{ZZ}}/g_{\text{SM}}^{\text{ZZ}})^2 \) (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 bb and (c): into \( \tau^+\tau^- \) pairs.
Note the holes where the leptons are too soft...

We need to allow for a mass gap with the LSP & also in the squark case when soft jets are possible. Light guys may slip through.
Example:

Tevatron Constraints: I  Squark & Gluino Search

• This is the first SUSY analysis to include these constraints

• 2,3,4 Jets + Missing Energy (D0)

Multiple analyses keyed to look for:

Squarks-> jet +MET
Gluinos -> 2 j + MET

The search is based on mSUGRA type sparticle spectrum assumptions which can be VERY far from our model points
SuSpect -> SUSY-Hit -> PROSPINO -> PYTHIA -> D0-tuned
PGS4 fast simulation (to reproduce the benchmark points)…
redo this analysis ~ $10^5$ times!

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

### TABLE II

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$(m_0, m_{1/2})$ (GeV)</th>
<th>$(m_{\tilde{g}}, m_{\tilde{q}})$ (GeV)</th>
<th>$\sigma_{\text{nom}}$ (pb)</th>
<th>$\epsilon_{\text{sig}}$ (%)</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{background}}$</th>
<th>$N_{\text{sig}}$</th>
<th>$\sigma_{95}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;dijet&quot;</td>
<td>(25,175)</td>
<td>(439,396)</td>
<td>0.072</td>
<td>6.8 ± 0.4^{+1.2}_{-1.2}</td>
<td>11</td>
<td>11.1 ± 1.2^{+2.9}_{-2.3}</td>
<td>10.4 ± 0.6^{+1.8}_{-1.8}</td>
<td>0.075</td>
</tr>
<tr>
<td>&quot;3-jets&quot;</td>
<td>(197,154)</td>
<td>(400,400)</td>
<td>0.083</td>
<td>6.8 ± 0.4^{+1.4}_{-1.3}</td>
<td>9</td>
<td>10.7 ± 0.9^{+2.1}_{-2.1}</td>
<td>12.0 ± 0.7^{+2.5}_{-2.5}</td>
<td>0.065</td>
</tr>
<tr>
<td>&quot;gluino&quot;</td>
<td>(500,110)</td>
<td>(320,551)</td>
<td>0.195</td>
<td>4.1 ± 0.3^{+0.7}_{-0.7}</td>
<td>20</td>
<td>17.7 ± 1.1^{+3.3}_{-3.3}</td>
<td>17.0 ± 1.2^{+2.9}_{-2.9}</td>
<td>0.165</td>
</tr>
</tbody>
</table>

### TABLE III

<table>
<thead>
<tr>
<th>Selection</th>
<th>&quot;dijet&quot;</th>
<th>&quot;3-jets&quot;</th>
<th>&quot;gluino&quot;</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{background}}$</th>
<th>$N_{\text{background}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination 1</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>8</td>
<td>9.4 ± 1.2^{+2.2}_{-2.1} (stat.)</td>
<td>1.2^{+2.2}_{-2.1} (syst.)</td>
</tr>
<tr>
<td>Combination 2</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>2</td>
<td>4.5 ± 0.6^{+0.7}_{-0.7}  (stat.)</td>
<td>0.7^{+0.7}_{-0.7} (syst.)</td>
</tr>
<tr>
<td>Combination 3</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>14</td>
<td>12.5 ± 0.9^{+3.6}_{-3.6} (stat.)</td>
<td>3.6^{+3.6}_{-3.6} (syst.)</td>
</tr>
<tr>
<td>Combination 4</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>1</td>
<td>1.1 ± 0.3^{+0.5}_{-0.3}  (stat.)</td>
<td>0.3^{+0.5}_{-0.3} (syst.)</td>
</tr>
<tr>
<td>Combination 5</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>4</td>
<td>4.5 ± 0.6^{+1.8}_{-1.8}  (stat.)</td>
<td>1.8^{+1.8}_{-1.8} (syst.)</td>
</tr>
<tr>
<td>Combination 6</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>2</td>
<td>0.6 ± 0.2^{+0.3}_{-0.3}  (stat.)</td>
<td>0.2^{+0.3}_{-0.3} (syst.)</td>
</tr>
<tr>
<td>Combination 7</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>31</td>
<td>32.6 ± 1.7^{+3.9}_{-3.9} (stat.)</td>
<td>1.7^{+3.9}_{-3.9} (syst.)</td>
</tr>
<tr>
<td>At least one selection</td>
<td></td>
<td></td>
<td></td>
<td>31</td>
<td>32.6 ± 1.7^{+3.9}_{-3.9} (stat.)</td>
<td>1.7^{+3.9}_{-3.9} (syst.)</td>
</tr>
</tbody>
</table>
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

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

This is an incredibly powerful constraint on our model set as we will have many close mass chargino-neutralino pairs. This search cuts out a huge parameter region as you will see later.

- No applicable bounds on charged sleptons...the cross sections are too small.
- This is the first SUSY analysis to include these constraints.
Survival Rates

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

- **Flat Priors**: $10^7$ models scanned, ~ 68.5 K (0.68%) survive

- **Log Priors**: $2 \times 10^6$ models scanned, ~ 2.5 K (0.12%) survive
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

Flat Priors

Log Priors
Gluino Can Be Light!!

Flat

Log

m_g [GeV]

number of models

m_{\text{LSP}} [GeV]

m_g = 6 m_{\text{LSP}}

m_g = 2 m_{\text{LSP}}

m_{\text{LSP}} [GeV]

m_g [GeV]
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 ANY of the 13 possibilities!
nLSP-LSP Mass Difference

1 MeV

D0 stable particle search

Flat
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.
'High-Purity' LSPs

LSP Mass Versus LSP-nLSP Mass Splitting

Flat

'HIGH-PURITY' LSPS

m_{LSP} in GeV

\Delta m

Bino
Wino
Higgsino
Summary

• The pMSSM has a far richer phenomenology than any of the conventional SUSY breaking scenarios. The many sparticle properties can be vastly different, e.g., the nLSP can be any other 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

• Squarks may exist within the range accessible to 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
See talks by John Conley on the implications of this study for LHC SUSY searches and James Gainer on implications for Dark Matter searches during the parallel sessions P4.I and P6.H, respectively.
BACKUP SLIDES
Kinematic Accessibility at the ILC: I

..the usual SuSpects

flat priors

$\mu^L \mu^L$

$\mu^R \mu^R$

$\mu^R \mu^L$

Final State

$e^+ e^-$

$e^+_L e^-_L$

$e^+_R e^-_R$

$\mu^+_L \mu^-_L$

$\mu^+_R \mu^-_R$

Any selectron or smuon

$\tau^+_1 \tau^-_1$

$\tau^+_2 \tau^-_2$

$\tau^+_1 \tau^-_2$

$\tau^+_2 \tau^-_1$

$\tilde{\nu}_{e\mu} \tilde{\nu}_{e\mu}^*$

$\tilde{\nu}_e \tilde{\nu}_e^*$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0$

Any charged sparticle

$\tilde{\chi}_2^\pm \tilde{\chi}_2^\mp$

$\tilde{\chi}_1^\pm \tilde{\chi}_1^-$

$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ only

$\tilde{\chi}_1^0 + \tilde{\nu}$ only

$\tilde{\chi}_2^0 \tilde{\chi}_2^0$

$\tilde{\chi}_1^0 \tilde{\chi}_3^0$

$\tilde{\chi}_2^0 \tilde{\chi}_2^0$

$\tilde{\chi}_3^0 \tilde{\chi}_3^0$

$\tilde{\chi}_1^0 \tilde{\chi}_3^0$

Nothing
Kinematic Accessibility at the ILC: III

Squarks!

% of models

accessible sparticles

flat priors

500 GeV LC
1 TeV LC
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!!
Distribution of Sparticle Masses By Species

Flat Priors

Log Priors
$\chi_1^+$

$\chi_2^0$

e_R : 1433

$\tau_1 : 1499$
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.. (1240+76)