New ‘No Prejudice’ pMSSM SUSY Scans

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So far there are no obvious signs of SUSY:

Options: no SUSY, SUSY is ‘just heavier’, or it doesn’t look like the CMSSM →→ enter the pMSSM...
What is our pMSSM ??? *

- The most general, CP-conserving MSSM w/ R-parity conservation
- Minimal Flavor Violation at the TeV scale
- The first two sfermion generations are degenerate & have negligible Yukawa couplings
- The lightest neutralino or the gravitino is the LSP

* Beware of the various alternative uses of this nomenclature
The 19(20) Parameter pMSSM

10 sfermion masses: $m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}$

3 gaugino masses: $M_1, M_2, M_3$

3 tri-linear couplings: $A_b, A_t, A_\tau$

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

$\rightarrow\rightarrow$ (1 gravitino mass : $m_{3/2}$)

Choose the ranges of these parameters & how they’re selected

Scan: look for points in this space satisfying all existing data & then study their signatures @ the LHC & elsewhere.. NO FITS!
Our Original $\chi$ LSP Random Scans

Flat Priors
emphasizes moderate masses

100 GeV $\leq m_{\text{sfermions}} \leq 1$ TeV
50 GeV $\leq |M_1, M_2, \mu| \leq 1$ TeV
100 GeV $\leq M_3 \leq 1$ TeV
$\sim 0.5 M_Z \leq M_A \leq 1$ TeV
$1 \leq \tan \beta \leq 50$
$|A_{t,b,\tau}| \leq 1$ TeV

Log Priors
emphasizes lower masses but also extends to higher masses

100 GeV $\leq m_{\text{sfermions}} \leq 3$ TeV
10 GeV $\leq |M_1, M_2, \mu| \leq 3$ TeV
100 GeV $\leq M_3 \leq 3$ TeV
$\sim 0.5 M_Z \leq M_A \leq 3$ TeV
$1 \leq \tan \beta \leq 60$ (flat prior)
10 GeV $\leq |A_{t,b,\tau}| \leq 3$ TeV

• Flat Priors: $10^7$ points scanned, 68422 survive
• Log Priors: $2 \times 10^6$ points scanned, 2908 survive
Important Experimental Constraints

- Precision Measurements & Heavy Flavors
  - $W$ mass $\rightarrow b \rightarrow s \gamma$
  - $\Delta(g-2)_\mu$ $\Gamma(Z \rightarrow \text{invisible})$
  - Meson-Antimeson Mixing
  - $B_s \rightarrow \mu\mu$ $B \rightarrow \tau\nu$

- Relic density: $\Omega h^2 < 0.121$. We treat this only as an upper bound on the neutralino thermal relic contribution.

- Direct Detection Searches for DM (CDMS, XENON...)

- Higgs & SUSY searches @ colliders: there are many searches & they are quite complicated with many caveats. These needed to be ‘revisited’ in detail for the more general pMSSM models, e.g., fast detector sims for the Tevatron
Comments

• All public codes (Pythia, SuSpect, Prospino, S/HDECAY,...) required ‘modifications’ (due to ‘features’) in order to handle our original pMSSM model sets

• Original model generation itself was fairly compute-intensive as were the subsequent ATLAS studies (~1/4 core-millennium)

• The complete set of the SUSY-Hit model files are publically available @ www.slac.stanford.edu/~rizzo
• Combining the 7 TeV ATLAS searches, what fraction of the model sets should not (yet) have shown a signal w/ $\text{Sig} \geq 5$??

→ The coverage is quite good for both model sets!
• However, certainly in the FLAT case, there is not much model space left! Even worse, we ask…

• What fraction of these models are excluded??

• We need to generate some new FLAT model sets going out to larger SUSY masses PLUS we need to cover the gravitino cases!

→ Develop a common framework for future scans
New pMSSM FLAT Scans

\(100 \text{ GeV} \leq m_{Ll_{1,2,3}} \leq 4 \text{ TeV}\)
\(400 \text{ GeV} \leq m_{\text{Qud}_{1,2}} \leq 4 \text{ TeV}\)
\(200 \text{ GeV} \leq m_{\text{Qud}_{3}} \leq 4 \text{ TeV}\)
\(50 \text{ GeV} \leq |M_1| \leq 4 \text{ TeV}\)
\(100 \text{ GeV} \leq |M_2, \mu| \leq 4 \text{ TeV}\)
\(400 \text{ GeV} \leq M_3 \leq 4 \text{ TeV}\)
\(|A_{t,b,\tau}| \leq 4 \text{ TeV}\)
\(100 \text{ GeV} \leq M_A \leq 4 \text{ TeV}\)
\(1 \leq \tan \beta \leq 60\) (both flat & log scans)

→→ For the gravitino LSP: \(1 \text{ ev} \leq m_{3/2} \leq 500 \text{ GeV}\), log scan

- All new non-MET constraints from EPS, DPF & L-\(\gamma\) incorporated and all codes updated to latest versions w/ fixes. Additional complexities, eg, BBN constraints, for the gravitino LSP case
Non-MET LHC searches are very important and have a significant impact on the pMSSM as shown here for the original model sets...some more so for gravitino LSPs!
Results

• Produced a single code to handle BOTH neutralino & gravitino LSPs. This work is still at an early stage & only some results from the neutralino LSP scans are now available in a very preliminary form. (The gravitino cases will soon follow but we found it’s best to ‘debug’ w/ the more familiar neutralino LSP !)

  • Flat tan β Priors : 2x10^6 points scanned , ~158k survived
  • Log tan β Priors : 2x10^6 points scanned , ~133k survived

• Higher masses → weaker impact of the non-MET/LEP/Tevatron constraints → greater efficiencies for finding successful models

• Log tan β scan is somewhat more sensitive to the M_A - tan β constraints (as expected) since it peaks at lower values

• Note fast changing data base of constraints thanks to LHC !
Comments

• **No** LHC MET analyses have yet been performed using these new model points

• Spectrum generator issues: SOFTSUSY (for new sets) vs. SuSpect (for the original ones) … interesting comparisons

• **History**: SuSpect has a tendency to generate highly degenerate LSPs in wino/Higgsino cases (with $\Delta m << \sim 100$ MeV) .. .the common wisdom is that this ‘can’t happen’. It was then ‘suggested’ to use a different generator, e.g., SOFTSUSY

• Here we’ll look at some plots from the FLAT tan $\beta$ scan….

• But first what is this degeneracy issue?
Note that SOFTSUSY also produces small $\Delta m$’s $\lesssim 100$ MeV though maybe less frequently than SuSpect.. problem?
• Basic spectra will persist in both neutralino/gravitino cases

• Pretty standard gaugino & slepton mass spectra given the input ranges

• Note the charginos & neutralinos ‘tracking’ each other…

  gluinos also look fairly vanilla
- Wait…1\textsuperscript{st}/2\textsuperscript{nd} generation squarks are seen far below 400 GeV while their associated Lagrangian parameters were so constrained. What the..? → check w/ SuSpect ..

- For some parameter values the radiative corrections to the squark masses are extremely large $\sim O(1)$ in both codes (though they don’t agree!).

→ Poor scale choice &/or a need to re-sum??…an issue?
• Compare SuSpect & SOFTSUSY requiring that both generators produce spectra which are ‘compatible’…all the ‘offending’ models go away!

• We are now investigating the source of these large RCs…
• Some had SOFTSUSY accuracy warnings. For 32/33 of these cases, SuSpect (for the same inputs) gives an error message (31 RGE/tachyon issues) & a ‘normal’ value in the other case

• Remove models where significant disagreement occurs between the generators
Completely Fine !

![Graph showing Light Higgs Mass in extended pMSSM](image)
While any sparticle can be the nLSP as before, charginos (followed by the 2nd neutralino) are now seen to be even MORE dominant than in earlier sets.

This can again be mostly traced to the parameter scan ranges chosen… it will be interesting to contrast the gravitino case.
• Incredibly wide range of nLSP-LSP mass splittings! Some very small values (below ~10 MeV) are seen in both scans

• Note ‘hole’ from stable sparticle collider searches

• Note also cases with mass splittings in excess of ~1 TeV! Yikes!
Conclusions

• Generating pMSSM model sets, if taken seriously, is a great learning experience for physicists of all ages.

• It is useful to employ more than one spectrum generator to make tests & comparisons wrt ‘funny’ parameter regions that lead to ‘unexpected’ sparticle masses as well as a check for ‘features’.

• Best to test complex codes using the more familiar neutralino LSPs…

• There may be some not well understood pMSSM regions not adequately described by the public generators.

• Plenty more results coming soon -- including gravitino LSPs!
BACKUP SLIDES
Now Included….
SUSY is so much more than mSUGRA!

**Problem**: SUSY might be complex & could be missed by standard searches if only signatures within specific breaking scenarios (mSUGRA, GMSB, AMSB ..) are employed. How complex we don’t know..

So a more general study of SUSY is clearly warranted. Such a study can also have important impact on other BSM searches.

But SUSY is a very messy theory…even the (100+parameter) MSSM is too difficult to study in full detail.
What are (aren’t) the Goals of this Study?

- **Original scans**: Obtain a large ‘model’ sample, ~50k, satisfying ‘all’ experimental constraints & which are **kinematically accessible** in early 7 TeV LHC runs & check for any ‘holes’ left in LEP/Tevatron ‘low-E’ searches for lighter sparticles.

- Perform LHC, DM & other analyses with these models.

- Our goal was **NOT** to find the ‘best-fit’ model(s) but to search for any new physics that is different/unusual.

- We are interested in the capability of the LHC (**here mostly ATLAS**) & Dark Matter experiments to discover signals for all these models.
ATLAS SUSY Analyses w/ pMSSM Sets

• **Issue**: Can the LHC find all the pMSSM model points?

• **Question**: We asked whether or not a standard set of LHC MET analyses, designed for the CMSSM, would find them.

• To be as realistic as possible we worked closely w/ ATLAS employing their SUSY analysis suite at the fast simulation level. We obtained their pre-data SM background estimates & employed their anticipated range of systematic errors.

• We followed their search analyses in detail (same cuts, etc.) as well as their statistical criterion for SUSY discovery for direct comparisons.
ISASUGRA generates spectrum & sparticle decays

Partial NLO cross sections using PROSPINO & CTEQ6M

Herwig for fragmentation & hadronization

GEANT4 for full detector sim

SuSpect generates spectra with SUSY-HIT# for decays

NLO cross section for all 85 processes using PROSPINO** & CTEQ6.6M (~6M K-factors)

PYTHIA for fragmentation & hadronization

PGS-ATLAS for fast detector simulation

** version w/ negative K-factor errors corrected
# version w/o negative QCD corrections, with 1st & 2nd generation fermion masses & other very numerous PS fixes included. e.g., explicit small Δm chargino decays, etc.
We first verified that we can approximately reproduce both the 7 & 14 TeV ATLAS results for their benchmark CMSSM models with our analysis techniques for each channel. .. BUT there were some analysis differences.

Finally, we passed all of ~71k points through the full suite of ATLAS MET analyses (~150 core-yrs of CPU).

SuSpect → SUSY-Hit → PROSPINO (~12M K-factors!) → PYTHIA → ATLAS-tuned PGS4 fast simulation

Many results! Here only the most basic: How well do the 7 TeV ATLAS analyses do at pMSSM model coverage?

(ATLAS = A Tool for Locating Any SUSY?)
Exclusion plot for 164 pb\(^{-1}\)

ATLAS/SUSY study of our model sets

The 1st 500 Flat Models

Not excluded points
Excluded by combined analyses for PLHC and papers 02/2011

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18.07.2011
mSUGRA + pMSSM parameter dependence
CMS Long-Lived Stable Particle Search

Theoretical Prediction
- gluino (NLO+NLL)
- stop (NLO+NLL)
- GMSB stau (LO)

Tk + TOF
- gluino; 50% gg
- gluino; 10% gg
- stop
- GMSB stau

CMS Preliminary $\sqrt{s} = 7$ TeV $1091$ pb$^{-1}$
Fine-Tuning SUSY?

- It is often claimed that if the LHC (@7 TeV) does not find anything then SUSY must be **VERY** fine-tuned & so ‘less likely’. Is this true for our pMSSM model sets??

![Graphs showing fine-tuning for models that fail all analyses for FLAT priors and 50% error]