SUSY on the Frontier: LHC Searches with the pMSSM


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The pMSSM SUSY Search Approach

- 19/20 parameter pMSSM is being used to study SUSY at 7, 8 & 14 TeV by duplicating ‘ALL’ ATLAS searches w/ fast MC to determine SUSY space coverage, look for unusual processes & ID weak areas needing more work

- Two large ~225k model sets with neutralino/gravitino LSPs

- Smaller ‘designer’ sets ~10k for low-FT study, etc, analyses

- Combine with other studies on DM searches, H properties, etc

- Here: (i) update $\chi^0_1$ @ 7/8 TeV to all available as of 3/1/13
  (ii) first look at a new low-FT set

→ 14 TeV & Higgs studies for Snowmass ongoing
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>2-6 jets</td>
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<td>A/H → ττ</td>
<td>CMS-PAS-HIG-12-050</td>
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✓ = Newly added search

Total Excluded ~37% (was ~32% !)

No effect from m_h = 126 ± 3 GeV cut

RESULTS ONLY !
pMSSM Low-FT Neutralino LSP Model Set

- $3.3 \times 10^8 \rightarrow \sim 10.2k$ models
- $m_h = 126 \pm 3$ GeV
- WMAP/Planck $\pm 5\sigma$
- FT better than 1% ($\Delta < 100$)
- expected to be very susceptible to ATLAS
LSPs are seen to be mostly bino-Higgsino admixtures as was expected with an occasional small wino component.

There's lots of physics in the patterns here that there's no time to discuss (see backups).

Essentially reflections!
The necessity of both a light bino to get the right relic density & a light Higgsino for low-FT forces the stop decays to be quite complex!

~ 60% of models also have winos below the stop/sbottom = leptons!

~ 30% also have a light slepton below stop (co-annihilators) = more leptons!
Coverage quite different than the more general set.....
### 7 TeV Searches

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<td>Z + jets + MET</td>
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Note: $B_s \to \mu\mu$ & $A \to \tau\tau$ constraints now applied during model generation

~73% killed by searches!
Summary

• Given time limitations this is only a brief overview of recent results

• Adding 15 new analyses (mostly 3\textsuperscript{rd} gen + leptons) has an important impact on the coverage of the pMSSM neutralino set

• Low-FT models generally have complex stop/sbottom decays

• The coverage of models w/ low-FT is much more significant & the importance of 3\textsuperscript{rd} generation & leptonic searches is quite obvious. The generation of a different new low-FT set is underway.

• Expect ~15 more analyses + gravitino set results for Snowmass

• Also: analysis @ 14 TeV as well as Higgs studies for Snowmass
BACKUPS
Comparison of Stop Search Effectiveness

Fraction of excluded models seen by 7 TeV heavy stop (0l) search

Fraction of excluded models seen by 7&8 TeV heavy stop (1l) searches

Fraction of excluded models seen by 7&8 TeV gluino mediated stop searches

Fraction of excluded models seen by 8 TeV heavy stop (2l) search
Comparison of Sbottom Search Effectiveness

Fraction of excluded models seen by 7 TeV heavy stop (0l) search

Fraction of excluded models seen by 768 TeV heavy stop (1l) searches

Fraction of excluded models seen by 768 TeV gluino mediated stop searches

Fraction of excluded models seen by 8 TeV heavy stop (2l) search
Before

After
• Some improvement is seen for the case of gauginos likely due to the new leptonic searches + secondary sources which filter into these results

• However the sensitivity here remains rather weak but should improve when more lumi is added soon
Using naïve scaling arguments we can make some VERY VERY crude estimates of the pMSSM coverage @ 14 TeV

With input from ATLAS we will perform analyses similar to those in the European Study Report for the pMSSM
More Low-FT Results

Four graphs showing the fraction of models excluded by LHC SUSY searches in different parameter spaces.
As the SUSY searches are roughly independent of the value of the Higgs mass, the predicted mass of the Higgs is roughly independent of the SUSY searches as well!
Low Fine-tuning in the pMSSM?

- $m_h \sim 125-6$ GeV in the MSSM requires large stop masses and/or mixings which then $\rightarrow$ significant FT expected

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{(\tan^2 \beta - 1)} + \mu^2$$

- To quantify FT we ask how the value of $M_Z$ depends upon any of the 19 parameters, $\{ p_i \}$, up to (in some cases) the 2-loop, NLL level (c/o Martin & Vaughn). We follow the traditional FT analysis of Ellis et.al. & Barbieri & Giudice:

$$A_i = |\partial \ln M_Z^2 / \partial \ln p_i |, \quad \Delta = \max \{A_i \}$$

- How many models have $\Delta$ less than a specific value?
As expected, the large Higgs mass ‘cut’ removes most of the models with the lowest FT values.
Lessons Learned

- Completely random scans are seen to produce few models with low FT values.

- Furthermore, as expected, the large Higgs mass ‘cut’ is seen to remove most of the models with the lowest FT values.

- The spectra of these low-FT models can make them difficult to see with existing searches (see next 2 slides).

- This is an important class of models. It is certainly worth performing dedicated scans to produce sets of low-FT models under various physics assumptions so that they can be studied in detail.

- We got a start on this so let’s have a look....
Some Constraints

- $\Delta \rho / W$-mass
- $b \rightarrow s \gamma$
- $\Delta (g-2)_\mu$
- $\Gamma (Z \rightarrow \text{invisible})$
- Meson-Antimeson Mixing
  - $B \rightarrow \tau \nu$
  - $B_s \rightarrow \mu \mu$
- Direct Detection of Dark Matter (SI & SD)
- WMAP Dark Matter density upper bound
- LEP and Tevatron Direct Higgs & SUSY searches
- LHC stable sparticle searches + $A \rightarrow \tau \tau$
- BBN energy deposition for gravitinos
- Relic $\nu$’s & diffuse photon bounds
- No tachyons or color/charge breaking minima
- Stable vacua only
An example low-FT model from the neutralino set

\[ t_1 \ (601 \text{ GeV}) \]

\[ t \ (18\%) \]

\[ h \ (18\%) \]

\[ t \ (18\%) \]

\[ t \ (17\%) \]

\[ \chi_3^0 \ (284 \text{ GeV}) \]

\[ b \ (24\%) \]

\[ Z \ (12\%) \]

\[ \chi_2^0 \ (284 \text{ GeV}) \]

\[ Z \ (25\%) \]

\[ h \ (12\%) \]

\[ W \ (24\%) \]

\[ W \ (77\%) \]

\[ \chi_2^+ \ (160 \text{ GeV}) \]

\[ h \ (8\%) \]

\[ Z \ (2\%) \]

\[ W \ (36\%) \]

\[ W^* \ (37\%) \]

\[ \chi_1^0 \ (134 \text{ GeV}) \]

\[ Z^* \ (59\%) \]

\[ \gamma \ (4\%) \]

\[ W^* \ (100\%) \]

\[ \chi_1^0 \ (127 \text{ GeV}) \]
Z and h poles

Slepton & gaugino co-annihilation

Multiple co-annihilators

Top threshold

Scan range cutoff

Low-FT edge

LSP Mass (GeV)

Bino Content
• SI direct detection cross sections for these models, since the LSP is mostly well-tempered, almost all lie within ~100 below the present limits & will be found (or not) by XENON-1T

• $\Delta(g-2)$ of the muon CAN be large for some of these models if there are also light sleptons which do appear in some cases to get DM co-annihilation to work
Our p(henomenological)MSSM

- General CP-conserving MSSM with R-parity
- MFV at the TeV scale (CKM)
- Lightest neutralino/gravitino is the LSP.
- $1^{st}/2^{nd}$ generation sfermions degenerate
- Ignore $1^{st}/2^{nd}$ generation A-terms & Yukawa’s.
- No assumptions wrt SUSY-breaking
- WMAP used as upper bound on relic density

→ the pMSSM with 19/20 parameters

Goal: obtain ~250k points in each of these 2 spaces satisfying existing data then study their signatures @ the LHC & elsewhere…

We’re going for breadth not depth! →→ New low-FT set(s)

- $50 \text{ GeV} \leq |M_1| \leq 4 \text{ TeV}$
- $100 \text{ GeV} \leq |M_2, \mu| \leq 4 \text{ TeV}$
- $400 \text{ GeV} \leq M_3 \leq 4 \text{ TeV}$
- $1 \leq \tan \beta \leq 60$
- $100 \text{ GeV} \leq M_{A, l, e} \leq 4 \text{ TeV}$
- $400 \text{ GeV} \leq q_1, u_1, d_1 \leq 4 \text{ TeV}$
- $200 \text{ GeV} \leq q_3, u_3, d_3 \leq 4 \text{ TeV}$
- $|A_{t,b,\tau}| \leq 4 \text{ TeV}$
- $1 \text{ eV} \leq m_{3/2} \leq 1 \text{ TeV}$ (log prior)
The pMSSM SUSY Search Approach

• The pMSSM - reduces the # of MSSM parameters w/ experimentally motivated assumptions & is ‘unprejudiced’ wrt high-scale SUSY. Can lead to complex spectra & decay patterns, allows for correlations between various experiments & searches → less constrained SUSY. But is computationally challenging….

• The pMSSM can be used to combine all of the searches (even the non-MET ones !) to obtain a complete picture of the overall coverage of the SUSY parameter space
ATLAS SUSY Analyses @ 7 & 8 TeV

- Goal: implement the entire ATLAS SUSY suite w/ fast MC.

- Generate signal (only) events for every model for all ~85 SUSY processes & then scale w/ Prospino = CPU!

- Validate each signal region in every analysis using ATLAS benchmarks; use ATLAS backgrounds & limits as input

- Determine which models are excluded by every analysis & then combine them to determine the ‘total’ exclusion

- Note: we lag behind ATLAS
For us the 3 big questions are:

1\textsuperscript{st} Question: How do each of the searches do in covering the pMSSM parameter space?

2\textsuperscript{nd} Question: When all the searches are combined what fraction of the space remains?

3\textsuperscript{rd} Question: Why are some models missed?
→ Update our set of 7 & 8 TeV analyses (+15) to include all ATLAS results as of 3/1/13. These are mostly 3rd gen & leptonic searches @ 13 fb$^{-1}$. Further updates will appear later this summer.

→ First look at the new low-FT model set

→ One Lesson: It is important to keep ‘old’, e.g., 7 TeV analyses even when 8 TeV ones are available as models can be missed by cut tightening. This may be especially important going to14 TeV.
pMSSM Low-FT Neutralino LSP Model Set

→→ Can we get models with the ‘right’ Higgs mass plus ‘low’-FT & the ‘right’ relic density in the pMSSM ??

- Generate a low-FT set by adjusting the scan ranges of the more sensitive parameters ($\mu$, $A_t$, $m_{Q3}$, $m_{u3}$, $M_3$, $M_{1,2}$, etc.) such that the models already have low-FT < 100 & likely ‘near correct’ relic density: $\sim 3.3 \times 10^8$ was ‘sufficient’

- Impose an updated set of the usual flavor, precision, DD/ID, non-MET LHC, LEP, Tevatron & $m_h$ constraints

- Impose WMAP/Planck relic density $\pm 5\sigma$ $\rightarrow \sim 10.2k$ models

Pre-LHC MET analyses, what do these models look like?
No correlation here with FT
pMSSM Low-FT Neutralino LSP Model Set

- $m_h = 126 \pm 3$ GeV
- $\Omega h^2 |_{\text{DM}} = 0.1153 \pm 0.0095$
- FT better than 1% ($\Delta < 100$)
- $\sim 10.2k$ model points
Some Numbers (again, pre-LHC MET Analyses !)

• ~1.4% of models have stop/sbottom BELOW the Higgsinos & winos. These are likely already excluded by the direct searches if sufficiently light unless compression occurs.

• ~59.5% of models have all gauginos & Higgsinos below the lightest stop/sbottom. ~16.4% of models have the winos lighter than the Higgsinos.

• ~11.0% of models have a sbottom lighter than the stop.

• ~30% of models have a light slepton of some kind below the stop/sbottom; it’s most likely a mixed stau.

• ~15% of models have light squarks/gluinos below the stop or sbottom & so are likely excluded except for compression.
Gaugino Mass spectra & splittings
BR VS stop mass

BR(t+N1) vs. \(m_\tilde{t}\)

BR(b+C1) vs. \(m_\tilde{b}\)

BR(\tilde{t}^0) vs. \(m_\tilde{t}\)

BR(\tilde{b}^\pm) vs. \(m_\tilde{b}\)