SUSY w/o Prejudice @ the LHC: Neutralino & Gravitino LSPs

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Searches for SUSY @ the LHC keep going and going but have not found any signals (yet)…

However they ARE eating into a lot of the model parameter space…

Figure 10: Observed (solid curve) and median expected (dot-dashed curve) 95% CL limits in the $(m_0, m_{1/2})$ CMSSM plane with $\tan\beta = 10$, $A_0 = 0$, $\text{sgn}(\mu) = +1$ from the razor analysis. The $\pm$ one standard deviation equivalent variations in the uncertainties are shown as a band around the median expected limit.
Some ‘interpretations’ of these results…

“The low hanging fruit has already been picked….”

“In vino, veritas”

From LHC2TeV @ CERN, 3/26-30/2012:

“The CMSSM/mSUGRA scenario has been ‘punched in the face’ ”
• ATLAS & CMS have ‘done a number’ on squark & gluinos below ~ 0.8-1 TeV -- even in the pMSSM scenario:

- At most, only ~1% of our old ~68k pMSSM model set w/ all sparticle masses below 1 TeV survives. They’re essentially ‘just walking dead’ …

→ New pMSSM models needed!

& so we begin anew once more..
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!
Two New **pMSSM Scans**: Neutralino & Gravitino LSPs

100 GeV \leq m_{\tilde{\chi}} \leq 4 \text{ TeV}

400 \text{ GeV} \leq m_{Q_{ud1,2}} \leq 4 \text{ TeV} \quad 200 \text{ GeV} \leq m_{Q_{ud3}} \leq 4 \text{ TeV}

50 \text{ GeV} \leq |M_1| \leq 4 \text{ TeV} \quad 100 \text{ GeV} \leq |M_2, \mu| \leq 4 \text{ TeV}

400 \text{ GeV} \leq M_3 \leq 4 \text{ TeV} \quad |A_{t,b,\tau}| \leq 4 \text{ TeV}

100 \text{ GeV} \leq M_A \leq 4 \text{ TeV}

\color{brown}{1 \leq \tan \beta \leq 60}

\rightarrow \rightarrow \text{ For the gravitino LSP: } \quad 1 \text{ ev} \leq m_G \leq 1 \text{ TeV} (\text{ log scan})

- Apply all the usual non-LHC + all LHC **non-MET** constraints (as of 12/1/2011).
- Additional complexities occur, eg, BBN constraints for the gravitino LSP case

(via SOFTSUSY + SuSpect + FeynHiggs)
A much larger volume needs to be explored…

\[ \text{~230k models} \]

\[ \text{~68k} \]

…. for both gravitino and neutralino LSPs
Let’s investigate the other side of life: gravitino LSPs

• This is **NOT** generalized **GMSB**.. We make NO assumptions except that the gravitino is the LSP.. *it could be light* ~1 ev or it could be heavy ~ 1 TeV! **Anybody** can be the NLSP.

• A big issue is **BBN**… NLSPs in this scenario tend to be long lived & their decays will inject hadronic &/or EM energy into the early universe, possibly disrupting **BBN**

• **Lots of NEW code needed**, e.g., generalize all NLSP/NNLSP decays to the case of *arbitrary gravitino mass* .. **Existing codes inadequate**!

• **Reminder:** No DD or ID constraints for G LSP models
Some of the (MANY) Changes & Additions

- Decays to G’s can no longer be performed in the Goldstino limit so all possible NLSP decay modes involving G’s need to be recalculated …
• For non-G decays (e.g., for the NNLSP → NLSP) add all 3-body sparticle decays not in SUSY-Hit via CalcHEP

• Add relevant 4-body decays for gluinos, \( t_1 \) & \( \chi_1^\pm \)

• Add 5-body decays of \( t_1 \) via RH-sfermions

→ All sparticles w/ masses larger than \( m_{\text{bottom}} + m_{\text{NLSP}} \) now have complete decay tables for collider & BBN studies. NNLSPs can be detector stable

• For NLSP decays to G, add all 3- & 4-body modes w/ BBN relevant lifetimes \((\sim 10^{-4} \text{ to } 10^{14} \text{ sec})\) via MadGraph

• Calculate NLSP density using Micromegas & rescale to the gravitino mass

• Use lifetime & BF info for NLSPs from modified SUSY-Hit & check the constraints on EM or hadronic energy deposition during BBN

• Add constraints from the cosmo relic \( \nu \) & diffuse photon fluxes
E.g., even if $t_1$ is the **NNLSP** it may STILL be **detector stable**
Sample constraints from BBN and diffuse $\gamma$'s for different hadronic branching fractions of the NLSP

Shaded areas show where our gravitino models live

We follow:

Jedamzik; Kusakabe et al.; Kanazki et al.; Kribs and Rothstein;
Some properties of the gravitino LSP models

At first glance, gravitino LSP models appear to be a bit different than the neutralino LSP ones… A comparison is quite interesting.
nLSP-LSP Mass Splitting

\( \chi_1^0 \) LSP

- \( \text{Ch1} \)
- \( \text{u}_L \)
- \( \text{b}_L \)
- \( \text{t}_L \)
- \( \text{d}_R \)
- \( \text{d}_R \)
- \( \text{u}_R \)
- \( \text{stau1} \)
- \( \text{sne} \)
- \( \text{snt} \)
- \( \text{snt} \)
- \( \text{e}_R \)
- \( \text{g} \)
- \( \text{X2} \)
Electroweak Content of $\chi_1^0$

<table>
<thead>
<tr>
<th>Lightest Neutralino</th>
<th>Definition</th>
<th>Neutralino LSP</th>
<th>Gravitino LSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bino</td>
<td>$</td>
<td>N_{11}</td>
<td>^2 &gt; 0.95$</td>
</tr>
<tr>
<td>Mostly Bino</td>
<td>$0.80 &lt;</td>
<td>N_{11}</td>
<td>^2 &lt; 0.95$</td>
</tr>
<tr>
<td>Wino</td>
<td>$</td>
<td>N_{12}</td>
<td>^2 &gt; 0.95$</td>
</tr>
<tr>
<td>Mostly Wino</td>
<td>$0.80 &lt;</td>
<td>N_{12}</td>
<td>^2 &lt; 0.95$</td>
</tr>
<tr>
<td>Higgsino</td>
<td>$</td>
<td>N_{13}</td>
<td>^2 +</td>
</tr>
<tr>
<td>Mostly Higgsino</td>
<td>$0.80 &lt;</td>
<td>N_{13}</td>
<td>^2 +</td>
</tr>
<tr>
<td>All other models</td>
<td>$</td>
<td>N_{11}</td>
<td>^2,</td>
</tr>
</tbody>
</table>

With most of the neutralino parameters $\sim 1$ TeV the mass & electroweak eigenstates are generally quite close!
The likelihood of various NLSP identities is very strongly dependent on the LSP choice.

This can have a potentially large influence on LHC SUSY searches (apart from, e.g., additional cascades).
• The mass spectra of the MSSM fields in our model sets are (indirectly) influenced by the nature of the LSP, i.e., the fact that gravitinos can be VERY light whereas $\chi_1^0$ must be $> \sim 30$-40 GeV in the scan.

• E.g., since the lightest neutralino is at best the NLSP in the G scan, its mass distribution must now extend to larger values.
• Mass distributions for sparticles that are restricted to be $>400$ GeV will be less affected than those that must be $>100$ GeV by the choice of LSP.

• However, some of these small spectrum shifts can & do influence other observables....
- Overall, these are quite minor differences. The important differences for LHC searches are the nature of the LSP & ID of the NLSP.
The first step in exploring the parameter space of either pMSSM model set is to apply the SUSY MET searches.

As is our tradition, we follow the ATLAS analysis suite as closely as possible & we began w/ the $\chi$ model set.

At ~1 fb$^{-1}$ this is ‘relatively straightforward’ as all the data & numerous benchmark model results exist that we can test/validate against. Only partial ~5 fb$^{-1}$ results available.

We combine the various analyses signal regions (as ATLAS does) into: nj0l, multi-j, nj1l, nj2l (+ multi-l & HF) and we quote the coverage for each as well as the combined result.. approach is CPU intensive.
% models excluded

<table>
<thead>
<tr>
<th></th>
<th>7 TeV ~1 fb⁻¹</th>
<th>7 TeV ~5 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>nj0l [5/11]</td>
<td>6.68%</td>
<td>23.23%</td>
</tr>
<tr>
<td>multi-j [5/6]</td>
<td>0.36%</td>
<td>1.61%</td>
</tr>
<tr>
<td>nj1l [8/3]</td>
<td>0.81%</td>
<td>2.64%</td>
</tr>
<tr>
<td>nj2l [5]</td>
<td>0.16%</td>
<td>0.22%</td>
</tr>
<tr>
<td>flavor</td>
<td>(in progress)</td>
<td>(ditto)</td>
</tr>
</tbody>
</table>

(sub)total | 6.73%         | 23.28%        |

→ nj0l is by far dominant in these searches

*** In this case, we extrapolated to ~5 fb⁻¹, since results have not yet been released. We assumed that the number of events observed equals the expected backgrounds & that the analysis cuts are exactly the same as at ~1 fb⁻¹

• Our analyses can be updated when more data is available.
(Preliminary) Extrapolation to $\sqrt{s} = 8$ TeV

• The extrapolation here is greater than for $\sim 1 \to \sim 5 \text{ fb}^{-1}$ @ 7 TeV

• **First pass**: assume the cuts & analyses are as for 7 TeV & the number of observed events equals the expected backgrounds in each SR.

• However, we need to know the backgrounds for 8 TeV!

• Rescale ATLAS 7 TeV backgrounds? How? Use MC to determine the RATIOS of the expected backgrounds in each signal region at 7 & 8 TeV and use them as transfer factors.

• When low statistics becomes an issue we closely follow ATLAS’ approach using the sideband ‘ABCD’ method & then rescale the control regions.

• Of course we still need to generate the relevant SM MC backgrounds.
SM Background Generation @ $\sqrt{s}=7$ & $8$ TeV

- $Z/W^\pm + (0\text{-}4)j$
- $WW/ZZ + (0\text{-}2)j$
- $tt\text{-}bar + (0\text{-}1)j$
- single $t + (0\text{-}2)j$
- QCD up to 6 jets

$\leftrightarrow$ ME + PS, weighted evts

$\sim 1$ TB

w/ Sherpa
- Not too surprisingly, the gain in pMSSM coverage going to 8 TeV is substantial due to the increases in $\sigma$’s. $nj0l$ continues to dominate:

<table>
<thead>
<tr>
<th></th>
<th>8 TeV 5 fb$^{-1}$</th>
<th>8 TeV 20 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$nj0l^{**}$</td>
<td>32.70%</td>
<td>45.11%</td>
</tr>
<tr>
<td>multi-$j^{**}$</td>
<td>6.26%</td>
<td>7.35%</td>
</tr>
<tr>
<td>$nj1l^{**}$</td>
<td>1.41%</td>
<td>1.53%</td>
</tr>
<tr>
<td>$nj2l^{++}$</td>
<td>0.35%</td>
<td>0.38%</td>
</tr>
<tr>
<td>flavor</td>
<td>(in progress)</td>
<td>(ditto)</td>
</tr>
<tr>
<td>(sub)total</td>
<td>32.75%</td>
<td>45.13%</td>
</tr>
</tbody>
</table>

** extrapolated from $\sim5$ fb$^{-1}$ analysis  ++ extrapolated from $\sim1$ fb$^{-1}$ analysis

- $\sqrt{s}=13$-$14$TeV is needed for more complete coverage
How does the pMSSM respond to negative searches?

Note that colored sparticles get heavier, i.e., the distributions peak at higher masses as the searches progress but color singlets distributions are just rescaled downward.
• The LHCb result removes a total of 4899 (5884) models in the neutralino (G) LSP model set … The soon to be expected observation of this mode will have a very substantial impact
• non-MET searches REALLY ARE important!
As in the case of $B_s \rightarrow \mu \mu$, improvement in non-MET searches impact the pMSSM analyses... 160(164) models removed from the $\chi$ (G) LSP set...
Impact of A,H $\rightarrow \tau\tau$ Searches

\[ \tan \beta \]

\[ M_A \]

- CMS 4.6 fb$^{-1}$
- 'Old' CMS
- G LSP
- ATLAS
...for example Higgs properties in the MSSM...

Low $M_A$ & large $\tan \beta$ can enhance $h$ signal rates...however this parameter range is excluded by B-physics & H,A $\rightarrow \tau\tau$ searches!
Impact of LHC SM Higgs Searches

..or what will a Higgs at ~125 GeV tell us
“Generally” living up to ~SM expectations…**

** see however, e.g., 1203.4254
Distribution of Predicted Higgs Masses

\( \chi_1^0 \) LSP: 19.4 %

G LSP: 9.0 %

Region of ‘interest’
Regions of ‘Interest’  → Few models larger than the SM
Impact of LHC SM Higgs Searches

\[ \frac{\Gamma(h\rightarrow \gamma\gamma)}{\Gamma(h)} \]

\[ m_h \]

\[ \sigma_{gg\rightarrow h} \cdot B_{\gamma\gamma} / SM \]

\[ R_{\gamma\gamma} \]

G LSP

SM 125 GeV

~19k
$R_{\gamma\gamma}$ distributions for $m_h = 125 \pm 2$ GeV. $\chi_1^0$ LSP.
$R_{\gamma\gamma}$ vs $R_{XX}$ for $m_h = 125 \pm 2$ GeV

$\chi_1^0$ LSP
And furthermore, in other channels such as WW fusion and associated production with a W or Z at the Tevatron.
The blue points seem to prefer negative values of $X_t$ as it drives the sign of the h coupling to the lighter stop. Stop$_1$ masses as low as ~250-300 GeV are still found for large $X_t/M_s$ values.

$$X_t = A_t - \mu/t_\beta$$

$$M_s^2 = m_{\text{stop}1} \cdot m_{\text{stop}2}$$
Fine-tuning in the pMSSM

• $m_h = 123$-$127$ GeV in the MSSM requires large stop masses and/or mixings which then $\rightarrow$ significant FT expected

• 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 FT approach of Ellis et.al. + Barbieri & Giudice:

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

• Specifically we ask for the number of models with $\Delta$ less than a specific value…
Hence, as expected, the large Higgs mass ‘cut’ removes many of the models with the lowest FT values.
• NB: Requiring Higgs masses of $125 \pm 2$ GeV, FT < 100 & the passing all LHC searches only 13(0) of the $\chi(G)$ LSP models survive out of the original ~230k!

Some Common Model Properties:

• Gluinos & 1$^{\text{st}}$/2$^{\text{nd}}$ gen. squarks all lie above 1.25 TeV

• Only wino/Higgsino LSPs appear w/ a chargino below 270 GeV in all cases. Binos are all above 1.3 TeV. For (the more common) wino LSP cases, there is significant wino-Higgsino mixing

• Lightest stop (sbottom) between 320 & 1120 (400 & 1700) GeV

• Sleptons all over the place but mostly ~ 1 TeV

• $M_A > 460$ GeV, $\tan \beta > 13.5$

• FT mostly driven almost entirely by $\mu$ & $A_t$
An Example:

#178770 w/ FT=56.3

- Light stop & sbottom w/ all other squarks & gluino heavy
- 5 EWK-inos accessible below the stop
- sleptons all inaccessible
- complex decay patterns
Light Stop Decays

\[ t_1 (318) \]

\[ t \rightarrow b \]

\[ \chi_2^+ (258) \]

\[ \chi_2^0 (142) \]

\[ b \rightarrow t \]

\[ \chi_1^+ (114) \]

\[ t \rightarrow t \]

\[ \chi_1^0 (108) \]
Light Sbottom Decays

\( b_1 (400) \)

\[ \xrightarrow{W} t_1 (318) \quad \text{below 0.3\%} \]

\[ \xrightarrow{b} \]

\( \chi_3^0 (258) \)

\[ \xrightarrow{b} \]

\( \chi_2^0 (142) \)

\[ \xrightarrow{t} \]

\( \chi_1^- (114) \)

\[ \xrightarrow{b} \]

\( \chi_1^0 (108) \)

\( \xrightarrow{Z} \)

\( W \)

\[ \xrightarrow{Z, h} \]

\( W \)

\[ \xrightarrow{W^*} \]

\( Z^* \)

(w/ these BFs the ATLAS 2b-jet + MET search would exclude this \( b_1 \) below ~240 GeV)
As is well-known, FT prefers lighter Higgs masses. Overall the G LSP models, on average, have slightly more FT than do χ LSP models.
Long-Lived Sparticles: The Chargino Example

Most LSPs are nearly pure wino or Higgsino

 decay inside the detector

\( \chi_1^0 \) LSP

Log (un-boosted chargino decay length in meters)

~10.8 k models

detector stable
• Searches for stable and/or long-lived sparticles can be quite powerful for both $\chi_1^0$ or G LSP sets

• E.g., detector-stable charginos are quite common in $\chi_1^0$ LSP models & extend out to large masses:

Many excluded!

$\sim 10.8k!$
• 3581 (!!) models (conservatively) are removed by stable particle searches w/ \( \sim 5 \text{ fb}^{-1} @ 7 \text{ TeV} \)

If CMS were to extend the curve to 600 GeV an additional \( \sim 1.4k \) models are also excluded...
Gravitino LSP scenarios produce many models with detector-stable charged/colored sparticles over a very wide range of masses & species. This will be a powerful means of probing models.

Specialized searches are required in many cases & to cover decays inside the detector (not shown here). This is work that is now in progress.
Summary & Conclusions

• The pMSSM with either neutralino or gravitino LSPs shows a wide range of very interesting properties. The gravitino case has not been explored until now & may yield some unexpected results.

• LHC searches, both with & w/o MET, are cutting into these two model parameter spaces.

• Going to 8 TeV will be a significant step in model coverage.

• Higgs results will play a critical role in all future studies.

• We look forward to the 8 TeV results in July -- Down Under!
"Take a look at this everyone - it just could be the signature we’ve been looking for!"
BACKUPS
\( \chi_1^0 \) LSP DM Observables

![Graphs showing LSP DM observables](image-url)
Impact of $A, H \rightarrow \tau\tau$ Searches

- $\chi_1^0$ LSP $\sim 1-1.6$ fb$^{-1}$

Increased lumi enhances coverage of the $M_A - \tan \beta$ plane

→ These searches have an important impact on other parts of the pMSSM.
The issue still remains as to just how many pMSSM models will lead to long lived charginos. Although the number is always large SuSpect predicts more degeneracies than does SOFTSUSY, i.e., it depends how & which RCs are included.