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

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Searches for SUSY @ the LHC have not found any signals (yet)...

It would seem useful to go beyond the cMSSM or any particular SUSY breaking scheme to study the MSSM more generally.
One Approach: The pMSSM

The MSSM has too many parameters so we make assumptions to reduce these to a reasonable level

- The most general, CP-conserving MSSM with R-parity
- Minimal Flavor Violation at the TeV scale
- The lightest neutralino or the gravitino 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

→ the pMSSM with 19/20 real, TeV/weak-scale parameters…

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

Scan: look for ~250k points in these spaces satisfying all existing data & study their signatures @ the LHC & elsewhere.. NO FITS!
Two New pMSSM Scans: Neutralino & Gravitino LSPs

100 GeV \leq m_{Le1,2,3} \leq 4 \text{ TeV}

400 \text{ GeV} \leq m_{Qud1,2} \leq 4 \text{ TeV} \quad 200 \text{ GeV} \leq m_{Qud3} \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}

1 \leq \tan\beta \leq 60

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

\bullet \textbf{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}
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

- BBN energy deposition for gravitinos
- Relic $\nu$'s & diffuse photon bounds

- No tachyons or color/charge breaking minima
- Stable vacua only
Let’s investigate the other side of life: gravitino LSPs

- **NOT** generalized GMSB. NO assumptions except that the gravitino is the LSP. **Anybody** can be the NLSP.

- **BBN**… NLSPs in this scenario tend to be long lived & decays inject hadronic &/or EM energy, 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**!
Some New Features

- 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 & 5-body decays for gluinos, $t_1$ & $\chi_1^\pm$

→ NNLSPs can be detector stable

- For NLSP decays to G, add all 3- & 4-body modes w/ BBN relevant lifetimes ($\sim 10^{-4}$ to $10^{14}$ 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**.
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.
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 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 $\sim 1$ fb$^{-1}$ this is ‘relatively straightforward’ as all the data & numerous benchmark model results exist that we can test/validate against. Only partial $\sim 5$ fb$^{-1}$ results available.

We combine the various analyses signal regions (as ATLAS does) into: $n_{j0l}$, multi-$j$, $n_{j1l}$, $n_{j2l}$ (+ multi-$l$ & HF) and we quote the coverage for each as well as the combined result. Approach is CPU intensive.
<table>
<thead>
<tr>
<th>% models excluded</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 [4/6]</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+ml</td>
<td>(in progress)</td>
<td>(ditto)</td>
</tr>
<tr>
<td>(sub)total</td>
<td>6.73%</td>
<td>23.28%</td>
</tr>
</tbody>
</table>

→ 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 $\sim 1 \rightarrow \sim 5$ 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

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

$\leftrightarrow$ ME + PS, weighted evts

~ 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+ml</td>
<td>(in progress)</td>
<td>(ditto)</td>
</tr>
<tr>
<td><strong>(sub)total</strong></td>
<td>32.75%</td>
<td>45.13%</td>
</tr>
</tbody>
</table>

** extrapolated from $\sim$5 fb$^{-1}$ analysis  ++ extrapolated from $\sim$1 fb$^{-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 LHC result removes a total of $6035$ ($7147$) 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 LHC SM Higgs Searches

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

.. so far..(but tomorrow ?)
The two different model sets lead to qualitatively similar yet quantitatively very different predictions…
Special parameter regions needed for the 125 GeV Higgs

\[ \chi_1^0 \text{ LSP} \]

\[ G \text{ LSP} \]

\[ \chi_i/M_s \]

\[ m(h) \text{ (GeV)} \]

\[ m(\tilde{t}_1) \text{ (GeV)} \]
$\chi_1^0$ LSP

$R_{\gamma\gamma}$

$R_{ZZ}$

$R_{\text{VBF}}$

$R_{\tau\tau}$

$R_{\gamma Z}$
$\chi_1^{0}$ LSP

Very Highly Correlated!
Why the correlations & why is ‘b’ different?

- Actually (almost) all of the partial $\Gamma$’s are very close to their SM values due to decoupling, i.e., for both LSP model sets we get highly peaked $\Gamma / \Gamma_{\text{SM}}$ distributions (here for the neutralino model set)
• However, for $h \rightarrow bb$ things are quite different…

• Large $hbb$ coupling loop corrections decouple very slowly especially if there is large sbottom mixing (Haber et al.)

• These leads to a significant Higgs width increase/decrease since it is the dominant decay mode
Fine-tuning in the pMSSM

\[ m_h = 123-127 \text{ GeV in the MSSM requires large stop masses and/or mixings which then } \rightarrow \text{ significant FT expected} \]

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:

\[
A_i = \left| \frac{\partial \ln M_Z^2}{\partial \ln p_i} \right|, \quad \Delta = \max \{A_i\}
\]

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.
Dominant FT Contributors

\[ \chi^0 \text{ LSP} \]

\[ \text{G LSP} \]

before

after

before

after
Fractional Contribution to FT

$\chi_1^0 \text{ LSP}$ before

$G \text{ LSP}$ before

after

after
• NB: Requiring Higgs masses of $125\pm2$ GeV, FT < 100 & the passing all (stable sparticle) LHC searches only $13(1)$ of the $\chi(G)$ LSP models survive out of the original $\sim230k$ !

Some Common Model Properties:

• Gluinos & $1^{st}/2^{nd}$ 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 (But in models w/ slightly more FT could also have a bino below the stop..but not as LSP.) There is always significant wino-Higgsino mixing

• Lightest stop (sbottom) between 320 & 1120 (400 & 1700)GeV. Sbottom is sometimes lighter than stop.

• Sleptons all over the place but mostly $\sim$ 1 TeV

• $M_A > 460$ GeV, tan $\beta > 13.5$

• For a 125 GeV Higgs FT mostly driven almost entirely by $\mu$ & $A_t$
The Better Models & Their Natures

Model 203285

Model 635796

Model 1584662

Model 2403883
Light Stop Decays

An Example:
#2403883 w/ FT=56.3

\[ t_1 (318) \]

\[ \chi_2^+ (258) \]

\[ \chi_2^0 (142) \]

\[ \chi_1^+ (114) \]

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

\( b_1 (400) \rightarrow W t_1 (318) \)

\( b \rightarrow b \chi_3^0 (258) \)

\( t \rightarrow \chi_2^0 (142) \)

\( \chi_1^- (114) \rightarrow b t \)

\( \chi_1^0 (108) \)

(w/ these BFs the ATLAS 2b-jet + MET search would exclude this \( b_1 \) below \( \sim 240 \) GeV)
An Example:
#146314G w/ FT=95.9

Light Stop Decays

$t_1 (669)$

- $b \rightarrow \chi_2^+ (620) \rightarrow W$,
- $t \rightarrow \chi_2^0 (399) \rightarrow Z, h$,
- $bt \rightarrow \chi_1^0 (384) \rightarrow W^*$,
- $t \rightarrow \chi_1^+ (381) \rightarrow W^* h$.
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:

$\sigma$ (pp) vs. Mass (GeV/c^2)
• 3581 (!!!) models (conservatively) are removed by stable particle searches w/ \(\sim 5 \text{ fb}^{-1} \) @ 7 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.

- Low FT models have similar features & could be tough to find.

- We look forward to more 8 TeV results!
[Jason is inquiring about the job of sheriff]

**Jason McCullough:** Well, gentlemen, I think it's only fair to tell you that I'd only be interested in this job on a temporary basis.

**Henry Jackson:** Oh?

**Jason McCullough:** Well, you see, actually I was on my way to Australia when I heard about your gold strike and I decided to, uh, travel through here and see if I couldn't pick myself up a little stake.

**Thomas Devery:** What do you want to go to Australia for?

**Jason McCullough:** Well, it's the last of the frontier country. Thought I might like to do a little pioneering.

**Fred Johnson:** I thought this was frontier country and we was pioneers.

**Henry Jackson:** So did I.
BACKUPS
“Take a look at this everyone - it just could be the signature we’ve been looking for!”
FT Gluino Mass Constraint

\[ Z^{NLL}_{M_3} = \frac{2\alpha_s X^2}{(3\pi^3)(t^2_\beta - 1)} \frac{M_3}{M_Z^2} \left[ -y_b^2(2M_3 - A_b) + t^2_\beta y_t^2(2M_3 - A_t) \right] \]

For large \( t_\beta^2 >> 1 \) & with \( \left( \frac{y_b}{t_\beta} y_t \right)^2 << 1 \) we get

\[ \approx 1.16 \frac{M_3 (2M_3 - A_t)}{\text{TeV}^2} < \sim 56 \quad \text{since} \quad M_3, |A_t| < 4 \text{ TeV} \]
Backing off to FT=120, what do we learn?

- 5 G models… Those gravitino LSP models have winos & Higgsino below the stop w/ the NLSP being the lightest neutralino or chargino quite similar to the neutralino cases.

- 50 $\chi$ models… of which 33 survive the 7 TeV ATLAS searches ~10% of these models have all the EWK-inos below the stop/sbottom …the heaviest EWK-ino is the bino.

- These results further verify the patterns seen in the original 13 models
$\chi_1^0$ LSP DM Observables

![Graphs showing LSP mass vs. DM observables](images)
Impact of A,H $\rightarrow \tau\tau$ Searches

$\tan \beta$

CMS 4.6 fb$^{-1}$

'Old' CMS

ATLAS

G LSP

$M_A$
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: $\mu, M_A, \tan\beta$

$\Rightarrow$ (+ 1 gravitino mass: $m_{3/2}$)
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.;
Kanazaki et al.;
Kribs and Rothstein;

…..
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!
\[ \mathbf{G \ LSP} \]
G LSP

Very Highly Correlated!
As is well-known, FT prefers lighter Higgs masses. Overall the G LSP models, on average, have slightly more FT than do $\chi$ LSP models.
• The mass spectra of the MSSM fields are (indirectly) influenced by the nature of the LSP, i.e., the fact that $G$ can be VERY light whereas $\chi_1^0$ must be $> \sim 10$’s of 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.

• Other sparticle masses are less influenced due to scan ranges.