Signatures of the Sparticle Landscape and of the Gluino NLSP

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and Pran Nath (NU)

*DF’s Location, ~ Aug 09
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The Flow

Colliders and Dark Matter in SUGRA

Part 1:

- SUSY at the LHC in SUGRA models from the point of view of Sparticle Mass Hierarchies.
- Probing the Nature of Dark Matter via direct detection experiments with Sparticle Mass Hierarchies.

Part 2:

- G-Co → LHC, Light gluinos out of the Landscape; the GNLSP.
- GNLSP are a very interesting class of models and quite remarkably they have only very recently been explored.
Focus on high scale models, specifically **SUGRA** models:

- Gauge coupling unification manifest at a high scale
- Naturally incorporate gravity (SUGRA) by gauging global SUSY; SUSY breaking in hidden sector
- Dynamic triggering of the spontaneous breaking of electroweak symmetry through RGE, R-Parity Leads to LSP; models are predictive
- Provide a framework for String and D-Brane model building
- Free parameters minimized drastically relative to global SUSY

Partial list of related talks in BSM-LHC and SUSY 09:

- H. Baer and X. Tata (SUSY 09)
- B. Dutta (BSM and SUSY 09) with R. Arnowitt, T. Kamon, D. Toback, et. al
- B. Mukhopadhyaya et. al (BSM and SUSY 09)
- Z. Liu (SUSY 09) with D. Feldman, and Pran Nath
MSSM: 32 sparticle masses; Including the constraints of sum rules one has in excess of $10^{25}$ mass hierarchies for all 32.

Focus on the lightest sparticles in mSUGRA and NUSUGRA.

Under constraints from WMAP, & Collider Data:
$\sim 10^4$ 4 particle hierarchies $\rightarrow \sim 20$

minimal sugra patterns ($mSPs$)

$\ (mSP1 - mSP16), \ \mu > 0,$

$\ (mSP17 - mSP22), \ \mu < 0.$

A similar mapping of NUSUGRA shows 'saturation' with 15 additional NUSUGRA patterns ($NUSP1 - NUSP15$).

(i) NUH: $M_{H_u} = m_0(1 + \delta_{H_u}), \ M_{H_d} = m_0(1 + \delta_{H_d}),$ (1)

(ii) NUq3: $M_{q3} = m_0(1 + \delta_{q3}), \ M_{u3,d3} = m_0(1 + \delta_{tbR}),$ (2)

(iii) NUG: $M_1 = m_{1/2}, \ M_{2,3} = m_{1/2}(1 + \delta_{M_{2,3}}).$ (3)
### Sparticle Mass Hierarchies


<table>
<thead>
<tr>
<th>mSP</th>
<th>Mass Pattern</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSP1</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\chi}^\pm_1 &lt; \tilde{\chi}^0_2 &lt; \tilde{\chi}^0_3)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP2</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\chi}^\pm_1 &lt; \tilde{\chi}^0_2 &lt; A/H)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP3</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\chi}^\pm_1 &lt; \tilde{\chi}^0_2 &lt; \tilde{\chi}_1)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP4</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\chi}^\pm_1 &lt; \tilde{\chi}^0_2 &lt; \tilde{\chi}_1)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP5</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{l}<em>R &lt; \tilde{\nu}</em>\tau)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP6</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{\chi}^\pm_1 &lt; \tilde{\chi}^0_2)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP7</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{l}_R &lt; \tilde{\chi}^\pm_1)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP8</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; A \sim H)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP9</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{l}_R &lt; A/H)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP10</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{l}_1 &lt; \tilde{l}_R)</td>
<td>(\mu_+)</td>
</tr>
<tr>
<td>mSP11</td>
<td>(\tilde{\chi}^0 &lt; \tilde{t}_1 &lt; \tilde{\chi}^\pm_1 &lt; \tilde{\chi}^0_2)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP12</td>
<td>(\tilde{\chi}^0 &lt; \tilde{t}_1 &lt; \tilde{\tau}_1 &lt; \tilde{\chi}^\pm_1)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP13</td>
<td>(\tilde{\chi}^0 &lt; \tilde{t}_1 &lt; \tilde{\tau}_1 &lt; \tilde{l}_R)</td>
<td>(\mu\pm)</td>
</tr>
<tr>
<td>mSP14</td>
<td>(\tilde{\chi}^0 &lt; A \sim H &lt; \tilde{H}\pm)</td>
<td>(\mu_+)</td>
</tr>
<tr>
<td>mSP15</td>
<td>(\tilde{\chi}^0 &lt; A \sim H &lt; \tilde{\chi}^\pm_1)</td>
<td>(\mu_+)</td>
</tr>
<tr>
<td>mSP16</td>
<td>(\tilde{\chi}^0 &lt; A \sim H &lt; \tilde{\tau}_1)</td>
<td>(\mu_+)</td>
</tr>
<tr>
<td>mSP17</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{\chi}^0_2 &lt; \tilde{\chi}^\pm_1)</td>
<td>(\mu_-)</td>
</tr>
<tr>
<td>mSP18</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{l}_R &lt; \tilde{t}_1)</td>
<td>(\mu_-)</td>
</tr>
<tr>
<td>mSP19</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{t}_1 &lt; \tilde{\chi}^\pm_1)</td>
<td>(\mu_-)</td>
</tr>
<tr>
<td>mSP20</td>
<td>(\tilde{\chi}^0 &lt; \tilde{t}_1 &lt; \tilde{\chi}^0_2 &lt; \tilde{\chi}^\pm_1)</td>
<td>(\mu_-)</td>
</tr>
<tr>
<td>mSP21</td>
<td>(\tilde{\chi}^0 &lt; \tilde{t}_1 &lt; \tilde{\tau}_1 &lt; \tilde{\chi}^\pm_2)</td>
<td>(\mu_-)</td>
</tr>
<tr>
<td>mSP22</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\chi}^\pm_2 &lt; \tilde{\chi}^0_1 &lt; \tilde{\chi}_1)</td>
<td>(\mu_-)</td>
</tr>
</tbody>
</table>

### Table: The Sparticle Landscape of Mass Hierarchies in mSUGRA.

<table>
<thead>
<tr>
<th>NUSP</th>
<th>Mass Pattern</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUSP1</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\chi}^\pm_1 &lt; \tilde{\chi}^0_2 &lt; \tilde{\chi}^0_1)</td>
<td>(\text{NU3,NUG})</td>
</tr>
<tr>
<td>NUSP2</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\chi}^\pm_1 &lt; A \sim H)</td>
<td>(\text{NU3})</td>
</tr>
<tr>
<td>NUSP3</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{\tau}_1 &lt; \tilde{\chi}^0_2)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP4</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{\chi}_1 &lt; \tilde{\chi}^0_1)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP5</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}<em>1 &lt; \tilde{\nu}</em>\tau &lt; \tilde{\tau}_2)</td>
<td>(\text{NU3})</td>
</tr>
<tr>
<td>NUSP6</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}<em>1 &lt; \tilde{\nu}</em>\tau &lt; \tilde{\chi}^\pm_1)</td>
<td>(\text{NU3})</td>
</tr>
<tr>
<td>NUSP7</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{t}_1 &lt; A/H)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP8</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{l}<em>R &lt; \tilde{\nu}</em>\mu)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP9</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}_1 &lt; \tilde{\chi}^\pm_1 &lt; \tilde{l}_R)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP10</td>
<td>(\tilde{\chi}^0 &lt; \tilde{t}_1 &lt; \tilde{\tilde{g}} &lt; \tilde{\chi}^\pm_1)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP11</td>
<td>(\tilde{\chi}^0 &lt; \tilde{t}_1 &lt; A \sim H)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP12</td>
<td>(\tilde{\chi}^0 &lt; A \sim H &lt; \tilde{\tilde{g}})</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP13</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tilde{g}} &lt; \tilde{\chi}^\pm_1 &lt; \tilde{\chi}^0_2)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP14</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tilde{g}} &lt; \tilde{\tau}_1 &lt; \tilde{\chi}^\pm_1)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>NUSP15</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tilde{g}} &lt; A \sim H)</td>
<td>(\text{NUG})</td>
</tr>
<tr>
<td>DBSP1</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}<em>1 &lt; \tilde{\tilde{v}}</em>\tau &lt; A/H)</td>
<td>(\text{DB})</td>
</tr>
<tr>
<td>DBSP2</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}<em>1 &lt; \tilde{\nu}</em>\tau &lt; \tilde{l}_R)</td>
<td>(\text{DB})</td>
</tr>
<tr>
<td>DBSP3</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tau}<em>1 &lt; \tilde{\nu}</em>\tau &lt; \tilde{\nu}_\mu)</td>
<td>(\text{DB})</td>
</tr>
<tr>
<td>DBSP4</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\tilde{g}} &lt; \tilde{\tau}<em>1 &lt; \tilde{\nu}</em>\tau)</td>
<td>(\text{DB})</td>
</tr>
<tr>
<td>DBSP5</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\nu}_\tau &lt; \tilde{\tau}<em>1 &lt; \tilde{\nu}</em>\mu)</td>
<td>(\text{DB})</td>
</tr>
<tr>
<td>DBSP6</td>
<td>(\tilde{\chi}^0 &lt; \tilde{\nu}_\tau &lt; \tilde{\tau}_1 &lt; \tilde{\chi}^\pm_1)</td>
<td>(\text{DB})</td>
</tr>
</tbody>
</table>

### Table: New patterns in NUSUGRA ; no new patterns seen in NUH.
mSP Frequencies

Comparison Between mSP and other Benchmarks

<table>
<thead>
<tr>
<th>Snowmass</th>
<th>mSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS1a, SPS1b, SPS5</td>
<td>mSP7</td>
</tr>
<tr>
<td>SPS2</td>
<td>mSP1</td>
</tr>
<tr>
<td>SPS3</td>
<td>mSP5</td>
</tr>
<tr>
<td>SPS4, SPS6</td>
<td>mSP3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Post-WMAP3</th>
<th>mSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A', B', C', D', G', H', J', M'</td>
<td>mSP5</td>
</tr>
<tr>
<td>I', L'</td>
<td>mSP7</td>
</tr>
<tr>
<td>E'</td>
<td>mSP1</td>
</tr>
<tr>
<td>K'</td>
<td>mSP6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CMS LM/HM</th>
<th>mSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM1, LM6, HM1</td>
<td>mSP5</td>
</tr>
<tr>
<td>LM2, LM5, HM2</td>
<td>mSP7</td>
</tr>
<tr>
<td>LM3, LM7, LM8, LM9, LM10, HM4</td>
<td>mSP1</td>
</tr>
<tr>
<td>LM4, HM3</td>
<td>mSP3</td>
</tr>
</tbody>
</table>

**Table**: Mapping between the mSPs and the Snowmass, Post-WMAP3, and CMS benchmark points.

**ONLY 5 Mass Patterns Covered in Previous Benchmarks**
Experimental Constraints

- Relic Density (WMAP) \(0.0855 < \Omega_{\chi^0} h^2 < 0.1189\) (2\(\sigma\))
  (recent analysis - updated to WMAP5 \(\Omega_{\chi^0} h^2 = 0.1131 \pm 0.0034\))

- Exp: \(\mathcal{B}r(b \rightarrow s\gamma) = (355 \pm 24^{+9}_{-10} \pm 3) \times 10^{-6}\)
  HFAG, BABAR, Belle, and CLEO

- \(\mathcal{B}r(b \rightarrow s\gamma) = (3.15 \pm 0.23) \times 10^{-4}\) at \(O(\alpha_s^2)\)

- \(\mathcal{B}r(B_s \rightarrow \mu^+\mu^-) < (5.8/4.7) \times 10^{-8}(95/90\% CL)\) (Tevatron)
  Conservative imposition: \(\mathcal{B}r(B_s \rightarrow \mu^+\mu^-) < 1.2 \times 10^{-7}\) (95\% CL)

- \(m_h > 100\) GeV (majority of models have \(m_h > 110\) GeV)

- \(m_{\tilde{\chi}^\pm_1} > 104.5, m_{\tilde{t}_1} > 101.5, m_{\tilde{g}} > 220, m_{\tilde{\tau}_1} > 98.8\) (GeV)

- \(-11.4 \times 10^{-10} < \delta(g_\mu - 2) < 9.4 \times 10^{-9}\)
  Brookhaven Muon (g-2) Collaboration
LHC Simulation Procedure

- micrOMEGAs\(^1\) + SuSpect (+SUSYHIT)\(^2\) [REWSB, RD, FC, Mass Limits+Decays]
- SUSY Les Houches Accord (SLHA) \(^3\) [Spectrum & Mixings]
- PYTHIA 6.4.11 + PGS4 [MSEL=39] \(^4,5\) [SUSY Production ]
- Compare PYTHIA and PROSPINO\(^6\) at LO
- b tagging \(^7\) \(\epsilon_b\) par is based on CDF Run 2 tight/loose SECVTX tagger
- TAUOLA \(^8\) for \(\tau\) decays with a DØ tested interface
- Level 1 (L1) triggers (CMS) and CMS Detector Parameters
- SM (QCD, \(b\bar{b}\), \(t\bar{t}\), DY, \(Z/W\), \(Z/W + \) jets, \(ZZ, WW\))
- SMART (= SUSY Matrix Routine) \([\text{find mSPs, NUSPs etc...}, \text{Post Trigger Level Cuts, Count, Histogram, Analyze}]\)
- \(N_{\text{SUSY}} > \text{Max} \left\{5\sqrt{N_{\text{SM}}}, 10\right\}\) [Discovery Limit]

1. G. Belanger, F. Boudjema, A. Pukhov, A. Semenov
2. A. Djouadi, J.L. Kneur, G. Moultaka + M.M. Muhlleitner, M. Spira
3. B. Allanach et al. (SLHA Collaboration)
4. T. Sjostrand, S. Mrenna, P. Skands
5. J. Conway (CDF)
6. J. A. Nielsen (CDF)
7. W. Beenakker, R. Hopker, T. Plehn, M. Spira
8. S. Jadach, J. Kuhn, Z. Was
How Good is our Simulations?  
Pretty, Pretty, Pretty Good (PGS4)

LM1 is mSUGRA $\in mSP5$

But it is one of many mass patterns (albeit a good standard candle).

As I just mentioned, in mSUGRA it is one of 20 mass patterns for the first 4 lightest sparticles.
More Generally: Stau-Co, Stop-Co, HiggsPoles, and HB/FP

Parameter Space is Large and mSPs illuminate the structure


**Figure:** The parameter space is large, even in mSUGRA, and the mSPs provide structure.
mSP: Connect Parameter Space to Signature Space


Figure: Pulling apart the mSPs with LHC Signatures - Binos, Higgsinos and Mixed Binos and Higgsinos, separate out (+ jets $\geq 2 + P_T^{miss} > 200$ GeV). Tagged b-jets and $P_T^{miss}$ are very important signatures for discriminating models.

HPs = Higgs Patterns, CP = Chargino Patterns, SUP = Stau Patterns, SOP = Stop Patterns
Effective Mass Distribution


Figure: Effective mass ($\sum_{Jet} P_{T}^{Jet} + P_{T}^{miss}$) distributions for different mSPs; Trigger and Post Trigger Level Cuts are crucial: Stops and Chargino Patterns are narrow, Stau and Higgs are broad; need specialized cuts per mass hierarchy.
Direct Detection of Dark Matter
Prism on the Landscape


mSUGRA, $\mu > 0$: mSP1–mSP16

$\sigma (\chi p)$ [cm$^2$] vs Mass LSP Neutralino $\chi$ [GeV]
Direct Detection of Dark Matter


\begin{figure}
\centering
\includegraphics[width=\textwidth]{mSUGRA_1.png}
\end{figure}
One of the interesting possibilities that arises within the landscape of possible sparticle mass hierarchies is that the gluino ($\tilde{g}$) is the next to the lightest supersymmetric particle (NLSP) where neutralino dark matter produces the correct relic abundance of such matter consistent with the WMAP observations.

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<tr>
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<tr>
<td>NUSP13</td>
<td>$\tilde{\chi}^0 &lt; \tilde{g} &lt; \tilde{\chi}_1 \lesssim \tilde{\chi}_2^0$</td>
</tr>
<tr>
<td>NUSP14</td>
<td>$\tilde{\chi}^0 &lt; \tilde{g} &lt; \tilde{t}_1 &lt; \tilde{\chi}_1^\pm$</td>
</tr>
<tr>
<td>NUSP15</td>
<td>$\tilde{\chi}^0 &lt; \tilde{g} &lt; A \sim H$</td>
</tr>
</tbody>
</table>

Table: Hierarchical sparticle mass patterns for the four lightest sparticles, where $\tilde{\chi}^0 \equiv \tilde{\chi}_1^0$ is the LSP neutralino, and where the gluino is the NLSP that arises in the NUSUGRA models. Mass patterns given in FLN arXiv:0711.4591, Phys.Lett.B662:190-198, (2008)

- Will refer to this subclass of NUSUGRA where Relic Density constraints are satisfied as the GNLSP class of models.
In general gaugino mass relations at the GUT scale may be non-universal, for ex: non-singlet F breaking. Ratios: \( R_{a=1,2,3} = M_1 : M_2 : M_3 \) important for collider signatures.

We find that a linear combination with two irreducible representations, a singlet \((1,1,1)\) and a non-singlet F term, can give rise to a GNLSP with: \( M_{a=1,2,3} = (1 + \alpha R_a)m_{1/2} \).

In several cases an interesting phenomenon arises in that the models with the same value of \( r \)

\[
r \equiv \frac{(M_2 - M_1)}{(M_3 - M_1)}
\]

are essentially equivalent (or rather phenomenologically indistinguishable) after redefinitions of arbitrary \(\alpha\) and overall scalings of \(m_{1/2}\) in the gaugino mass sector.

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1See recent work by S.P. Martin (arXiv:0903.3568, PRD 79, 095019): Non-universal gaugino masses from non-singlet F-terms
Several possibilities for which the GNLSP class of models can arise, here are some cases:

1. Model GNLSP\textsubscript{A} (ISO-I): This class of models arises in $SU(5), SO(10), E_6$ models\textsuperscript{2}

$$
\begin{align*}
\frac{M_1 : M_2 : M_3}{\begin{array}{c}
-1/2 : -3/2 : 1 \\
19/10 : 5/2 : 1 \\
-1/5 : -1 : 1 \\
\end{array}} \quad \rightarrow \quad r = -2/3.
\end{align*}
$$

2. Model GNLSP\textsubscript{B}: This is an $E_6$ model with F type breaking with 2430 plet which gives $M_1 : M_2 : M_3 = 0 : 0 : 1$. This model can generate a GNLSP upon the addition of breaking with a singlet

3. Model GNLSP\textsubscript{C}: Here $r$ is free and thus defining $r = \delta_2/\delta_3$ the gaugino masses at the GUT scale may be parametrized as

$$
\begin{align*}
\widetilde{M}_1 &= m_{1/2}, \\
\widetilde{M}_2 &= (1 + \delta_2)m_{1/2}, \\
\widetilde{M}_3 &= (1 + \delta_3)m_{1/2},
\end{align*}
$$

and $\delta_2$ and $\delta_3$ can be varied independently.

\textsuperscript{2}for other ISO (Isomorphic) examples see FLN arXiv:0905.1148
(Ωh^2)\bar{\chi}^0 \text{ controlled by Gluino Co, Boltzmann suppression factor}

\gamma_i = \frac{n_i^{\text{eq}}}{n^{\text{eq}}} = \frac{g_i(1 + \Delta_i)^{3/2}e^{-\Delta_i x}}{\sum_j g_j(1 + \Delta_j)^{3/2}e^{-\Delta_j x}}, \tag{6}

Typical for Bino LSP in the GNLSP are $\tilde{\chi}^0\tilde{\chi}^0 \rightarrow t\bar{t}(\lesssim 3\%), \tilde{\chi}^0\tilde{\chi}^0 \rightarrow \tau^+\tau^-(\sim 1\%), 
\tilde{\chi}^0\tilde{g} \rightarrow t\bar{t}(\lesssim 3\%), \tilde{g}\tilde{g} \rightarrow gg(\sim 50\%), \tilde{g}\tilde{g} \rightarrow q\bar{q}(\sim 40\%).$

$\Delta_{\tilde{g}\tilde{\chi}^0} \equiv (m_{\tilde{g}} - m_{\tilde{\chi}^0})/m_{\tilde{\chi}^0} \in (0.08 - 0.20).$

$\langle \sigma_{\text{eff}} v \rangle$ to be integrated has cross section dependance approx

$$
\sigma_{\text{eff}} \simeq \sigma_{\tilde{g}\tilde{g}} \left( \gamma^2 + 2\gamma \frac{\sigma_{\tilde{\chi}^0\tilde{g}}}{\sigma_{\tilde{g}\tilde{g}}} + \frac{\sigma_{\tilde{\chi}^0\tilde{\chi}^0}}{\sigma_{\tilde{g}\tilde{g}}} \right), \tag{7}
$$

where $\gamma = \gamma_{\tilde{g}}$ and where $\gamma_i$ are defined by Eq.(6).

Non-perturbative effects, aka Sommerfeld Enhancement of $\langle \sigma_{\text{eff}} v \rangle$, i.e. reduction of $(\Omega h^2)\tilde{\chi}^0$ requires $\Delta_{\tilde{g}\tilde{\chi}^0}$ increase by (2 to 3)% for $m_{\tilde{g}} \lesssim \text{TeV}$ to maintain $(\Omega h^2)\tilde{\chi}^0 \in \text{WMAP}.$

We also find cases where the GNLSP emerges without significant coannihilation which occurs when the LSP has a significant higgsino component.
Models with Light Gluinos

- **S. Profumo, C.E. Yaguna** - Gluino-Co for Bino Dark Matter, Relic Density Studied and DM Detection

- **H. Baer, A. Mustafayev, E. Park , S. Profumo, X. Tata** - Gluinos are relatively Light [not GNLSP though], analysis of DM and Colliders, and Re-emphasis on $\tilde{g} \rightarrow \tilde{\chi}^0 g$ – JHEP 0604:041,2006


- **J. Alwall, M. Le, M. Lisanti, J. Wacker; J. Alwall, Simon de Visscher, Fabio Maltoni**
  - Hadron Collider Study, Light gluinos, -Emphasis on ISR - Matching of ME with PS


Consistent Parameter Space (LARGE and DENSE)

FLN arXiv:0905.1148
Compression of the Gluino Mass in GNLSP models
And 2nd Gen. Sleptons Squark Degeneracy

FLN arXiv:0905.1148

- Here the gluino mass will be typically much lighter relative to the squark masses. It is useful to define

\[ \Delta_{ed}^{(i)} = 2 \frac{(m_{\tilde{d}_1} + m_{\tilde{d}_2}) - (m_{\tilde{e}_1} + m_{\tilde{e}_2})}{(m_{\tilde{d}_1} + m_{\tilde{d}_2}) + (m_{\tilde{e}_1} + m_{\tilde{e}_2})}, \quad i = 1, 2, \quad (8) \]

- For mSUGRA \( \Delta_{ed}^{(i)} \) are positive and typically a significant fraction. However, for the GNLSP case one has

\[ |\Delta_{ed}^{(i)}| \ll 1, \quad \sim 1\% \quad (9) \]

<table>
<thead>
<tr>
<th>model</th>
<th>Pattern</th>
<th>( m_{\tilde{e}<em>1} + m</em>{\tilde{e}_2} )</th>
<th>( m_{\tilde{d}<em>1} + m</em>{\tilde{d}_2} )</th>
<th>( \Delta_{de}^{(1)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSUGRA</td>
<td>mSP3</td>
<td>5377</td>
<td>7652</td>
<td>35%</td>
</tr>
<tr>
<td>NUSUGRA SU(5)</td>
<td>NUSP13</td>
<td>7386</td>
<td>7373</td>
<td>-0.1%</td>
</tr>
<tr>
<td>NUSUGRA SO(10)</td>
<td>NUSP13</td>
<td>7369</td>
<td>7300</td>
<td>-0.1%</td>
</tr>
</tbody>
</table>
Gaugino Mass Discrimination

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Figure: Left panel: An exhibition of the scaling between the light chargino mass and the LSP mass for the GNLSP models GNLSP\textsubscript{A}, GNLSP\textsubscript{B} and GNLSP\textsubscript{C} vs the mSUGRA model. The figure shows that GNLSP\textsubscript{A} produces the ratio $m_{\tilde{\chi}^\pm}/m_{\tilde{\chi}^0} \sim 3$ which differentiates it from the bino branch of mSUGRA and for GNLSP\textsubscript{B}. Right panel: An exhibition of scaling in $m_g/m_{\tilde{\chi}^0}$. All GNLSP models are well separated from mSUGRA in this figure.
Overwhelming dominance of the $\tilde{g}\tilde{g}$ production process for the GNLSP. Actually, a large number of events pass L1 trigger ....
Figure: Left panel: An analysis of events/bin/fb$^{-1}$ as a function of the azimuthal angle $\Delta \phi(jet_1, jet_2)$ between the two hardest jets in the GNLSP model relative to the SM backgrounds with C2 cuts. Right panel: $H_T = \sum_{jets} P_T$ distributions of GNLSP models and SM backgrounds with C2 cuts. These distributions act as a guide for implementing the C3 cuts.
The dominant SM background for GNLSP models are from QCD, $Z/W+\text{ jets, }\bar{b}b$, and $tt$.

Can cut on large $\Delta\phi(jet_1, jet_2)$ to suppress the QCD background due to light quark flavors and $\bar{b}b$ as well as $tt$.

Reject isolated $e/\mu$ from background $W/Z$ leptonic decays. $e/\mu$ veto significantly enhances the GNLSP signals over the standard model background.
(iii) Class 3 Post Trigger Level Cuts (C3)

1. Electrons, and muons with $P_T > 10$ GeV and $|\eta| < 2.4$ are selected.
2. Jets with $P_T > 50$ GeV and $|\eta| < 3$ are selected.
3. Events with $\sum_j P_T > 150$ GeV are selected.
4. Events with at least 2 jets are selected.
5. Electron or muon veto is imposed.
6. $H_T \equiv \sum_{\text{jets}} P_T > 400$ GeV.
7. The azimuthal angle $\Delta \phi(jet_1, jet_2)$ between jet1 (the hardest jet) and jet2 (the second hardest jet) is chosen so that $\Delta \phi(jet_1, jet_2) < 3\pi/4$.
8. The azimuthal angle $\Delta \phi(jet_1, P_T)$ between jet1 (the hardest jet) and $P_T$ is chosen so that $\Delta \phi(jet_1, P_T) > \pi/2$.
9. The azimuthal angle $\Delta \phi(jet_2, P_T)$ between jet2 (the second hardest jet) and $P_T$ is chosen so that $\Delta \phi(jet_2, P_T) > \pi/4$. 
\( \langle \mathbf{P}_{\text{miss}} \rangle \) GeV

\( L = 10 \text{ fb}^{-1} \)

\( \text{LHC } \sqrt{s} = 14\text{TeV} \)

\( \Omega h^2 \in \text{WMAP5} \)

\( \tilde{g} \) is the NLSP

Figure: The analysis above is with post trigger level cuts C3 and with an integrated luminosity of 10 fb\(^{-1}\). Left panel: average \( \mathbf{P}_{\text{miss}} \) vs the gluino mass; Right panel: the discovery reach in SUSY events vs the gluino mass.

If the GNLSP exists its signatures should appear at the LHC for \( m_{\tilde{g}} < 800 \text{ GeV} \) with early runs
Figure: Left panel: the discovery reach with 10/fb for SUSY events with 1 tagged b-jet vs the gluino mass, and Right panel: C3 enhance the 4J reach by roughly 100 GeV relative to the post trigger level cuts C1.

Lots of multi-jets
C3 Cuts can enhance the discovery reach.
Figure: An exhibition of the spin independent cross section $\sigma_{SI}$ as a function of the neutralino mass. NUSP13 (light blue), NUSP14 is given in dark (magenta).

- GNLSP Models are beginning to be constrained (Higgsino LSP)
- Possible to have very light gluino with large Spin Indep. Xsec.
Knowledge of Sparticle Mass Hierarchies play an important role in sorting out SUSY at Colliders and in Dark Matter experiments.

Light Higgses are being constrained in high scale models and by CDMS and Xenon-10 [and by CDF and DØ in the $2\tau$ channel].

Direct Detection of Dark Matter: Copious number of models sit on the Chargino Wall. Nature may be pointing towards light gauginos, they are the dominant pattern out of the landscape of possibilities.
Gluino Coannihilation $\rightarrow$ Relic Denisty of Neutralinos $\in$ WMAP 5 ;
Under Naturalness range, models exists over the entire span
$\sim 200 \text{ GeV} < m_{\tilde{g}} < 1 \text{ TeV} \in \text{WMAP 5}$.

GNLSP LHC $\implies$ Gluino Factory

Combining all the channels analyzed $\rightarrow \tilde{g}$ masses up to 800 GeV are discoverable in GNLSP models with just 10 fb$^{-1}$.

Thus the validity of the GNLSP models can be tested with first data from the LHC.

Such models should therefore be included in CMS and ATLAS benchmark analyses.