Searches for Prompt Light Gravitino Production

Peter Krieger, Carleton University, Ottawa Canada, for the OPAL Collaboration

- SUSY models with light gravitinos
- Gauge-Mediated Supersymmetry Breaking
- Neutralino NLSP Scenario
- Slepton NLSP Scenario
- GMSB scan
- Gravitino Pair Production
- GMSB signatures with lifetime
- Summary

Final Results at $\sqrt{s} = 189$ GeV

Preliminary updates at $\sqrt{s} = 200-209$ GeV
SUSY models with a Light Gravitino

- Some SUSY models predict that the LSP is an almost massless gravitino (models with gauge-mediated supersymmetry breaking, no-scale supergravity)
- Richest phenomenology is from GMSB models

<table>
<thead>
<tr>
<th>Gravity</th>
<th>SUSY in hidden sector</th>
<th>Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M \sim M_p \sim 10^{18}$ GeV</td>
<td>$\sqrt{F} \sim \sqrt{M}$</td>
<td>$10^3 &lt; M &lt; 10^{15}$ GeV</td>
</tr>
<tr>
<td>$\sqrt{F} \sim 10^{11}$ GeV</td>
<td>$G^1/2$</td>
<td>$10^3 &lt; \sqrt{F} &lt; 10^{10}$ GeV</td>
</tr>
<tr>
<td>FCNC</td>
<td>Visible Sector</td>
<td>No FCNC</td>
</tr>
<tr>
<td>$M_G \sim 2.5$ TeV</td>
<td>$e, \mu, \tau, \ldots, W^-, Z^0$</td>
<td>$\Lambda \sim k \frac{F}{M}$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{e}, \tilde{\mu}, \tilde{\tau}, \ldots, \tilde{W}^-, \tilde{Z}^0$</td>
<td>$M_G &lt; 1$ GeV</td>
</tr>
</tbody>
</table>

**R-parity conservation assumed throughout this talk**

Well defined particle spectrum
No FCNC
LSP = light gravitino
Phenomenology depends on NLSP

Problems with FCNC
Gravitino phenomenologically unimportant
Phenomenology depends on LSP
Experimental Signatures

Scale of SUSY breaking $\sqrt{F}$ determines $\tilde{G}$ mass and NLSP lifetime

$$M_{\tilde{G}} \approx 2.37 \times 10^{-2} \left( \frac{\sqrt{F}}{10 \text{ TeV}} \right)^2 \text{eV}$$
$$c \tau(\text{NLSP}) \approx \left( \frac{M_{\text{NLSP}}}{100 \text{ GeV}} \right)^{-5} \left( \frac{\sqrt{F}}{10 \text{ TeV}} \right)^4 \mu \text{m}$$

Phenomenology dictated by the NLSP (usually either $\tilde{\chi}_1^0$ or $\tilde{\tau}$) and on NLSP lifetime (decay length w.r.t detector volume)

<table>
<thead>
<tr>
<th>NLSP</th>
<th>short</th>
<th>intermediate</th>
<th>long</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>photons + $E_T$</td>
<td>Non-pointing photons + $E_T$</td>
<td>as in gravity-mediated SUSY</td>
</tr>
<tr>
<td>$\tilde{\tau}$</td>
<td>leptons + $E_T$</td>
<td>Kinked charged tracks + $E_T$</td>
<td>Long-lived heavy charged particles</td>
</tr>
</tbody>
</table>

Scenarios with particularly low SM backgrounds

This talk: Prompt Production

Unusual signatures in the case of intermediate $\tau_{\text{NLSP}}$
Experimental Signatures

Can be co-NLSPs

Contribute to exclusion regions from GMSB scan

NLSP Pair Production

Other sparticle pair production, associated pair production

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Neutralino NLSP Pair Production

Acoplanar photons

\[ e^+ e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\tilde{G} \gamma)(\tilde{G} \gamma) \rightarrow \gamma \gamma + E_T \]

Irreducible SM background from \[ e^+ e^- \rightarrow \nu \bar{\nu} \gamma \gamma \]

Large fraction of signal contribution expected at M\(_{\text{recoil}}\) values well below the Z peak

Selected events can be classified according to maximum mass for which they remain kinematically consistent with the above decay sequence (M\(_{X}^{\text{max}}\))

OPAL published results from \(\sqrt{s} = 189 \text{ GeV}\)

<table>
<thead>
<tr>
<th>M(_X) (GeV)</th>
<th>Selection Efficiency (%)</th>
<th>Selection efficiency with M(_X^{\text{max}}) &gt; M(_X) - 5 GeV</th>
<th>N(_{\text{data}})</th>
<th>N(_{\nu \gamma \gamma})</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>70.2 +/- 1.2</td>
<td>67.7 +/- 1.3</td>
<td>14</td>
<td>13.67 +/- 0.20</td>
</tr>
<tr>
<td>60</td>
<td>74.0 +/- 1.1</td>
<td>71.1 +/- 1.2</td>
<td>11</td>
<td>10.05 +/- 0.18</td>
</tr>
<tr>
<td>70</td>
<td>71.4 +/- 1.2</td>
<td>69.2 +/- 1.2</td>
<td>9</td>
<td>7.22 +/- 0.15</td>
</tr>
<tr>
<td>80</td>
<td>72.3 +/- 1.2</td>
<td>68.7 +/- 1.4</td>
<td>7</td>
<td>4.81 +/- 0.13</td>
</tr>
<tr>
<td>90</td>
<td>71.3 +/- 1.2</td>
<td>67.5 +/- 1.3</td>
<td>5</td>
<td>2.40 +/- 0.09</td>
</tr>
<tr>
<td>94</td>
<td>72.2 +/- 1.2</td>
<td>70.4 +/- 1.2</td>
<td>3</td>
<td>1.34 +/- 0.07</td>
</tr>
</tbody>
</table>

Gravitino-LSP model with M\(_\chi^\prime\) = 1.35 M\(_\chi^0\), M\(_\chi^1\) = 2.7 M\(_\chi^0\)

Expected limit @95% CL

NLSP = \(\tilde{B}\)

Gravitino-LSP model with M\(_\chi^\prime\) > 88.3 GeV

OPAL \(\sqrt{s} = 189 \text{ GeV}\)

\[ N_{\text{exp}} = 26.9 \pm 0.3 \pm 1.2 \]

\[ N_{\text{obs}} = 24 \]
Update of OPAL Acoplanar Photons Selection

No evidence for non-Standard Model contributions (especially in low recoil-mass region)
Other Channels: Neutralino NLSP

Other production channels:

\[ e^+ e^- \rightarrow \tilde{\tau}^+ \tilde{\tau}^- \rightarrow (\tilde{\chi}_1^+ \tilde{\chi}_1^-) \rightarrow (\tilde{\chi}_1^0 \tilde{\chi}_1^-) \rightarrow (1^+ \gamma \tilde{G})(1^- \gamma \tilde{G}) \rightarrow 1^+ 1^- \gamma \gamma + E_T \]

\[ e^+ e^- \rightarrow \chi_1^+ \chi_1^- \rightarrow (W^{(*)+} \tilde{\chi}_1^0)(W^{(*)-} \tilde{\chi}_1^-) \rightarrow (W^{(*)+} \gamma \tilde{G})(W^{(*)-} \gamma \tilde{G}) \rightarrow \text{Leptons and/or jets } + \gamma \gamma + E_T \]

\[ e^+ e^- \rightarrow \chi_2^0 \chi_1^0 \rightarrow Z^{(*)} \tilde{\chi}_1^0 \tilde{\chi}_1^- \rightarrow (Z^{(*)} \gamma \tilde{G})(\gamma \tilde{G}) \rightarrow \text{Leptons or jets } + \gamma \gamma + E_T \]

Separate selections into high/low multiplicity parts (depending on W,Z final states)

Efficiencies depend on mass-difference of NLSP and produced particles

Limits in \([M(X), M(\tilde{\chi}_1^0)]\) plane: \(X = \tilde{\tau}^+, \tilde{\chi}_1^+, \tilde{\chi}_2^0\)
Other Channels: Neutralino NLSP

~ model independent cross-section limits at $\sqrt{s} = 189 \text{GeV}$

$\sigma(e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^-)$
$\tilde{\mu}^\pm \rightarrow \mu^\pm \tilde{\chi}_1^0 \rightarrow \mu^\pm \gamma \tilde{G}$

Efficiency ~ 30-50%

$\mu^+\mu^-\gamma\gamma + E_T$

(a) OPAL

$34 - 45 \text{ fb}$

$\sigma(e^+e^- \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1)$
$\tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0 \rightarrow W^{(*)}\gamma \tilde{G}$

Efficiency ~ 20-50%

$W^{(*)}W^{(*)}\gamma\gamma + E_T$

(b) OPAL

$40 - 360 \text{ fb}$

$\sigma(e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^-)$
$\tilde{\tau}^\pm \rightarrow \tau^\pm \tilde{\chi}_1^0 \rightarrow \tau^\pm \gamma \tilde{G}$

Efficiency ~ 20-40%

$\tau^+\tau^-\gamma\gamma + E_T$

(c) OPAL

$40 - 180 \text{ fb}$

$\sigma(e^+e^- \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_1)$
$\tilde{\chi}_2^0 \rightarrow Z^{(*)}\tilde{\chi}_1^0 \rightarrow Z^{(*)}\gamma \tilde{G}$

Efficiency ~ 20-50%

$Z^{(*)}\gamma\gamma + E_T$

(d) OPAL

$40 - 130 \text{ fb}$

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Other Channels: Neutralino NLSP (Update)

\[ \sim \text{model independent cross-section limits at } \sqrt{s} = 205.5 \text{ GeV} \]

For slepton co-NLSP scenario with large \( M(\tilde{\tau}) - M(\tilde{\chi}^0_1) \)
see 4 events where 1.3 +/- 0.3 are expected from SM

<table>
<thead>
<tr>
<th>( M(\tilde{\tau}) - M(\tilde{\chi}) )</th>
<th>N(data)</th>
<th>( N_{\text{SM}}(\text{MC}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 3 - 10 \text{ GeV} )</td>
<td>1</td>
<td>0.5 +/- 0.2</td>
</tr>
<tr>
<td>( 10 \text{ GeV} - M(\tilde{\tau}) / 2 )</td>
<td>2</td>
<td>0.7 +/- 0.2</td>
</tr>
<tr>
<td>( M(\tilde{\tau}) / 2 - M(\tilde{\tau}) )</td>
<td>4</td>
<td>1.3 +/- 0.3</td>
</tr>
</tbody>
</table>
**$1^+1^-\gamma\gamma$ Events**

2/4 events have a single high-energy photon consistent with radiative return to the $Z^0$

Other 2 each have 2 high energy photons

(55 GeV, 22 GeV) (42 GeV, 40 GeV)

Background in this kinematic regime is essentially $e^+e^- \rightarrow \tau^+\tau^-\gamma\gamma$

Prob of two events with 2 photons $> 20$ GeV estimated from $e^+e^- \rightarrow \tau^+\tau^-\gamma\gamma$ Monte Carlo (assuming only SM background)

Prob $\sim 3 \times 10^{-4}$
Slepton NLSP Pair Production

Acoplanar leptons

\[ e^+ e^- \rightarrow \tilde{\nu}^+ \tilde{\nu}^- \rightarrow (\tilde{\nu}^+ \tilde{\nu})(\tilde{\nu}^- \tilde{\nu}) \rightarrow \ell^+ \ell^- + E_T \]

Large irreducible SM background from W pair production

Published results at 183-189 GeV CERN EP/99-122

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>selectrons</th>
<th>smuons</th>
<th>staus</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>81.4</td>
<td>81.9</td>
<td>38.2</td>
</tr>
<tr>
<td>65</td>
<td>85.8</td>
<td>76.0</td>
<td>24.9</td>
</tr>
<tr>
<td>85</td>
<td>64.0</td>
<td>71.1</td>
<td>51.2</td>
</tr>
<tr>
<td>94</td>
<td>34.5</td>
<td>38.8</td>
<td>56.0</td>
</tr>
</tbody>
</table>

\[ \sqrt{s} = 189 \text{ GeV} \]

\[ \int L = 181.0 \text{ pb}^{-1} \]

Good consistency with Standard Model
Limits from Acoplanar Leptons

Limits along $M_{\text{LSP}} = 0$ axis applicable to light gravitino scenario

$$\sqrt{s} = 183 - 189 \text{ GeV}$$

$$\int L = 237.4 \text{ pb}^{-1}$$

95% CL lower mass limits (for BR=1.0)

$$M(\tilde{\mu}_R) > 85.4 \text{ GeV}$$

$$M(\tilde{\tau}_R) > 81.1 \text{ GeV}$$

$$M(\tilde{\tau}_1) > 80.0 \text{ GeV}$$

for any degree of stau mixing
Slepton NLSP Pair Production @ 205.5 GeV

Preliminary results from OPAL 2000 data

<table>
<thead>
<tr>
<th>Mass</th>
<th>selectrons</th>
<th>smuons</th>
<th>staus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>$N_{SM}(MC)$</td>
<td>CL(%)</td>
</tr>
<tr>
<td>50 GeV</td>
<td>15</td>
<td>16.51 +/- 0.25</td>
<td>47.6</td>
</tr>
<tr>
<td>70 GeV</td>
<td>20</td>
<td>20.45 +/- 0.25</td>
<td>41.8</td>
</tr>
<tr>
<td>90 GeV</td>
<td>11</td>
<td>11.22 +/- 0.17</td>
<td>65.8</td>
</tr>
<tr>
<td>101 GeV</td>
<td>1</td>
<td>2.63 +/- 0.08</td>
<td>82.9</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 200 - 209$ GeV

$\int L = 83.1$ pb$^{-1}$

Good consistency with Standard Model
Other Channels: Slepton NLSP

Other production channels

Final states with 4 or 6 leptons + missing energy

Slepton co-NLSP

\[ \text{e}^+ \text{e}^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\tilde{l}^\pm l^\mp)(l'^\pm l'^\mp) \rightarrow l l l' l' \tilde{G}\tilde{G} \]

\[ l, l' \equiv e, \mu, \tau \]

\[ \text{Equal branching fractions assumed} \]

\[ \tilde{\chi}_1^0 \text{ is a Majorana fermion: can lead to same sign for two highest energy leptons (i.e. those from the slepton decays)} \]

Stau NLSP

\[ \text{e}^+ \text{e}^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\tilde{\tau}^\pm \tau^\mp)(\tilde{\tau}^\pm \tau^\mp) \rightarrow \tau\tau\tau\tau \tilde{G}\tilde{G} \]

\[ \tau\tau\tau\tau + E_T \]

\[ \text{e}^+ \text{e}^- \rightarrow \tilde{l}^+ \tilde{l}^- \rightarrow (l^+\tilde{\tau}\tau)(l^-\tilde{\tau}\tau) \rightarrow l^+ l^- \tau\tau\tau\tau \tilde{G}\tilde{G} \]

\[ l^+ l^- \tau\tau\tau\tau + E_T \]

\[ l \equiv e, \mu \]

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Other Channels: Slepton NLSP

~ model independent cross-section limits at $\sqrt{s} = 189\text{GeV}$

Assumes equal BRs to $e, \mu, \tau$

$\ell^+ \ell^- \ell^+ \ell^- + E_T$

$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$

$\tilde{\chi}_1^0 \rightarrow \tilde{\ell}_L \tilde{\ell}_L \rightarrow \ell \tilde{G}$

$\ell \ell \tau \tau \tau \tau + E_T$

$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$

$\tilde{\chi}_1^0 \rightarrow \tilde{\tau}^+ \tilde{\tau}^-, \tilde{\tau} \rightarrow \tau \tilde{G}$

$e e \tau \tau \tau \tau + E_T$

$\sigma(e^+e^- \rightarrow \tilde{e}^+ \tilde{e}^-)$

$\tilde{e} \rightarrow \tilde{\tau} \tau e, \tilde{\tau} \rightarrow \tau \tilde{G}$

$\mu \mu \tau \tau \tau \tau + E_T$

$\sigma(e^+e^- \rightarrow \tilde{\mu}^+ \tilde{\mu}^-)$

$\tilde{\mu} \rightarrow \tilde{\tau} \tau \mu, \tilde{\tau} \rightarrow \tau \tilde{G}$
Slepton NLSP Results at 200-209 GeV

Cross-section limits at $\sqrt{s} = 205.5\text{GeV}$

$\sigma(e^+e^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1)$
$\tilde{\chi}^0_1 \rightarrow \tilde{\tau}^+ \tilde{\tau}^-, \tilde{\tau} \rightarrow \tau \tilde{G}$
$\tau^+ \tau^- \tau^+ \tau^- + E_T$

$\sigma(e^+e^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1)$
$\tilde{\chi}^0_1 \rightarrow \tilde{\tau}^+ \tilde{\tau}^-, \tilde{\tau} \rightarrow \tau \tilde{G}$
$\tau^+ \tau^- \tau^+ \tau^- + E_T$

$\sigma(e^+e^- \rightarrow \tilde{\tau}^+ \tilde{\mu}^-)$
$\tilde{\mu} \rightarrow \tau \tau \mu, \tilde{\tau} \rightarrow \tau \tilde{G}$
$\mu \mu \tau \tau \tau + E_T$

<table>
<thead>
<tr>
<th>channel</th>
<th>data</th>
<th>SM background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow (l\bar{l}\tilde{G})(l\bar{l}^\prime \tilde{G})$</td>
<td>0</td>
<td>0.6 +/- 0.1</td>
</tr>
<tr>
<td>$\tilde{l}^+ \tilde{l}^- \rightarrow (l^+ \tau \tilde{G})(l^- \tau \tilde{G})$</td>
<td>6</td>
<td>2.1 +/- 0.2</td>
</tr>
</tbody>
</table>

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Prob $\sim 2\%$
GMSB Scan: Exclusion regions in \((\tan \beta, \Lambda)\) plane

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range for scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sqrt{F})</td>
<td>SUSY breaking scale</td>
<td>fixed (5 - 200 \text{ TeV})</td>
</tr>
<tr>
<td>(\Lambda)</td>
<td>sets mass scale for sparticles</td>
<td></td>
</tr>
<tr>
<td>(M)</td>
<td>mass scale of messengers</td>
<td>(1.01\Lambda - 10^6 \text{ TeV})</td>
</tr>
<tr>
<td>(N)</td>
<td>number of sets of messenger particles</td>
<td>1 - 4</td>
</tr>
<tr>
<td>(\tan \beta)</td>
<td>as usual</td>
<td>2 - 50</td>
</tr>
<tr>
<td>(\text{sgn}(\mu))</td>
<td>as usual</td>
<td>+1/−1</td>
</tr>
</tbody>
</table>

Exclusions for \(\mu > 0\) are somewhat stronger

\[\Lambda > 48 \text{ TeV}\]
\[\Lambda > 31 \text{ TeV}\]
\[\Lambda > 22 \text{ TeV}\]
\[\Lambda > 19 \text{ TeV}\]

\(M = 10^6 \text{ TeV}\)
\(M = 250 \text{ TeV}\)
\(M = 1.01\Lambda\)

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\[
\begin{align*}
M_{\tilde{\chi}_1^0} < 76 \text{ GeV} \\
M_{\tilde{\chi}_1^0} &< 88 \text{ GeV} \\
M_{\tilde{\chi}_1^0} &< 99 \text{ GeV}
\end{align*}
\]
\[\tan \beta = 20\]

Theoretically inaccessible

\[m(\tau_{\tilde{\chi}_1}) < 85 \text{ GeV}\]

\[m_{\text{NLSP}} < 70 \text{ GeV}\]

\[\tan \beta = 2\]

\[m(\chi_\mu) \approx 0\]

\[m(\chi_\tau) \approx 1\]

\[m(\gamma) \approx 2\]

\[m(\chi_\mu) \approx 0\]

\[m(\chi_\tau) \approx 1\]

\[m(\gamma) \approx 2\]

\[m(\chi_\mu) \approx 0\]

\[m(\chi_\tau) \approx 1\]

\[m(\gamma) \approx 2\]

OPAL Scan: Exclusion Regions in \((m_{\chi_0^1}, M_{\text{NLSP}})\) plane
Slepton NLSP with lifetime

- Decay length $\sim$ detector size: kinked charged tracks (analysis in progress)
- Decay length $>>$ detector size: long lived stable charged particles

\[ \sqrt{s} = 205.5 \text{ GeV} \]
\[ \int L = 87.9 \text{ pb}^{-1} \]

\[ M(\tilde{l}_R^+) > 96.0 \text{ GeV @ 95\% CL} \]
\[ M(\tilde{l}_L^+) > 96.5 \text{ GeV @ 95\% CL} \]

Results valid for lifetimes > 1 us
Neutralino NLSP with Lifetime

- Decay length $\sim$ detector size: non-pointing photons (in progress)
- Decay length $\gg$ detector size: conventional SUSY signatures

Can quantify sensitivity of $\gamma\gamma + E_T$ analysis to finite lifetime

Evaluate selection efficiency as function of lifetime for $\tau = 10^{-15} - 10^{-7} \text{ s} \quad (c\tau \sim 30 \text{ m})$
Gravitino Pair Production $e^+e^- \rightarrow \tilde{G}\tilde{G}\gamma$

Brignole, Feruglio and Zwirner: models with superlight gravitino

Single photon + $E_\gamma$ signature

$$\frac{d^2\sigma}{dx_\gamma d\cos \theta} = \left( \frac{\alpha G_N^2}{45} \right) \frac{s^3}{m_G^4} f_{GG\gamma}(x_\gamma, \cos \theta)$$

$$f_{GG\gamma}(x,y) = 2(1-x)^2 \left[ \frac{(1-x)(2-2x+x^2)}{x(1-y^2)} + \frac{x(-6+6x+x^2)}{16} - \frac{x^3(1-y^2)}{32} \right]$$

Soft photon spectrum:
Event counting in region $E_\gamma < 30$ GeV
195 events observed
$179.6 \pm 5.4$ expected $\nu\nu\gamma(\gamma)$ from KORALZ

$\sigma_{95} \rightarrow m_G > 8.7 \mu$eV @ 95%CL
Conclusions

• The end of LEP draws near: still no signs of SUSY
• Lots of work to still be done:
  – Update to highest energies and maximum luminosity
  – Results on intermediate / long lifetimes in progress

• Still some hope for discovery at LEP ?
  – Wait a few months ……..
  – Or wait a few years