GMSB searches at LEP

Outline

◆ GMSB phenomenology
◆ Searches and combined results for:
  ◆ neutralino NLSP
  ◆ slepton NLSP
◆ Interpretation
◆ Conclusions

http://www.pp.rhul.ac.uk/~garcia/pubs/lepgmsb02.ps.gz
The LEP Dataset

Integrated luminosities seen by experiments from 1989 to 2000

1000 pb-1 since 1989

Distribution of Delivered Integrated luminosity by Energy

total 02/11/00 = 233 pb-1

Thanks LEP!
Mediation of SUSY breaking

SUSY breaking can be communicated down to the visible sector via:

<table>
<thead>
<tr>
<th>Gravity</th>
<th>Gauge interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCNC?</td>
<td>no FCNC: low energy + flavour blind</td>
</tr>
<tr>
<td></td>
<td>$m_\tilde{G} \simeq 2.4 \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^2 \text{ eV}$</td>
</tr>
<tr>
<td></td>
<td>$m_\tilde{G} \sim \text{few TeV}$</td>
</tr>
<tr>
<td></td>
<td>$10^{-2} &lt; m_\tilde{G} &lt; 10^4 \text{ eV}$</td>
</tr>
</tbody>
</table>

$\tilde{\chi}_1^0$ LSP $\tilde{G}$ LSP

Gauge Mediated SUSY Breaking

Six parameters to define minimal GMSB models:

- $\sqrt{F}$: SUSY breaking scale in the messenger sector
- $N_5$: number of messenger pairs
- $M_{\text{mess}}$: messenger mass scale
- $\Lambda$: universal mass scale of SUSY particles
- $\tan \beta$: ratio of Higgs vacuum expectation values
- $\text{sign}(\mu)$: sign of Higgs sector mixing parameter
GMSB phenomenology

- $\tilde{G}$ is the LSP: $10^{-2} \text{ eV} \lesssim m_{\tilde{G}} \lesssim 3 \text{ keV}$

- $NLSP = \left\{ \begin{array}{c} \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \\ \tilde{\ell} \rightarrow \ell \tilde{G} \end{array} \right.$

- $\tilde{\tau}_R$ and $\tilde{\tau}_L$ mix $\Rightarrow \tilde{\tau}_1$ NLSP (large tan $\beta$)

- Decay length of the NLSP:
  \[ cT \approx \frac{0.01}{\kappa \gamma} \left( \frac{100 \text{ GeV}}{m_{NLSP}} \right)^5 \left( \frac{m_{\tilde{G}}}{2.4 \text{ eV}} \right)^2 \text{ cm} \]

  ($\kappa \gamma = 1$ for $\tilde{\ell}$ NLSP)

Signatures depend on the NLSP type and NLSP decay length

Many different topologies!
\( \tilde{\chi} \) NLSP

**Short \( \tilde{\chi} \) lifetime: \( c\tau < 1 \text{ cm} \)**

- Also \( e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\gamma} \rightarrow \gamma \tilde{G} \tilde{G} \) and \( e^+e^- \rightarrow \tilde{G}\tilde{G}\gamma_{ISR} \leftrightarrow M_{\tilde{G}} \sim 10^{-4} \text{ eV} \)
- Suffer irreducible bkg: \( e^+e^- \rightarrow \nu \bar{\nu}\gamma(\gamma) \)

**Medium \( \tilde{\chi} \) lifetime: \( c\tau \sim l_{\text{detector}} \)**

- Require impact parameter > 40 cm
- Impact parameter reconstructed from the EM shower axis
- Bkg: \( \nu \bar{\nu}\gamma(\gamma) + \text{cosmic rays} \rightarrow \text{bremsstrahlung from out-of-time muons} \)

\( \text{If} \ c\tau > l_{\text{detector}}: \text{Indirect limits from 'standard' } \tilde{l} \text{ and } \tilde{\chi}^\pm \text{ searches} \)
NLSP: No lifetime

Topology: two acoplanar photons pointing to the vertex and $E_T$
- Look for two high energy photons and $p_T$
- Use as discriminant: recoil mass against the photon system
- CDF event $2e+2\gamma+E_T$ ruled out

130 $\leq \sqrt{s} \leq$ 208 GeV
ALEPH DELPHI L3 OPAL

Data: 387
Bkg: 403.9

$\tilde{\chi}^0$ mass (GeV/c$^2$)

Observed
Expected

$\sigma$ LIMIT at $\sqrt{s} = 208$ GeV (pb)

50 60 70 80 90 100

100 200 300 400 500

Excluded at 95% C.L.

$e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow G\gamma\gamma$

$130 \leq \sqrt{s} \leq 209$ GeV
ALEPH DELPHI L3 OPAL

$\tilde{\chi}^0_1 > 97$ GeV/c$^2$ for $m_{\tilde{e}_R} = 2 \times m_{\tilde{\chi}^0_1}$
**NLSP: Medium lifetime**

Topology: **Non pointing photon(s)**

(unlikely that both $\chi$ decay inside the detector)

- Reconstruct impact parameter from EM shower axis ($d_0 > 40$ cm)
- Good agreement in total number of events:
  - **ALEPH (189-209 GeV):** 2 obs./1.0 exp.
  - **DELPHI(130-209 GeV):** 16 obs./14.6 exp.

**ALEPH**

$\sqrt{s} = 189-209$ GeV

$\sqrt{s} = 192-209$

$\chi_1^0$ mass limit (GeV/c$^2$)

Excluded at 95% C.L.
Short $\tilde{\ell}$ lifetime: $c\tau < 1$ cm ➞ 2 acoplanar $\ell + E_T$

- Major bkg.: WW production, $\gamma\gamma$ processes

Medium $\tilde{\ell}$ lifetime: $c\tau \sim \ell_{detector}$ ➞ kinks + large IP

- Look for large Impact Parameter tracks ($1 \lesssim L \lesssim 40$ cm) and kinked tracks ($10 \lesssim L \lesssim 200$ cm)
- Major bkg.: cosmic rays, $\gamma\gamma$ and decays of $K^0_s$ (large IP) and $K^\pm$ (kinks)

Long $\tilde{\ell}$ lifetime: $c\tau > \ell_{detector}$ ➞ Heavy Stable Ch. part.

- Two back to back particles: highly ionising tracks
NLSP: Prompt decay

Topology: $e^+ e^- \rightarrow \tilde{\ell}^+_R \tilde{\ell}^-_R \rightarrow \ell^+ \ell^- \tilde{G} \tilde{G}$ (acoplanar leptons)

- Identical to $\tilde{\ell}^+_R \tilde{\ell}^-_R \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ with $m_{\tilde{\chi}_1^0} \sim 0$ in SUGRA
- Search for two identified leptons and $\tilde{\ell}$
- No excess seen \(\implies\) set limits:

<table>
<thead>
<tr>
<th>ADLO lower limits @ $m_{\tilde{\chi}} = 0$</th>
<th>$m_{\tilde{e}}$</th>
<th>$m_{\tilde{\mu}}$</th>
<th>$m_{\tilde{\tau}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>obs</td>
<td>99.6</td>
<td>94.9</td>
<td>85.9</td>
</tr>
<tr>
<td>exp</td>
<td>99.2</td>
<td>91.4</td>
<td>85.8</td>
</tr>
</tbody>
</table>

\[ \sqrt{s} = 183-208 \text{ GeV} \]

Excluded at 95\% CL

($\mu = 200 \text{ GeV}/c^2$, $\tan\beta = 1.5$)
\[ \tilde{\ell} \text{ NLSP: Medium lifetime} \]

- Slepton decays before reaching tracking devices \(\rightarrow\) \text{large IP}
  - \(\star\) Require at least one (non-tau) track with \(|d_0| > 1\) cm
- Slepton decays in the tracking chamber \(\rightarrow\) \text{kinked track}
  - \(\star\) Use kink angle and energy veto to discern from hard bremsstrahlung and hadronic interactions: \(\pi^\pm \rightarrow \mu^\pm \nu\), \(K^\pm \rightarrow \mu^\pm \nu\) or \(\pi^\pm \pi^0\)

\[ \text{Large IP, TPC kink, ITC kink} \]

\[ \text{189 GeV, OPAL Preliminary} \]

\[ \text{ALEPH} \quad \text{DELPHI} \quad \text{OPAL} \]
\[ \begin{align*}
\text{1 obs./1.1 exp.} \quad & \quad \text{9 obs./7.4 exp.} \quad & \quad \text{1 obs./1.1 exp.}(\tilde{e}, \tilde{\mu}) \\
\text{7 obs./4.4 exp.}(\tilde{\tau})
\end{align*} \]
\[ \tilde{\ell} \text{ NLSP: Long lifetime} \]

Topology: Heavy Stable Charged particles
- Look for two back-to-back tracks
- with anomalous high or low \( dE/dx \)
- High efficiency (\( \sim 90\% \))
  & very low SM bkg

\( \sqrt{s} = 189 - 209 \text{ GeV} \)

**ALEPH:** 1 obs./2.3 exp.

**DELPHI:** 1 obs./2.7 exp.

**OPAL:** 1 obs./0.6 exp.

\[ m_{\tilde{\mu}} = 70 \text{ GeV}, \quad Q/e = \pm 1 \]

\[ m_{\tilde{\mu}} = 45 \text{ GeV}, \quad Q/e = \pm 1 \]

\[ E_{cm} = 189 \text{ GeV}, \quad E_{cm} = 183 \text{ GeV}, \quad E_{cm} = 172 \text{ GeV}, \quad E_{cm} = 161 \text{ GeV} \]

\[ \bar{\mu}_L: \sigma_{\text{exp.}} \text{ at } \sqrt{s}=208 \text{ GeV} \]

\[ \bar{\mu}_R: \sigma_{\text{exp.}} \text{ at } \sqrt{s}=208 \text{ GeV} \]

excluded at 95\% CL for stable particles
Slepton mass combined limits

ADO Preliminary

\[ m(\tilde{e} \sim) > 65.8 \text{ GeV/c}^2 \]

ADO Preliminary

\[ m(\tilde{\mu} \sim) > 96.3 \text{ GeV/c}^2 \]

ADLO Preliminary

\[ m(\tilde{\tau} \sim) > 86.9 \text{ GeV/c}^2 \]

(limits at 95% CL, valid for all lifetimes and \( N_5 \leq 5 \) )
Study $e^+e^- \rightarrow \chi\chi$ with $\chi \rightarrow \ell\tilde{\chi}$ to benefit from larger ($\times 2$) cross section

Topology: Final state with 4 lepton/tau + $E_T$

- Search for two energetic and two soft $\ell$
  - also new searches with lifetime: kinks or large IP
- $\chi$'s decay independently → six selections: $\tilde{e}\tilde{e}$, $\tilde{\mu}\tilde{\mu}$, $\tilde{\tau}\tilde{\tau}$, $\tilde{e}\tilde{\mu}$, $\tilde{e}\tilde{\tau}$, $\tilde{\mu}\tilde{\tau}$
  - Strong dependence on $\Delta M = m_\chi - m_\tilde{\ell}$
- No excess $\Rightarrow$ 95% C.L. limits on production cross section:

**OPAL Preliminary $\sqrt{s} = 189 - 209$ GeV**

<table>
<thead>
<tr>
<th>$m_\tilde{\tau}$ (GeV/c$^2$)</th>
<th>$\sigma_{95}$ for Pair-Produced $\tilde{\chi}_0$ ($\tilde{\chi}<em>0 \rightarrow \tilde{\tau}\tilde{\tau}$) for all $cT</em>\tilde{\tau} \leq 3$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>60</td>
<td>0.09</td>
</tr>
<tr>
<td>70</td>
<td>0.08</td>
</tr>
<tr>
<td>80</td>
<td>0.07</td>
</tr>
<tr>
<td>90</td>
<td>0.06</td>
</tr>
<tr>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>110</td>
<td>0.04</td>
</tr>
<tr>
<td>120</td>
<td>0.03</td>
</tr>
<tr>
<td>130</td>
<td>0.02</td>
</tr>
<tr>
<td>140</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**4$\ell + E_T$:**

<table>
<thead>
<tr>
<th></th>
<th>$\tilde{\tau}\tilde{\tau}$ selection, $\sqrt{s}=189-209$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>22 obs./16.5 exp.</td>
</tr>
<tr>
<td>D</td>
<td>15 obs./11.6 exp.</td>
</tr>
<tr>
<td>O</td>
<td>5 obs./5.0 exp.</td>
</tr>
</tbody>
</table>

**large $d_0$ and kinks:**

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<tbody>
<tr>
<td>A</td>
<td>5 obs./5.3 exp.</td>
</tr>
<tr>
<td>O</td>
<td>0.5 obs./5.4 exp.</td>
</tr>
</tbody>
</table>
Other possibilities (DO)

Charginos with $\tilde{\ell}$ NLSP: $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-\nu\bar{\nu} \rightarrow \ell^+\ell^-\tilde{G}\tilde{G}\nu\bar{\nu}$

- Look for $2 \ell + \not{E}$ like in SUGRA. Different kinematics in lifetime case
- $m_{\tilde{\chi}_1^\pm} > 95.2$ GeV/$c^2$ at 95% C.L. for $\Delta M \geq 0.3$ GeV/$c^2$

Sgoldstinos: $e^+e^- \rightarrow S\gamma \rightarrow \gamma\gamma\gamma$

- For ultralight $\tilde{G}$ ($\Leftrightarrow \sqrt{F}$ very small) $\rightarrow \tilde{G}$ is mainly goldstino
- Search for its heavy SUSY partner: Sgoldstino $S$ (+ monochr. $\gamma$)
- Not seen $\Rightarrow$ exclude $\sqrt{F} - m_S$ plane for different gaugino mass values

DELPHI $\sqrt{s}=189-202$
DELPHI $\sqrt{s}=189-208$
Perform scan over parameter space, eg:

Combine:

- all topologies and all lifetimes
- LEP1 exclusion
- MSSM $\tilde{l}$ & $\tilde{\chi}^\pm$ limits
- Higgs limits from $(m_h, \sin^2(\beta - \alpha))$

Absolute (indirect) lower mass limit on the NLSP:

$$M_{NLSP} > 54 \text{ GeV}/c^2$$

(independent of lifetime)
GMSB Interpretation

Gaugino and sfermion masses depend on $\Lambda$ and $N_5$

\[
M_\lambda \propto N_5 \Lambda \\
M_J^2 \propto N_5 \Lambda^2
\]

$\Lambda$ controls the mass scale of SUSY particles

Set an absolute limit on $\Lambda$:

$\boldsymbol{\Lambda > 10 \, (16) \, \text{TeV/c}^2}$

Since $\Lambda \lesssim \sqrt{F}$ and $m_{\tilde{G}} = \frac{F}{\sqrt{3}M_{\text{Planck}}}$

$\downarrow$

$m_{\tilde{G}} > 0.024 \, (0.061) \, \text{eV/c}^2$
Conclusions

➤ No hint for alternative SUSY at LEP

➤ Many different topologies have been studied up to the highest energies in GMSB scenarios

➤ Now covering all lifetimes and most of the parameter space

➤ (almost) Independent limits on the NLSP mass and the gravitino mass are set

➤ Still working on final results and combinations

➤ The quest is now open to Tevatron and LHC: good hunt!

Visit: http://lepsusy.web.cern.ch/lepsusy for updates
Extra1: Stau limit with searches

\[ m(\tilde{\tau}) \text{ (GeV/c}^2\text{)} \]

\[ \tau \sim (\tilde{\tau} \text{ NLSP}) \]

ADLO Preliminary

\[ \sqrt{s} = 189-209 \text{ GeV} \]

\[ \log(\tau) \]

-12 -11 -10 -9 -8 -7 -6
Extra2: Tevatron reach and LEP impact

Scan in GMSB parameter space following

Example: N=2, medium M, \( \mu > 0 \), short lifetime

Preliminary excluded (sleptons)

not excluded (photons)

theoretically not accessible

\( n \) = 2, \( \frac{M}{\Lambda} = 3 \), \( tan\beta = 15 \), \( \mu > 0 \)

J. Quian, hep-ph/9903548 v2:

\[ N = 2, \quad \frac{M}{\Lambda} = 3, \quad tan\beta = 15, \quad \mu > 0 \]

\( \Lambda > 35.5 \text{ TeV/c}^2 \)

5\sigma discovery reach vs 95\%CL exclusion