Search for
SUSY and Extra Dimensions at LEP

Katja Klein (OPAL)
1. Physikalisches Institut B, RWTH Aachen

On behalf of the LEP collaborations

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Four abstracts submitted:

**Supersymmetry**


**Extra dimensions**

- Search for one large extra dimension with the DELPHI detector at LEP2 (DELPHI; 2006-002 CONF 748, June 22nd, 2006)

All limits are at 95% C.L.!
GMSB: Motivation

- No SUSY particles discovered yet → Supersymmetry (SUSY) is a broken symmetry
- Two most popular mechanisms for spontaneous SUSY breaking:
  - Gravity Mediated (SUGRA) and Gauge Mediated SUSY Breaking (GMSB)

**SUGRA**

\[ M \sim M_p \]

Hidden sector; breaks SUSY

gravitational interaction

SUSY breaking scale \( \sqrt{F} \sim 10^{11}\) GeV

**GMSB**

\[ M \sim M_p \]

gravitational interaction

100 TeV < \( \sqrt{F} \) < 2000 TeV

gauge interactions

**Messenger sector**

Mass scale \( M \)

**Visible sector:**

SM and SUSY particles

Mass scale \( \Lambda \)

\[ M_\tilde{G} \sim F / M_p \Rightarrow \tilde{G} \text{ heavy} \]

\[ \tilde{G} \text{ light} \]
6 parameters in minimal GMSB model:

- \( M \) messenger mass scale
- \( N \) number of generations of messenger particles
- \( \sqrt{F} \) SUSY breaking scale
- \( \Lambda \) SUSY particles mass scale
- \( \tan \beta \) ratio of VEVs of Higgs doublets
- \( \text{sign} \mu \) sign of Higgs sector mixing parameter

\( M_\tilde{G} \sim \text{eV} - \text{GeV} \Rightarrow \text{gravitino is the Lightest SUSY Particle (LSP)} \)

Three possibilities for the Next-to LSP (NLSP) and its decay:

- stau NLSP scenario: \( \tilde{\tau}_1 \rightarrow \tau \tilde{G} \)
- slepton co-NLSP scenario: \( \tilde{l} \rightarrow l \tilde{G} ; \tilde{l} = \tilde{\epsilon}_R, \tilde{\mu}_R, \tilde{\tau}_1 \)
- neutralino NLSP scenario: \( \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \)

NLSP lifetime is arbitrary:

\[
L_{NLSP} \sim \left( \frac{100 \text{GeV}}{m_{NLSP}} \right)^5 \left( \frac{\sqrt{F}/k}{100 \text{TeV}} \right)^4 \sqrt{\frac{E_{NLSP}^2}{m_{NLSP}^2}} - 1 \times 10^{-2} \text{ cm}
\]

(k = model dep. parameter of SUSY breaking)
**GMSB (OPAL): Slepton NLSP Topologies**

**Topology in detector depends on slepton lifetime:**
- prompt decay: 2, 4 or 6 leptons + $\not{E}$
- decay in detector: tracks with large impact parameters or kinks + $\not{E}$ (+ 2 or 4 leptons)
- decay outside detector: tracks with anomalous dE/dx + $\not{E}$ (+ 2 or 4 leptons)
• **Zero lifetime (l.t.): acoplanar leptons**
  - Irreducible BG from WW production

• **Short l.t.: tracks with large impact parameters**

• **Medium l.t.: tracks with kinks**
  - refit of kink vertex

**BG for short & medium l.t.:**
  - cosmics and beam gas/wall events
  - two-photon ($\sigma = O(10\text{nb})$)

• **Long l.t.: tracks with anomalous dE/dx**
  - basically BG free topology
• No significant excesses observed $\rightarrow$ limits on production cross sections, sparticle masses and model parameters

• Theoretical framework based on Dimopoulos, Thomas, Wells; Nucl. Phys. B488 (1997) 39

• $m_G = 2 \text{ eV} \leftrightarrow \text{BR}(\text{NNLSP} \rightarrow \tilde{G} X) \approx 0$

• $\sqrt{F}$ is eliminated by lifetime independence of experimental cross section limits

• Parameter scan:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scan points</th>
<th>Step size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>5 – 150 TeV</td>
<td>1 TeV</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>1 – 50</td>
<td>0.2</td>
</tr>
<tr>
<td>$M$</td>
<td>1.01 $\cdot \Lambda$, 250 TeV, $10^6$ TeV</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>1, 2, 3, 4, 5</td>
<td></td>
</tr>
<tr>
<td>sign($\mu$)</td>
<td>+1, -1</td>
<td></td>
</tr>
</tbody>
</table>

• Minimal expected $\sigma \cdot \text{BR}^2$ calculated for each slepton and neutralino mass: $(\sigma \cdot \text{BR}^2)_{\text{min}}$
• SUSY MC produced with SUSYGEN or DFGT in mass-lifetime grid

• Combination of analyses for different lifetimes taking overlaps into account

• $\sqrt{s} = 189 - 209$ GeV, $\int L \approx 600$ pb$^{-1}$ Combination of $\sqrt{s}$ bins with $(\sigma \cdot BR^2)_{\text{min}}$

• Statistical treatment according to Junk; Nucl. Instrum. Meth. A434 (1999) 435

• Statistical and systematic errors included

• Similar limits $O(0.1\text{pb})$ in slepton co-NLSP scenario
Comparison of $\sigma_{95}$ with $(\sigma \cdot BR^2)_{\text{min}}$ ⇒ slepton mass limits

- $m_{\tilde{\tau}_1} > 87.4 (88.2) \text{ GeV}$
- $m_{\tilde{\mu}_R} > 93.7 (93.6) \text{ GeV}$

Slepton co-NLSP scenario: sleptons degenerate within $\tau$ mass ⇒

$m_{\tilde{\mu} - \tau} \rightarrow m_{\tilde{l}} > 91.9 \text{ GeV}$
GMSB (OPAL): Neutralino NLSP Topologies

**Topology in detector depends on neutralino lifetime:**
- prompt decay: photons + $E_T$ (+ leptons/jets)
- decay in detector: non-pointing photons + $E_T$ (+ leptons/jets)
- decay outside detector: $E_T$ (+ leptons/jets)
Chargino & slepton pair-production:

- Short lifetime:

- **Long lifetime:** photons not visible, higher $E_T$

- Combination of $\sqrt{s}$ bins:
  - Chargino pair-production: $\sigma \sim \beta/s$
  - Slepton pair-production: $\sigma \sim \beta^3/s$

- Minimization in neutralino lifetime
  ⇒ *lifetime-independent cross section limits*
GMSB (OPAL): Interpretation

Lifetime-independent exclusions in GMSB parameter space:

- LEPI search region
- not allowed by theory
- $\tilde{\tau}_1, \tilde{\mu}_R, \tilde{e}_R$ (neutralino NLSP)
- $\tilde{\chi}_1^0$ (neutralino NLSP)
- $\tilde{\tau}_1, \tilde{\mu}_R, \tilde{e}_R$ (neutralino NLSP)
- $\tilde{\chi}_1^0$ (neutralino NLSP)
- $\tilde{\tau}_1, \tilde{\mu}_R, \tilde{e}_R$ (neutralino NLSP)

Lifetime-independent limits on $\Lambda$:

$\Lambda > 40, 27, 21, 17, 15$ TeV
for $N = 1, 2, 3, 4, 5$
($N =$ number of messenger generations)

Sign($\mu$) > 0

$N = 3, M = 250$ TeV/$c^2$

$m_h > 114.4 \pm 3$ (theo) $\pm 5$ ($m_t$) GeV
Hierarchy between electroweak scale $M_{EW}$ and Planck scale $M_p$ explained by two popular models: the **ADD model** (Arkani-Hamed, Dimopoulos, Dvali) and the **Randall Sundrum model**

### ADD model

- **n large** compact extra spatial dimensions
- we live in 4 dimensions ("on the brane"), gravity can propagate in the 4+n dim. bulk
- gravitational mass scale $M_D$ in $D = 4+n$ dimensions is of the order of the weak scale
- effective $M_p$ in 4 dim. is large only due to the hidden volume $R^n$ of the extra dimensions:
  \[ M_p^2 \approx M_D^{2+n} R^n \]
- for $n=1$, $R \sim 10^{13}\text{cm} \approx$ distance between earth and sun $\Rightarrow$ astronomically excluded
- for $n=2$, $R \sim 100\mu\text{m} \Rightarrow$ not excluded yet

### Phenomenological consequence of EDs:

- massive excitation states of the graviton: "**Kaluza Klein** (KK) tower"
- in ADD framework: large multiplicity of states, gravitiational interaction with SM particles, invisible
• Single Graviton production at LEP:

\[ \frac{d^2 \sigma}{dx_y d \cos \theta_y} = \frac{\alpha}{32 s} \frac{\pi^{n/2}}{\Gamma(n/2)} \left( \frac{\sqrt{s}}{M_D} \right)^{n+2} f(x_y, \cos \theta_y) \]

\[ \theta = \text{polar angle}, \quad x_y = \frac{E_y}{E_{\text{beam}}}, \quad \alpha = \text{fine-structure constant} \]

(Guidice, Rattazzi, Wells; Nucl. Phys. B544 (1999) 3)

• Background from \( e^+ e^- \to \nu \bar{\nu} \gamma(y) \) and \( e^+ e^- \to e^+ e^- \gamma(y) \)
• Photon candidates must have $E_\gamma > 1\text{GeV}$

• Two event topologies are studied:

  • **High energy single-photons**: $p_T > 0.02 \sqrt{s}$
    - purity for $e^+ e^- \to \nu \bar{\nu} \gamma(\gamma) = 99.1\%$
    $\Rightarrow N_{\text{obs}} / N_{\text{exp}} = 1898 / 1905.1$

  • **Low energy single-photons**: $0.008 \sqrt{s} < p_T < 0.02 \sqrt{s}$
    - one photon candidate in the barrel (single-$\gamma$ trigger)
    $\Rightarrow N_{\text{obs}} / N_{\text{exp}} = 566 / 577.8$

• Theoretical differential cross section
  $\Rightarrow$ number of exp. signal events as function of $(1/M_D)^{n+2}$
  $\Rightarrow$ **limits on** $M_D$ from fit to $x_\gamma$ vs. $\cos \theta_\gamma$ distribution

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• LEP combination including ADL: LEP Exotica WG 2004-03
• For each $n$, the log likelihood functions are added and limits calculated using Bayesian likelihood method
Search for one large ED (Delphi)

- ADD limits from single-photon signature for \( n > 1 \) only
- But \( n = 1 \) allowed for a slightly warped geometry: based on RS1 type model, but no light KK modes (Guidice, Plehn, Strumia; Nucl. Phys. B706 (2005) 455)
- Photon energy spectrum depends strongly on \( n \rightarrow \) new analysis necessary

\[
\sigma\cdot d\sigma/\left( e^+ e^- \right) \rightarrow \gamma G/\gamma \gamma,
\]

\[
\begin{align*}
\delta = 1 & \quad \text{\( \delta = 6 \)} \\
\delta = 2 & \quad \text{\( \delta = 3 \)} \\
\end{align*}
\]

\[
\begin{align*}
\gamma & \quad = 1.25 \text{ TeV} \\
\gamma & \quad = 1 \text{ TeV}
\end{align*}
\]

- Expected number of single-photon events in DELPHI electromagn. calorimeter
- Corrected for cal. efficiency & resolution
• Pre-selection of single-photon events using tracker and ECAL
\((\sqrt{s}=183\text{-}209\ \text{GeV}, \int L=650\ \text{pb}^{-1})\)
- High density Projection Chamber (HPC)
  - \(x_\gamma > 0.06\)
- Forward ElectroMagnetic Cal. (FEMC)
  - \(x_\gamma > 0.10\)
- Small angle Tile Calorimeter (STIC)
  (BG dominated \(\rightarrow\) not used for final analysis)

• Final event selection with likelihood-ratio based on \(E_\gamma\)

\[
\begin{array}{|c|c|c|}
\hline
& N_{\text{obs}} & N_{e^+e^- \rightarrow \nu\bar{\nu}(\gamma)} & N_{\text{other SM BG}} \\
\hline
\text{FEMC} & 705 & 623 \pm 3 & 49.1 \\
\text{HPC} & 498 & 540 \pm 4 & 0.6 \\
\hline
\end{array}
\]

\[\Rightarrow M_D \geq 1.69 \ (1.71) \quad \text{TeV} \pm 3\% \text{ for } n = 1\]
Search for Branons (L3)

- ADD type geometries: brane oscillations corresponding to a brane tension $\tau = f^4$
  $\Rightarrow$ New scalar fields = Goldstone bosons corresponding to the SSB of the translational invariance produced by presence of the brane: "branons" $\tilde{\pi}$

- Translational invariance is not exact $\rightarrow$ branons are massive

- For tension scale $f \ll M_D$, Gravitons decouple from SM particles
  (e.g. Cembranos, Dobado, Maroto, Phys. Rev. Lett. 90 (2003) 241301)
Search for Branons (L3)

- $\gamma + \not{E}$ and $Z \rightarrow q \bar{q} + \not{E}$ covered, but low sensitivity in $Z$ channel due to phase space
- Two different analysis for $\gamma + \not{E}$, depending on $p_T$:

**High $p_T$:**
- $0.04 \ E_{\text{beam}} < p_T < 0.6 \ E_{\text{beam}}$
- purity for $e^+ e^- \rightarrow \nu \bar{\nu} \gamma (\gamma) = 99\%$

$\Rightarrow N_{\text{obs}} / N_{\text{exp}} = 838 / 811.2$
(N$_s = 351.4$ for $M = 0$ and $f = 150 \text{GeV}$)

**Low $p_T$:**
- $0.016 \ E_{\text{beam}} < p_T < 0.04 \ E_{\text{beam}}$
- barrel only (photon trigger!)
- BG mainly from $e^+ e^- \rightarrow e^+ e^- \gamma (\gamma)$

$\Rightarrow N_{\text{obs}} / N_{\text{exp}} = 543 / 554$
(N$_s = 95.3$ for $M = 0$, $f = 150 \text{GeV}$)

$\sqrt{s} = 189-209 \text{ GeV}, \int L \approx 630 \text{ pb}^{-1}$
Search for Branons (L3)

- One light branon with mass $M$ assumed
- Efficiency for branons from SM MCs for $e^+ e^- \rightarrow \nu \bar{\nu} Z \rightarrow \nu \bar{\nu} q \bar{q}$ and $e^+ e^- \rightarrow \nu \bar{\nu} \gamma (\gamma)$, reweighted with diff. cross section from Alcaraz et al. (Phys. Rev. D67 (2003) 075010)
- Bin-wise comparison of observed and expected number of events for $x$ vs. $\cos \theta$ distribution, assuming Poisson probability distribution
Summary

- No evidence for new physics observed in searches for GMSB signatures and extra dimensions
  ⇒ Limits on slepton and neutralino masses as well as on the SUSY mass scale $\Lambda$ within the GMSB scenario:

$$\Lambda > 40, 27, 21, 17, 15 \text{ TeV for } N = 1, 2, 3, 4, 5$$

⇒ Limits on gravitational mass scale $M_D$ in extra dimensions:

$$M_D > 1.69, 1.60, 0.66 \text{ TeV for } n = 1, 2, 6$$

- LHC startup very soon – discoveries might be just around the corner!