Searching for Standard SUSY at LEP2

R.A. McPherson
Department of Physics and Astronomy,
University of Victoria,
PO BOX 3055 MS7700,
Victoria, BC, Canada V8W 3P6

The status of the search for supersymmetry at LEP with a neutralino lightest supersymmetric particle and R-parity conservation is reviewed. The results presented are primarily based on the 1998 LEP run at centre-of-mass energies around 189 GeV. New results are presented in the searches for scalar leptons, scalar quarks, charginos and neutralinos. No evidence for their existence was found. Limits on production cross sections are presented, as well as limits on particle masses in the context of the constrained Minimal Supersymmetric Standard Model.
1 Introduction

The Large Electron Positron collider (LEP) at CERN has provided increasingly higher energies and luminosities since moving above the $Z^0$ pole in 1995. The LEP data sets acquired and expected are listed in Table 1. As the energies and luminosities increase, the four LEP collaborations (ALEPH, DELPHI, L3 and OPAL) have systematically searched for signs of new physics, including signatures of the the production of supersymmetric (SUSY) particles.

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Year</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP 1</td>
<td>$\approx 91$</td>
<td>1989-1995</td>
<td>175 pb$^{-1}$</td>
</tr>
<tr>
<td>LEP 1.5</td>
<td>130-140</td>
<td>1995</td>
<td>5 pb$^{-1}$</td>
</tr>
<tr>
<td>LEP 2</td>
<td>161</td>
<td>1996</td>
<td>10 pb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>172</td>
<td>1996</td>
<td>10 pb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>183</td>
<td>1997</td>
<td>55 pb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>189</td>
<td>1998</td>
<td>150-180 pb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>1999/2000</td>
<td>$\sim$ 300 pb$^{-1}$</td>
</tr>
</tbody>
</table>

Table 1: Luminosities from the LEP electron-positron collider.

SUSY is not a well-constrained theory; adding the minimal number of new particles and fields to the Standard Model (the Minimal Supersymmetric Standard Model, or MSSM) involves 105 additional parameters$^1$, and most of that parameter space is excluded by low energy experiments. Instead, restrictive models which are phenomenologically viable are constructed and used as benchmarks for searches. One such model is minimal supergravity, or mSUGRA, which contains only 4 parameters beyond the Standard Model. In fact, mSUGRA has restrictions which are not required by low energy phenomenology, such as requiring a common mass among the scalar fermions and higgs particles at the GUT scale. The LEP experiments use a somewhat less restrictive model, the “SUGRA-inspired” constrained MSSM, or CMSSM, using the parameters listed in Table 2, for interpreting their results. This review will only consider R-Parity conserving modes, implying that SUSY particles are produced in pairs and the lightest SUSY particle, the LSP, is neutral, weakly interacting, and stable. We will concentrate on models with a lightest neutralino LSP, the $\chi^0_1$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_2$</td>
<td>EW-scale $SU(2)$ Gaugino Mass (GUT Unification gives $M_1, M_3$)</td>
</tr>
<tr>
<td>$m_0$</td>
<td>Common GUT-scale scalar mass (EW-scale masses from RGE's)</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>$v_2/v_1$, Ratio of vev's of two higgs doublets</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Higgs mixing parameter</td>
</tr>
<tr>
<td>$m_A$</td>
<td>Pseudo scalar higgs mass</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Common trilinear coupling</td>
</tr>
</tbody>
</table>

Table 2: Parameters of the constrained MSSM.

Even within the CMSSM, the experimental channel that will show the first signs of SUSY depends on what point in the parameter space nature has actually chosen. The “discovery channels” are listed for different extremes in the parameters in Table 3. The topologies all share the classic SUSY “missing energy” signature, since the observation is of the production of a particle which decays into the invisible $\chi^0_1$ which carries away energy and momentum. The analyses select events with significant missing energy, and then classify them according to the
number of hadronic jets, identified leptons or photons, and event visible energy. If the mass difference between the produced SUSY particle and the $\Delta M$, is large, the SUSY events will have large visible energy, but there are large backgrounds from the Standard Model processes $e^+e^- \rightarrow W^+W^-$ and $e^+e^- \rightarrow ZZ$. If $\Delta M$ is small, the dominant background is from "gamma-gamma" collision events, $e^+e^- \rightarrow e^+e^-\gamma\gamma' \rightarrow e^+e^-\nu\bar{\nu}$, where $f$ is a lepton or quark. In the intermediate $\Delta M$ region, backgrounds are lower and signal detection is more straightforward. The experiments optimize different selections in these different visible energy, or $\Delta M$, regions.

### Table 3: SUSY search channels

<table>
<thead>
<tr>
<th>Parameter Region</th>
<th>Discovery Channel</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu &lt; M_2$ (Higgsino Region)</td>
<td>$\tilde{\mu}$ coupling</td>
<td>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</td>
</tr>
<tr>
<td>$\mu &gt; M_2$ (Gaugino Region)</td>
<td>Large $m_0$</td>
<td>$\tilde{\chi}_1^+$, $\tilde{\chi}_2^+$</td>
</tr>
<tr>
<td></td>
<td>Small $m_0$</td>
<td>$\tilde{\ell}^+$, $\tilde{\ell}^-$</td>
</tr>
</tbody>
</table>

Figure 1: Scalar electron candidate from the L3 experiment. It is also consistent with $W^+W^-$ production, with both decaying $W \rightarrow \ell\nu$.

2 Search Processes

2.1 Scalar Leptons

Scalar leptons, or sleptons ($\tilde{\ell}$), may be discovered in the pair production process $e^+e^- \rightarrow \ell^+\ell^- \rightarrow \tilde{\chi}_1^0\ell\tilde{\chi}_1^0$. The signature is a pair of leptons with significant missing energy. A candidate for scalar electron (selectron) pair production from L3 is shown in Figure 1. While consistent with selectron pair production, this event is also consistent with $e^+e^- \rightarrow W^+W^- \rightarrow e^+\mu\nu_e\nu_e$. There is no significant excess observed by any of the LEP experiments in the $\ell^+\ell^- + \not{E}_T$ searches, and using cross-sections expected in the CMSSM regions in the $m(\tilde{\chi}_1^0)$ vs. $m(\tilde{\ell})$ mass plane can be excluded as shown in Figure 2.

The situation for scalar tau leptons, $\tilde{\tau}$, is slightly more complicated, because the large $\tau$-lepton mass may allow the $\tilde{\tau}$ electro-weak eigenstates to have significant mixing, which may affect the production cross-section for $e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^-$. Limits from ALEPH for "no-mixing" and
Figure 2: Excluded regions at the 95% confidence level in neutralino vs. slepton mass, for scalar electrons (from DELPHI, valid for \( \mu = -100 \) GeV and \( \tan \beta = 1.5 \)) and scalar muons (from OPAL, with limits shown for different branching ratios, BR, of \( \tilde{\mu} \rightarrow \mu \tilde{\chi}_1^0 \)).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( m_{\tilde{e}_R} ) (GeV)</th>
<th>( m_{\tilde{\mu}_R} ) (GeV)</th>
<th>( m_{\tilde{\tau}_R} ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>( &gt; 88 ) GeV</td>
<td>( &gt; 80 ) GeV</td>
<td>( &gt; 67 ) GeV</td>
</tr>
<tr>
<td></td>
<td>( \Delta M &gt; 10 ) GeV, ( \tan \beta = 2 )</td>
<td>( \Delta M &gt; 10 ) GeV, ( \tan \beta = 2 )</td>
<td>( \Delta M &gt; 10 ) GeV, ( \tan \beta = 2 )</td>
</tr>
<tr>
<td>DELPHI</td>
<td>( &gt; 87 ) GeV</td>
<td>( &gt; 73 ) GeV</td>
<td>( &gt; 74 ) GeV</td>
</tr>
<tr>
<td></td>
<td>( \Delta M &gt; 10 ) GeV, ( \tan \beta = 1.5 )</td>
<td>( \Delta M &gt; 5 ) GeV, ( \tan \beta = 1.5 )</td>
<td>( \Delta M &gt; 10 ) GeV, ( \tan \beta = 1.5 )</td>
</tr>
<tr>
<td>L3</td>
<td>( &gt; 87 ) GeV</td>
<td>( &gt; 77 ) GeV</td>
<td>( &gt; 65 ) GeV</td>
</tr>
<tr>
<td></td>
<td>( \Delta M &gt; 10 ) GeV, ( \tan \beta = \sqrt{2} )</td>
<td>( \Delta M &gt; 5 ) GeV, ( \tan \beta = \sqrt{2} )</td>
<td>( \Delta M &gt; 10 ) GeV, ( \tan \beta = \sqrt{2} )</td>
</tr>
<tr>
<td>OPAL</td>
<td>( &gt; 77 ) GeV</td>
<td>( &gt; 78.4 ) GeV</td>
<td>( &gt; 69.4 ) GeV</td>
</tr>
<tr>
<td></td>
<td>( \Delta M &gt; 5 ) GeV, ( \tan \beta = 1.5 )</td>
<td>( \Delta M &gt; 2 ) GeV, ( \tan \beta = 1.5 )</td>
<td>( \Delta M &gt; 10 ) GeV, ( \tan \beta = 1.5 )</td>
</tr>
</tbody>
</table>

Table 4: 95% confidence level limits on scalar lepton masses from the 4 experiments.

also minimal production cross-section are shown in Figure 3. Finally, limits on the masses of all the sleptons from all four experiments are summarized in Table 4.

2.2 Scalar Quarks

The scalar stop or sbottom quarks may be light due to mixing effects induced by the heavy top and bottom quarks. They could be detected in processes such as \( e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 c\tilde{\chi}_1^0 \) (two-body decays) or \( e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow b\tilde{\tau}_L\tilde{\tau}_L \) (three-body decays). The signature is two jets, or two jets plus two leptons, and missing energy. No excesses are observed, and excluded regions in the \( m(\tilde{q}) \) vs. \( m(\tilde{\chi}_1^0) \) plane are shown in Figure 4. The results can also be interpreted in the \( m(\tilde{q}) \) vs. \( m(\tilde{g}) \) (where \( \tilde{g} \) is the gluino) plane, assuming degenerate squarks and using GUT unification to obtain the gluino mass from the neutralino mass. Limits from ALEPH for this are also shown in Figure 4. Limits on scalar top and bottom quarks for the different possible decay modes are summarized in Table 5.

2.3 Charginos and Neutralinos

The lightest chargino can be pair produced, \( e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \), via either s-channel \( Z/\gamma \) or t-channel \( \tilde{\nu}_e \) exchange, which destructively interfere, making the cross-section small if the \( \tilde{\nu}_e \) is light.
Figure 3. Excluded region at the 95% confidence level in the \( \tilde{\chi}_1^0 \) vs. \( \tilde{\tau} \) mass plane from the ALEPH experiment. The solid line assumes no mixing, while the dotted line is for the minimal \( \tau^+\tau^- \) production cross-section.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( t \to c\tilde{\chi}_1^0 )</th>
<th>( t \to b\ell\bar{\nu} )</th>
<th>( b \to b\tilde{\chi}_1^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>&gt;84 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
<td>&gt;86 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
<td>&gt;76 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
</tr>
<tr>
<td>DELPHI</td>
<td>&gt;79 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
<td>&gt;82 GeV ( \Delta M &gt; 15 \text{ GeV} )</td>
<td>&gt;62 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
</tr>
<tr>
<td>L3</td>
<td>&gt;78 GeV ( \Delta M &gt; 20 \text{ GeV} )</td>
<td>&gt;86 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
<td>&gt;57 GeV ( \Delta M &gt; 35 \text{ GeV} )</td>
</tr>
<tr>
<td>OPAL</td>
<td>&gt;87.2 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
<td>88.0 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
<td>65.8 GeV ( \Delta M &gt; 10 \text{ GeV} )</td>
</tr>
</tbody>
</table>

Table 5: 95% confidence level limits on the scalar quark masses from the 4 experiments. All limits assume minimal production cross-sections.

\( m_0 \) is small). Additionally, if \( m_0 \) is small, the \( \tilde{\chi}_1^\pm \) is phenomenology more complicated, since it can undergo two- and three-body leptonic decays, and can decay nearly invisibly. If \( m_0 \) is large, in most of the parameter space of the CMSSM, the lightest chargino is expected to decay with a branching ratio near 100% via \( \tilde{\chi}_1^\pm \to W^*\tilde{\chi}_1^0 \). None of the LEP experiments see any excess in the search for charginos; limits from the OPAL collaboration on the cross section for \( e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \) times the branching ratio squared for the decay \( \tilde{\chi}_1^\pm \to W^*\tilde{\chi}_1^0 \) are shown in Figure 5. In the large \( m_0 \) limit, the chargino pair production cross-section is always large, and stringent limits can be placed on its mass. Limits on \( m(\tilde{\chi}_1^\pm) \) from DELPHI for large \( m_0 \) limit are also plotted against the chargino-neutralino mass difference in Figure 5.

Neutralinos may be produced via the process \( e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \). In the CMSSM, this process is particularly important in the “higgsino” region (\( M_\Sigma >> \mu \)), where the \( \tilde{\chi}_2^0 \) has a mass only slightly larger than the \( \tilde{\chi}_1^0 \) and thus decays almost invisibly. Throughout much of the CMSSM parameter space, the dominant \( \tilde{\chi}_2^0 \) decay mode is \( \tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0 \). No excess is observed, and limits from DELPHI on the production cross-section for \( e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \) times the branching ratio for \( \tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0 \to q\bar{q}\tilde{\chi}_1^0 \) are shown in Figure 6.
Figure 4: Excluded regions in the $\tilde{\chi}_1^0$ vs. squark mass plane for stop quarks for two body stop decays (DELPHI), three body stop decays (L3), and sbottom (OPAL). The experiments all show the limits assuming no squark mixing, and for the minimal allowed production cross section. Also shown is the excluded region in the squark mass vs. gluino mass plane (ALEPH) assuming degenerate squarks and gaugino unification, superimposed on the limits from the Tevatron experiments.
Figure 5: Limits on the $\tilde{\chi}_1^\pm$ production cross-section at $\sqrt{s} = 189$ GeV from OPAL (assuming 100% BR for $\tilde{\chi}_1^0 \rightarrow W^\pm \tilde{\chi}_1^\pm$), and limits on the $\tilde{\chi}_1^0$ mass valid for large $m_0$ from DELPHI.

Table 6: 95% confidence level mass limits on the lightest neutralino in the constrained MSSM.

<table>
<thead>
<tr>
<th></th>
<th>LSP $\tilde{\chi}_1^0$ limit (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Large $m_0$</td>
</tr>
<tr>
<td>ALEPH</td>
<td>32.3</td>
</tr>
<tr>
<td>DELPHI</td>
<td>31.4</td>
</tr>
<tr>
<td>L3</td>
<td>32.7</td>
</tr>
<tr>
<td>OPAL</td>
<td>32.8</td>
</tr>
</tbody>
</table>

Constraining the mass of the lightest neutralino in the CMSSM requires the inclusion of the slepton, chargino and neutralino search results. For much of the parameter space, the constraints from $e^+e^- \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ dominates. In the higgsino region, the chargino decays are difficult to observe, and the process $e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0$ becomes important. Finally, if $m_0$ is small, the cross-section for $e^+e^- \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ can be small and the chargino decays may be difficult to observe; in that region, the slepton searches are the critical inputs. The limit on the lightest neutralino mass from L3, using all of these inputs, is plotted against $\tan \beta$ in Figure 6. Limits from all the LEP experiments are summarized in Table 6.

3 Conclusions

Searches for supersymmetry have been conducted using an integrated luminosity of about 250 pb$^{-1}$ at centre-of-mass energies up to 189 GeV by the four LEP collaborations. No evidence for SUSY was found, and limits are placed on parameters within the CMSSM.

Acknowledgements

The results presented here are almost entirely new for this conference, and therefore do not have published references to cite. They were provided by my colleagues from the four LEP experiments, mostly on a private basis, up to (and beyond) the last minute, and I would like to
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References