Searches for Higgs bosons and supersymmetry at LEP

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This note presents an overview of the main results from searches for Higgs bosons and supersymmetry at LEP. Most of the results presented here are combined results from the four LEP experiments (ALEPH, DELPHI, L3 and OPAL). No signal is observed and the (negative) search results are interpreted in a wide class of models allowing parameter space to be excluded. All limits are set at 95% CL.

1 Introduction

During its many years of operation the LEP accelerator has produced a large data-set of $e^+e^-$ collisions up to a centre-of-mass energy of 209 GeV. The integrated luminosity above 130 GeV was around 2.7 $fb^{-1}$ and although LEP operation stopped more than 3 years ago, the hunt for new particles has not stopped. In this note a review of the main results on the searches for new particles at LEP is presented. The note is split in two parts: first, in Section 2, the results on the search for the Standard Model (SM) Higgs boson (final) and those from Higgs boson production in extensions to the SM are presented. Section 3 then gives an overview of the main results on the searches for supersymmetry.

2 Higgs boson searches

This section reviews the final results from the search for the SM Higgs boson followed by results from Higgs boson searches in extensions to the SM: general Two Higgs Doublet Models (2HDM) and in particular the Minimal Supersymmetric Standard Model (MSSM). A selection of preliminary results from ongoing analyses in more exotic scenarios is presented at the end of this section.
In the SM the Higgs mechanism is usually assumed to be responsible for breaking the Electroweak (EW) symmetry and the generation of masses for the elementary particles. The Higgs mechanism predicts a doublet of complex scalar fields and thereby the existence of a single neutral scalar particle, the Higgs boson, with well defined properties as a function of its (unknown) mass. Indirect limits on the mass of the Higgs boson are obtained from precision measurements of EW parameters that depend on its mass (through radiative corrections). Including the new top quark mass combination from the Tevatron\(^1\), the preferred Higgs boson mass from all EW precision measurements is \(117 \pm 4\) GeV/c\(^2\) and the 95\% CL upper limit is set at 251 GeV/c\(^2\).

At LEP the main focus is however on the search for direct Higgs boson production. If the Higgs boson exists it is mainly produced in association with a Z boson through the Higgsstrahlung process \(e^+ e^- \rightarrow Z^* \rightarrow hZ\) (as is shown in Figure 1) with a small contribution from weak boson fusion. As long as the massive electroweak boson decay channels are kinematically closed, the SM Higgs boson decays preferentially into the heaviest accessible fermion pair. In the Higgs boson mass range accessible at LEP (up to 115 GeV/c\(^2\)) this leads to dominance of the \(b\bar{b}\) decay mode with a 74\% branching ratio.

The decays to \(\tau^+ \tau^-\), WW and gluons are all close to 7\%. The analyses require the presence of identified (jets from) \(b\)-quarks in the final state and the final states that have been considered originate from the different decays of the accompanying Z boson: the four-jet channel \((h \rightarrow b\bar{b})(Z \rightarrow q\bar{q})\), the missing energy channel \((h \rightarrow b\bar{b})(Z \rightarrow \nu\bar{\nu})\) and the leptonic channel \((h \rightarrow l^+l^-)(Z \rightarrow l^+l^-)\), where \(l\) denotes electron or muon. The final states with \(\tau\)s covered both the \(h\) and \(Z\) decay into \(\tau^+ \tau^-\).

The total LEP data-set used for the search for the Standard Model (SM) Higgs boson was 2461 pb\(^{-1}\) at \(\sqrt{s} \geq 189\) GeV (of which 536 pb\(^{-1}\) at \(\sqrt{s} \geq 206\) GeV) and the results from the individual experiments have been combined\(^2\) by the LEP Higgs working group using the likelihood ratio technique. The compatibility of the observed data with the background-only hypothesis, \(1-\text{CL}_{1b}\), as a function of the Higgs boson mass hypothesis is shown in the left plot of Figure 2. The observed excess\(^2\) at \(m_h=98(115)\) GeV/c\(^2\) corresponds to a 2.3(1.7)\(\sigma\) deviation from the background-only hypothesis and for \(m_h=115\) GeV/c\(^2\) the compatibility of the observed data with the signal+background hypothesis, \(\text{CL}_{s+b}\), is 0.15.

For each Higgs boson mass hypothesis the signal+background hypothesis is excluded at 95\% CL if the confidence in the signal hypothesis (\(\text{CL}_S = \text{CL}_{s+b}/\text{CL}_{1b}\)) is smaller than 0.05. The observed (median expected) lower limit on the mass of the SM Higgs boson is 114.4(115.3) GeV/c\(^2\). The (negative) search results are also presented as upper limits on the hZZ coupling relative to that in the SM using \(\xi^2 = (g_{hZZ}/g_{\text{SM}ZZ})^2\) as is shown in the right plot of Figure 2.

### 2.2 Flavour independent Higgs searches

In extensions to the SM, the Higgs boson’s coupling to down-type fermions (like \(b\)-quarks) might be suppressed. This can occur for example in a general 2HDM, in the MSSM or in special composite models in which the dominant Higgs boson decay channel is gluonic. The searches for the SM Higgs boson at LEP strongly rely on the identification of \(b\)-quarks in the final state and therefore have a reduced sensitivity to the final states predicted by such alternative models.
To test these models experimentally and to reduce the model dependence of the results, dedicated searches have been developed that are independent of the gluon or quark flavour into which the Higgs boson decays. All LEP collaborations have performed such flavour-independent searches using analyses that are similar to the SM searches, but removing the information on the b-quark content in the final state. Production through Higgsstrahlung results in expected topologies identical to those from the SM Higgs boson: four-jets (qqqq), missing energy (qqνν) and leptonic (qql+q⁻).

The (negative) search results are presented as model-independent upper limits on production cross sections (relative to that of SM hZ production and assuming the Higgs boson decays 100% into hadrons). These results allow to test the predictions from a wide class of models. Assuming a SM cross section, the combined median observed(expected) limit is set at \( m_h = 112.9(113.0) \text{ GeV/c}^2 \), while the sensitivity for a 5σ discovery extended up to 107 GeV/c².

2.3 Two Higgs doublet models

The simplest extension of the Higgs sector of the SM have requires two complex Higgs doublets. These so-called 2HDM models predict five physical Higgs bosons: two CP-even neutral scalars h and H, one CP-odd neutral scalar A and two charged scalars H⁺ and H⁻. Different types of models exist: in so-called type-I models the first(second) doublet couples only to down(up)-type fermions, while in type-II models quarks and leptons couple only to the second doublet. The parameter space in the most general model covers a wide range of production processes and decay properties and is too large to be fully explored at LEP.

The reach in parameter space exclusion in a general 2HDM model has been investigated by individual experiment and a LEP combination is planned for the near future. It is common, for searches to be performed and interpreted in more predictive models like, as is done in the rest of this section, the MSSM.

a) The MSSM Higgs bosons (CP-conserving scenarios)

The (constrained) MSSM is the SUSY extension of the SM with minimal new particle content. The Higgs boson sector of the MSSM corresponds to a 2HDM of type-II and its phenomenology in terms of production cross section and branching fractions can be described at tree level by only two parameters, often taken to be \( \tan \beta \) and the mass of the pseudoscalar neutral Higgs boson, \( m_A \). At the level of radiative corrections additional parameters appear: \( M_\text{SUSY} \), \( M_2 \),
**Figure 3:** The MSSM exclusion plots for the $m_{h}$-max benchmark scenario (left) and the no-mixing scenario (right). The figures show both the excluded and theoretically forbidden regions.

$p$, $A$ and $m_{3/2}$. $M_{R}$(~$M_{2}$) is the common sfermion(gaugino) mass at the EW scale and $\mu$ is the supersymmetric Higgs boson mass parameter. The gluino mass is given by $m_{3/2}$ and $A$ is a (common) trilinear Higgs-squark coupling parameter.

Search for neutral Higgs bosons
At LEP the neutral $h$ and $A$ are produced via the Higgsstrahlung process $e^{+}e^{-} \rightarrow hZ$ and through pair-production $e^{+}e^{-} \rightarrow Z^{*} \rightarrow hA$. The cross sections for these processes are suppressed with respect to the SM $hZ$ cross section and are complementary since the suppression factors are proportional to $\sin^{2}(\beta - \alpha)$ and $\cos^{2}(\beta - \alpha)$ respectively. Here, $\alpha$ is the mixing angle that describes the combination of the two CP even weak Higgs eigenstates to produce the two CP even Higgs mass eigenstates and $\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. The $hA$ production is additionally suppressed by a P-wave suppression factor.

Also in the MSSM the parameter space is in general too large to be explored fully and so-called benchmark scenarios have been proposed. These specific parameter points are meant to represent the full parameter space and in each point all parameters are fixed and only $\tan \beta$ and $m_{A}$ are scanned over. In the large-$\mu$ scenario for example, the highest mass of the lightest Higgs boson, produced via Higgsstrahlung production is below 108 GeV/$c^{2}$ and therefore accessible at LEP. The challenge in this scenario is to cover parts of the parameter space that have a strongly reduced Higgs boson coupling to b-quarks. Using the flavour independent Higgs boson searches (Section 2.2) this scenario is entirely excluded at 95% CL. The $m_{h}$-max scenario is designed to yield the maximal value of $m_{h}$ for a given $(\tan \beta, m_{A})$ and provides the most conservative range of excluded $\tan \beta$ regions while the no-mixing scenario describes a point where there is no mixing between the left- and right-handed stop squarks. The excluded regions in parameter space for these last two benchmarks are shown in the left and right plot of Figure 3 respectively and the corresponding limits on the neutral Higgs boson masses and excluded $\tan \beta$ regions are given in table 1.

Search for charged Higgs bosons
At LEP charged Higgs bosons are expected to be produced in pairs, $e^{+}e^{-} \rightarrow H^{+}H^{-}$ through s-channel exchange of a $\gamma$ or a $Z$ boson. For masses accessible at LEP, the charged $H^{+}$ decays into $c\bar{s}$ and $\tau^{+}\nu_{\tau}$ (and charged conjugate), resulting in three different final states for pair-production. No signal was observed and the lower limit on the mass of the charged Higgs boson is set at 78.6 GeV/$c^{2}$, independent of the unknown branching ratio $BR(H^{+} \rightarrow \tau^{+}\nu_{\tau})$. 

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Table 1: The observed (expected) limits on $m_h$ and $m_A$ in the MSSM $m_{h\text{-max}}$ and no-mixing benchmark scenarios for a top mass of 174.3 GeV/c$^2$.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$m_h$-limit in GeV/c$^2$ obs. (exp.)</th>
<th>$m_A$-limit in GeV/c$^2$ obs. (exp.)</th>
<th>Excluded tan $\beta$ region obs. (exp.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{h\text{-max}}$</td>
<td>91.0 (94.6)</td>
<td>91.9 (95.0)</td>
<td>0.5 &lt; tan $\beta$ &lt; 2.4 (0.5 &lt; tan $\beta$ &lt; 2.6)</td>
</tr>
<tr>
<td>no-mixing</td>
<td>91.5 (95.0)</td>
<td>92.2 (95.3)</td>
<td>0.7 &lt; tan $\beta$ &lt; 10.5 (0.8 &lt; tan $\beta$ &lt; 16.0)</td>
</tr>
</tbody>
</table>

b) The MSSM Higgs bosons (CP non-conserving scenarios)

In the MSSM the Higgs potential is assumed to be invariant under CP transformation at tree level. It is however possible to break CP symmetry in the Higgs sector by radiative corrections, especially by contributions from complex trilinear couplings $A_{1,2}$ of third generation squarks.

In such scenarios, like the new CPX MSSM benchmark$^5$ the three neutral Higgs bosons are mixtures of the CP-even and CP-odd Higgs fields. They couple to each other and the Z boson with varying strengths, and the Higgsstrahlung process $e^+e^- \rightarrow H_iZ$ ($i=1,2,3$) and pair production $e^+e^- \rightarrow H_iH_j$ ($j \neq i$) can now all occur with widely varying cross sections. In particular, in large domains of the model parameters the lightest neutral Higgs boson $H_1$ may escape detection if its coupling to the Z boson is too weak. The results obtained by the OPAL experiment$^5$ for a particular set of parameters is shown in Figure 4.

The most important conclusion is that in these scenarios no universal limits on Higgs boson masses can be set.

More exotic scenarios

There are a number of more exotic Higgs boson scenarios that have been considered. These include fermiophobic Higgs searches$^6$ (no Higgs-fermion couplings), invisibly decaying Higgs bosons (into a pair of stable neutralinos), Yukawa couplings (Higgs bosons produced by radiation off quarks), doubly charged Higgs bosons, etc. An overview of the results in all Higgs searches can be found on the homepage of the LEP Higgs working group$^7$.

3 Supersymmetry searches

Supersymmetry (SUSY) is at present one of the most attractive extensions of the SM. It provides a solution to many problems of the SM (like the hierarchy problem) and results in a natural unification of the gauge couplings at the GUT scale. Its signatures could be observed at LEP in a wide variety of channels and signals from many models have been searched for.

In SUSY models each particle is accompanied by a supersymmetric partner (sparticle) whose spin differs by half a unit. Up to now no sparticle has been observed, which means that sparticles have a mass different from their matter counterparts (much heavier) and that supersymmetry,
if it exists, is broken. Several SUSY breaking mechanisms have been suggested: the anomaly-mediated SUSY breaking (AMSB), the gauge-mediated SUSY breaking (GMSB) or, the most popular, the supergravity-mediated SUSY breaking (SUGRA).

Even in the minimal supersymmetric extension of the SM already more than 100 new parameters are introduced and combined with the variety of SUSY breaking schemes (and their specific phenomenology at lower energies) results in a parameter space that is too large to be fully explored at LEP. For this reason often assumptions are made to make the model more predictive. In the CMSSM for example, the gaugino and sfermion masses are unified at the GUT scale, \( m_0 \) and \( m_{1/2} \) respectively and it is possible to have a single parameter \( A \) describing all Yukawa coupling between the sfermions. Another important issue is the (non-)conservation of R-parity. R-parity is a quantum number which is +1 for particles and -1 for sparticles. Its conservation implies that the lightest supersymmetric particle (LSP) is stable, that SUSY particles are always pair-produced and that they decay through cascades to ordinary particles and the LSP. Since the LSPs escape detection, the events are characterized by missing energy and momentum. The amount of missing energy, crucial for the phenomenology of the event and the search(strategy), is given by the quantity \( \Delta m = m_{\text{NLSP}} - m_{\text{LSP}} \).

To remain as model independent as possible, the LEP working group produces upper limits on production processes. These cross section limits are then interpreted in various models to constrain parameter space. The searches presented here were performed in the framework of the CMSSM and minimal SUGRA (mSUGRA) where the LSP is assumed to be the lightest neutralino (\( \chi_1^0 \)). In the next sections the main results from searches for pair-produced sleptons, charginos and neutralinos are presented. In the last section the (negative) searches are then combined to extract a universal lower limit on the mass of the LSP in both these models. Results from other SUSY breaking schemes and R-parity violating searches can be found elsewhere.

### 3.1 Sleptons and squarks

In the case of sfermion pair-production at LEP, the sfermions predominantly decay to their corresponding fermion (if kinematically allowed) and the lightest neutralino, \( \tilde{f} \rightarrow f \chi_1^0 \). The expected event topologies are therefore a pair of acoplanar leptons or jets and missing energy for sleptons and squarks respectively. When \( \Delta m \) is small the leptons in the event are very soft and these topologies can not be covered experimentally. In the left plot of Figure 5 the excluded regions for pair-produced right handed sleptons are shown. Assuming that \( \Delta m > 15 \text{ GeV/c}^2 \), the universal slepton mass limits are: \( m_{\tilde{e}} > 99.6 \text{ GeV/c}^2 \), \( m_{\tilde{\mu}} > 94.9 \text{ GeV/c}^2 \) and \( m_{\tilde{\tau}} > 85.9 \text{ GeV/c}^2 \).

In the third slepton and squark family, mass eigenstates can be a mixture of the interadion eigenstates \( (f_{L/R}) \). This so-called left-right mixing is usually labeled by a mixing angle \( \theta_{m_{3/1}} \) which depends on the particular set of parameters of the SUSY model. For a specific mixing angle the sfermion can even completely decouple from the \( Z \), thereby decreasing the total production cross section and weakening the corresponding mass limit. Since a possible slepton mixing would be largest in the third family, an overall lower limit for the stau mass (85.0 GeV/c^2) has been computed in the scenario where the stau production cross section is minimal.

The mixing in the third squark family is expected to be larger than for sleptons. In the case of the stop, the decay \( \tilde{t} \rightarrow c \chi_1^0 \) is not allowed at LEP and the dominant 2-body decay channel is \( \tilde{t} \rightarrow c \chi^0_1 \) (the decay \( \tilde{t} \rightarrow b \chi^0_1 \) is disfavored by limits on the chargino mass) and if \( m_b < M_{\tilde{\tau}} \), also the 3-body decay \( \tilde{t} \rightarrow b \nu \chi^0_1 \) can be important. The exclusion regions from the searches for sbottom squarks are shown in the right plot of Figure 5 in both the no-mixing and decoupling scenario (\( \theta_{m_{3/1}} = 0^\circ, 68^\circ \) respectively). The lower limits on the squark masses are given in Table 2. Since the lightest stop and sbottom squark are expected to be lighter than squarks from the first 2 families only results for the third family are given and as for the slepton mass limits, they are only valid for large values of \( \Delta m \).
Table 2: LEP combined lower limits on squark masses for $\Delta m > 20$ GeV/c$^2$. The values between brackets reflect the limit when the squark is decoupled from the $Z$ ($\Theta_{\text{mix}} = 56^\circ/68^\circ$ for stop and sbottom squark respectively).

<table>
<thead>
<tr>
<th>channel</th>
<th>$t \rightarrow c\chi^\pm_1$</th>
<th>$t \rightarrow b\nu \chi^\mp_1$</th>
<th>$b \rightarrow b\nu \chi^0_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>lower limit on squark mass (in GeV/c$^2$)</td>
<td>100(98)</td>
<td>99(96)</td>
<td>99(95)</td>
</tr>
</tbody>
</table>

Figure 5: The left plot shows the 95% CL exclusion regions (solid lines) for pair-produced right-handed selectrons, smuons and staus. The dotted lines represent the expected limits. The right plot shows the excluded sbottom masses in both the no-mixing and decoupling ($\Theta_{\text{mix}} = 68^\circ$) scenario.

3.2 Charginos and neutralinos

Charginos could be pair-produced at LEP through s-channel $\gamma$ or $Z$ exchange or through sneutrino exchange in the t-channel. The production cross sections are large for most of the parameter space and when $m_0$ is large the negative interference diagram from t-channel sneutrino exchange is negligible, making it one of the 'golden' SUSY search channels at LEP. For large $m_0$ the $\chi^\pm_1$ decays into a $\tilde{\ell}^\pm_1$ and $W$ giving rise to 2 decays: $\chi^\pm_1 \rightarrow \chi^0_1 \ell^\pm \nu$ (leptonic decay) or into a neutralino and a quark pair: $\chi^\pm_1 \rightarrow \chi^0_1 q\bar{q}$ (hadronic decay). The experimental signature of pair-produced charginos is therefore: missing energy and either two acoplanar leptons, one lepton plus jets or multi-jets.

Also for the charginos the value of $\Delta m$ plays a crucial role in the analysis (strategy). For large $\Delta m$ the lower limit on the mass of the lightest chargino can be set very close to the kinematic limit ($\sqrt{s}/2$), but for small $\Delta m$ values the visible energy in the event is very small, making it experimentally hard to detect. A combination of dedicated analyses was performed to cover all $\Delta m$ values. These include triggering these soft events using initial state (photon) radiation and, for very small values of $\Delta m$, the search for long-lived charged particles. In the left plot of Figure 6 the excluded chargino masses are shown as a function of $\Delta m$. For large values of $\Delta m$ (and for large values of $m_0$), the lower limit on the mass of the lightest chargino is set at 103.5 GeV/c$^2$.

3.3 Lower limit on the mass of the LSP

The negative search results in all channels were used to exclude regions of parameter space and to compute lower mass limits for sparticles in specific models. Another important result is the extraction of the lower limit on the mass of the LSP in both the CMSSM and mSUGRA models since, assuming R-parity is conserved, the LSP is a good candidate for cold dark matter. In the right plot of Figure 6 the excluded region in the $\tan \beta$, $m_{\tilde{\chi}^0_1}$ plane is shown within the CMSSM and after a combination of all analyses, the universal lower limit on the mass of the LSP in
the CMSSM was set at 45 GeV/c². A similar interpretation was done in the more restrictive mSUGRA model, which resulted in a lower limit on the mass of the $\chi_0^1$ of 50.8(50.3) GeV/c² when $\text{sign}(\mu)$ is assumed to be positive(negative).

4 Conclusions

The data collected at LEP has allowed a search for Higgs bosons and signals from supersymmetry covering a large region of SUSY parameter space. After an exciting last year of operation, unfortunately no Higgs boson discovery could be claimed and no sign of sparticle production has been observed. These negative search results from the four LEP experiments have been combined and interpreted in a wide class of models, allowing stringent limits on masses of new particles to be set.

Acknowledgments

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References

1. See talks from K. Bloom and Y. Kulik in these proceedings.