SEARCHES FOR THE NEUTRAL HIGGS BOSONS OF THE MSSM USING LEP DATA

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Representing LEP Collaborations
Outline

• LEP performance

• Theoretical framework

• Search for neutral Higgs bosons
  – Search for $h^0Z^0$
  – Search for $h^0A^0$
  – Combination
    Mainly from contributed papers for EPS’01 in Budapest

• Updates
LEP Performance

870 pb\(^{-1}\) at \(E > 200\) GeV ;  510 pb\(^{-1}\) at \(E > 206\) GeV
Type II Two-Higgs Doublet Models (2HDM)

2 complex scalar field doublets:

\[ \phi_1 \text{ couples to “up-type” fermions} \]
\[ \phi_2 \text{ couples to “down-type” fermions} \]

8 degrees of freedom:

\[ \begin{cases} 
3 \text{ longitudinal polarisation states of the gauge bosons } W^+ W^- Z^0 \\
5 \text{ physical scalar Higgs states } h^0, H^0, A^0, H^+, H^- 
\end{cases} \]

In MSSM \( m_{h^0} < 135 \text{ GeV/c}^2 \)
MSSM Higgs Searches

- **SM** just 1 unknown parameter $m_H$

- **MSSM** 7 parameters in this model
  - $M_2$ EW scale SU(2) Gaugino mass
    (assume Gaugino masses unified at GUT scale)
  - $M_{\text{SUSY}}$ Common sfermion mass (squark, lepton, sneutrino)
    at the EW scale
  - $\tan\beta$ Ratio of the vacuum expectation values of the two Higgs doublets
  - $\mu$ Higgs mass parameter
  - $A_0$ Common trilinear Higgs-squark coupling parameter
  - $M_{A^0}$ Mass of the CP-odd Higgs boson
  - $m_{\text{gluino}}$ Gluino mass (via loops)

**Three benchmark scenarios:**
- No stop-quark mixing scenario
- Max -$m_h$ scenario
- Large-$\mu$ scenario
MSSM Higgs Searches $h^0 Z^0$

$e^+ e^- \rightarrow h^0 Z^0$
MSSM Higgs Searches $h^0 Z^0$

SM Search (CERN-EP / 2001 – 055) for $H^0 Z^0$ reinterpreted

- **Production**
  
  $e^+ e^- \rightarrow h^0 Z^0 \div \sin^2 (\beta - \alpha)$

- **Topologies**

  ![Topologies Diagram](image)

  - 4 jets
  - Missing energy
  - Leptonic
  - Tau
Tight selection to increase purity
for illustration of the agreement between data and simulation
(not used for limits)

**CERN-EP / 2001 - 055**

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MSSM Higgs Searches $h^0 A^0$

\[ e^+ e^- \rightarrow h^0 A^0 \]
LHWG Note 2001-04

- Production $e^+ e^- \rightarrow h^0 A^0 \div \cos^2 (\beta - \alpha)$

- Topologies

  Predominently

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<table>
<thead>
<tr>
<th>Year 2000 data</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHWG Note 2001-04</td>
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</tr>
</tbody>
</table>

### $h^0 A^0 \rightarrow b\ b\ b\ b$ channel

<table>
<thead>
<tr>
<th>Total Int. luminosity (pb$^{-1}$)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>217</td>
<td>224</td>
<td>217</td>
<td>208</td>
</tr>
<tr>
<td>Total background</td>
<td>10</td>
<td>5</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Efficiency (mh = mA = 90 GeV/c$^2$)</td>
<td>5.5</td>
<td>6.5</td>
<td>9.4</td>
<td>10.3</td>
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<tr>
<td>Expected signal (mh = mA = 90 GeV/c$^2$)</td>
<td>47%</td>
<td>47%</td>
<td>42%</td>
<td>48%</td>
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<tr>
<td>Efficiency (mh = mA = 90 GeV/c$^2$)</td>
<td>3.5</td>
<td>3.6</td>
<td>3.2</td>
<td>3.4</td>
</tr>
</tbody>
</table>

### $h^0 A^0 \rightarrow b\ b\ \tau^+\ \tau^-$ channel

<table>
<thead>
<tr>
<th>Total Int. luminosity (pb$^{-1}$)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>217</td>
<td>224</td>
<td>217</td>
<td>205</td>
</tr>
<tr>
<td>Total background</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Efficiency (mh = mA = 90 GeV/c$^2$)</td>
<td>3.0</td>
<td>6.0</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Expected signal (mh = mA = 90 GeV/c$^2$)</td>
<td>41%</td>
<td>25%</td>
<td>33%</td>
<td>43%</td>
</tr>
<tr>
<td>Expected signal (mh = mA = 90 GeV/c$^2$)</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

| Obs. (exp. Med.) limit for $m_h$            | 89.6 (91.7) | 89.7 (88.8) | 83.2 (88.1) | 79.3 (85.1) |
| Obs. (exp. Med.) limit for $m_A$            | 90.0 (92.1) | 90.7 (89.7) | 83.9 (88.3) | 80.6 (86.9) |

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MSSM Higgs Searches

$h^0 A^0$ and $h^0 Z^0$ Full Combination

Distribution of $\text{CL}_b$ in the $(m_{h^0}, m_{A^0})$ plane

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MSSM Higgs Searches

In the domains labelled $\geq 1\sigma$ and $\geq 2\sigma$
the observation shows an excess above the SM prediction

Structures on the $m_h = m_A$ line could arise from $h^0 A^0$
Vertical structures could be due to the features of the $h^0 Z^0$

Effects $\geq 2\sigma$ are consistent with the expectation
for $H^0 Z^0$, $h^0 Z^0$ and $h^0 A^0$ production
for some MSSM parameter combinations such as

<table>
<thead>
<tr>
<th>$m_A$</th>
<th>$m_h$</th>
<th>$m_H$</th>
<th>$\tan\beta$</th>
<th>$M_{\text{SUSY}}$</th>
<th>$M_2$</th>
<th>$\mu$</th>
<th>$A$</th>
<th>$\sigma_{Hz}^{208}$</th>
<th>$\sigma_{hA}^{208}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>90.0</td>
<td>114.0</td>
<td>16</td>
<td>1000</td>
<td>500</td>
<td>500</td>
<td>0</td>
<td>118</td>
<td>44</td>
</tr>
<tr>
<td>100</td>
<td>99.3</td>
<td>114.0</td>
<td>16</td>
<td>1000</td>
<td>500</td>
<td>-500</td>
<td>0</td>
<td>97</td>
<td>8</td>
</tr>
</tbody>
</table>

Masses in GeV
Cross-sections in fb

Communication of André Sopczak

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MSSM Higgs Searches

Max- $m_h$ scenario

LHWG

Note 2001-04
MSSM Higgs Searches

No stop - mixing scenario

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Note 2001-04
MSSM Higgs Searches

Observed and expected limits
for $m_h^0$ and $m_A^0$
for the “$m_h$-max” scenario and the “no-mixing” scenario

| Scenario      | $m_h^0$ limit (GeV/c²) | $m_A^0$ limit (GeV/c²) | Excluded $\tan\beta$
<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$m_h^0$-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>

LHWG Note 2001-04

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Large $\mu$ scenario
designed to illustrate choices of the MSSM parameters for
which $h^0$ does not decay into a pair of $b$ quarks
⇒ include the flavour-independent searches in this scenario

Add enough sensitivity to exclude this scenario at the 95% CL
MSSM Higgs Searches

**Coupling strength limits**

\[ m_h^0 \approx m_A^0 \]

energy dependence of \( e^+e^- \rightarrow h^0 A^0 \) cross-section

from the “mh-max” scenario

\[ \tan \beta > 10 \]

\[ \text{Br} (h^0 \rightarrow bb) = 0.94 \]

\[ \text{Br} (A^0 \rightarrow bb) = 0.92 \]

\[ \text{Br} (h^0 \rightarrow \tau^+ \tau^-) = 0.06 \]

\[ \text{Br} (A^0 \rightarrow \tau^+ \tau^-) = 0.08 \]

**LHWG Note 2001-04**

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Updates

**ALEPH**
- year 2000 data sample fully reprocessed
  (final detector calibrations, alignment constants)
- precise knowledge of the LEP c.m. energy propagated to final results (~ -140 MeV, essentially affects hZ)
- additional simulated evt samples → more accurate prediction of the SM background
- algorithm to reject beam-related backgrounds (4-jet channel)

**L3**
- year 2000 data sample fully reprocessed
  (final detector calibrations, alignment constants)
- precise knowledge of the LEP c.m. energy propagated to final results
- improved efficiency

**OPAL**
- $H^0Z^0$ channel analyses to be upgraded by EPS HEP 2002
- $h^0A^0$ channel update with the final calibration comes soon
  No big change is expected in the results

**DELPHI**
- final reprocessing of data
- New MC simulation samples
  (statistics x 4, Pythia $\rightarrow$ KK2F, Excalibur $\rightarrow$ WPHACT generators used)
- Dedicated b-tagging for $hA \rightarrow bbbb$ channel analysis
  Only small changes expected
Updates

ALEPH mh-max scenario

Excluded regions (95% CL)

- $m_h < 89.6$ (91.7) GeV/c$^2$
- $m_A < 90.0$ (92.1) GeV/c$^2$
- $0.7 < \tan\beta < 2.2$

ALEPH 2001-022


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Updates

ALEPH no-mixing scenario

Excluded regions (95% CL)

\[ m_h < 89.8 \ (91.3) \ \text{GeV/c}^2 \]
\[ m_A < 90.1 \ (91.6) \ \text{GeV/c}^2 \]

\[ 0.5 < \tan \beta < 6.0 \]
\[ 0.5 < \tan \beta < 6.2 \]

**ALEPH 2001-022**


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Updates

DELPHI mh-max scenario

Excluded regions (95% CL)

$0.49 < \tan \beta < 2.36$

DELPHI 2001-078 CONF 506

$0.5 < \tan \beta < 2.4$

DELPHI 2002-021 TALK 31

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Updates

L3 mh-max scenario

Excluded regions (95% CL)

\[ m_h < 86.0 \ (88.4) \ \text{GeV/c}^2 \]
\[ m_A < 86.5 \ (88.6) \ \text{GeV/c}^2 \]
\[ 0.55 < \tan \beta < 2.2 \]

New! Still preliminary

L3 Note 2692

L3 Note 2735

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Excluded regions (95% CL)

- $m_h < 85.5 \ (88.5) \ \text{GeV}/c^2$
- $m_A < 86.3 \ (88.6) \ \text{GeV}/c^2$
- $0.4 < \tan\beta < 4.9$

New! Still preliminary
Updates

- New, final results for ALEPH
- New, almost final results for L3
- OPAL
  - $H^0Z^0$ channel analyses to be upgraded by EPS HEP 2002
  - $h^0A^0$ channel update with the final calibration comes soon
  No big change is expected in the results
- Final results for DELPHI expected to be published very soon.
- Final combination of the 4 experiments starting now
  New, final LEP results expected to be ready for EPS HEP 2002