Combined LEP Higgs Searches

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Ottawa, Canada

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Preliminary update of the LEP Higgs Working group, with many thanks to the ALEPH, DELPHI, L3 and OPAL Collaborations, and the Accelerator divisions at CERN.
Data Sets

\[ \int Ldt \quad [\text{pb}^{-1}] \]

<table>
<thead>
<tr>
<th>Experim.</th>
<th>Sept 5</th>
<th>Oct 10</th>
<th>New Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>149</td>
<td>178</td>
<td>29</td>
</tr>
<tr>
<td>DELPHI</td>
<td>160</td>
<td>160</td>
<td>**</td>
</tr>
<tr>
<td>L3</td>
<td>145</td>
<td>170</td>
<td>25</td>
</tr>
<tr>
<td>OPAL</td>
<td>140</td>
<td>165</td>
<td>25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>594</td>
<td>673</td>
<td>79</td>
</tr>
</tbody>
</table>

**DELPHI suffered from a TPC short. Current data still being calibrated/analyzed.**

Average \( E_{\text{CM}} \) for the year: 206.0 GeV

New data: mostly 206.6 GeV (a little at 208.x.)

\( E_{\text{CM}} \) very important to extend sensitivity

Goal from Sep. LEPC: double the lumi >206 GeV
What’s also New: Analysis and Reprocessing

Many detailed checks have been carried out since the September 5 LEPC. Some problems found and fixed:

ALEPH: Improved background estimation in the four-jet channel
DELPHI: Improved signal and background estimations in the four-jet channel
L3: Reprocessing of data for TEC
     Change to Neutrino channel analysis
OPAL: Reprocessing for better Silicon hit association

Three sets of results to watch:

“NEW” All data up to October 10 LEPC
“REFERENCE” Data used for September 5 LEPC but with new analysis
“OLD” Results for September 5 LEPC
Reconstructed $m_H$ of selected candidates

Have to cut somewhere. For illustration only.
Cut on mass independent variables (like b-tags) so that
\[
\frac{s_{\text{expected}}}{b_{\text{expected}}} \approx 0.3 \quad \text{For } m_{\text{rec}} > 109 \text{ GeV}
\]
for a 114 GeV Higgs

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Backg</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>All $m_{\text{rec}}$</td>
<td>354</td>
<td>328</td>
<td>20.2</td>
</tr>
<tr>
<td>$m_{\text{rec}} &gt; 109$ GeV</td>
<td>39</td>
<td>37.1</td>
<td>12.0</td>
</tr>
</tbody>
</table>
Cutting a Little Harder

This time, adjust cuts so that

\[
\frac{s_{\text{expected}}}{b_{\text{expected}}} \approx 1.0
\]

For \( m_{\text{rec}} > 109 \text{ GeV} \)

for a 114 GeV Higgs

<table>
<thead>
<tr>
<th>Events / 3 GeV/c²</th>
<th>( \sqrt{s} = 200-210 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LEP S/B=1.0</td>
</tr>
<tr>
<td>background</td>
<td></td>
</tr>
<tr>
<td>hZ Signal</td>
<td></td>
</tr>
<tr>
<td>(( m_h = 114 \text{ GeV} ))</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>All ( m_{\text{rec}} )</th>
<th>103</th>
<th>92.5</th>
<th>11.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\text{rec}} &gt; 109 \text{ GeV} )</td>
<td>7</td>
<td>7.5</td>
<td>7.2</td>
</tr>
</tbody>
</table>
**Very Hard Cuts**

\[ \frac{s_{\text{expected}}}{b_{\text{expected}}} \approx 2.0 \]

For \( m_{\text{rec}} > 109 \) GeV

for a 114 GeV Higgs

\[ \sqrt{s} = 200-210 \text{ GeV} \]

LEP S/B=2.0

**Data**

\[ \text{Events / 3 GeV/c}^2 \]

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Backg</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>All ( m_{\text{rec}} )</td>
<td>42</td>
<td>34.0</td>
<td>5.6</td>
</tr>
<tr>
<td>( m_{\text{rec}} &gt; 109 ) GeV</td>
<td>5</td>
<td>2.3</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Losing Efficiency -- but “really good” events kept
Why Cut at All?

- Need to separate the expected signal from the expected background

- **Pick good variables to optimize separation**
  - reconstructed $m_H$
  - b-tags
  - kinematic variables

- **Express in bins**
  - Experimental Data
  - Monte Carlo Signal Expectation
  - Monte Carlo Background Expectation

- **Systematic Uncertainties**
  - By search channel, on signal and background
  - Signed errors, labeled by source name
  - Correlated errors properly treated

Need a language: classical confidence levels
All LEP Data in bins of Expected Signal/Background

Important Candidates stand out

And the integral -- the optimal answer to the questions:

“How many did you see? How many did you expect? Where did you cut?”
Comparing Signal and Background Hypotheses

• Construct a parameter that orders outcomes as more signal-like, or less signal-like

\[ Q = \frac{P_{\text{poiss}}(\text{data} \mid \text{signal + background})}{P_{\text{poiss}}(\text{data} \mid \text{background})} \]

\[ \log Q = -s_{\text{tot}} + \sum_{\text{bins}} n_{i}^{\text{data}} \log \left( 1 + \frac{s_{i}}{b_{i}} \right) \]

Sep 5 LEPC: “Old”
Updated Analysis 1: ALEPH

Four-Jet Channels:
Improved background modeling.
Some candidates become less significant

“Old” --- Sept. 5 Results

“Reference” --- Sept. 5 Data with New Analysis
Updated Analysis 2: DELPHI

More Monte Carlo -- Better modeling of signal and background.
Increased Sensitivity. Some candidates become more significant.

“Old”

“Reference”
Just the New Data

Hard cuts, only the best candidates shown.

\[ \sqrt{s} = 200-210, \text{ after Sept.5 GeV} \]

- LEP S/B=2.0
- **background**
- **hZ Signal**

\[(m_h=114 \text{ GeV})\]

<table>
<thead>
<tr>
<th>all</th>
<th>&gt; 109 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>cnd</td>
<td>12</td>
</tr>
<tr>
<td>bgd</td>
<td>9.71</td>
</tr>
<tr>
<td>sgl</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Reconstructed Mass \( m_H \) [GeV/c^2]
The Effect of New Data

“Reference” Set

New data for October 10. Same procedures as reference set:
How Significant is it?

→ Confidence Levels

• CL_s -- compatibility with signal hyp. 
  CL_s < 0.05: Signal hypothesis ruled out at the 95% CL.

• CL_b -- compatibility with background hyp. 
  1-CL_b < 5.7×10^{-7} is a 5σ discovery

CL calculations cross-checked by several people:
  • MC ensemble
  • Folding of probabilities
  • FFT
  • Different test-statistics (LR or others)

Systematic errors can be treated in more than one way.

**Spread in CL significances:** ±0.2σ

Preliminary!
Lower Limit on $m_H$ in Combination

Observed limit: $m_H > 113.2$ GeV @95% CL
Median Expected: 115.0 GeV,

in many experiments with only background present

Reference set: new analyses, data for Sep. 5:
observed limit: $m_H > 113.2$ GeV, expected 114.8 GeV
Observations by Channel

Lepton, Neutrino, Tau

Combined they are as sensitive as the four-jet channels

LEP $\sqrt{s} \leq 210$ GeV

-2 \ln(Q)

Observed

Expected background

Expected signal
# SM Higgs Limit Summary

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>110.2</td>
<td>113.0</td>
</tr>
<tr>
<td>DELPHI</td>
<td>111.2</td>
<td>112.3</td>
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<tr>
<td>OPAL</td>
<td>109.3</td>
<td>112.2</td>
</tr>
<tr>
<td>LEP 4J</td>
<td>111.8</td>
<td>114.1</td>
</tr>
<tr>
<td>LEP Neutrinos</td>
<td>110.9</td>
<td>112.1</td>
</tr>
<tr>
<td>LEP Tau</td>
<td>103.7</td>
<td>105.7</td>
</tr>
<tr>
<td>LEP Lepton</td>
<td>110.6</td>
<td>110.0</td>
</tr>
<tr>
<td>LEP</td>
<td>113.2</td>
<td>115.0</td>
</tr>
</tbody>
</table>

- All limits are preliminary
- Limits are quoted at 95% CL
- All computed consistently with the same test-statistic, error handling, etc. and may differ from the experiments’ limits esp. when CL curves are near the 5% edge.
**Background Confidence Level**

**Evolution: Reanalysis and New Data**

Situation  

<table>
<thead>
<tr>
<th>Situation</th>
<th>Significance of 1-CL$_b$ Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept. LEPC</td>
<td>2.6$\sigma$</td>
</tr>
<tr>
<td>“Reference”</td>
<td>2.2$\sigma$</td>
</tr>
<tr>
<td>October 10:</td>
<td>2.5$\sigma$</td>
</tr>
</tbody>
</table>
Current Status of $1-{\text{CL}}_b$ on the Roadmap

- **Background-Only Hypothesis**
  - $m_H = 115$ GeV
  - We are here

- **Signal+Background Hypothesis**
  - $m_H = 115$ GeV
  - Expectation
The Neutral Higgses of the MSSM

Two Higgs Doublets: 5 Higgses

$h^0$ light CP-even Higgs
$H^0$ heavy CP-even Higgs
$A^0$ CP-odd Higgs
$H^+, H^-$ Charged Higgs

$m_{h^0} < \sim 135$ GeV

Higgs-strahlung

$$\sigma_{hZ} = \sin^2 (\beta - \alpha) \sigma_{hZ}^{SM}$$

And fusion processes too!

Associated Production

$$\sigma_{hA} = \cos^2 (\beta - \alpha) \bar{\lambda} \sigma_{hZ}^{SM}$$

$\bar{\lambda}$: kinematic factor $(m_h, m_A, \sqrt{s})$
**Reconstructed Mass Distribution of hA Search Candidates**

MSSM constraint: cross-section is large only for $m_h \approx m_A$. So plot $m_h + m_A$ for the minimum mass difference (4jet).

**Four-b channel:**

**bbττ channel:**
MSSM Exclusions in the Max-\(m_H\) Scenario

Mass Limits:

\[ m_H > 89.9 \quad 93.8 \]
\[ m_A > 90.5 \quad 94.1 \]

\(\tan\beta\) excluded from
\[ 0.52 \text{ to } 2.25 \quad \text{obs.} \]
\[ 0.48 \text{ to } 2.48 \quad \text{expected} \]
Summary and Plans for the LEP Higgs WG

- Much progress for one month:
  - 79 pb$^{-1}$ of data added in combination
  - Detailed systematic checks
    - Excess is robust under scrutiny
    - Excess is more consistent -- two experiments see excess candidates

- Minimal SM Higgs excluded for $m_H < 113.2$ GeV -- but we expected to exclude up to 115.0 GeV

- 2.5σ excess persists at $m_H = 115$ GeV.
  September LEPC: 2.6σ
  Same data with new analysis: 2.2σ
  With new data: 2.5σ

Actual history of CL$_b$ will depend on the discrete arrival of candidates.
  Sawtooth CL$_b$ vs. time (if there is a signal)

- Another combination planned for the 3 November LEPC.