Combined LEP Higgs Searches

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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**

\[ \int L dt \ [\text{pb}^{-1}] \]

<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.

**OPAL Preliminary**

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

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

\(E_{CM}\) 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

$$\frac{s_{\text{expected}}}{b_{\text{expected}}} \approx 0.3$$

For $m_{\text{rec}} > 109$ GeV

for a 114 GeV Higgs

---

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

This time, adjust cuts so that

\[
\frac{s_{\text{expected}}}{b_{\text{expected}}} \approx 1.0 \quad \text{For } m_{\text{rec}} > 109 \text{ GeV}
\]

for a 114 GeV Higgs

\[
\begin{array}{ccc}
\text{Events / 3 GeV/c}^2 & \text{Data} & \text{Backg} & \text{Signal} \\
\text{All } m_{\text{rec}} & 103 & 92.5 & 11.3 \\
\text{m}_{\text{rec}} > 109 \text{ GeV} & 7 & 7.5 & 7.2
\end{array}
\]
Very Hard Cuts

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

For m_{rec} > 109 GeV
for a 114 GeV Higgs

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

LEP S/B=2.0

Data   Backg   Signal

\begin{tabular}{lccc}
All m_{rec} & 42 & 34.0 & 5.6 \\
m_{rec} > 109 GeV & 5 & 2.3 & 3.9 \\
\end{tabular}

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

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”

Background-like

Signal-like
**Updated Analysis 1: ALEPH**

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

```
-2 ln(Q)

m_H (GeV/c^2)

ALEPH-4j \sqrt{s} \leq 210 GeV

Observed
Expected background
Expected signal

“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

Events / 3 GeV/c^2

background

hZ Signal

(m_h=114 GeV)

all > 109 GeV
cnd= 12 0
bgd= 9.71 0.44
gsl= 1.13 0.78

Reconstructed Mass m [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

- **$\text{CL}_s$** -- compatibility with signal hyp.
  $\text{CL}_s < 0.05$: Signal hypothesis ruled out at the 95% CL.

- **$\text{CL}_b$** -- compatibility with background hyp.
  $1 - \text{CL}_b < 5.7 \times 10^{-7}$ is a $5\sigma$ 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:** $\pm 0.2\sigma$

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

Lepton
Neutrino
Tau

Combined they are as sensitive as the four-jet channels
### 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>
</tr>
<tr>
<td>L3</td>
<td>113.0</td>
<td>110.9</td>
</tr>
<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**

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

Background-Only Hypothesis

Signal+Background Hypothesis

Expected 1-CL$_b$ vs. Additional Luminosity/experiment at 206.6 GeV

$m_H = 115$ GeV

We are here

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

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

Higgs-strahlung

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

And fusion processes too!

Associated Production

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

$\overline{\lambda}$: 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: $b\bar{b}\tau\tau$ channel:
MSSM Exclusions in the Max-$m_H$ Scenario

Mass Limits:

<table>
<thead>
<tr>
<th></th>
<th>obs</th>
<th>expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H$</td>
<td>&gt; 89.9</td>
<td>93.8</td>
</tr>
<tr>
<td>$m_A$</td>
<td>&gt; 90.5</td>
<td>94.1</td>
</tr>
</tbody>
</table>

$\tan\beta$ excluded from

<table>
<thead>
<tr>
<th></th>
<th>obs</th>
<th>expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tan\beta$</td>
<td>0.52 to 2.25</td>
<td>0.48 to 2.48</td>
</tr>
</tbody>
</table>
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

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