Status of Higgs Boson Searches

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ALEPH, DELPHI, L3, OPAL
and the
LEP Higgs Working Group

- Statistics ... definitions
- Data sets ... REF, DELTA, TOTAL
- RESULTS ... REF, DELTA, TOTAL
- Consistency ... btw Experiments / Channels
- Extrapolations ... the “Road map”
TASK ... to combine “channels” from four experiments
Data sets @ different $E_{cm}$ and Luminosities

Different decay-channels

$$e^+e^- \rightarrow Z \rightarrow b\bar{b}, \tau^+\tau^-$$

$$\rightarrow q\bar{q}, \nu\bar{\nu}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$

(1) INPUTS ... for each “channel” ... binned in two discriminating variables (both contribute to the search sensitivity)

- Reconstructed Higgs mass $M_H^{rec}$
- Global variable $g$ ... containing
  
  b-tag, kinematics, jet-properties ...

In each bin $i$ ...

- Bkgd. (MC) $b_i$
- Signal (MC) $s_i(m_H)$ for “test-mass” $m_H$
- Nbr of candidates $N_i$

\[
\begin{array}{c|c|c|c}
\uparrow & g & s_i/b_i & M_H^{rec} \\
\hline
\end{array}
\]

MC estimates of $s_i(m_H)$ and $b_i$ take into account the exp’tal details (e.g. $E_{cm}$, lumi, signal eff., mass-resol., bkgds ...)

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For “test-mass” $m_H$ ...

(2) **LIKELIHOOD TEST** ... “sig + bkgd” $\leftrightarrow$ “bkgd”

$$-2 \ln Q(m_H) = 2s_{tot} - 2 \sum N_i \ln [1 + s_i(m_H)/b_i]$$

$$Q(m_H) = \mathcal{L}(s + b)/\mathcal{L}(b) \quad \text{“test-statistic”}$$

to rank the observed event configuration between “$s + b$” and “$b$” hypotheses

For arbitrary test-mass $m_H$ ... and replacing the data set by ficticious MC sets of “$s + b$” and “$b$” configurations

$\Rightarrow$ expected curves ... and statistical spread


(3) CONFIDENCE LEVELS ...

- **$1 - CL_b$** ... a measure of incompatibility with "b"
  
  Given an ensemble of "b" experiments ...
  
  probability to obtain an event configuration less bkgd-like than the observed event configuration

<table>
<thead>
<tr>
<th>$1 - CL_b$</th>
<th>0.32</th>
<th>0.046</th>
<th>$2.7 \times 10^{-3}$</th>
<th>$6.3 \times 10^{-5}$</th>
<th>$5.7 \times 10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $\sigma$</td>
<td>2 $\sigma$</td>
<td>3 $\sigma$</td>
<td>4 $\sigma$</td>
<td>5 $\sigma$</td>
<td></td>
</tr>
</tbody>
</table>

- **$CL_{s+b}$** ... a measure of incompatibility with "s + b"

$$CL_s = CL_{s+b}/CL_b \Rightarrow \text{lower bound on Higgs mass}$$
Data Sets

- **REFERENCE** data set ... where it all begun ...
  data set combined for the **Sept 5 LEP seminar** ...

  **Revisited** ... changes within the experiments
  ⇒ Recalibration of data
  ⇒ Revision of procedures (corrections)
  ⇒ Improvements ... better sensitivity

- **DELTA** set ... data collected since “REF”
  (... until the “cutoff date” ... Oct 18-25)

- **TOTAL** = REF + DELTA

Integrated luminosities ... A+D+L+O = “ADLO”
(contributions from single experiments ... within ±5%)
Not included ... latest data ... = 30 pb⁻¹

<table>
<thead>
<tr>
<th>( \mathcal{L} ) (pb⁻¹)</th>
<th>REF</th>
<th>DELTA</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{cm} &gt; 200 \text{ GeV} )</td>
<td>596.6</td>
<td>213.7</td>
<td>810.3</td>
</tr>
<tr>
<td>( E_{cm} &gt; 206 \text{ GeV} )</td>
<td>303.5</td>
<td>184.5</td>
<td>488.0</td>
</tr>
</tbody>
</table>
Reference ⇒ Total

No spectacular changes anticipated
(limited additional luminosity)

Relevant question ... the TREND

● Does the “effect” increase / decrease ?

● Towards a better distribution ...
  between experiments ?
  between decay channels ?
• Derived independently by three people ...  
same sets of input, differing combination software

• Results of individual experiments ... reproduced  
comparisons of $-2 \ln Q, \; CL_s, \; 1 - CL_b$

• Detailed checking of non-trivial technical details  
problems fed back to the experiments

• Alternative test statistics ...  $\Delta = \pm 0.1 \sigma$

• Bypassing the syst. errors ...  $\Delta = +0.1 \sigma$

$\Rightarrow$ GLOBAL COMBINATION UNCERTAINTY  
on OBSERVED effect ...  
$\lesssim 0.2 \sigma$
\(-2 \ln(Q) \ldots \text{REF, DELTA, TOTAL}\)

\[ m_H(\text{GeV/c}^2) \]

\[ -2 \ln(Q) \]

\[ m_H(\text{GeV/c}^2) \]

\[ m_H = 115.0^{+1.3}_{-0.9} \text{ GeV} \]

Minimum @\( m_H \approx 115 \text{ GeV} \)

Agreement with SM Higgs cross-sect. for
Prob. density $@m_H = 115$ GeV ... REF, DELTA, TOTAL

REFERENCE

DELTA

TOTAL

ADLO

<table>
<thead>
<tr>
<th>Observed $-2 \ln(Q)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
</tr>
<tr>
<td>DEL</td>
</tr>
<tr>
<td>TOT</td>
</tr>
</tbody>
</table>
$1 - CL_b$ ... REF, DELTA, TOTAL

<table>
<thead>
<tr>
<th>ADLO</th>
<th>$1 - CL_b$</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>$2.5 \times 10^{-2}$</td>
<td>$2.2\sigma$</td>
</tr>
<tr>
<td>DEL</td>
<td>$2.2 \times 10^{-2}$</td>
<td>$2.3\sigma$</td>
</tr>
<tr>
<td>TOT</td>
<td>$4.2 \times 10^{-3}$</td>
<td>$2.9\sigma$</td>
</tr>
</tbody>
</table>
(values quoted @ $m_H = 115$ GeV)

<table>
<thead>
<tr>
<th></th>
<th>$1 - CL_b$</th>
<th></th>
<th></th>
<th>$1 - CL_b$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ALEPH</strong></td>
<td></td>
<td></td>
<td><strong>DELPHI</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>REF</td>
<td>$1.6 \times 10^{-4}$</td>
<td>$3.8\sigma$</td>
<td>REF</td>
<td>0.67</td>
<td>bkgd-like</td>
</tr>
<tr>
<td>DEL</td>
<td>0.43</td>
<td>bkgd-like</td>
<td>DEL</td>
<td>0.52</td>
<td>bkgd-like</td>
</tr>
<tr>
<td>TOT</td>
<td>$6.5 \times 10^{-4}$</td>
<td>$3.4\sigma$</td>
<td>TOT</td>
<td>0.68</td>
<td>bkgd-like</td>
</tr>
<tr>
<td><strong>L3</strong></td>
<td></td>
<td></td>
<td><strong>OPAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>REF</td>
<td>0.84</td>
<td>bkgd-like</td>
<td>REF</td>
<td>0.47</td>
<td>bkgd-like</td>
</tr>
<tr>
<td>DEL</td>
<td>$9.0 \times 10^{-3}$</td>
<td>$2.6\sigma$</td>
<td>DEL</td>
<td>$6.2 \times 10^{-2}$</td>
<td>$1.9\sigma$</td>
</tr>
<tr>
<td>TOT</td>
<td>$6.8 \times 10^{-2}$</td>
<td>$1.8\sigma$</td>
<td>TOT</td>
<td>$1.9 \times 10^{-1}$</td>
<td>$1.3\sigma$</td>
</tr>
</tbody>
</table>
Results by Experiments

for TOTAL data set, $@m_\text{H} = 115$ GeV

ALEPH

DELPHI

L3

OPAL

-2 ln Q

Prob. Density

Observed

Background

Signal
Results by Decay-Channel

for TOTAL data set, $m_H = 115$ GeV
Contributions from Single Candidates

(for TOTAL data set)

\[-2 \ln(Q) \sim \sum \ln(1 + s_i/b_i)\]

\[1 + s/b \text{ ... an indicator of event “weight”}\]
Distributions of Event “weights”

(for TOTAL data set @ $m_H = 115$ GeV)

“Bkgd”-like or “Signal+bkgd”-like?

[Graph showing distributions of event weights with data points and histograms for expected signal and background.]
Expected rates @ $m_H = 115$ GeV ..... TOTAL

Integrating bkgd, signal and data ...
for $s/b \gtrsim 1$

<table>
<thead>
<tr>
<th></th>
<th>Backgd</th>
<th>Signal</th>
<th>Candidates</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADLO 4-jet</td>
<td>0.93</td>
<td>1.60</td>
<td>3</td>
</tr>
<tr>
<td>E-miss</td>
<td>0.30</td>
<td>0.46</td>
<td>1</td>
</tr>
<tr>
<td>Lept</td>
<td>0.35</td>
<td>0.68</td>
<td>0</td>
</tr>
<tr>
<td>Taus</td>
<td>0.14</td>
<td>0.29</td>
<td>0</td>
</tr>
<tr>
<td>ADLO All chan.</td>
<td>1.72</td>
<td>3.03</td>
<td>4</td>
</tr>
</tbody>
</table>

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Distributions of Reconstructed Mass

Sequence: “Loose”, “Medium” and “Tight” selection (*)

(*) Special selection ... not biasing the mass distribution
Perfect compatibility with SM Higgs cross section for

\[ m_H = 115.0^{+1.3}_{-0.9} \text{ GeV} \]

! ALL THIS ISVERY EXCITING !

Current bound on Higgs boson mass

\[ m_H > 113.5 \text{ GeV @95% c.l.} \]

for 115.3 GeV expected
The “Road-Map” ... Since Sept’ 2000

If accumulating background only ...

If accumulating signal + background ...

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The “Road-Map” ... Running at $E_{cm} = 208.2$ GeV

If accumulating background only ...

If accumulating signal + background ...

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RECOMMENDATION

Given the consistency for the combined results with the hypothesis of the production of a SM Higgs boson with a mass of 115 GeV, and an observed excess in the combined data set of \(2.9\sigma\), a further run with \(200 \text{ pb}^{-1}\) per experiment at 208 GeV would enable the four experiments to establish a \(5\sigma\) discovery.

The four experiments consider the search for the SM Higgs boson to be of the highest importance, and CERN should not miss such a unique opportunity for a discovery.

Therefore, we request to run LEP in 2001 to collect \(\mathcal{O}(200 \text{ pb}^{-1})\) at \(\sqrt{s} \geq 208\) GeV.

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