Higgs Searches at LEP (2)

Combination & non-SM Higgs Bosons

W. Adam

HEPHY, Vienna

on behalf of the four LEP collaborations

- Combined results of the search for the SM Higgs
- Search for MSSM neutral Higgs Bosons
- Search for $H^+H^-$
- General 2HDMs and special decay channels
- Conclusions

All results shown in this talk are preliminary !!!
The basic approach:
reconstructed mass spectra
(sum of expt’s and channels irrespective of separation power)

... but that’s only part of the story!
**SM - combined**

ALEPH

≈ 209 pb\(^{-1}\) of ’00 data*  
+ previous years

DELPHI

≈ 214 pb\(^{-1}\) of ’00 data*  
+ previous years

L3

≈ 201 pb\(^{-1}\) of ’00 data*  
+ previous years

OPAL

≈ 219 pb\(^{-1}\) of ’00 data*  
+ previous years

* indicative; data of last few days not yet used in combined results
SM - combined

Classification of the LEP result for different \( m_H \):

Channels

Likelihood ratio vs. \( m \)

Separation of B- and S+B lines indicates power

Median S+B line for varying hypotheses

Fixed mass signal creates “cross-talk” to other hypotheses!
SM - combined

Single event weights

Weight evolution reflects mass resolution and \( \sigma(m_h) \)

summed to obtain \( \ln Q \)
SM - combined

Distribution of all event weights

∫ gives

Signal size is limited by cross section and preselection efficiencies!

Points are correlated!
SM - combined

-2\ln Q / channel for \( m_h = 115 \text{GeV} \)

-2 ln Q / channel for \( m_h = 115 \text{GeV} \)

Hll  
Hvv  
Hqq  
H\tau\tau + \tau\tau Z

Observed  
Background  
signal

ee, \( \mu\mu \) channels are clean, but low \( \sigma \times \text{BR} \)!

Reminder: SM H branching ratios
**SM - combined**

Exclusion?

- Check $CL_S$

(conservative estimate for $S+B$ confidence level)

Hard to exclude with an excess of high weight events!

Note exclusion potential!
Or a hint of a Higgs?

- Check $1-CL_B$
  (compatibility with B-hypothesis)

**Definition of n-$\sigma$ lines:**

$$1 - CL_b = 1 - \int_{-n}^{+n} G(x; 0, 1) \, dx$$

Incompatibility with B-hypothesis: $2.9\sigma$
(uncertainty $\approx 0.2\sigma$)
SM - combined

3-σ discovery potentials

Probability to discover a Higgs at mass $m_H$

... /channel and ...

... /experiment
SM - combined

Evolution September → November

If there was no Higgs in reach ...

Significance of the 114 / 115 GeV hypotheses on Sep. 5

... or one at 114 or 115 GeV

If there was no Higgs in reach ...

Additional Luminosity @ 206.6 GeV (pb⁻¹)

Expected 1-CLb
**MSSM (h, A)**

Neutral Higgs bosons in the MSSM

- Assume CP conservation

  - Two CP even states $h, H$
    (defined by $m_h < m_H$)
  - One CP odd state $A$

Production: main mechanisms at LEP

- **Higgsstrahlung** $hZ$
  (similar to SM $H$)

  \[
  e^- e^+ \rightarrow Z^+ \rightarrow h \propto \sin(\beta - \alpha) \\
  e^- e^+ \rightarrow Z^+ \rightarrow A \propto \cos(\beta - \alpha)
  \]

- **Pair production** $hA$

Assume CMSSM with 7 parameters

- $m_{SUSY}$ (sfermion masses at EW scale)
- $m_2$ (gaugino masses at EW scale, $\rightarrow m_1$)
- $m_{\text{gluino}}$
- $X_t$ (off-diagonal in stop mixing matrix)
- $\mu$ (Higgs mass parameter)
- $\tan \beta$ (ratio of vacuum expectation values)
- $m_A$
MSSM (h, A)

Still a lot of parameters → “benchmarks”

- “no mixing”: $X_+ = 0$
  - $m_{\text{SUSY}} = 1\text{TeV}$, $m_2 = -\mu = 200\text{GeV}$, $m_{\text{gluino}} = 800\text{GeV}$, $0.4 < \tan\beta < 50$, $m_A < 1\text{TeV}$
  - maximise reach

- “mh max”: $X_+ = 2m_{\text{SUSY}}$ (FD* scheme)
  - other parameters as above
  - maximise $m_h$ for each $\tan\beta$

- “large $\mu$”: highlight non-bb decays

* Two calculations at two loop level
  - Feynman-diagrammatic approach (FD)
  - Renormalisation group approach (RG)

Good agreement, but different renormalisation schemes!
**MSSM (h, A)**

**m_h-max benchmark**

**conservative assumptions for tanβ exclusion**

$$m_h > 89.9\text{GeV} \\ (\text{exp}:93.8)$$

$$m_A > 90.5\text{GeV} \\ (\text{exp}:94.1)$$

$$\tan\beta \notin [0.52, 2.25] \\ (\text{exp}:[0.48, 2.48])$$

Branching ratios to b-pairs $\rightarrow$
MSSM (h, A)

$m_h$-max benchmark

same scenario presented in the $\tan\beta$-$m_A$ and ...

... $m_h$-$m_A$ plane

W. Adam: Higgs Searches at LEP (2)  Aspen, Jan. 8, 2001
**MSSM (h, A)**

no-mixing benchmark

---

**DELPHI**

Preliminary

\( \sqrt{s} \) from 130 to 208.2 GeV

- \( m_{t_{top}} = 175 \text{ GeV}/c^2 \)
- \( M_{\text{supy}} = 1 \text{ TeV}/c^2 \)
- \( M_{2} = -\mu = 200 \text{ GeV}/c^2 \)
- \( \tan \beta \geq 0.4 \)
- No mixing

---

Experimentally excluded

Theoretically forbidden

h→AA dominant, low BR(A→bb)

---

W. Adam: *Higgs Searches at LEP (2)*

Aspen, Jan. 8, 2001
Charged Higgs

- Consider general 2HD model
  - (in MSSM: $m_{H^±} > m_{W^±}$ at tree level)
  - cross section determined by $H^±$ mass (at tree level)
  - search assumes $\text{BR}(\rightarrow \tau \nu) + \text{BR}(\rightarrow cs) = 1$
    $\rightarrow$ search for hadronic, semi-leptonic and purely leptonic topologies

irreducible background: $W^+W^-$

H$^±$ cross section

\[ \text{e}^+\text{e}^- \rightarrow H^+H^- \]

at $E_{CMS} = 206\text{GeV}$
Charged Higgs

Combined LEP exclusion

W-mass “hurdle” (partially) passed

L3 flavour independent 4-jet, equal mass

ALEPH preliminary
L=178.3 pb⁻¹
Data = 889
MC = 893.77

ALEPH charged Higgs 4-jet channel

DELPHI charged Higgs analysis
Flavour independent

Motivation:
Reduce model dependence:

- limits on $S^0Z^0$ scalar production
- limits in general 2HD models
- e.g.: flavour independent search for hadronic decays of $S^0 (\rightarrow qq$ or $gg$)

Exclusion for a type II 2HDM

Similar, more generally, for $BR_{\text{had}} \times \sigma/\sigma_{\text{SM}}$
Fermiophobic

Look for $h \rightarrow \gamma \gamma$

Tiny in SM

**Motivation** e.g. type I 2HD models:
- one Higgs doublet doesn't couple to fermions
- coupling $hff \propto \cos \alpha$
  ($\alpha =$ mixing angle in CP even Higgs sector)
- production via Higgsstrahlung

![ADLO Combined Photonic Higgs Search](image)

**Upper Limit on $B(h^0 \rightarrow \gamma \gamma)$**

- 5 September Update
- Excluded Region

**Median expected**

- +2 sigma expected
- -2 sigma expected

**Limit = 107.7 GeV**

**exp.: 105.8 GeV**

assumes SM cross section

(otherwise use $\sin^2(\beta-\alpha)$)
Extend search to $h_A - 2HDM(I)$

Additional topologies include:

- $\gamma\gamma A$ (long-lived) and $\gamma\gamma bb$ from $h_A$
- $\gamma\gamma Z$ from $h_A$ with $A \rightarrow h_Z$
- 6b final state from $h_A$ with $h \rightarrow AA$

exclusion for 2HDM(I):
complementarity $h_Z - h_A$
(H-H-interactions: potential A)

W. Adam: Higgs Searches at LEP (2) Aspen, Jan. 8, 2001
**Invisible Higgs decays**

**Typical scenario:**

- $h \rightarrow \text{LSPs in SUSY}$
- look for $hZ$ production
- exp. similar to the $Z \rightarrow \nu\nu, h \rightarrow bb$ channel, but no selection of $b$-tagged events

For BR=1: $m > 113.7\text{GeV}$ (exp: 112.8GeV)
Conclusions

- The SM Higgs search shows an excess in data compatible with a Higgs boson mass of about 115GeV.

No more data from LEP
→ be patient !!!

- A multitude of other Higgs channels are covered by LEP searches (in particular MSSM neutral Higgs bosons).

- Trend to investigate more models, to perform parameter scans and search for unusual decay channels.

The LEP accelerator may have stopped, but the analysis teams are still active
→ stay tuned !!!