Higgs searches at LEP: Beyond the SM and MSSM models

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Where oh where’s my underwear?  
Where oh where can they be? I can’t find them anywhere!

They must be hiding from me...
Have we looked everywhere?

Done so far:
- Fermiophobic and invisible decays
- Yukawa couplings
- Charged and doubly-charged Higgs searches
- Flavour and decay-mode independent searches
- Low $m_A$ search
- Anomalous Higgs couplings
- 2HDM interpretations
Extensios to SM and MSSM

- Standard Model predicts one Higgs doublet:
  - one physical state: $H^0$

- Simplest extension: 2HDM with 5 physical states:
  - 2 CP-odd: $h^0$, $H^0$
  - 1 CP-even: $A^0$
  - 2 charged: $H^\pm$

  $H^0$ the heaviest: not expected at LEP

- 2HDM Type I: one doublet couples to fermion; one to bosons
- 2HDM Type II: one doublet couples to up-type ($\nu, u, c, t$)
  - one doublet couples to down-type ($\tau, d, s, b$)

  (MSSM is a special case of 2HDM Type II)

- Another possibility: one couples to leptons, one to quarks
- Higgs triplets models $\Rightarrow H^{++}$
Higgs production and decay at LEP

3 Higgs production modes at LEP:

- **Higgsstrahlung**
  - Diagram:
  - Equation: $e^+e^- \rightarrow h^0Z^0$ 
    \[ \sigma_{hZ} = \sin^2(\beta - \alpha) \sigma_{Hz}^{SM} \]
  - Couplings to fermions depend on the mixing angle $\alpha$ between the two doublets and $\tan\beta = v_2/v_1$

- **Pair production**
  - Diagram:
  - Equation: $e^+e^- \rightarrow h^0A^0$ 
    \[ \sigma_{hA} = \cos^2(\beta - \alpha) \bar{\lambda} \sigma_{Hz}^{SM} \]

- **Yukawa production**
  - Diagram:
  - Equation:

$\bar{\lambda}$: accounts for suppression of P-wave near threshold
Fermiophobic Higgs decays

- SM allows $H^0 \rightarrow \gamma \gamma$ only at one-loop level ($\text{BR} \leq 10^{-3}$)
- Several models predict bosonic Higgs couplings
- In 2HDM(I), one doublet couples to bosons only

 Benchmark fermiophobic Higgs boson: SM production $\sigma$ with fermionic BR turned off

$$\Rightarrow \sigma(h^0 Z) \ast \text{BR}(h^0 \rightarrow \gamma \gamma)$$

becomes sizeable
Combined LEP data for \( \text{BR}(h^0 \rightarrow \gamma \gamma) \) in \( h^0Z \) events

Mass limit: 109.7 GeV (fermiophobic benchmark scenario)
OPAL general fermiophobic search

Search for $e^+e^- \rightarrow XY$
for $\sqrt{s} = \{205-207\}$ GeV
- For $X$: scalar $X \rightarrow \gamma \gamma$
- $Y$: scalar or vector
- $Y \rightarrow ff$ ($qq, ll, \nu\nu$)

Set limits on $\sigma(XY) \times BR(X \rightarrow \gamma \gamma) \times BR(Y \rightarrow ff)$
Search for $h^0Z$: $h^0 \rightarrow WW, ZZ$ at L3
Fermiophobic LEP searches

- **Delphi**: search for $h^0Z^0$ and $h^0A^0 \rightarrow \gamma \gamma \gamma \gamma$
  

- **Opal**: search for $e^+e^- \rightarrow XY$, and $X \rightarrow \gamma \gamma$
  

- **L3**: $hZ$ with $h^0 \rightarrow WW, ZZ$: CERN-EP/2002-080
  
  $h^0 \rightarrow \gamma \gamma$
  


- **LEP combined**: $h^0Z$ with $h^0 \rightarrow \gamma \gamma$: LHWG Note/2002-02
Invisible Higgs decay: $h^0 \rightarrow \chi^0 \chi^0$

- Dominant invisible Higgs decays possible in
  - Majoron models
  - Supersymmetric models depending on parameters choice

- $h$ detected via associated $Z$: acoplanar jets or dileptons
**Combined LEP data for $h^0 \rightarrow \chi^0 \chi^0$**

<table>
<thead>
<tr>
<th>Experiment:</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
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</thead>
<tbody>
<tr>
<td>Integrated luminosity in 2000 (pb$^{-1}$):</td>
<td>215.6</td>
<td>225.1</td>
<td>217.3</td>
<td>210</td>
</tr>
<tr>
<td>Backg. predicted / Evts. observed:</td>
<td>8.17 / 8</td>
<td>35.9 / 30</td>
<td>56.2 / 50</td>
<td>61.8 / 47</td>
</tr>
<tr>
<td>Acoplanar jets:</td>
<td>6.7 / 7</td>
<td>21.7 / 13</td>
<td>5.9 / 9</td>
<td>–</td>
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<tr>
<td>Acoplanar leptons:</td>
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<tr>
<td>Events in all channels</td>
<td>14.9 / 15</td>
<td>57.6 / 43</td>
<td>62.1 / 59</td>
<td>61.8 / 47</td>
</tr>
<tr>
<td>Median 95% CL Limit (GeV/c$^2$):</td>
<td>112.6/111.8</td>
<td>110.7/110.7</td>
<td>110.2/110.1</td>
<td>107.4*/108.5</td>
</tr>
<tr>
<td>Observed 95% CL Limit (GeV/c$^2$):</td>
<td>114.1/113.1</td>
<td>113.0/113.0</td>
<td>107.6/107.5</td>
<td>107.0/107.4</td>
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</tbody>
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**Test statistics:** 
- $-2 \ln Q$: a negative value would indicate a signal.

**Mass limit:** 114.4 GeV

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**Diagram:**
- Observed
- Median Background
- Mean, Signal

For $-2\ln Q$ at 115.0 GeV/c$^2$ is 2.97
Latest publications on $h^0 \rightarrow \chi^0 \chi^0$

- **Aleph:** Phys Lett B526 (2002) 191
- **Delphi:** 2002-025-CONF-559 (ICHEP 2002)
- **L3:** Note #2690 (EPS 2001)
- **Opal:** Physics Note #472 (ICHEP 2002)
- **LEP combined:** hep-ex/0107032 – Summer 2001
Yukawa production

Three Higgs production modes at LEP:

- Higgsstrahlung
- Pair production
- Yukawa production

Yukawa process could dominate if:

- Higgsstrahlung is suppressed (mixing of 2 doublets in 2HDM)
- Pair production impossible if $m_A + m_h > \sqrt{s}$

Scenario possible in general 2HDM model
Cross-section of Yukawa process

\[ \sigma_{\text{Yukawa}} \propto m_f^2 N_c \xi_f^2 \]

- \( N_c \): color factor
- \( \xi_f \): enhancement factor

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<thead>
<tr>
<th></th>
<th>down-type</th>
<th>up-type</th>
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<tbody>
<tr>
<td>( \xi_f )</td>
<td>( \xi_d )</td>
<td>( \xi_u )</td>
</tr>
<tr>
<td>( A )</td>
<td>( \tan \beta )</td>
<td>( 1/\tan \beta )</td>
</tr>
<tr>
<td>( h )</td>
<td>(- \sin \alpha /\cos \beta )</td>
<td>( \cos \alpha /\sin \beta )</td>
</tr>
</tbody>
</table>

Two possible cases:

- For \( \xi_d < 1 \): \( \xi_u > 1 \)
  - cc radiates Higgs
- For \( \xi_d > 1 \):
  - bb radiates Higgs
  - \( A/h \rightarrow \tau \tau \) or bb

Only LEP I data: \( \sigma(bb)_{\text{LEP I}} = 100 \times \sigma(bb)_{\text{LEP II}} \)
Decay signature in Yukawa production

- Opal search channel:
  \[ e^+e^- \rightarrow b\ b\ \ A/h^0 \]
  \[ A/h^0 \rightarrow \tau\ \ \tau \]

- Higgs emitted at high energy: decay products constrained to one single jet
Opal results on Yukawa couplings

95% CL on $\xi_d$ in 2HDM type II model

a) for CP-odd $A^0$

b) for CP-even $h^0$

Delphi search: more general

Search modes:

\[ A/h^0 \rightarrow \tau \tau \text{ or } b b \]
\[ b b \tau \tau \text{ and } b b b b \]
Search for $h^0A^0 \rightarrow \tau\tau\tau\tau$ at Delphi

- Possible in 2HDM if one doublet couples only to leptons
- Look for 4 narrow, low-multiplicity jets
- Look in 2, 3, 4-jets events
- $m_A = [4-170]$ GeV
- $m_h = [4-90]$ GeV
- Signal efficiency: 21% - 58.6%

<table>
<thead>
<tr>
<th>observed in data</th>
<th>expected from SM</th>
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<tbody>
<tr>
<td>6 events</td>
<td>9.5 events</td>
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</table>

see Delphi 2002-037-CONF-571 ICHEP 2002 (still preliminary)
Charged Higgs

- Predicted by 2-doublet extensions of SM
- Production mechanism: $e^+e^- \rightarrow H^+H^-$
- In MSSM, at tree level
  $m_{H^+} > m_{W^+}$
- $m_{H^+} < m_{W^+}$ barely allowed by MSSM but possible with R-parity violation

Assume all decays to be $H^+ \rightarrow cs$ and $\tau^+\nu$:

- $H^+H^- \rightarrow \tau^+\nu\tau^-\nu$
- $H^+H^- \rightarrow cs\tau^-\nu$
- $H^+H^- \rightarrow cs\ cs$

$H^+H^-$ signal implies beyond MSSM physics
**L3 excess at $m_{H^+} = 68$ GeV**

- Slight excess seen in 189-202 GeV data

- Mass limits then were between 67.4-79.9 GeV depending on $BR(H^+ \rightarrow \tau^+\nu)$

  Excess most significant for low $BR(H^+ \rightarrow \tau^+\nu)$

<table>
<thead>
<tr>
<th></th>
<th>$\tau^+\nu$</th>
<th>$\tau^-\nu$</th>
<th>CS $\tau^-\nu$</th>
<th>CS CS</th>
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<tbody>
<tr>
<td><strong>data</strong></td>
<td>44</td>
<td>171</td>
<td>961</td>
<td></td>
</tr>
<tr>
<td><strong>bgnd</strong></td>
<td>49.8</td>
<td>171.8</td>
<td>883.3</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing data and background differences](image)

**Legend**
- Data–Background
  - $\sqrt{s} = 183–209$ GeV
- $H^+H^- \rightarrow c\bar{s}s$ and $c\bar{s}\tau^+\nu$: $M_H = 68$ GeV
No signal elsewhere in $m_{H^+}$

All data taken in $H^+H^- \rightarrow cs\, cs$ channel, signal: $m_{H^+} \sim 70$ GeV

ALEPH

OPAL

Delphi
Combined LEP limits on $m_{H^+}$

- No signal elsewhere at 68 GeV even emulating L3 analysis
- No flaws found in L3 analysis despite great scrutiny

Interpreted as a 4.2 $\sigma$ background fluctuation

$m_{H^+} > 78.6$ GeV

Excluded by LEP

Expected
Latest publications on $H^+$

- **Aleph**: CERN-EP-2002-054
- **L3**: Note 2686 - (EPS 2001)
- **Opal**: PN509 - (ICHEP 2002)
- **LEP**: Summer 2001, hep-ex/0107031
- **Delphi**: 2002-038-CONF-572 (ICHEP 2002)

includes $H^+ \rightarrow W^* A$
Search for doubly charged Higgs

- Exist in two Higgs triplet models
- At tree level, $H^{++}$ only couples to charged leptons and gauge bosons
- Production mode: $e^+e^- \rightarrow H^{++}H^{--}$
- Occur naturally in left-right symmetric models
  - these allow small neutrino masses
  - $\sigma (e^+e^- \rightarrow H_{R}^{++}H_{R}^{--}) \neq \sigma (e^+e^- \rightarrow H_{L}^{++}H_{L}^{--})$
  - Do not conserve baryon and lepton number
Decay characteristics for $H^{++}$

- $H^{++} \rightarrow l^+ l^+$, $l = e, \mu, \tau$
- Search for events with 4 leptons + missing energy (if $l = \tau$)
- $\Gamma(H^{++} \rightarrow \tau\tau) \propto h_{\tau\tau}$, $m_{{H^{++}}}$
  - $h_{\tau\tau}$: Yukawa coupling
- $H^{++}$ lifetime ~ zero for $h_{\tau\tau} > 10^{-7}$
- Long-lived if $h_{\tau\tau} < 10^{-7}$

<table>
<thead>
<tr>
<th></th>
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<th>Opal</th>
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<tr>
<td>$E_{cm}$ (GeV)</td>
<td>189-209</td>
<td>189-209</td>
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<tr>
<td>Total int. $L$</td>
<td>570 pb$^{-1}$</td>
<td>614 pb$^{-1}$</td>
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<tr>
<td>$h_{\tau\tau} &gt; 10^{-7}$</td>
<td>$m_H &gt; 99.6$</td>
<td>$m_H &gt; 98.5$</td>
</tr>
<tr>
<td>$h_{\tau\tau} &lt; 10^{-9}$</td>
<td>$m_H &gt; 99.3$</td>
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Flavour-independent searches

- Higgs to bb coupling can be suppressed in 2HDM, MSSM and composite models
- Would have been missed if h couples to any quark

Repeat SM searches without b-tag except for the 4-jet channel: add constraints to reduce background

- All LEP experiments have searched for HZ in qqqq, qqνν, qqℓ+ℓ− channels where q = any flavour
LEP mass and cross-section limits

SM $\sigma(HZ)$ and $BR(H \rightarrow qq) = 1$

Using HZ channel only
Gluon jets have higher multiplicity than quark jets

Search topologies:
1) 4-jet: if $m_A \sim m_h$,
2) 3-jet: if $m_h$ or $m_A$ light
3) 3-jet + high thrust: if both are light

**h^0 A^0 channel at Delphi with A^0 \rightarrow 4g**
Decay-mode independent search at OPAL

- Topological search
- Recoil mass spectrum of $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$
- Uses LEP I and II data

OPAL: CERN-EP-2002-032
Decay-mode independent limits

\[ k = \frac{\text{production cross-section}}{\text{SM cross-section}} \]

Excluded parameters in stealthy-Higgs scenario
Low mA search at OPAL

Low $m_A$ region not explored in MSSM

This is where $m_A$ is below the $b\bar{b}$ threshold
$h^0Z^0$ topology with $h^0 \rightarrow A^0A^0$

$A^0$ has high boost:
see only 2 jets
$Z^0 \rightarrow \nu\nu$ or $l^+l^-$

**CERN-EP/2002-058**

Pauline Gagnon – Indiana University
2HDM interpretations

- Re-interpretation of all MSSM data in the framework of 2HDM
- Done at OPAL for 2HDM Type II
  - EPJC 18 (2201) 425 and OPAL PN475
- Soon to be redone with all LEP data
- Scan the parameter space for \((m_A, m_h, \tan \beta, \alpha)\)
2HDM interpretation at OPAL

For any value of $\alpha$

For specific values of $\alpha$
Anomalous couplings at L3

If any of these couplings is large, expect to see enhancement w.r.t. SM cross-sections.

Depend on various couplings: $d, d_B, \Delta g_1^Z, \Delta \kappa^\gamma, \delta_Z$

- $e^+e^- \rightarrow H\gamma$
- $e^+e^- \rightarrow H e^+e^-$
- $e^+e^- \rightarrow H Z$
Get limits on $\sigma \times \text{BR}$ and couplings

See L3 note 2774 (ICHEP2002)
## LEP Higgs search modes summary

<table>
<thead>
<tr>
<th>mode</th>
<th>Aleph</th>
<th>Delphi</th>
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<th>L3</th>
<th>LEP</th>
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<tr>
<td>$h^0 \rightarrow \gamma \gamma$</td>
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<td>$h^0 \rightarrow WW, ZZ$</td>
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<td>$h^0 \rightarrow \chi^0 \chi^0$</td>
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<tr>
<td>Yukawa coupling</td>
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<td>$H^\pm$</td>
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<td>$H^{\pm \pm}$</td>
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<td>anomalous coupling</td>
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- **final**
- **preliminary**
- **started**
- **not done**

PASCOS'03 – January 2003

Pauline Gagnon – Indiana University
What will we find on the way?

I found a sock I thought I lost a long, long time ago.

I found a doll I thought I'd never see again.

New particles???
But if we find a Higgs, we’ll see it everywhere