Search for Higgs in the two Doublet Models

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representing the LEP collaborations

● Description of the Model

● The Neutral sector
  - 2HDM general scan
  - Yukawa production mechanism

● The Charged sector

● Conclusions
Two Higgs Doublet Models

- 2HDMs are interesting since they add new phenoenomena wrt to the SM with the fewest parameters:

<table>
<thead>
<tr>
<th>SM</th>
<th>2HDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Higgs doublet</td>
<td>2 Higgs doublets</td>
</tr>
<tr>
<td>1 physical Higgs</td>
<td>5 physical Higgs bosons</td>
</tr>
</tbody>
</table>

✓ Five physical Higgs bosons:
- two neutral CP even scalars, $h^0$ and $H^0$ ($m_h < m_H$)
- one CP odd scalar, $A^0$
- two charged scalars, $H^{\pm}$

✓ $\rho = \frac{m_w^2}{m_Z^2 \cos^2 \theta_w} \sim 1$

✓ no FCNC

✓ in the absence of SUSY no extra particles besides those of the SM are required
The Type of 2HDM determined by the couplings of the Higgs doublets to the fermions:

**Type I:** is the case in which quarks and leptons do not couple to the first Higgs doublet, but couple to the second Higgs doublet in a manner analogous to the minimal Higgs model: 2HDM(I)

**Type II:** is the case in which the first Higgs doublet couples only to down-type quarks and leptons and the second doublet couples only to up-type quarks and neutrinos: 2HDM(II)

The Higgs sector of the MSSM is a 2HDM Type II in which the introduction of supersymmetry adds new particles and constrains the parameter space of the model.

study of 2HDM (II) more “general”
2HDM(II) Parameters

6 free parameters, assuming no CP violation:

- 4 masses:
  - $m_h$, $m_H$, $m_A$, $m_H^\pm$

- 2 angles:
  - $\alpha$, mixing angle that relates physical mass eigenstates with the field doublets
    \[
    h^0 = \sqrt{2} \left[ (\text{Re}(\phi_2) - \nu_2) \cos \alpha - (\text{Re}(\phi_1) - \nu_1) \sin \alpha \right]
    \]
    \[-\pi/2 \leq \alpha \leq \pi/2\]

- $\beta$, where $\tan \beta = \nu_2 / \nu_1$ ratio of the vacuum expectation values of the scalar fields
  \[0 \leq \beta \leq \pi/2\]
Neutral Sector

- tree level production cross-sections

\[ \sigma_{hZ} = \sin^2(\beta - \alpha) \sigma_{HZ}^{\text{SM}} \]

\[ \sigma_{hA} = \cos^2(\beta - \alpha) \bar{\lambda} \sigma_{HZ}^{\text{SM}} \]

Higgs-Strahlung

Pair-Production
- tree level couplings relative to SM values

\[
\begin{array}{c|c|c|c|c|c|c}
\hline
 & h^0 c\bar{c} & h^0 b\bar{b} & A^0 c\bar{c} & A^0 b\bar{b} \\
\hline
\hline
= & \frac{\cos \alpha}{\sin \beta} & -\frac{\sin \alpha}{\cos \beta} & \cot \beta & \tan \beta \\
\hline
\end{array}
\]

where allowed the \( h^0 \rightarrow A^0 A^0 \) decay can be the dominant one

\[ m_A = 16 \text{ GeV} \quad m_h = 60 \text{ GeV} \]


2HDM final state topologies

<table>
<thead>
<tr>
<th>hZ analysis</th>
<th>hA analysis</th>
</tr>
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<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
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</tr>
</tbody>
</table>

- SM hZ channels with $H_{\text{SM}}^0 = h^0$ with $h^0$ decaying into $b\bar{b}$ can be reinterpreted in 2HDM
- the decay $h^0 \rightarrow A^0 A^0$ is relevant where $m_h > 2m_A$: $Z^0 A^0 A^0 / A^0 A^0 A^0$ channels with $A^0 \rightarrow b\bar{b}$
- for low $|\alpha|$ and $\beta$ $\text{BR}(h^0 / A^0 \rightarrow b\bar{b}) \sim 0$ both b-tag and flavour independent searches are needed
2HDM(II) general scan by OPAL

- PN475, submitted to EPS01

HZHA generator (P. Janot CERN 96-01) to extract $\sigma_{hZ}$, $\sigma_{hA}$, BR’s

Covered parameter space:

- $1 \leq m_h \leq 120$ GeV
- $3\text{GeV} \leq m_A \leq 2$ TeV
- $0.4 \leq \tan \beta \leq 58.0$
- $\alpha = +\pi/2,+\pi/4,0,-\pi/4$ and $-\pi/2$
- $m_{H^+}$ and $m_H$ above the kinematically accessible region

LEP1+ LEP2 Data

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ [GeV]</th>
<th>Luminosity [pb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1999</td>
<td>$m_Z$, 183,189</td>
<td>115, 55, 171</td>
</tr>
<tr>
<td>1999</td>
<td>202,192,196, 200</td>
<td>215</td>
</tr>
<tr>
<td>2000</td>
<td>200- 209</td>
<td>208</td>
</tr>
</tbody>
</table>

- $h^0Z^0$ and $h^0A^0$ channels with and without b-tagging
- Constraint extracted by the limit on non standard contributions to the $Z^0$ width:
  $\Delta \Gamma_{\text{inv}} < 2.0 \text{ MeV} @95\% \text{CL}$ (CERN-EP 2000-153)
**mA vs mh projection:** a particular \((m_h, m_A, \alpha)\) point is excluded at 95%CL if it is excluded for all scanned values of \(\tan\beta\) - \(0.4 < \tan\beta < 58\).
a particular \((m_h, \tan \beta, \alpha)\) point is excluded at 95%CL if it is excluded for all scanned values of \(m_A\)

**OPAL PRELIMINARY**

(a) \(\alpha = \pm \pi/2\)

(b) \(\alpha = \pi/4\)

(c) \(\alpha = 0\)

(d) \(\alpha = -\pi/4\)
a particular \((m_A, \tan\beta, \alpha)\) point is excluded at 95\%CL if it is excluded for all scanned values of \(m_h\)

\[\tan\beta \text{ vs } m_A\]
DELPHI study (DELPHI 2001-068 CONF 496)

This study is dedicated to specific final states all Higgs decays are into b final states:

1. $e^+e^\to Z^0\to A^0h^0\to 4b$
2. $e^+e^\to Z^0\to A^0h^0\to A^0A^0A^0\to 6b$
3. $e^+e^\to Z^0\to Z^0h^0\to Z^0A^0A^0\to 4b2q$
   - dominant if $m_h > 2m_A$
   - not present in HZHA
4. $e^+e^\to Z^0\to A^0h^0\to h^0Z^0h^0\to 4b2q$
   - dominant if $m_A > m_h + m_Z$

DELPHI-LEP2

<table>
<thead>
<tr>
<th>Year</th>
<th>Lumi(pb$^{-1}$)</th>
<th>$\sqrt{s}$(GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>158.0</td>
<td>189</td>
</tr>
<tr>
<td>1999</td>
<td>228.0</td>
<td>192-202</td>
</tr>
<tr>
<td>2000</td>
<td>225.1</td>
<td>205-208</td>
</tr>
</tbody>
</table>

$c=\cos^2(\beta-\alpha)\sin\alpha/\cos\beta\tan\beta$

suppression factor for x-sec and BR
No exclusion for process \( e^+ e^- \rightarrow Z^0 \rightarrow A^0 h^0 \rightarrow h^0 Z^0 h^0 \rightarrow 4b2q \)
Yukawa Production in 2HDM

\[ \sigma_{\text{Yukawa}} \propto m_f^2 N_c \phi^2_{h/A} \]

- \( m_f \) = fermion mass
- \( N_c \) = colour factor of emitting fermion
- \( \phi^2_{h/A} \) = enhancement factor, describes the coupling of \( h/A \) to the emitting fermion
- SM Yukawa production suppressed by \( m_f^2/m_h^2 \)

\[ \begin{align*}
\sin^2(\beta-\alpha) &\sim 0 \quad \Rightarrow \quad \text{Higgs-Strahlung process suppressed} \\
A^0/h^0 &> \sqrt{s} \quad \Rightarrow \quad \text{Pair-Prodution kinematically forbidden}
\end{align*} \]

\[ \begin{align*}
\text{Yukawa enhancement factor to down-quarks(leptons)} &\\
hb\bar{b} \ (h\tau^-\tau^+) &\propto -\sin\alpha/\cos\beta \sim \tan\beta \quad \text{if } \sin(\beta-\alpha)\sim 0 \\
Ab\bar{b} \ (h\tau^-\tau^+) &\propto \tan\beta \\
\end{align*} \]

\( \tan\beta >> 1 \)

\[ \times \] enhancement of coupling to up-quarks(leptons) for \( \tan\beta << 1 \)

Not sufficient for the production and detection - is already excluded by search for \( Z \to h^0(A^0) \gamma \)

(M.Krawczyk et al. hep-ph/9811256)
Yukawa final topologies at LEP1

LEP2 number of produced b quarks 100 times smaller than LEP1 ⇒ LEP1 data analysed

Contributions from:
- ALEPH PA13-027 (ICHEP’96), DELPHI 99-76 CONF 263 (EPS’99), L3 submitted to EPS’95
- DELPHI 01-68 CONF-496, submitted to EPS’01, Budapest
- OPAL PN483, submitted to EPS’01, Budapest
New study: \( e^+e^- \rightarrow b\bar{b}A^0/h^0 \rightarrow b\bar{b}b\bar{b} \)

- 3-jet topology (one of \( bb \) pair \( \sim m_b \))
- 4-jet topology \( (m_{h/A} \sim m_Z/2) \)

study performed on 1994-1995 LEP1 data

Previous study:
- measurement of gluon splitting into \( b\bar{b} \) in the process \( Z^0 \rightarrow b\bar{b}g \Rightarrow \text{Not optimal} \) (DELPHI 99-76 CONF 263)
- 4\( \tau \) final state (DELPHI 99-76 CONF 263)
OPAL study  (OPAL PN 483)

\[ e^+e^- \rightarrow b\bar{b}A^0/h^0 \rightarrow b\bar{b}\tau^+\tau^- \]

- 2HDM(II) BRs (A^0/h^0 \rightarrow \tau^+\tau^-)
- mixing of \(b\bar{b}\) bound states and h/A included

Luminosity =113.1 pb\(^{-1}\) 1992-1995 data (5% off peak)
Anomalous Muon Magnetic Moment
Implications

Precise Measurement of $a_\mu$, Muon(g-2) Collaboration:
(PRL 86 (2001) 2227)

$$a_\mu(\text{exp}) - a_\mu(\text{SM}) = (43 \pm 16) \times 10^{-10}$$

2.6 $\sigma$ deviation

The contribution of the Higgs sector of the SM is suppressed by a factor $m_\mu^2/m_h^2$, but 2HDM(II) can explain $a_\mu$

1-loop 2HDM contribution
positive contribution from light $h^0$ enhanced wrt SM:
- enhanced $h\mu\mu$ coupling $\propto \tan \beta \Rightarrow \tan \beta > 1$
- suppressed $hZZ$ coupling $\propto \sin (\beta - \alpha) \Rightarrow \sin (\beta - \alpha) \sim 0$
(to have $m_h$ below LEP SM limit)

M.Krawczyk and J. Zochowshi, PRD 55 (1997) 6968,
M.Krawczyk , May 2001, hep-ph/0103223,
A.Dedes and H.Haber, hep-ph/0102297

2-loop 2HDM contribution
positive contribution from light $A^0 \propto \tan \beta \Rightarrow \tan \beta > 1$

K.Cheung et al., hep-ph/0103183
1-loop contribution to $a_{\mu}$

if 2HDM(II) is contributing to $a_{\mu}$, then with $\sin^2(\beta-\alpha)=0$ at 90%CL at 1-loop order:

- $215 \times 10^{-11} \leq \delta a_{\mu} \leq 637 \times 10^{-11}$ (A.Czarnecki and W.J. Marciano, PRD64(2001)013014)
- $170 \times 10^{-11} \leq \delta a_{\mu} \leq 690 \times 10^{-11}$ (M.Davier and A.Hoker, PLB435(1998)427)
- $112 \times 10^{-11} \leq \delta a_{\mu} \leq 537 \times 10^{-11}$ (S.Narison, hep-ph/013199(2001))

$\tan \beta$}

Interesting region

$\delta a_{\mu}^{Higgs}$ [in units of $10^{-11}$]

$Y \rightarrow H\gamma$

CUSB Coll.

PRD35(1987)2883

H. E. Haber and A. Dedes, hep-ph/0102297

OPAL bb\tau\tau search

Excluded!

OPAL bb\tau\tau search

LEP searches in the channels:
4b, 2q2\tau, 4\tau

- ALEPH -ICHEP
  Warsaw,July 96
- DELPHI-EPS
  Tampere,July 99

PRD35(1987)2883
Two-Loop Contributions to $\alpha_\mu$

become larger than one-loop contributions for $m_{h/A}$ larger than few GeV.

Largest contribution from $\Delta\alpha_\mu$ is preferred to come from the pseudoscalar $A^0$: the 2-loop contribution of the $h^0$ is negative, while the data require a positive contribution to $\Delta\alpha_\mu$.

Large portion of the admissible solution is excluded by DELPHI Yukawa study and OPAL 2HDM(II) general scan.
Charged Higgs $H^\pm$

searched in 2HDM since in the MSSM $m_{H^\pm} > m_W \Rightarrow$ no sensitivity because of WW backg.

$$B(H^+ \to cs^-) + B(H^+ \to \tau^+ \nu) = 1$$

$$e^+ e^- \to H^+ H^- \to cs^- sc^-$$

$$e^+ e^- \to H^+ H^- \to cs^- \tau^+ \nu + sc^- \tau^- \nu$$

$$e^+ e^- \to H^+ H^- \to \tau^+ \nu \tau^- \nu$$

![LEP combined graph](image)

$m_{H^\pm} > 78.6$ (78.8 exp.) GeV 95%CL for any $B(H^+ \to \tau^+ \nu)$
Conclusions

• The study of 2HDM is appealing and interesting

• 2HDM study has stimulated the development of several new analyses:
  - flavour independent channels
  - $h^0 \rightarrow A^0 A^0$ channels
  - $A^0 \rightarrow h^0 Z^0$
  - Yukawa process

• still new results have to be expected from all the collaborations together with the ADLO combined general scan of the 2HDM parameter space