12 Years of Higgs Hunt at LEP or...

1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
The LEP Higgs Boson Saga

- August 1989 - Nov 2000
- 12 Years of Higgs Hunt

Eilam Gross, Weizmann Institute of Science
The LEP Higgs Boson Saga / SUSY 2002 / Eilam Gross, Weizmann
The LEP Higgs Boson Saga / SUSY 2002 / Eilam Gross, Weizmann

Total LEP I luminosity ~200 pb⁻¹/experiment
LEP II luminosity ~750 pb⁻¹/experiment
**Precision Measurements and the Higgs Boson**

From LEP Electroweak WG and the SLD Heavy Flavor Group, May 2002

<table>
<thead>
<tr>
<th></th>
<th>LEP I+II (incl W)</th>
<th>All Z pole +m_W,Γ_W</th>
<th>All Data Excluding NuTeV</th>
<th>All Data Including NuTeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_t</td>
<td>185 +13,-11</td>
<td>181 +11,-9</td>
<td>175.8 +4.3,-4.2</td>
<td>174.7 +4.5,-4.3</td>
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<tr>
<td>log m_H</td>
<td>2.38 +4.1,-.39</td>
<td>2.08 +.38,-.33</td>
<td>1.91 +.21,-.22</td>
<td>1.93 +.21,-.23</td>
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<tr>
<td>m_H</td>
<td>238 +371,-141</td>
<td>121 +166,-65</td>
<td>81 +49,-32</td>
<td>85 +54,-34</td>
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<tr>
<td>χ²/dof</td>
<td>14.3/9</td>
<td>18.5/12</td>
<td>19.6/14</td>
<td>28.8/15</td>
</tr>
</tbody>
</table>

m_t=174.3(5.1) 

Stability

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Constraints on the Standard Model

\[ \log m_H = 1.93^{+0.21}_{-0.23} \]
\[ m_H = 85^{+54}_{-34} \]
\[ m_H < 196 \text{ GeV} \ @ 95\% \text{ CL} \]
Higgs Production and the Wall

$E_{\text{CM}} = 206.6 \text{ GeV}$

At the wall $\sigma \sim 0.05 \text{ pb}$

$= 206.6 - 91.2 = 115.4$
SM Higgs Decay

- B-tag is an essential ingredient in Higgs search
Higgs Search Channels

\[ H \rightarrow b\bar{b}(\sim 75-85\%), \tau^+\tau^- (\sim 8\%) \]

- Energy-momentum conservation

- The 2 most probable b-tagged jets recoil against a di-jet compatible with a Z-boson

\[ Z \rightarrow q\bar{q}(70\%), \nu\bar{\nu}(20\%), e^+e^- + \mu^+\mu^- (6.6\%), \tau^+\tau^- (3.3\%) \]

- The recoil mass of the 2 b-tagged jets is compatible with a Z boson

- 2 high energetic leptons with a mass compatible with a Z boson recoil against 2 jets.

- **Clean channel**

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First Higgs Limit Procedures

Statistical Procedure in a Background FREE environment

\[ N_{\text{exp}} = L_{\text{um}} \cdot \sigma(ee \rightarrow hZ) \cdot \text{eff} \]

\[ \text{Prob}(N_{\text{obs}} = 0 \mid N_{\text{exp}} = N_{95} = 3) = 5\% \]

\[ m_H > 35.4 \text{ GeV} \]
The final LEP I limit is based on $N_{95} \sim 3$, i.e. no background.

At the end of LEP I the need to develop a statistical method that can cope with non-vanishing background and events with finite mass resolution was emerged.
Golden Signatures

Evidence for Top Quark
CDF June 13, 1994
Prob for BG fluctuation 0.26%

A Tentative Higgs Discovery
OPAL @ 189 GeV
SUSY 1999
LEP 2001

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Is that IT?

Now, go and convince people
That mass histograms are “just for illustrative purposes”

Is there a “hidden” variable behind the signal region events?

Perhaps their b-tag content is bigger than that of the other events?

One has to FEEL the statistical procedure at his fingertips to really appreciate if such a signature could indicate a 115 GeV Higgs boson or not!
Q: What is a High Ranked ("top") Higgs candidate?

A: A "top" Higgs candidate is an event with an observed reconstructed mass $m_{\text{rec}} = 110$ GeV that for a given hypothetic test Higgs mass $m_H$ has a high weight $\ln\left(1 + \frac{s_i}{b_i}\right)$.
**Most Significant Events**

<table>
<thead>
<tr>
<th>Expt</th>
<th>$E_{cm}$ (GeV)</th>
<th>Decay channel</th>
<th>$M_{H^0}$ (GeV)</th>
<th>$\ln(1 + s/b) \oplus 115$ GeV</th>
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<tbody>
<tr>
<td>1</td>
<td>Aleph 206.7</td>
<td>±-jet</td>
<td>114.3</td>
<td>1.73</td>
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<tr>
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<tr>
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<tr>
<td>4</td>
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<td>E-miss</td>
<td>115.0</td>
<td>0.53</td>
</tr>
<tr>
<td>5</td>
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<td>0.53</td>
</tr>
<tr>
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<td>7</td>
<td>Aleph 205.0</td>
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<td>118.1</td>
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<tr>
<td>8</td>
<td>Aleph 208.1</td>
<td>Tau</td>
<td>115.4</td>
<td>0.41</td>
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<td>0.40</td>
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<td>10</td>
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<tr>
<td>11</td>
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<td>97.2</td>
<td>0.36</td>
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<td>12</td>
<td>L3 206.4</td>
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<td>0.31</td>
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<tr>
<td>13</td>
<td>Aleph 206.5</td>
<td>±-jet</td>
<td>114.4</td>
<td>0.27</td>
</tr>
<tr>
<td>14</td>
<td>Aleph 207.6</td>
<td>±-jet</td>
<td>103.0</td>
<td>0.26</td>
</tr>
<tr>
<td>15</td>
<td>Opal 205.4</td>
<td>E-miss</td>
<td>104.0</td>
<td>0.25</td>
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<tr>
<td>16</td>
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<td>0.22</td>
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<td>17</td>
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<td>0.21</td>
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<tr>
<td>18</td>
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<td>0.20</td>
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<tr>
<td>19</td>
<td>Delphi 206.7</td>
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<tr>
<td>20</td>
<td>L3 206.4</td>
<td>E-miss</td>
<td>110.1</td>
<td>0.18</td>
</tr>
</tbody>
</table>
4j Aleph Higgs Candidate

$E_{CM} = 206.7$  
$M_{rec} = 114$ GeV  
B-tag = 0.99, 0.99, 0.14, 0.01, 0.01
L3 Missing Energy Candidate

$E_{\text{CM}} = 206.4$ GeV
$M_{\text{rec}} = 115$ GeV
Simulating bg Experiments

- Construct a **Discriminator** (Not necessarily mass, could be 2-D)
- Divide the **discriminator** to bins $i=1,...$
  There are $N_i$ observed candidate events in each bin; we then calculate the likelihood ratio $-2\ln Q$
- The likelihood ratio, $-2\ln Q(m_H)$ tells us how much the outcome of an experiment is signal-like

![Graph showing discriminator and likelihood ratio](attachment:image.png)
The Statistical Procedure or Ranking Experiments

\[ Q = \frac{P_{\text{poisson}}(\text{data}|s+b)}{P_{\text{poisson}}(\text{data}|b)} = \frac{L(s+b)}{L(b)} = \frac{e^{-(s_{\text{TOT}}+b_{\text{TOT}})}}{e^{-b_{\text{TOT}}}} \prod_{i=1}^{N_i} \frac{s_i + b_i}{b_i} \]

Each observed event is counted with a weight

\[ \ln \left(1 + \frac{s_i}{b_i}\right) \]

\[-2\ln Q = 2s_{\text{TOT}} - 2 \sum_{i=1}^{N_i} N_i \ln \left(1 + \frac{s_i}{b_i}\right)\]

The likelihood ratio, \(-2\ln Q(m_H)\) ranks the experimental events configuration between two hypotheses: “s+b”-like and “b”-like,
Now we let’s play the “game” from a 115 GeV Higgs point of view...

\[ -2 \ln Q = 2s_{TOT} - 2 \sum_{i=1}^{N_i} \ln \left( 1 + \frac{S_i}{b_i} \right) \]
Signal-Background Separation

- Low Higgs Mass, High cross section
  - GOOD SEPARATION

- Medium Separation

- High Higgs Mass, Low cross section
  - POOR SEPARATION

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The Real Thing: 4 Experiments, 4 Likelihoods

YES! Excess!

OH NO!

NO!

And NO!
Maximum Likelihood for $m_H=115.6$
Enormous sensitivity to test mass due to the kinematical wall!
Its 4 Jets Again
• Note that lnQ is additive
• completely dominate the fluctuation

By Experiment

By Channel
If there is a Higgs

- If there is a Higgs in the year 2000 data its mass could be interpreted from the maximum likelihood: $m_H = 115.6^{+1.5}_{-1.1}$
Confidence Levels

- How probable is a result of an experiment?
- The PDF of $-2\ln Q$ was created from an ensemble of "b" or "s+b" experiments
- $1-CL_b$ is the probability for a background only experiment to give a more signal-like likelihood than the observed one!
- LEP Result: $1-CL_b = 0.034$ (2.1 $\sigma$)
- In 3.4% background experiments we expect to observe at least as signal-like result as we observe

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$1-CL_b$</th>
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<tbody>
<tr>
<td>Aleph</td>
<td>2.0x10^{-3}</td>
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<tr>
<td>DELPHI</td>
<td>0.87</td>
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<tr>
<td>L3</td>
<td>0.24</td>
</tr>
<tr>
<td>OPAL</td>
<td>0.22</td>
</tr>
<tr>
<td>DLO</td>
<td>0.49</td>
</tr>
</tbody>
</table>

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A Higgs Discovery?

- Look for a minimum in $1-\text{CL}_b$
- A Higgs Discovery?
- Not really....

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• $\text{CL}_{s+b}$ measures the compatibility of the experiment with “s+b” hypothesis.

• A bigger $\text{CL}_{s+b}$ means the experimental result is more “s+b” like.

• YOU CANNOT EXCLUDE AN “S+B” HYPOTHESIS WITH A LARGE $\text{CL}_{s+b}$.

• An “s($m_H$) +b” hypothesis can be excluded at >95% CL if only in <5% of the hypothetical “s+b” experiments the result would be more “b” like.

Looks like DELPHI could exclude the “s ($m_H=115.6$) +b” hypothesis at the 98% CL.

However, can they exclude a 115.6 “s” hypothesis?

Define $CL_s = \frac{CL_{s+b}}{CL_b}$.
• When $CL_s(m_H) < 5\%$ a Higgs boson with a mass $m_H$ is excluded at >95% CL!

• LEP Excludes a 114.1 GeV Higgs Boson (expected 115.4) at the 95% CL!

<table>
<thead>
<tr>
<th></th>
<th>Exp</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>113.8</td>
<td>111.5</td>
</tr>
<tr>
<td>DELPHI</td>
<td>113.5</td>
<td>114.3</td>
</tr>
<tr>
<td>DLO</td>
<td>114.9</td>
<td>114.8</td>
</tr>
<tr>
<td>LEP</td>
<td>115.4</td>
<td>114.1</td>
</tr>
</tbody>
</table>
SM Higgs candidates likelihood confidence levels

Type I 2HDM
Fermiophobia

MSSM Road

h, A, H

Don't Care

Invisible

cc, gg

Non SM H Decays

H → cc, gg

H → Don't Care

H → Invisible

Candidates Likelihood Confidence Levels

m_H > 114.1

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Higgs Decay Mode Independent Searches

- Search for acoplanar leptons
- Look for a peak in the recoil mass, however, sensitivity is retained for continuous wide recoil mass
- LEP 1: Z is off shell
  - Look for acoplanar leptons (µ's and e's) with $m_{ll}>20$ GeV
  - Use photon and conversions veto
  - For $S^0 \rightarrow \gamma \gamma$ and $S^0 \rightarrow ee$ (with $m_{ee}<0.5$) use $ee \rightarrow Z^0 S^0 \rightarrow \nu \nu \gamma \gamma, \nu \nu ee$
- LEP 2: Z is on shell
  - Look for acoplanar leptons with $m_{ll} \sim m_Z$
  - Veto radiative return photons
At LEP II, as the Higgs boson becomes lighter the Z boson is boosted and the leptons tend to be more energetic and collinear.

This results in

- Worse recoil mass resolution
- Worse signal/bg separation
• Set limits on
  \[ k = \frac{\sigma(ee \rightarrow s^0 \gamma)}{\sigma(ee \rightarrow H_{SM}^0 \gamma)} \]

• SM Higgs is excluded up to 81 GeV irrespective of its decay mode

For more details see talk by Jochen Cammin

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Flavour Independent Higgs Decay Modes

- In various Models $H \rightarrow bb$ suppressed
- Search for $ee \rightarrow hZ \rightarrow qqqq, qQLL$
- Optimize event selection for each test mass
- Take lowest efficiency

Compatibility with Background,

LEP PRELIMINARY

OPAL preliminary

The LEP Higgs Boson Saga/ SUSY 2002/ Eilam Gross, Weizmann
**Flavour Independent Higgs Decay Modes**

- 95% Upper Limit on the Production Cross-Section \( \times \) BR(hadrons)
- For SM-like BR of \(~75\%\) (typical for \( m_H \sim 115 \) \( H \rightarrow bb \)) a Higgs boson with mass below 112 GeV is excluded, this is almost as strong as the SM Higgs Boson limit (114.1 GeV)
- \( m_H > 112.9 \) (113.0) GeV
  - With BR(\( H \rightarrow \text{hads} \))=1.0

For Exotic Higgs Searches see talk by Marcel Stanitzki

The LEP Higgs Boson Saga/ SUSY 2002/ Eilam Gross, Weizmann
Search for Invisible Decaying Higgs Boson

- In SUSY models the Higgs boson might decay to neutralinos $H \rightarrow \chi_0 \chi_0$
- Search for acoplanar jets or leptons ($\mu$, e and $\tau$ for Delphi)
- Results are given in terms of upper limit on $\epsilon = \frac{\sigma_{HZ}}{\sigma_{SM}} \cdot BR(H \rightarrow \text{invisible})$
- For BR=100% invisibly decaying, a SM-like Higgs is excluded up to 114.2 (113.6 ) GeV at the 95% CL
2 Higgs Doublets Models (2HDM)

- Addition of doublets to the SM keeps the parameter $\rho_{\text{tree}} = \frac{m_W}{m_Z \cos \theta_W} = 1$

$$H_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \quad H_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

- Real parts mix with an angle $\alpha$ to give the two neutral scalars $h, H$

- Imaginary part (not eaten by $Z$) is the pseudo scalar $A$

- In total 6 parameters characterize the model:

$$m_{H^\pm}, m_h, m_H, m_A, \quad \tan\beta = \frac{v_2}{v_1}, \alpha$$

Complementarity

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

<table>
<thead>
<tr>
<th>Couples to</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>d-type leptons</td>
<td>$H_2$</td>
<td>$H_1$</td>
</tr>
<tr>
<td>u-type quarks</td>
<td>$H_2$</td>
<td>$H_2$</td>
</tr>
<tr>
<td>d-type quarks</td>
<td>$H_2$</td>
<td>$H_2$</td>
</tr>
</tbody>
</table>

$g_{hff} \sim \cos \alpha$

For $\alpha = \pi/2$ fermiophobic

e.g. MSSM

The LEP Higgs Boson Saga/ SUSY 2002/ Eilam Gross, Weizmann
In 2HDM (type I) and other models $H \to \gamma\gamma$, $WW$ dominantly.

All experiments searched for the two-photons final state. L3 also searched for the $WW$ decay mode.

SM BRs with fermionic modes turned off
• Higer expected $\sigma \times BR$ are easier to exclude
• LEP published a combined upper limit on the $H \rightarrow \gamma \gamma$ BR
• Assuming a Fermiophobic Higgs one gets $m_H > 108.2$ (109.0) GeV lower limit on the Higgs mass
• A 115 GeV Fermiophobic Higgs has a $BR(H \rightarrow gg) < 0.3$ and is therefore NOT excluded
• Individual experiments limits based on $H \rightarrow \gamma \gamma$: 106.4 (Aleph), 105.4 (L3)...

See Marcel Stanitzki Talk
The LEP High Higgs Scalability 2002/ Eilam Gross, Weizmann

Fermiophobic Higgs: $h \rightarrow WW$ Decay Mode

- $h \rightarrow WW^*$,
  - $hZ \rightarrow qqqq(nn), qqln(nn), qqln(qq)$ [Missing Energy Channels] $hZ \rightarrow qqqq(qq)$ [6 jets]
  - Small but consistent excess in observed events, e.g. in year 2000, in $qql\nu$ channel, except 57.4 events, observe 73 with an expected signal of 2.5 for $m_h=115$ GeV. Due to excess $h \rightarrow WW$ alone cannot set a limit!
  - However, when combined with $h \rightarrow \gamma\gamma$, L3 $WW+\gamma\gamma$ has a sensitivity equivalent to the combined $h \rightarrow \gamma\gamma$ LEP sensitivity, 109.4 GeV (expected) with 105.4 GeV observed

For more details see talk by Marcel Stanitzki

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Two Higgs Double Models (2HDM) type II

- Parameter Scan in General 2HDM(type II)
  1 \leq m_h \leq 120 \text{ GeV}
  3 \leq m_A \leq 2000 \text{ GeV}
  0.4 \leq \tan \beta \leq 58.0
  \alpha = \pi / 2, \pi / 4, -\pi / 4, -\pi / 2

  - Below \tan \beta = 0.4 \ m_A and m_h not well defines,
  - Below \ m_A \sim 3 \ radiative corrections unstabe

m_{H^\pm} and m_H beyond kinematic reach

The lower you allow \tan \beta \ the exclusion is weaker
Yukawa Production of Light Higgs

- A light Higgs with mass < 2 m_b could easily escape detection
- Even though LEP 2 has 5 times the luminosity than LEP 1, the number of Z \rightarrow b\bar{b} is x100 in LEP 1
- Analysis performed with LEP 1 data in the e+e- \rightarrow b\bar{b} (OPAL) and e+e- \rightarrow b\bar{b} (DELPHI Prel)

\begin{align*}
\sigma & \sim \sin^2 \theta \\
A & = \frac{1}{\tan \beta} \\
h & = -\frac{\cos \alpha}{\sin \beta}
\end{align*}

\begin{equation}
\sigma = m_f^2 \xi_f^2(\alpha, \beta)
\end{equation}
• With $\text{BR}(h \rightarrow \tau \tau) = 100\%$
  one finds limits on:
  □ $\xi_{A^0}^{b^0} \approx 8.6 - 11.6$ and
  □ $\xi_{h^0}^{b^0} \approx 8.3 - 13.8$
• MSSM is a 2HDM type II Supersymmetric Model

• Tree level: 2 pars \((m_h, m_A)\) or \((\tan \beta, m_h)\) or \((\tan g, m_A)\) determines \(\alpha\) and the mass spectrum

\[
m_h = m_Z \cdot |\cos 2\beta| \leq m_Z
\]

\[
m_{H^+} < m_W
\]

• “LEP 2 must discover the light Higgs boson or MSSM is out”, but ALLAS MSSM is saved by radiative corrections that shift the Higgs mass upward.

As \(\tan \beta\) gets bigger \(m_h \sim m_A\) till it saturates at \(m_{h_{\text{max}}}\)

For low \(m_A\) there might also be sensitivity to the heavier \(H\)
The trilinear Higgs-stop coupling

\[ A_t = \text{The trilinear Higgs-stop coupling} \]

\[ A_t = A_t - \mu \cdot \text{ctg} \beta \]

\[ m_s = \sqrt{\frac{m_{t_1}^2 + m_{t_2}^2}{2}} \]

Higgs mixing parameter

\[ \mu \epsilon_{ij} \hat{H}_1^i \hat{H}_2^j \]

Charged Higgs mass can go below the W mass for small A mass

\[ m_{H^\pm} \approx m_A^2 + m_W^2 + \frac{\mu^2 m_t^4}{\sin^2 \beta} f\left(\frac{m_{t_1}^2, m_{t_2}^2}{m_t^2}\right) \]
**L3 Charged Higgs Anomaly**

**WORKING ASSUMPTION**

\[ BR(H^+ \rightarrow \tau^+ \nu) + BR(H^+ \rightarrow c\bar{s}) = 1 \]

**Djouadi, Kalinowski, Zerwas, hep-ph/9511342**

- This 4.2\sigma anomaly has not been seen by any other experiment!

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Charged Higgs

WORKING ASSUMPTION

\[ BR(H^+ \to \tau^+\nu) + BR(H^+ \to c\bar{s}) = 1 \]

- There is loss of sensitivity near \( m_W \)
- \( m_{H^+} > 81\, \text{GeV} \) for \( BR(H^+ \to \tau\nu) = 0 \)
- \( m_{H^+} > 78.6\, \text{GeV} \) for any \( BR(H^+ \to \tau\nu) \)

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**Charged Higgs At Low $\tan \beta$**

As $\tan \beta$ gets lower, the $BR(H^+ \rightarrow AW^{*+})$ becomes dominant and the assumption of

$$BR(H^+ \rightarrow \tau^+ \nu) + BR(H^+ \rightarrow c\bar{s}) = 1$$

breaks!

- The $H^+ \rightarrow AW^{*+}$ decay mode must be taken into account!
- LEP has just now started to look into that (in the framework of 2HDM (II))
- However…. next

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**Djouadi, Kalinowski, Zerwas, hep-ph/9511342**

**Akeroyd et.al. hep-ph/0205094**

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**EMERGENCY!**

See Marcel Stanitzki Talk

The LEP Higgs Boson Saga/ SUSY 2002/ Eilam Gross, Weizmann
• In type I 2HDM the $H^+ \rightarrow AW^{++}$ decay mode might be dominant for $\tan \beta > 1$
• $A$ is assumed to decay for $b\bar{b}$, so no scan was done for $m_A < 12$ GeV
• OPAL searched for $H^+ H^- \rightarrow \tau \nu qqbb$, $H^+ H^- \rightarrow q\bar{q}bb$ $q\bar{q}bb$, $H^+ H^- \rightarrow l\nu bb$ $q\bar{q}bb$
Search for Doubly Charged Higgs Boson

• Doubly charged Higgs bosons, $H^{±±}$ exist in LR symmetric models

• In LR symmetric models $\sigma(ee \rightarrow H_L^{++} H_L^{--}) \neq \sigma(ee \rightarrow H_R^{++} H_R^{--})$

• $H^{++} \rightarrow e^+e^+, \mu^+\mu^+, \tau^+\tau^+, e^+m^+, ...$

• $\Gamma(H^{++} \rightarrow \ell^+\ell^+) \sim h_{H^{++}}^2 \cdot m_{H^{++}}$

• Indirect constraints

  $h_{H^{++}} > 10^{-7}$ → Decay at Interaction Point, smaller couplings → long lived doubly charged (large impact parameter, kinked tracks, stable long lived).

• DELPHI searched only for $\tau\tau$ decays but all possible lifetimes, OPAL for all possible decay channels assuming decay at IP

Huitu-Maalampi
Hep-ph/9410342

EMERGENCY!

See Marcel Stanitzki Talk

The LEP Higgs Boson Saga/ SUSY 2002/ Eilam Gross, Weizmann
Search for Doubly Charged Higgs Boson

- For $h_{H^{+\tau}} > 10^{-7}$ OPAL/DELPHI set limits $m(H_L^{++}) > 99.0/99.6$ GeV
  $m(H_R^{++}) > 98.5/99.1$ GeV

- For all possible lifetimes DELPHI sets a limit $m(H^{++}) > 97.3$ GeV
The LEP Higgs boson Saga/ SUSY 2002/ Eilam Gross, Weizmann

Candidates

SM

Higgs

Likelihood

Confidence

Levels

Fermiophobia

Type I

Type II

MSSM Road

h, A, H

H

Don’t Care

Invisible

H→cc, gg

Non SM H Decays

H→bbH

H→cc, gg

H→Invisible

H→H

H→H++

h, A, H

H

Road

SSM

Yukawa

bbH

H

H

Type II

Type I
The Max $m_h$ scenario was designed to yield the maximal value of the higgs mass

The Large $\mu$ scenario is designed to produce suppressed Higgs to $b\bar{b}$ decays, yet either the $h$ or the $H$ are kinematically accessible at LEP 2.

Analysis is done using FeynHiggsDecay (Heinemeyer, Hollik, Weiglein ’98)
Incorporating HDecay (Djouadi, Kalinowski, Spira), www.feynhiggs.de

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In this region $\tan \beta \sim 0.4$ and $m_{H^+} \sim 74$ GeV. Dedicated searches to $H^+ \to W^+ A$ and flavour independent searches can help. Part of this region is already covered by DELPHI flavour independent searches. This region will probably be completely covered in the next LEP iteration.
With the flavour independent searches the all pre-LEP II defined region is now excluded!
Almost all accessible region is excluded, except near the hZ and hA kinematical wall!

\[ m_A > 91.9 \ (\text{exp} \ 95.0) \ GV \]

Without Radiative Corrections MSSM would have been widely excluded

\[ m_h > 91.0 \ (\text{exp} \ 94.6) \]
• Exclusion at the 2σ level does not mean there cannot be an excess at the 2σ level!

• You see something but it's not what you expect from your model!

• Excess in LEP 189 (at ~97 GeV) and LEP 206 (~115) is seen
Excess 189

\[ \sqrt{s} = 183 - 189 \text{ GeV} \]

- LEP data combined
- background
- HZ-Signal \((m_H = 91 \text{ GeV})\)

\[ I_{CL} \]

- Observed
- Expected signal (MEDIAN)
- Expected background (average)

Reconstructed Mass \(m_H [\text{GeV}]\)

\(m_H (\text{GeV}/c^2)\)
Maximal $m_h$

For more details on MSSM searches and individual experiments results including final results from Aleph see talk by Elizabetha Locci

0.5 < $tg\beta$ < 2.4
Casting Doubts!

A new version of Feynhiggs including $O(\alpha_t^2)$ two loop corrections to the neutral CP even Higgs boson mass (Brignole et. Al. HEP-PH 0112177) and incorporating a modified and more stable renormalization scheme might weaken existing sensitivities (see talk by S. Heynemeyer)

For example, in the mh-max scheme the max Higgs mass was shifted from 128 to $\sim$134 GeV, which weaken LEP limits on $tg\beta$!

LEP will soon introduce modified benchmarks to accommodate the recent theoretical and experimental developments (e.g. the large m scenario has exhausted itself)
• The LEP puzzle is still alive and kicking (and so is the puzzle of mass generation)

• Still lots of pieces to fit in (CP Violating Higgs, General Scan MSSM....)

• Unfortunately, so far, none of the pieces in this puzzle seems to be a Higgs boson but there is lots of space for exotic physics to be explored by the After-LEP TEVATRON, LHC and LC!
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If the conclusions are not clear by the end of this talk, you have probably not been listening.