Search for MSSM Higgs at LEP

Haijun Yang
University of Michigan, Ann Arbor

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• Introduction of MSSM

• Main Backgrounds

• L3 Analysis Procedure

• LEP Combined Results

• Conclusions
• Minimal Supersymmetric Standard Model

Two Higgs doublets $\implies$ 5 Higgs bosons

$\rightarrow$ 3 neutral (h & H CP-even, A CP-odd),

$\rightarrow$ 2 charged Higgs.

• Neutral Higgs - Two Complementary Processes

Higgsstrahlung

Pair Production

$$
\sigma_{hZ} = \sin^2(\beta - \alpha)\sigma_{hZ}^{SM} \\
\sigma_{hA} = \cos^2(\beta - \alpha)\bar{\lambda}\sigma_{hZ}^{SM}$$
\(\Rightarrow hZ\) production is dominant at low \(\tan\beta\).

\[\sqrt{s} = 206\ \text{GeV}\]

\[\Rightarrow hA\] is dominant at large \(\tan\beta\).
**Introduction**

● **Parameters of the MSSM**

1. Ratio of two Higgs vacuum expectation values: $\tan \beta$

2. Mass of $A$ boson: $m_A$

3. Gaugino mass parameter: $M_2$

4. Scalar fermion mass: $m_0$

5. Higgsino mass parameter: $\mu$

6. Higgs-sfermion trilinear coupling: $A$

● **Three Benchmark Scenarios**

→ $m_h$ Maximal

$X_t = A - \mu \cot \beta = \sqrt{6} \text{ TeV}$

→ Minimal Mixing: No mixing in stop sector

$X_t = A - \mu \cot \beta = 0$

→ large $\mu$
Higgs decay into $b\bar{b}$ and $\tau^+\tau^-$ is dominant.

$m_h = 95$ GeV

$m_A = 80$ GeV

$\Rightarrow$ focused on $hA \rightarrow b\bar{b}b\bar{b}$ and $hA \rightarrow b\bar{b}\tau^+\tau^-$. 
Main backgrounds come from $WW$, $ZZ$, $q\bar{q}$, $e\nuqq$ and $Zee$ etc.
Distribution of Delivered Integrated luminosity by Energy

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Integrated Luminosity/nb-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.0 - 100.39 GeV</td>
<td>819</td>
</tr>
<tr>
<td>101.0 - 101.49 GeV</td>
<td>651</td>
</tr>
<tr>
<td>101.6 - 101.99 GeV</td>
<td>1745</td>
</tr>
<tr>
<td>102.0 - 102.49 GeV</td>
<td>7884</td>
</tr>
<tr>
<td>102.5 - 102.99 GeV</td>
<td>70169</td>
</tr>
<tr>
<td>103.0 - 103.49 GeV</td>
<td>131725</td>
</tr>
<tr>
<td>103.50 - 103.99 GeV</td>
<td>4906</td>
</tr>
<tr>
<td>104.0 - 104.49 GeV</td>
<td>10734</td>
</tr>
<tr>
<td>104.50 - 104.99 GeV</td>
<td>7</td>
</tr>
</tbody>
</table>

total 02/11/00 = 233 pb⁻¹
4-jet channel: $hA \rightarrow \bar{b}b\bar{b}\bar{b}$

**Step 1. Preselection:** To reject low multiplicity backgrounds while keeping high signal efficiencies ($\sim 90\%$).

**Step 2. Neural Network:** Discriminant distributions are combined in a neural network.

**Step 3. Final Discriminant:** Neural network outputs are used to construct final discriminant variable.
Preselection Cuts

1. Number of tracks $\geq 20$

2. Number of calorimetric clusters $\geq 35$

3. Visible energy: $0.6 < \frac{E_{vis}}{\sqrt{s}} < 1.4$

4. Perpendicular imbalance energy $\leq 0.35 \cdot E_{vis}$

5. Lepton energy $< 65$ GeV

6. Longitudinal component of the missing momentum: $P_{miss}^{L}/(m_{vis} - m_{Z}) < 0.4$

Event $\Rightarrow$ 4-jet using DURHAM algorithm

Kinematic fit: 4-momentum conservation(4C) fit
• Neural Network Inputs:

1. Event $B_{tag}$
2. Event Sphericity
3. Event Thrust
4. $P_{miss}^L$
5. Polar angle of Higgs boson: $\theta_{Higgs}$
6. DURHAM jet resolution parameter: $Y_{34}^D$
7. mass $\chi^2$

$$\chi^2(m_A, m_h) = \frac{(\Sigma_i - m_h - m_A)^2}{\sigma^2_{\Sigma}} + \frac{(\Delta_i - |m_h - m_A|)^2}{\sigma^2_{\Delta}}$$

• Neural Network Outputs:

Three outputs, $Y_{hA}$, $Y_{WW}$ and $Y_{qq}$
The Final Discriminant is defined as:

\[ F_{hA} \equiv Y_{hA} \cdot (1 - Y_{WW}) \cdot (1 - Y_{q\bar{q}}) \]

\( \Rightarrow \) Data agree with MC backgrounds.
\( \Rightarrow \) Efficiency is insensitive to Higgs Mass.
- High Discriminant = 0.98
- High B-tag = 0.6
- $m_h + m_A = 178.8$ GeV
## Selection Results

<table>
<thead>
<tr>
<th></th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int. Lumi. ($pb^{-1}$)</td>
<td>217</td>
<td>224</td>
<td>217</td>
<td>208</td>
</tr>
<tr>
<td>$hA \rightarrow bbbb$ (channel)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>10</td>
<td>5</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Total Background</td>
<td>5.5</td>
<td>6.5</td>
<td>7.8</td>
<td>10.3</td>
</tr>
<tr>
<td>4-fermion Bkgd.</td>
<td>4.1</td>
<td>4.4</td>
<td>5.6</td>
<td>6.9</td>
</tr>
<tr>
<td>$q\bar{q}$ Bkgd.</td>
<td>1.4</td>
<td>2.1</td>
<td>2.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Efficiency</td>
<td>47%</td>
<td>47%</td>
<td>42%</td>
<td>48%</td>
</tr>
<tr>
<td>Expected Signal</td>
<td>3.5</td>
<td>3.6</td>
<td>3.2</td>
<td>3.4</td>
</tr>
</tbody>
</table>

- The signal efficiency and rate are shown for $m_h = m_A = 90 \text{ GeV}/c^2$, with $\tan \beta \sim 20$. 
- **Tau channel:** $hA \rightarrow \bar{b}\bar{b}\tau^+\tau^-$

**Preselection**

- **Particle based**
- **Jet based selection**

**Final Discriminant**

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**Step 1. Preselection:** To reject low multiplicity backgrounds while keeping high signal efficiencies ($\sim 80\%$).

**Step 2. Final Selection:** Two inclusive selections are performed. One based on tau identification (Particle based selection) and the other relying on event kinematics (Jet based selection).

**Step 3. Final Discriminant:** B-tag of jets, di-jet masses are used to construct final discriminant.
Analysis Procedure

• Preselection Cuts:

\[ N_{scnt} \geq 4 \]
\[ N_{gtrk} \geq 5 \]
\[ N_{src} \geq 15 \]
\[ E_{vis}/\sqrt{S} \geq 0.4 \]
\[ LOG(Y_{34}) \geq -7 \]
\[ \text{effective energy} \geq 100 \text{ GeV} \]

• Final Selection Cuts:

<table>
<thead>
<tr>
<th>particle-based</th>
<th>jet-based</th>
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<tr>
<td>( LOG(Y_{34}) \geq -6 )</td>
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</tr>
<tr>
<td>( E_{\gamma,e,\mu} \leq 40 \text{ GeV} )</td>
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</tr>
<tr>
<td>( E_{vis}/\sqrt{S} \leq 0.95 )</td>
<td>( E_{vis}/\sqrt{S} \leq 0.90 )</td>
</tr>
<tr>
<td>( \theta_{qq}, \theta_{\tau\tau} \geq 70^\circ )</td>
<td>( \theta_{qq}, \theta_{\tau\tau} \geq 70^\circ )</td>
</tr>
<tr>
<td>( 25 \leq M_{qq}, M_{\tau\tau} \leq 125 \text{ GeV} )</td>
<td>( 25 \leq M_{qq}, M_{\tau\tau} \leq 125 \text{ GeV} )</td>
</tr>
<tr>
<td>no 3-3 prong decay</td>
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</tr>
<tr>
<td>( N_{\tau} \geq 2 )</td>
<td>( \theta_{jj}^{\text{min}} \geq 25^\circ )</td>
</tr>
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<td></td>
<td>(</td>
</tr>
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</table>
- N-1 plots of Tau channel
Discriminant Variables of Tau Channel

- Distributions used to construct final discriminant.

![Graphs showing distributions for B-tag1 and B-tag2](image)

![Graphs showing distributions for M_{q\ell-4C} (GeV) and M_{\tau-4C} (GeV)](image)

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Final Discriminant Calculation

⇒ Compute the probability density function $f_j^i$,

$j$ means event class(hA, WW, ZZ, qq etc.),
i denotes certain variables(b-tag, 2-jet mass etc.).

⇒ Derive figure of merit for event class $j$ based only on variable $i$ is defined as:

\[ P_j^i = \frac{f_j^i}{\sum_k f_k^i} \]  

(1)

⇒ Compute final event discriminant based on all variables and assume hA event class:

\[ F_{hA} = \frac{\prod_i P_{hA}^i}{\sum_k \prod_i P_k^i} \]  

(2)
Final Discriminant of Tau Channel

Final Discriminant

Data

Background

hA → bbττ(ττbb), 90 GeV

Events/0.05

Final Discriminant
$F_{hA} = 0.91, \ B_{tag1} = 0.965, \ B_{tag2} = 0.359, $

$M_{jj} = 90.68 \text{ GeV}, \ M_{\tau\tau} = 98.28 \text{ GeV}. $

$\Rightarrow e^+e^- \rightarrow hA, \ h \rightarrow b\bar{b}, \ A \rightarrow \tau^+\tau^- (\tau^\pm \rightarrow \mu^\pm\nu\bar{\nu})$
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<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Total Background</td>
<td>3.0</td>
<td>6.0</td>
<td>3.2</td>
<td>4.5</td>
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<td>2.8</td>
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<td>25%</td>
<td>33%</td>
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<td>Expected Signal</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
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- The signal efficiency and rate are shown for \(m_h = m_A = 90 \text{ GeV}/c^2\), with \(\tan\beta \sim 20\).
Confidence Level Calculation

- Likelihood Ratio test-statistic:
  
  \[ Q = \frac{L(s + b)}{L(b)} \]

- Monte Carlo experiments are based on Poisson statistics.

\[ CL_s \equiv \frac{CL_{s+b}}{CL_b} \]
L3 Result

\[ m_h \] Maximal Scenario

\[ \Rightarrow m_h : \text{obs} / \text{exp} = 83.7 / 88.1 \text{ GeV} \]

\[ \Rightarrow m_A : \text{obs} / \text{exp} = 83.9 / 88.3 \text{ GeV} \]
• $m_h$ maximal scenario, $\tan \beta > 20$
\( \tan \beta \)

\( m_h \) (GeV) | ALEPH | DELPHI | L3 | OPAL  
<table>
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<tbody>
<tr>
<td>obs. limit</td>
<td>89.6</td>
<td>89.8</td>
<td>83.7</td>
<td>79.3</td>
</tr>
<tr>
<td>med. limit</td>
<td>91.7</td>
<td>89.0</td>
<td>88.1</td>
<td>85.1</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \text{LEP Combined Results: } 91.0 / 94.6 \text{ GeV.} \]
\[ m_A (\text{GeV}) \]  
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<td>obs. limit</td>
<td>90.0</td>
<td>90.8</td>
<td>83.9</td>
<td>80.6</td>
</tr>
<tr>
<td>med. limit</td>
<td>92.1</td>
<td>90.0</td>
<td>88.3</td>
<td>86.9</td>
</tr>
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</table>

⇒ LEP Combined Results: 91.9 / 95.0 GeV.
• No Mixing Scenario

⇒ \( m_h > 91.5 / 95.0 \text{ GeV} \), for \( \tan\beta > 1.2 \)

⇒ \( m_A > 92.2 / 95.3 \text{ GeV} \), for \( \tan\beta > 1.2 \)

⇒ \( 0.8 < \tan\beta < 9.6 \) is excluded
• **Large $\mu$ Scenario**

![Graph showing LEP 88-209 GeV Preliminary results for $\tan\beta$ vs. $m_A$ (GeV/c^2)].

- $h^0$ decays into $c\bar{c}$, $gg$, $W^+W^-$ etc.

- $M_{\text{SUSY}} = 400$ GeV
- $M_2 = 400$ GeV
- $\mu = 1$ TeV
- $m_{\text{gluino}} = 200$ GeV
- $X_t = -300$ GeV
Three final states: hadronic, semi-leptonic and leptonic decays.

\[ e^+ \gamma / Z^* \rightarrow H^+ \rightarrow c, \bar{c}, \nu_\tau, \bar{\nu}_\tau \]

\[ s, \tau^- \]

\[ \bar{s}, \tau^+ \]

\[ H^- \rightarrow c, \bar{c}, \nu_\tau, \bar{\nu}_\tau \]

\[ \text{Br} (H^+ \rightarrow \tau^+\nu_\tau) = 1 \]

Data: m_s = 189–209 GeV

Preliminary

H^+H \rightarrow \tau^+\nu_\tau\bar{\nu}_\tau; M_H = 70 \text{ GeV}
• $H^\pm$ semi-leptonic decays.
• $H^\pm$ hadronic decays.
Excess of Events at 68 GeV

$\text{Br}(H^+ \rightarrow \tau^+ \nu_{\tau}) = 0.1$

$\sqrt{s} = 183-209 \text{ GeV}$

$H^+H^- \rightarrow c\overline{c}c\overline{c}$ and $c\overline{c}\tau^+\tau^-$

$M_H = 68 \text{ GeV}$

- 10% of $H^\pm$ decay into $\tau$.

⇒ Apparent excess at 68 GeV
Excess of Events at 68 GeV

\[ \Rightarrow 4.2 \, \sigma \text{ excess at } 68 \, \text{GeV from L3.} \]

But ......
\[ \Rightarrow \text{Br}(H^\pm \to \tau \nu = 0.0), \ M_{H^\pm} > 77.2 \ (77.1) \text{ GeV}. \]
\[ \Rightarrow \text{Br}(H^\pm \to \tau \nu = 0.1), \ M_{H^\pm} > 66.9 \ (76.0) \text{ GeV}. \]
\[ \Rightarrow \text{Br}(H^\pm \to \tau \nu = 0.5), \ M_{H^\pm} > 69.7 \ (75.7) \text{ GeV}. \]
\[ \Rightarrow \text{Br}(H^\pm \to \tau \nu = 1.0), \ M_{H^\pm} > 82.7 \ (84.6) \text{ GeV}. \]
⇒ LEP Combined Data agree well with SM backgrounds
\[ \Rightarrow M_{H^\pm} > 78.6 \text{ GeV at 95\% C.L.} \]
Conclusions

- More than 200 pb$^{-1}$ data were collected per experiment in the Year 2000. In total $\sim 700$ pb$^{-1}$ were collected above $Z^0$ pole by each experiment.

⇒ No significant evidence of MSSM neutral and charged Higgs are observed up to $\sqrt{s} = 209$ GeV.

⇒ Neutral Higgs limits with 95% C.L.

\[ m_h > 91.0 \text{ GeV}, \ m_A > 91.9 \text{ GeV} \]

\[ \tan \beta \text{ is excluded from 0.5 to 2.4} \]

⇒ Charged Higgs limits with 95% C.L.

\[ m_{H^\pm} > 78.6 \text{ GeV} \]