SM HIGGS BRANCHING RATIO
MEASUREMENTS AT A LINEAR COLLIDER

\[(e^+ e^- \rightarrow Z H \rightarrow b\bar{b}, \sqrt{s} = 500 GeV)\]

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Session P1 Working Group 2
J. Brau, C. Potter, and M. Iwasaki
University of Oregon
PARAMETERS

We assume for this study:

- $\sqrt{s} = 500$ GeV Linear Collider
- Luminosity $\int dtL = 500$ fb$^{-1}$
- 250 fb$^{-1}$ running with 80% right polarized electrons
- 250 fb$^{-1}$ running with 80% left polarized electrons
- 115, 120, 140 and 160 GeV Standard Model Higgs boson masses
DATA SIMULATION

Pandora v2.1 Monte Carlo (M. Peskin) includes:

- Polarized beams
- Beamstrahlung
- Initial state radiation

Interface to Tauola and Pythia (M. Iwasaki):

- $\tau$ decay
- Parton shower
- Hadronization
DETECTOR SIMULATION

NLD Large Detector Configuration:

- Vertex Detector: 5 $\mu$m res., $r_{in} = 1.2$ cm
- Central Tracker: 25-200 cm
- Electromagnetic Calorimeter: 200-250 cm
- Hadronic Calorimeter: 250-374 cm
- 3 T Magnetic Coil
- Muon Detector: 450-650 cm

NLD detector simulation implemented on Root C++ libraries (M. Iwasaki)
EVENT SELECTION

We select for $e^+e^- \rightarrow HZ \rightarrow l^+l^- \ (l = e, \mu)$

- Reconstruct all lepton pair masses in an event
- Select pair with mass closest to $m_Z$
- Calculate recoil mass
- Apply cuts on masses:

$$|m_Z - m_{l^+l^-}| < 10 \text{ GeV}$$

$$m_H - 10 \text{ GeV} < m_{\text{recoil}} < m_H + 20 \text{ GeV}$$

- Include hadronic $Z$ decays by scaling signal up by a factor of 4 (D. Strom, LEP II experience)

Signal event reconstructed $Z$ and recoil mass distributions.
Cross sections for $e^+e^- \rightarrow ZH$ with $Z \rightarrow l^+l^-$ ($l = e, \mu$) are in fb with 80% left polarized electrons.

<table>
<thead>
<tr>
<th>Mode</th>
<th>115</th>
<th>120</th>
<th>140</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>5.9</td>
<td>3.5</td>
<td>1.5</td>
<td>0.24</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>0.68</td>
<td>0.74</td>
<td>2.4</td>
<td>5.8</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td>0.24</td>
<td>0.14</td>
<td>0.064</td>
<td>0.0099</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>0.62</td>
<td>0.38</td>
<td>0.17</td>
<td>0.027</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>0.41</td>
<td>0.27</td>
<td>0.16</td>
<td>0.033</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>0.050</td>
<td>0.08</td>
<td>0.34</td>
<td>0.19</td>
</tr>
</tbody>
</table>
BACKGROUND

Approximately 29%/31%/36%/39% (115/120/140/160) of signal events pass the mass selection cuts and are then subjected to decay mode cuts.

A small fraction of backgrounds also pass the cuts. Primary backgrounds, with cross sections for left, right polarizations are:

- $e^+e^- \rightarrow W^+W^-$ \quad (\sigma \approx 14300, 1700 \text{ fb})
- $e^+e^- \rightarrow q\bar{q}$ \quad (\sigma \approx 16000, 11000 \text{ fb})
- $e^+e^- \rightarrow ZZ$ \quad (\sigma \approx 560, 340 \text{ fb})
- $e^+e^- \rightarrow t\bar{t}$ \quad (\sigma \approx 740, 400 \text{ fb})

The most pernicious of these is $e^+e^- \rightarrow ZZ$, especially for the lighter Higgs cases.

Therefore the Higgs mass is reconstructed using tracks and unassociated clusters and cuts are made at the Higgs decay mode level.
CUT-BASED DECAY MODE TAGS

For $H \to \tau^+\tau^-$ :

- reconstructed Higgs mass inconsistent with Z mass
- low track multiplicity ($\leq 6$)

For $H \to WW^* \to 2 \text{ jets}$ :

- high momentum lepton in event ($>10 \text{ GeV}$)
- high momentum lepton is isolated ($E_{\text{cone}} < 10 \text{ GeV}$)

For $H \to WW^* \to 4 \text{ jets}$ :

- force event to 4 jets
- best jet pair must satisfy $|m_W - m_{jj}| < 10 \text{ GeV}$
- jet algorithm $y_{\text{cut}}$ value $y_{32} > 0.04$
- thrust in Higgs frame $< 0.88$
CUT-BASED TAGS (CONT.)

For $H \rightarrow b\bar{b}$:

- force event to 2 jets
- calculate $m_{p_t}$ with ZVTop (D. Jackson, impl. T. Abe)
- require $m_{p_t} > 2$ GeV for at least one jet

For $H \rightarrow c\bar{c}$:

- force event to 2 jets
- tag jet charm if $m_{p_t} < 2$ GeV, $N_{sig} > 10$, $p_{jet}/p_{kin} > 0.45$
- require no jet tagged as beauty, at least one jet tagged as charm, and neither jet contains tertiary vertices

For $H \rightarrow gg$:

- require no tags from preceding modes
- neither jet has secondary vertices
- no high momentum leptons ($< 1$ GeV)
NEURAL NETWORK STRUCTURE AND TRAINING

In order to optimize these results, the parameters and their cut values were used as inputs to a neural network.

- The neural network has 14 input units (one for each parameter), 15 hidden units, and 6 outputs (one for each decay mode).

- It is fully connected and uses standard back propagation as its learning algorithm.

- To speed and perhaps improve the training, the parameters were mapped to the interval [0,1] by the map \( p \mapsto 1 - \exp[-(p/p_{\text{cut}})^2 \ln 2] \).

- For each set parameters in an event \( H \to X \), training asked the network to output a 1 for the \( H \to X \) output unit and a 0 for the other output units.
NEURAL NETWORK TOPOLOGY

State of the neural network for an event $H \rightarrow c\bar{c}$. 

11
NEURAL NETWORK OPTIMIZATION

- The space \( C \) of all possible neural network output cut values is the unit cube in \( \mathbb{R}^6 \).

- Each point in \( C \) maps to signal \( S \) and background \( B \) for a given mode \( H \to X \) and thence to fractional branching ratio \( \delta_{BR}/BR = \sqrt{S + B}/S \), purity \( p = S/(S + B) \), and efficiency \( \epsilon = S/(\sigma \int dtL) \).

- Minimizing \( \sqrt{S + B}/S \) for a particular mode mode \( H \to X \) is equivalent to finding the optimal set of neural network output cut values for \( H \to X \).

- For a given mode \( H \to X \), the boundary of the image of \( C \) under the \((p, \epsilon)\) map is the optimal purity/efficiency curve.

- We sampled \( S \) and \( B \) for each mode in the cube on a lattice with \( 10^6 \) points.
MISTAGS AND SIGNAL FOR 120 GEV CASE

The analyzed 500 \( fb^{-1} \) data sample is listed vertically. The number of signal event tags is listed horizontally.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( WW^* )</th>
<th>( b\bar{b} )</th>
<th>( c\bar{c} )</th>
<th>( \tau^+\tau^- )</th>
<th>( gg )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow WW^* )</td>
<td>214</td>
<td>12.7</td>
<td>3.3</td>
<td>0.5</td>
<td>98</td>
</tr>
<tr>
<td>( H \rightarrow b\bar{b} )</td>
<td>27.9</td>
<td>1599</td>
<td>59.7</td>
<td>0</td>
<td>13.9</td>
</tr>
<tr>
<td>( H \rightarrow c\bar{c} )</td>
<td>7.0</td>
<td>13.6</td>
<td>29.3</td>
<td>0.02</td>
<td>12.2</td>
</tr>
<tr>
<td>( H \rightarrow \tau^+\tau^- )</td>
<td>0.3</td>
<td>0</td>
<td>0.3</td>
<td>189.6</td>
<td>0</td>
</tr>
<tr>
<td>( H \rightarrow gg )</td>
<td>52.7</td>
<td>9.8</td>
<td>3.0</td>
<td>0</td>
<td>112.8</td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* )</td>
<td>1.0</td>
<td>0.6</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( e^+e^- \rightarrow ZZ )</td>
<td>123.2</td>
<td>524.7</td>
<td>38.6</td>
<td>24.8</td>
<td>161.1</td>
</tr>
<tr>
<td>( e^+e^- \rightarrow WW )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( e^+e^- \rightarrow q\bar{q} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( e^+e^- \rightarrow t\bar{t} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Purity vs. efficiency for the case $m_H = 120$ GeV. The maximum possible efficiency is 0.31 due to mass cuts.
FRACTIONAL BRANCHING RATIO RESULTS

Listed below are the fractional branching ratio errors $\delta_{BR}/BR$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>115</th>
<th>120</th>
<th>140</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>0.027</td>
<td>0.029</td>
<td>0.038</td>
<td>0.13</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>0.16</td>
<td>0.10</td>
<td>0.03</td>
<td>*</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td>0.31</td>
<td>0.39</td>
<td>0.44</td>
<td>-</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>0.16</td>
<td>0.18</td>
<td>0.23</td>
<td>*</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>0.07</td>
<td>0.08</td>
<td>0.10</td>
<td>*</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c} + gg$</td>
<td>0.15</td>
<td>0.16</td>
<td>0.20</td>
<td>*</td>
</tr>
</tbody>
</table>

* in progress
OTHER HIGGS BRANCHING RATIO STUDIES

<table>
<thead>
<tr>
<th>Study</th>
<th>$\sqrt{s}$/GeV</th>
<th>$\int dtL/\text{fb}^{-1}$</th>
<th>Mode</th>
<th>$P(e^{-})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H/B/B</td>
<td>500</td>
<td>50</td>
<td>ZH</td>
<td>0</td>
</tr>
<tr>
<td>N/K</td>
<td>300</td>
<td>50</td>
<td>ZH</td>
<td>-0.95</td>
</tr>
<tr>
<td>B</td>
<td>350</td>
<td>500</td>
<td>ZH + $H\nu\bar{\nu}$</td>
<td>0</td>
</tr>
<tr>
<td>B/R</td>
<td>350</td>
<td>500</td>
<td>ZH</td>
<td>0</td>
</tr>
<tr>
<td>B/P/I</td>
<td>500</td>
<td>500</td>
<td>ZH</td>
<td>$\pm 0.8$</td>
</tr>
</tbody>
</table>


COMPARISON TO OTHER HIGGS BR STUDIES

The fractional branching ratio errors $\delta_{BR}/BR$ from each study are shown in the table below. Here $m_H = 120$ GeV.

<table>
<thead>
<tr>
<th>Mode</th>
<th>H/B/B</th>
<th>N/K</th>
<th>B</th>
<th>B/R</th>
<th>B/P/I</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>0.48</td>
<td>-</td>
<td>0.054</td>
<td>0.051</td>
<td>0.10</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>0.07</td>
<td>0.041</td>
<td>0.024</td>
<td>-</td>
<td>0.029</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td>-</td>
<td>0.80</td>
<td>0.083</td>
<td>-</td>
<td>0.39</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>-</td>
<td>-</td>
<td>0.055</td>
<td>-</td>
<td>0.18</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>0.14</td>
<td>0.15</td>
<td>0.06</td>
<td>-</td>
<td>0.08</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c} + gg$</td>
<td>0.39</td>
<td>0.17</td>
<td>-</td>
<td>-</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Given the different parameters assumed in each study, such a direct comparison may be misleading.
The fractional branching ratio error $\delta_{BR}/BR$ goes like $(\sigma \int dt L)^{-1/2}$. The former divided by the latter is plotted against the latter for the case $m_H = 120$ GeV.

Broadly, the results are consistent though there is some discrepancy in the $H \rightarrow c\bar{c}$ and $H \rightarrow gg$ results.
IMPROVING THE STUDY

By the end of Snowmass 2001, this study should be extended and improved in the following ways:

• Analyze higher Higgs mass cases.
• Confer with other authors to resolve differences in results ($H \rightarrow c\bar{c}$ and $H \rightarrow gg$).
• Consider how to apply this analysis to the light MSSM $h^0$ in the decoupling limit.