The Higgs Mechanism and Electroweak Symmetry Breaking at $e^+e^-$ Colliders

Jim Brau
University of Oregon

Snowmass 2001
Workshop on the Future of High Energy Physics
The LHC (or the Tevatron) should initiate the experimental measurement of the particle(s) associated with EWSB

These first discoveries will likely provide a limited view of the nature of the Higgs mechanism

A Linear Collider will be a crucial tool in advancing the understanding that the LHC/Tevatron begins
Outline

Present knowledge of Electroweak Symmetry Breaking
Parameters of the proposed future Linear Colliders
Standard Model Higgs
MSSM Higgs
Strong coupling gauge models of EWSB
Other scenarios
Value added to LHC observations
Electroweak Symmetry Breaking

The Standard Model has been remarkably successful

\[
\begin{array}{l|c|c|c}
\text{Measurement} & \text{Pull} & \text{Pull} \\
\hline
\Delta a_{\text{had}}^{(g)}(m_Z) & 0.02761 \pm 0.00036 & -0.35 \\
M_Z [\text{GeV}] & 91.1875 \pm 0.0021 & 0.03 \\
\Gamma_Z [\text{GeV}] & 2.4982 \pm 0.0023 & -0.48 \\
\sigma_{\text{had}}^{0} [\text{nb}] & 41.540 \pm 0.037 & 1.60 \\
R_b & 20.767 \pm 0.025 & 1.11 \\
A_{b^0} & 0.01714 \pm 0.00095 & 0.69 \\
A_{b} & 0.1465 \pm 0.0033 & 0.54 \\
R_b & 0.21646 \pm 0.00055 & 1.12 \\
R_b & 0.1719 \pm 0.0031 & -1.12 \\
A_{b^0} & 0.0900 \pm 0.0017 & -2.90 \\
A_{b} & 0.0685 \pm 0.0034 & -1.71 \\
A_{b^0} & 0.922 \pm 0.020 & 0.64 \\
A_{b} & 0.670 \pm 0.026 & 0.06 \\
A_{\text{SLD}} & 0.1513 \pm 0.0021 & 1.47 \\
\sin^2\theta_W^{\text{eff}}(Q_0) & 0.2324 \pm 0.0012 & 0.86 \\
m_W^{(\text{LH})} [\text{GeV}] & 80.450 \pm 0.039 & 1.32 \\
m_t [\text{GeV}] & 174.3 \pm 5.1 & -3.30 \\
m_W^{(\text{TH})} [\text{GeV}] & 80.454 \pm 0.060 & 0.93 \\
\sin^2\theta_W^{(\text{TH})} & 0.2255 \pm 0.0021 & 1.22 \\
Q_W(Cu) & -72.50 \pm 0.70 & 0.56 \\
\end{array}
\]
(SM) $M_{\text{higgs}} < 195$ GeV at 95% CL.
LEP2 limit $M_{\text{higgs}} > 113.5$ GeV.
Tevatron can discover up to 180 GeV

**LEP Higgs search - Maximum Likelihood for Higgs signal at**

$m_H = 115.0$ GeV with overall significance (4 experiments) = 2.9$\sigma$

J.Brau, Snowmass, July 17, 2001
S, T, and U parameters describe new physics which enters through vacuum-polarization (self-energy) to vector-boson propagators of the SM.

Light SM Higgs is in good agreement with measured EW radiative corrections, as expressed as S and T.

Sizeable contributions to S and T would be expected from many models of New Physics.
Establishing Standard Model Higgs

*precision studies of the Higgs boson will be required to understand Electroweak Symmetry Breaking; just finding the Higgs is of limited value*

*We expect the Higgs to be discovered at LHC (or tevatron) and the measurement of its properties will begin at the LHC*

*We need to measure the full nature of the Higgs to understand EWSB*

*The 500 GeV (and beyond) Linear Collider is the tool needed to complete these precision studies*

**References:**
- TESLA Technical Design Report
- Linear Collider Physics Resource Book for Snowmass 2001 (contain references to many studies)
The “next” Linear Collider

The next Linear Collider proposals include plans to deliver a few hundred fb$^{-1}$ of integrated lum. per year

<table>
<thead>
<tr>
<th></th>
<th>TESLA</th>
<th>JLC-C</th>
<th>NLC/JLC-X *</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{design}}$ (10$^{34}$)</td>
<td>3.4 $\rightarrow$ 5.8</td>
<td>0.43</td>
<td>2.2 $\rightarrow$ 3.4</td>
</tr>
<tr>
<td>$E_{\text{CM}}$ (GeV)</td>
<td>500 $\rightarrow$ 800</td>
<td>500</td>
<td>500 $\rightarrow$ 1000</td>
</tr>
<tr>
<td>Eff. Gradient (MV/m)</td>
<td>23.4 $\rightarrow$ 35</td>
<td>34</td>
<td>70</td>
</tr>
<tr>
<td>RF freq. (GHz)</td>
<td>1.3</td>
<td>5.7</td>
<td>11.4</td>
</tr>
<tr>
<td>$\Delta t_{\text{bunch}}$ (ns)</td>
<td>337 $\rightarrow$ 176</td>
<td>2.8</td>
<td>1.4</td>
</tr>
<tr>
<td>#bunch/train</td>
<td>2820 $\rightarrow$ 4886</td>
<td>72</td>
<td>190</td>
</tr>
<tr>
<td>Beamstrahlung (%)</td>
<td>3.2 $\rightarrow$ 4.4</td>
<td></td>
<td>4.6 $\rightarrow$ 8.8</td>
</tr>
</tbody>
</table>

We can plan for 500 fb$^{-1}$ in a few years, and 1000 fb$^{-1}$ within about five years

* US and Japanese X-band R&D cooperation, but machine parameters may differ
The “next” Linear Collider

Standard Package:
\( e^+ e^- \) Collisions
Initially at 500 GeV
Electron Polarization, \( \geq 80\% \)

Options:
Energy upgrades to \( \sim 1.0 - 1.5 \) TeV
Positron Polarization (\( \sim 40 - 60\% \) ?)
\( \gamma\gamma \) Collisions
\( e^- e^- \) and \( e^- \gamma \) Collisions
Giga-Z (precision measurements)
Special Advantages of Experiments at the Linear Collider

Elementary interactions at known $E_{cm}^*$

eg. $e^+e^- \rightarrow ZH$

Democratic Cross sections

eg. $\sigma(e^+e^- \rightarrow ZH) \sim 1/2 \sigma(e^+e^- \rightarrow d\overline{d})$

Inclusive Trigger

total cross-section

Highly Polarized Electron Beam

$\sim 80\%$

Exquisite vertex detection

eg. $R_{\text{beampipe}} \sim 1 \text{ cm}$ and $\sigma_{\text{hit}} \sim 3 \mu\text{m}$

Calorimetry with Jet Energy Flow

$\sigma_E/E \sim 30-40\%/\sqrt{E}$

* beamstrahlung must be dealt with, but it’s manageable
The Linear Collider provides very special experimental conditions (eg. superb vertexing and jet calorimetry)

CCD Vertex Detectors

Silicon/Tungsten Calorimetry

SLD Lum (1990)
Aleph Lum (1993)
Opal Lum (1993)

Snowmass - 96 Proceedings

NLC Detector - fine gran. Si/W

Now TESLA & NLD have proposed Si/W as central elements in jet flow measurement

J.Brau, Snowmass, July 17, 2001
Candidate Models for Electroweak Symmetry Breaking

Standard Model Higgs
  excellent agreement with EW precision measurements
  implies $M_H < 200 \text{ GeV}$ (but theoretically ugly - h'archy prob.)

MSSM Higgs
  expect $M_h < \sim 135 \text{ GeV}$
  light Higgs boson ($h$) may be very “SM Higgs-like”
    (de-coupling limit)

Non-exotic extended Higgs sector
  eg. 2HDM

Strong Coupling Models
  New strong interaction
Electroweak precision measurements suggest there should be a relatively light Higgs boson:

When we find it, we will want to study its nature. The LC is capable of contributing significantly to this study.

Mass Measurement
Total width
Particle couplings
  vector bosons
  fermions (including top)
Spin-parity-charge conjugation
Self-coupling

J.Brau, Snowmass, July 17, 2001
Example of Precision of Higgs Measurements at the Next Linear Collider

For $M_H = 140$ GeV, 500 fb$^{-1}$ @ 500 GeV

| Mass Measurement | $\delta M_H \approx 60$ MeV $\approx 5 \times 10^{-4} M_H$ |
| Total width | $\delta \Gamma_H / \Gamma_H \approx 3\%$ |
| Particle couplings | (needs higher $\sqrt{s}$ for 140 GeV, except through $H \rightarrow gg$) |
| $t\bar{t}$ | $\delta g_{Hbb} / g_{Hbb} \approx 2\%$ |
| $b\bar{b}$ | $\delta g_{Hcc} / g_{Hcc} \approx 22.5\%$ |
| $c\bar{c}$ | $\delta g_{Ht\tau} / g_{Ht\tau} \approx 5\%$ |
| $\tau^+\tau^-$ | $\delta g_{Hww} / g_{Hww} \approx 2\%$ |
| $W W^*$ | $\delta g_{HZZ} / g_{HZZ} \approx 6\%$ |
| $Z Z$ | $\delta g_{Hgg} / g_{Hgg} \approx 12.5\%$ |
| $g g$ | $\delta g_{H\gamma\gamma} / g_{H\gamma\gamma} \approx 10\%$ |

Spin-parity-charge conjugation

establish $J^{PC} = 0^{++}$

Self-coupling

$\delta \lambda_{HHH} / \lambda_{HHH} \approx 32\%$

(statistics limited)

If Higgs is lighter, precision is often better
Recall, $\sigma_{pt} = 87 \text{ nb} / (E_{cm})^2 \sim 350 \text{ fb} @ 500 \text{ GeV}$
Cross-sections at the Next Linear Collider
Higgs Production Cross-section at the Next Linear Collider

$e^+e^- \rightarrow ZH \rightarrow l^+l^- X$

@ 500 GeV

<table>
<thead>
<tr>
<th>$M_H$ (GeV)</th>
<th>events/500 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>2020</td>
</tr>
<tr>
<td>140</td>
<td>1910</td>
</tr>
<tr>
<td>160</td>
<td>1780</td>
</tr>
<tr>
<td>180</td>
<td>1650</td>
</tr>
<tr>
<td>200</td>
<td>1500</td>
</tr>
<tr>
<td>250</td>
<td>1110</td>
</tr>
</tbody>
</table>
The LC can produce the Higgs recoiling from a Z, with known CM energy, which provides a powerful channel for unbiased tagging of Higgs events, allowing measurement of even invisible decays (beamstrahlung).

- Tag Z \( \ell^+ \ell^- 
- Select M_{\text{recoil}} = M_{\text{Higgs}}

Invisible decays are included

500 fb\(^{-1}\) @ 500 GeV, TESLA TDR, Fig 2.1.4
Higgs Studies - the Mass Measurement

\( \delta M/M \sim 1.2 \times 10^{-3} \) from recoil alone (decay mode indep.), but reconstruction of Higgs decay products and fit does even better......

500 fb\(^{-1}\), LC Physics Resource Book, Fig. 3.17

\( m=120 \text{ GeV} @ 500 \text{ GeV} \)
# Higgs Studies - the Mass Measurement

<table>
<thead>
<tr>
<th>$M_H$</th>
<th>$\delta M_H$(Recoil)</th>
<th>$\delta M_H$(Recon &amp; fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 GeV</td>
<td>40 MeV ($3.3 \times 10^{-4}$)</td>
<td></td>
</tr>
<tr>
<td>150 GeV</td>
<td>90 MeV</td>
<td>70 MeV ($2 \times 10^{-4}$)</td>
</tr>
<tr>
<td>180 GeV</td>
<td>100 MeV</td>
<td>80 MeV ($4 \times 10^{-4}$)</td>
</tr>
</tbody>
</table>

500 fb$^{-1}$ @ 350 GeV, TESLA TDR, Table 2.2.1
Total Width of the Higgs

\[ \Gamma_{\text{TOT}} = \Gamma_x / \text{BR}(H \to X) \]

- \( \text{BR}(H \to WW^*) = \Gamma_{WW} / \Gamma_{\text{TOT}} \)
- \( \Gamma_{WW} \) from WW fusion cross section

<table>
<thead>
<tr>
<th>( M_H )</th>
<th>WW fusion</th>
<th>Higgs-strahlung</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 GeV</td>
<td>6.1%</td>
<td>5.6%</td>
</tr>
<tr>
<td>140 GeV</td>
<td>4.5%</td>
<td>3.7%</td>
</tr>
<tr>
<td>160 GeV</td>
<td>13.4%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

500 fb\(^{-1}\) @ 350 GeV, TESLA TDR, Table 2.2.4

\[ \Gamma_{\text{TOT}} \text{ to few\%} \]
Higgs Z/W Couplings

$g_{_{HZZ}}$ is measured through Higgs-strahlung cross section, or Higgs branching ratio

<table>
<thead>
<tr>
<th>$M_H$</th>
<th>cross section</th>
<th>branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 GeV</td>
<td>6.5%</td>
<td></td>
</tr>
<tr>
<td>140 GeV</td>
<td>6.5%</td>
<td></td>
</tr>
<tr>
<td>160 GeV</td>
<td>6%</td>
<td>8.5%</td>
</tr>
<tr>
<td>200 GeV</td>
<td>7%</td>
<td>4%</td>
</tr>
</tbody>
</table>

500 fb$^{-1}$ @ 500 GeV, LC Physics Resource Book, Table 3.2

$g_{_{HWW}}$ is measured through the WW fusion cross section, or the Higgs branching ratio

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<tr>
<th>$M_H$</th>
<th>cross section</th>
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<td>2%</td>
</tr>
<tr>
<td>160 GeV</td>
<td>17%</td>
<td>1.5%</td>
</tr>
<tr>
<td>200 GeV</td>
<td>3.5%</td>
<td></td>
</tr>
</tbody>
</table>

500 fb$^{-1}$ @ 500 GeV, LC Physics Resource Book, Table 3.2
Higgs Couplings - the Branching Ratios
**Higgs Couplings - the Branching Ratios**

<table>
<thead>
<tr>
<th>$M_H$</th>
<th>$H \rightarrow b \bar{b}$</th>
<th>$H \rightarrow c \bar{c}$</th>
<th>$H \rightarrow gg$</th>
<th>$H \rightarrow \tau^+ \tau^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 GeV</td>
<td>2.9 %</td>
<td>39 %</td>
<td>18 %</td>
<td>7.9 %</td>
</tr>
<tr>
<td>140 GeV</td>
<td>4.1 %</td>
<td>45 %</td>
<td>23 %</td>
<td>10 %</td>
</tr>
</tbody>
</table>

(through Higgs-strahlung, only)

500 fb$^{-1}$ @ 500 GeV, LC Physics Resource Book, Table 3.1

At lower energy, including $e^+e^- \rightarrow H \nu \nu$, along with $e^+e^- \rightarrow ZH$

<table>
<thead>
<tr>
<th>$M_H$</th>
<th>$H \rightarrow bb$</th>
<th>$H \rightarrow cc$</th>
<th>$H \rightarrow gg$</th>
<th>$H \rightarrow \tau^+ \tau^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 GeV</td>
<td>2.4 %</td>
<td>8.3 %</td>
<td>5.5 %</td>
<td>5.0 %</td>
</tr>
<tr>
<td>140 GeV</td>
<td>2.6 %</td>
<td>19.0 %</td>
<td>14.0 %</td>
<td>8.0 %</td>
</tr>
<tr>
<td>160 GeV</td>
<td>6.5 %</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

500 fb$^{-1}$ @ 350 GeV, TESLA TDR, Table 2.2.5

Measurement of BR's is powerful indicator of new physics

*e.g. in MSSM, these differ from the SM in a characteristic way. Higgs BR must agree with MSSM parameters from many other measurements.*
hbb coupling for Heavier Higgs

R. Van Kooten, Fermilab Line-Drive
Invisible Higgs Decays

**Invisible Branching Ratio**

- $hZ \rightarrow all$ (Explicitly search for $Z$ recoiling against "nothing" (previously, e.g., $[1 - \Sigma \text{Br's}]$))

- $h \rightarrow invisible$

- PYTHIA, FastMC, Large NLC (Idmar01) detector, NLC beamst.
  $M_{h^0} = 120 \text{ GeV}$

- Test case, e.g., Wells et al., hep-ph/002178,
  $\delta = 4$ extra dimensions,
  $\text{Br}(h \rightarrow \text{invis}) = 38\%$, $\Gamma_{\text{inv}} \sim 2 \text{ MeV}$

- Recoil mass $\pm 10 \text{ GeV}$ of $M_{h^0}$, thrust hemispheres,
  veto neutral clusters $> 5 \text{ GeV}$ and any track activity
  in "away" hemisphere

---

**Snowmass Study**

- **Preliminary**: Measure
  \[
  \frac{\delta \text{Br}(h \rightarrow \text{invis})}{\text{Br}(h \rightarrow \text{invis})} \\
  \sim 12\%
  \]

- Add hadronic $Z$ decays! (should gain factor $\sim 2$
  in above precision)

---

J.Brau, Snowmass, July 17, 2001
With 500 fb\(^{-1}\) @ 500 GeV, expect 10% precision at 140 GeV

J.Brau, Snowmass, July 17, 2001
Due to the large top mass, the Higgs Yukawa coupling to top is very large: \( g_{ttH}^2 \approx 0.5 \)

This measurement will require large luminosity, and probably high energy.
Higgs Spin Parity and Charge Conjugation ($J^{PC}$)

$H \rightarrow \gamma\gamma$ or $\gamma\gamma \rightarrow H$ rules out $J=1$ and indicates $C=+1$.

Threshold cross section ($e^+e^- \rightarrow Z H$) for $J=0$

$\sigma \sim \beta$, while for $J > 0$, generally higher power of $\beta$ (assuming $n = (-1)^J P$)

Production angle ($\theta$) and Z decay angle in Higgs-strahlung reveals $J^P (e^+e^- \rightarrow Z H \rightarrow \gamma\gamma)$

$\frac{d\sigma}{d\cos \theta} \quad \sin^2 \theta \quad (1 - \sin^2 \theta)$

$\frac{d\sigma}{d\cos \phi} \quad \sin^2 \phi \quad (1 +/\ - \cos \phi)^2$

$\phi$ is angle of the fermion, relative to the Z direction of flight, in Z rest frame

LC Physics Resource Book, Fig 3.23(a)

Also e$^+e^- \rightarrow e^+e^-Z$

Han, Jiang

TESLA TDR, Fig 2.2.8

J.Brau, Snowmass, July 17, 2001
Measures Higgs potential $\lambda$

$$V(\Phi) = \lambda(\Phi^2 - \frac{1}{2} v^2)^2 \quad v \sim 246 \text{ GeV}$$

$$m_h^2 = 4 \lambda v^2$$

Study $Zhh$ production and decay to 6 jets (4 b’s). Cross section is small; premium on very good jet energy resolution. Can enhance x5 with positron polarization.

<table>
<thead>
<tr>
<th>$m_h$ (GeV/$c^2$)</th>
<th>$\sigma_{hhZ}$ (nb)</th>
<th>$N_{hhZ}^{500}$</th>
<th>$\epsilon_{hhZ}$</th>
<th>$L = 500$ (nb$^{-1}$)</th>
<th>$L = 1000$ (nb$^{-1}$)</th>
<th>$L = 2000$ (nb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.186</td>
<td>93</td>
<td>43%</td>
<td>24.1%</td>
<td>17.3%</td>
<td>11.6%</td>
</tr>
<tr>
<td>130</td>
<td>0.149</td>
<td>74</td>
<td>43%</td>
<td>26.6%</td>
<td>19%</td>
<td>17.7%</td>
</tr>
<tr>
<td>140</td>
<td>0.115</td>
<td>57</td>
<td>39%</td>
<td>32%</td>
<td>23%</td>
<td>17%</td>
</tr>
</tbody>
</table>

$\Delta \lambda/\lambda$ error 36% → 18%
Is This the Standard Model Higgs?

For $M_H = 140$ GeV, 500 fb$^{-1}$ @ 500 GeV

- **Mass Measurement**
  $\delta M_H \approx 60$ MeV $\approx 5 \times 10^{-4} M_H$

- **Total width**
  $\delta \Gamma_H / \Gamma_H \approx 3\%$

- **Particle couplings**
  (needs higher $\sqrt{s}$ for 140 GeV, except through $H \rightarrow gg$)

  - $t\bar{t}$
    $\delta g_{Ht\bar{t}} / g_{Ht\bar{t}} \approx 5\%$

  - $b\bar{b}$
    $\delta g_{Hb\bar{b}} / g_{Hb\bar{b}} \approx 2\%$

  - $c\bar{c}$
    $\delta g_{Hc\bar{c}} / g_{Hc\bar{c}} \approx 22.5\%$

  - $\tau^+\tau^-$
    $\delta g_{H\tau^+\tau^-} / g_{H\tau^+\tau^-} \approx 5\%$

  - $WW$
    $\delta g_{HWW} / g_{HWW} \approx 2\%$

  - $ZZ$
    $\delta g_{HZZ} / g_{HZZ} \approx 6\%$

  - $gg$
    $\delta g_{Hgg} / g_{Hgg} \approx 12.5\%$

  - $\gamma\gamma$
    $\delta g_{H\gamma\gamma} / g_{H\gamma\gamma} \approx 10\%$

- **Spin-parity-charge conjugation**
  establish $J^{PC} = 0^{++}$

- **Self-coupling**
  $\delta \lambda_{HHH} / \lambda_{HHH} \approx 32\%$
  (statistics limited)
Is This the Standard Model Higgs?

1.) Does the $hZZ$ coupling saturate the $Z$ coupling sum rule?

$$\Sigma g_{hZZ} = M_Z^2 \frac{g_{ew}^2}{4 \cos^2 \theta_W}$$

eg. $g_{hZZ} = g_Z M_Z \sin(\beta-\alpha)$

$$g_{HZZ} = g_Z M_Z \cos(\beta-\alpha) \quad g_Z = \frac{g_{ew}}{2 \cos \theta_W}$$

2.) Are the measured BRs consistent with the SM?

eg. $g_{hbb}^{MSSM} = g_{hbb}(-\sin \alpha / \cos \beta) \rightarrow -g_{hbb}(\sin(\beta-\alpha) - \cos(\beta-\alpha) \tan \beta)$

$g_{htt}^{MSSM} = g_{htt}(-\sin \alpha / \cos \beta) \rightarrow -g_{htt}(\sin(\beta-\alpha) - \cos(\beta-\alpha) \tan \beta)$

$g_{htt}^{MSSM} = g_{htt}(-\cos \alpha / \sin \beta) \rightarrow g_{htt}(\sin(\beta-\alpha) + \cos(\beta-\alpha) / \tan \beta)$

(in MSSM only for smaller values of $M_A$ will there be sensitivity, since $\sin(\beta-\alpha) \rightarrow 1$ as $M_A$ grows -decoupling)

3.) Is the width consistent with SM?

4.) Have other Higgs bosons or super-partners been discovered?

5.) etc.
MSSM Higgs

$M_1 = 175 \pm 15 \text{ GeV}$
$M_{Higgs} = m_A = 1 \text{ TeV}$
$\mu = -200 \text{ GeV}$

$\sin(\beta - \alpha) \rightarrow 1$ as $M_A$ grows
-decoupling

$\sin^2(\beta - \alpha) \rightarrow 1$
-as $M_A$ grows
-decoupling
Is This the Standard Model Higgs?

Are the measured BRs consistent with the SM? (only for smaller values of $M_A$ will there be sensitivity -decoupling)

$\Rightarrow$

M. Carena, H.E. Haber, H.E. Logan, and S. Mrenna, FERMILAB-Pub-00/334-T

If $M_A$ is large, decoupling sets in.
Is This the Standard Model Higgs?

Arrows at:
- $M_A = 200-400$
- $M_A = 400-600$
- $M_A = 600-800$
- $M_A = 800-1000$

HFITTER output

Conclusion:
for $M_A < 600$, likely distinguish

TESLA TDR, Fig 2.2.6
**MSSM Higgs Bosons**

For $M_A > 150$ GeV, MSSM Higgs sector approaches decoupling

Accessible production mechanisms for heavier MSSM Higgs':

\[
\begin{align*}
e^+ e^- & \rightarrow Z^* \rightarrow H^0 A^0 \quad \text{for } \sqrt{s} > M_A/2 \\
e^+ e^- & \rightarrow \gamma^* \rightarrow H^+ H^- \quad \text{for } \sqrt{s} > M_H/2 \\
\gamma \gamma & \rightarrow A^0 \\
\gamma \gamma & \rightarrow H^0
\end{align*}
\]

J.Brau, Snowmass, July 17, 2001
Complementarity with LHC

The SM-like Higgs Boson

<table>
<thead>
<tr>
<th></th>
<th>( M_H ) (GeV)</th>
<th>( \delta(X)/X ) LHC 2 ( \times ) 300 fb(^{-1} )</th>
<th>( \delta(X)/X ) LC 500 fb(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_H )</td>
<td>120</td>
<td>( 9 \times 10^{-4} )</td>
<td>( 3 \times 10^{-4} )</td>
</tr>
<tr>
<td>( M_H )</td>
<td>160</td>
<td>( 10 \times 10^{-4} )</td>
<td>( 4 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \Gamma_{tot} )</td>
<td>120-140</td>
<td>-</td>
<td>( 0.04 - 0.06 )</td>
</tr>
<tr>
<td>( g_{Hud} )</td>
<td>120-140</td>
<td>-</td>
<td>( 0.02 - 0.04 )</td>
</tr>
<tr>
<td>( g_{Hdd} )</td>
<td>120-140</td>
<td>-</td>
<td>( 0.01 - 0.02 )</td>
</tr>
<tr>
<td>( g_{HWW} )</td>
<td>120-140</td>
<td>-</td>
<td>( 0.01 - 0.03 )</td>
</tr>
<tr>
<td>( g_{Hua} )</td>
<td>120-140</td>
<td>-</td>
<td>( 0.023 - 0.052 )</td>
</tr>
<tr>
<td>( g_{Hud} )</td>
<td>120-140</td>
<td>-</td>
<td>( 0.012 - 0.022 )</td>
</tr>
<tr>
<td>( \lambda_{HHH} )</td>
<td>120</td>
<td>0.070</td>
<td>0.023</td>
</tr>
<tr>
<td>( \lambda_{HWW} )</td>
<td>120</td>
<td>0.050</td>
<td>0.022</td>
</tr>
</tbody>
</table>

These precision measurements will be crucial in understanding the Higgs Boson

TESLA TDR, Table 2.5.1

Table 2.5.1: Comparison of the expected accuracy in the determination of the SM-like Higgs profile at the LHC and at TESLA. The mass, width, couplings to up-type and down-type quarks and to gauge bosons, several of the ratios of couplings, the triple Higgs coupling and the sensitivity to a CP-odd component are considered.
Suppose EWSB is not explained by fundamental scalars. Suppose a new strong interaction provides the Higgs mechanism for EWSB.

At the LC, strong coupling composite 'higgs' should be constrained to $< 500$ GeV with Giga Z.

\[ \Delta T, \delta M_W = 30 \text{ MeV}, \delta M_{\text{Top}} = 2 \text{ GeV} \]
**Strong coupling Observables at LC:**

Bound states of new fermions should occur on the TeV scale.

Since the longitudinal components of \( W/Z \) are primordial higgs particles, \( WW \) (\( ZZ \)) scattering is modified:

- a broad resonance is seen at LHC

LC sees modification to \( e^+ e^- \rightarrow WW \) cross section

Technirho relative signal significance for LHC and LC at 500, 1000, 1500 GeV
Expect observable modifications to WWγ coupling.

For Δκ_{γ,Z}, LC at 500 GeV has precision 10-20 times better than LHC - in the range expected in Strong Coupling models.

γγ → WW gives orthogonal information of comparable precision.

Errors on WWγ / WWZ coupling for LHC and LC at 500, 1000, 1500 GeV

Discovery reach for Z' at LC500 is better or comparable to LHC for different models; better for LC1000 by factor ~2.

Anomalous top couplings to Z,γ are expected, only observable at LC.
Imagined other scenarios must introduce EWSB consistent with precision EW measurements.

Scenarios have been investigated. (Peskin & Wells hep-ph/0101342)
Generally, additional new physics emerges which the LC is able to detect.

Examples (these are highly selective, to match PrEW):
- Heavy Higgs (say 500 GeV) + light SU(2)xSU(2)
  (observe new particles)
- Heavy Higgs (say 500 GeV) + Z' (observable)
- Heavy Higgs (say 500 GeV) + extra dimen.
  (detectable)
- Heavy Higgs (say 500 GeV) + new particles
  with large up/down flavor asymmetry
  (Giga-Z effects)
The Linear Collider Options

Energy upgrades to ~ 1.0 - 1.5 TeV
Positron Polarization (~ 40 - 60%?)
$\gamma \gamma$ Collisions
$e^- e^-$ and $e^- \gamma$ Collisions
Giga-Z (precision measurements) and WW threshold

$\delta M_W = 6 \text{ MeV}$
(positron polarization, one year)
Some scenarios for the results of high energy measurements would motivate higher precision studies of the Z pole (100 days)

eg. A light Higgs is found, but nothing else.
Given the mass of the higgs, its contribution to electroweak loop corrections would be known

\[ \delta \sin^2 \theta_w = 0.000013, \delta m_W = 6 \text{ MeV}, \delta m_t = 100 \text{ MeV} \]

In MSSM or non-minimal Higgs context, EW corrections could narrow unknown
Blue blob is 2HDM for which no Higgs Boson is detected.

Inner ellipse for Giga-Z assuming $M_H = 115$ GeV.

$\star$ is expectation for $M_H = \sqrt{s}$

LC Physics Resource Book, Fig 3.15
Example of Giga-Z constraints on high mass:

$e^+ e^- \rightarrow \tilde{t}_1^+ \tilde{t}_1^-$ observed at LC,
$M_{\tilde{t}_1} = 500$ GeV

light higgs found:
$M_h = 120$ GeV
"Topcolor" seesaw model (Dobrescu and Hill)
This model has little or no signatures of new physics at the LHC or the LC
However, the Giga-Z run would be sensitive through the Giga-Z precision measurements

This model introduces a heavy, weak SU(2)-singlet fermion $\chi$ which adds positive $\Delta T$ to the EW measurements:

<table>
<thead>
<tr>
<th>$M_\chi$</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 TeV</td>
<td>+7.2</td>
</tr>
<tr>
<td>5 TeV</td>
<td>+0.3</td>
</tr>
</tbody>
</table>
Giga-Z: Precision Studies at the Z

“Topcolor” seesaw model
\[ M_\chi = 5 \text{ TeV} \]

This is an example of a general principle:

If the electroweak measurements are to be explained by a “conspiracy” between a heavy SM Higgs and other new physics, that other new physics will generally be detectable at the LC experimentalist paraphrase of Peskin and Wells hep-ph/0101342
One option that a linear collider provides is the capability to do gamma-gamma collisions

Measure $\gamma\gamma \rightarrow H \rightarrow X$

Also:
- Production of Higgs at $\gamma\gamma$ collider establishes $C$ to be positive (and rules out $J=1$)
- Can produce CP even and odd states separately using polarized $\gamma\gamma$ collisions (Separate Susy H/A)

$\gamma\gamma \rightarrow H$ or $A$ (can reach higher masses than $e^+e^-$)
The Gamma-Gamma Collider

Expected precision for \( M_H = 120 \text{ GeV} \)
\[
\delta[\sigma(\gamma\gamma \rightarrow H)] = 2\% \text{ for 43 fb}^{-1} \text{ of hard spectrum (TESLA TDR)}
\]
\[
\delta[\sigma(\gamma\gamma \rightarrow H)] = 5\% \text{ for more conservative spectrum (LC Physics Res. Bk)}
\]
(However better as a result of Snowmass studies)

for \( M_H = 160 \text{ GeV} \) 5% increases to 20%

J.Brau, Snowmass, July 17, 2001
Adding Value to LHC measurements

The Linear Collider will add value to the LHC measurements ("enabling technology")

How this happens depends on the Physics:

• Add precision to the discoveries of LHC
  • eg. light higgs measurements
• Susy parameters may fall in the $\tan \beta / M_A$ wedge.
• Directly observed strong WW/ZZ resonances at LHC are understood from asymmetries at Linear Collider
• Analyze extra neutral gauge bosons
• Giga-Z constraints
Complementing the LHC: the tan$\beta$ - $M_A$ wedge

For $\tan \beta \sim 4$-8 and $M_A > 250$ GeV, the LHC will have a difficult time detecting MSSM.

LC should add the detection.

Four b jets

J. Hobbs, Snowmass
$\sqrt{s} = 1$ TeV, 50 fb$^{-1}$

J. Brau, Snowmass, July 17, 2001
Scheduling the Run Parameters

The Linear Collider has a broad role in elucidating the new physics:

• follow up on results of LHC
  • Higgs boson discovered?
  • Other new particles?
  • Evidence for strong coupling?
• measure details of light Higgs
• scan threshold of new particles
• W/top threshold scans
• Giga-Z

Can we devise a run plan that measures what we need to know in available time?

YES! Constrain time to that needed for 1000 fb\(^{-1}\) at 500 GeV.

Statistics for Higgs BRs equivalent to 700 fb\(^{-1}\) at 350 GeV

Example:
Light Higgs and superpartners seen at LHC

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Luminosity (fb(^{-1}))</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>320 GeV</td>
<td>160 fb(^{-1})</td>
<td>sit</td>
</tr>
<tr>
<td>500 GeV</td>
<td>245 fb(^{-1})</td>
<td>span</td>
</tr>
<tr>
<td>255 GeV</td>
<td>20 fb(^{-1})</td>
<td>Chargino threshold scan</td>
</tr>
<tr>
<td>265 GeV</td>
<td>100 fb(^{-1})</td>
<td>Slepton ((l_R \rightarrow l_L^{-1})) threshold scan</td>
</tr>
<tr>
<td>310 GeV</td>
<td>20 fb(^{-1})</td>
<td></td>
</tr>
<tr>
<td>350 GeV</td>
<td>20 fb(^{-1})</td>
<td></td>
</tr>
<tr>
<td>450 GeV</td>
<td>100 fb(^{-1})</td>
<td>Neutralino((\chi_{2}^{0}, \chi_{3}^{0})) threshold scan</td>
</tr>
<tr>
<td>470 GeV</td>
<td>100 fb(^{-1})</td>
<td>Chargino((\chi_{1}^{+}, \chi_{2}^{+})) threshold scan</td>
</tr>
</tbody>
</table>

Ref: Linear Collider Physics Resource Book, SM2001

J.Brau, Snowmass, July 17, 2001
The Linear Collider will be a powerful tool for studying the Higgs Mechanism and Electroweak Symmetry Breaking.

Current status of Electroweak Precision measurements strongly suggests that the physics will be rich and greatly advance our understanding of the elementary particles.

If Nature turns out to be more complicated than the simplest models, its precision could be critical.