Higgs Boson Studies at an $e^+e^-$ Linear Collider: Intermediate Mass and Heavy

Outline

- The NLC Collider and Detectors
- Mass region
- Profile of Higgs Boson, Part II
  - Cross sections
  - Branching Ratios
  - Couplings
- Width/Mass
- Nastier scenarios
- Conclusions/Summary

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TESLA TDR, FNAL Report, Orange Book authors/editors

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Indiana University
3 May 2001
Baseline for NLC 2001: two linacs inclined at 20 mrad crossing angle, no bend angle at high-energy IP, can work at multi-TeV energies. Low-energy IP does have bend, max. energy well beyond $t \bar{t}$ threshold.
- Lateral separation of 25 m, longitudinal separation of 440 m
- e.g., "L" or "SD" NLC detector at one IR, "SD" or "P" NLC detector at other, push-pull at either possible (e.g., operation?)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition Rate</td>
<td>120 Hz (can be split 60-60)</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>11.4 GHz</td>
</tr>
<tr>
<td>Bunch Separation</td>
<td>1.4 nsec</td>
</tr>
<tr>
<td>Beamstrahlung</td>
<td>4.6%</td>
</tr>
<tr>
<td>Electron polarization</td>
<td>~80% (known to 0.25 – 1.0% from polarimetry)</td>
</tr>
<tr>
<td>Positron polarization possible</td>
<td></td>
</tr>
</tbody>
</table>
Low-energy IR
- Running at \( Z \) pole
- Scan \( W \)-pair threshold
- Scan \( HZ \) threshold
- Sit at \( HZ \) production peak
  \[ (s \sim M_Z + M_h + \sim 20 \text{ GeV}) \]
  for precision property measurements
- Scan \( t \bar{t} \) threshold

High-energy IR
- Rest of LC program (plus Higgs properties)
- Higgs self-coupling
- \( t \bar{t} h \)
NLC_DETECTORS

TRACKING SYSTEM FOR SD DETECTOR

5 T, Energy flow calorimetry

Si-Strip Disk Tracker

Cos( ) = 0.80

Cos( ) = 0.90

Cos( ) = 0.99

NLC DETECTOR DESIGN "L"

Muon Detector/Iron

Magnet Coil (3 T)

Hadronic Calor.

EM Calorimeter

Central Tracker (TPC)

Vertex Detector (CCD Pixels)

Si-Strip Disk Tracker

Silicon (SDD or s-stripe) barrel

CCD-Vertex Detector (+ cryostat)

Z (cm)

R (cm)
- $b$ and $c$-quark tagging efficiency and purity similar for all detectors:
- Momentum Resolution

![Graph showing momentum resolution vs p (GeV)]

- $e^\pm$ and photon backgrounds in vertex detector and TPC

![Graph showing VXD hit density vs radius (cm) and photon flux vs radius (cm)]
For "SM-like" Higgs (for SM-only Higgs, much of intermediate/heavy mass region ruled out by precision measurements)

Decays into weak bosons, fermion decays "rare" until top turns on
For couplings: \( g_{hZZ} \quad g_{hWW} \)

- Even for the intermediate mass range, the "nominal" \( s = 500 \text{ GeV} \) not necessarily the best place to be to take advantage of the tagging utility of \( hZ \) associated production:

- Strength of low-energy IR flexibility

- e.g., low end of range, \( M_h = 160 \text{ GeV}, s = 350 \text{ GeV}, 500 \text{ fb}^{-1} \)

\[ \frac{(HZ)}{(HZ)} \sim 5\% \quad \frac{(H^{-})}{(H)} \sim 17\% \]
Measuring Br's

For couplings: $g_{hZZ}$, $g_{hWW}$, $g_{hbb}$, $g_{htt}$

- How far can one go measuring the "rare" decay into $b\bar{b}$?

  At low end of range, $M_h=160$ GeV, $s = 350$ GeV, 500 fb$^{-1}$, stat. error on $\text{Br}(b\bar{b})/\text{Br}(b\bar{b}) \sim 6.5\%$, but degrades rapidly...

- Numbers of events, tag associated $Z^0$ with leptons, assuming also tags from hadronic $Z^0$ decays with reasonable mass cuts

![Graph showing events vs. Higgs mass](image-url)

Adapted from FNAL Report
- \( \text{Br}(\bar{b}b)/\text{Br}(b\bar{b}) \)

...but needs more full simulations

- \( \text{Br}(WW)/\text{Br}(WW) \leq 7\% \) in mass range 150–200 GeV

\[ e^+e^- \quad ZH \quad q\bar{q}WW(*) \quad q\bar{q}q\bar{q}\ell \]

\[ M_\text{jet-jet} \sim M_z, \quad M_\text{recoil} \sim M_h, \quad \text{soft anti-b-tag} \]

\[
\text{Br}(WW)/\text{Br}(WW) = 2.1\%
\]

for \( M_h = 160 \) GeV, extend to higher masses

(Borisov, Richard)
- $\text{Br}(ZZ)/\text{Br}(ZZ)$ : provides detector benchmark, distinguishing hadronic $Z$ decays from hadronic $W$ decays

e.g., if identify one of the two $Z$'s (via leptons or $bb$) 40% of time, same luminosity,

$$
\text{Br}(ZZ)/\text{Br}(ZZ) \sim 8\% \text{ for } M_h = 210 \text{ GeV}
$$
degraded to

$$
\sim 17\% \text{ for } M_h = 160 \text{ GeV} \text{ (TESLA TDR)}
$$

$$
e^+e^- \quad Z \ H \quad Z \ Z \ Z^{(*)} \quad \ell^+\ell^-q\bar{q} \ell^+\ell^-
\quad q\bar{q} \ell^+\ell^-q\bar{q}
$$

$$
M_{\text{jet-jet}} \sim M_Z, \ M_{\ell\ell q\bar{q}} \sim M_h
$$

$$
M_{\ell\ell} \sim M_Z
$$
Heavy Higgs

- No need for more difficult radiative $tth$ production channel, $h \rightarrow t\bar{t}$

- $\sqrt{s} = 800$ GeV
  1000 fb$^{-1}$

- $e^+e^- \rightarrow H \rightarrow t\bar{t}$
  6 jets + missing $E_T$

- 5 signal for range $350 < M_h < 500$ GeV

- $\text{Br}(t\bar{t})/\text{Br}(t\bar{t})$ for $M_h = 400 (500)$ GeV
  $= 10\% (24\%)$
## Couplings

### Benchmark

| $m_H$ (GeV) | 120 | 140 | 160 | 200 | 400–500
|------------|-----|-----|-----|-----|---------|

<table>
<thead>
<tr>
<th>$ZH / ZH$</th>
<th>~6.5%</th>
<th>~6.5%</th>
<th>~6%</th>
<th>~7%</th>
<th>~10%</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>$H$</th>
<th>$Br (b\bar{b}) / Br$</th>
<th>~3.5%</th>
<th>~6%</th>
<th>~17%</th>
<th>–</th>
<th>–</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>$\frac{g_{hxx}}{g_{hxx}}$ (from Br's)</th>
<th>$t\bar{t}$</th>
<th>7–20%</th>
<th>–</th>
<th>–</th>
<th>–</th>
<th>~10%</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>$b\bar{b}$</th>
<th>~1.5%</th>
<th>~2%</th>
<th>~3.5%</th>
<th>~12.5%</th>
<th>–</th>
</tr>
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</table>

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<tr>
<th>$c\bar{c}$</th>
<th>~20%</th>
<th>~22.5%</th>
<th>–</th>
<th>–</th>
<th>–</th>
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<table>
<thead>
<tr>
<th>$+ -$</th>
<th>~4%</th>
<th>~5%</th>
<th>–</th>
<th>–</th>
<th>–</th>
</tr>
</thead>
</table>

(e.g., HFITTER can be used for combining with cross section info)

<table>
<thead>
<tr>
<th>$WW^*$</th>
<th>~4.5%</th>
<th>~2%</th>
<th>~1.5%</th>
<th>~3.5%</th>
<th>~8.5%</th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>$ZZ^*$</th>
<th>–</th>
<th>–</th>
<th>~8.5%</th>
<th>~4%</th>
<th>~10%</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>$gg$</th>
<th>~10%</th>
<th>~12.5%</th>
<th>–</th>
<th>–</th>
<th>–</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>~7%</th>
<th>~10%</th>
<th>–</th>
<th>–</th>
<th>–</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>$g_{hhh}$</th>
<th>~23%</th>
<th>–</th>
<th>–</th>
<th>–</th>
<th>–</th>
</tr>
</thead>
</table>

$\div s = 500$ GeV

$500$ fb$^{-1}$

$\div s = 800$ GeV
Over much of range of intermediate and heavy Higgs masses, SM Higgs width is measurable and distinguishable from heavier SUSY states.
Total Width Determination

$m_H \gtrsim 115$ GeV

\[
tot = \frac{(H \to WW^*)}{\text{Br}(H \to WW^*)} \quad \text{LC}
\]

Where \((H \to WW^*)\) from:

\[
\begin{align*}
&\cdot (H \to b\bar{b}) \quad \text{LC} \\
&\cdot \frac{(HZ)}{\text{SM}(HZ)} \cdot \frac{1}{\text{SM}(H \to ZZ^*)} \quad \text{(coupling universality)} \\
&\cdot \text{SM}(H \to WW^*)
\end{align*}
\]

\(\text{tot}\) to \(\sim 10\%\) with \(200\) fb\(^{-1}\) and \(120\) GeV Higgs, to a few percent for less than \(150\) GeV

\(m_H \gtrsim 205\) GeV,

\(\text{SM}_{\text{tot}} \sim 2\) GeV, directly resolvable

\[
\begin{align*}
\text{SM} = 0 \\
\text{SM} = \frac{m_{H_{\text{rec}}}}{\text{events / GeV / 500 fb}^{-1}} \quad \text{HZ \ e^+e^-X} \\
\div s = 500\text{ GeV} \\
m_H = 240\text{ GeV}
\end{align*}
\]

**Plus:** still do the above for indirect measurement:

\[
(H \to WW^*) \quad \text{from:} \quad \cdot (H \to WW) \cdot \text{Br}(H \to WW) \quad \text{LC}
\]

Check if observed Higgs boson gives all the mass to \(W, Z\)
Using only direct width measurement only, NLC "L" detector estimated jet-energy resolution

\[ \sqrt{s} = m_Z + m_{h_{\text{SM}}} + 20 \quad \sqrt{s} = 500 \text{ GeV} \]

Complementary to indirect width determination

% Error in \( \Gamma_{h_{\text{SM}}} \)
Heavy Higgs: SUSY States

Mass, Br's, SUSY parameters

\[ e^+e^- \rightarrow H^0A^0 \quad b\bar{b}b\bar{b} \]

- \[ \sqrt{s} = 800 \text{ GeV}, \ 200 \text{ fb}^{-1} \]
- Close to mass degenerate, \[ M_A \sim M_H = 300 \text{ GeV} \]

\[ \cdot \frac{\text{Br}^2}{\text{Br}^2} = 5 - 11\% \quad \frac{M_A}{2} = 0.2 - 0.4\% \]

for \( 260 < M_A < 340 \text{ GeV} \)

Similar precisions as for SM-like case
• Mass degeneracy, sample SUSY point, ~resolution of NLC "L" detector

\[ e^+e^- \quad H^0A^0 \quad b\bar{b}\bar{b} \]
|cos| < 0.5
\[\tan = 7\]
\[M_A = 300 \text{ GeV}\]
\[= \pm 2 \text{ GeV}\]
$e^+e^- \quad H^+H^- \quad t\bar{b}\bar{t}b$

or

$W^+h^0 \quad W^-h^0 \quad b\bar{b}$

- $\sqrt{s} = 800 \text{ GeV}, \ 500 \text{ fb}^{-1}$
- 8 jets, 4 of them $b$ jets
- $b$-tagging, mass constraints

$M_{H^\pm} = 300 \text{ GeV}$

$\cdot \frac{\text{Br}}{\text{Br}} < 15\% \quad M_{H^\pm} = 1.0 \text{ GeV}$
"Nastier stuff":

Invisible Decays

\[ h ~^{0~0}_{1~1} \]

Majorons

heavy neutrinos

Higgs singlets

-Handled with recoil mass in Higgstrahlung

compare no. events tagged with \( Z ~^\nu_\nu^- \) with total no. observed Higgs decays into known states

number of events with no detector activity recoiling from \( Z ~^\nu_\nu^- \)

For light Higgs...

500 fb\(^{-1}\)
- "Stealth" model, Higgs decays to light Higgs singlets coupling with strength \( w \) to SM Higgs can have large invisible width, no peak in recoil mass

- General SUSY, multiple fermiophobic Higgs, \( i \) of them with different masses, decaying: \( e^+e^-, Z h_i, h_i VV \) (Espinosa et al., Gunion et al.)

- Light decoupled Higgs with **no** \( VV \) couplings still produced through quartic couplings...

With 1000 fb\(^{-1} \), still observable:
- \( \sqrt{s} = 500 \text{ GeV} \) up to \( \sim 150 \text{ GeV} \)
- \( \sqrt{s} = 800 \text{ GeV} \) up to \( \sim 250 \text{ GeV} \)
Giga-Z Contribution

- e.g., no Higgs found in intermediate mass range
- Giga-Z: $M_W$, $\sin^2_{\text{eff}}$ plus $M_h$ and SUSY

MSSM@GigaZ

- $m_{\tilde{t}_1} = 500 \pm 2 \text{ GeV}$
- $\sin \tilde{t} = -0.69 \pm 0.014$

more indications of where heavier states may lie
Intermediate mass and heavy Higgs:

So the PDG entry (see Klaus Desch's talk) *may be somewhat shorter (fewer Br's)*...

**But**
- still powerful measurements, complementary, couplings to bosons and some fermions
- If heavy, how is it able to contradict precision EW? new physics? *More PDG entries...!*
- If no intermediate mass Higgs (e.g. at √s = 500 GeV)
  - Giga-Z measurements (no states)
  - and/or
  - light Higgs "profile"
  - indications of where heavy states may be.

Linear Collider results still essential!