Representing the conveners of the Higgs/EWSB Working Group:

Timothy Barklow, Christophe Grojean, Howard Haber, Shinya Kanemura, Philipp Roloff, Jungping Tian
### Contributions to the Higgs/EWSB Working group sessions

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<td>2</td>
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</tr>
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32 talks in total; many new analyses were presented!
Three examples of recent analyses:

- Increasing the accuracy of the measurement of \( \sigma(e^+e^- \rightarrow HZ) \) using the \( Z \rightarrow q\bar{q} \) hadronic decays. 
  (ILC: Suehara; CLIC: Thomson)
  See A. Miyamoto, arXiv:1311.2248

- At CLIC: updated Higgs self-coupling analysis 
  (Lastovicka)

- Improving the theoretical precision of \( M_H \) 
  in the MSSM via resummation of large logs 
  (Heinemeyer)
Recoil Mass

★ To date, most studies only use $Z \rightarrow \mu \mu$ and $Z \rightarrow ee$
★ Statistical precision limited by leptonic BRs of 3.5 %
★ Here: extend to $Z \rightarrow qq \sim 70$ % of Z decays
★ Strategy – identify $Z \rightarrow qq$ decays and look at recoil mass
★ Can never be truly model independent:
  ▪ unlike for $Z \rightarrow \mu \mu$ can’t cleanly separate H and Z decays

Muons “always” obvious

Here jet finding blurs separation between H and Z

Different efficiencies for different Higgs decays
Summary

- $llh$ 250 GeV – 3.0/2.5% with 250 fb$^{-1}$ $e^-_L e^+_R$
- Various channels for $\sigma_{ZH}$
  - $llH$ 500 GeV – 4.8% with 500 fb$^{-1}$ $e^-_L e^+_R$
  - $qqH$ 350 GeV – 3.6% with 150 + 150 fb$^{-1}$
  - $qqH$ 500 GeV – 3.9% with 500 fb$^{-1}$ $e^-_L e^+_R$
  - $qqH$ 250 GeV (VERY PRELIMINARY)
    - 2.6% with 250 fb$^{-1}$ $e^-_L e^+_R$
    - 1.4% with 250 fb$^{-1}$ $e^-_R e^+_L$
    - Study ongoing
- Systematic effects should be investigated
SUMMARY

- Results were presented of the Higgs self-coupling measurement with 3 TeV CLIC machine and $m_H = 126$ GeV
  - Full simulation and reconstruction in CLIC_SiD; realistic beam spectrum, ISR, ...
  - Unpolarised beams – beam polarization impact discussed
  - Accounted for realistic $\gamma\gamma \rightarrow$ hadrons event pile-up/overlay and for $\gamma\gamma$, $e^+\gamma$, $e^-\gamma$ backgrounds
  - Event selection based on a poll of neural networks, overtraining checked
  - Two methods: cut-and-count, template fitting

- We observe 15-18% $\lambda_{HHH}$ uncertainty @ 3 TeV
  - Estimated 10% and 12% for (-80,30) and (-80,0) beam polarization, resp.
  - Updated numbers for 1.4 TeV are not available yet
    - EPS HEP 2013: 28% unpolarized beams

- Similar approach applied to quartic coupling $g_{HHWW}$ leading to 3% uncertainty @ 3 TeV.
$M_h(M_S)$ for $\tan \beta = 1$ ($X_t = 0$) or $\tan \beta = 40$ ($X_t/M_S = 2$):

$\Rightarrow$ “upper bound”: $M_S \lesssim 650$ TeV $\Rightarrow$ needs refinement!
Many of the ILC results presented at LCWS 13 were employed in the ILC Higgs White paper, which was submitted to the 2013 Snowmass Study

ILC Higgs White Paper

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ILC Energy/Luminosity scenarios

<table>
<thead>
<tr>
<th>Stage #</th>
<th>nickname</th>
<th>$E_{cm}(1)$ (GeV)</th>
<th>Lumi (1) (fb$^{-1}$)</th>
<th>$E_{cm}(2)$ (GeV)</th>
<th>Lumi (2) (fb$^{-1}$)</th>
<th>$E_{cm}(3)$ (GeV)</th>
<th>Lumi (3) (fb$^{-1}$)</th>
<th>Runtime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ILC (250)</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>ILC (500)</td>
<td>250</td>
<td>250</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>1000</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>ILC (1000)</td>
<td>250</td>
<td>250</td>
<td>500</td>
<td>500</td>
<td>1000</td>
<td>1000</td>
<td>2.9</td>
</tr>
<tr>
<td>4,5,6</td>
<td>ILC(LumUp)</td>
<td>250</td>
<td>1150</td>
<td>500</td>
<td>1600</td>
<td>1000</td>
<td>2500</td>
<td>5.8</td>
</tr>
</tbody>
</table>

- At each stage, the *accumulated* luminosity of a given energy is listed. The runtimes listed consist of actual elapsed *cumulative* running time at the end of each stage. Assuming that the ILC runs for 1/3 of the time, then the actual time elapsed is equal to the runtime times 3.

- Assume that the ILC is run at its baseline luminosity at 250 GeV (stage 1), then at 500 GeV (stage 2), and finally at 1000 GeV (stage 3)

- Then, stages 4,5,6 repeat the successive stages 1, 2 and 3 at the upgraded luminosity.

In real time, this entire program would require $5.8 \times 3 = 17.4$ years.
What does the ILC actually experimentally measure?

1. $\sigma(e^+e^- \rightarrow ZH)$ at $\sqrt{s} = 250$ GeV.

- The $Z$ can be reconstructed in charged lepton and quark channels.
- The $H$ can be “seen” in the mass spectrum recoiling against the $Z$ (including the invisible Higgs decays).
- The $H$ can be reconstructed in all of its (main) decay channels.
2. By explicitly reconstructing $H$, one obtains

$$\sigma_{ZH} \times \text{Br}(H \rightarrow XX)$$

for $XX = b\bar{b}, c\bar{c}, gg, WW^*, \tau^+\tau^-, ZZ^*, \gamma\gamma$ and $\mu^+\mu^-$. Strictly speaking $g$ stands for a hadron jet not identified as a $b$ or $c$ quark. For a SM-like Higgs boson, the Higgs decay into $gg$ dominates over the decays into $u\bar{u}, d\bar{d}$ and $s\bar{s}$. (Likewise, Higgs decay into $e^+e^-$ is assumed to be negligible.)

3. Since the $ZH$ production cross section dominates the cross section for $e^+e^- \rightarrow \nu\bar{\nu}W^+W^- \rightarrow \nu\bar{\nu}H$ at $\sqrt{s} = 250$ GeV, one can only measure $\sigma_{\nu\bar{\nu}H} \times \text{Br}(H \rightarrow b\bar{b})$. 
4. $e^+e^- \rightarrow \nu\bar{\nu}H, \; t\bar{t}H$ and $ZH\bar{H}$ at $\sqrt{s} = 500$ GeV

- The $WW$ fusion cross section is now competitive with the $ZH$ cross section. Thus, one can now measure

$$\sigma_{\nu\bar{\nu}H} \times \text{Br}(H \rightarrow XX),$$

for all the relevant Higgs channels.

- The cross section for $e^+e^- \rightarrow t\bar{t}H$ is enhanced near threshold, and yields a measurement of $\sigma_{t\bar{t}H} \times \text{Br}(H \rightarrow b\bar{b})$. From this, one can determine the top quark–Higgs Yukawa coupling.

- The process $e^+e^- \rightarrow ZH\bar{H}$ is sensitive to the $HH\bar{H}$ coupling, although there are other diagrams contributing to $ZH\bar{H}$ production that do not depend on the triple Higgs vertex.
5. $e^+e^- \rightarrow \nu\bar{\nu}H$, $t\bar{t}H$ and $\nu\bar{\nu}HH$ at $\sqrt{s} = 1$ TeV

At $\sqrt{s} = 1$ TeV, the ILC provides better measurements of the top quark Yukawa coupling and the triple Higgs coupling. Moreover, the Higgs production rate has increased significantly from its rate at $\sqrt{s} = 500$ GeV due to the increasing $WW$ fusion cross section.
Model-independent determinations of Higgs couplings

Example--consider the following four independent measurements:

\[ Y_1 = \sigma_{ZH} = F_1 \cdot g_{HZZ}^2 \]

\[ Y_2 = \sigma_{ZH} \times \text{Br}(H \rightarrow b\bar{b}) = F_2 \cdot \frac{g_{HZZ}^2 g_{Hb\bar{b}}^2}{\Gamma_T} \]

\[ Y_3 = \sigma_{\nu\bar{\nu}H} \times \text{Br}(H \rightarrow b\bar{b}) = F_3 \cdot \frac{g_{HWW}^2 g_{Hb\bar{b}}^2}{\Gamma_T} \]

\[ Y_4 = \sigma_{\nu\bar{\nu}H} \times \text{Br}(H \rightarrow WW^*) = F_4 \cdot \frac{g_{HWW}^4}{\Gamma_T} \]
\( \Gamma_T \) is the Higgs total width, \( g_{HZZ} \), \( g_{HWW} \), and \( g_{Hb\bar{b}} \) are the Higgs couplings to \( ZZ \), \( WW \), and \( b\bar{b} \), respectively, and \( F_1, F_2, F_3, F_4 \) are calculable quantities. For example,

\[
F_2 = \left( \frac{\sigma_{ZH}}{g_{HZZ}^2} \right) \left( \frac{\Gamma_{H \to b\bar{b}}}{g_{Hb\bar{b}}^2} \right).
\]

The couplings are obtained as follows:

1. From \( Y_1 \) \( \iff \) \( g_{HZZ} \)

2. From \( Y_1 Y_3/Y_2 \) \( \iff \) \( g_{HWW} \)

3. From \( g_{HWW} \) and \( Y_4 \) \( \iff \) \( \Gamma_T \)

4. From \( g_{HZZ}, g_{HWW}, \Gamma_T \) and \( Y_2 \) or \( Y_3 \) \( \iff \) \( g_{Hb\bar{b}} \)
Summary of expected accuracies $\Delta g_i/g_i$ and $\Gamma_T$ for model independent determinations of the Higgs boson couplings

<table>
<thead>
<tr>
<th>Mode</th>
<th>ILC(250)</th>
<th>ILC(500)</th>
<th>ILC(1000)</th>
<th>ILC(LumUp)</th>
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<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>250</td>
<td>250+500</td>
<td>250+500+1000</td>
<td>250+500+1000</td>
</tr>
<tr>
<td>$L$ (fb$^{-1}$)</td>
<td>250</td>
<td>250+500</td>
<td>250+500+1000</td>
<td>1150+1600+2500</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>18 %</td>
<td>8.4 %</td>
<td>4.0 %</td>
<td>2.4 %</td>
</tr>
<tr>
<td>$gg$</td>
<td>6.4 %</td>
<td>2.3 %</td>
<td>1.6 %</td>
<td>0.9 %</td>
</tr>
<tr>
<td>$WW$</td>
<td>4.9 %</td>
<td>1.2 %</td>
<td>1.1 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>1.3 %</td>
<td>1.0 %</td>
<td>1.0 %</td>
<td>0.5 %</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>–</td>
<td>14 %</td>
<td>3.2 %</td>
<td>2.0 %</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>5.3 %</td>
<td>1.7 %</td>
<td>1.3 %</td>
<td>0.8 %</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>5.8 %</td>
<td>2.4 %</td>
<td>1.8 %</td>
<td>1.0 %</td>
</tr>
<tr>
<td>$c\bar{c}$</td>
<td>6.8 %</td>
<td>2.8 %</td>
<td>1.8 %</td>
<td>1.1 %</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>91 %</td>
<td>91 %</td>
<td>16 %</td>
<td>10 %</td>
</tr>
<tr>
<td>$\Gamma_T$</td>
<td>12 %</td>
<td>5.0 %</td>
<td>4.6 %</td>
<td>2.5 %</td>
</tr>
<tr>
<td>$hhh$</td>
<td>–</td>
<td>83 %</td>
<td>21 %</td>
<td>13 %</td>
</tr>
</tbody>
</table>

The theory errors are $\Delta F_i/F_i=0.5\%$. For the invisible branching ratio, the numbers quoted are 95% confidence upper limits.
Summary of expected accuracies for the three cross sections and eight branching ratios obtained from an eleven parameter global fit of all available data.

<table>
<thead>
<tr>
<th>process</th>
<th>ILC(250)</th>
<th>ILC500</th>
<th>ILC(1000)</th>
<th>ILC(LumUp)</th>
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<tbody>
<tr>
<td>$e^+e^- \rightarrow ZH$</td>
<td>2.6 %</td>
<td>2.0 %</td>
<td>2.0 %</td>
<td>1.0 %</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \nu\bar{\nu}H$</td>
<td>11 %</td>
<td>2.3 %</td>
<td>2.2 %</td>
<td>1.1 %</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow ttH$</td>
<td>-</td>
<td>28 %</td>
<td>6.3 %</td>
<td>3.8 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mode</th>
<th>$\Delta Br/Br$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>19 %</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>6.9 %</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>2.9 %</td>
</tr>
<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td>8.7 %</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>7.5 %</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>4.9 %</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>34 %</td>
</tr>
<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>100 %</td>
</tr>
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</table>
Further improvement beyond the ILC Higgs White paper (due to Peskin)

- Use ATLAS projected result of the HL-LHC Higgs analysis
  \[
  \Delta \frac{\text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)} = 2.9\%
  \]
  along with the ILC precision measurement of the $HZZ$ coupling to obtain a very precise determination of the $H\gamma\gamma$ coupling.

- Improve precision determinations of Higgs couplings by imposing the constraint that
  \[\sum_{i} \text{BR}_i = 1\]
The reason for this is that I used a 9-parameter fit constrained to the relation \[ \sum_i BR_i = 1 \].

This constraint is very powerful because determinations of Higgs couplings require constraining the Higgs total width.

\[
\sigma(A\overline{A} \rightarrow h) \cdot BR(h \rightarrow B\overline{B}) \sim \frac{\Gamma(h \rightarrow A\overline{A})\Gamma(h \rightarrow B\overline{B})}{\Gamma_T}
\]

The constraint has a large effect here:

<table>
<thead>
<tr>
<th>error in ( \Gamma_T )</th>
<th>unconstrained</th>
<th>( \sum BR = 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC 500</td>
<td>5.0%</td>
<td>1.6%</td>
</tr>
<tr>
<td>ILC 500 up</td>
<td>2.8%</td>
<td>0.75%</td>
</tr>
<tr>
<td>ILC 1000</td>
<td>4.6%</td>
<td>1.2%</td>
</tr>
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</table>
Conclusions

- Precision Higgs studies are essential for probing the dynamics of electroweak symmetry breaking (EWSB).

- Future $e^+e^-$ colliders (ILC/CLIC/TLEP) have the capability of significantly reducing the uncertainties in many of the observed Higgs properties that will be measured at LHC, with less reliance on specific model assumptions.

- Beyond coupling measurements, one can also make precision measurements of the Higgs mass and total width, check the CP-properties (including potential CP-violating effects) and the Lorentz structure of Higgs interactions, etc.

- The Higgs boson can serve as a portal to physics beyond the Standard Model (BSM). Thus, precision Higgs studies could provide critical clues to the nature of BSM physics.