Measurement of Higgs couplings and self-coupling at the ILC

Junping Tian (KEK)
---on behalf of the ILD detector concept group
EPS-HEP 2013, Jul. 18-24, KTH, Stockholm

ILC TDR completed, welcome to check the 5 volumes!
Primary Goal
Mystery Test of the 2nd pillar, then BSM

2 Main Pillar of SM

There’s a good chance that the dark matter is in the ILC range

ACFA Report

Wd do not know how firm this pillar is. The answer surely lines in the TeV Region

First test the 2nd pillar by precision Higgs study and then put Beyond the Standard Model roof!
Our Mission = Bottom-up Model-Independent
Reconstruction of the EWSB Sector
through Precision Higgs Measurements

<table>
<thead>
<tr>
<th>Mass &amp; $J^{CP}$</th>
<th>$M_h$</th>
<th>$\Gamma_h$</th>
<th>$J^{CP}$</th>
<th>test CP mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{Higgs}$</td>
<td>$hhh$ : $-6i\lambda v = -3i\frac{m_h^2}{v}$, $hhhh$ : $-6i\lambda = -3i\frac{m_h^2}{v^2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{Gauge}$</td>
<td>$W_\mu W^- h : i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}$, $W_\mu W^- hh : i\frac{g^2}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Z_\mu Z^- h : i\frac{g^2 + g'^2 v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}$, $Z_\mu Z^- hh : i\frac{g^2 + g'^2}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{Yukawa}$</td>
<td>$h\bar{f}f : -i\frac{y_f}{\sqrt{2}} = -i\frac{m_f}{v}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{Loop}$</td>
<td>$h\gamma\gamma$</td>
<td>$hgg$</td>
<td>$h\gamma Z$</td>
<td>sensitive to the new particles in the loop</td>
</tr>
</tbody>
</table>

observe the force to make higgs condense

test the SSB, SU(2), saturation to $<\text{vev}>$

crucial to test the mass coupling proportionality

comprehensively reveal the Higgs nature and with precision
Precision is the light on new physics BSM

- **Multiplet structure:**
  - Additional singlet?
  - Additional doublet?
  - Additional triplet?

- **Underlying dynamics:**
  - Weakly interacting or strongly interacting? = elementary or composite?

- **Relations to other problems:**
  - DM
  - EW baryogenesis
  - neutrino mass
  - inflation?

There are many possibilities!

Different models predict different deviation patterns --> Fingerprinting!

<table>
<thead>
<tr>
<th>Model</th>
<th>μ</th>
<th>τ</th>
<th>b</th>
<th>c</th>
<th>t</th>
<th>g_\nu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet mixing</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>2HDM-I</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>2HDM-II (SUSY)</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>2HDM-X (Lepton-specific)</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>2HDM-Y (Flipped)</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
</tbody>
</table>

Mixing with singlet

\[
\frac{g_{hVV}}{g_{hSMVV}} = \frac{g_{hff}}{g_{hSMff}} = \cos \theta \approx 1 - \frac{\delta^2}{2}
\]

Composite Higgs

\[
\frac{g_{hVV}}{g_{hSMVV}} \approx 1 - 3\% (1 \text{ TeV}/f)^2
\]

\[
\frac{g_{hff}}{g_{hSMff}} \approx \begin{cases} 1 - 3\% (1 \text{ TeV}/f)^2 & (\text{MCHM4}) \\ 1 - 9\% (1 \text{ TeV}/f)^2 & (\text{MCHM5}) \end{cases}
\]

SUSY

\[
\frac{g_{hbb}}{g_{hSMbb}} = \frac{g_{h\tau\tau}}{g_{hSM\tau\tau}} \approx 1 + 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2
\]

Expected deviations are small --> Precision!

Rzehak @ ECFA2013
Gupta, Rzehak, Wells, arXiv:1206.3560
✓ sufficient production rate solidified by what observed at LHC
✓ very clean signal making most of the decay modes accessible

expected branching ratio values from LHC Higgs cross section working group
arxiv:1101.0593

ref: TDR Physics Volume
A staged running program (Higgs Part)
(canonical / upgraded luminosity)

250/1150 fb\(^{-1}\) @ 250 GeV (as a Higgs Factory)

- Higgs mass, spin, CP
- Absolute HZZ coupling
- Br(H\(\rightarrow bb, cc, gg, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \gamma Z\))
- Total width (initial)

500/1600 fb\(^{-1}\) @ 500 GeV

- WW-fusion full activated, Absolute HWW coupling
- Total Higgs width \(\rightarrow\) absolute normalization of all other couplings
- BRs with high statistics
- Top-Yukawa coupling through ttH
- Higgs self-coupling through ZHH

1000/2500 fb\(^{-1}\) @ 1 TeV

- accumulate much more Higgs events
- H\(\rightarrow\mu\mu\) accessible
- improve Top-Yukawa coupling
- Higgs self-coupling through v\(\nu HH\)

@ 350 GeV

- precision top physics, indirect top-Yukawa
- Total width

beam polarisation likes a luminosity doubler

P(e\(-,e+)\=(-0.8,+0.3) @ 250 - 500 GeV
P(e\(-,e+)\=(-0.8,+0.2) @ 1 TeV
state-of-art detector performance achievable by ILD
Particle Flow Algorithm, High Granularity, ~4π Coverage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum resolution: $\sigma_{1/p_T}$</td>
<td>$\sim 2 \times 10^{-5}$ GeV$^{-1}$</td>
</tr>
<tr>
<td>Driven by</td>
<td>recoil mass measurement $ZH\rightarrow l^+l^-X$.</td>
</tr>
<tr>
<td>Jet energy resolution: $\sigma_E/E$</td>
<td>$\sim 3 - 4% \sim 30%/\sqrt{E}$ @100GeV</td>
</tr>
<tr>
<td>Driven by</td>
<td>3σ separation of the hadronic decay of W and Z bosons.</td>
</tr>
<tr>
<td>Impact parameter resolution: $\sigma_{r\phi}$</td>
<td>$= 5 \mu m \oplus \frac{10}{p(GeV \sin^{3/2} \theta)} \mu m$</td>
</tr>
<tr>
<td>Driven by</td>
<td>excellent tagging and untagging of heavy flavor jets (H--&gt;bb, cc and gg).</td>
</tr>
</tbody>
</table>

![Graphs and diagrams showing momentum resolution, jet energy resolution, and impact parameter resolution for particles at 1 TeV.]
ILC 250 GeV

Recoil Mass

$g_{HZZ}$

The flagship measurement of LC 250

Recoil Mass

$M^2_X = (p_{CM} - (p_{\mu^+} + p_{\mu^-}))^2$

Invisible decay detectable!

250 fb$^{-1}$ @ 250 GeV $m_H = 125$ GeV

$\Delta \sigma_{ZH} / \sigma_{ZH} = 2.6\%$

$\Delta m_H = 30$ MeV

$BR$(invisible) < 0.95\% @ 95\% C.L.

$\Delta g_{HZZ}$ / $g_{HZZ}$

<table>
<thead>
<tr>
<th></th>
<th>Canonical</th>
<th>LumiUP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.3%</td>
<td>0.61%</td>
</tr>
</tbody>
</table>
ILC 500 GeV

WW-fusion production fully activated: 14 fb @ 250 GeV \rightarrow 150 fb @ 500 GeV

\[ Y_1 = \sigma_{\nu\bar{\nu}H} \cdot \text{Br}(H \rightarrow b\bar{b}) \propto g_{HWW}^2 \cdot \text{Br}(H \rightarrow b\bar{b}) \]

\[ Y_2 = \sigma_{ZH} \cdot \text{Br}(H \rightarrow b\bar{b}) \propto g_{HZZ}^2 \cdot \text{Br}(H \rightarrow b\bar{b}) \]

\[ \frac{Y_1}{Y_2} \] gives accurate test of SU(2), and with \( g_{HZZ} \) gives absolute normalization of \( g_{HWW} \).

\( (Y_2 \text{ done at 250 GeV}) \)

C. Durig @ LCWS12, J. Tian @ KILC12 and new DBD study

\[ e^+ + e^- \rightarrow \nu\bar{\nu}H \rightarrow \nu\bar{\nu}(b\bar{b}) \]

\[ \int L = 500 \text{ fb}^{-1} \]

\( P(e^+, e^-) = (-0.8, +0.3) \)

\[ \Delta g_{HWW} / g_{HWW} \]

<table>
<thead>
<tr>
<th></th>
<th>250 GeV</th>
<th>250 GeV + 500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canonical</td>
<td>4.8%</td>
<td>1.4%</td>
</tr>
<tr>
<td>LumiUP</td>
<td>2.3%</td>
<td>0.67%</td>
</tr>
</tbody>
</table>
Higgs total width $\Gamma_0$

$\Gamma_0 = \frac{\Gamma_{HZZ}}{\text{Br}(H \rightarrow ZZ^*)} \propto \frac{g_{HZZ}^2}{\text{Br}(H \rightarrow ZZ^*)}$

$\Gamma_0 = \frac{\Gamma_{HWW}}{\text{Br}(H \rightarrow WW^*)} \propto \frac{g_{HWW}^2}{\text{Br}(H \rightarrow WW^*)}$

Br($H\rightarrow ZZ^*$) very small, not very precisely measured

Br($H\rightarrow WW^*$) much larger, more precisely measured

$Y_1 = \sigma_{\nu\bar{\nu}H} \cdot \text{Br}(H \rightarrow b\bar{b}) \propto g_{HWW}^2 \cdot \text{Br}(H \rightarrow b\bar{b})$

$Y_2 = \sigma_{ZH} \cdot \text{Br}(H \rightarrow b\bar{b}) \propto g_{HZZ}^2 \cdot \text{Br}(H \rightarrow b\bar{b})$

$Y_3 = \sigma_{\nu\bar{\nu}H} \cdot \text{Br}(H \rightarrow WW^*) \propto \frac{g_{HWW}^4}{\Gamma_0}$

$Y_3$ and $g_{HWW}$ gives Higgs total width --> absolute normalization of other couplings.

(Y2 done at 250 GeV)
Top Yukawa Coupling
The largest among matter fermions

\[
\begin{align*}
\text{\sigma} & \text{ [fb]} \\
\text{\sqrt{s} [GeV]} & \\
500 & 600 & 700 & 800 & 900 & 1000 \\
10^3 & 10^2 & 10^1 & 10^{-1} & 10^{-2} & 10^{-3} \\
\text{Pol}(e^+) = 0 & \\
\text{t\bar{t}Z (w/ NRQCD)} & \\
\text{t\bar{t}H (w/ NRQCD)} & \\
1.2 \text{ fb} & \\
0.45 \text{ fb} & \\
\text{t\bar{t}g (g \rightarrow bb)} & \\
\text{t\bar{t}H (w/o NRQCD)} & \\
\text{t\bar{t}H (H off Z)} & \\
\end{align*}
\]

A factor of 2 enhancement from QCD bound-state effects

<table>
<thead>
<tr>
<th>(\Delta g_{t\bar{t}H}/g_{t\bar{t}H})</th>
<th>500 GeV</th>
<th>500 GeV + 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canonical</td>
<td>14%</td>
<td>3.2%</td>
</tr>
<tr>
<td>LumiUP</td>
<td>7.8%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

Notice \(\sigma(500+20\text{GeV})/\sigma(500\text{GeV}) \sim 2\)
Moving up a little bit helps significantly!

main BG: ttZ / ttg (g-->bb)

R. Yonamine, et. al, Phys.Rev. D84 (2011) 014033, confirmed by full simulation
T. Tanabe, T. Price, et. al, LC-REP-2013-004

ILC 500 GeV & 1 TeV
Higgs self-coupling measurement

Higgs Potential: \[ V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda \eta_H^3 + \frac{1}{4} \lambda \eta_H^4 \]

- just the force that makes the Higgs boson condense in the vacuum (a new force, non-gauge interaction).
- direct determination of the Higgs potential.
- accurate test of this coupling may reveal the extended nature of Higgs sector, like 2HDM and SUSY.

physical Higgs field \( \eta_H \)

mass term \( m_H^2 \eta_H^2 \)

trilinear coupling \( \lambda \eta_H^3 \)

quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

just the force that makes the Higgs boson condense in the vacuum (a new force, non-gauge interaction).

direct determination of the Higgs potential.

accurate test of this coupling may reveal the extended nature of Higgs sector, like 2HDM and SUSY.

one of the reasons why 500 GeV
General issue: sensitivity of coupling to the cross section

$$\sigma = \lambda^2 S + \lambda I + B$$

$$\frac{\Delta \lambda}{\lambda} = F \cdot \frac{\Delta \sigma}{\sigma}$$

F = 0.5 if no BG diagrams

### Signal diagram

**Irreducible BG diagrams**

These diagrams significantly degraded the sensitivity
ILC 500 GeV & 1 TeV

**Higgs Self-coupling Projections @ ILC**

full simulation done w/ mH = 120 GeV, extrapolated to mH = 125 GeV

<table>
<thead>
<tr>
<th>Δλ_{HHH}/λ_{HHH}</th>
<th>500 GeV</th>
<th>500 GeV + 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Canonical</td>
<td>104%</td>
<td>83%</td>
</tr>
<tr>
<td>LumiUP</td>
<td>58%</td>
<td>46%</td>
</tr>
</tbody>
</table>

Scenario A: HH-->bbbb, full simulation done
Scenario B: by adding HH-->bbWW*, full simulation ongoing,
expect ~20% relative improvement
Scenario C: color-singlet clustering, future improvement,
expected ~20% relative improvement (conservative)

if positron polarisation 30%(20%) --> 60%(40%), gain relatively 10% improvement

J. Tian, LC-REP-2013-003 M. Kurata @ ECFA2013
# Summary table of Higgs measurements @ ILC

MH = 125 GeV
P(e-,e+) = (-0.8, +0.3) @ 250, 500 GeV
P(e-,e+) = (-0.8, +0.2) @ 1 TeV

<table>
<thead>
<tr>
<th>ECM</th>
<th>@ 250 GeV</th>
<th>@ 500 GeV</th>
<th>@ 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity \cdot fb</td>
<td>250</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>polarization (e-,e+)</td>
<td>(-0.8, +0.3)</td>
<td>(-0.8, +0.3)</td>
<td>(-0.8, +0.2)</td>
</tr>
<tr>
<td>process</td>
<td>ZH</td>
<td>vvH(fusion)</td>
<td>ZH</td>
</tr>
<tr>
<td>cross section</td>
<td>2.6%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H--&gt;bb</td>
<td>1.2%</td>
<td>10.5%</td>
<td>1.8%</td>
</tr>
<tr>
<td>H--&gt;cc</td>
<td>8.3%</td>
<td>13%</td>
<td>6.2%</td>
</tr>
<tr>
<td>H--&gt;gg</td>
<td>7.0%</td>
<td>11%</td>
<td>4.1%</td>
</tr>
<tr>
<td>H--&gt;WW*</td>
<td>6.4%</td>
<td>9.2%</td>
<td>2.4%</td>
</tr>
<tr>
<td>H--&gt;ττ</td>
<td>4.2%</td>
<td>5.4%</td>
<td>9.0%</td>
</tr>
<tr>
<td>H--&gt;ZZ*</td>
<td>19%</td>
<td>25%</td>
<td>8.2%</td>
</tr>
<tr>
<td>H--&gt;γγ</td>
<td>29-38%</td>
<td>29-38%</td>
<td>20-26%</td>
</tr>
<tr>
<td>H--&gt;μμ</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ttH, H--&gt;bb</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H--&gt;Inv. (95% C.L.)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

being updated by new studies with mH = 125 GeV
Global Fit

32 $Y_i = \sigma \times \text{Br}$ measurements, each of which can be predicted by

$$Y'_i = F_i \cdot \frac{g_{HZZ}^2 g_{HXX}^2}{\Gamma_0}$$
or

$$Y'_i = F_i \cdot \frac{g_{HWW}^2 g_{HXX}^2}{\Gamma_0}$$
or

$$Y'_i = F_i \cdot \frac{g_{Htt}^2 g_{HXX}^2}{\Gamma_0}$$

$F_i$ is what we can calculate

1 $Y_{33} = \sigma_{ZH}$ measurements, which can be predicted by

$$Y'_{33} = F_{33} \cdot g_{HZZ}^2$$

define a $\chi^2$, which can be parameterized with 9 couplings and Higgs total width

$$\chi^2 = \sum_{i=1}^{i=33} (\frac{Y_i - Y'_i}{\Delta Y_i})^2$$

$\Delta Y_i$ is the measurement error

global fit: minimize the $\chi^2$ ---> get the 10 parameters

model independent, no theoretical errors included
### Absolute Higgs Couplings @ ILC

<table>
<thead>
<tr>
<th>coupling $\Delta g/g$</th>
<th>250 GeV</th>
<th>250 GeV + 500 GeV</th>
<th>250 GeV + 500 GeV + 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZZ</td>
<td>1.3%</td>
<td>1.3%</td>
<td>1.3%</td>
</tr>
<tr>
<td>HWW</td>
<td>4.8%</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Hbb</td>
<td>5.3%</td>
<td>1.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Hcc</td>
<td>6.8%</td>
<td>2.9%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Hgg</td>
<td>6.4%</td>
<td>2.4%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Hττ</td>
<td>5.7%</td>
<td>2.4%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Hγγ</td>
<td>18%</td>
<td>8.4%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Hμμ</td>
<td>-</td>
<td>-</td>
<td>16%</td>
</tr>
<tr>
<td>$\Gamma_0$</td>
<td>11%</td>
<td>5.9%</td>
<td>5.6%</td>
</tr>
<tr>
<td>Htt</td>
<td>-</td>
<td>14%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Br(H---&gt;Inv.) 95% C.L.</td>
<td>&lt; 0.95%</td>
<td>&lt; 0.95%</td>
<td>&lt; 0.95%</td>
</tr>
<tr>
<td>HHH</td>
<td>-</td>
<td>104%</td>
<td>66% (*)</td>
</tr>
</tbody>
</table>

(*) including H-->WW* and better jet-clustering

<table>
<thead>
<tr>
<th>MH = 125 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV</td>
</tr>
<tr>
<td>P(e-,e+)=(-0.8,+0.2) @ 1 TeV</td>
</tr>
</tbody>
</table>

### Canonical

- 250 GeV: 250 fb-1
- 500 GeV: 500 fb-1
- 1 TeV: 1000 fb-1

Moho = 125 GeV

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV

P(e-,e+)=(-0.8,+0.2) @ 1 TeV
## Absolute Higgs Couplings @ ILC

MH = 125 GeV  
P(e-,e+)=(−0.8,+0.3) @ 250, 500 GeV  
P(e-,e+)=(−0.8,+0.2) @ 1 TeV

<table>
<thead>
<tr>
<th>coupling Δg / g</th>
<th>250 GeV</th>
<th>250 GeV + 500 GeV</th>
<th>250 GeV + 500 GeV + 1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZZ</td>
<td>0.61%</td>
<td>0.61%</td>
<td>0.61%</td>
</tr>
<tr>
<td>HWW</td>
<td>2.3%</td>
<td>0.67%</td>
<td>0.65%</td>
</tr>
<tr>
<td>Hbb</td>
<td>2.5%</td>
<td>0.90%</td>
<td>0.74%</td>
</tr>
<tr>
<td>Hcc</td>
<td>3.2%</td>
<td>1.5%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Hgg</td>
<td>3.0%</td>
<td>1.3%</td>
<td>0.93%</td>
</tr>
<tr>
<td>Hττ</td>
<td>2.7%</td>
<td>1.2%</td>
<td>0.99%</td>
</tr>
<tr>
<td>Hγγ</td>
<td>8.2%</td>
<td>4.5%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Hμμ</td>
<td>-</td>
<td>-</td>
<td>10%</td>
</tr>
<tr>
<td>Γ₀</td>
<td>5.4%</td>
<td>2.8%</td>
<td>2.7%</td>
</tr>
<tr>
<td>Htt</td>
<td>-</td>
<td>7.8%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Br(H→Inv.) 95% C.L.</td>
<td>&lt; 0.44%</td>
<td>&lt; 0.44%</td>
<td>&lt; 0.44%</td>
</tr>
<tr>
<td>HHH</td>
<td>-</td>
<td>58%</td>
<td>37%(*)</td>
</tr>
</tbody>
</table>

(*) including H→WW* and better jet-clustering  

**Model independent fit**

- 250 GeV: 1150 fb⁻¹  
- 500 GeV: 1600 fb⁻¹  
- 1 TeV: 2500 fb⁻¹
Power of Staged Running

e.g., assuming 10y running at 250 GeV + 500 GeV

- Precision of couplings / %

- $g_{\text{HWW}}$, $g_{\text{Hbb}}$, $g_{\text{Hcc}}$, $g_{\text{Hgg}}$

- Running time at 250 GeV / $10^7$ s
ILC is the ideal precision machine complementary to LHC discovery power, to reveal the mechanism of EWSB and mass generation; performance of ILD can exactly meet the physics goal.

recoil mass measurement @ 250 GeV gives the absolute HZZ coupling, be able to model independently normalize all the Higgs couplings and total width.

ILC @ 500 GeV and 1 TeV is essential to significantly improve precision and access top-Yukawa coupling and Higgs self-coupling.

ability of energy scan can make ILC run at optimal energy and complementary to whatever LHC would discover.

Full ILC Program
- 250 fb⁻¹ @ 250 GeV
- 500 fb⁻¹ @ 500 GeV
- 1000 fb⁻¹ @ 1000 GeV

ILC ready to go!
backup
almost model-free fitting, constraint:

Branching ratios sum up to 1
General issue: running of the sensitive factor and expected coupling precision at different \( E_{cm} \)

\[
\frac{\Delta \lambda}{\lambda} = F \cdot \frac{\Delta \sigma}{\sigma}
\]

Factor increases quickly as going to higher energy

for \( ZHH \), the expected optimal energy \( \sim 500 \text{ GeV} \) (though cross section is maximum \( \sim 600 \text{ GeV} \))

for \( \nu\nu HH \), expected precision improves slowly as going to higher energy
General issue: cross sections of each contribution

\[ \sigma_0 = a\lambda^2 + b\lambda + c = \sigma_S + \sigma_I + \sigma_B \]
new weighting method to enhance the coupling sensitivity

differential cross-section

\[ \frac{d\sigma}{dx} = B(x) + \lambda I(x) + \lambda^2 S(x) \]

irreducible interference self-coupling

observable: weighted cross-section

\[ \sigma_w = \int \frac{d\sigma}{dx} w(x) dx \]

equation of the optimal \( w(x) \) (variance principle):

\[ \sigma(x)w_0(x) \int (I(x) + 2S(x))w_0(x)dx = (I(x) + 2S(x)) \int \sigma(x)w_0^2(x)dx \]

general solution:

\[ w_0(x) = c \cdot \frac{I(x) + 2S(x)}{\sigma(x)} \]

c: arbitrary normalization factor
Higgs Physics at Higher Energy

Self-coupling with WBF, top Yukawa at xsection max., other higgses, ...

- \(vvH @ \text{at } >1\text{TeV} : 2a\text{b}^\wedge{-1} \text{ (pol e+, e-)} = (+0.2, -0.8)\)
- allows us to measure rare decays such as \(H \rightarrow \mu^+\mu^-; \ldots\)
- further improvements of coupling measurements
- \(vvHH @ 1\text{TeV or higher} : 2a\text{b}^\wedge{-1} \text{ (pol e+, e-)} = (+0.2, -0.8)\)
- self-coupling through WW-fusion.
- If possible, we want to see the running of the self-coupling (very very challenging).
- \(ttH @ 1\text{TeV} : 1a\text{b}^\wedge{-1}\)
- improve the top-Yukawa coupling

Obvious but most important advantage of higher energies in terms of Higgs physics is its higher mass reach to other Higgs bosons expected in an extended Higgs sector and higher sensitivity to \(W_LW_L\) scattering to decide whether the Higgs sector is strongly interacting or not.

In any case we can improve the mass-coupling plot by including the data at 1TeV!
Quantum Numbers $J^{CP}$

in addition to the spin study by $H\rightarrow ZZ^*$ and $WW^*$, ILC offers an orthogonal way and be able to measure the mixture of CP even and CP odd

three-20 fb$^{-1}$-points threshold scan

if a mixture of CP even and CP odd

precision measurement of the HZZ coupling, 500 fb$^{-1}$ @ 350 GeV

--> few % of mixing angle

ref: DBD Physics Volume
Branching ratios of H→bb,cc,gg

each jet is tagged by a b-likeness and a c-likeness

patterns of the 2-D b-likeness and c-likeness

excellent b-tagging and c-tagging -->
template fitting can give the fractions
of Higgs to bb, cc, gg events

σ_{ZH} \cdot \text{Br}(H \rightarrow bb)
σ_{ZH} \cdot \text{Br}(H \rightarrow cc)
σ_{ZH} \cdot \text{Br}(H \rightarrow gg)

H. Ono @ LCWS12
Euro. Phys. J. C, 73, 2343
(LoI study, MH=120 GeV)
Branching ratios of $H\rightarrow\tau\tau$

- full simulation (LoI study, $MH = 120$ GeV)
- 1-prong and 3-prongs $\tau$-finder
- $Z\rightarrow ll$: recoil mass
- $Z\rightarrow qq$: collinear approximation

\[
\frac{\Delta (\sigma \cdot Br)}{\sigma \cdot Br} = 3.5\% 
\]

<table>
<thead>
<tr>
<th></th>
<th>$Z \rightarrow ee$</th>
<th>$Z \rightarrow \mu\mu$</th>
<th>$Z \rightarrow qq$</th>
<th>$Z \rightarrow vv$</th>
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<tr>
<td>Significance</td>
<td>$8.0\sigma$</td>
<td>$8.8\sigma$</td>
<td>$25.7\sigma$</td>
<td>$3.0\sigma$</td>
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</tbody>
</table>

S. Kawada, et al, LC-REP-2013-001
Branching ratio of $H \rightarrow \mu^+\mu^-$

- rare decay
- low multiplicity
- clean and narrow mass peak
- main BG: $v\bar{v}Z$, $WW$

\[
\frac{\Delta(\sigma \cdot Br)}{\sigma \cdot Br} = 31\% \ @ \ 1 \ ab^{-1}
\]

C. Calancha @ LCWS12
Invisible Higgs Decay

- In the SM, an invisible Higgs decay is $H \rightarrow ZZ^* \rightarrow 4\nu$ process and its BF is small $\sim 0.1\%$
- If we found sizable invisible Higgs decays, it is clear new physics signal.
  - The decay products are dark matter candidates.
- At the LHC, one can search for invisible Higgs decays by using recoil mass from $Z$ or summing up BFs of observed decay modes with some assumptions.
  - The upper limit is $O(10\%)$.
- At the ILC, we can search for invisible Higgs decays using a recoil mass technique with model independent way!
  - $e^+e^- \rightarrow ZH$

$$P_H = P_{e^+e^-} - P_Z$$

known measured

A. Ishikawa @ Snowmass, Seattle
prospect of Higgs self-coupling

scatter plot of two Higgs masses  
vvHH mode: (ZZH and ZZZ)

perfect jet-clustering

real jet-clustering

✦ the mis-clustering of particles degrades the mass resolution very much
✦ it is studied using perfect color-singlet jet-clustering can improve $\delta \lambda \sim 40\%$
✦ Mini-jet based clustering (Durham works when $N_p$ in mini-jet $\sim 5$, need better algorithm to combine the mini-jets, using such as color-singlet dynamics)
✦ looks very challenging now...
✦ including H--$\rightarrow$WW* (ongoing)
✦ kinematic fitting
new couplings to be added: $g_{ZZHH}, g_{WWHH}$

---would be unique at Linear Collider

$$
\frac{\delta \lambda_{HHH}}{\lambda_{HHH}} = 1.8 \frac{\delta \sigma_{ZHH}}{\sigma_{ZHH}} \\
\frac{\delta g_{ZZHH}}{g_{ZZHH}} = 0.97 \frac{\delta \sigma_{ZHH}}{\sigma_{ZHH}} \\
\frac{\delta \lambda_{HHH}}{\lambda_{HHH}} = 0.85 \frac{\delta \sigma_{\nu\bar{\nu}HH}}{\sigma_{\nu\bar{\nu}HH}} \\
\frac{\delta g_{WWHH}}{g_{WWHH}} = 0.29 \frac{\delta \sigma_{\nu\bar{\nu}HH}}{\sigma_{\nu\bar{\nu}HH}}
$$

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<th>coupling</th>
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<tbody>
<tr>
<td>HHH</td>
<td>104%</td>
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<tr>
<td></td>
<td>58% (LU)</td>
<td>16% (LU)</td>
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<tr>
<td>ZZHH</td>
<td>62%</td>
<td>-</td>
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<tr>
<td>WWHH</td>
<td>-</td>
<td>11%</td>
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preliminary! correlation with HHH not included