Prospects of Higgs self-coupling measurements at the ILC using ILD detector

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On behalf of ILD group
International Linear Collider Project

- $e^+e^-$ linear collider to be built in Japan
- Higgs factory (250 GeV) starting at 2035-2040
  - Beam polarization ($e^-$: 80%, $e^+$: 30% expected)
  - 2 ab$^{-1}$, similar physics potential with FCCee (by polarization)
- Upgradable by increasing tunnel length and accelerating gradient

<table>
<thead>
<tr>
<th>Energy</th>
<th>Physics</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 GeV</td>
<td>Top threshold</td>
<td>Better surface treatment (up to $\sim$50 MV/m)</td>
</tr>
<tr>
<td>$\sim$500 GeV</td>
<td>Higgs self coupling (ZHH)</td>
<td>Thin-film superconductor (up to $\sim$100 MV/m)</td>
</tr>
<tr>
<td>$\sim$1 TeV</td>
<td>Higgs self coupling ($\nu\nu$HH)</td>
<td></td>
</tr>
<tr>
<td>Up to a few TeV</td>
<td>BSM search (eg. TeV Wino)</td>
<td></td>
</tr>
<tr>
<td>30 TeV</td>
<td>?</td>
<td>Plasma accelerator? ($\sim$1 GV/m)</td>
</tr>
</tbody>
</table>
ILD detector

• International Large Detector (ILD)
  - One of two detector concepts for ILC

• Particle flow concept
  - Separate particles in jets by highly-segmented calorimeters

• Key subsystems
  - Monolithic vertex detector
  - TPC + silicon tracker
  - High granular calorimeter (silicon/scintillator ECAL, scintillator/RPC HCAL)

Unprecended performance by precise particle imaging
  - b/c tagging, momentum resolution, jet energy resolution...
Higgs self coupling and baryogenesis

$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^4 + \frac{1}{4} \lambda \eta_H^4$

$\lambda$ determines the quadratic term of Higgs potential
$\rightarrow$ Unique probe for structure of vacuum

Electroweak baryogenesis requires strong 1st order EW transition
$\rightarrow$ In the two-Higgs doublet models, $\lambda$ positively deviates by $>20$
$\rightarrow$ should be an experimental target
Higgs self-coupling at ILC

\[ \sqrt{s} = 500 \text{ GeV}: \; e^+e^- \rightarrow ZHH \]

\[ \sqrt{s} \geq 1 \text{ TeV}: \; e^+e^- \rightarrow \nu_e\bar{\nu}_eHH \]

Extremely low cross section: \( \mathcal{O}(100 \text{ ab}) \)

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### Decay channels

- **dominant channels covered for ZHH @ 500 GeV**

<table>
<thead>
<tr>
<th>$Z$ decay mode</th>
<th>$HH$ decay mode</th>
<th>BranchingRatio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \to e^+e^-$</td>
<td>$HH \to bbbb$</td>
<td>1.1%</td>
</tr>
<tr>
<td>$Z \to \mu^+\mu^-$</td>
<td>$HH \to b\bar{b}b\bar{b}$</td>
<td>1.1%</td>
</tr>
<tr>
<td>$Z \to v^+\bar{v}$</td>
<td>$HH \to b\bar{b}b\bar{b}$</td>
<td>6.7%</td>
</tr>
<tr>
<td>$Z \to b\bar{b}$</td>
<td>$HH \to b\bar{b}b\bar{b}$</td>
<td>5.0%</td>
</tr>
<tr>
<td>$Z \to q\bar{q}$</td>
<td>$HH \to b\bar{b}b\bar{b}$</td>
<td>17%</td>
</tr>
<tr>
<td>$Z \to b\bar{b}$</td>
<td>$HH \to b\bar{b}W^<em>W^</em>, WW^* \to 4q$</td>
<td>1.7%</td>
</tr>
<tr>
<td>$Z \to c\bar{c}$</td>
<td>$HH \to b\bar{b}W^<em>W^</em>, WW^* \to 4q$</td>
<td>1.4%</td>
</tr>
<tr>
<td>$Z \to b\bar{b}$</td>
<td>$HH \to b\bar{b}W^<em>W^</em>, WW^* \to l\nu 2q$</td>
<td>1.1%</td>
</tr>
<tr>
<td>$Z \to c\bar{c}$</td>
<td>$HH \to b\bar{b}W^<em>W^</em>, WW^* \to l\nu 2q$</td>
<td>0.92%</td>
</tr>
<tr>
<td>$Z \to l^+l^-$</td>
<td>$HH \to b\bar{b}W^<em>W^</em>, WW^* \to 4q$</td>
<td>0.76%</td>
</tr>
<tr>
<td>$Z \to l^+l^-$</td>
<td>$HH \to b\bar{b}W^<em>W^</em>, WW^* \to l\nu 2q$</td>
<td>0.50%</td>
</tr>
</tbody>
</table>

*Table 1:* signal channels analysed for $e^+e^- \to ZHH$ at $\sqrt{s} = 500$ GeV.

(for $e^+e^- \to vvHH@1$TeV: $HH \to bbbb/bbWW^*$ are covered)
Result of full simulation studies

- results (example individual channels)

<table>
<thead>
<tr>
<th>ZHH channel</th>
<th>s (HH $\rightarrow$ bbbb)</th>
<th>b</th>
<th>$\sigma_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>eeHH</td>
<td>3.9 ± 0.03 (2.6)</td>
<td>7 ± 0.6</td>
<td>1.29$\sigma$</td>
</tr>
<tr>
<td>$\mu\mu HH$</td>
<td>5.1 ± 0.03 (2.8)</td>
<td>9 ± 0.5</td>
<td>1.48$\sigma$</td>
</tr>
<tr>
<td>$\nu\nu HH$</td>
<td>5.6 ± 0.04 (5.5)</td>
<td>7 ± 1.0</td>
<td>1.78$\sigma$</td>
</tr>
<tr>
<td>bbHH</td>
<td>8.5 ± 0.10 (8.0)</td>
<td>22 ± 1.3</td>
<td>1.75$\sigma$</td>
</tr>
<tr>
<td>qqHH</td>
<td>12.6 ± 0.1 (10.9)</td>
<td>55 ± 2.0</td>
<td>1.65$\sigma$</td>
</tr>
</tbody>
</table>

Table 2: Results of the event selection of ZHH with HH $\rightarrow$ bbbb corresponding to an integrated luminosity of $\mathcal{L} = 2$ ab$^{-1}$ and a beam polarisation of $P(e^+e^-) = (0.3, -0.8)$.

major bkg.: tt, ZZ, ZZZ, ZZH

- results (combined)

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$\int L dt$</th>
<th>$\Delta \sigma / \sigma$</th>
<th>$\Delta \lambda_{HHH} / \lambda_{HHH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZHH @ 500 GeV</td>
<td>4 ab$^{-1}$ (*)</td>
<td>17%</td>
<td>27%</td>
</tr>
<tr>
<td>$\nu \nu$ HH @ 1 TeV</td>
<td>4 ab$^{-1}$ (***)</td>
<td>15%</td>
<td>10%</td>
</tr>
</tbody>
</table>

$P(e^+, e^-) =$ *: equally shared by (-0.8, +0.3) and (+0.8, -0.3); **: (-0.8, +0.2)
from di-Higgs cross section to $\lambda_{HHH}$

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

(signal diagram) interference: constructive in ZHH, destructive in $\nu\nu HH$

(background diagram)

ZHH final states (500 GeV) $\nu\nu HH$ final states (>1 TeV)
Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

- $\lambda_{HHH}$ can be enhanced significantly in BSM
- complementarity between ZHH & $\nu \nu HH$ (& LHC): interference nature
- if $\lambda_{HHH} / \lambda_{SM} = 2$, $\lambda_{HHH}$ be measured to $\sim 13\%$ using ZHH at 500 GeV $e^+e^-$

A strong probe for electroweak baryogenesis
Higgs self-coupling: impact of ECM

optimal $\sqrt{s} \sim 500$-$600$ GeV

preferred $\sqrt{s} \geq 1$ TeV

large room for improving full simulation results in future
\( \lambda_{hhh} \): can we really determine it mode independently?

\( \sigma_{hhh} \) depends on many other couplings

in a general model by SMEFT
λ_{hhh}: can we really determine it mode independently? yes!

\[
\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 = 0.565c_6 - 3.58c_H + 16.0(8c_{WW}) + 8.40(8c_{WB}) + 1.26(8c_{BB}) \\
-6.48c_T - 65.1c'_{HL} + 61.1c_{HL} + 52.6c_{HE},
\]

all parameters determined simultaneously: EWPOs + TGCs + Higgs @ HL-LHC & ILC

\[
c_6 = \frac{1}{0.565} \left[ \frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 - \sum_i a_i c_i \right]
\]

\[
\frac{\Delta \lambda_{hhh}}{\lambda_{SM}} = \Delta c_6 = \frac{1}{0.565} \left[ (\frac{\Delta \sigma_{Zhh}}{\sigma_{SM}})^2 + \sum_{i,j} a_i a_j (V_c)_{ij} \right]^{\frac{1}{2}}
\]

Given the full ILC program of 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV

\[
\left[ \sum_{i,j} a_i a_j (V_c)_{ij} \right]^{\frac{1}{2}} = 0.04 \ll \frac{\Delta \sigma_{Zhh}}{\sigma_{SM}} = 0.168
\]

(systematic error) (statistical error)
Prospects of improvements

• Current result on $\lambda_{HHH}$
  - 27%: ZHH 500 GeV 4 ab$^{-1}$
  - 10%: $\nu\nu$HH 1 TeV 4 ab$^{-1}$

• Performance drivers
  - b-tagging: separation of ttbar background
  - Jet clustering: selection of Z and H
  - Analysis method (event selection)

• Possible improvements
  - $K/\pi/p$ separation by dE/dx and ToF
  - Pattern recognition by deep learning
Possible improvements

**Pico-sec ToF**

\[ K/\pi/p \] separation by combining dE/dx at TPC and timing at ECAL

**Hardware:**
Fast silicon detector (LGAD)

**Software:**
Precise timing reconstruction
Flavor tagging with PID
Particle flow with timing

**Jet clustering by deep learning**

Jet clustering as well as flavor tagging and event selection should be improved by deep learning techniques (convolutional network, recurrent network, graph network...) various trials ongoing

**Target:** 20-30% improvement in a few years
Summary

• Higgs self-coupling measurement is an essential probe for vacuum structure
  - Also essential for EW baryogenesis
• ILC gives powerful probe to the self coupling
  - 27%: ZHH 500 GeV 4 ab\(^{-1}\)
    Positive interference: preferred for \(\lambda > 1\)
  - 10%: \(\nu\nu HH\) 1 TeV 4 ab\(^{-1}\)
    Negative interference (as LHC): better for \(\lambda < 1\)
• Various hardware/software efforts ongoing for improvements: results in a few years
The only probe for Higgs potential: 
self coupling

<table>
<thead>
<tr>
<th>Lagrangian term</th>
<th>example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge force</td>
<td>QCD, electroweak</td>
</tr>
<tr>
<td>Yukawa force</td>
<td>Higgs-fermion</td>
</tr>
<tr>
<td>Higgs force</td>
<td>Higgs self-coupling</td>
</tr>
</tbody>
</table>

- The last force in SM
- A good probe for BSM with ~30% accuracy

\[ V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 + \text{h.c.}, \quad \mu^2 < 0, \lambda > 0 \]
full simulation studies @ ILC

• generator: Whizard 1.95, Physsim (realistic beamsstrahlung, ISR, pile-up)
• parton shower & hadronization: Pythia 6
• detector model: ILD (as realistic as possible material budget, blind areas)
• simulation & reconstruction: Geant 4, iLCSoft (realistic algorithms for tracking, particle flow, flavor tagging, jet-clustering, etc)
• event selection: full SM background, realistic cuts, careful categorization, kinematic fitting, multivariate method