Prospects of the Higgs self-coupling measurements @ the linear colliders

— focusing on the physics issues and impact of ecm

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Motivation to measure Higgs self-coupling

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

- discover the force that makes Higgs condense in vacuum
- direct probe of the Higgs potential
- test the EWSB mechanism
- test extended Higgs sector
- test electroweak baryogenesis

\[
\begin{array}{c|c|c|c}
\lambda_{hhh}/\lambda_{hhh}^{(SM)} & (I) & (II) & (III) \\
\hline
1.7 & 1.8 & 1.8 \\
\lambda_{hhhhh}/\lambda_{hhhhh}^{(SM)} & 3.7 & 4.3 & 4.5 \\
\end{array}
\]

Endo, Sumino, arXiv:1505.02819
measurement of Higgs self-coupling @ LHC

LHC Run1: pp→hh @ ATLAS

95% C.L. upper limit: $\sigma / \sigma_{SM} < 70$ (48)

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\gamma\gamma bb$</th>
<th>$\gamma\gamma WW^*$</th>
<th>$b\bar{b}\tau\bar{\tau}$</th>
<th>$b\bar{b}b\bar{b}$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>1.0</td>
<td>6.7</td>
<td>1.3</td>
<td>0.62</td>
<td>0.47</td>
</tr>
<tr>
<td>Observed</td>
<td>2.2</td>
<td>11</td>
<td>1.6</td>
<td>0.62</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Upper limit on the cross section relative to the SM prediction

| Expected | 100 | 680 | 130 | 63 | 48 |
| Observed | 220 | 1150| 160 | 63 | 70 |

Snowmass Higgs working group: $\delta\lambda_{HHH} / \lambda \sim 50\% @ 14$ TeV, 3000 fb$^{-1}$

(arXiv: 1310.8361)
prospects of Higgs self-coupling @ linear colliders

prospects from full simulation studies:

<table>
<thead>
<tr>
<th>$\Delta \lambda_{HHH}/\lambda_{HHH}$</th>
<th>500 GeV</th>
<th>+ 1 TeV</th>
<th>1.4 TeV</th>
<th>+3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snowmass</td>
<td>46%</td>
<td>13%</td>
<td>21%</td>
<td>10%</td>
</tr>
<tr>
<td>H20</td>
<td>29%</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ILC

CLIC

(ref. H20 arXiv: 1506.07870)
J. Tian, LC-REP-2013-003

(arXiv: 1307.5288)
C. Dürig @ ALCW15

M. Kurata, LC-REP-2014-025
For ZHH: 500 GeV seems not the optimal energy?
For \(\nu\nu HH\): isn’t 3 TeV much better than 1 TeV?
physics issues: diagrams for double Higgs production

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

(signal diagram) (interference) (background diagram)

- the sensitivity of $\lambda$ is determined not just by the apparent total cross section, in fact is determined by $S$ and $I$ term;
- if $B$ term dominates, measurement would be very difficult
breakdown of $\sigma$ to $S$, $I$ and $B$ terms

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

- **B term (green) >> S term (red) —> more difficult than expected**
- **interference I term (blue) plays an crucial role in both cases; larger I term for $\nu\nuHH$ indicates potential better sensitivity in $\nu\nuHH$ than ZHH**
- **For ZHH: clearly ~500-600 GeV is preferred; peak positions of I or S term are smaller than that of B term and the apparent total $\sigma$ (black)**
- **For $\nu\nuHH$: dependence on ecm, S term < apparent $\sigma < B$ term \approx I term**
sensitivity of $\lambda$ to the direct measured $\sigma$

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

\[ F = \frac{\sigma}{2S\lambda^2 + I\lambda} \]

sensitivity factor

- smaller $F$ means better sensitivity; if only signal diagram, $F=0.5$
- $F$ in $ZHH$ indeed much worse than $F$ in $\nu\nuHH$
- in both cases $F$ increases significantly when $ecm$ increases

| $|F|$ | $|F|$ (relative to 1 TeV) |
|-----|---------------------------|

<table>
<thead>
<tr>
<th>$e^+e^- \rightarrow ZHH$</th>
<th>$e^+e^- \rightarrow \nu\nuHH$</th>
<th>$e^+e^- \rightarrow ZHH$</th>
<th>$e^+e^- \rightarrow \nu\nuHH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>sensitivity factor</td>
<td>sensitivity factor (relative)</td>
<td>sensitivity factor</td>
<td>sensitivity factor (relative)</td>
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<tr>
<td>3000</td>
<td>6</td>
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</tbody>
</table>
two expectations: (red) theoretical precision assuming 100% signal efficiency and no background; (blue) realistic precision based on the state-of-the-art full detector simulation studies at the ILC

in both cases at all energies, integrated luminosity of 4 ab\(^{-1}\) is assumed, which is reasonable according to H20 scenarios

for ZHH: 500 GeV is the optimal energy, \(\delta \lambda / \lambda \sim 30\%\), but rather mild dependence at around 500-600 GeV, significantly worse if much lower or higher than that

for \(\nu \nu HH\): \(\delta \lambda / \lambda \sim 10\%\) achievable when ecm > 1TeV; better precision at higher ecm, but not drastically, from 1 TeV to 3 TeV, improved by 50%
what’s the expectation if $\lambda \neq \lambda_{SM}$? @ LCs

- For ZHH, interference is constructive, enhanced $\lambda$ will increase the total $\sigma$, and improve sensitive factor as well, e.g. if $\lambda = 2\lambda_{SM}$, $\sigma$ increase by 60%, $F$ decease by half, $\delta \lambda / \lambda \sim 15\%$, $\rightarrow$ we may finish the $\lambda$ story at 500 GeV ILC.

- For $\nu \nu HH$, interference is destructive, enhanced $\lambda$ will decrease $\sigma$, minimum when $\lambda \sim 1.5\lambda_{SM}$, $\delta \lambda / \lambda$ degrade significantly if $\lambda / \lambda_{SM} \in (1.3, 1.7)$.

- But if $\lambda < \lambda_{SM}$, more difficult to use ZHH, have to rely on more on $\nu \nu HH$.

- Two channels are complementary in terms of $\lambda$ measurement in BSM.
what’s the expectation if $\lambda \neq \lambda_{SM}$? @ LHC

- interference is destructive, $\sigma$ minimum at $\lambda \sim 2.5\lambda_{SM}$; if $\lambda$ is enhanced, it’s going to be very difficult (from snowmass study by 3000 fb-1 @ 14 TeV, significance of double Higgs production is only $\sim 2\sigma$, if cross section deceases by a fact of 2~3, very challenging to observe pp$\rightarrow$HH)
resolve the two solutions of $\lambda$

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

$$\lambda = \frac{-I \pm \sqrt{I^2 - 4SB + 4S\sigma}}{2S}$$

- $\lambda < 0$ can be excluded by LHC with 600 fb$^{-1}$ @ 14 TeV (arxiv: 1301.3492)
- if we don’t have constraints by ZHH, the two solutions from $\nu\nu$HH are still possible
- in this sense, $\lambda$ by ZHH is actually very important (e.g. by 500 GeV data); these two channels are again complementary

which one is the correct solution?
impact of beam polarisations

- at ILC TDR: $P(80\%,30\%)$ @ 500 GeV and $P(80\%,20\%)$ @ 1 TeV promised for electron and positron beams; 60% for positron beam is sometimes mentioned possible

- at CLIC CDR: nominal studies assume no beam polarisations, but 80% is achievable for electron beam, not very clear about positron polarisation

- clearly beam polarisation is helpful for both $ZHH$ and $\nu\nuHH$; $\sigma(ZHH)$ increase by a factor of 1.4 at 500 GeV; $\sigma(\nu\nuHH)$ increase by a factor of 2.2 @ 1 TeV

- for fair comparison, throughout this talk, I assumed same polarisation at all energies: $P(-80\%,+30\%)$ for $ZHH$ processes, $P(-80\%,+20\%)$ for $\nu\nuHH$ process.
a new general method to improve the sensitivity of $\lambda$

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

- 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:

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

c: arbitrary normalization factor

differential cross-section

optimal weighing function

graphical representation of $\frac{d\sigma}{dx}$, $B(x)$, $I(x)$, and $S(x)$
improvement of sensitivity by weighting method

(Improved sensitivity factor)

| $|F|$ | ZHH @ 500 GeV | ZHH @ 1 TeV | $\nu\nuHH @ 1$ TeV |
|-----|----------------|-------------|------------------|
| default | 1.73 | 2.62 | 0.8 |
| by weighting | 1.62 | 1.84 | 0.73 |
status of full simulation analysis @ ILC

- DBD full simulation analyses (mH=125 GeV): ZHH @ 500 GeV, ννHH @ 1 TeV
- SGV fast simulation analysis: ννHH @ 1 TeV (consistent with full simulation)

- updating analysis with mH=125 GeV
- impact of beam background from γγ→hadrons
- impact of beam polarisations
- improving analysis technique / strategy
  - isolated lepton tagging
  - kinematic fitting
  - optimize cuts for coupling instead of cross section
  - matrix element method and color-singlet-jet-clustering
development of new color-singlet jet clustering

- mis-clustering is one of the major limiting factor
- $\delta \lambda / \lambda$ could be improved by 40% if we could achieve perfect clustering
- but it’s very difficult to improve general jet clustering algorithm
- so far we only know mis-clustering starts mainly at the step when # mini-jet = 20
- need better algorithm to combine those mini-jets
- idea: deconstruct the who parton shower history, find the combination with largest probability
summary

- $\lambda$ is very important to measure, however challenging at both LHC and LCs
- The best expectation we have now, in SM case, $\delta\lambda/\lambda \sim 29\%$ at 500 GeV, 10\% at 1 TeV at the ILC; further potential improvement at CLIC
- Two channels ZHH and $\nu\nuHH$ are complementary; interference is crucial to determine $\lambda$ in both channels
- 500 GeV is optimal energy for ZHH; the improvement by $\text{ecm} > 1\text{TeV}$ is rather mild due to the increased sensitivity factor
- In some BSM scenario, $\delta\lambda/\lambda$ can be already well determined just at 500 GeV ILC
- Analysis is very challenging and improvement being pursued