Triple-Higgs coupling measurement at future e+e- colliders

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Higgs Coupling 2016, SLAC
Outline

• Introduction

• Indirect measurement of triple-Higgs coupling

• Direct measurement of triple-Higgs coupling
  – complementarity with LHC

• Model-independent extraction of the triple-Higgs coupling in EFT [NEW!]
Circular Colliders

**CEPC**

Circular Electron-Positron Collider
- Site: **China**
- CM energy: **90-240 GeV**
- Single main ring + booster ring
- Circumference: **50 km**
- # of IPs: **2**
- Precursor to 70 TeV pp collider (**SPPC**)

**FCC-ee**

Future Circular Collider: **e+e-**
- Site: **CERN**
- CM energy: **90-350 GeV**
- Two main rings + booster ring
- Circumference: **100 km**
- # of IPs: **2-4**
- Possible precursor to 100 TeV pp collider (**FCC-hh**)
Linear Colliders

**ILC**

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TDR 2013

International Linear Collider
- Based on superconducting RF cavities
- Potential site: Japan
- CM energy: 250-500 GeV (upgradable to 1 TeV)
- Length: 34 km (for 500 GeV)
```

**CLIC**

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CDR 2012

Compact Linear Collider
- Based on 2-beam acceleration scheme
- Site: CERN
- CM energy: 340 GeV → 3 TeV
- Length: 50 km (for 3 TeV)
```
Higgs Couplings

Model-Independent:
Only possible at e+e-

Includes systematic uncertainties [arXiv:1506.05992]

Model-Dependent:
Compare with LHC

Sub-percent precision on most Higgs couplings
with full ILC program
Motivation

Motivation for measuring the triple-Higgs coupling:

1. Crucial test of electroweak symmetry breaking in the SM
   - Direct probe of the Higgs potential

2. New Physics
   - Deviations expected by new physics in the Higgs sector
   - Predicted deviations are typically large
     - Grojean, Servant, Wells, PRD71, 036001
     - Hashino, Kanemura, Orikasa, 1508.03245
     - Fuyuto, Senaha, PLB747, 152
     - Perelstein, Katz, JHEP1407, 108

\[ V(\eta) = \frac{1}{2} m^2 \eta^2 + \lambda \nu \eta^3 + \frac{1}{4} \lambda \eta^4 \]
Higgs Production (e+e-)

Double Higgs Production:

\[
e^+e^- \rightarrow ZHH
\]

\[
e^+e^- \rightarrow \nu\nu HH
\]

Cross section \( \sigma(e^+e^- \rightarrow HX) \) in [fb]

CM Energy (GeV) \( \sqrt{s} \) in [GeV]

Require at least \( \sim 500 \) GeV for the direct measurement of the triple-Higgs coupling via double Higgs production.
Use ZH process (e.g. 250 GeV):

\[
\delta^{240}_\sigma = 100 \left( 2\delta_Z + 0.014\delta_h \right) \% 
\]

- **NLO** vertex correction has triple-Higgs coupling
- Take advantage of high luminosity (e.g. circular colliders)
  - If \( \delta\sigma_{ZH} = 0.4\% \), then \( \delta\lambda = 28\% \), assuming SM ZZH coupling; \( \delta\lambda \) is larger for modified ZZH.
- Important consistency check of the SM; offers complementary measurement (cf. direct measurement) about the loop process (model-dependent)
Direct Measurement

Cross section vs CM energy (e+e-)

- $e^+ + e^- \rightarrow ZHH$
- $e^+ + e^- \rightarrow \nu \nu HH$ (WW-fusion)
- $e^+ + e^- \rightarrow \nu \nu HH$ (Combined)

$M(H) = 125$ GeV  \( P(e^-,e^+) = (-0.8,+0.3) \)

Expected precision based on full detector simulation studies:

**ILC**
- 500 GeV, 4 ab-1
- \( \delta \lambda = 27\% \)

**ILC**
- 500 GeV, 4 ab-1 & 1 TeV, 8 ab-1
- \( \delta \lambda = 10\% \)

References:
- J. Tian, LC-REP-2013-003
- M. Kurata, LC-REP-2014-025
- C. Duerig, Ph.D. thesis at DESY, 2016
- HH\(\rightarrow\)bbbb, bbWW* combination

**Diagrams with triple-Higgs coupling**

**CLIC**
- 1.4 TeV, 1.5 ab-1
- \( \delta \lambda = 21\% \)

**CLIC**
- 1.4 TeV, 1.5 ab-1 & 3 TeV, 2 ab-1
- \( \delta \lambda = 10\% \)

References:
- arXiv: 1307.5288
- HH\(\rightarrow\)bbbb only, upgrade in progress including bbWW*
Strawman Running Scenario for ILC

- **500 GeV:** General purpose Higgs & top physics, *triple-Higgs coupling*, top Yukawa, BSM
- **350 GeV:** Top threshold scan
- **250 GeV:** Dedicated Higgs measurements (mass, CP, …)

### Integrated Luminosities [fb]

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
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<tbody>
<tr>
<td>250</td>
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</tr>
<tr>
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**Total integrated luminosities:**

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Reasonable assumption on integrated luminosities

Luminosity upgrade based on self-imposed limit on the power consumption of 200 MW.

Actual profile will depend on new physics, funding, and other projects.
BSM can modify the triple-Higgs coupling. What effect does it have on the total cross section?

At 500 GeV, the cross section increases with increasing $\lambda$.

At 1 TeV, the cross section decreases with increasing $\lambda$. [Same as LHC]
The authors ask the question: **If there is a deviation from the SM cross section, how to interpret this as a shift of the Higgs potential?**

EFT analysis with dimension 6 operators: goal is to extract the parameter \( c_6 \) in

\[
\Delta \mathcal{L} = -c_6 \frac{\lambda}{\nu^2} (\Phi^{\dagger}\Phi)^3
\]

**9 additional dimension 6 coefficients** contribute to the double Higgs production. Of which:
- 3 are determined by **precision electroweak** data
- 3 are determined by measurement of \( e^+e^- \to W^+W^- \)
- 1 combination is constrained by the **small size of** \( h \to \gamma\gamma \)

**Need 2 more constraints \( \to \) will be provided by** \( e^+e^- \to Zh \)
Model-independent extraction with EFT (2)
[Barklow, Fujii, Jung, Peskin, Tian]

- Estimates of $e^+e^- \to Zh$ for the ILC program [Ogawa, Fujii, Tian]:
  - $\delta(c_H) = 1\%$  $\delta(16c_{WW}) = 0.25\%$ (highly correlated)

- The effect of these parameters on the double Higgs cross section is

$$\frac{\sigma(e^+e^- \to Zhh)}{\sigma_{SM}} = 1 - 3.6c_H + 7.4(16c_{WW}) + 0.56c_6$$

*These are issues for any double Higgs production process.

For $e^+e^- \to Zhh$, precision measurement of single-Higgs process brings these effects under control at the **10% level in $c_6$**. Within this uncertainty, the extraction of $c_6$ is completely **model-independent**.
Conclusions
on triple-Higgs coupling at future e+e- colliders

• **Indirect measurement** at the **30%-level** may be possible with high luminosity (e.g. circular colliders)
  – Provides complementary (but model-dependent) information about the loop process.

• For **direct measurement**, expected precision is $\delta\lambda/\lambda = 27\%$ at 500 GeV, and $\delta\lambda/\lambda = 10\%$ combining 1 TeV. These numbers are supported by studies with full detector simulation.
  – **500 GeV** has unique sensitivity when $\lambda > \lambda_{SM}$.
  – This condition is theoretically well-motivated.
  – This is complementary to 1 TeV and LHC, which are sensitive for $\lambda < \lambda_{SM}$.

• Based on EFT analysis, a **model-independent** extraction of the coefficient $c_6$ is possible at the **10% level**.
Additional Slides
physics issues: diagrams for double Higgs production

\[ \sigma = S\lambda^2 + I\lambda + B \]

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) $\rightarrow$ more difficult than expected
- interference I term (blue) plays an crucial role in both cases; larger I term for $\nu\nu HH$ indicates potential better sensitivity in $\nu\nu HH$ than $ZH H$
- For ZHH: clearly $\approx$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 $\nu\nu HH$: dependence on ecm, S term $<$ apparent $\sigma$ $<$ B term $\approx$ I term

Junping Tian
how we measure it at ILC and analysis strategy

searching mode and main backgrounds: \( e^+ + e^- \rightarrow ZHH \) @ 500 GeV

- \( llHH: \) \( llbb \) (ZZ, \( \gamma Z \), bbZ), \( lvbbqq \) (tt-bar), \( llbbbb \) (ZZZ/ZZH)
- \( vvHH: \) \( bbbb \) (ZZ, \( \gamma Z \), bbZ), \( \tau vbbqq \) (tt-bar), \( vvbbbb \) (ZZZ/ZZH)
- \( qqHH: \) \( bbbb \) (ZZ, \( \gamma Z \), bbZ), \( bbqqqq \) (tt-bar), \( qqbbbb \) (ZZZ/ZZH)

event selection:
- isolated-lepton selection or rejection
- jet clustering and flavor tagging
- missing energy or visible energy requirement
- event reconstructed as from signal and dominant background
- each dominant background is suppressed by training a neural-net

\( \frac{B}{S} \approx 10^{3-4} \)
status of full simulation analysis @ ILC

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

- updating analysis with mH=125 GeV
- impact of beam background from $\gamma\gamma$->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

J. Tian, LC-REP-2013-003  C. Dürrig @ ALCW15  M. Kurata, LC-REP-2014-025