sensitivity of anomalous HVV coupling @ ILC

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14th Regular Meeting of the New Higgs Working Group, Aug. 4-5 @ Toyama

ongoing study, results are rather preliminary
outline

- methodology to measure anomalous HVV @ ILC
- sensitivity of aHZZ obtained by analysis based on full detector simulation @ ILC
- comparison with aHVV @ LHC
- summary and next plan
H(125): J=0 is now strongly favoured by LHC data

**Fixed Spin and Parity Tests**

(P. Savard@EPS-HEP2015)

Test alternative fixed spin and parity hypotheses relative to the SM 0⁺ hypothesis

Results favour the spin 0⁺ hypothesis

Alternatives: 0-, 1-, 1+, various spin 2 models are typically excluded at > 99.9% CL

Large anomalous couplings are excluded. Next step: look for presence of smaller contributions

Also Tevatron results:
PRL 114, 151802 (2015)
next: probe tensor structure of HVV coupling

\[ L_{HVV} = 2M_V^2 \left( \frac{1}{v} + \frac{a}{\Lambda} \right) HV_\mu V^\mu + \frac{b}{\Lambda} HV_{\mu\nu} V^{\mu\nu} + \frac{\tilde{b}}{\Lambda} HV_{\mu\nu} \tilde{V}^{\mu\nu} \]

strategy we follow @ ILC:

- **effective field theory approach (dimension 5)**
- **V**: W/Z; **V_{\mu\nu}**: field tensor; **\tilde{V}_{\mu\nu}**: dual tensor
- **\Lambda**: new physics scale (set to 1 TeV)
- **a, b, \tilde{b}**: anomalous coupling (dimensionless)
- **a term**: SM like, CP-even
- **b term**: “B \cdot B - E \cdot E” type, CP-even
- **b-tilde term**: “E \cdot B” type, CP-odd
observables sensitive to anomalous couplings

- cross section \((a,b, bt)\)
- angle between two decay planes \((bt)\)
- \(V\) momentum \((b, bt)\)
- helicity angle in \(V\rightarrow ff\) \((b, bt)\)

example in \(H\rightarrow WW^*\)

Y. Takubo et al, arxiv:1011.5805
previous study: use just \( e^+e^- \rightarrow ZH \rightarrow (\nu\nu)(WW^*) \)

- O(1) constraints on b and b-tilde
- mainly limited by low efficiencies of c-tagging, in the case of soft jets from W* 

Y. Takubo et al, arxiv:1011.5805
new study: more comprehensive channels

- exploit all production vertex at ILC, $V^* \rightarrow VH$, $V^*V \rightarrow H$, and all decay vertex $H \rightarrow VV^*$
- interesting channels: $e^+e^- \rightarrow e^+e^-H$ via ZZ-fusion, where $\Delta \phi$ can be very well reconstructed (but cross section is not large)
- $e^+e^- \rightarrow \nu\nu H$ via WW-fusion, where cross section is very large (but $\Delta \phi$ is difficult due to missing neutrinos)
- $e^+e^- \rightarrow ZH$, using both $Z \rightarrow ll$ or $Z \rightarrow qq$, where cross section is large and full kinematics are reconstructed (the most sensitive channel)
example in $e^+e^- \rightarrow e^+e^-H$ via ZZ-fusion

$\Delta \phi$ between two decay planes $\rightarrow \Delta \phi$ between final electron pairs
example in $e^+e^- \rightarrow \nu\nu H$ via WW-fusion

though $\Delta \phi$ can’t be reconstructed, $P_H$ is very useful
example in $e^+e^- \rightarrow ZH, Z \rightarrow ll/qq$

$Z^*$ is at rest $\rightarrow \Delta \phi$ can be simplified by $\Delta \phi$ between production plane and Z decay plane.
full simulation analysis probing anomalous HZZ @ ILC

brief procedure:

- produce SM signal and all SM background events based on full detector simulation
- do the “normal” analysis to suppress BG (not to bias the distribution of observables used for probing aHZZ)
- extract the observables for signals and get acceptance function by comparing to generator
- use the acceptance function to give the observables in case of any anomalous coupling
- compare the observables by SM events and anomalous events, to draw the sensitivity of aHZZ coupling
example in e+e- → ZH → qqbb
results of sensitivity of aHZZ @ ILC (a vs. bt)

ZH→qqbb @ 250 GeV
ZH→llh @ 250 GeV

ZH→eeh→eebb @ 500 GeV

All combined

250 fb^{-1} @ 250 GeV
500 fb^{-1} @ 500 GeV

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

use Δφ & x-sec

three contours for each color: 1σ/2σ/3σ constraints
results of sensitivity of aHZZ @ ILC (b vs. bt)

ZH->qqbb @ 250 GeV
ZH->llh @ 250 GeV
eeh->eebb @ 500 GeV
All combined

250 fb$^{-1}$ @ 250 GeV
500 fb$^{-1}$ @ 500 GeV

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

use Δφ & x-sec
results of sensitivity of aHZZ @ ILC (a vs. b)

ZH->qqbb @ 250 GeV
ZH->llh @ 250 GeV
eeh->eebb @ 500 GeV
All combined

250 fb^{-1} @ 250 GeV
500 fb^{-1} @ 500 GeV

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

use cosθ & x-sec
Probe potential CP-mixing and tensor structure of Higgs interactions

• Amplitude describing interaction between a spin 0 and two spin 1 particles:

\[ A(HVV) \sim \left[ a_1^{VV} + \frac{\kappa_1^{YY} q_1^2 + \kappa_2^{YY} q_2^2}{(\Lambda_1^{YY})^2} \right] m_{VV}^2 |V_1|^2 |V_2|^2 + a_2^{VV} f_{\mu\nu}^{(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{(1)} \bar{f}^{*(2),\mu\nu} \]

\[ f_{\Lambda 1} = \frac{\sigma_{\Lambda 1}}{(\Lambda_1^{YY})^4}, \quad f_{a 2} = \frac{|a_2|^2}{|a_1|^2 + |a_2|^2 + |a_3|^2 + \frac{\sigma_{\Lambda 1}}{(\Lambda_1^{YY})^4} + \ldots}, \quad f_{a 3} = \frac{|a_3|^2}{|a_1|^2 + |a_2|^2 + |a_3|^2 + \frac{\sigma_{\Lambda 1}}{(\Lambda_1^{YY})^4} + \ldots} \]

\[ \sigma_i : \text{xs for } a_i = 1 \]

\[ \Lambda_1 = 1 \text{ TeV} \]

Phys Rev D. 89.035007

9.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
Lagrangian describing interaction between a spin 0 and a pair of W or Z bosons (from JHEP 1311 (2013) 043):

\[
L_0^V = \left\{ c_\alpha \kappa_{\text{SM}} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W_-^\mu \right] - \frac{1}{4} \Lambda \left[ c_\alpha \kappa_{HZZ} Z_\mu Z_{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}_{\mu\nu} \right] - \frac{1}{2} \Lambda \left[ c_\alpha \kappa_{HW} W_\mu^+ W_-^\mu + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}_{\mu\nu} \right] \right\} X_0.
\]

\[J^P\] | Model | Choice of tensor couplings |
---|---|---|
\[0^+\] | Standard Model Higgs boson | \[\kappa_{\text{SM}} \ 0 \ 0 \ 0 \ 0\] |
\[0^+\] | BSM spin-0 CP-even | \[0 \ 1 \ 0 \ 0 \ 0\] |
\[0^-\] | BSM spin-0 CP-odd | \[0 \ 0 \ 1 \ \pi/2\] |

CMS/ATLAS comparison (Michael Duehrssen)

No significant contributions from BSM terms are observed
Comparison of aHV in Snowmass

(arxiv: 1310.8361; 1309.4819)

Conversion: translate $f_{ai}$ at different collider, Ecm to $f_{ai}$ in decay

\[ A(X_{J=0} \to VV) = v^{-1} \left( a_1 \frac{m_V^2}{2} \epsilon_1 \epsilon_2^* + a_2 f_{\mu \nu}^{* (1)} f_{\mu \nu}^{* (2)} \right) \]

\[ f_{CP} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i} \]

<table>
<thead>
<tr>
<th>Collider</th>
<th>$pp$</th>
<th>$pp$</th>
<th>$e^+e^-$</th>
<th>$e^+e^-$</th>
<th>$e^+e^-$</th>
<th>$e^+e^-$</th>
<th>$\gamma\gamma$</th>
<th>$\mu^+\mu^-$</th>
<th>target (theory)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (GeV)</td>
<td>14,000</td>
<td>14,000</td>
<td>250</td>
<td>350</td>
<td>500</td>
<td>1,000</td>
<td>126</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{L}$ (fb$^{-1}$)</td>
<td>300</td>
<td>3,000</td>
<td>250</td>
<td>350</td>
<td>500</td>
<td>1,000</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>spin-2$^+_m$</td>
<td>$\sim 10\sigma$</td>
<td>$\gg 10\sigma$</td>
<td>$&gt; 10\sigma$</td>
<td>$&gt; 10\sigma$</td>
<td>$&gt; 10\sigma$</td>
<td>$&gt; 10\sigma$</td>
<td>$&gt; 10\sigma$</td>
<td>$&gt; 10\sigma$</td>
<td>$&gt; 5\sigma$</td>
</tr>
</tbody>
</table>

| $VVH^\dagger$ | 0.07 | 0.02 | $\checkmark$ | $\checkmark$ | $\checkmark$ | $\checkmark$ | $\checkmark$ | $\checkmark$ | $< 10^{-5}$ |
| $VVH^\ddagger$ | $4 \cdot 10^{-4}$ | $1.2 \cdot 10^{-4}$ | $7 \cdot 10^{-4}$ | $1.1 \cdot 10^{-4}$ | $4 \cdot 10^{-5}$ | $8 \cdot 10^{-6}$ | $-$ | $-$ | $< 10^{-5}$ |
| $VVH^\diamond$ | $7 \cdot 10^{-4}$ | $1.3 \cdot 10^{-4}$ | $\checkmark$ | $\checkmark$ | $\checkmark$ | $\checkmark$ | $-$ | $-$ | $< 10^{-5}$ |

$^\dagger$ estimated in $H \to ZZ^*$ decay mode

$^\ddagger$ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

Translate our new result $O(0.1)$ sensitivity on $b$-tilde at 250 GeV using 250 fb$^{-1}$

$\rightarrow f_{CP} \sim 1.0 \times 10^{-4}$, which is already improved by a factor of 7

$\rightarrow f_{CP} \sim 1.2 \times 10^{-5}$, $b$-tilde $\sim O(0.03)$, assuming 2 ab$^{-1}$ in H20 scenario

$\rightarrow f_{CP} \sim 1.0 \times 10^{-6}$, $b$-tilde $\sim O(0.01)$, + 4 ab$^{-1}$ @ 500 GeV in H20 scenario
Spin 0 is favoured for H(125), and CP-even fraction should be dominant; next experimental challenge is to probe a possible small CP-odd mixture.

d5 effective field theory approach is commonly adopted to study the tensor structure of HVV coupling.

At the ILC, taking advantage of the major Higgs production channels, HVV coupling can be precisely measured.

Based on full simulation analysis, anomalous couplings, a/b/b-tilde, can be probed up to $O(0.01)$ with $\Lambda=1\text{TeV}$ at ILC assuming H20 operating scenario; what kind of BSM models can be tested?

Next step: finish remaining HZZ channels and move to HWW channels; combine individual observables to get better sensitivity, and eventually use optimal matrix element method.
backup
Simulation Test

>. Procedure

>. What we want to do : Estimate the sensitivity to anomalous components with several parameters using $\chi^2$ test (MC simulation)

>. What we have to do : Estimate the detector acceptance for each sensitive parameter “$\theta^*$ and $\Phi$” with bias as less as possible (Full simulation)

\[
\chi^2 = \sum_{bin=1}^{\text{Nbins}} \left( \frac{y_{SM-MC}^{bin} - f_{\text{Theory model}}(x_{bin}; a, b, \tilde{b})}{\sigma_{SM-MC}^{bin}} \right)^2
\]

multiply by the effect of detector acceptance

Error of observed signals

>. For less bias : Any angle cut (also related to angles) for Bkgs suppression should not be used.

>. For less error : Values of each cut variables for Bkgs suppression are set to take the maximum significance.
Difference of the Cross Section

$> 250 \text{GeV}$, $Z \rightarrow e\mu \mu \gamma$ (recoil analysis)

$b$ affect $\sigma$ strongly

$x$ axis: $a$

$x$ axis: $b$
Difference of the Angle Distributions (calculation is based on Lab frame)

>. 250GeV, Zh \rightarrow eeh/\mu\mu h (recoil analysis)

>. Parameter “b” is changed

>. Parameter “b” is changed

>. Parameter “bt” is changed

>. 250GeV, Zh \rightarrow qqbb (hadronic process)

>. 500GeV, eeh \rightarrow eebb (ZZ-fusion)
TABLE II: Description of processes used for HVV tensor structure measurements with the corresponding cross sections ratios, where $\sigma_1$, $\sigma_2$, or $\sigma_4$ corresponds to $g_1 = 1$, $g_2 = 1$, or $g_4 = 1$, respectively, and $\sigma_+ = \sigma_1 (g_+ = g_1)$ for all processes except couplings to massless vector bosons ($Z\gamma, \gamma\gamma, gg$) where $\sigma_+ = \sigma_2 (g_+ = g_2)$. MC simulation parameters used in studies are shown, where the generated coupling $g_4$ values correspond to certain $f_{a2}$ and $f_{a3}$ values. The expected precision on the $f_{a2}$ and $f_{a3}$ parameters are quoted for 300 fb$^{-1}$ (first row) and 3000 fb$^{-1}$ (second row) scenarios on LHC and four energy scenarios on an $e^+e^-$ machine, as discussed in Table I. This expected precision corresponds to about 3σ deviation from zero of the MC simulated values. The $f_{a2}^{\text{dec}}$ and $f_{a3}^{\text{dec}}$ values correspond to cross sections defined in decay.

<table>
<thead>
<tr>
<th>process description</th>
<th>MC simulation parameters</th>
<th>expected precision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$g_2/g_1</td>
<td>g_4/g_+</td>
</tr>
<tr>
<td>any any $H \rightarrow ZZ^*$ 0.362 0.153</td>
<td>0 1.20 0 0.18</td>
<td>– 0.06</td>
</tr>
<tr>
<td>any any $H \rightarrow WW^*$ 0.776 0.322</td>
<td>0 1.76 0 0.50</td>
<td>– 0.04</td>
</tr>
<tr>
<td>any any $H \rightarrow \gamma\gamma, gg$ N/A 1.0</td>
<td>N/A 1.0 0 0.50</td>
<td>– 0.05</td>
</tr>
<tr>
<td>any any $H \rightarrow Z\gamma$ N/A 1.0</td>
<td>N/A 1.0 0 0.50</td>
<td>– 0.05</td>
</tr>
<tr>
<td>pp 14 TeV $gg \rightarrow H$ N/A 1.0</td>
<td>N/A 1.0 0 0 0.50 0.50</td>
<td>– 0.50</td>
</tr>
<tr>
<td>pp 14 TeV $V^<em>V^</em> \rightarrow H$ 14.0 11.3</td>
<td>0 0.299 0 0 0.50 0.013</td>
<td>– 0.190</td>
</tr>
<tr>
<td>pp 14 TeV $V^<em>V^</em> \rightarrow H$ 14.0 11.3</td>
<td>0 0.109 0 0 0.50 0.013</td>
<td>– 0.190</td>
</tr>
<tr>
<td>pp 14 TeV $V^* \rightarrow VH$ 76.1 46.8</td>
<td>0 0.145 0 0 0.50 0.0032</td>
<td>– 0.32</td>
</tr>
<tr>
<td>pp 14 TeV $V^* \rightarrow VH$ 76.1 46.8</td>
<td>0 0.095 0 0 0.50 0.0032</td>
<td>– 0.32</td>
</tr>
<tr>
<td>$e^+e^-$ 250 GeV $Z^* \rightarrow ZH$ 34.1 8.07</td>
<td>0 0.117 0 0 0.10 1.2 × 10$^{-3}$</td>
<td>2 × 10$^{-3}$</td>
</tr>
<tr>
<td>$e^+e^-$ 350 GeV $Z^* \rightarrow ZH$ 84.2 50.6</td>
<td>0 0.0469 0 0 0.10 1.2 × 10$^{-3}$</td>
<td>2 × 10$^{-3}$</td>
</tr>
<tr>
<td>$e^+e^-$ 500 GeV $Z^* \rightarrow ZH$ 200.8 161.1</td>
<td>0 0.0263 0 0 0.10 1.2 × 10$^{-3}$</td>
<td>2 × 10$^{-3}$</td>
</tr>
<tr>
<td>$e^+e^-$ 1 TeV $Z^* \rightarrow ZH$ 916.5 870.8</td>
<td>0 0.0113 0 0 0.10 1.2 × 10$^{-3}$</td>
<td>2 × 10$^{-3}$</td>
</tr>
</tbody>
</table>