Measuring the Higgs boson self-coupling in $e^+e^- \to \nu\bar{\nu}HH$

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Ulrich Baur
State University of New York at Buffalo

1 – Introduction

- If it exists, the Standard Model (SM) Higgs boson will be discovered at the LHC
- The LHC promises complete coverage of Higgs decay scenarios
- Quantitatively at the LHC: measure
  - ☞ M_H to 0.1%
  - ☞ Γ_H to $\leq 10\%$
  - ☞ $\sigma\times$ Br to 10%

- what remains to be done: determine Higgs potential

$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \tilde{\lambda} \eta_H^4 ,$$

η_H: physical Higgs field, $v = (\sqrt{2} G_F)^{-1/2}$,
SM: $\tilde{\lambda} = \lambda = \lambda_{SM} = m_H^2/(2v^2)$
☞ λ and $\tilde{\lambda}$ are *per se* free parameters

- to measure λ ($\tilde{\lambda}$), experiments must observe HH (HHH) production
  - ☞ HHH cross sections too small to probe $\tilde{\lambda}$ at any machine considered so far
  - ☞ concentrate on λ in the following
- radiative corrections to HHH coupling:
  - ☞ SM: $-4\% - -11\%$ for 120 GeV $< M_H <$ 200 GeV (Yuan *et al.*)
  - ☞ can be up to 100% in general 2HDM
  - ☞ MSSM: up to 8% for light stop squarks (Hollik *et al.*)

- The measurement of the Higgs self-coupling, λ, is one of the benchmarks which is used to determine the performance of the ILC (and also CLIC)
- Can measure λ in ZHH and $\nu\bar{\nu}HH$ production: $\sigma(ZHH) \gg \sigma(\nu\bar{\nu}HH$ at $\sqrt{s} = 500$ GeV, $\sigma(ZHH) < \sigma(\nu\bar{\nu}HH)$ for $\sqrt{s} \geq 1$ TeV
- Results for ZHH production are presented in the jets working group
- Here, I present calculations using `MadEvent`
  - ☞ for $m_H = 120$ GeV and $m_H = 140$ GeV
  - ☞ $\sqrt{s} = 1$ TeV and 3 TeV
  - ☞ for $e^+e^- \rightarrow \nu\bar{\nu}HH \rightarrow \nu\bar{\nu}4b$ and $e^+e^- \rightarrow \nu\bar{\nu}HH \rightarrow \nu\bar{\nu}b\bar{b}WW^*$
  - ☞ with the backgrounds, including the non-resonant diagrams, calculated using exact matrix elements

2 – $\nu\bar{\nu}HH$ Production

- Consider $\nu\bar{\nu}HH \to \nu\bar{\nu}4b$ first and require that the four b's form two pairs which are compatible with a Higgs boson

$$100\ (120)\ \mathrm{GeV} < m(b\bar{b}) < 126\ (150)\ \mathrm{GeV}$$

for $m_H = 120\ (140)$ GeV.

- require ≥ 3 tagged b-quarks
- include $ZHH \to \nu_l\bar{\nu}_l 4b$ with $l = \mu,\ \tau$
- include minimal detector effects by Gaussian smearing (ILC detector expectations):

$$\frac{\Delta E}{E}(\mathrm{had}) = \frac{0.405}{\sqrt{E}}, \qquad \frac{\Delta E}{E}(\mathrm{lep}) = \frac{0.102}{\sqrt{E}},$$

- cuts:

$$E_{j(b)} > 15\ \mathrm{GeV}, \qquad 5^\circ < \theta(j(b), \mathrm{beam}) < 175^\circ$$

$$\theta(j(b), j'(b')) > 10^\circ \qquad \theta(j, b) > 10^\circ$$

$$\not{p}_T > 15\ \mathrm{GeV}$$

- assume a b-tagging efficiency of $\epsilon_b = 0.9$, and charm and light quark/gluon jet misidentification probabilities of $P_{c\to b} = 10\%$, $P_{j\to b} = 0.5\%$
- take energy loss of b-quarks into account via a parametrized function
- m_{HH} distribution is sensitive to λ

- main backgrounds:
  - ☞ non-resonant diagrams (≈ 2300 $\mathcal{O}(\alpha^6)$, and $\mathcal{O}(\alpha_s^2\alpha^4)$ diagrams)
  - ☞ $\nu\bar{\nu}b\bar{b}c\bar{c}$ ($\nu\bar{\nu}b\bar{b}jj$) production with two mis-identified charm (light quark/gluon) jets (900 [2100] diagrams)
- other backgrounds: $4b$ and $b\bar{b}jj$ production with the missing transverse momentum originating from jet mismeasurements and the energy loss of b-quarks
  require $\not{p}_T > 15$ GeV
- assume b-jet charge can be measured with 100% efficiency (expectation for ILC: $\approx 90\%$)

- results: solid black: SM signal,

  magenta: SM resonant and non-resonant diagrams

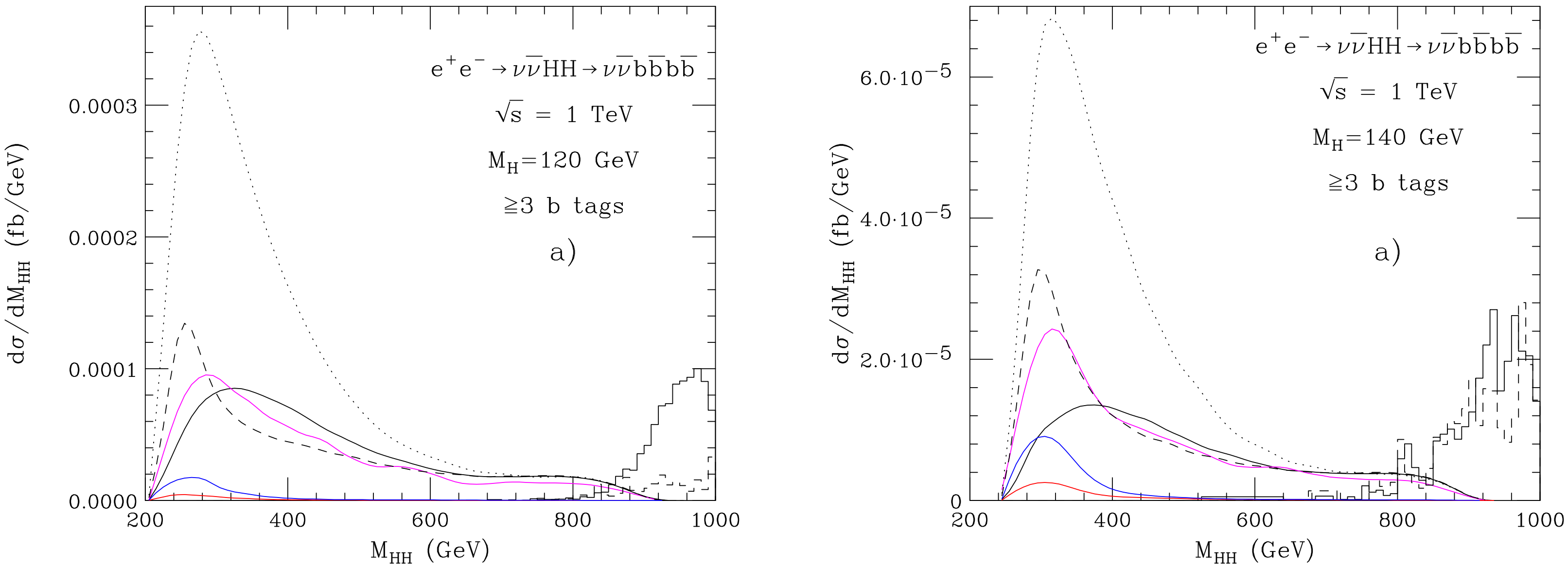
  dash (dots): $\Delta\lambda_{HHH} = (\lambda/\lambda_{SM} - 1) = +1\ (-1)$

  blue: $\nu\bar{\nu}b\bar{b}c\bar{c}$ background

  red: $\nu\bar{\nu}b\bar{b}jj$ background

  solid (dashed) histogram: $4b$ ($b\bar{b}jj$) background

$\sqrt{s} = 1$ TeV



- The $\nu\bar{\nu}b\bar{b}c\bar{c}$ and $\nu\bar{\nu}b\bar{b}jj$ backgrounds are small
- The $4b$ and $b\bar{b}jj$ backgrounds pose no threat to the measurement of λ
- non-resonant contributions can easily be mistaken for a positive anomalous Higgs self-coupling

- For $m_H = 140$ GeV: $B(H \to WW^* \to 4f) \approx 50\%$, $B(WW^* \to 4j) \approx 46\%$
  → one can significantly increase the signal cross section by taking into account the $\nu\bar{\nu}b\bar{b}4j$ final state
- Also take into account $H \to ZZ^* \to 4j$ ($B(H \to ZZ^*) \approx 10\%$ for $m_H = 140$ GeV)
- require

$$|m_H - m(4j)| < 20 \text{ GeV}$$

  and one un-tagged jet pair with

$$|m_W - m(jj)| < 8 \text{ GeV}$$

- main backgrounds: non-resonant $\nu\bar{\nu}b\bar{b}4j$, $\nu\bar{\nu}4c$ and $\nu\bar{\nu}b\bar{b}c\bar{c}jj$ production

- problem: these are $2 \to 8$ processes with $> 10^5$ Feynman diagrams
  - ☞ too many diagrams for `MadEvent` (takes more than 200h CPU time (3ghz Xeon) to *generate* diagrams
  - ☞ `WHIZARD` could not compile code (compilation terminated after > 48h)
  - ☞ `HELAC-PHEGAS` bombed with a glibc error
  - ☞ `SHERPA` can't handle it in its current version (V1.1), but, according to Frank Krauss will be able to so in V1.2
  - ☞ `CARLOMAT` should be able to handle it, but is not publically available (author never replied to my email request)

- A substantial portion of the contribution of the non-resonant $\nu\bar{\nu}b\bar{b}4j$ diagrams should come from the off-shell $W^* \to jj$ pair.
  ➞ most of the non-resonant effects can be captured by calculating

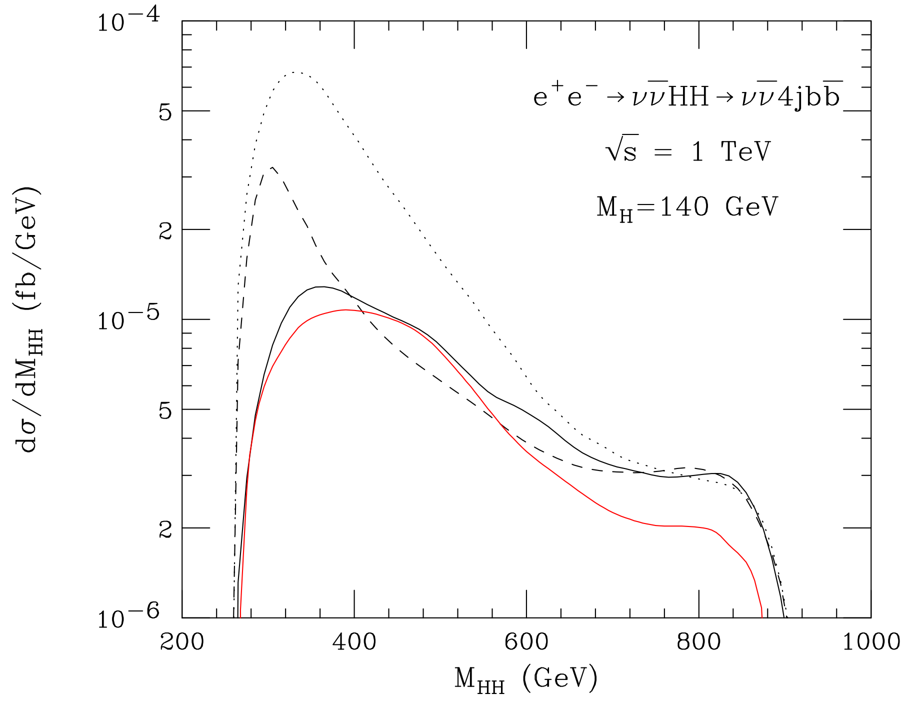
$$e^+e^- \to \nu\bar{\nu}Wjjb\bar{b} \qquad \text{with} \qquad W \to jj$$

or

$$e^+e^- \to \nu\bar{\nu}H4j \qquad \text{with} \qquad H \to b\bar{b}$$

- Calculate $e^+e^- \to \nu\bar{\nu}Wjjb\bar{b}$, $W \to jj$ here (about 7000 Feynman diagrams)
- Expect $\nu\bar{\nu}b\bar{b}c\bar{c}jj$ and $\nu\bar{\nu}4c$ backgrounds to be small (as in $\nu\bar{\nu}b\bar{b}c\bar{c}$ case)
- The $b\bar{b}4j$ background (with $\not{p}_T$ from jet mismeasurement and energy loss of the b-quarks) is very small

$\sqrt{s} = 1$ TeV



- Non-resonant diagrams substantially reduce the cross section at large values of m_{HH}
- The non-resonant diagrams not included in $\nu\bar{\nu}Wjjb\bar{b}$ jet production may well affect the cross section to a similar degree

3 – Sensitivity limits

- Perform a log-likelihood test
- Assume a 10% systematical uncertainty on cross section (probably optimistic)
- assume $\int \mathcal{L} dt = 1~\mathrm{ab}^{-1}$ (corresponds to 5 years of running at ILC design luminosity)

- 68% CL limits:
  - ☞ $\nu\bar{\nu}HH \to \nu\bar{\nu}4b$ and $\nu\bar{\nu}HH \to \nu\bar{\nu}b\bar{b}4j$:
    $\sqrt{s} = 1$ TeV, $m_H = 120$ GeV: $-0.21 < \Delta\lambda_{HHH} < 0.30$
    $\sqrt{s} = 1$ TeV, $m_H = 140$ GeV: $-0.38 < \Delta\lambda_{HHH} < 0.94$
    $\sqrt{s} = 3$ TeV, $m_H = 120$ GeV: $-0.12 < \Delta\lambda_{HHH} < 0.14$
    $\sqrt{s} = 3$ TeV, $m_H = 140$ GeV: $-0.19 < \Delta\lambda_{HHH} < 0.15$
  - ☞ At CLIC ($\sqrt{s} = 3$ TeV), limits can be improved by up to a factor of 1.5 if 3 ab^{-1} (5 years of running at design luminosity) can be achieved
  - ☞ for comparison: $ZHH \to jj4b$:
    $\sqrt{s} = 1$ TeV, $m_H = 120$ GeV: $-0.45 < \Delta\lambda_{HHH} < 0.53$
    $\sqrt{s} = 1$ TeV, $m_H = 140$ GeV: $-1.0 < \Delta\lambda_{HHH} < 1.1$
  - ☞ limits from $\nu\bar{\nu}HH$ production are significantly more stringent

4 – Conclusions

- Non-resonant diagrams can significantly affect the total and differential cross sections in $e^+e^- \to \nu\bar{\nu}HH$
- Non-resonant diagrams in $\nu\bar{\nu}4b$ production can mimic the effects of non-standard Higgs self-couplings
- At a 1 TeV machine, with 1 ab^{-1}, $\nu\bar{\nu}HH$ production makes it possible to probe the Higgs self-coupling with a precision of $20 - 30\%$ for $m_H = 120$ GeV, and $40 - 90\%$ for $m_H = 140$ GeV
- For CLIC ($\sqrt{s} = 3$ TeV, 3 ab^{-1}) can measure the Higgs self-coupling with a precision of $10 - 15\%$.