How well can we measure the Higgs self-coupling at the ILC?

UB in preparation

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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
- Past investigations have focused on a very light Higgs boson ($m_H = 120$ GeV) with $\sqrt{s} = 500$ GeV
- and the background was estimated using shower Monte Carlos
- I present calculations using `MadEvent`
  - ☞ for $m_H = 120$ GeV and $m_H = 140$ GeV
  - ☞ $\sqrt{s} = 500$ GeV and 1 TeV
  - ☞ for $e^+e^- \to ZHH \to jj4b$ and $e^+e^- \to \nu\bar{\nu}HH \to \nu\bar{\nu}4b$
  - ☞ with the backgrounds, including the non-resonant diagrams, calculated using exact matrix elements

2 – ZHH Production

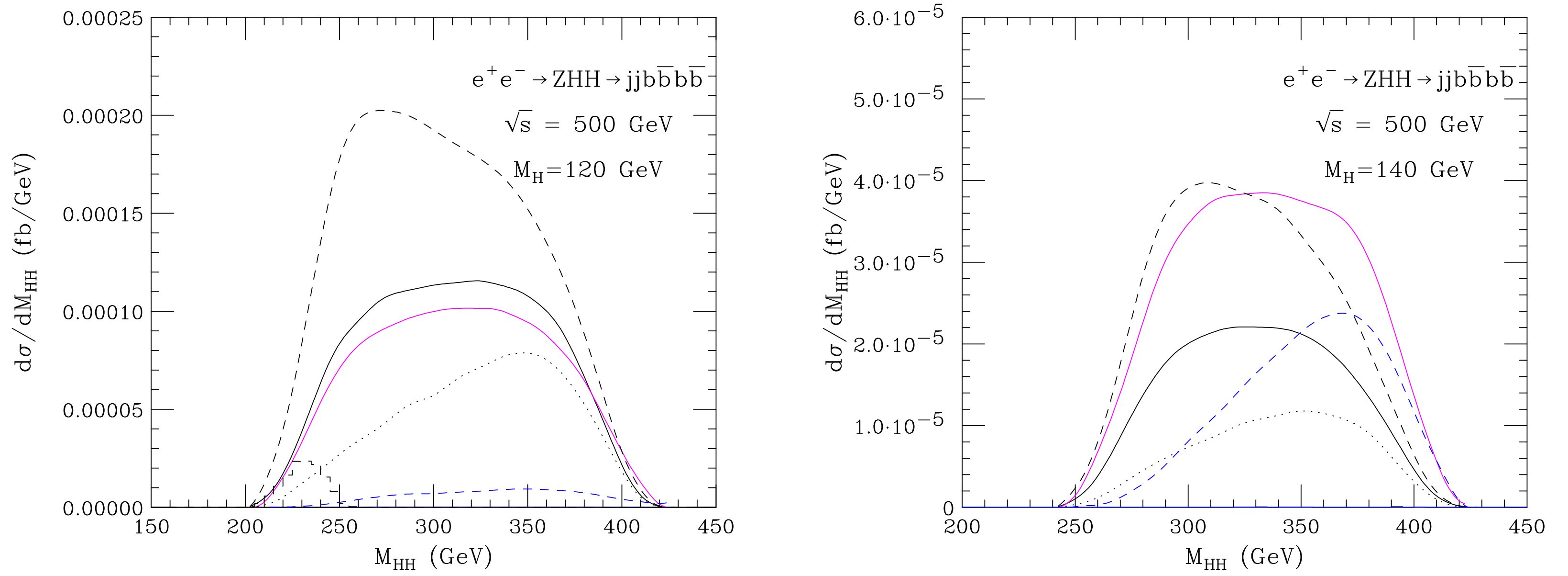
- I focus on $ZHH \to jj4b$ and require that the jj is compatible with a Z boson, and the $4b$'s form two pairs which are compatible in invariant mass with a Higgs boson
- require 4 tagged b-quarks
- include minimal detector effects by Gaussian smearing (ILC detector expectations):

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

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

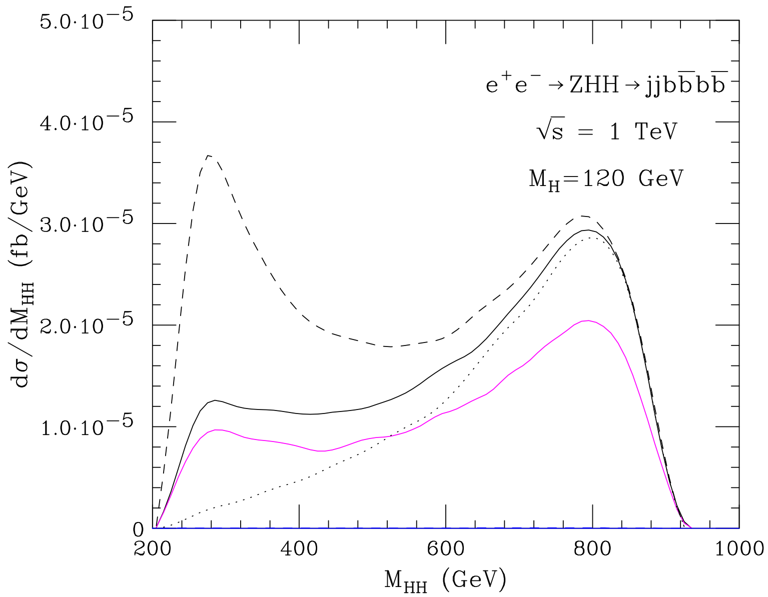
- main backgrounds:
  - ☞ non-resonant diagrams (≈ 8500 $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s^4\alpha^2)$ and $\mathcal{O}(\alpha_s^2\alpha^4)$ diagrams)
  - ☞ $jjb\bar{b}c\bar{c}$ ($b\bar{b}4j$) production with two mis-identified charm (light quark/gluon) jets (7300 [15600] diagrams)
  - ☞ 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)
  dashed blue: $jjb\bar{b}c\bar{c}$ background

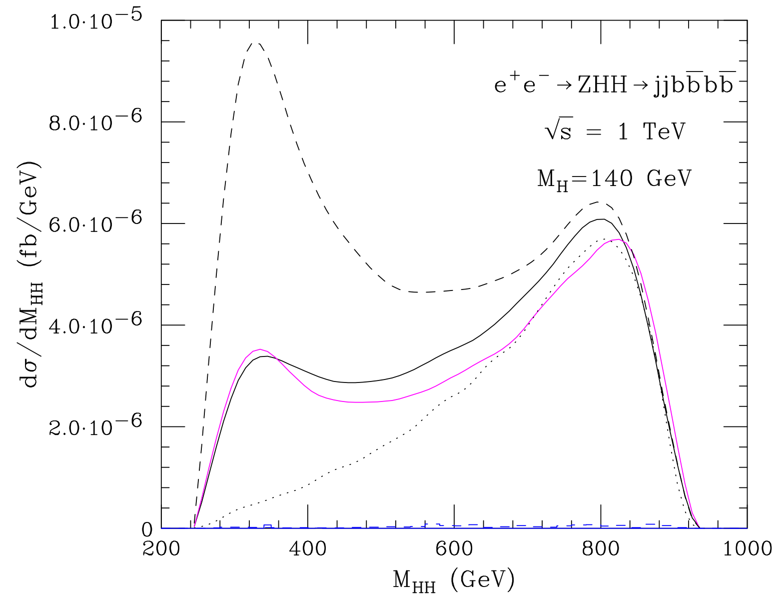
$\sqrt{s} = 500$ GeV



- The $jjb\bar{b}c\bar{c}$ and non-resonant backgrounds for $m_H = 140$ GeV are much larger than for $m_H = 120$ GeV
- The cross section for $m_H = 140$ GeV is tiny ($Br(H \to b\bar{b}) \approx 30\%$)
- black dashed histogram: combinatorial background from pairing the wrong b and $\bar{b}$

$\sqrt{s} = 1$ TeV





- The background for $m_H = 140$ GeV is significantly smaller for $\sqrt{s} = 1$ TeV
- The $b\bar{b}4j$ background is negligible at both $\sqrt{s} = 500$ GeV and 1 TeV

- The $e^+e^- \to ZHH \to jj4b$ rate is very small
- The signal rate can be increased by requiring ≥ 3 tagged b-quarks instead of 4 b-tags
  gain: factor ≈ 1.4
- Unfortunately, the gain is more than compensated by the increase in the $b\bar{b}4j$ and $jjb\bar{b}c\bar{c}$ background.
- In addition, $b\bar{b}cjjj$ production contributes to the background
- Note: the background cross section is $\propto \alpha_s^4$ and thus carries a substantial renormalization scale uncertainty
- can marginally improve signal cross section for $m_H = 140$ GeV by including other final states such as $HH \to WW^* \to 4j$ ($Br \sim 50\%$ for $m_H = 140$ GeV)

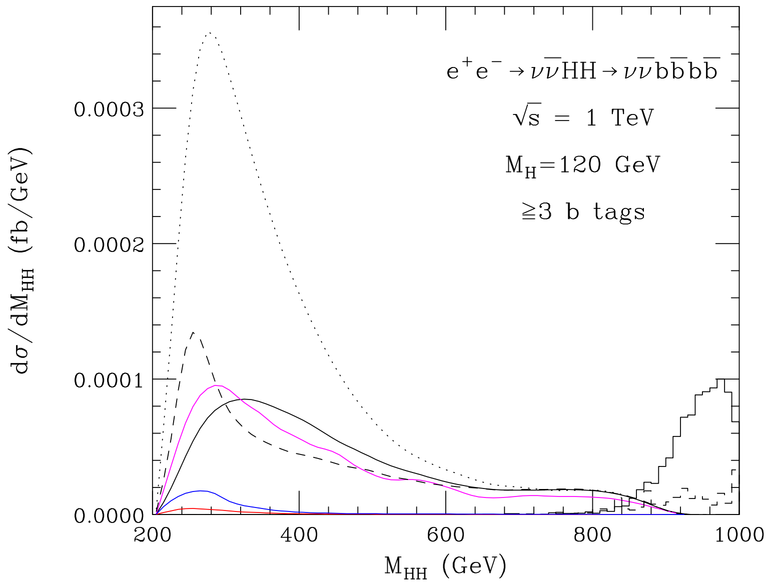
3 – $\nu\bar{\nu}HH$ Production

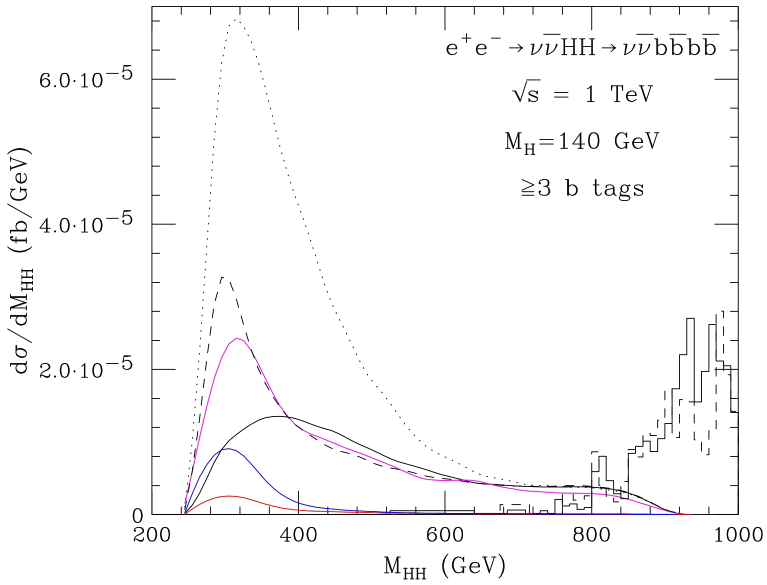
- For $\sqrt{s} = 500$ GeV: $\sigma(\nu\bar{\nu}HH) \ll \sigma(ZHH)$
- For $\sqrt{s} = 1$ TeV: $\sigma(\nu\bar{\nu}HH) > \sigma(ZHH)$
- Focus on $\nu\bar{\nu}HH \to \nu\bar{\nu}4b$ with ≥ 3 tagged b-quarks
- main backgrounds: (2300) non-resonant diagrams, $\nu\bar{\nu}b\bar{b}c\bar{c}$ production (900 diagrams) and $\nu\bar{\nu}b\bar{b}jj$ production (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

- 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

4 – Sensitivity limits

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

- 68% CL limits:
  - ☞ $ZHH \to jj4b$:

    $\sqrt{s} = 500$ GeV, $m_H = 120$ GeV: $-0.41 < \Delta\lambda_{HHH} < 0.44$

    $\sqrt{s} = 500$ GeV, $m_H = 140$ GeV: $-6.8 < \Delta\lambda_{HHH} < 2.1$

    $\sqrt{s} = 1$ TeV, $m_H = 120$ GeV: $-0.45 < \Delta\lambda_{HHH} < 0.53$

    $\sqrt{s} = 1$ TeV, $m_H = 140$ GeV: $-1.0 < \Delta\lambda_{HHH} < 1.1$
  - ☞ $\nu\bar{\nu}HH \to \nu\bar{\nu}4b$:

    $\sqrt{s} = 1$ TeV, $m_H = 120$ GeV: $-0.21 < \Delta\lambda_{HHH} < 0.30$

    $\sqrt{s} = 1$ TeV, $m_H = 140$ GeV: $-0.38 < \Delta\lambda_{HHH} < 0.94$

5 – Conclusions

- Non-resonant diagrams can significantly affect the total and differential cross sections for $e^+e^- \to jj4b$ and $e^+e^- \to \nu\bar{\nu}4b$
- Non-resonant diagrams in $\nu\bar{\nu}4b$ production can mimic the effects of non-standard Higgs self-couplings
- At a 500 GeV e^+e^- machine, one can measure the Higgs boson self-coupling only if the Higgs mass is close to the current lower experimental limit
- 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