How well can we measure the Higgs self-coupling at the ILC in the $jj4b$ final state?

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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 gauge 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
- Here, I present calculations using `MadEvent`
  - ☞ for $m_H = 120$ GeV and $m_H = 140$ GeV
  - ☞ $\sqrt{s} = 500$ GeV and 1 TeV
  - ☞ for $e^+e^- \to ZHH \to jj4b$
  - ☞ with the backgrounds, including the non-resonant diagrams, calculated using exact matrix elements
  - ☞ Results for $e^+e^- \to \nu\bar{\nu}HH$ are presented in the Missing Energy Working Group on Friday

2 – ZHH Production

- I focus on $ZHH \to jj4b$ and require that the jj system is compatible with a Z boson, and the $4b$'s form two pairs which are compatible in invariant mass with a Higgs boson:

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

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

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

- require 4 tagged b-quarks
- include minimal detector effects by Gaussian smearing (ILC detector expectations):

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

- cuts:

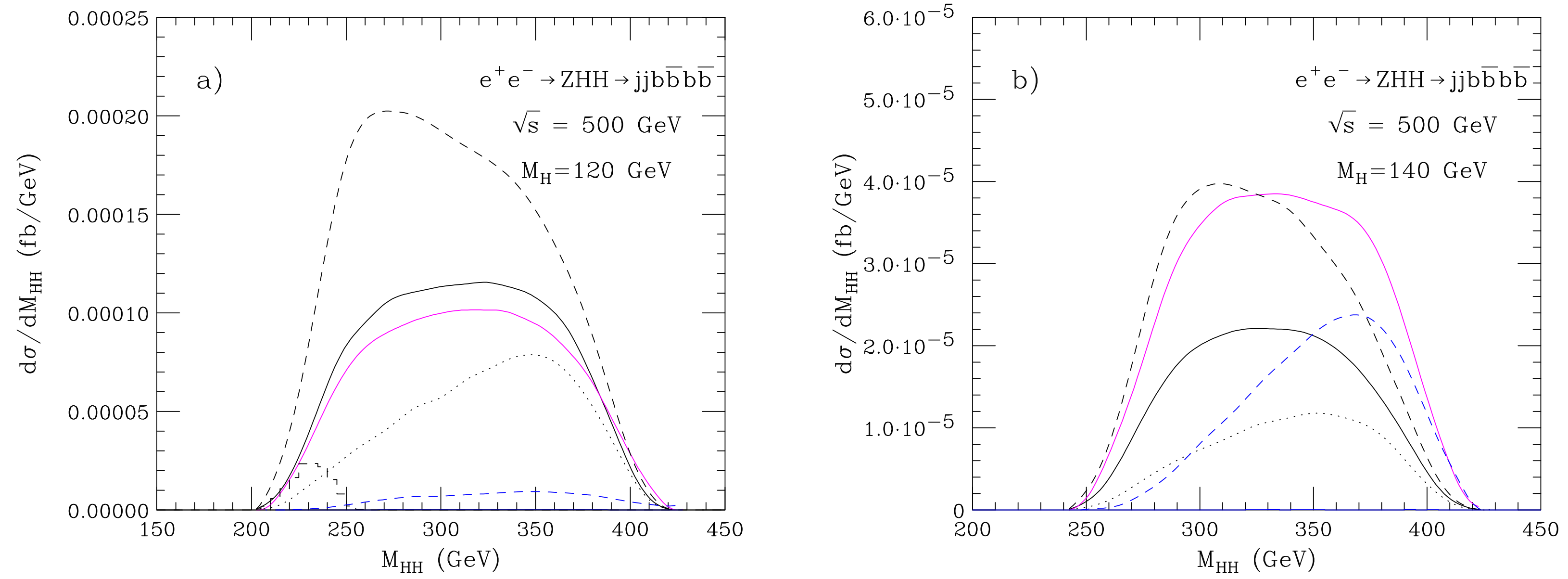
$$E_{j(b)} > 15 \text{ GeV}, \qquad 5^\circ < \theta(j(b), \text{beam}) < 175^\circ$$

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

- assume a b-tagging efficiency of $\epsilon_b = 0.9$, and charm and light quark/gluon jet misidentification probabilities of $P_{c\to b} = 10\%$, $P_{j\to b} = 0.5\%$
- also investigate $\epsilon_b = 0.8$ and $P_{c\to b} = 2\%$, $P_{j\to b} = 0.1\%$
- take energy loss of b-quarks into account via a parametrized function
- m_{HH} distribution is sensitive to λ

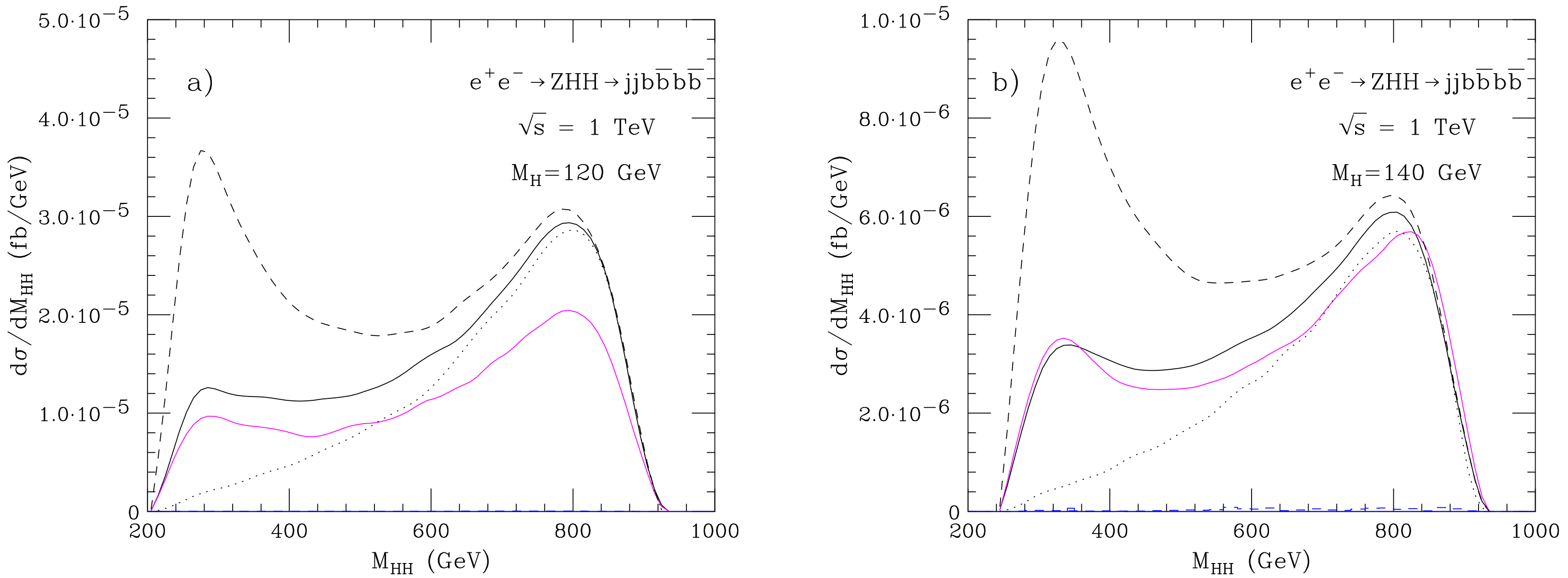
- main backgrounds:
  - ☞ non-resonant diagrams ($\approx 8500\ \mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s^4\alpha^2)$ and $\mathcal{O}(\alpha_s^2\alpha^4)$ diagrams)
  - ☞ $jjb\bar{b}c\bar{c}$ ($b\bar{b}4j$) production with two mis-identified charm (light quark/gluon) jets (7300 [15600] diagrams)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

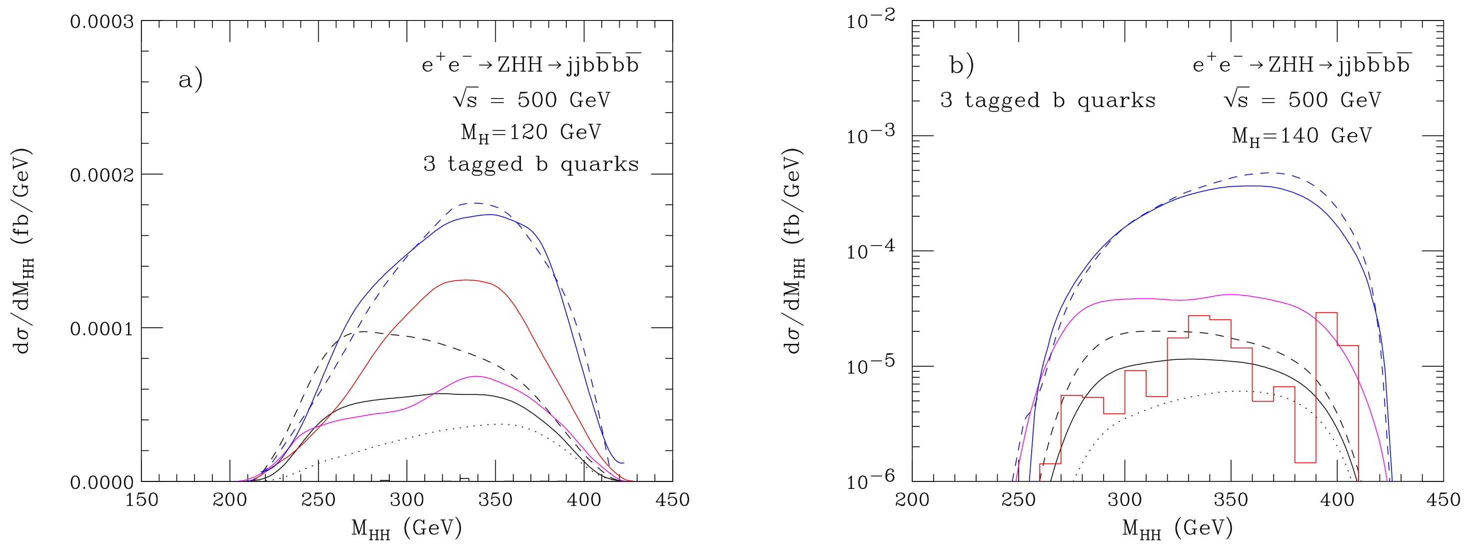
$\sqrt{s} = 1$ TeV



- 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 $\geq$ 3 tagged b-quarks instead of 4 b-tags
  gain: factor ≈ 1.4

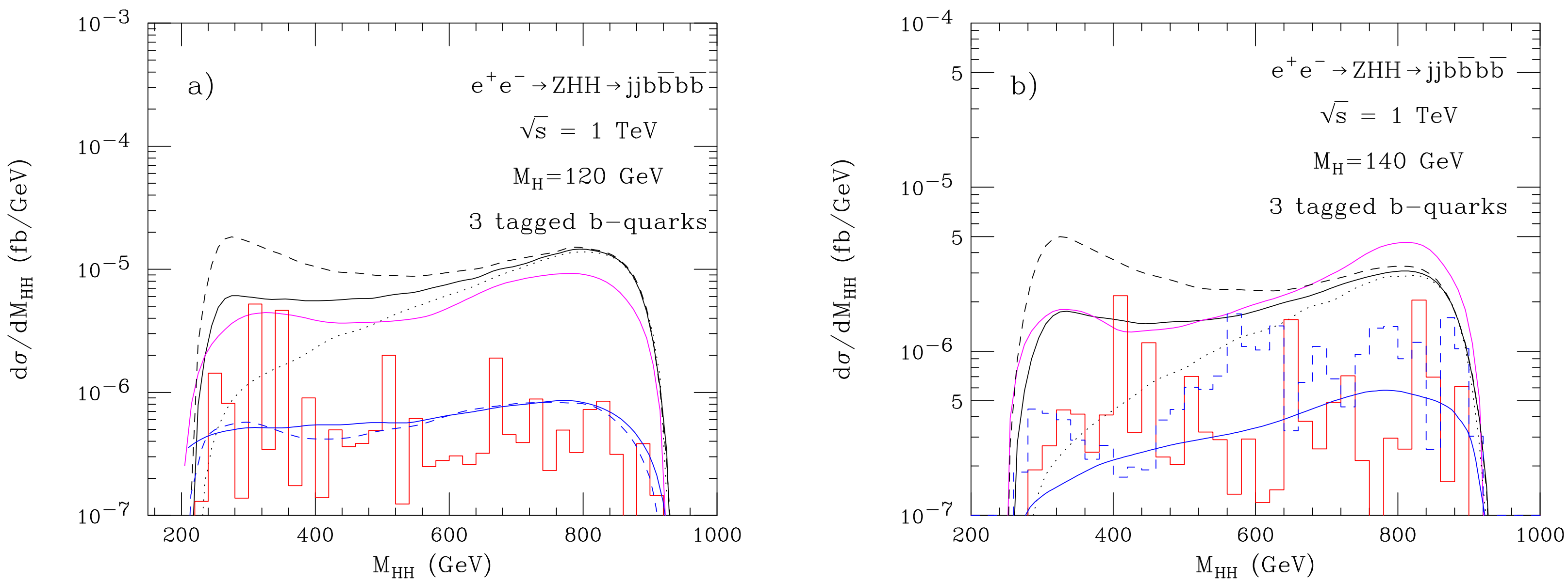
$$\sqrt{s} = 500\ \text{GeV}$$



- require a jj pair consistent with Z, a $b\bar{b}$ pair, and a bj pair consistent with a Higgs

- lines:
  solid (dashed) blue: $b\bar{b}cjjj$ ($b\bar{b}c\bar{c}jj$)
  red: $b\bar{b}4j$
  all others have the same meaning as before
- Unfortunately, at $\sqrt{s} = 500$ GeV, 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
  → either need NLO QCD corrections calculated for backgrounds (good luck with that!) or have to measure backgrounds

$\sqrt{s} = 1$ TeV



- background much more favorable at $\sqrt{s} = 1$ TeV; however, it is still non-negligible

3 – Sensitivity limits

- Perform a log-likelihood test
- Assume a 10% systematical uncertainty on cross section (probably optimistic)
- assume $\int \mathcal{L} dt = 1\ \text{ab}^{-1}$ (corresponds to 5 years of running at ILC design luminosity)
- no (marignal) gain from including final states with only 3 tagged b-quarks for $\sqrt{s} = 500$ GeV (1 TeV)
  → considering a working point with a somewhat reduced b-tagging efficiency, but a much reduced light/charm misidentification probabilty may help

- 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: $-1.0 < \Delta\lambda_{HHH} < 1.1$
  - ☞ for comparison: $\nu\bar{\nu}HH \to \nu\bar{\nu}4b$:
    $\sqrt{s} = 1$ TeV, $m_H = 120$ GeV: $-0.21 < \Delta\lambda_{HHH} < 0.30$
    $\sqrt{s} = 1$ TeV, $m_H = 140$ GeV: $-0.38 < \Delta\lambda_{HHH} < 0.94$
- for $m_H = 140$ GeV, $\sqrt{s} = 1$ TeV and $\nu\bar{\nu}HH$ production, the $HH \to b\bar{b}WW^*$ final states are included in the analysis

4 – Conclusions

- Non-resonant diagrams can significantly affect the total and differential cross sections for $e^+e^- \to jj4b$
- 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 gives more precise limits than $e^+e^- \to ZHH$.