Update of the Higgs Self-coupling Projections from Di-Higgs Production in Detailed Simulation of the ILD Detector Concept

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This contribution summarizes the update of the projections for the determination of the tri-linear Higgs self-coupling from di-Higgs production at future $e^+ e^-$ colliders. In particular, we will present an update of the analysis of Z H H production at $500\,\mathrm{GeV}$ in detailed simulations of the ILD detector concept, covering the $HH \to b\bar{b}b\bar{b}$ and $Z \to q\bar{q}/e^+e^-/\mu^+\mu^-/\nu\bar{\nu}$ channels. Based on the experience of previous analyses, we will extrapolate these to contain some of the remaining decay modes, e.g. $HH \to b\bar{b}WW^*$ or $Z \to \tau^+\tau^-$, as well as the contribution from the W W fusion production mode. We will study the dependency of the results on the centre-of-mass energy (in particular discussing $550\,\mathrm{GeV}$, $600\,\mathrm{GeV}$ and $1\,\mathrm{TeV}$) as well as on the value of the tri-linear coupling realised in nature. **[Note: the X, Y, Z "values" in the text will be replaced by actual numbers by January 24, 2025.]**

1 Introduction

Double Higgs production at $e^+ e^-$ colliders with centre-of-mass energies $\sqrt{s} \geq 450\,\mathrm{GeV}$ comprises both di-Higgs production from W W fusion, $\nu \bar{\nu}$ H H, dominant at centre-of-mass energies above $1\,\mathrm{TeV}$, as well as double Higgs-strahlung, Z H H, dominant at lower centre-of-mass energies. Both processes have been studied about 10 years ago in detailed, Geant4-based simulation of the ILD detector concept, considering the H H $\rightarrow$ 4b [1, 2] and H H $\rightarrow$ b $\bar{b}$ W W * [3] final states. For the SM value of the tri-linear Higgs self-coupling λ, the combination of the two channels yielded precisions of $27\,\%$ at $500\,\mathrm{GeV}$ and $10\,\%$ when combining both centre-of-mass energies. A few years later, CLICdp studied the prospects at $\sqrt{s}$ =1.4 and $3\,\mathrm{TeV}$ [4], also in detailed, Geant4-based simulation, reaching precisions down to $8\,\%$, again assuming the SM value of λ. It should be noted that in particular for the Z H H process, i.e. the measurements at around $500\,\mathrm{GeV}$, it has been shown explicitly that all other parameters entering the interpretation of the Z H H cross-section will be determined sufficiently precise at a Higgs factory so that their impact on the extraction of λ is negligible [5].

2 Update of the ILD Di-Higgs Analysis

The analysis of Z H H production at $500\,\mathrm{GeV}$ has been updated in detailed simulations of the ILD detector concept, covering the H H $\rightarrow$ b $\bar{b}$ b $\bar{b}$ and Z $\rightarrow$ q $\bar{q}$/ e^+ e^-/ μ^+ μ^-/ ν $\bar{\nu}$ channels. The complete set of SM backgrounds as well as overlay from pair-background and photon-induced low-p_t hadron production has been included, based on the MC production for the ILD Interim Design Report [6]. All numbers below have been scaled to the standard ILC running scenario [7], i.e. $4\,\mathrm{ab}^{-1}$ with $P(e^-, e^+) = (\mp 80\%, \pm 30\%)$.

The analysis concept follows Ref. [1], capitalizing however on significant improvements in central high-level reconstruction tools like flavour tagging, kinematic fitting and overlay removal [8] as well as on the usage of machine-learning algorithms in the event selection. From this re-analysis of the channels studied in [1], the obtained precision on the Z H H production cross-section improves from the $21.1\,\%$ obtained in [1] to now X % for the SM case.

In combination with the H H $\rightarrow$ b $\bar{b}$ W W * channel, the precision on the cross-section improves from from the $16.8\,\%$ obtained in [1] to now X % , again for the SM case, while the corresponding precision on the self-coupling reduces from $26.6\,\%$ to Y %.

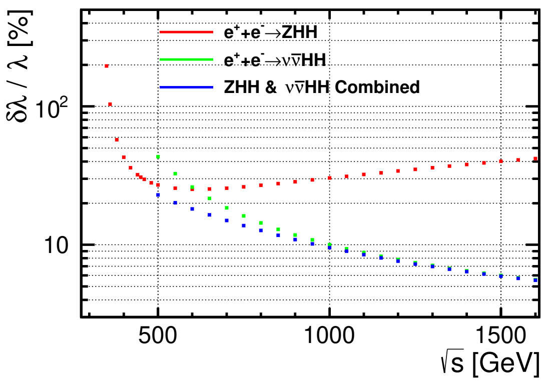
By including Z $\rightarrow \tau^+ \tau^-$, the expected precision on λ_{SM} improves further to Z %. The main limiting factor in the analysis is now the jet clustering. Assuming that future developments, e.g. based on machine-learning will improve the di-jet mass resolution by Z, we estimate that λ_{SM} could be determined with a precision of Z %. The analysis of the W W fusion production follows Refs. [2, 3]. It is similar to the Z H H case in the neutrino channel, however the requirement of the missing mass being consistent with the mass of the Z boson is inverted, ensuring the absence of overlap. Including the same H H decay modes as before, we obtain a precision on the W W fusion cross-section of X % with current tools and Y % when assuming improved jet clustering. In combination with the Z H H, we obtain finally X % precision on λ_{SM} with current tools and Y % when assuming improved jet clustering.

3 Extrapolation to other Centre-of-Mass Energies and to BSM values of λ

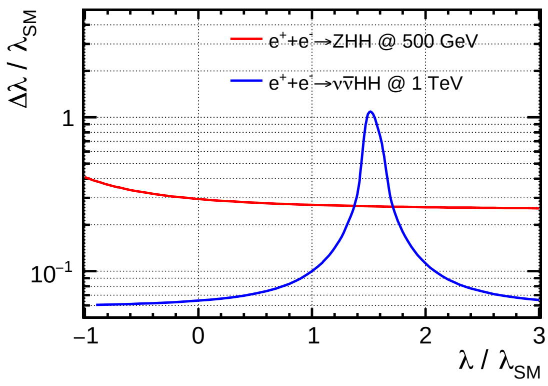
The results summarised in the previous section have been extrapolated to other centre-of-mass energies. In particular partial MC productions have been performed in full, Geant4-based simulation of ILD as well as using SGV [9] and centre-of-mass energies of $550\,\mathrm{GeV}$ and $600\,\mathrm{GeV}$, showing that beyond the expected scaling with cross-section, both the flavour tag as well as the kinematic reconstruction profit from the higher boost of the produced bosons.

Figure 1(a) shows the resulting evolution of the expected precision on λ with the centre-of-mass energy, for both production modes separately and for their combination. For instance at $\sqrt{s}$ =$550\,\mathrm{GeV}$, the envisioned energy for C^3 as well as for a Linear Collider Facility at CERN, the expected combined precision on λ_{SM} is X%, a substantial improvement over the $26.6\,\%$ of [1].

Enlarging the scope to the BSM case, it is important to note that the two production modes play very complementary roles due to their very different interference patterns. This is illustrated in Figure 1(b), which shows



(a) [PLACEHOLDER, TO BE UPDATED by JAN 24]



(b) [PLACEHOLDER, TO BE UPDATED by JAN 24]

Figure 1: Projected precision on the tri-linear Higgs self-coupling λ for double Higgs-strahlung, di-Higgs production from W W fusion and their combination as a function of (a) the center-of-mass energy and (b) the value of λ normalised to the SM prediction.

the behaviour of the expected precision as a function of λ/λ_{SM} for the two production modes at $\sqrt{s}=550\,\mathrm{GeV}$, as well at $\sqrt{s}=1\,\mathrm{TeV}$. This shows that measurements of Z H H production at centre-of-mass energies around $500\,\mathrm{GeV}$ play a crucial role in pinning down the BSM behaviour of the tri-linear Higgs self-coupling.

4 References

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