Sensitivity to anomalous ZZH couplings at the ILC

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This presentation gives the prospects of measuring the general Lorentz structures of VVH ($V = Z$, γ and W) couplings at the International Linear Collider (ILC). Sensitivities to Higgs CP-even and CP-odd structures are evaluated by using various Higgs production channels and employing measurements of kinematical distributions. The evaluation is performed based on full detector simulation of the International Large Detector (ILD) at center-of-mass energies $\sqrt{s} = 250$ and 500 GeV. Combined sensitivities on the anomalous ZZH couplings are provided for a realistic operating scenario of the ILC.

EPS-HEP 2017, European Physical Society conference on High Energy Physics
5-12 July 2017
Venice, Italy

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PoS(EPS-HEP2017)322

1. Introduction

The LHC's discovery of the 125 GeV Higgs boson [1, 2] completed the particle spectrum of the Standard Model (SM) and proved the general idea that the electroweak symmetry was broken by some Higgs field condensed in the vacuum. However the SM does not explain why the Higgs condensate formed. To reveal this fundamental question new physics describing new phenomena is necessary. And the new physics could manifest itself as anomalies not only in the strengths but also in Lorentz structures of the couplings between the Higgs boson and vector bosons VVH ($V = Z$, γ and W) [3]. This paper studies the measurement of such anomalies in ZZH couplings, which relate to the electroweak symmetry breaking directly. The study was performed with the simulation framework of the International Large Detector (ILD) concept [4] for the International Linear Collider (ILC) [5], and the Lorentz structures of the ZZH couplings are based on an effective Lagrangian from the Effective Field Theory (EFT) [6]:

$$\mathscr{L}_{ZZH} = M_Z^2\Big(\frac{1}{\mathrm{v}} + \frac{a_Z}{\Lambda}\Big)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H, \tag{1.1}$$

where v is the vacuum expectation value of 246 GeV, Λ is the new physics scale which is assumed to be 1 TeV in our study, a_Z, b_Z and $\tilde{b}_Z$ are three dimension-less parameters representing anomalous couplings. The field strength tensor $\hat{Z}_{\mu\nu}$ and the dual field strength tensor $\tilde{\hat{Z}}_{\mu\nu}$ of the Z boson are defined as $\hat{Z}_{\mu\nu} \equiv \partial_\mu Z_\nu - \partial_\nu Z_\mu$ and $\tilde{\hat{Z}}_{\mu\nu} \equiv \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}\hat{Z}^{\rho\sigma}$. The a_Z term has the same Lorentz structure as that of the SM and affects only the total cross-section while the b_Z and $\tilde{b}_Z$ terms have new tensor structures that can affect angular distributions as well as the total cross-sections for the Higgs-strahlung $e^+e^- \to ZH$ (ZH) and the ZZ-fusion $e^+e^- \to eeH$ (ZZ) processes, as illustrated in Figure. 1.

2. Analysis on sensitivity to the anomalous ZZH couplings

2.1 Monte Carlo samples and a criterion for background suppression

The Monte Carlo samples used in the study were generated and reconstructed with the framework of the ILD-software for ILC physics and ILD optimization studies [4, 7]. Not only the signal processes but also all SM backgrounds are taken into account for the analysis. Background suppression is performed by maximizing signal significance (=$N_{sig}/\sqrt{N_{sig}+N_{bkg}}$, N_{sig} and N_{bkg} denote the number of events of the signal and background processes), in which a criterion that any angular and corresponding momenta observables are not imposed for the suppression is given. This is because angular information is key observables for determining the anomalous couplings, thus complete insensitive areas become a bias and must be avoided.

2.2 Strategy for evaluating the anomalous couplings

Sensitivities to anomalous couplings are evaluated by minimizing χ^2 defined as follows: the first term in the χ^2 formula represents the sensitivity derived from angular information, and the second term from the total cross-section,

$$\chi^2 = \sum_{i=1}^{n}\left[\frac{N_{SM}\cdot\frac{1}{\sigma}\frac{d\sigma}{dx}(x_i)\cdot f_i - N_{SM}\cdot\frac{1}{\sigma}\frac{d\sigma}{dx}(x_i;a_Z,b_Z,\tilde{b}_Z)\cdot f_i}{\Delta n_{SM}^{obs}(x_i)}\right]^2 + \left[\frac{N_{SM}-N_{BSM}(a_Z,b_Z,\tilde{b}_Z)}{\delta\sigma\cdot N_{SM}}\right]^2, \tag{2.1}$$

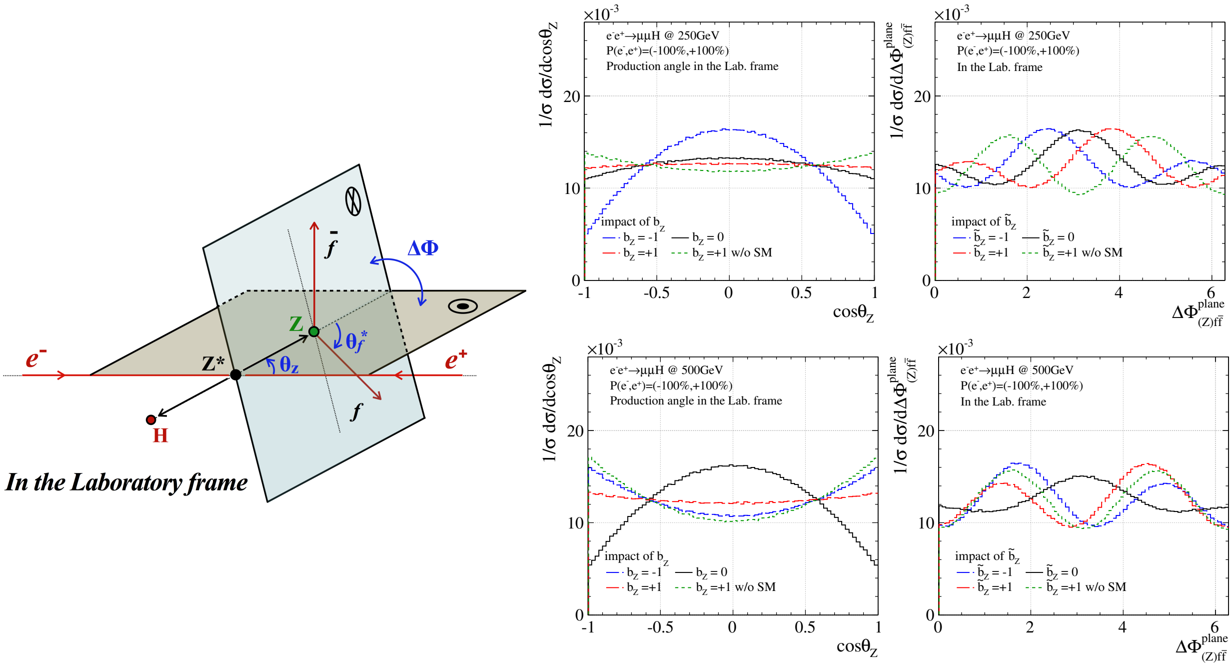

Figure 1: (Left) A schematic view of the Higgs-strahlung (ZH) process. θ_Z and θ^*_f show the production angle of the Z boson and the helicity angle of a daughter fermion of the Z boson. $\Delta\Phi$ shows the angle between two production planes. (Right) Distributions of main observables, $\cos\theta_Z$ and $\Delta\Phi$, with different anomalous parameters which are set to be $b_Z = \pm 1$ and $\tilde{b}_Z = \pm 1$.

where $\frac{1}{\sigma}\frac{d\sigma}{dx}(x_i)$ and $\frac{1}{\sigma}\frac{d\sigma}{dx}(x_i; a_Z, b_Z, \tilde{b}_Z)$ are the normalized theoretical angular distributions for the SM and for the non-zero anomalous couplings, respectively, x is an angular variable, n and i denote the total number of bins and bin number in an angular distribution. f is a detector response function for reconstructing the i-th bin, which includes detector acceptance, resolution and migration effects. $\Delta n^{obs}_{SM}(x_i)$ is an observed statistical error for the i-th bin. N_{SM} and N_{BSM} are the numbers of expected events for the SM and for non-zero anomalous couplings, respectively. $\delta\sigma$ is the relative total statistical error of the total cross-section and for ZH is taken from the recoil mass studies [8].

2.3 Effects of shape, total cross-section and $\sqrt{s}$ on the parameter evaluation

Figure. 2 shows distributions of $\Delta\chi^2$ ($\equiv \chi^2 - \chi^2_{min}$ and $\chi^2_{min} = 0$) projected onto the a_Z-b_Z plane (upper row) and the b_Z-$\tilde{b}_Z$ plane (lower row) at $\sqrt{s} = 250$ GeV. Three plots in each row correspond to evaluations using information on the shape only, the total cross-section only, or both. And both of the ZH and the ZZ processes were included in the evaluations. Regarding angular distributions, for three channels ($Z \to \mu\mu$, ee and $ZH \to qqbb$) of the ZH process, three-dimensional distributions $x(\cos\theta_Z,\ \cos\theta^*_f,\ \Delta\Phi)$ are used for both $\sqrt{s}$ = 250 and 500 GeV, and for one channel of the ZZ process ($H \to bb$) one- and two-dimensional distributions, $x(\Delta\Phi)$ and $x(\cos\theta_h,\ \Delta\Phi)$, are used for $\sqrt{s}$ = 250 and 500 GeV, respectively. The following can be learned from Figure. 2.:

- if only the shape information is used, there would be no sensitivity for a_Z when b_Z=0. This is because the a_Z term is composed of the same Lorentz structure with that of the SM.

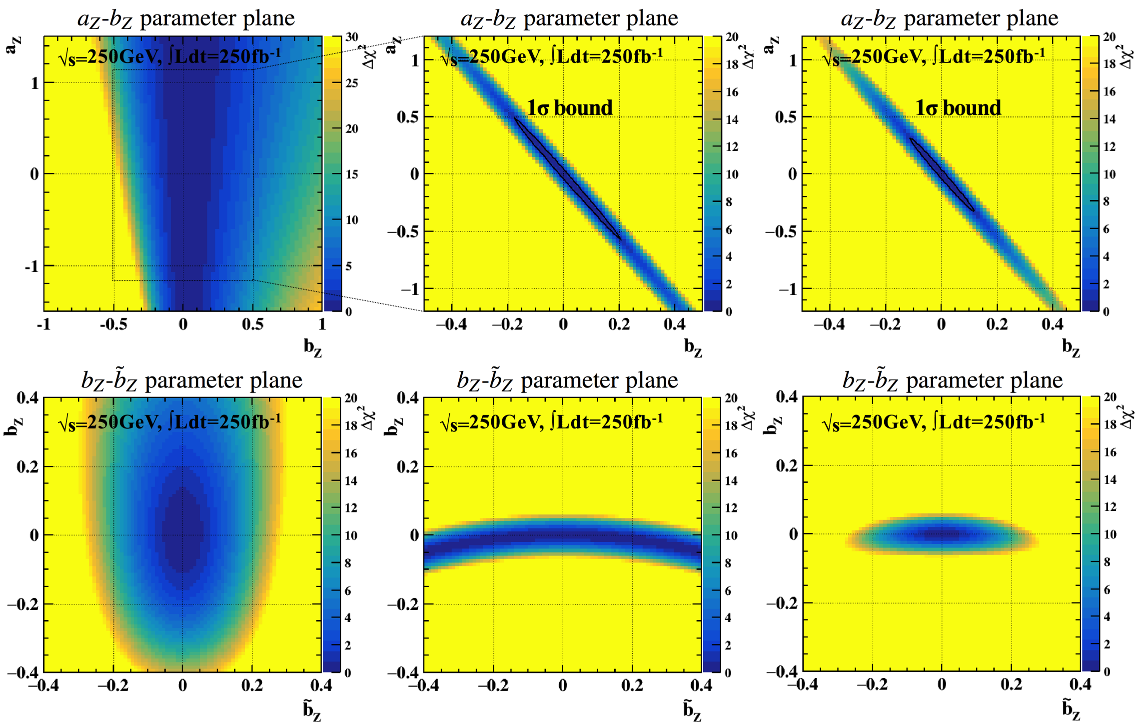

Figure 2: $\Delta\chi^2$ distributions in the a_Z-b_Z parameter plane (upper row) and the b_Z-$\tilde{b}_Z$ parameter plane (lower row). From left to right, the shape only, the total cross-section only and both information are used for the evaluation of $\Delta\chi^2$. Black lines on the upper middle and right plot correspond to $\Delta\chi^2 = 1$ bounds. $\sqrt{s} = 250$ GeV with the integrated luminosity of 250 fb^{-1} is assumed. Three channels ($Z \to \mu\mu$, ee and $ZH \to qqbb$) of the ZH and one channel ($H \to bb$) of the ZZ processes are considered as the shape information.

- there exists a strong correlation between a_Z and b_Z. This is because values of a_Z and b_Z can be adjusted correspondingly to make both of the shape and the total cross-section SM-like.
- the sensitivity of $\tilde{b}_Z$ is almost completely determined by the shape information, and almost uncorrelated with the other two parameters. This is because the CP-odd term has no linear contribution to the total cross-section.

Figure. 3 plots the 1σ ($\Delta\chi^2 = 1$) and 2σ ($\Delta\chi^2 = 4$) contours in the a_Z-b_Z plane after performing 3-parameter simultaneous fit under the assumption of $\sqrt{s} = 250$ GeV with 250 fb^{-1} and $\sqrt{s} = 500$ GeV with 500 fb^{-1} of a beam polarization $P(e^-, e^+) = (-80\%, +30\%)$. It clearly shows that at $\sqrt{s}$ =500 GeV the correlation between a_Z and b_Z becomes much lower and sensitivities become much better. This is because the b_Z term is momentum dependent.

2.4 Sensitivity to the anomalous *ZZH* couplings

The nominal sensitivities showing 1σ bounds to the anomalous ZZH couplings and their correlation matrices ρ from 3-parameter simultaneous fit are given as follows, where the integrated luminosities of 250 fb^{-1} at $\sqrt{s} = 250$ GeV and 500 fb^{-1} at $\sqrt{s} = 500$ GeV and two beam polarization states are assumed. For the nominal sensitivities, only the ZH process is used with both shape

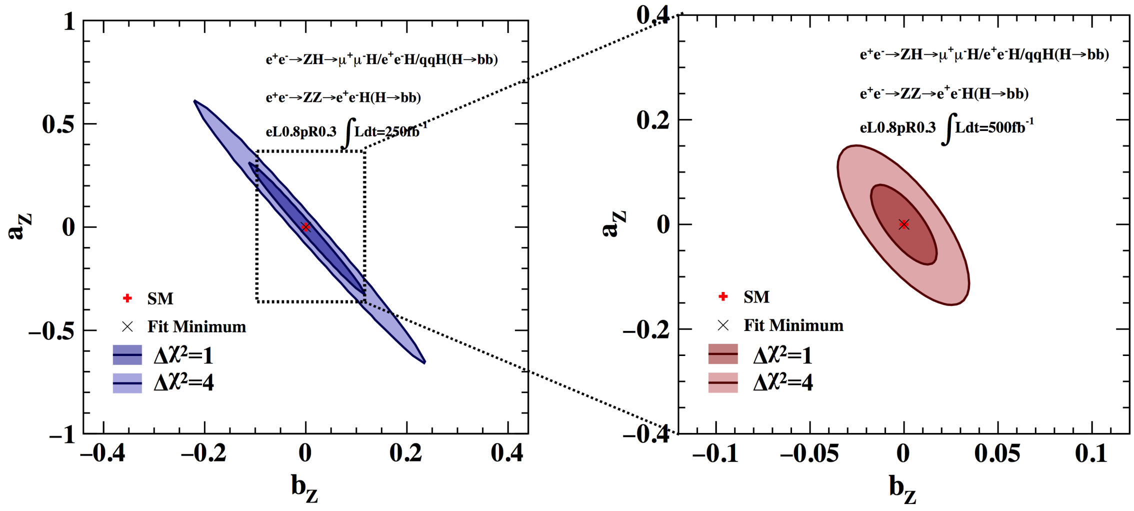

Figure 3: Comparison of the impact of $\sqrt{s} = 250$ (left) and 500 (right) GeV in the a_Z-b_Z parameter plane. The evaluations are performed with the simultaneous fitting in the three-parameter space and projected onto the a_Z-b_Z parameter plane, where both of the shape and the cross-section information are used by exploiting four channels of the two processes of the ZH and the ZZ processes. Contours show the bounds of $\Delta\chi^2 = 1$ and 4.

and total cross-section information.

$$ZH \text{ at 250 GeV with } e_L^- e_R^+ : \begin{cases} a_Z = \pm 0.409 \\ b_Z = \pm 0.147 \\ \tilde{b}_Z = \pm 0.066 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -0.999 & 0.006 \\ - & 1 & -0.006 \\ - & - & 1 \end{pmatrix} \tag{2.2}$$

$$ZH \text{ at 250 GeV with } e_R^- e_L^+ : \begin{cases} a_Z = \pm 0.441 \\ b_Z = \pm 0.159 \\ \tilde{b}_Z = \pm 0.074 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -0.999 & -0.006 \\ - & 1 & 0.006 \\ - & - & 1 \end{pmatrix} \tag{2.3}$$

$$ZH \text{ at 500 GeV with } e_L^- e_R^+ : \begin{cases} a_Z = \pm 0.123 \\ b_Z = \pm 0.029 \\ \tilde{b}_Z = \pm 0.023 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -0.992 & 0.006 \\ - & 1 & -0.009 \\ - & - & 1 \end{pmatrix} \tag{2.4}$$

$$ZH \text{ at 500 GeV with } e_R^- e_L^+ : \begin{cases} a_Z = \pm 0.132 \\ b_Z = \pm 0.031 \\ \tilde{b}_Z = \pm 0.023 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -0.993 & -0.002 \\ - & 1 & 0.001 \\ - & - & 1 \end{pmatrix} \tag{2.5}$$

where $e_L^- e_R^+$ and $e_R^- e_L^+$ denote the beam polarization states of $P(e^-, e^+) = (-80\%, +30\%)$ and $P(e^-, e^+) = (+80\%, -30\%)$, respectively. The combined sensitivities assuming the ILC operating scenario $H20$ [8], where the total luminosity of 2 ab^{-1} and 4 ab^{-1} are accumulated for $\sqrt{s}$ =250 and 500 GeV, are given as follows, with both ZH and ZZ processes included.

$$ZH \text{ with the } H20 \text{ scenario}: \begin{cases} a_Z = \pm 0.0311 \\ b_Z = \pm 0.0087 \\ \tilde{b}_Z = \pm 0.0083 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -0.911 & 0.006 \\ - & 1 & -0.007 \\ - & - & 1 \end{pmatrix} \quad (2.6)$$

$$ZH + ZZ \text{ with the } H20 \text{ scenario}: \begin{cases} a_Z = \pm 0.0237 \\ b_Z = \pm 0.0070 \\ \tilde{b}_Z = \pm 0.0078 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -0.857 & 0.004 \\ - & 1 & -0.006 \\ - & - & 1 \end{pmatrix} \quad (2.7)$$

3. Summary

Based on the framework of the EFT, the sensitivity to the anomalous ZZH couplings at the ILC was evaluated by exploiting the angular and the total cross-section information using the major Higgs production channels of the Higgs-strahlung and the ZZ-fusion processes, for both $\sqrt{s} = 250$ and 500 GeV. Sensitivities in $H20$ scenario to the anomalous couplings b_Z and $\tilde{b}_Z$ with the new Lorentz structures can reach < 1 %, and the sensitivity to the anomalous coupling a_Z can reach a few %. This would be very useful to probe the new physics beyond the SM. Once the anomalous ZZH couplings is assumed, anomalous γZH couplings must be considered since Z and γ are mixing with each other through the electroweak symmetry. However, because of the limit on length, results with the γZH couplings are not included in this proceedings, but they can be found in the slides of the talk [10] at the conference EPS-HEP17 and a paper in preparation.

Acknowledgements: The authors would like to thank Kiyotomo Kawagoe, Jenny List and Ivanka Bozovic-Jelisavcic for helpful comments on the study. This research was partially supported by JSPS Grants-in-Aid for Science Research No. 16H02176.

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