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Estimate of the $\sigma(e^+e^- \to HZ) \times \mathcal{B}r(H \to ZZ^*)$ accuracy at the 250 GeV ILC

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We report on the studies of the $e^+e^- \to HZ$ process with the subsequent decay of the Higgs boson $H \to ZZ^\star$, where the $ZZ^\star$ combination is reconstructed in the final states with two jets and two leptons. The analysis is performed using Monte Carlo data samples obtained with detailed ILD detector simulation assuming the integrated luminosity of 2 ab^{-1}, the beam polarizations $\mathcal{P}_{e^-e^+} = (-0.8, +0.3)$, and the center-of-mass energy $\sqrt{s} = 250$ GeV. The analysis is also repeated for the case of two 0.9 ab^{-1} data samples with polarizations $\mathcal{P}_{e^-e^+} = (\mp 0.8, \pm 0.3)$. The process is measured in four decay channels, which correspond to two combinations for the Higgs final states and two decay modes of the directly produced Z boson, $Z \to q\bar{q}$ and $Z \to \nu\bar{\nu}$. We propose a model-independent method for obtaining the width of the Higgs boson using the measurement of the $e^+e^- \to HZ$ process.

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1. Introduction

The model-independent measurement of the width of the Higgs boson is difficult to perform at the Large Hadron Collider (LHC). However, this task can be successfully solved with high accuracy at the future International Linear Collider (ILC) [1]. A large number of Higgs bosons will be produced at ILC, whereas backgrounds are expected to be relatively small. Events in the ILD detector [2] at ILC have clean and well-defined signatures and, therefore, processes of interest can be identified and studied in detail.

We propose to use the process $e^+e^- \to ZH$ with the subsequent decay $H \to ZZ^\star$ to measure the product of the cross section and the decay branching fraction, which can theoretically be expressed as:

$$\sigma(e^+e^- \to HZ) \times Br(H \to ZZ^\star) = C \cdot \mathrm{g}_Z^4/\Gamma_H \tag{1}$$

Here C is a constant which can be calculated theoretically with an uncertainty of less than 1 % [3], g_Z is the Higgs boson coupling HZZ which is expected to be determined combining ILC and LHC results with an uncertainty of about 0.5 % [4], and Γ_H is the Higgs boson width.

2. Results

In this analysis we study the following channels:

$$Channel\ 1: \quad e^+e^- \to Z_1(q_1q_2)\,H, \quad H \to Z(q_3q_4)Z^\star(\ell_1\ell_2) \tag{2}$$

$$Channel\ 2: \quad e^+e^- \to Z_1(q_1q_2)\,H, \quad H \to Z(\ell_1\ell_2)Z^\star(q_3q_4) \tag{3}$$

$$Channel\ 3: \quad e^+e^- \to Z_1(\nu\bar{\nu})\,H, \quad H \to Z(q_1q_2)Z^\star(\ell_1\ell_2) \tag{4}$$

$$Channel\ 4: \quad e^+e^- \to Z_1(\nu\bar{\nu})\,H, \quad H \to Z(\ell_1\ell_2)Z^\star(q_1q_2) \tag{5}$$

The datasets with $\mathcal{P}_{e^-e^+} = (\mp1.0, \pm1.0)$ beam polarization is used in Monte-Carlo (MC) data analysis. The MC samples studied for signal and backgrounds are preselected using the processes identification on the MC event generator level. All following selections are applied using the information on the reconstruction level.

Events with two isolated leptons are selected from all MC datasets using machine learning algorithms. Therefore energetic ISR photons are identified and removed. The jet reconstruction is performed using FastJet [5] clustering tools. To get the expected number of signal or background events with $\mathcal{P}_{e^-e^+} = (-0.8, +0.3)$ polarization and the integrated luminosity 2 ab^{-1}, we apply a weight factor to each event from the MC samples. The weight factor W is calculated as:

$$W = \left[\frac{1 \pm 0.8}{2} \cdot \frac{1 \pm 0.3}{2}\right] \cdot \frac{2\ \mathrm{ab}^{-1}}{\mathcal{L}} \tag{6}$$

where $\mathcal{L}$ - stands for integrated luminosity of a sample.

The number of Higgs boson signal events is obtained by fitting distributions of the invariant mass $M(jj\ell\ell)$. For the channels with $Z \to jj$ and $Z^\star \to \ell\ell$ decays M_Δ is used instead of $M(jj\ell\ell)$:

$$M_\Delta = M(jj\ell\ell) - M(jj) + M(Z_{\mathrm{nom}}) \tag{7}$$

where $M(Z_{\mathrm{nom}}) = 91.2$ GeV. This formula results in a narrower Higgs boson mass peak, because uncertainties of the jet reconstruction are mostly canceled in the mass difference.

The four channels are studied and the signal statistical uncertainties are evaluated. The distributions are fitted separately for the signal and background by the corresponding functions (see Fig. 1). Finally, the toy MC method is applied to obtain statistical dispersion of the signal count.

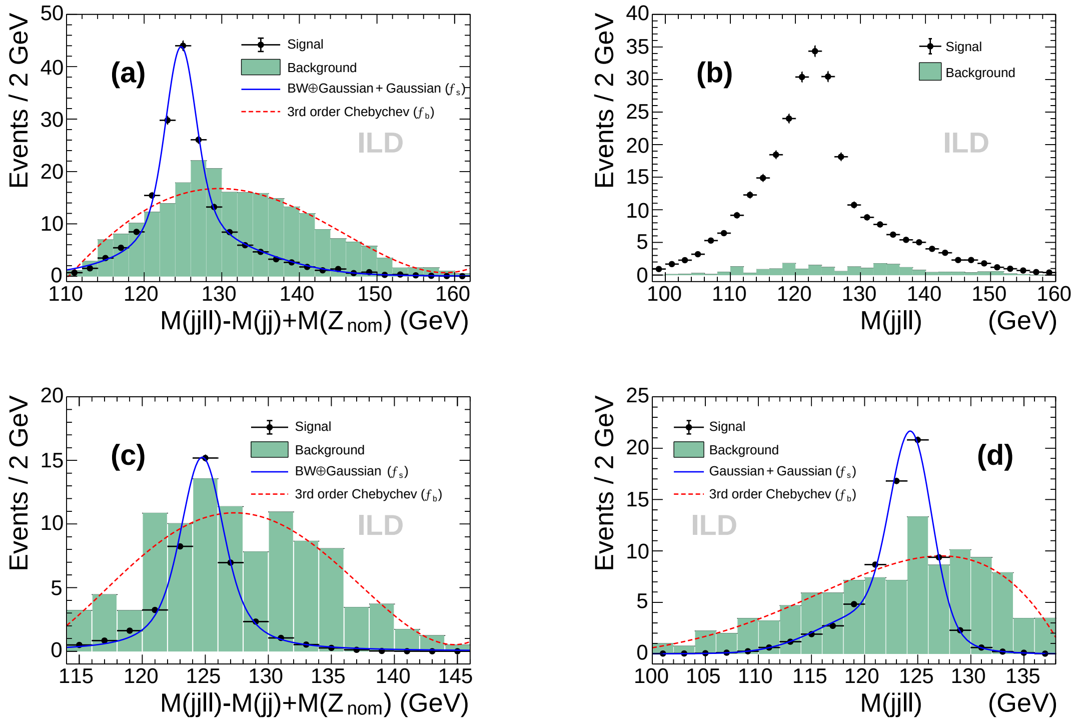

Figure 1: Distributions of $M_\Delta = M(jj\ell\ell) - M(jj) + M(Z_{\mathrm{nom}})$ for channels 1 and 3 (a and c) and $M(jj\ell\ell)$ for channels 2 and 4 (b and d) based of the analysis results. Distributions are presented separately for signal (black dots) and background (solid histograms). The fit results are overlaid: a blue solid curve for the signal and a red dashed curve for background.

For channel 1 the dominant backgrounds come from the $e^+e^- \to W^+W^-\gamma^\star$ and $e^+e^- \to ZZ\gamma^\star$ processes, with the off-shell $\gamma^\star$ decaying to two leptons and the W and Z bosons decaying to two jets. We found no significant backgrounds in channel 2 after applied cuts. For channels 3 and 4 the similar significant background sources are studied. Special attention is paid to the $e^+e^- \to Z(2j)Z(\tau^+\tau^-)$ process with leptonic τ decays, and also to the $e^+e^- \to W(2j)W(\ell\nu)$ process with a lepton produced within one of the jets.

The signal distribution for the channel 1 is modeled by the sum of two functions: a Breit-Wigner function convolved with a Gaussian function and an additional wide Gaussian function to account for residual $Z^\star Z^\star$ events. The same model is applied for the channel 3 signal distribution except additional Gaussian. The number of the signal events is calculated for the channel 2 as an integral over the signal distribution. The signal distribution for the channel 4 is described by the sum of two Gaussians. The wide Gaussian accounts for the $H \to Z^\star Z^\star$ contribution. The background distributions for all channels except channel 2 are modelled by the third order Chebychev polynomial function.

An important result of this study is an estimate of accuracy which can be reached for the Higgs width measurement. To estimate the accuracy, we calculate the combined statistical uncertainty for the four studied channels using the formula $S_{\text{comb}} = 1/\sqrt{\sum_{i=1}^{4} S_i^{-2}}$. Results obtained for all studied channels and the combined value of statistical uncertainty are given in Table 1.

Table 1: The fitted number of signal events and their relative statistical uncertainties obtained from the toy MC for each channel. The relative statistical uncertainties for the fitted number of signal events correspond directly to the relative statistical uncertainties for $\sigma(e^+e^- \to HZ) \times \mathcal{B}r(H \to ZZ^*)$.

	$Z_1(jj)$, $Z(jj)$, $Z^*(\ell\ell)$	$Z_1(jj)$, $Z(\ell\ell)$, $Z^*(jj)$	$Z_1(\nu\bar{\nu})$, $Z(jj)$, $Z^*(\ell\ell)$	$Z_1(\nu\bar{\nu})$, $Z(\ell\ell)$, $Z^\star(jj)$	Sum
		2 ab^{-1} eLpR			
Number of events	192.4 ± 24.9	275.3 ± 17.2	51.9 ± 13.0	73.3 ± 14.2	-
Statistical uncertainty	12.9%	6.3%	25.1%	19.3%	5.3%
		0.9 ab^{-1} eLpR + 0.9 ab^{-1} eRpL			
Number of events	135.2 ± 20.4	202.2 ± 14.7	30.9 ± 10.7	67.3 ± 14.3	-
Statistical uncertainty	15.1%	7.3%	34.6%	21.2%	6.2%

As given in Table 1, the statistical uncertainty of the proposed method is 5.3 % for the integrated luminosity 2 ab^{-1} and polarization $\mathcal{P}_{e^-e^+} = (-0.8, +0.3)$. Alternatively, we assumed two data samples with the polarizations $\mathcal{P}_{e^-e^+} = (\mp 0.8, \pm 0.3)$ and the integrated luminosity of 0.9 ab^{-1} each. The same analysis is repeated for this data taking scheme and the total statistical uncertainty of 6.2 % is obtained.

As a conclusion, the Higgs boson width can be experimentally measured at ILC in a model-independent approach with an accuracy of about (5-6)%. The detailed results of this study are published in [1]. At 250 GeV the accuracy of this method is similar to one obtained in [3, 6] using the combination of four channels measurements. The results of both methods can be combined to further improve the statistical accuracy. Our measurement can be compared to the Higgs width value obtained within the SM, as well as within the EFT approach. The theoretical accuracy of the Higgs width within the EFT approach is expected to be about 2 % [7].

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