Analysis of $ZHH$ in the 4-jet mode

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Measurement of the cross-section of $e^+e^- \rightarrow ZHH$ offers the information of the trilinear Higgs self-coupling, which is important to confirm the mechanism of the electro-weak symmetry breaking. Since there is huge background in the signal region, background rejection is key point to identify $ZHH$ events. In this paper, we study the possibility to observe the $ZHH$ events at ILC by using $ZHH \rightarrow \nu\bar{\nu}HH$, resulting 4 jets.

1 Introduction

In the standard model, particle masses are generated through the Higgs mechanism. This mechanism relies on a Higgs potential, $V(\Phi) = \lambda(\Phi^2 - \frac{1}{2}v^2)^2$, where $\phi$ is an iso-doublet scalar field, and $v$ is the vacuum expectation value of its neutral component ($v \sim 246$ GeV). Determination of the Higgs boson mass, which satisfies $m_H^2 = 2\lambda v^2$ at tree level in the standard model, will provide an indirect information about the Higgs potential and its self-coupling, $\lambda_{HHH}$. The measurement of the trilinear self-coupling, $\lambda_{HHH} = 6\lambda v$, offers an independent determination of the Higgs potential shape and the most decisive test of the mechanism of the electro-weak symmetry breaking.

$\lambda_{HHH}$ can be extracted from the measurement of the cross-section for the Higgs-strahlung process ($\sigma_{ZHH}$), $e^+e^- \rightarrow ZHH$. For a Higgs mass of 120 GeV, the $W$ fusion process is negligible at $\sqrt{s} = 500$ GeV. Figure 1 shows the relevant Feynman diagrams for this process. The information of $\lambda_{HHH}$ is included in the diagram of Fig. (a), and the relation between the cross-section of $ZHH$ and $\lambda_{HHH}$ is characterized by $\frac{\Delta \lambda_{HHH}}{\lambda_{HHH}} \approx 1.75 \frac{\Delta \sigma_{ZHH}}{\sigma_{ZHH}}$, where $\Delta \lambda_{HHH}$ and $\Delta \sigma_{ZHH}$ are measurement accuracy of $\lambda_{HHH}$ and $\sigma_{ZHH}$, respectively [2]. For that reason, precise measurement of the cross-section for the $ZHH$ production is essential to determination of the strength of the trilinear Higgs self-coupling. In this paper, we report status of our feasibility study for the observation of $ZHH$ events at the ILC.

2 Target mode

In this study, we assumed a Higgs mass of 120 GeV, $\sqrt{s} = 500$ GeV, and an integrated luminosity of $2\,ab^{-1}$. The final states of the $ZHH$ production can be categorized into 3 types, depending on the decay modes of $Z$: $ZHH \rightarrow q\bar{q}HH$ (135.2 $ab^{-1}$), $ZHH \rightarrow \nu\bar{\nu}HH$ (38.8 $ab^{-1}$), and $ZHH \rightarrow \ell\bar{\ell}HH$ (19.8 $ab^{-1}$), where the cross-sections were calculated without the beam polarization, initial-state radiation, and beamstrahlung. Since $ZHH \rightarrow q\bar{q}HH$ has the largest cross-section, this mode is the most attractive to observe $ZHH$ events. However, we study $ZHH \rightarrow \nu\bar{\nu}HH$ in this paper, because the 4-jet final state is easy to analyze. For
the Higgs mass of 120 GeV, the Higgs boson mainly decays into $b\bar{b}$ (76% branching ratio). Therefore, we concentrated on $ZH H \rightarrow \nu \bar{\nu} b \bar{b}$ from $\nu \nu H H$ events. As background events, we considered $ZZ \rightarrow b\bar{b}b\bar{b}$ (9.05 fb), $tt$ (583.6 fb), $ZH$ (62.1 fb), and $tb\bar{b}$ (1.2 fb). They have much larger cross-sections than $ZH H$, necessitating powerful background rejection.

3 Simulation tools

We have used MadGraph [3] to generate $\nu \nu H H$ and $t\bar{t}b\bar{b}$ events, while $ZZ \rightarrow b\bar{b}b\bar{b}$, $tt$, and $ZH$ events have been generated by Physsim [4]. In this study, the beam polarization, initial-state radiation, and beamstrahlung have not been included in the event generations. We have ignored the finite crossing angle between the electron and positron beams. In both event generations, helicity amplitudes were calculated using the HELAS library [5], which allows us to deal with the effect of gauge boson polarizations properly. Phase space integration and the generation of parton 4-momenta have been performed by BASES/SPRING [6]. Parton showering and hadronization have been carried out by using PYTHIA6.4 [7], where final-state tau leptons are decayed by TAUOLA [8] in order to handle their polarizations correctly.

The generated Monte Carlo events have been passed to a detector simulator called JS-QQuickSimulator, which implements the GLD geometry and other detector-performance related parameters [9]. Figure 2 shows a typical event display of $ZH H \rightarrow \nu \bar{\nu} \nu \bar{\nu} H H$.

4 Analysis

The clusters in the calorimeters are combined to form a jet if the two clusters satisfy $y_{ij} < y_{cut}$, where $y_{ij}$ is the $y$-value of the two clusters. All events are forced to have four jets by adjusting $y_{cut}$. Then, mass of the Higgs boson was reconstructed to identify $\nu \nu H H$ events by minimizing $\chi^2$ value defined as

$$\chi^2 = \frac{(\text{rec} M_{H1} - \text{true} M_H)^2}{\sigma_{H1}^2} + \frac{(\text{rec} M_{H2} - \text{true} M_H)^2}{\sigma_{H2}^2}, \quad (1)$$

where $\text{rec} M_{H1,2}$, $\text{true} M_{H1,2}$, and $\sigma_{H1,2}$ are the reconstructed Higgs mass, the true Higgs mass (120 GeV), and the Higgs mass resolution, respectively. $\sigma_{H1,2}$ was evaluated for each reconstructed Higgs boson by using $31\%/\sqrt{E_{jet}}$, where $E_{jet}$ is the jet energy. Figure 3 shows the distribution of the sum of the two reconstructed Higgs boson masses for $\nu \nu H H$ and background events. With no selection cuts, the signal is swamped in huge number of background events.

Figure 3: Distribution of the sum of the two reconstructed Higgs masses for $\nu \nu H H$ and background events.

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To identify the signal events from the backgrounds, we applied the following selection cuts. We required $\chi^2 < 20$ and $95 \text{ GeV} < M_{H1,2} < 125 \text{ GeV}$ to select events, for which the Higgs bosons could be well reconstructed. Then, since a $Z$ boson is missing in $\nu\nu HH$ events, we set the selection cut on the missing mass $(\text{miss } M)$: $90 \text{ GeV} < \text{miss } M < 170 \text{ GeV}$. The angular distribution of the particles reconstructed as the Higgs bosons has a peak at $\cos \theta = \pm 1$ for $ZZ$ events whereas the distribution becomes more uniform in $\nu\nu HH$ events. We applied the angular cut of $|\cos \theta_{H1,2}| < 0.9$ to reject these $ZZ$ events.

The 4-jet events from $ZH$ events have small missing transverse momentum $(\text{miss } P_T)$, which contaminate in the signal region. For that reason, we required $\text{miss } P_T$ above 50 GeV.

After the selection cuts so far, the dominant background was $tt$ events. The leptonic decay mode of $W$ from $t \to bW$ can be rejected by indentifying isolated charged leptons. We define the energy deposit within 20 deg. around a track as $E_{20}$. The isolated lepton track was defined to be a track with $10 \text{ GeV} < E_{20} < \frac{1}{2} E_{\text{trk}} - 1.8 \text{ GeV}$, where $E_{\text{trk}}$ is energy of the lepton track. We required the number of isolated lepton tracks $(N_{\text{lepton}})$ to be zero.

Finally, the flavor tagging was applied. We identified a jet as a $b$-jet, when it has 2 tracks with 3-sigma separation from the interaction point. Figure 4 shows the distribution of the number of jets tagged as $b$-jets after the selection cuts for $\nu\nu HH$ (a) and backgrounds (b).

| Cut                                | $\nu\nu HH$ | $ZZ \to bbbb$ | $tt$    | $ZH$    | $tbb$ |
|------------------------------------|------------|--------------|--------|--------|------|
| No cut                             | 77.6       | 18,100       | 1,167,200 | 124,200 | 2,154|
| $\chi^2 < 20$                     | 43.7       | 12,169       | 364,921  | 83,065 | 468  |
| $95 \text{ GeV} < M_{H1,2} < 125 \text{ GeV}$ | 29.5       | 387          | 70,557   | 8,570  | 82   |
| $90 \text{ GeV} < \text{miss } M < 170 \text{ GeV}$ | 26.2       | 127          | 32,570   | 696    | 45   |
| $|\cos \theta_{H1,2}| < 0.9$     | 23.0       | 34.4         | 26,521   | 447    | 37   |
| $\text{miss } P_T > 50 \text{ GeV}$ | 18.4       | 3.6          | 17,591   | 137    | 25   |
| $N_{\text{lepton}} = 0$           | 17.8       | 3.6          | 6,708    | 37.3   | 9.7  |
| $N_{b-\text{tag}} = 4$            | 7.3        | 1.8          | 65       | 0      | 2.4  |

Table 1: Cut statistics.
necessary.

5 Summary

The $ZHH \rightarrow \nu\bar{\nu}HH$ process was studied to investigate the possibility of the trilinear Higgs self-coupling at the ILC. In this study, we assumed the Higgs boson mass of 120 GeV, $\sqrt{s} = 500$ GeV, and the integrated luminosity of 2 ab$^{-1}$.

After the selection cuts, the signal significance of 0.9 was obtained. The dominant background was $tt$ events. To extract the information of $\lambda_{HHH}$, we must improve the background rejection. In addition, $ZHH \rightarrow qqHH$ will be studied to obtain certain signal significance.

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