Identifying the higgs-gauge boson couplings signs at leptonic colliders

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Abstract. We investigate in this work the Higgs-gauge bosons couplings \( hVV \) \((V = W, Z)\) through different final states at \( e^+e^- \) colliders. These couplings could be modified with respect to the SM in many SM extensions, as \( g_{hVV} = \kappa_V g_{hVV}^{SM} \), either via radiative corrections or if the Higgs is composite. Therefore, we consider the final states \( bb + \not{E}_T \mathcal{O} 250 \text{ GeV} \), \( hW^+W^- \rightarrow bb + l^+l^- + \not{E}_T \mathcal{O} 500 \text{ GeV} \); and \( ZW^+W^- \rightarrow jj + l^+l^- + \not{E}_T \mathcal{O} 1 \text{ TeV} \) within the corresponding luminosity at the ILC. Then, by considering that there will be no significant deviation with respect to the SM at HL-LHC, i.e., \( |\delta\kappa_V/\kappa_V| \leq 0.04 \), we show that the sign of the \( hVV \) couplings can be probed to be \( \kappa_V = \pm 1 \).

1. Introduction
After the discovery of the Higgs boson with a mass of 125.09 GeV [1, 2], most of the measurements show that it is Standard Model (SM)-like, and therefore the precise determination of its properties is very important before talking about any new physics (NP) phenomenon beyond SM (BSM). In particular, the determination of \( hVV \) \((V \text{ stands for } Z \text{ and } W \text{ vector bosons})\) couplings is crucial to extract information on the true nature of electroweak symmetry breaking (EWSB). Although the Large Hadron Collider (LHC) was/is able to probe the couplings of the Higgs boson, the search for any experimental hints for NP was negative. The High-Luminosity LHC (HL-LHC) program is expected to operate in some not too far future as well as planned high-energy leptonic/hadronic colliders projects that will precisely measure the Higgs boson couplings to the SM particles. The assumption that the Higgs scalar potential respects the residual global \( SU(2) \) symmetry called the custodial symmetry [3] in the SM after the EWSB, is to ensure that the \( \rho \)-parameter is within the 1.00039 \( \pm 0.00019 \) interval and that the ratio \( \lambda_{WZ} \) of the \( hWW \) and the \( hZZ \) couplings is also equal to 1 at tree level. From experimental searches [4, 5, 6], this ratio can be positive or negative in general. Generally speaking, both the \( hVV \) couplings and the \( \lambda_{WZ} \) can deviate from the SM predictions. The magnitude of \( \lambda_{WZ} \) could be probed by the Higgs decay rates, while tree level/one-loop interference effects are important to probe the...
overall $\lambda_{WZ}$ sign [7, 8, 9, 10]. In some BSM extensions where the $hVV$ couplings get modified, a possible enhancement in the events number in final states including these couplings can be observed at high energy collisions, either at leptonic or hadronic colliders. Such enhancements can be observed in the kinematic variables distributions. Previous studies of the anomalous $hVV$ couplings were performed by both the CMS and ATLAS experiments although the current data are consistent with the SM predictions [11, 12, 13, 14, 15, 16]. In this work, we investigate the $hVV$ couplings sign with respect to the SM by considering the processes $b\bar{b} + E_T \@ 250 GeV$, $hW^+W^- \rightarrow b\bar{b} + \ell^+\ell^- + E_T \@ 500 GeV$; and $ZW^+W^- \rightarrow jj + \ell^+\ell^- + E_T \@ 1TeV$ at an $e^-e^+$ colliders for both unpolarized and polarized $P(e^-, e^+) = [-0.8, +0.3]$ beams. We start with a brief description of the Higgs-gauge bosons couplings status in section II. Then, the identification of the Higgs-gauge couplings signs for the mentioned processes. Finally, we give our conclusion.

2. The Higgs-gauge bosons couplings status

For a generic SM extensions, the Higgs couplings to the gauge bosons get modified either via mixtures or via significant radiative corrections. Then and BSM modification of the $hVV$ couplings can be parametrised as

$$\kappa_W = \frac{g_{hWW}}{g_{hWW}^{SM}}, \kappa_Z = \frac{g_{hZZ}}{g_{hZZ}^{SM}},$$

where $\kappa_W$ and $\kappa_Z$ are the scale factors, and the ratio of these factors $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$ could be a useful quantity that may give crucial information on the nature of EWSB and the electroweak properties of the $h_{125}$ resonance. Also it may help to derive the necessary information about the Higgs triple coupling. While recent measurements by ATLAS and CMS of $h \rightarrow WW$ and $h \rightarrow ZZ$ decay rates or production for the $h_{125}$ resonance are sensitive to the overall sign and magnitude of $\lambda_{WZ}$ [16]. This has been shown by the combined measurements of the LHC Run-II [17, 18, 19]

$$-1.39 \lesssim \lambda_{WZ} \lesssim -0.97 \text{ or } 0.92 \lesssim \lambda_{WZ} \lesssim 1.37. \quad (2)$$

The $hVV$ couplings and $\kappa_q$ coupling which is the Higgs-gluon that are constrained from combined measurements of LHC Run-I and Run-II with $2\sigma$ C.L. as

$$0.84 \lesssim |\kappa_W| \lesssim 1.38, \ 0.77 \lesssim |\kappa_Z| \lesssim 1.21, \ 0.88 \lesssim |\kappa_g| \lesssim 1.44, \quad (3)$$

respectively.

3. The $hVV$ signs

In order to identify the Higgs-gauge couplings signs, we propose to consider the final states $b\bar{b} + E_T \@ 250 GeV$ [Fig. 2 (a) and (b)], $hW^+W^- \rightarrow b\bar{b} + \ell^+\ell^- + E_T \@ 500 GeV$ [Fig. 2 (c) and (d)] and $ZW^+W^- \rightarrow jj + \ell^+\ell^- + E_T \@ 1TeV$ [Fig. 2 (e)] at the corresponding luminosity at leptonic colliders such as the International Linear Collider (ILC) for both cases with and without polarized beams. With variation of the center-of-mass energy $\sqrt{s}$ from 250 GeV to 3 TeV, we get the cross section of $b\bar{b} + E_T$, $hW^+W^-$ and $ZW^+W^-$ final states with and without polarized beams as seen in Fig. 1.

One notice from Fig. 1 that the cross section with polarized beams $P(e^-, e^+) = [-0.8, +0.3]$ is always greater than its value with unpolarized beams by twice. The future lepton colliders features, such as the ILC, let us to consider: $e^-e^+ \rightarrow b\bar{b} + E_T$ process at 250 GeV to avoid the huge $t\bar{t}$ background, although, its cross section is increasing with CM energy. Also, the process $e^-e^+ \rightarrow hW^+W^-$ since its cross section reaches gets maximized around 500 GeV. For the last process $e^-e^+ \rightarrow ZW^+W^-$, we consider $\sqrt{s} = 1TeV$.

1 These values are considered within the assumption that there are no additional BSM contributions to the Higgs boson width, i.e., $B_{BSM} = 0$. 
Figure 1. The cross section of the processes $e^-e^+ \to b\bar{b} + E_T$, $e^-e^+ \to hW^+W^-$ and $e^-e^+ \to ZW^+W^-$ as function of $\sqrt{s}$, where the solid/dashed line represent $P(e^-,e^+) = [0,0] / P(e^-,e^+) = [-0.8, +0.3]$. 

Figure 2. Some relevant Feynman diagrams for the considered process, where the Higgs-gauge couplings $hVV$ appear.

Each of these processes occurs via many Feynman diagrams, which we can classify according to the number of the vertices $hWW$ and $hZZ$. Therefore, for modified $hVV$ couplings $(\kappa_W, \kappa_Z)$, the cross section can be written as summation of powers of $\kappa_V$, as

$$\sigma(\kappa_W, \kappa_Z) = \sum_{n,m} \sigma_{[n,m]} \kappa_W^n \kappa_Z^m. \quad (4)$$

Using Madgraph5 [20] at the partonic level, we generate each process for both unpolarized and polarized beams with the polarization $P(e^-,e^+) = [-0.8, +0.3]$. In our analysis, the effects from initial state radiation (ISR) and bremsstrahlung are not including in the quoted cross sections. We consider the following pre-cuts

$$\Delta R_{n,m} > 0.4, \ |\eta_n| < 2.5, \ p_T^{b,j} > 20 \text{ GeV}, \ p_T^{\ell} > 10 \text{ GeV}, \quad (5)$$

with $n,m$ denote $b,j,\ell$. For both cases of polarized and unpolarized beams, we estimate different cross section contributions $\sigma_{[n,m]}$ given in (4) for each considered process $^2$. We give in Table 1,

$^2$ Here, the b-tagging efficiency is considered to be the ILC value, $\varepsilon_b = 0.8$. 
the non-vanishing cross section contributions $\sigma_{[n,m]}$ for both unpolarized and polarized beams.

Table 1. The non-vanishing cross sections contributions $\sigma_{[n,m]}$ given in (4) for the considered processes without and with polarized beams. Here, all cross section values are given in $fb$.

|                | $P(e^-, e^+) = [0, 0]$ | $P(e^-, e^+) = [-0.8, +0.3]$ |
|----------------|------------------------|-------------------------------|
| $\sigma_{[2,0]}$ | 7.221                  | 15.821                        |
| $\sigma_{[0,2]}$ | 35.853                 | 52.873                        |
| $\sigma_{[1,1]}$ | 2.358                  | 2.682                         |
| $\sigma_{[1,0]}$ | -1.565                 | -2.661                        |
| $\sigma_{[0,1]}$ | -1.549                 | -1.262                        |
| $\sigma_{[0,0]}$ | 60.788                 | 109.297                       |
| $\sigma_{[2,2]}$ | 5.927                  | 13.380                        |
| $\sigma_{[0,2]}$ | 0.582                  | 1.073                         |
| $\sigma_{[1,1]}$ | -1.194                 | -2.458                        |
| $\sigma_{[0,0]}$ | 59.268                 | 134.931                       |

Here, one notice that the cross section for the processes $e^-e^+ \rightarrow b\bar{b} + E_T$ and $e^-e^+ \rightarrow ZW^+W^-$ is dominated by the $\sigma_{[0,0]}$, i.e., by the term that does not include any $hVV$ vertex. The use of polarized beams will enhance the cross section values. For the SM case ($\kappa_W = \kappa_Z = 1$), the cross section values get enhanced by 71%, 126%, 129% for the processes used in Table 1, respectively. By varying both $\kappa_W$ and $\kappa_Z$ within the range in eq. (2) and eq. (3), and using eq. (4) we found the cross section for unpolarized and polarized beams shown in Fig. 3 and its relative difference with respect to the SM in Fig. 4.

It is clear that for both cases with unpolarized and polarized beams, the cross sections of all processes deviate from the SM value for any deviation of the $hWW$ and $hZZ$ couplings from the SM. Moreover, for all values $|\kappa_V| \geq 1$, the we can get a an enhancement whatever the signs of $\kappa_V$. However, the relative enhancement is not the same for the three processes, and therefore it is possible to combine the three cross section values to extract the values and signs of $\kappa_V$.

4. Conclusions

It is so important to understand New physics beyond the SM in the Higgs sector using among the planned future leptonic/hadronic colliders. Here, we investigated the possibility of extracting
Figure 3. The cross section (shown in the palette) of the three processes in the $\kappa_W - \kappa_Z$ plan without (up) and with polarized beams (bottom). The triangle (▲) refers to the SM case.

Figure 4. The cross section relative difference with respect to the SM ($\kappa_W = \kappa_Z = 1$) (shown in the palette) for the three processes in the $\kappa_W - \kappa_Z$ plan without (up) and with polarization (bottom).

the values and signs of the Higgs gauge couplings $\kappa_V = \frac{g_{\nu V}}{g_{\nu V}}$. We investigated the value $\kappa_V$ using the processes $b\bar{b} + E_T @ 250 \text{GeV}$, $hW^+W^- \rightarrow b\bar{b} + \ell^+\ell^- + E_T @ 500 \text{GeV}$; and $ZW^+W^- \rightarrow jj + \ell^+\ell^- + E_T @ 1 \text{TeV}$ at an $e^-e^+$ collider for both unpolarized and polarized beams with $P(e^-, e^+) = [-0.8, +0.3]$. We have shown the possibility of identifying the $\kappa_W$ and $\kappa_Z$ couplings sign by considering the recent combined measurements of the LHC Run-II.
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