Research Article

Constraints on Higgs Effective Couplings in $H\nu\bar{\nu}$ Production of CLIC at 380 GeV

H. Denizli and A. Senol

Department of Physics, Abant Izzet Baysal University, 14280 Bolu, Turkey

Correspondence should be addressed to A. Senol; abdulkadirsenol@gmail.com

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The potential of the $e^+e^- \rightarrow \nu\bar{\nu}H$ process in the first stage of CLIC considering center-of-mass energy of 380 GeV and assuming the baseline integrated luminosity of 500 fb^{-1} is examined to probe CP-conserving dimension-six operators in a model-independent Standard Model effective field theory framework. In the analysis, a detailed fast simulation on $e^+e^- \rightarrow \nu\bar{\nu}H$ signal processes and dominant backgrounds is performed including parton showering with PYTHIA and detector simulation based on ILD type detector with DELPHES in MadGraph. The obtained best limits on $\bar{c}_{HB}$, $\bar{c}_W = -\bar{c}_B$, and $\bar{c}_{HW}$ are $[-4.82; 1.53] \times 10^{-2}$, $[-5.11; 4.13] \times 10^{-3}$, and $[-6.58; 5.55] \times 10^{-3}$, respectively.

1. Introduction

The recent Large Hadron Collider (LHC) discovery of a scalar particle with 125 GeV which is compatible with Standard Model (SM) Higgs boson predicted by Brout-Englert-Higgs symmetry breaking mechanism opens up a gateway to search for physics beyond the SM [1, 2]. But evidence for new physics beyond the SM using analysis of combined ATLAS and CMS data for probing the couplings of Higgs boson has not been observed yet. Possible deviation from the SM predictions of Higgs boson couplings would imply the presence of new physics involving massive particles that are decoupled at energy scales much larger than the Higgs sector energies being probed [3]. The SM Effective Field Theory (EFT) is a well-known model-independent method for investigation of any deviation from SM [4, 5]. The origin of this method is based on all new physics contributions to the SM described by a systematic expansion in a series of high dimensional operators beyond the SM fields. All high dimensional operators conform to $SU(3)_C \times SU(2)_L \times U(1)_Y$ SM gauge symmetry. The dimension-6 operators play an important role in the framework since they match ultraviolet (UV) models which are simplified by the universal one-loop effective action. There have been many analyses for constraints on SM EFT operators with available data from LHC-Run 1 [6–13]

and with electroweak precision measurements provided from a previous accelerator, namely, Large Electron Positron (LEP) [14–17]. In particular, the prediction on dimension-6 operators has been examined in many rewarding studies at High Luminosity LHC (HL-LHC) [18–20] and future e^+e^- colliders [21–29].

The precision measurements of Higgs boson couplings with the other SM particles at the LHC and planned future colliders will give us detailed information about its true nature. The future multi-TeV e^+e^- colliders with extremely high luminosity and clean environment due to the absence of hadronic initial state would grant access to precise measurement, especially for the Higgs couplings. The Compact Linear Collider (CLIC) is one of the mature proposed linear colliders with center-of-mass energies from a few hundred GeV up to 3 TeV [30]. The first energy stage of CLIC operation was chosen to be $\sqrt{s} = 380 \text{ GeV}$, with the predicted integrated luminosity of 500 fb^{-1} . The primary motivation of this stage is the precision measurements of SM Higgs properties and also the model-independent Higgs couplings to both fermions and bosons [30, 31].

In this study, we focus on the analysis of $e^+e^- \rightarrow \nu\bar{\nu}H$ production process in order to assess the projection of the first energy stage of the CLIC on the CP-conserving dimension-6 operators involving the Higgs and gauge bosons

($W^\pm$, γ , Z) defined by an SM EFT Lagrangian in the next section.

2. Effective Operators

The well-known SM Lagrangian ($\mathcal{L}_{\text{SM}}$) involving renormalizable interactions is suppressed by higher dimensional operators in SM EFT approach. All these operators are parametrized by an energy scale of nonobserved states assumed larger than vacuum expectation value of Higgs field (v). A few different operator bases are presented in the literature; we consider SM EFT operators as the strongly interacting light Higgs Lagrangian ($\mathcal{L}_{\text{SILH}}$) in bar convention [18, 33, 34]. Assuming the baryon and lepton number conservation, the most general form of dimension-6 effective Lagrangian including Higgs boson couplings that keep SM gauge symmetry is given as follows:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \bar{c}_i O_i, \quad (1)$$

where $\bar{c}_i$ are normalized Wilson coefficients that are free parameters. In this work, we consider the dimension-6 CP-conserving interactions of the Higgs boson and electroweak gauge boson in SILH basis as [34]

$$\begin{aligned} \mathcal{L}_{\text{SILH}} = & \frac{\bar{c}_H}{2v^2} \partial^\mu [\Phi^\dagger \Phi] \partial_\mu [\Phi^\dagger \Phi] + \frac{\bar{c}_T}{2v^2} [\Phi^\dagger \overleftrightarrow{D}^\mu \Phi] \\ & \cdot [\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] - \frac{\bar{c}_6 \lambda}{v^2} [\Phi^\dagger \Phi]^3 - \left[\frac{\bar{c}_u}{v^2} y_u \Phi^\dagger \Phi \Phi^\dagger \cdot \bar{Q}_L u_R \right. \\ & \left. + \frac{\bar{c}_d}{v^2} y_d \Phi^\dagger \Phi \Phi \bar{Q}_L d_R + \frac{\bar{c}_l}{v^2} y_l \Phi^\dagger \Phi \Phi \bar{L}_L e_R + \text{h.c.} \right] \\ & + \frac{ig\bar{c}_W}{m_W^2} [\Phi^\dagger T_{2k} \overleftrightarrow{D}^\mu \Phi] D^\nu W_{\mu\nu}^k + \frac{ig'\bar{c}_B}{2m_W^2} [\Phi^\dagger \overleftrightarrow{D}^\mu \Phi] \\ & \cdot \partial^\nu B_{\mu\nu} + \frac{2ig\bar{c}_{HW}}{m_W^2} [D^\mu \Phi^\dagger T_{2k} D^\nu \Phi] W_{\mu\nu}^k \\ & + \frac{ig'\bar{c}_{HB}}{m_W^2} [D^\mu \Phi^\dagger D^\nu \Phi] B_{\mu\nu} + \frac{g'^2 \bar{c}_\gamma}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} \\ & + \frac{g_s^2 \bar{c}_g}{m_W^2} \Phi^\dagger \Phi G_{\mu\nu}^a G_a^{\mu\nu}, \end{aligned} \quad (2)$$

where λ represents the Higgs quartic coupling; y_u , y_d , and y_l are the 3×3 Yukawa coupling matrices in flavor space; g' , g , and g_s denote coupling constant of $U(1)_Y$, $SU(2)_L$, and $SU(3)_C$ gauge fields, respectively; the generators of $SU(2)_L$ in the fundamental representation are given by $T_{2k} = \sigma_k/2$, σ_k being the Pauli matrices; Φ is Higgs field that contains a single $SU(2)_L$ doublet of fields; $B^{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ and $W^{\mu\nu} = \partial_\mu W_\nu^k - \partial_\nu W_\mu^k + g\epsilon_{ijk} W_\mu^i W_\nu^j$ are the electroweak field strength tensors; $G^{\mu\nu}$ is the strong field strength tensors; and the Hermitian derivative operators are defined as $\Phi^\dagger \overleftrightarrow{D}_\mu \Phi = \Phi^\dagger D_\mu \Phi - D_\mu \Phi^\dagger \Phi$. The SM EFT Lagrangian (see (2)) containing the Wilson coefficients in the SILH bases of dimension-6 CP-conserving operators can be defined in terms of the

mass eigenstates after electroweak symmetry breaking (Higgs boson, W , Z , photon, etc.) as follows:

$$\begin{aligned} \mathcal{L} = & -\frac{m_H^2}{2v} g_{hhh}^{(1)} h^3 + \frac{1}{2} g_{hhh}^{(2)} h \partial_\mu h \partial^\mu h - \frac{1}{4} g_{hgg} G_{\mu\nu}^a G_a^{\mu\nu} h \\ & - \frac{1}{4} g_{h\gamma\gamma} F_{\mu\nu} F^{\mu\nu} h - \frac{1}{4} g_{hzz}^{(1)} Z_{\mu\nu} Z^{\mu\nu} h - g_{hzz}^{(2)} Z_\nu \partial_\mu Z^{\mu\nu} h \\ & + \frac{1}{2} g_{hzz}^{(3)} Z_\mu Z^\mu h - \frac{1}{2} g_{haz}^{(1)} Z_{\mu\nu} F^{\mu\nu} h - g_{haz}^{(2)} Z_\nu \partial_\mu F^{\mu\nu} h \\ & - \frac{1}{2} g_{hww}^{(1)} W^{+\mu\nu} W_{\mu\nu}^- h - [g_{hww}^{(2)} W^{+\nu} \partial^\mu W_{\mu\nu}^- h \\ & + \text{h.c.}] + g \left(1 - \frac{1}{2} \bar{c}_H \right) m_W W_{\mu\nu}^- W^{+\mu} h \\ & - \left[\tilde{y}_u \frac{1}{\sqrt{2}} [\bar{u} P_R u] h + \tilde{y}_d \frac{1}{\sqrt{2}} [\bar{d} P_R d] h \right. \\ & \left. + \tilde{y}_\ell \frac{1}{\sqrt{2}} [\bar{\ell} P_R \ell] h + \text{h.c.} \right], \end{aligned} \quad (3)$$

where $W_{\mu\nu}$, $Z_{\mu\nu}$, and $F_{\mu\nu}$ are the field strength tensors of W -boson, Z -boson, and photon, respectively; m_H represents the mass of the Higgs boson; the effective couplings in gauge basis defined as dimension-6 operators are given in Table 1 in which a_H (g_H) coupling is the SM contribution to the Higgs boson to two photons' (gluons) vertex at loop level.

We use the parametrization in [34] based on the formulation given in [33] in our analysis. The parametrization is not complete as described in detail in Section 3 of [35] and also [36]. It chooses to remove two fermionic invariants while retaining all the bosonic operators. This choice assumes completely unbroken $U(3)$ flavor symmetry of the UV theory where the coefficients of these operators are unit matrices in flavor space. Therefore, we assume flavor diagonal dimension-six effects. It is sufficient for the purpose of this paper in which we do not consider higher order electroweak effects but only claim a sensitivity study for $\bar{c}_W$, $\bar{c}_B$, $\bar{c}_{HW}$, $\bar{c}_{HB}$, and $\bar{c}_\gamma$ couplings.

We have used the Monte Carlo simulations with leading order in `MadGraph5_aMC@NLO` [37] involving effect of the dimension-6 operators on $H\nu\bar{\nu}$ production mechanism in e^+e^- collisions. The effective Lagrangian of the SM EFT in (2) is implemented into the `MadGraph5_aMC@NLO` based on `FeynRules` [38] and `UFO` [39] framework. In this study, we focus on searching for the dimension-6 Higgs-gauge boson couplings via $e^+e^- \rightarrow \gamma\bar{\nu}H$ process as shown in Figure 1. This process is sensitive to Higgs-gauge boson couplings; g_{hzz} , g_{hww} , and g_{hzy} and the couplings of a quark or lepton pair and one single Higgs field; and $\tilde{y}_u$, $\tilde{y}_d$, and $\tilde{y}_\ell$ in the mass basis. In the gauge basis, $e^+e^- \rightarrow \gamma\bar{\nu}H$ process is sensitive to the seven Wilson coefficients— $\bar{c}_W$, $\bar{c}_B$, $\bar{c}_{HW}$, $\bar{c}_{HB}$, $\bar{c}_H$, $\bar{c}_\gamma$, and $\bar{c}_T$ —related to Higgs-gauge boson couplings and also effective fermionic couplings. Due to the small Yukawa couplings of the first- and second-generation fermions, we neglect the effective fermionic couplings. We set $\bar{c}_W + \bar{c}_B$ and $\bar{c}_T$ to zero in all our calculations since the linear combination of $\bar{c}_W + \bar{c}_B$ and $\bar{c}_T$ is strongly constrained from the electroweak precision test of the oblique parameters S and T . The cross sections of

TABLE 1: The relations between Lagrangian parameters in the mass basis (see (2)) and the Lagrangian in gauge basis (see (3)) ($c_W \equiv \cos \theta_W$, $s_W \equiv \sin \theta_W$).

$g_{hhh}^{(1)} = 1 + \frac{7}{8}\bar{c}_6 - \frac{1}{2}\bar{c}_H$	$g_{hhh}^{(2)} = \frac{g}{m_W}\bar{c}_H$
$g_{hgg} = g_H - \frac{4\bar{c}_g g_s^2 v}{m_W^2}$	$g_{h\gamma\gamma} = a_H - \frac{8g\bar{c}_\gamma s_W^2}{m_W}$
$g_{hzz}^{(1)} = \frac{2g}{c_W^2 m_W} [\bar{c}_{HB} s_W^2 - 4\bar{c}_\gamma s_W^4 + c_W^2 \bar{c}_{HW}]$	$g_{hzz}^{(2)} = \frac{g}{c_W^2 m_W} [(\bar{c}_{HW} + \bar{c}_W) c_W^2 + (\bar{c}_B + \bar{c}_{HB}) s_W^2]$
$g_{hzz}^{(3)} = \frac{gm_W}{c_W^2} [1 - \frac{1}{2}\bar{c}_H - 2\bar{c}_T + 8\bar{c}_\gamma \frac{s_W^4}{c_W^2}]$	$g_{haz}^{(1)} = \frac{gs_W}{c_W m_W} [\bar{c}_{HW} - \bar{c}_{HB} + 8\bar{c}_\gamma s_W^2]$
$g_{haz}^{(2)} = \frac{gs_W}{c_W m_W} [\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W]$	$\tilde{y}_d = y_d \left[1 - \frac{1}{2}\bar{c}_H + \frac{3}{2}\bar{c}_d \right]$
$g_{hww}^{(1)} = \frac{2g}{m_W} \bar{c}_{HW}$	$\tilde{y}_u = y_u \left[1 - \frac{1}{2}\bar{c}_H + \frac{3}{2}\bar{c}_u \right]$
$g_{hww}^{(2)} = \frac{g}{m_W} [\bar{c}_W + \bar{c}_{HW}]$	$\tilde{y}_\ell = y_\ell \left[1 - \frac{1}{2}\bar{c}_H + \frac{3}{2}\bar{c}_\ell \right]$

FIGURE 1: The Feynman diagrams for the process $e^+e^- \rightarrow \nu\bar{\nu}H$.

$e^+e^- \rightarrow \nu\bar{\nu}H$ process as a function of $\bar{c}_W$, $\bar{c}_B$, $\bar{c}_{HW}$, $\bar{c}_{HB}$, and $\bar{c}_\gamma$ couplings are shown in Figure 2. There have been many studies in the literature considering individual, subset, or simultaneous change of dimension-6 operators [23, 26]. Here, we vary individually dimension-6 operators and calculate the contributions to the corrections from new physics in the analysis. We presume that only one of the effective couplings is nonzero at any given time, while the other couplings are fixed to zero. One can easily see the deviation from SM for these couplings even in a small value region for $e^+e^- \rightarrow \nu\bar{\nu}H$ process. Therefore, we will only consider these five among the Higgs-gauge boson effective couplings in the detailed analysis including detector simulations through the process $e^+e^- \rightarrow \nu\bar{\nu}H$ at CLIC with 380 GeV center-of-mass energy in the next section.

3. Signal and Background Analysis

We perform the detailed analysis of $\bar{c}_W$, $\bar{c}_B$, $\bar{c}_{HW}$, $\bar{c}_{HB}$, and $\bar{c}_\gamma$ effective couplings via $e^+e^- \rightarrow \nu\bar{\nu}H$ process as well as other

FIGURE 2: The total cross section as a function of CP-conserving $\bar{c}_W = -\bar{c}_B$, $\bar{c}_{HW}$, $\bar{c}_{HB}$, and $\bar{c}_\gamma$ couplings for $e^+e^- \rightarrow \nu\bar{\nu}H$ process at the CLIC with $\sqrt{s} = 380$ GeV.

FIGURE 3: Normalized distributions of transverse momentum of tagged b -jets; b_1 (a) and b_2 (b) versus reconstructed Higgs boson-mass from b_1 and b_2 ($M_{b,\bar{b}}$) for signal with $\bar{c}_{HW} = 0.05$ and relevant background processes.

relevant backgrounds at the first energy stage of CLIC. The $e^+e^- \rightarrow \nu\bar{\nu}H$ signal process includes both s-channel $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow ZH \rightarrow \nu\bar{\nu}H$ process (Higgs-strahlung) and t-channel $e^+e^- \rightarrow \nu\bar{\nu}W^*/W^* \rightarrow \nu\bar{\nu}H$ process (WW-fusion) as shown in Figure 1. In the initial energy stage of CLIC at $\sqrt{s} = 380$ GeV, these two processes have approximately the same amount of contribution to the production cross section of the $e^+e^- \rightarrow \nu\bar{\nu}H$ process. In our analysis, we include effective dimension-6 couplings and SM contribution as well as interference between effective couplings and SM contributions ($S+B_H$) that lead to $e^+e^- \rightarrow \nu\bar{\nu}H$ process where Higgs decays to a pair of b -quarks. We consider the following relevant backgrounds: B_H : $e^+e^- \rightarrow \nu\bar{\nu}H$ process which has the same final state of the considered signal process including only SM contribution where the Higgs decays to a pair of b -quarks; B_{ZZ} : $e^+e^- \rightarrow ZZ$ process where one Z decays to $b\bar{b}$ and the other decays to $\nu\bar{\nu}$; B_{tt} : $e^+e^- \rightarrow t\bar{t}$ process where two b -quarks are from $t(\bar{t})$ decaying to $W^+b(W^-\bar{b})$ in which $W^\pm$ decay leptonically; $B_{Z\nu\nu}$: $e^+e^- \rightarrow \nu\bar{\nu}Z$ process in which Z decays to $b\bar{b}$. The generated signal and all backgrounds at parton level in `MadGraph5_aMC@NLO` are passed through `Pythia 6` [40] for parton shower and hadronization. The detector responses are taken into account with ILD detector card [41] in `Delphes 3.3.3` [42] package. Then, all events are analyzed using the `ExRootAnalysis` utility [43] with `ROOT` [44].

Requiring missing energy transverse (E_T), no charged leptons and at least 2 jets with their transverse momenta (p_T^j) greater than 20 GeV and pseudorapidity (η^j) between -2.5 and 2.5 are the preselection of the event to be further analyzed. The energy resolution of jets for $|\eta^j| \leq 3$ is assumed to be

$$\frac{\Delta E_{\text{jets}}}{E_{\text{jets}}} = 1.5\% + \frac{50\%}{\sqrt{E_{\text{jets}} \text{ (GeV)}}}. \quad (4)$$

The momentum resolution for jets as a function of p_T^j and η^j is

$$\begin{aligned} \frac{\Delta p_T^j}{p_T^j} &= (1.0 + 0.01 \times p_T^j) \times 10^{-3} \quad \text{for } |\eta^j| \leq 1 \\ \frac{\Delta p_T^j}{p_T^j} &= (1.0 + 0.01 \times p_T^j) \times 10^{-2} \quad \text{for } 1 < |\eta^j| \leq 2.4. \end{aligned} \quad (5)$$

Jets are clustered with the anti- k_t algorithm [45] using `FastJet` [46] where a cone radius is used as $R = 0.5$. In order to select the signal and background events, the following kinematic cuts and requirements are applied. (i) At least two jets tagged as the b -jet are required, which significantly suppresses the light-quark jet backgrounds; these two b -jets are used to reconstruct Higgs boson-mass. (ii) One of the b -tagged jets with the highest p_T is defined as b_1 while the other is b_2 with lower p_T . Figure 3 shows p_T distributions of b_1 and b_2 of signal (for $\bar{c}_{HW} = 0.05$) and all relevant background processes versus reconstructed Higgs boson-mass from b_1 and b_2 ($M_{b,\bar{b}}$). As it can be seen in Figure 3, b_1 with $p_T^{b_1} > 50$ GeV, b_2 with $p_T^{b_2} > 30$ GeV, and pseudorapidity of the b -tagged jets to be $|\eta^{b_1,b_2}| \leq 2.0$ are considered to reduce B_{ZZ} and $B_{Z\nu\nu}$. In ILD detector card, both b -tagging efficiency and misidentification rates are given as a function of jet transverse momentum. For the transverse momentum of leading jet (b_1) ranging from 50 GeV to 180 GeV, b -tagging efficiency is between 64% and 72%, c -jet misidentification rate is 17%–20%, and misidentification rate of light jet is 1.2%–1.76%. The missing transverse energy (E_T) and scalar transverse energy sum (H_T) for signal (for $\bar{c}_{HW} = 0.05$) and all relevant background processes versus $M_{b,\bar{b}}$ are shown in Figure 4. (iii) The missing transverse energy is required to be $E_T > 30$ GeV to suppress the backgrounds at low missing energy region. (iv) In particular, to reduce tt background

FIGURE 4: Normalized distributions of missing transverse energy (a) and scalar transverse energy sum (b) for signal versus reconstructed Higgs boson-mass from $b1$ and $b2$ ($M_{b1,b2}$) with $\bar{c}_{HW} = 0.05$ and relevant background processes.

process, the scalar transverse energy sum (H_T) is required to be $100 \text{ GeV} < H_T < 200 \text{ GeV}$. Normalized distributions of reconstructed invariant mass of Higgs boson from $b\bar{b}$ for signal with $\bar{c}_{HW} = 0.05$, $\bar{c}_{HB} = 0.05$, $\bar{c}_\gamma = 0.05$, and $\bar{c}_W = -\bar{c}_B = 0.05$ and relevant background processes are given in Figure 5. (v) Finally, the reconstructed invariant mass of Higgs boson from two b -jets is selected to be in the range $92 \text{ GeV} < M_{\text{inv}}^{\text{rec}}(b1, b2) < 136 \text{ GeV}$. The kinematic distributions for each process are normalized to the number of expected events which is defined to be the cross section of each process time integrated luminosity with $L_{\text{int}} = 500 \text{ fb}^{-1}$.

Effects of the cuts used in the analysis can be seen from Table 2, which shows the number of events after each cut. Requiring two b -tagged jets reduces the B_{ZZ} , B_{tt} , and $B_{Z\gamma\gamma}$ backgrounds more than signal $S + B_H$ and background with the same final state, B_H . Cut-2 affects both signal and all relevant backgrounds, especially B_{ZZ} and $B_{Z\gamma\gamma}$. $\cancel{E}_T$ cut decreases both B_{tt} and B_{ZZ} backgrounds while H_T cut significantly suppresses B_{tt} background. Final effect of all cuts is approximately 15% for signal $S + B_H$ and B_H background and 0.3%–0.8% for other relevant backgrounds.

4. Sensitivity of Higgs-Gauge Boson Couplings

We calculate the sensitivity of the dimension-6 Higgs-gauge boson couplings in $e^+e^- \rightarrow \nu\bar{\nu}H$ process by applying χ^2 criterion with and without a systematic error. The χ^2 function is defined as follows:

$$\chi^2(\bar{c}_i) = \sum_i^{n_{\text{bins}}} \left(\frac{N_i^{\text{NP}}(\bar{c}_i) - N_i^B}{N_i^B \Delta_i} \right)^2, \quad (6)$$

where N_i^{NP} is the total number of events in the existence of effective couplings (S) and total backgrounds (B_H , B_{ZZ} , B_{tt} , and $B_{Z\gamma\gamma}$), N_i^B is the number of events of total backgrounds in i th bin of the invariant mass distributions of reconstructed

Higgs boson, and $\Delta_i = \sqrt{\delta_{\text{sys}}^2 + 1/N_i^B}$ is the combined systematic (δ_{sys}) and statistical errors in each bin. So, the numerator in (6) is equal to the number of extra events due to the presence of new operators. In this analysis, we focused on $\bar{c}_{HB}$, $\bar{c}_W = -\bar{c}_B$, and $\bar{c}_{HW}$ couplings which are the main coefficients contributing to $e^+e^- \rightarrow \nu\bar{\nu}H$ signal process. The 95% Confidence Level (CL) limits including only statistical error on dimension-6 Higgs-gauge boson couplings at $\sqrt{s} = 380 \text{ GeV}$ and $L_{\text{int}} = 500 \text{ fb}^{-1}$ (CLIC-380) are compared with the LHC at 14 TeV center-of-mass energies for the integrated luminosity of 300 fb^{-1} (LHC-300) and 3000 fb^{-1} (LHC-3000) [18] in Figure 6. We see that CLIC-380 results would be significantly more sensitive to $\bar{c}_{HW}$ and somewhat sensitive to $\bar{c}_W = -\bar{c}_B$, whereas sensitivity to $\bar{c}_{HB}$ is comparable with expected LHC results. The prediction on the limits for the future lepton colliders: ILC [23, 28] of an integrated luminosity $L_{\text{int}} = 300 \text{ fb}^{-1}$ at the center-of-mass energy $\sqrt{s} = 500 \text{ GeV}$, FCC-ee [23] for $L_{\text{int}} = 10 \text{ ab}^{-1}$ at $\sqrt{s} = 240 \text{ GeV}$, and CEPC [32] for $L_{\text{int}} = 5 \text{ ab}^{-1}$ at $\sqrt{s} = 240 \text{ GeV}$ are also shown in Figure 6. In order to include the systematical uncertainties, we recompute the bounds. For example, including a 10% conservative systematic uncertainty, the constraint on $\bar{c}_{HW}$ is $[-0.07959; 0.02423]$. This bound is four times lower than the obtained limits without systematic uncertainties.

5. Conclusions

We have investigated the CP-conserving dimension-6 operators of Higgs boson with other SM gauge bosons via $e^+e^- \rightarrow \nu\bar{\nu}H$ process using an effective Lagrangian approach at first energy stage of CLIC ($\sqrt{s} = 380 \text{ GeV}$, $L_{\text{int}} = 500 \text{ fb}^{-1}$). We have used leading-order strongly interacting light Higgs basis assuming vanishing tree-level electroweak oblique parameterization and flavor universality of the new physics sector. We analyzed only hadronic ($b\bar{b}$) decay channel of the Higgs

TABLE 2: Number of signal and background events after applied kinematic cuts used for the analysis for $\bar{c}_{HW} = 0.05$ with $L_{\text{int}} = 500 \text{ fb}^{-1}$.

Cuts	Definitions	$S + B_H$	B_H	B_{ZZ}	B_{tt}	$B_{Z\gamma\gamma}$
Cut-0	$N_j \geq 2$, lepton vetos, MET > 0 with preselection cuts	30432.5	19383.2	207847	211384	94405.6
Cut-1	Two jets with b -tagging	8003.41	5035.96	10047.4	25636.2	6995.5
Cut-2	$p_T^{b1} > 50 \text{ GeV}$, $p_T^{b2} > 30 \text{ GeV}$, and $ \eta^{b1,b2} \leq 2.0$	5862.8	3421.5	6662.6	24766.9	3205.9
Cut-3	$\cancel{E}_T > 30 \text{ GeV}$	5548.4	3109.1	2705.4	8686.6	3122.5
Cut-4	$100 \text{ GeV} < H_T < 200 \text{ GeV}$	5407.9	3017.9	2158.1	1927.1	2823.3
Cut-5	$100 \text{ GeV} < M_{\text{inv}}^{\text{rec}}(b1, b2) < 136 \text{ GeV}$	4211.6	2433.7	17.9	824.8	20.9

FIGURE 5: Normalized distributions of reconstructed invariant mass of Higgs boson from $b\bar{b}$ for signal with $\bar{c}_{HW} = 0.05$, $\bar{c}_{HB} = 0.05$, $\bar{c}_\gamma = 0.05$, and $\bar{c}_W = -\bar{c}_B = 0.05$ and relevant background processes.

FIGURE 6: Obtained allowed range (CLIC-380); LHC at 14 TeV center-of-mass energies for the integrated luminosity of 300 fb^{-1} (LHC-300) and 3000 fb^{-1} (LHC-3000) [18]; ILC-300 at $\sqrt{s} = 500 \text{ GeV}$ with $L_{\text{int}} = 300 \text{ fb}^{-1}$ [23, 28]; FCC-ee for $L_{\text{int}} = 10 \text{ ab}^{-1}$ at $\sqrt{s} = 240 \text{ GeV}$ [23]; CEPC for $L_{\text{int}} = 5 \text{ ab}^{-1}$ at $\sqrt{s} = 240 \text{ GeV}$ [32] at 95% CL for $\bar{c}_{HW}$, $\bar{c}_{HB}$, and $\bar{c}_W = -\bar{c}_B$ coefficients. The limits are each derived with all other coefficients set to zero.

boson including dominant background processes by considering realistic detector effect in the analysis. We have shown the kinematic distributions of b -jets in final state, missing transverse energy, scalar transverse energy sum, and invariant mass distributions. Due to the fact that the signal final state consists of two neutrinos and two b -jets, the distributions of missing transverse energy and scalar transverse energy sum are performed for determining a cut-based analysis. We have obtained 95% CL limits on dimension-six operators analyzing invariant mass distributions of two b -jets from Higgs decay in $e^+e^- \rightarrow \nu\bar{\nu}H$ signal process and the other dominant backgrounds. The $e^+e^- \rightarrow \nu\bar{\nu}H$ process is more sensitive to $\bar{c}_{HW}$ couplings than the other dimension-six couplings at first energy stage of CLIC. Our results show that a CLIC with $\sqrt{s} = 380 \text{ GeV}$ and $L_{\text{int}} = 500 \text{ fb}^{-1}$ will be able to probe the dimension-six couplings of Higgs-gauge boson interactions in $e^+e^- \rightarrow \nu\bar{\nu}H$ process especially for $\bar{c}_{HW}$ couplings at scales beyond the HL-LHC bounds while they become competitive with the $\bar{c}_{HB}$, $\bar{c}_W = -\bar{c}_B$ couplings.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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