The Higgsstrahlung process in the Standard model extensions

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Abstract

Within the left-right symmetric model (LRM) and the effective rank 5 models (ER5M's) the Higgsstrahlung process

$$e^+e^- \to ZH$$

is considered. It was shown that the deviations from the SM predicted by the LRM are larger than that predicted by the ER5M's. Investigation of the Higgsstrahlung disclosed that with its help one could make a choice between the SM and the SM extensions under consideration.

1 Introduction

On July 4, 2012 the discovery of a narrow resonance, with a mass near 125.7 GeV, in the search for the Standard Model (SM) Higgs boson at the Large Hadron Collider (LHC) was announced at CERN by both the ATLAS [1] and CMS [2]. This discovery shows once again that with the advent of the LHC, particle physics has entered a new exciting era. The Higgs boson observation not only confirmed the so-called Higgs mechanism for the electroweak symmetry breaking, but also opened a new possibility to perform a precise test of the SM. Within the current experimental and theoretical uncertainties the properties of the newly discovered particle are thus far in very good agreement with the predictions for a SM Higgs boson.

Due to its gauge charges the Higgs boson may interact with the beyond SM particles. This new interaction can also modify the couplings between the Higgs and SM particles at tree level or loop level. Some of the simplest extensions of the SM are those that add new neutral gauge boson Z' which could arise from a variety of contexts, ranging from simple extra $U(1)$ gauge symmetries [3], left-right models (LRM's)[3], 3-3-1 models [4], little Higgs models [5], technicolour models [6] and so on.

It is obvious that deviations from the SM predictions could be interpreted in terms of Z' parameters. Properties of Z' boson are mainly being investigated in collider experiments (see for review [7]). At hadron colliders the Z' boson could be produced via Drell-Yan production and would then be observed in the invariant mass distribution of the pair produced final state particles. In the case of e^+e^- colliders the basic processes for studying Z' boson parameters are fermion pair production, Bhabha and Möller scattering, along with W pair production.

When the LHC reaches its design energy and luminosity it should be able to see evidence for Z' up to ~ 5 TeV for a large variety of the SM extensions [8], and the HL-LHC will extend this reach up to $\sim$ 6 TeV. The high energy LHC (HE-LHC) would substantially extend this reach to $\sim$ 11 TeV. In comparison, a 500 GeV e^+e^- collider with $\mathcal{L} = 500$ fb^{-1} will be sensitive to $m_{Z'}$ $\sim$ 6 TeV that is comparable to potentiality of the HL-LHC while a 1 TeV e^+e^- collider with $\mathcal{L} = 1$ ab^{-1} will be able to detect Z' with the mass $\sim$ 12 TeV which has the same order as the lower bound of $m_{Z'}$ at HE-LHC.

In this paper we shall centre on the two most popular GUT scenarios, namely, the LRM's and models coming from E_6 grand unification (effective rank-5 models — ER5M's). Within these SM extensions we shall consider the associated Higgs boson production with Z boson at the electron-positron annihilation

$$e^+ + e^- \to Z + H, \tag{1}$$

where H is an analog of the SM Higgs boson. The cross section of (1) are function of $m_{Z'}$ and contain the coupling constants g_{HZZ} and $g_{HZZ'}$ which describe interaction of the Higgs boson H with the neutral gauge bosons Z and Z'. The aim of the work is to investigate the influence of these parameters on the reaction in question. To avoid confusion, for every SM extensions we shall use the notations which have been universally accepted. For example, in the LRM the analog of the SM neutral gauge boson and the extra neutral gauge boson are symbolized by Z_1 and Z_2, respectively, while in the ER5M's they are indicated by the symbols Z and Z'.

2 Models

The LRM, based on the low-energy gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, can arise from an $SO(10)$ or E_6 GUT. In this model, because of a symmetry between the two gauge $SU(2)$ groups quarks and leptons enter both into the left- and right-handed doublets. The LRM has three gauge coupling constants: g_L, g_R, and g' for the $SU(2)_L$, $SU(2)_R$, and $U(1)_{B-L}$ groups, respectively. In the more simplest case (canonical LRM) the Higgs sector includes one bi-doublet $\Phi\left(\frac{1}{2}, \frac{1^*}{2}, 0\right)$

$$\Phi = \begin{pmatrix} \Phi_1^0 & \Phi_2^+ \\ \Phi_1^- & \Phi_2^0 \end{pmatrix}, \tag{2}$$

and two triplets $\Delta_L(1,0,2)$, $\Delta_R(0,1,2)$

$$(\boldsymbol{\sigma}\cdot\boldsymbol{\Delta}_L) = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}, \qquad (\boldsymbol{\sigma}\cdot\boldsymbol{\Delta}_R) = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}. \tag{3}$$

The symmetry breaking is triggered by the following VEVs

$$<\Phi>= \begin{pmatrix} k_1/\sqrt{2} & 0 \\ 0 & k_2/\sqrt{2} \end{pmatrix}, \qquad <\Delta_{L,R}>= \begin{pmatrix} 0 & 0 \\ v_{L,R}/\sqrt{2} & 0 \end{pmatrix}.$$

The bidoublet VEVs k_1 and k_2 break the SM symmetry and are of the order of the electroweak scale (EWS). Therefore, the VEVs obey to the following hierarchy

$$v_L << \max(k_1, k_2) << v_R. \tag{4}$$

After the spontaneous symmetry breaking we have 14 physical Higgs bosons: four doubly-charged scalars $\Delta_{1,2}^{(\pm\pm)}$, four singly-charged scalars $\tilde{\delta}^{(\pm)}$ and $h^{(\pm)}$, four neutral scalars $S_{1,2,3,4}$, and two neutral pseudoscalars $P_{1,2}$. The S_1 boson is an analog of the SM Higgs boson.

In the case $g_L = g_R$ the Lagrangians which will be needed in our calculation are as follows (see the book [9])

$$-L_{NC}^{LRM} = \sum_f \{\overline{\psi}_f(x)\gamma_\mu(g_{V_f}^{(1)} - g_{A_f}^{(1)}\gamma_5)Z_1^\mu(x)\psi_f(x) + \overline{\psi}_f(x)\gamma_\mu(g_{V_f}^{(2)} - g_{Af}^{(2)}\gamma_5)Z_2^\mu(x)\psi_f(x), \tag{5}$$

$$L_{S_1Z_nZ_k} = g_{S_1Z_nZ_k} S_1(x) Z_n^{\mu}(x) Z_{k\mu}(x), \qquad (n,k=1,2), \tag{6}$$

where

$$g_{Vf}^{(1)} = \frac{1}{2}\Bigg\{ec_\phi c_W^{-1} s_W^{-1}\Bigg[S_3^W(f_L) - 2Q(f)s_W^2\Bigg] +$$

$$+\frac{es_\phi c_W^{-1}}{\sqrt{e^{-2}g_R^2c_W^2-1}}\Bigg[e^{-2}g_R^2c_W^2S_3^W(f_R) + S_3^W(f_L) - 2Q(f)\Bigg]\Bigg\},$$

$$g_{Af}^{(1)} = \frac{1}{2}\Bigg\{ec_\phi c_W^{-1} s_W^{-1} S_3^W(f_L) - \frac{es_\phi c_W^{-1}}{\sqrt{e^{-2}g_R^2c_W^2-1}}\Bigg[e^{-2}g_R^2c_W^2S_3^W(f_R) - S_3^W(f_L)\Bigg]\Bigg\},$$

$$g_{Vf}^{(2)} = g_{Vf}^{(1)}\left(\phi \to \phi + \frac{\pi}{2}\right), \qquad g_{Af}^{(2)} = g_{Af}^{(1)}\left(\phi \to \phi + \frac{\pi}{2}\right), \qquad c_\phi = \cos\phi, \qquad s_\phi = \sin\phi,$$

$$g_{S_1Z_1Z_1} = -\frac{g_L^2(k_-^2c_\theta + 2k_1k_2s_\theta)}{2\sqrt{2}c_W^2k_+}(c_\Phi - \sqrt{c_W^2 - s_W^2}s_\Phi)^2, \qquad k_- = \sqrt{k_1^2 - k_2^2},$$

$$g_{S_1Z_1Z_2} = \frac{g_L^2(k_-^2c_\theta + 2k_1k_2s_\theta)}{\sqrt{2}c_W^2k_+}[2c_W^2c_\Phi s_\Phi + \sqrt{c_W^2 - s_W^2}(c_\Phi^2 - s_\Phi^2)],$$

$$g_{S_1Z_2Z_2} = -\frac{g_L^2(k_-^2c_\theta + 2k_1k_2s_\theta)}{2\sqrt{2}c_W^2k_+}(\sqrt{c_W^2 - s_W^2}c_\Phi + s_\Phi)^2,$$

$s_W = \sin\theta_W$, $c_W = \cos\theta_W$, θ_W is the Weinberg angle, and θ is the mixing angle in the sector of the neutral Higgs bosons S_1 and S_2 ($\tan 2\theta \sim k_-^2/v_R^2$). Since the mixing angle in the neutral gauge boson sector ϕ is very small (it was found $-0.0023 < \phi < 0.0027$) then in what follows we shall ignore by the mixing in the neutral gauge boson sector. In this case the couplings constants $g_{V_f}^{(1)}$ and $g_{A_f}^{(1)}$ are the same as in the SM ($g_{V_f}^{(1)} = g_{V_f}, g_{A_f}^{(1)} = g_{A_f}$).

There are two possibilities of defining the left-right (LR) symmetry as a generalized parity P and as a generalized charge conjugation C. However, instead of using parity or charge conjugation, one could choose D-parity, which is broken spontaneously [10]. In this case the discrete parity symmetry gets broken (by the VEV of a parity odd singlet scalar field) much before the $SU(2)_R$ gauge symmetry breaks. The gauge group is effectively $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$, where P is the discrete left-right symmetry which we call D-parity. This D-parity symmetry is different from the Lorentz parity in the sense that Lorentz parity interchanges left handed fermions with the right handed ones but the bosonic fields remain the same. Whereas, the D-parity also interchanges the $SU(2)_L$ Higgs fields with the $SU(2)_R$ Higgs fields. The parity odd singlet field breaks this gauge symmetry at high scale $\sim (10^{16} - 10^{19})$ GeV to $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ which further breaks down to the SM gauge group at a lower scale. In such a version of the LRM's the relation between gauge boson masses does not hold and the charged gauge boson $W_R^{\pm}$ appears to be more massive than the neutral gauge boson Z_R. Then a collider analysis using the 8 TeV ATLAS 20.3 fb^{-1} luminosity dilepton data [11] derives $m_{Z_R} \geq 2.5$ TeV for $g_L = g_R$.

Further we consider the simplest E_6-based low-energy group, $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ resulting from compactification of 10-dimensional $E_8 \times E_8'$ superstring theory to four dimensions on a manifold with a $SU(3)$ holonomy [12]. The compactification scheme of the model predicts that the matter fields occur in three supersymmetric chiral multiplets, each transforming according to the quantum numbers of the fundamental **27** of E_6. Among the fields associated with each such multiplet are five colorless neutral superfields: one is usually assigned nonzero lepton number, while two, $H_1^{(a)}$ and $H_2^{(a)}$ ($a = 1,2,3$), belong to doublets of the residual $SU(2)$, and the remaining two, $N_1^{(a)}$ and $N_2^{(a)}$, are singlets under $SU(2)$. Usually one works in the basis when the breaking of the $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ symmetry down to $U(1)_{em}$ is realized when only the neutral components of the third-family Higgs fields $N_1^{(3)}$, $N_2^{(3)}$ and $H_1^{(3)}$ acquire nonzero VEV's — v_1, v_2 and n ($v_1, v_2 \ll n$), respectively. As usual, several of the degrees of freedom of these third-family Higgs bosons are eaten by the W, Z, and Z' in acquiring mass, and we are left with the six physical Higgs bosons: one neutral pseudoscalar H_3^0, three neutral scalars H_α^0 ($\alpha = 2, deg, Z'$), and two singly-charged scalars $H^\pm$ (the neutral scalar degenerate with H_3^0 and $H^\pm$ is denoted by H_{deg}^0 and that degenerate with Z' by $H_{Z'}^0$).

The third-family Higgs bosons will have trilinear tree-level couplings to vector-boson pairs and their Yukawa couplings to fermions of all generations will be tied to the fermion masses. In contrast, the Higgs fields of the first and second families by definition do not have VEV's and they possess only quartic couplings to vector-boson pairs, and their Yukawa couplings to fermions of their own and other generations cannot be very large. Therefore, only the Higgs bosons associated with the third-generation **27** multiplet of E_6 participate in the electroweak symmetry breaking.

Below we give the Lagrangians of the neutral Higgs boson H_2^0 being an analog of the SM Higgs with the fermions and neutral gauge bosons:

$$-L_{NC}^{E_6} = \sum_f \{\overline{\psi}_f(x)\gamma_\mu(g_{V_f} - g_{A_f}\gamma_5)Z^\mu(x)\psi_f(x) + \overline{\psi}_f(x)\gamma_\mu(g'_{V_f} - g'_{A_f}\gamma_5)Z'^\mu(x)\psi_f(x), \qquad (7)$$

$$L_{NGB}^{E_6} = g_{H_2^0 ZZ} H_2^0(x) Z_\mu(x) Z^\mu(x) + g_{H_2^0 ZZ'} H_2^0(x) Z_\mu(x) Z'^\mu(x), \qquad (8)$$

where

$$Z = Z_1 \cos\phi + Z_2 \sin\phi, \qquad Z' = Z_1 \sin\phi + Z_2 \cos\phi,$$

$$g'_{V_l} = -g'_{V_d} = \frac{e c_\beta}{c_W}\sqrt{\frac{5}{30}}, \qquad g'_{A_l} = g'_{A_d} = \frac{e}{2c_W}\sqrt{\frac{5}{3}}\left[\frac{c_\beta}{\sqrt{10}} + \frac{s_\beta}{\sqrt{6}}\right],$$

$$g'_{V_\nu} = g'_{A_\nu} = \frac{e}{2c_W}\sqrt{\frac{5}{3}}\left[\frac{3c_\beta}{\sqrt{40}} + \frac{s_\beta}{\sqrt{24}}\right], \qquad g'_{V_u} = \frac{e}{2c_W}\sqrt{\frac{5}{3}}\left[-\frac{c_\beta}{\sqrt{10}} + \frac{s_\beta}{\sqrt{6}}\right], \qquad g'_{A_u} = 0,$$

$$g_{H_2^0 ZZ} = \frac{e m_Z}{s_W c_W}, \qquad g_{H_2^0 ZZ'} = \frac{e m_Z}{3 c_W}(c_\beta^2 - 4 s_\beta^2), \qquad \tan\beta = \frac{v_2}{v_1}$$

$c_\beta = \cos\beta$ and $s_\beta = \sin\beta$ (the expressions for $g_{H_2^0 ZZ}$ and $g_{H_2^0 ZZ'}$ are given in the limit of large n and small neutral gauge boson mixing). β is treated as a free parameter and its particular values correspond to special models. The more popular models of this kind (effective rank-5 models — ER5M's) are as follows: the Z_χ model ($\beta = 0$), the Z_ψ model ($\beta = \pi/2$), the Z_η model ($\beta = \pi - \arctan\sqrt{5/3}$), the Z_I model — the inert model ($-\beta = \arctan\sqrt{3/5}$), the Z_N model — the neutral model ($\beta = \arctan\sqrt{15}$), the Z_N model — the secluded sector model ($\beta = \arctan\sqrt{15}/9$).

At present, the highest mass bounds on most extra neutral gauge bosons are obtained by searches at the LHC by the ATLAS and CMS experiments. The current direct limits of $m_{Z'}$ are ~ 3 TeV. For example, results based on dilepton resonance searches in $\mu^+\mu^-$ and e^+e^- final states have used data from the 7 TeV proton collisions collected in 2011 and the more recent 8 TeV data collected in 2012. ATLAS [?] has obtained exclusion limits at 95% C.L. of $m_{Z_\eta} > 2.44$ TeV, $m_{Z_\chi} > 2.54$ TeV and $m_{Z_\psi} > 2.38$ TeV from 8 TeV collisions with 20 fb^{-1} integrated luminosity, while CMS [13] has obtained 95% C.L. exclusion limits of $m_{Z_\psi} > 2.60$ TeV from 8 TeV collisions using 20 fb^{-1} of integrated luminosity.

3 The process $e^+e^- \to ZH$

Now we investigate the Higgsstrahlung (HS) that should be measured with precision at high-energy e^+e^- colliders. At present various options of such devices are being considered. The most nature concept is a linear e^-e^+ collider, and two projects are being developed, namely, the International Linear Collider (ILC) that would operate at energies up to 1 TeV, and Compact Linear Collider (CLIC) that could possibly operate at energies up to 3 TeV.

Let us start with the LRM. The Feynman diagram corresponding to the process $e^+e^- \to Z_1S_1$ are shown on Fig.1. The total cross section is defined by the expression

$$\sigma^{LRM}(e^+e^- \to Z_1S_1) = \frac{\beta_{Z_1}(3m_{Z_1}^2 + \beta_{Z_1}^2)}{18\pi m_{Z_1}^2\sqrt{s}}\Bigg\{\frac{g_{S_1Z_1Z_1}^2(g_{V_e}^2 + g_{A_e}^2)}{[(s-m_{Z_1}^2)^2 + m_{Z_1}^2\Gamma_{Z_1}^2}+$$

$$+\frac{2g_{S_1Z_1Z_1}g_{S_1Z_1Z_2}(g_{V_e}g_{V_e}^{(2)} + g_{A_e}g_{A_e}^{(2)})[(s-m_{Z_1}^2)(s-m_{Z_2}^2) + m_{Z_1}m_{Z_2}\Gamma_{Z_1}\Gamma_{Z_2}]}{[(s-m_{Z_1}^2)^2 + m_{Z_1}^2\Gamma_{Z_1}^2][(s-m_{Z_2}^2)^2 + m_{Z_2}^2\Gamma_{Z_2}^2]}+$$

$$+\frac{g_{S_1Z_1Z_2}^2[(g_{V_e}^{(2)})^2 + (g_{A_e}^{(2)})^2]}{[(s-m_{Z_2}^2)^2 + m_{Z_2}^2\Gamma_{Z_2}^2]}\Bigg\}, \quad (9)$$

where

$$\beta_{Z_1} = \frac{\sqrt{s-(m_{Z_1}^2 - m_{S_1}^2)}\sqrt{s-(m_{Z_1}^2 + m_{S_1}^2)}}{2\sqrt{s}},$$

and s is the center-of-mass energy squared.

The first term in Eq. (9) which we shall symbolize as a $\sigma_{Z_1Z_1}$ is connected with the Feynman diagram for $e^-e^+ \to Z_1Z_1^* \to Z_1S_1$ and when $g_{S_1Z_1Z_1} = g_{HZZ} = 2em_Z/\sin 2\theta_W$ it coincides with the SM result [14]. The third term denoted by $\sigma_{Z_2Z_2}$ is associated with the Feynman diagram for $e^-e^+ \to Z_1Z_2^* \to Z_1S_1$. The second term $\sigma_{Z_1Z_2}$ describes the interference of the diagrams with the Z_1- and Z_2-boson in the virtual states. Since at the substitution

$$g_{S_1Z_1Z_2} \to g_{S_1Z_1Z_1}, \qquad g_{V_e}^{(2)} \to g_{V_e}, \qquad g_{A_e}^{(2)} \to g_{A_e}, \qquad m_{Z_2} \to m_{Z_1}, \quad \Gamma_{Z_2} \to \Gamma_{Z_1}, \quad (10)$$

the diagram describing $e^-e^+ \to Z_1Z_2^* \to Z_1S_1$ passes into the diagram describing $e^-e^+ \to Z_1Z_1^* \to Z_1S_1$, then the expression (25) admits the following simple checking. When we fulfill the replacement (10) then the third term must change over to the first one and the second term (interference term) divided by two converts to the first one too, that is to say,

$$\sigma_{Z_2Z_2} \to \sigma_{Z_1Z_1}, \qquad \frac{1}{2}\sigma_{Z_1Z_2} \to \sigma_{Z_1Z_1}. \quad (11)$$

In Refs.[15, 16] the HS has been considered within the $SU(2)_L\times U(1)_Y\times U(1)_{B-L}$ model with the extra Z' boson. The results of these works do not coincide even with each other. Moreover, in the cross section obtained in Ref. [15] the term σ_{ZZ} does not equal to the SM expression. In regard to the work [16], then here the obtained cross section holds the SM contribution but at the replacement of the type (10) the interference term divided by two does not change-over to the SM term as one should expect.

At e^+e^- collider the Higgsstrahlung process is dominant for moderate values of the ratio $m_H/\sqrt{s}$. At high energies it falls off according to the scaling law s^{-1}. When $\sqrt{s} = m_{Z_2}$ there is the resonance peak whose high crucially depends on the ratio $r = g_{S_1Z_1Z_2}/g_{S_1Z_1Z_1}$ and the total decay width of Z_2 boson. By virtue of the fact that in the LRM $r = -2\sqrt{c_W^2 - s_W^2}$, the resonance effect will be important.

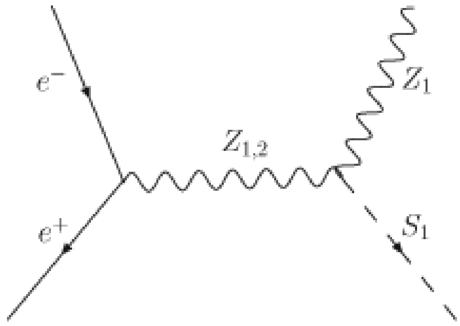

Figure 1: The Feynman diagrams for $e^+e^- \to Z_1 S_1$.

If one assumes that $g_{S_1Z_1Z_1}$ takes the SM value, then we may directly compare the SM cross section with the LRM one. In this case the latter will look like

$$\sigma^{LRM} = \sigma^{SM} + \Delta\sigma, \tag{12}$$

where

$$\Delta\sigma = \frac{g_L^4 \beta_{Z_1}(3m_{Z_1}^2 + \beta_{Z_1}^2)}{72\pi c_W^4 \sqrt{s}} \left\{ \frac{(16s_W^4 - 6s_W^2)[(s - m_{Z_1}^2)(s - m_{Z_2}^2) + m_{Z_1} m_{Z_2} \Gamma_{Z_1} \Gamma_{Z_2}]}{[(s - m_{Z_1}^2)^2 + m_{Z_1}^2 \Gamma_{Z_1}^2][(s - m_{Z_2}^2)^2 + m_{Z_2}^2 \Gamma_{Z_2}^2]} - \right.$$
$$\left. - \frac{20s_W^4 - 12s_W^2 + 2}{[(s - m_{Z_2}^2)^2 + m_{Z_2}^2 \Gamma_{Z_2}^2]} \right\}.$$

Calculations show that in the case under consideration contributions coming from the second term in (12) are sizable

$$\left.\frac{\Delta\sigma}{\sigma^{SM}}\right|_{\sqrt{s}=0.5\ TeV} \simeq \begin{cases} 8.3\%, & \text{when } m_{Z_2} = 2.5 \text{ TeV}, \\ 3.2\%, & \text{when } m_{Z_2} = 4 \text{ TeV}, \\ 0.5\%, & \text{when } m_{Z_2} = 10 \text{ TeV}, \end{cases} \tag{13}$$

and

$$\left.\frac{\Delta\sigma}{\sigma^{SM}}\right|_{\sqrt{s}=1\ TeV} \simeq \begin{cases} 35\%, & \text{when } m_{Z_2} = 2.5 \text{ TeV}, \\ 13.5\%, & \text{when } m_{Z_2} = 4 \text{ TeV}, \\ 2.1\%, & \text{when } m_{Z_2} = 10 \text{ TeV}. \end{cases} \tag{14}$$

Once it will prove that the coupling constant $g_{S_1Z_1Z_1}$ does not equal to the SM value, then we have to examine the case of the polarized electron-positron beams. With this object in mind the following quantities are introduced

$$\lambda_{\pm}^{SM} = \frac{\sigma_{\pm}^{SM}}{\sigma_{+}^{SM} + \sigma_{-}^{SM}}, \qquad \lambda_{\pm}^{LRM}(s) = \frac{\sigma_{\pm}^{LRM}}{\sigma_{+}^{LRM} + \sigma_{-}^{LRM}}, \qquad \lambda_{\pm}^{LRM}(s) = \lambda_{\pm}^{SM} + \delta_{\pm}^{LRM}(s), \tag{15}$$

where σ_+^{SM} (σ_-^{SM}) is the SM cross section for the left- (right-) polarized electrons. Then we have

$$\left.\frac{\delta_+^{LRM}(s)}{\lambda_+^{SM}}\right|_{\sqrt{s}=0.5\ TeV} \simeq \begin{cases} 1.7\%, & \text{when } m_{Z_2} = 2.5 \text{ TeV}, \\ 0.6\%, & \text{when } m_{Z_2} = 4 \text{ TeV}, \\ 0.1\%, & \text{when } m_{Z_2} = 10 \text{ TeV}, \end{cases} \tag{16}$$

and

$$\left.\frac{\delta_+^{LRM}(s)}{\lambda_+^{SM}}\right|_{\sqrt{s}=1\ TeV} \simeq \begin{cases} 9\%, & \text{when } m_{Z_2} = 2.5 \text{ TeV}, \\ 2.8\%, & \text{when } m_{Z_2} = 4 \text{ TeV}, \\ 0.4\%, & \text{when } m_{Z_2} = 10 \text{ TeV}. \end{cases} \tag{17}$$

The total cross section of the Higgsstrahlung for the ER5M's follows from Eq. (9) under replacements like (10). In that event we shall also work with the polarized electron-positron beams. Analysis reveals that the maximal deviation from the SM prediction occurs for the η-model. But now the value of $\delta_+^{E_6}$ is one order of magnitude less than in the LRM case. To cite an example, we have

$$\left.\delta_+^{E_6}(s)\right|_{\sqrt{s}=1\ TeV} \simeq \begin{cases} -0.026, & \text{when } m_{Z_2} = 1.5 \text{ TeV} \\ -0.013, & \text{when } m_{Z_2} = 2 \text{ TeV}, \\ -0.003, & \text{when } m_{Z_2} = 4 \text{ TeV}. \end{cases} \tag{18}$$

At ILC one could achieve luminosity $\mathcal{L} \sim \mathcal{O}(\text{ab}^{-1})$ at $\sqrt{s} \sim \mathcal{O}(\text{TeV})$. In this range, for example, the SM cross section has the order of magnitude of $few \times 10^{-1}$ pb. Then, the number of the produced Higgs bosons which is predicted by the SM is as large as

$$n = \sigma^{SM}(e^+e^- \to ZH) \times \mathcal{L} \sim \text{few pb} \times 1 \text{ ab}^{-1} \sim \text{few} \times 10^5.$$

So, we have a good chance to establish whether deviations from the SM take place or not.

The cleanest channel for isolating the Higgsstrahlung from the background is provided by the $\mu^+\mu^-$ or e^+e^- decay mode for the Z boson and $b\bar{b}$ decay mode for H boson. The detail analysis of the background processes could be found in Ref. [14].

4 Conclusion

Two kinds of models arising in a GUT scenario, the LRM and ER5M's, have been considered. The associated Higgs production with Z boson at the electron positron annihilation (Higgsstrahlung)

$$e^+ + e^- \to Z + H$$

has been investigated. For the LRM two cases, $g_{S_1Z_1Z_1} = g_{HZZ}$ and $g_{S_1Z_1Z_1} \neq g_{HZZ}$, have been treated. In the former the total cross sections of the LRM and the SM have been compared directly. Analysis shows that even at the first stage of the ILC ($\sqrt{s} = 0.5$ TeV) one could get the lower bound on the extra neutral gauge boson mass equal to 7 TeV. To do this, one should measure the Higgsstrahlung with the precision of about 1%.

For the case $g_{S_1Z_1Z_1} \neq g_{HZZ}$ we have compared the ratios of the cross section with the left-polarized electrons to the cross section with the unpolarized electrons for the SM and LRM. If one supposes that the cross sections would be measured with the precision of about 1%, then the lower bound on the extra neutral gauge boson mass equal to 6.4 TeV would be obtained only at the second stage of the ILC ($\sqrt{s} = 1$ TeV).

The Higgsstrahlung investigation has shown that among the ER5M's the maximal deviations from the SM gives the η model. In that event the deviations from the SM predictions appear to be small than for the LRM, and, as a result, the 1% precision of the cross section measurement allows to obtain the bound $m_{Z'} \geq 2.5$ TeV only at $\sqrt{s} = 1$ TeV.

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