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The Higgs decay $H \to Z\overline{f}f$

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Two most popular GUT scenarios, namely, the left-right symmetric model and models coming from E_6 grand unification are considered. Both models predict existence of the additional neutral gauge boson. Its contributions to the decay of the Higgs boson being an analog of the standard model (SM) Higgs boson $H \to Z\overline{f}f$ are found.

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1. Introduction

The discovery of a Higgs boson with a mass near 125 GeV by the experiments ATLAS [1] and CMS [2] at the CERN Large Hadron Collider (LHC) is an important milestone, and it is of fundamental interest to study the properties of this state, its quantum numbers and couplings. Using all of the available data, with a total luminosity of 25 fb^{-1} from the pp collisions with energies of $\sqrt{s} = 7$ and 8 TeV runs at the LHC, such properties of the discovered Higgs boson as a spin, parity, mass, and the couplings to other standard model (SM) particles, has been further investigated. According to the present data properties of this Higgs particle are in good agreement with the standard model (SM) expectations. However, the experimental uncertainties are still large though, for example, the total decay width of the SM Higgs (Γ_t) being around 4 MeV is not expected to be directly observable at the LHC by virtue of the fact that Γ_t is several orders of magnitude smaller than the experimental mass resolution. The High Luminosity-LHC is a major upgrade of the LHC to produce an integrated luminosity of 3000 fb^{-1}. It is scheduled that the precision of measuring the Higgs couplings will be improved from at present several tens of percent to about 10%. The future electron-positron linear collider (ILC) can further enlarge the accuracy bringing it up to 1%.

Since the SM cannot explain gravity, nonbaryonic cold dark matter, dark energy, the baryon asymmetry of the Universe, violation of the individual lepton flavors, neutrino masses and mixings, $(g-2)_\mu$-anomaly, and hierarchy problem, then it can be interpreted to be a ultimate truth. It may be safely suggested that the SM appears to be a good effective field theory at the least up to the energies probed by the first run of LHC.

In many the SM extensions an additional neutral gauge boson appears. It could arise from a variety of contexts, ranging from simple extra $U(1)$ gauge symmetries [3], left-right models (LRM's)[3, 4], 3-3-1 models [5] and so on. The recent bounds from LHC indicate that this additional neutral gauge boson should be heavier than about 1.5 TeV. Future LHC runs at 13-14 TeV will increase this mass bound or luckily will find evidence of its presence.

In this work we are going to investigate the decay of an analog of the Higgs boson

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through the channel

$$H \to Z + f + \overline{f} \qquad (1)$$

in the context of the two most popular GUT scenarios, namely, the LRM's and models coming from E_6 grand unification (effective rank-5 models — ER5M's). In the next section we shall give the short description of the models under consideration. In section III the partial width of the decay (1) will be obtained and analyzed. Section IV summarizes our results.

2. Description of the 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. Here quarks and leptons enter both into the left- and right-handed doublets

$$q^i_L(\frac{1}{2}, 0, \frac{1}{3}), \qquad q^i_R(0, \frac{1}{2}, \frac{1}{3}), \qquad l^a_L(\frac{1}{2}, 0, -1), \qquad l^a_R(0, \frac{1}{2}, -1)$$

where in brackets the values of S^W_L, S^W_R and $B-L$ are given, S^W_L (S^W_R) is the weak left-handed (right-handed) isospin while B and L are the baryon and lepton numbers, respectively. 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. The Higgs sector includes one bi-doublet $\Phi\left(\frac{1}{2}, \frac{1^*}{2}, 0\right)$ and two triplets $\Delta_L(1, 0, 2)$, $\Delta_R(0, 1, 2)$ The symmetry breaking is triggered by the following vacuum expectation values (VEV's)

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

where

$$v_L << \max(k_1, k_2) << v_R.$$

After the spontaneous symmetry breaking (SSB) we are left with 14 physical Higgs bosons: four doubly-charged scalars $\Delta^{(\pm\pm)}_{1,2}$, four singly-charged scalars $\tilde{\delta}^{(\pm)}$ and $h^{(\pm)}$, four neutral scalars $S_{1,2,3,4}$, and two neutral pseudoscalars $P_{1,2}$ (S_1 is an analog of the SM Higgs). In the case $g_L = g_R$ the Lagrangians that will be needed in our calculations are as follows [6]

$$-L^{LRM}_{NC} = \overline{\psi}_f\gamma_\mu(g^{(1)}_{V_f} - g^{(1)}_{A_f}\gamma_5)Z^\mu_1\psi_f + \overline{\psi}_f\gamma_\mu(g^{(2)}_{V_f} - g^{(2)}_{Af}\gamma_5)Z^\mu_2\psi_f, \qquad (2)$$

$$L_{S_1Z_nZ_k} = g_{S_1Z_nZ_k}S_1(x)Z^\mu_n(x)Z_{k\mu}(x), \qquad (3)$$

where

$$g^{(1)}_{Vf} = \frac{1}{2}\Bigg\{ec_\phi c^{-1}_W s^{-1}_W\left[S^W_3(f_L) - 2Q(f)s^2_W\right] +$$

$$+\frac{es_\phi c^{-1}_W}{\sqrt{e^{-2}g^2_Rc^2_W - 1}}\left[e^{-2}g^2_Rc^2_W S^W_3(f_R) + S^W_3(f_L) - 2Q(f)\right]\Bigg\},$$

$$g^{(1)}_{Af} = \frac{1}{2}\Bigg\{ec_\phi c^{-1}_W s^{-1}_W S^W_3(f_L) - \frac{es_\phi c^{-1}_W}{\sqrt{e^{-2}g^2_Rc^2_W - 1}}\left[e^{-2}g^2_Rc^2_W S^W_3(f_R) - S^W_3(f_L)\right]\Bigg\},$$

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

$$g_{S_1Z_1Z_1} = -\frac{g_L^2(k_-^2 c_\theta + 2k_1k_2 s_\theta)}{2\sqrt{2}c_W^2 k_+}(c_\Phi - \sqrt{c_W^2 - s_W^2}s_\Phi)^2,$$

$$g_{S_1Z_1Z_2} = \frac{g_L^2(k_-^2 c_\theta + 2k_1k_2 s_\theta)}{\sqrt{2}c_W^2 k_+}[2c_W^2 c_\Phi s_\Phi + \sqrt{c_W^2 - s_W^2}(c_\Phi^2 - s_\Phi^2)],$$

$$g_{S_1Z_2Z_2} = -\frac{g_L^2(k_-^2 c_\theta + 2k_1k_2 s_\theta)}{2\sqrt{2}c_W^2 k_+}(\sqrt{c_W^2 - s_W^2}c_\Phi + s_\Phi)^2,$$

$s_W = \sin\theta_W,\ k_\pm = \sqrt{k_1^2 \pm k_2^2}$. In what follows in order 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'.

We shall also 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 [7]. The matter fields occur in three supersymmetric chiral multiplets, each transforming according to the quantum numbers of the fundamental **27** of E_6. In each multiplet there are five colorless neutral superfields: one is usually assigned nonzero lepton number, while two, $H_1^{(a)}$ and $H_2^{(a)}$ belong to doublets of the residual $SU(2)$, and the remaining two, $N_1^{(a)}$ and $N_2^{(a)}$, are singlets under $SU(2)$. Breaking $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ 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 VEV's (v_1, v_2 and n). After SSB we have: 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. The Lagrangians of the H_2^0 being an analog of the SM Higgs with the fermions and neutral gauge bosons have the form [8]

$$-L_{NC}^{E_6} = \sum_f \{\overline{\psi}_f \gamma_\mu (g_{V_f} - g_{A_f}\gamma_5) Z^\mu \psi_f + +\overline{\psi}_f \gamma_\mu (g'_{V_f} - g'_{A_f}\gamma_5) Z'^\mu \psi_f, \tag{4}$$

$$L_{NGB}^{E_6} = g_{H_2^0 ZZ} H_2^0(x) Z_\mu(x) Z^\mu(x) + g_{H_2^0 ZZ'} H_2^0(x) Z_\mu(x) Z'^\mu(x), \tag{5}$$

where

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

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

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

and $g_{H_2^0 ZZ}$ 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 are as follows: the χ model ($\beta = 0$), the ψ model ($\beta = \pi/2$), the η model ($\beta = \pi - \arctan\sqrt{5/3}$) [7], the inert model ($-\beta = \arctan\sqrt{3/5}$) [9], the neutral N model ($\beta = \arctan\sqrt{15}$) [10], the secluded sector model ($\beta = \arctan\sqrt{15}/9$) [11].

3. Calculation of the Higgs decay width

The Higgs decay modes into gauge bosons, with one of them being off-shell are important. For the first time within the SM this decay was investigated in [12]. In this three-body decay, although suppressed by an additional power of the electroweak coupling squared compared to the dominant $H \to b\overline{b}$ case and by the virtuality of the intermediate vector boson state, there is a compensation since in the SM the Higgs couplings to gauge bosons Z and W bosons are proportional to their masses and as a result much larger than the Higgs Yukawa coupling to b quarks. However, the similar proportionality does not always happen in the SM extensions. For example, in the LRM the $W_1W_1S_1$ coupling is proportional to m_{W_1}, while the $Z_1Z_1S_1$ does not.

At first, we shall speak about the LRM. In the second order of the perturbation theory this decay proceeds through the diagrams in Fig.1 with one real and one virtual neutral gauge bosons. Neglecting the fermion masses and summing over polarization of the final

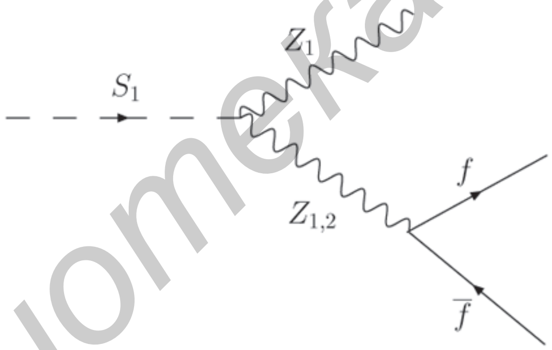

Figure 1: The Feynman diagrams for $S_1 \to Z_1\overline{f}f$.

particles, for the partial decay width we get

$$\Gamma^{LRM} = \Gamma(S_1 \to Z_1Z_1^*) + \Gamma(S_1 \to Z_1Z_2^*), \tag{6}$$

$$\Gamma(S_1 \to Z_1Z_1^*) = \frac{g^2_{S_1Z_1Z_1} m_{S_1}[(g^{(1)}_{V_f})^2 + (g^{(1)}_{A_f})^2]}{48\pi^3 m^2_{Z_1}} f(\epsilon),$$

$$\Gamma(S_1 \to Z_1Z_2^*) = \frac{g_{S_1Z_1Z_1} g_{S_1Z_1Z_2} m_{S_1}[g^{(1)}_{V_f} g^{(2)}_{V_f} + g^{(1)}_{A_f} g^{(2)}_{A_f}]}{24\pi^3 m^2_{Z_1}\eta} F(\epsilon),$$

$$f(\epsilon) = \frac{3(1 - 8\epsilon^2 + 20\epsilon^4)}{\sqrt{4\epsilon^2 - 1}} \arccos\Big(\frac{3\epsilon^2 - 1}{2\epsilon^3}\Big) - (1 - \epsilon^2)\Big(\frac{47\epsilon^2}{2} - \frac{13}{2} + \frac{1}{\epsilon^2}\Big) -$$

$$-3(1 - 6\epsilon^2 + 4\epsilon^4)\ln\epsilon,$$

$$F = \sqrt{4\epsilon^2 - 1}(4\epsilon^2 - 12\epsilon^4 - 1)\arccos\Big(\frac{3\epsilon^2 - 1}{2\epsilon^3}\Big) + (1 - \epsilon^2)\Big(\frac{11}{6} - \frac{61\epsilon^2}{6} + \frac{19\epsilon^4}{3}\Big) +$$

$$+(6\epsilon^2 - 36\epsilon^4 - 1)\ln\epsilon, \qquad \epsilon = \frac{m_{Z_1}}{m_{S_1}}, \qquad \eta = \frac{m_{Z_2}^2 - m_{Z_1}^2}{m_{S_1}^2}.$$

Summing over all fermions we come to the result

$$\Gamma^{LRM}(S_1 \to Z_1 \sum f\overline{f}) \simeq \frac{g_L^6(k_-^2 c_\theta + 2k_1k_2s_\theta)^2 m_{S_1}}{4096\pi^3 c_W^6 k_+^2 m_{Z_1}^2}\Big[f(\epsilon)\Big(7 - \frac{40}{3}s_W^2 + $$
$$+\frac{160}{9}s_W^4\Big) - \frac{2F(\epsilon)}{\eta}\Big(\frac{320}{9}s_W^4 - \frac{38}{3}s_W^2\Big)\Big]. \quad (7)$$

The first term in the square bracket significantly exceeds the second one: e.g., at $m_{Z_2} = 1.5$ TeV ($m_{Z_2} = 2$ TeV) their ratio is 1.5×10^{-3} (0.8×10^{-3}).

So, there are two possibilities. The first is: this partial width is measured with the high precision and it coincides with the SM prediction. In this case the LRM could not be ruled out provided that the coupling constant $g_{S_1Z_1Z_1}$ is equal $g_{HZZ} = em_Z/(c_W s_W)$, as happens with the SM. Then comparing (7) with the SM result and taking into consideration that [6]

$$m_{Z_1} \simeq \frac{g_L^2}{2}(k_+^2 + 4v_L^2),$$

we obtain

$$k_+^2 + 4v_L^2 \simeq \frac{(k_-^2 c_\theta + 2k_1k_2s_\theta)^2}{c_W^2 k_+^2}. \quad (8)$$

From (8) it follows

$$k_2 \preceq 0.25k_1. \quad (9)$$

The second possibility speculates that the measured partial decay width differs from the value the SM predicts. In this case, having evaluated the coupling constant $g_{S_1Z_1Z_1}$ from the Higgs decay under investigation, we could achieve good agreement between the LRM and experiment.

Thus, there exist ambiguity connected with the coupling constant defining interaction between neutral gauge boson and the SM Higgs. To keep this ambiguity as small as possible, and to display deviations from the SM prediction, we introduce the following quantities

$$\Delta_\pm = \Lambda_\pm^{SM} - \Lambda_\pm^{LRM}, \quad (10)$$

where

$$\Lambda_\pm^{SM} = \frac{\Gamma_\pm^{SM}}{\Gamma_+^{SM} + \Gamma_-^{SM}}, \qquad \Lambda_\pm^{LRM} = \frac{\Gamma_\pm^{LRM}}{\Gamma_+^{LRM} + \Gamma_-^{LRM}},$$

$\Gamma_+^{SM}(\Gamma_-^{SM})$ is the SM expression for the total width of the decay $H \to Ze^-e^+$ in the case of left- (right-) polarized electrons.

With the help of $\Delta_\pm$ we can find the number of the left- or right-polarized electrons pointing to deviation from the SM

$$N_\pm = \sigma(gg \to H) \times \mathcal{L} \times \mathrm{Br}(H \to Ze^-e^+) \times \Delta_\pm,$$

where $\sigma(gg \to H)$ is the Higgs boson production total cross section via gluon+gluon fusion, and $\mathcal{L}$ is the collider integrated luminosity. Setting $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000$ fb^{-1} we get

$$N_+^{LRM} \simeq \begin{cases} 103 \text{ events}, & \text{when } m_{Z_2} = 1.5 \text{ TeV}, \\ 58 \text{ events}, & \text{when } m_{Z_2} = 2 \text{ TeV}, \\ 15 \text{ events}, & \text{when } m_{Z_2} = 4 \text{ TeV}. \end{cases}$$

To obtain the expression for the decay of the Higgs being an analog of the SM Higgs in the ER5M's, we should make in the LRM partial decay width the following replacements

$$g_{S_1Z_1Z_1} \to g_{H_2^0ZZ}, \qquad g_{S_1Z_1Z_2} \to g_{H_2^0ZZ'}, \qquad g^{(1)}_{V_f} \to g_{V_f},$$

$$g^{(1)}_{A_f} \to g_{A_f}, \qquad g^{(2)}_{V_f} \to g'_{V_f}, \qquad g^{(2)}_{A_f} \to g'_{A_f}.$$

Analysis shows that $N_+^{E_6}$ has the maximum value for the case of the η-model. Calculations result in

$$N_+^{\eta} \simeq \begin{cases} 74 \text{ events}, & \text{when } m_{Z_2} = 1.5 \text{ TeV}, \\ 42 \text{ events}, & \text{when } m_{Z_2} = 2 \text{ TeV}, \\ 11 \text{ events}, & \text{when } m_{Z_2} = 4 \text{ TeV}. \end{cases}$$

4. Conclusions

Two kinds of models arising in a GUT scenario, the LRM and ER5M's, has been considered. Within these models the three body decay of the Higgs being an analog of the SM Higgs (ASMH)

$$H \to Z + f + \overline{f}$$

has been investigated.

In the LRM the coupling constant $g_{S_1Z_1Z_1}$ which defines interaction between the ASMH and Z_1 boson, may equal to or not equal to the SM coupling constant g_{HZZ} ($g_{S_1Z_1Z_1}$ contains the VEV's k_1 and k_2 whose values could be fixed by the experimental data only). To keep this ambiguity as small as possible, and to display deviations from the SM prediction, we have investigated the decay $H \to Ze^+e^-$ when the final electrons were left-polarized. Analysis demonstrated that discrepancy between predictions of the LRM and the SM could be detected for $m_{Z_2} \leq 4$ TeV. It should be noted that the experimental data give the following limits on the extra neutral gauge boson of the LRM [13]

$$m_{Z_2} = \begin{cases} > 630 \text{ GeV}, & (p\overline{p} \text{ direct search}), \\ > 1162 \text{ GeV}, & (\text{electroaweak fit}), \end{cases}$$

while the low bounds on m_{Z_2} theoretically obtained are larger. For example, in Ref. [14] this bound is ~ 4.25 TeV.

As far as the ER5M's are concerned, the maximal deviations from the SM predictions for the $H \to Ze^+e^-$ decay width hold for the η model. Detecting the polarized electrons in the final state, one could reveal discrepancy between the SM and the η model at $m_{Z'}$ values of no more than 4 TeV.

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