The $Z_H \to \gamma H$ decay in the Littlest Higgs Model

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We present the calculation of the $Z_H \to \gamma H$ decay in the context of the Littlest Higgs model at one-loop level. Our calculations include the contributions of fermions, scalars and gauge bosons in accordance with the most recent experimental constraints on the parameters space of the model. We find branching ratios of the order of $10^{-5}$ for the energy scale $f = 2, 3, 4$ TeV on the $0.1 < c < 0.9$ region. In order to provide a complementary study we calculated the production cross section of the $Z_H$ boson in $pp$ collisions at Large Hadron Collider with a center of mass energy of 14 TeV. By using the integrated luminosity projected for the Large Hadron Collider in the last stage of operation, we estimated the number of events for this process.

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I. INTRODUCTION

Alternative formulations for the study of electroweak symmetry breaking that have the property of canceling quadratic divergences are the so called little Higgs models (LHM) [9, 10]. These models are based on dimensional deconstruction [3, 4], where the quadratic divergence induced at the one-loop level by the Standard Model gauge bosons are canceled via the quadratic divergence introduced by heavy gauge bosons at the same perturbative level. Also, it is proposed the existence of heavy-mass fermions interacting with the Higgs Field in such a way that the one-loop quadratic divergence induced in the Yukawa sector of the Standard Model (SM) due to top quark coupling with the Higgs boson is canceled [2, 5]. Furthermore, the Higgs fields acquire mass becoming pseudo-Goldstone bosons via an approximate global symmetry breaking, where a massless Higgs appears. Quadratically divergent corrections to the Higgs mass arise at loop level, therefore, this naturally ensure a light Higgs.

As far as the littlest Higgs (LTHM) is concerned, a remarkable feature is that there is no new degrees of freedom beyond the SM below TeV scale. Moreover, above few TeV’s the LTHM needs a very small new degrees of freedom to stabilize the Higgs boson mass. At the TeV energy scale, the arising new particles are a set of four gauge bosons with the same quantum numbers as the electroweak SM gauge bosons, namely, $A_H$, $Z_H$, and $W_H^\pm$, an exotic quark with the same charge as the top quark, and a scalar triplet [2]. The construction details of the model can be found in Refs. [1, 2]. In general, these extensions of the SM predict new particles emerging at the TeV scale and the new physics that could appear at these energies that soon will be tested at the Large Hadron Collider (LHC) [6].

In particular, little Higgs models predict the existence of a new neutral massive gauge boson, known as $Z_H$, which could offer another theoretical framework to justify the experimental scrutiny about the possible existence of heavy-mass (at the TeV scale) particles like the $Z$ gauge boson of the SM. On the other hand, there are several models that predict the existence of a neutral massive gauge boson, identified as $Z'$ gauge boson, such as the 331 model [7] or grand unified models [8]. These type of particles are under exhaustive search at the LHC [6, 11], where the ATLAS and CMS collaborations have imposed experimental bounds over the mass of a new particle related to $Z'$ gauge boson, their results indicate that the mass of the $Z'$ gauge boson must be greater than 2.49 TeV and 2.59 TeV, respectively.

In this work we are interested in the physics of the $Z_H$ gauge boson, specifically, the main concern of this paper is to study the $Z_H \to H \gamma$ decay in the context of the linearized theory of the littlest Higgs model [2]. The relevance of this process brings the possibility of testing the LTHM, since the parameters space has been severely constrained by the Higgs discovery channels and electroweak precision observables [11]. Previous studies on the $Z' \to H \gamma$ decay have been performed in the context of left-right symmetric models [12], where the associated branching ratio is estimated, however, the used parameters such as the mass $m_{Z'}$ are below the present bounds established by the experimental measurements [3, 10]. The paper is organized as follows. In Section II we briefly describe the theoretical framework of the LTHM. In Sec. III we outline the analytical results for the $Z_H \to H \gamma$ decay in the LTHM. In Sec. IV it is presented the numerical analysis. Finally, the conclusions appear in Sec. V.
The littlest Higgs model is based on a nonlinear sigma model with $SU(5)$ global symmetry and the gauged subgroup $[SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]$ \cite{2,3}. The global symmetry of the $SU(5)$ group is spontaneously broken down $SU(5) \rightarrow SO(5)$ at the energy scale $f$, where $f$ is constrained to be of the order of 2–4 TeV \cite{11}. Simultaneously, the $[SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]$ group is also broken to its subgroup $SU_L(2) \otimes U_Y(1)$, which results to be the SM electroweak gauge group. The global symmetry breaking pattern leaves 14 Goldstone bosons which transform the sigma model contributions of the LTHM, $SU(5)$ at the energy scale $f$ breaking (SSB), both the real singlet and the real triplet are absorbed by the longitudinal components of the gauge bosons at the energy scale $f$. At this scale, the complex doublet and the complex triplet remain massless. The complex triplet acquires a mass of the order of $f$ by means of the Coleman-Weinberg type potential when the global symmetry of the group $SO(5)$ breaks down. The complex doublet is identified as the SM Higgs field.

The effective Lagrangian invariant under the $[SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]$ group is \cite{3}
\[ \mathcal{L}_{LTHM} = \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_Y + VCW, \]
where $\mathcal{L}_G$ represents the gauge bosons kinetic contributions, $\mathcal{L}_F$ the fermion kinetic contributions, $\mathcal{L}_Y$ the non-linear sigma model contributions of the LTHM, $\mathcal{L}_Y$ the Yukawa couplings of fermions and pseudo-Goldstone bosons, and the last term symbolizes the Coleman-Weinberg potential.

The standard form of the Lagrangian of the non-linear sigma model is
\[ \mathcal{L}_\Sigma = \frac{r^2}{8} \text{tr} [D_\mu \Sigma]^2, \]
where the covariant derivative is written as
\[ D_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^{2} \left[ g_j \sum_{a=1}^{3} W^a_{\mu j} (Q^a_j \Sigma + \Sigma Q'^a_j) + g'_j B_{\mu j} (Y_j \Sigma + \Sigma Y'_j) \right]. \]

Here, $W^a_{\mu j}$ are the $SU(2)$ gauge fields, $B_{\mu j}$ are the $U(1)$ gauge fields, $Q^a_j$ are the $SU(2)$ gauge group generators, $Y_j$ are the $U(1)$ gauge group generators, $g_j$ are the coupling constants of the $SU(2)$ group, and $g'_j$ are the coupling constants of the $U(1)$ group \cite{5}. After SSB around $\Sigma_0$, it is generated the mass eigenstates of order $f$ for the gauge bosons \cite{5}
\[ W'_\mu = - c W_{\mu 1} + s W_{\mu 2}, \]
\[ B'_\mu = - c' B_{\mu 1} + s' B_{\mu 2}, \]
\[ W_{\mu 1} = s W_{\mu 1} + c W_{\mu 2}, \]
\[ B_{\mu 1} = s' B_{\mu 1} + c' B_{\mu 2}, \]
where $W_{\mu j} \equiv \sum_{a=1}^{3} W^a_{\mu j} Q^a_j$ and $B_{\mu j} \equiv B_{\mu j} Y_j$ for $j = 1, 2$; $c = g_{1} / \sqrt{g_{1}^2 + g_{2}^2}$, $c' = g'_{1} / \sqrt{g'_{1}^2 + g'_{2}^2}$, $s = g_{2} / \sqrt{g_{1}^2 + g_{2}^2}$, and $s' = g'_{2} / \sqrt{g'_{1}^2 + g'_{2}^2}$. Notice that $\Sigma$ field has been expanded around $\Sigma_0$ holding dominant terms in $\mathcal{L}_\Sigma$ \cite{5}. At this stage of SSB the $B_{\mu}$ and $W_{\mu}$ fields remain massless.
The SSB at the Fermi scale provides mass to the SM gauge bosons ($B$ and $W$) and induces mixing between heavy and light gauge bosons. The arising masses at the leading order (neglecting terms of order $\mathcal{O}\left(\frac{v^2}{T^2}\right)$, with $v$ being the vacuum expectation value at the Fermi scale) are

$$m_{Z_H} = \frac{g f}{2 s c},$$
$$m_{A_H} = \frac{g' f}{2 \sqrt{3} s' c'},$$
$$m_{W_H} = \frac{g f}{2 s c}$$

(11) (12) (13)

As it is known $c = m_{W_H}/m_{Z_H}$ and takes the value equals to one at the leading order, we may assume that the $c$ parameter ranges from $0.1$ to $0.9$ [3], in order to have values for the masses of the weak gauge bosons not very different, as it occurs in the electroweak sector of the SM.

The LTHM incorporate new heavy fermions which couple to Higgs field in a such way that the quadratic divergence of the top quark is canceled [2, 5]. In particular, this model introduces a new set of heavy fermions arranged as a vector-like pair ($\tilde{t}, \tilde{t}'$) with quantum numbers $(3, 1)_{Y_t}$ and $(\bar{3}, 1)_{-Y_t}$, respectively. The new Yukawa interactions are proposed to be

$$\mathcal{L}_Y = \frac{1}{2} \lambda_1 f \epsilon_{ijk} \epsilon_{xy} \chi_i \sum_{j,k} u_{jk} u_{yi}^c + \lambda_2 f \tilde{t} \tilde{t} + \text{H.c.},$$

where $\chi_i = (b_3, t_3, \tilde{t})$; $\epsilon_{ijk}$ and $\epsilon_{xy}$ are antisymmetric tensors for $i,j,k = 1, 2, 3$ and $x,y = 4, 5$ [2]. Here, $\lambda_1$ and $\lambda_2$ are free parameters, where the $\lambda_2$ parameter can be fixed such that, for given $(f, \lambda_1)$, the top quark mass adjust to its experimental value [11].

Expanding the $\Sigma$ field and retaining terms up to $\mathcal{O}(v^2/f^2)$ after diagonalizing the mass matrix, it can be obtained the mass states $t_L, t_R^c, T_L,$ and $T_R^c$, which correspond to SM top quark and the heavy top quark, respectively [2, 11].

The explicit remaining terms of the Lagrangian $\mathcal{L}_{LTHM}$ as well as the complete set of new Feynman rules can be found in Ref. [2].

III. DECAY $Z_H \rightarrow \gamma H$

We now turn our attention to obtain the analytical expression for the amplitude and decay width of the $Z_H \rightarrow \gamma H$ process. In Fig. 1 [1] we show the contributions at one-loop level to the $Z_H \rightarrow \gamma H$ coming from fermions, gauge boson and scalars. In the fermion loops we are taking into account only the SM fermion contributions since. The analysis is based on three sets of Feynman diagrams: the set (a) contains the triangle loop contributions mediated by fermions; the set (b) includes triangle and bubble loop contributions mediated by SM charged gauge bosons and new heavy charged gauge bosons, where also it is include the mixing effects between these two types of charged gauge bosons; for the set (c), we take into account the bubble loop contributions induced by scalars and scalars plus gauge bosons, together with triangle loop contributions mediated by gauge bosons and scalars.

The respective decay amplitude is given by

$$\mathcal{M}(Z_H \rightarrow \gamma H) = M_T^{\mu \nu} \epsilon_{\mu}(q) \epsilon^\nu(k_1),$$

(15)

where $M_T^{\mu \nu} = M_T^{\mu \nu} + M_G^{\mu \nu} + M_S^{\mu \nu}$. Here, $M_T^{\mu \nu}$ represents the contribution of the set (a), $M_G^{\mu \nu}$ contains the contribution of the set (b), and $M_S^{\mu \nu}$ includes the contribution of the set (c). Moreover, $\epsilon_{\mu}(q)$ and $\epsilon^\nu(k_1)$ are the polarization vectors associated to photon and $Z_H$ boson, respectively. After tedious algebraic manipulations we can write down a generic expression for the total decay amplitude as follows

$$M_T^{\mu \nu} = A_T g^{\mu \nu} + B_T k_1^{\mu} q^\nu,$$

(16)

where $k_1 = k_1/m_{Z_H}$ and $q = q/m_{Z_H}$. The $A_T$ and $B_T$ functions are in terms of Passarino-Veltman scalar functions. In specific, $A_T = \sum f A_f + \sum G_i + \sum A_S$, and $B_T = \sum f B_f + \sum G_i + \sum B_S$. Here, $f$ runs over all charged fermions, $G_i$ represents charged gauge bosons ($W$, $W_H$), and $S_i$ symbolizes charged scalars ($\phi^+$, $\phi^-$, $\phi^{++}$, and $\phi^{--}$). We found that the total contribution arising from tadpole and self-energies diagrams vanishes.
The explicit form for the $A_f$, $A_{G_1}$, $A_{S_1}$, $B_f$, $B_{G_1}$, and $B_{S_1}$ coefficients are presented below

$$ A_f = \frac{g^2}{4m_W} \frac{m_{Z_H}}{y_H - 1} \left( 2(B_a - B_b) + (y_H - 1)(C_a(4y_f - y_H + 1) + 2) \right), $$

$$ B_f = \left( \frac{2}{y_H - 1} \right) A_f, $$

where $B_a \equiv B_0(m_{Z_H}^2, m_f^2, m_1^2)$, $B_b \equiv B_0(m_{Z_H}^2, m_f^2, m_2^2)$, $C_a \equiv m_{Z_H}^2 C_0(m_{Z_H}^2, m_f^2, m_1^2, m_2^2)$, and $C_b \equiv m_{Z_H}^2 C_0(m_{Z_H}^2, m_{Z_H}^2, m_f^2, m_2^2)$ are the known Passarino-Veltman scalar functions. Also, we used $y_f = m_f^2/m_{Z_H}^2$ and $y_H = m_{Z_H}^2/m_{Z_H}^2$. Notice that for this particular process $h_R = 0$ and $h_L = g c T^3/s$, where, as usual $T^3$ represents the third component of isospin being $T^3 = 1 (-1)$ for fermions up (down) type. The $A_{G_1}$ and $B_{G_1}$ coefficients contain the contributions of $W$ and $W_H$ bosons as follows

$$ A_{G_1} = C_{G_1} \left( \frac{1}{2(y_H - 1)y_W} \right) \left( (B_{G_{1a}} - B_{G_{1b}})(y_H(1 - 2y_W) + 2(1 - 6y_W)y_W) - 2C_{G_{1a}} y_W (y_H^2 (1 - 6y_W) + 3y_H (4y_W^2 + 4y_W - 1) - 12y_W^2 - 6y_W + 2) + y_W^2 (1 - 2y_W) + y_H (-12y_W^2 + 4y_W - 1) + 2y_W (6y_W - 1) \right), $$

$$ B_{G_1} = \left( \frac{2}{y_H - 1} \right) A_{G_1}, $$

where $B_{G_{1a}} \equiv B_0(m_{W}^2, m_{W}^2, m_{W}^2)$, $B_{G_{1b}} \equiv B_0(m_{Z_H}^2, m_{W}^2, m_{W}^2)$, and $C_{G_{1a}} \equiv m_{Z_H}^2 C_0(m_{W}^2, m_{Z_H}^2, m_{W}^2, m_{W}^2)$. Moreover, $y_W = m_{W}^2/m_{Z_H}^2$ and $C_{G_1} = -\frac{1}{27} \left( 4s^2 \left( c^2 - s^2 \right) s_W v^3 \right)$. The $A_{G_2}$ and $B_{G_2}$ coefficients can be obtained from $A_{G_1}$ and $B_{G_1}$ by replacing: $m_W \rightarrow m_{W_H}$ and $C_{G_1} \rightarrow C_{G_2}$, where $C_{G_2} = -\frac{1}{27} \left( 4s^2 \left( c^2 - s^2 \right) s_W v^3 \right)$. The $A_{G_3}$ and
$B_{G_3}$ coefficients are given by

\[
A_{G_3} = C_{G_3} \frac{1}{2(y_H - 1)ygWy_H} \left[(B_{G_3a} - B_{G_3b})\left[-ygWy_H(y + 10yw - 1) - (yw - 1)(y_H + y) - y^2w_H\right] - C_{G_3a}(y_H - 1)y\left[yH(1 - y - 5yw_H) + y^2 + 10yw yw_H + yw^2 + 5yw - 2\right] - C_{G_3b}(y_H - 1)yw_H \right]
\]

\[
B_{G_3} = \frac{2}{(y_H - 1)}A_{G_3},
\]

where $B_{G_3a} = B_0(m^2_H, m^2_W, m^2_{W_H}), B_{G_3b} = B_0(m^2_{Z_H}, m^2_W, m^2_{W_H}), C_{G_3a} = m^2_{Z_H} C_0(m^2_H, m^2_{Z_H}, m^2_W, m^2_{W_H}, m^2_W), C_{G_3b} = m^2_{Z_H} C_0(m^2_H, m^2_{Z_H}, m^2_W, m^2_{W_H}, m^2_W).$ In addition, $yw_H = m^2_{W_H}/m^2_{Z_H}$ and $C_3 = g^2/\pi v (c^2 - s^2)/4cs.$ Notice that Eqs. (21) and (22) reflect the mixing between $W$ and $W_H$ gauge bosons. The $A_{S_1}$ and $B_{S_1}$ coefficients are

\[
A_{S_1} = C_{S_1} \frac{1}{(y_H - 1)y} \left[(B_{S_1a} - B_{S_1b})(y_H + y - y_0) + C_{S_1a}(y_H - 1)y_0(y_H + y - y_0) - C_{S_1b}(y_H - 1)y_0(y_H y_0 + y - 2) + (y_H - 1)(y_H + y - y_0)\right],
\]

\[
B_{S_1} = \frac{2}{(y_H - 1)}A_{S_1},
\]

where $B_{S_1a} = B_0(m^2_H, m^2_W, m^2_3), B_{S_1b} = B_0(m^2_{Z_H}, m^2_W, m^2_3), C_{S_1a} = m^2_{Z_H} C_0(m^2_H, m^2_{Z_H}, m^2_W, m^2_3, m^2_W), C_{S_1b} = m^2_{Z_H} C_0(m^2_H, m^2_{Z_H}, m^2_3, m^2_W, m^2_3).$ Here, $y_0 = m^2_{W_H}/m^2_{Z_H}$ and $C_{S_1} = g^2/\pi v (c^2 - s^2)/4cs.$ The $A_{S_2}$ and $B_{S_2}$ coefficients can be get by replacing: $m_W \rightarrow m_{W_H}$ and $C_{S_1} = g^2/\pi v (c^2 - s^2)/4cs.$ The expression for the decay amplitude of the $Z_H \rightarrow \gamma H$ can be written as

\[
M(Z_H \rightarrow \gamma H) = A_T \left( g^{\mu \nu} + \frac{2}{y_H - 1} \hat{e}_1 \gamma \nu \right) \epsilon_\mu (q) \epsilon_\nu (k_1).
\]

Finally, the decay width for the process reads as

\[
\Gamma(Z_H \rightarrow \gamma H) = \frac{A_T^2 (1 - y_H)}{8\pi m_{Z_H}}.
\]

It should be recalled that all the $A_i$ terms in $A_T$ are free of ultraviolet divergences and the Lorentz structure in Eq. (25) satisfies the Ward identity $k_{1\nu} M_T^{\mu \nu} = 0.$

IV. NUMERICAL RESULTS

A. Production of extra neutral $Z_H$ boson

In this part of our work, we present the production cross section of the extra neutral $Z_H$ gauge boson at LHC in the context of the LTHM, where it is assumed a search for a mass resonance in the dilepton channel $e^+e^- \rightarrow \mu^+\mu^- [14].$ Here, we used an updated version of the WHIZARD package, which is a program designed for the calculation of multi-particle scattering cross sections and simulated event samples [13] to perform our calculations. As a test of the WHIZARD package, we carried out the calculation of $\sigma(pp \rightarrow Z_H X)$ cross section as a function of $m_{Z_H}$ for $c = \pi/4$ and our results coincided with previous ones reported in Ref. [14]. We simulate $pp$ collisions with a center of mass energy of 14 TeV. In Fig. [2] it can be appreciated $\sigma(pp \rightarrow Z_H X)$ as a function of the $Z_H$ boson mass throughout the interval $1.6$ TeV $< m_{Z_H} < 13.13$ TeV, where we have employed three different values for $f$, namely, 2, 3, 4 TeV. The mass interval used for the $Z_H$ boson will be justified below.
FIG. 2: Production cross section of the $Z_H$ boson at LHC. (a) For $f = 2$ TeV. (b) For $f = 3$ TeV. (c) For $f = 4$ TeV.

B. Branching ratio for the $Z_H \rightarrow \gamma H$ decay

Let us analyze the branching ratio behavior of the $Z_H \rightarrow \gamma H$ decay. Recall that the $m_{Z_H}$ is a function of two model-dependent parameters $c$ and $f$, where $c$ and $f$ are the mixing angle of the $SU(2)_L \times U(1)_Y$ extended gauge group and the energy scale at which the $SU(5)$ gauge group breaks into $SO(5)$ group, respectively. It is known that experimental data constrain the symmetry breaking scale to be in the interval $2 \text{ TeV} < f < 4 \text{ TeV}$, for $c' = 1/\sqrt{2}$ and $c$ between $[0.1, 0.995]$ [11]. To make predictions, we will take three distinct values for $f$, namely, $f = 2, 3, 4 \text{ TeV}$ and will carry out an exhaustive study at the $c$ parameter region given above. This analysis will provide us crucial information to test the experimental possibility for $Z_H \rightarrow \gamma H$ decay in the LTHM context. Moreover, it should be recalled that the recent results reported by ATLAS and CMS collaborations, established lower mass limits for a new neutral massive gauge boson, identified as $Z'$. ATLAS collaboration reports that a sequential $Z'$ gauge boson is excluded at 95% C.L. for masses below 2.39 TeV in the electron channel, 2.19 TeV in the muon channel, and 2.49 TeV in the two channels combined [8]; $Z'$ bosons coming from $E_6$-motivated models are excluded at 95% C.L. for masses below 2.09-2.24 TeV [9]. In accordance with CMS results, in the context of the sequential $Z'$ model and the superstring-inspired model, the lower mass limits at 95% C.L. for the $Z'$ gauge boson correspond to 2.59 TeV and 2.26 TeV, respectively [10]. Motivated by the above results, we will take a lower mass limit for the $Z_H$ gauge boson to be 2.6 TeV in order to explore the physical possibilities for the $Z_H \rightarrow \gamma H$ decay. In a previous work it has been studied the dominant decays of the $Z_H$ boson [17] in the context of the LTHM. We employ this information to compute the total decay width of the $Z_H$ boson for different values of the energy scale $f$ proposed above.

From Fig. 3(a), for $f = 2$ TeV, it can be observed that the permitted region corresponds to $0.1 < c < 0.26$ for a $Z_H$ mass interval $6.56 \text{ TeV} > m_{Z_H} > 2.6$ TeV, where the branching ratio ranges from $4 \times 10^{-6}$ to $2 \times 10^{-5}$; the
maximum value of the branching ratio is $1.58 \times 10^{-5}$ for $c = 0.19$ and $m_{Z_H} = 3.5$ TeV. In Fig. 3(b), for $f = 3$ TeV, we can observe a permitted region for the $c$ parameter ranging between $0.1 < c < 0.41$, due to $Z_H$ mass interval $9.84$ TeV $> m_{Z_H} > 2.6$ TeV, being the associated branching ratio around $1.14 \times 10^{-5} - 4.6 \times 10^{-5}$; in this case, the maximum value of the branching ratio is $1.19$ and $m_{Z_H} = 3.5$ TeV. Finally in Fig. 3(c), we show the branching ratio as a function of $c$ and $m_{Z_H}$ for $f = 4$ TeV. This figure tell us that the whole interval for the $c$ parameter $0.1 < c < 0.9$ is permitted, accordingly with the interval $2.6$ TeV $< m_{Z_H} < 13.13$ TeV, where the related branching ratio is as high as $6.96 \times 10^{-6}$ for $c = 0.31$ and $m_{Z_H} = 4.43$ TeV.

In order to explore the predictability of the LTHM, we take the expected luminosity at the final stage of operation of LHC (14 TeV at the center of mass energy), which is projected to be 3000 fb$^{-1}$ [18]. Let us consider different values of the $Z_H$ mass for which it is produced few events. For $f = 2$ TeV and around $c = 0.19$ or equivalently $m_{Z_H} = 3.5$ TeV, we estimate 4 events. For $f = 3$ TeV and $c = 0.28$ or $m_{Z_H} = 3.64$ TeV, we found around 3 events. For $f = 4$ TeV and $c = 0.4$ or $m_{Z_H} = 3.56$ TeV, we calculated 1 event. Notice that the number of events estimated can grow up if we take values of $m_{Z_H}$ close to 2.6 TeV.

V. CONCLUSIONS

The LTHM resides on a nonlinear sigma model with a $SU(5)$ global symmetry and the gauged subgroup $[SU(2)_1 \otimes U(1)_1] \otimes [SU(2)_2 \otimes U(1)_2]$, where it is predicted the existence of heavy gauge bosons, particularly, a new neutral massive boson known as $Z_H$. This gauge boson is another $Z'$ type gauge boson which at present is under experimental scrutiny.
at the LHC. Although the parameters space of the LTHM has been severely constrained, yet there is room left to test the predictability of the model. In specific, the $Z_H \to \gamma H$ decay was used to explore the current parameters space of the LTHM, where we have analyzed physical regions according with experimental bounds and results; specifically we have taken the following parameters: $f = 2, 3, 4$ TeV for $0.1 < c < 0.9$. It is found that for $f = 2$ TeV there is a permitted region $0.1 < c < 0.26$ corresponding to $6.56$ TeV $> m_{Z_H} > 2.6$ TeV. In particular, for a $m_{Z_H} = 3.5$ TeV it is calculated around $4$ events for the $Z_H \to H$ decay at LHC operating at $14$ TeV. Similarly, for $f = 3$ TeV the permitted region is $0.1 < c < 0.41$ or a $Z_H$ mass interval $9.84$ TeV $> m_{Z_H} > 2.6$ TeV. In this case, for $m_{Z_H} = 3.64$ TeV it is estimated $3$ events for the process in question. Finally, for the same process and taking $f = 4$ TeV we have found the permitted region in the interval of masses $2.6$ TeV $< m_{Z_H} < 13.13$ TeV. Here, it is computed around $1$ event for $m_{Z_H} = 3.56$ TeV. Although we have chosen specific values of $m_{Z_H}$ to get few events, our numerical results tell us that there are several intervals in which the number of events are larger than the previous ones. For instance, for $f = 2$ and $c = 0.26$ we could obtain tens of events for the $Z_H \to H$ decay.

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