Higgs and $Z'$ Phenomenology in $B - L$ extension of the Standard Model at LHC

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Abstract: The phenomenology of the low scale $U(1)_{B-L}$ extension of the standard model and its implications at LHC is presented. In this model, an extra gauge boson corresponding to $B - L$ gauge symmetry and an extra SM singlet scalar (heavy Higgs) are predicted. We show a detailed analysis of both heavy and light Higgses decay and production in addition to the possible decay channels of the new gauge boson. We find that the cross sections of the SM-like Higgs production are reduced by $\sim 20\% - 30\%$, while its decay branching ratios remain intact. The extra Higgs has relatively small cross sections and the branching ratios of $Z' \rightarrow l^+l^-$ are of order $\sim 20\%$ compared to $\sim 3\%$ of the SM results. Hence, the search for $Z'$ is accessible via a clean dilepton signal at LHC.

Keywords: Low scale $B - L$, Higgs production, Higgs decays, $Z'$ gauge boson.
# 1. Introduction

The Standard Model (SM) of elementary particles has been regarded only as a low energy effective theory of the yet-more-fundamental theory. Several attempts have been proposed to extend the gauge symmetry of the SM via one or more $U(1)$ gauge symmetries beyond the hypercharge gauge symmetry, $U(1)_Y$ [1–3]. The evidence for non-vanishing neutrino masses, based on the apparent observation of neutrino oscillation, strongly encourages this type of extensions. In this class of models [1, 2], three SM singlet fermions arise quite naturally due to the anomaly cancellation conditions. These three particles are accounted for right handed neutrinos, and hence a natural explanation for the seesaw mechanism is obtained.

A low scale $B - L$ symmetry breaking, based on the gauge group $G_{B-L} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$, has been considered recently [2]. It was shown that this model can account for the current experimental results of the light neutrino masses and their large mixing. Therefore, it can be considered as one of the strong candidates for minimal extensions of the SM. In addition, one extra neutral gauge boson corresponding to $B - L$ gauge symmetry and an extra SM singlet scalar (extra Higgs) are predicted. In fact, the SM Higgs sector can be generally extended by adding extra singlet scalars without enlarging its gauge symmetry group [4, 5]. In Ref.[2], it has been emphasized that these new particles may have significant impact on the SM phenomenology, hence lead to interesting signatures at Large Hadron Collider (LHC).
The aim of this paper is to provide a comprehensive analysis for the phenomenology of such TeV scale extension of the SM, and its potential discovery at the LHC. The production cross sections and the decay branching ratios of the SM like Higgs, $H$, and the extra Higgs boson $H'$ are analyzed. We also consider the decay branching ratios of the extra gauge boson, $Z'$.

We show that the cross sections of the Higgs production are reduced by $\sim 20\% - 30\%$ in the interesting mass range of $\sim 120 - 250$ GeV relative to the SM predictions. However, its decay branching ratios remain intact. In addition, we find that the extra Higgs ($\sim$ TeV) is accessible at LHC, although it has relatively small cross sections. We also examine the availability of the decay channel $H' \rightarrow HH$, which happens to have very small partial decay width. Concerning the $Z'$ gauge boson, the branching ratios of $Z' \rightarrow l^+l^-$ are found to be of order $\sim 20\%$ compared to $\sim 3\%$ of the SM BR ($Z \rightarrow l^+l^-$).

This paper is organized as follows. In section 2 we review the Higgs mechanism and symmetry breaking within the minimal $B-L$ extension of the SM. We also discuss the mixing between the SM-like Higgs and the extra Higgs boson. Section 3 is devoted for the phenomenology of the two Higgs particles. The production cross sections and decay branching ratios of these Higgs particles at LHC are presented. In section 4 we study the decay of the extra gauge boson $Z'$. In section 5 we briefly discuss the scenario of very light Higgs. Finally we give our concluding remarks in section 6.

2. $B-L$ extension of the SM

2.1 Symmetry breaking

The fermionic and kinetic sectors of the Lagrangian in the case of $B-L$ extension are given by

$$\mathcal{L}_{B-L} = i \bar{l} D_\mu \gamma^\mu l + i \bar{e}_R D_\mu \gamma^\mu e_R + i \bar{\nu}_R D_\mu \gamma^\mu \nu_R - \frac{1}{4} W_{\mu\nu}W^{\mu\nu} - \frac{1}{4} B_{\mu\nu}B^{\mu\nu} - \frac{1}{4} C_{\mu\nu}C^{\mu\nu}. \tag{2.1}$$

The covariant derivative $D_\mu$ is different from the SM one by the term $i g'' Y_{B-L} C_\mu$, where $g''$ is the $U(1)_{B-L}$ gauge coupling constant, $Y_{B-L}$ is the $B-L$ charge, and $C_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$ is the field strength of the $U(1)_{B-L}$. The $Y_{B-L}$ for fermions and Higgs are given in Table 1.

| particle | $l$ | $e_R$ | $\nu_R$ | $q$ | $\phi$ | $\chi$ |
|----------|-----|-------|---------|-----|--------|--------|
| $Y_{B-L}$ | $-1$ | $-1$ | $-1$ | $1/3$ | $0$ | $2$ |

Table 1: $B-L$ quantum numbers for fermions and Higgs particles

The Higgs and Yukawa sectors of the Lagrangian are given by

$$\mathcal{L}_{B-L} = (D^\mu \phi)(D_\mu \phi) + (D^\mu \chi)(D_\mu \chi) - V(\phi, \chi) - \left( \lambda_e \bar{\phi} e_R + \lambda_{\nu} \bar{\nu} \phi \nu_R + \frac{1}{2} \lambda_{\nu R} \bar{\nu}^R R \nu_R + h.c. \right). \tag{2.2}$$
Here, $\lambda_e$, $\lambda_\nu$ and $\lambda_{\nu R}$ refer to $3 \times 3$ Yukawa matrices. The interaction terms $\lambda_e \bar{\nu} \nu R \chi$ and $\lambda_{\nu R} \bar{\nu} \ni \bar{\nu} R \nu R$ give rise to a Dirac neutrino mass term: $m_D \simeq \lambda_e v$ and a Majorana mass term: $M_R = \lambda_{\nu R} v'_R$, respectively. The $U(1)_{B-L}$ and $SU(2)_L \times U(1)_Y$ gauge symmetries can be spontaneously broken by a SM singlet complex scalar field $\chi$ and a complex $SU(2)$ doublet of scalar fields $\phi$, respectively. We consider the most general Higgs potential invariant under these symmetries, which is given by

$$V(\phi, \chi) = m_1^2 \phi^\dagger \phi + m_2^2 \chi^\dagger \chi + \lambda_1 (\phi^\dagger \phi)^2 + \lambda_2 (\chi^\dagger \chi)^2 + \lambda_3 (\chi^\dagger \chi)(\phi^\dagger \phi),$$

(2.3)

where $\lambda_3 > -2 \sqrt{\lambda_1 \lambda_2}$ and $\lambda_1, \lambda_2 \geq 0$, so that the potential is bounded from below. For non-vanishing vacuum expectation values (vev’s), we require $\lambda_3^2 < 4 \lambda_1 \lambda_2$, $m_1^2 < 0$ and $m_2^2 < 0$. The vev’s, $|\langle \phi \rangle| = v/\sqrt{2}$ and $|\langle \chi \rangle| = v'/\sqrt{2}$, are then given by

$$v^2 = \frac{4 \lambda_2 m_1^2 - 2 \lambda_3 m_2^2}{\lambda_3^2 - 4 \lambda_1 \lambda_2}, \quad v'^2 = \frac{-2(m_1^2 + \lambda_1 v^2)}{\lambda_3}.$$

Depending on the value of the $\lambda_3$ coupling, one can have $v' \gg v$ or $v' \approx v$. Therefore, the symmetry breaking scales, $v$ and $v'$, can be responsible for two different symmetry breaking scenarios. In our analysis we take $v = 246$ GeV and constrain the other scale, $v'$, by the lower bounds imposed on the mass of the extra neutral gauge boson.

After the $B - L$ gauge symmetry breaking, the gauge field $C_\mu$ (will be called $Z'$ in the rest of the paper) acquires the following mass:

$$m_{Z'}^2 = 4 g'' v'^2.$$

(2.4)

The experimental search for $Z'$ at CDF experiment leads to $m_{Z'} \gtrsim O(600)$ GeV. However, the strongest limit comes from LEP II [6]:

$$m_{Z'}/g'' > 6\text{TeV}.$$

(2.5)

This implies that $v' \gtrsim O(\text{TeV})$. Moreover, if the coupling $g''$ is $< O(1)$, one can still obtain $m_{Z'} \gtrsim O(600)$ GeV.

2.2 Higgs sector

In addition to the SM complex $SU(2)_L$ doublet, another complex scalar singlet arise in this class of models. Out of these six scalar degrees of freedom, only two physical degrees of freedom, $(\phi, \chi)$, remain after the $B - L$ and electroweak symmetries are broken. The other four degrees of freedom are eaten by $Z'$, $Z$ and $W^\pm$ bosons.

The mixing between the two Higgs scalar fields is controlled by the coupling $\lambda_3$. In fact, one finds that for positive $\lambda_3$, the $B - L$ symmetry breaking scale, $v'$, becomes much higher than the electroweak symmetry breaking scale, $v$. In this case, the SM singlet Higgs, $\phi$, and the SM like Higgs, $\chi$, are decoupled and their masses are given by

$$M_\phi = \sqrt{2 \lambda_1} v, \quad M_\chi = \sqrt{2 \lambda_2} v'.$$

(2.6)
For negative $\lambda_3$, however, the $B-L$ breaking scale is at the same order of the the electroweak breaking scale. In this scenario, a significant mixing between the two Higgs scalars exists and can affect the SM phenomenology. This mixing can be represented by the following mass matrix for $\phi$ and $\chi$:

$$\frac{1}{2} M^2(\phi, \chi) = \begin{pmatrix} \lambda_1 v^2 & \frac{\lambda_3}{2} v v' \\ \frac{\lambda_3}{2} v v' & \lambda_2 v'^2 \end{pmatrix}. \quad (2.7)$$

Therefore, the mass eigenstates fields $H$ and $H'$ are given by

$$\begin{pmatrix} H \\ H' \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \phi \\ \chi \end{pmatrix}, \quad (2.8)$$

where the mixing angle $\theta$ is defined by

$$\tan 2\theta = \frac{|\lambda_3| v v'}{\lambda_1 v^2 - \lambda_2 v'^2}. \quad (2.9)$$

The masses of $H$ and $H'$ are given by

$$m_{H,H'}^2 = \lambda_1 v^2 + \lambda_2 v'^2 \pm \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + \lambda_3^2 v^2 v'^2}. \quad (2.10)$$

We call $H$ and $H'$ as light and heavy Higgs bosons, respectively. In our analysis we consider a maximum mixing between the two Higgs bosons by taking $|\lambda_3| \simeq \lambda_1^{\text{max}} \lambda_2^{\text{max}}$, where $\lambda_1^{\text{max}}$ and $\lambda_2^{\text{max}}$ are given by

$$\lambda_1^{\text{max}} = \frac{m_H^2 + m_{H'}^2 - \sqrt{4m_H^2 m_{H'}^2 + 1 + 1}}{4v^2},$$
$$\lambda_2^{\text{max}} = \frac{m_H^2 + m_{H'}^2 + \sqrt{4m_H^2 m_{H'}^2 + 1 - 1}}{4v'^2}, \quad (2.11)$$

and the maximum mixing angle is then given by

$$\tan 2\theta = \frac{\lambda_1^{\text{max}} \lambda_2^{\text{max}} v v'}{\lambda_1^{\text{max}} v^2 - \lambda_2^{\text{max}} v'^2}. \quad (2.12)$$

By considering the maximum mixing and fixing $v = 246$ GeV and $v' = 1$ TeV, we have reduced the number of free parameters of this model into just two, namely $m_H$ and $m_{H'}$. In Figure 1, we present the maximum mixing as a function of the light Higgs mass, $m_H$ for $m_{H'} = 500$ GeV and 1 TeV.

Due to the mixing between the two Higgs bosons, the usual couplings among the SM-like Higgs, $H$, and the SM fermions and gauge bosons are modified. In addition, there are new couplings among the extra Higgs, $H'$, and the SM particles:

$$g_{Hff} = \frac{i m_f}{v} \cos \theta, \quad g_{H'ff} = \frac{i m_f}{v} \sin \theta,$$
$$g_{HVV} = -2i \frac{m_V^2}{v} \cos \theta, \quad g_{H'VV} = -2i \frac{m_V^2}{v} \sin \theta,$$
$$g_{HZ'Z'} = 2i \frac{m_{Z'}^2}{v'} \sin \theta, \quad g_{H'Z'Z'} = -2i \frac{m_{Z'}^2}{v'} \cos \theta,$$
$$g_{H\nu_R\nu_R} = -i \frac{m_{\nu_R}}{v'} \sin \theta, \quad g_{H'\nu_R\nu_R} = i \frac{m_{\nu_R}}{v'} \cos \theta. \quad (2.13)$$
The Higgs self couplings are give by

\[ g_{H^3} = 6i(\lambda_1 v \cos^3 \theta - \frac{\lambda_3}{2} v' \cos^2 \theta \sin \theta), \]
\[ g_{H'^3} = 6i(\lambda_2 v' \cos^3 \theta + \frac{\lambda_3}{2} v \cos^2 \theta \sin \theta), \]
\[ g_{H^4} = 6i\lambda_1 \cos^4 \theta, \]
\[ g_{H'^4} = 6i\lambda_2 \cos^4 \theta, \]
\[ g_{HH^2} = 2i(\frac{\lambda_3}{2} v \cos^3 \theta + \lambda_3 v' \cos^2 \theta \sin \theta - 3\lambda_2 v' \cos^2 \theta \sin \theta), \]
\[ g_{H'H'^2} = 2i(\frac{\lambda_3}{2} v' \cos^3 \theta - \lambda_3 v \cos^2 \theta \sin \theta + 3\lambda_1 v \cos^2 \theta \sin \theta), \]
\[ g_{H^2H'^2} = i\lambda_3 \cos^4 \theta. \] (2.14)

These new couplings lead to a different Higgs phenomenology from the well known one, predicted by the SM. The detailed analysis of Higgs bosons in this class of models and their phenomenological implications, like their productions and decays at the LHC, will be discussed in the next section.

3. Higgs Production and Decay at Hadron Colliders

3.1 Higgs Production

At the LHC, two 7-TeV proton beams with a center-of-mass energy of 14 TeV and a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ will collide with each other. The machine is expected to start running early 2008. The detection of the SM Higgs boson is the primary goal of the LHC project.
Figure 2: The dominant Higgs boson production mechanisms in hadronic collisions.

At hadron colliders, the two Higgs bosons couple mainly to the heavy particles: the massive gauge bosons $Z'$, $Z$ and $W^\pm$ and the heavy quarks $t$, $b$. The main production mechanisms for Higgs particles can be classified into four groups [7]: the gluon–gluon fusion mechanism[8], the associated Higgs production with heavy top or bottom quarks[9], the associated production with $W/Z/Z'$ bosons[10], and the weak vector boson fusion processes[11]:

\[
\begin{align*}
    gg &\rightarrow H \\
    gg, q\bar{q} &\rightarrow Q\bar{Q} + H, \\
    q\bar{q} &\rightarrow V + H \\
    qq &\rightarrow V^*V^* \rightarrow qq + H.
\end{align*}
\]

The Feynman diagrams of these processes are displayed in Figure 2. The cross sections of the Higgs production in these four mechanisms are directly proportional to the the Higgs couplings with the associated particles.

In case of the gluon–gluon fusion mechanism the Higgs production is mediated by triangular loops of heavy quarks. Thus, the cross section of this process is proportional to the Higgs coupling with the heavy quark mass. In case of $B - L$ extension of the SM, the production cross sections for the light Higgs, $H$, and the heavy Higgs, $H'$, can be approximated as

\[
\begin{align*}
    \sigma_H &\propto \alpha_s^2 \left( \frac{m_Q}{v^2} \cos^2 \theta \right) \times \left( \frac{m_Q}{m_H^2} \right), \\
    \sigma_{H'} &\propto \alpha_s^2 \left( \frac{m_Q}{v^2} \sin^2 \theta \right) \times \left( \frac{m_Q}{m_{H'}^2} \right),
\end{align*}
\]

where the first bracket is due to the coupling $QQH(H')$, while the second bracket corresponds to an approximated loop factor. As can be seen from Equations 3.5 and 3.6, the
cross section of the light Higgs production is reduced respect to the SM one by the factor of \( \cos^2 \theta \). On the other hand, the heavy Higgs production is suppressed by two factors: the small \( \sin \theta \), and the large \( m_{H'} \). Therefore, the heavy Higgs production is typically less than that of the light Higgs by two orders of magnitudes, i.e.,

\[
\frac{\sigma_{H'}}{\sigma_H} \approx \frac{\sin^2 \theta}{\cos^2 \theta} \frac{m_H^2}{m_{H'}^2} \approx \mathcal{O}(10^{-2}).
\] (3.7)

Now, we consider the mechanism of Higgs production in association with heavy quark pairs, Equation 3.2. In addition to the Feynman diagram shown in Figure 2, a set of other diagrams that also contribute to this process is given in Figure 3. Note that although this process shares the same coupling with the gluon-gluon fusion process, the leading order expression of its cross section indicates that it is less by one order of magnitude, for \( m_{H(H')} < 1 \) TeV. Furthermore, the typical ratio of \( \sigma(gg \to H'Q\bar{Q}) \) to \( \sigma(gg \to HQ\bar{Q}) \) is of order \( (\sin \theta / \cos \theta)^2 \approx \mathcal{O}(0.1) \).

Finally, we study the Higgs production in association with \( W/Z/Z' \) bosons and in the weak vector boson fusion processes, Equations 3.3 and 3.4 respectively. In \( B-L \) extension of the SM, the cross sections of these channels are proportional to the mass of the gauge boson and the mixing angle \( \theta \) of the two Higgs bosons:

\[
V \equiv W/Z : \sigma_H \propto \frac{m_V^4}{v^2} \cos^2 \theta \times \frac{g^2}{m_V^2} \times \text{Loop function},
\] (3.8)

\[
\sigma_{H'} \propto \frac{m_V^4}{v^2} \sin^2 \theta \times \frac{g^2}{m_V^2} \times \text{Loop function}.
\]

In case of \( V \equiv Z' \), The production is enhanced by the \( HZ'Z' \) coupling arising with \( m_{Z'} \). However, it is suppressed by a large value of \( v' \) and the mass of the virtual gauge boson(s), \( m_{Z'} \):

\[
V \equiv Z' : \sigma_H \propto \frac{m_{Z'}^4}{v'^2} \sin^2 \theta \times \frac{(g''Y_{B-L})^2}{m_{Z'}^2} \times \text{Loop function},
\] (3.10)

\[
\sigma_{H'} \propto \frac{m_{Z'}^4}{v'^2} \cos^2 \theta \times \frac{(g''Y_{B-L})^2}{m_{Z'}^2} \times \text{Loop function}.
\] (3.11)

From these equations, one can observe that the relative ratio between the light Higgs production associated with \( W/Z \) and \( Z' \) gauge bosons is given by \( \sigma_H(W/Z)/\sigma_H(Z') \sim \)
Figure 4: The cross sections of the light Higgs production as function of $m_H$: $100 \text{ GeV} \leq m_H \leq 1 \text{ TeV}$, for $m_{H'} = 1 \text{ TeV}$.

$\sigma_H(W/Z) \text{ can be larger than } \sigma_H(Z') \text{ by one order of magnitude at most. In contrary, the situation is reversed for the heavy Higgs production and one finds that } \sigma_H'(Z') > \sigma_H'(W/Z) \text{, which confirms our earlier discussion.}$

The cross sections for the Higgs bosons production in these channels (Equations 3.1-3.4) have been calculated using the FORTRAN codes: HIGLU, HQQ, V2HV, and VV2HV, respectively [12]. Extra subroutines have been added to these programs for the new couplings associated with the two higgs scalars and the extra gauge boson [12]. As inputs, we use $v = 246 \text{ GeV}$, $v' = 1 \text{ TeV}$, and center of mass energy $\sqrt{s} = 14 \text{ TeV}$. We also fix the mass of the extra gauge boson at $m_{Z'} = 600 \text{ GeV}$. The cross sections for the light Higgs boson production are summarized in Figure 4, as functions of the light Higgs mass with $m_{H'} = 1 \text{ TeV}$. Figure 5, on the other hand, represents the heavy Higgs productions as functions of $m_{H'}$ with $m_H = 200 \text{ GeV}$.

As shown in Figure 4, the salient feature of this low scale $B - L$ extension is that all cross sections of the light Higgs production are reduced by about 25 – 35% in the interesting mass range: $m_H < 250 \text{ GeV}$. As in the SM, the main contribution to the production cross section comes from the gluon-gluon fusion mechanism with a few tens of pb. The next relevant contribution is given by the Higgs production in the weak vector boson mechanism, Equation 3.4. This contribution is at the level of a few pb, as estimated above. Furthermore, the production associated with $Z/W$ is dominant over the production associated with $Z'$ for $m_H < 300 \text{ GeV}$.

Now, we analyze the production of the heavy Higgs. It turns out that its cross sections are smaller than the light Higgs ones. As shown in Figure 5, all these cross sections are scaled down by factor $O(10^{-2})$, which is consistent with the result obtained in Equation 3.7. Unlike the light Higgs scenario, the production associated with $Z'$ is dominant over the
production associated with Z/W in agreement with our previous prediction.

3.2 Higgs Decay

The Higgs particle tends to decay into the heaviest gauge bosons and fermions allowed by the phase space. The Higgs decay modes can be classified into three categories: Higgs decays into fermions (Figure 6), Higgs decays into massive gauge bosons (Figure 7), and Higgs decays into massless gauge bosons (Figure 8).

The decay widths into fermions are directly proportional to the $Hf\bar{f}$ couplings

\[ \Gamma(H \rightarrow ff) \approx m_H \left( \frac{m_f}{v} \right)^2 \left( 1 - \frac{4m_f^2}{m_H^2} \right)^{3/2} \cos^2 \theta, \quad (3.12) \]

\[ \Gamma(H' \rightarrow ff) \approx m_{H'} \left( \frac{m_f}{v} \right)^2 \left( 1 - \frac{4m_f^2}{m_{H'}^2} \right)^{3/2} \sin^2 \theta. \quad (3.13) \]
Figure 7: Diagrams for the Higgs boson decays into massive gauge bosons.

Figure 8: Loop induced Higgs boson decays into a) two photons ($Z\gamma$) and b) two gluons.

Figure 9: Diagrams for the three–body decays of the Higgs boson into $t\bar{b}W$ final states.

In case of the top quark, three-body decays into on-shell and off-shell states (Figure 9) were taken into consideration.

On the other hand, the decay widths into massive gauge bosons $V = Z', Z, W$ are directly proportional to the $HVV$ couplings. This includes two-body, three-body, and four-body decays

$$V \equiv W/Z : \Gamma_H \approx \frac{m_H^2}{v^2} \left( 1 - \frac{4m_V^2}{m_H^2} \right)^{3/2} \cos^2 \theta, \quad \Gamma_{H'} \approx \frac{m_{H'}^2}{v^2} \left( 1 - \frac{4m_V^2}{m_{H'}^2} \right)^{3/2} \sin^2 \theta, \quad (3.14)$$

$$V \equiv Z' : \Gamma_H \propto \frac{m_H^2}{v^2} \left( 1 - \frac{4m_V^2}{m_H^2} \right)^{3/2} \sin^2 \theta, \quad \Gamma_{H'} \propto \frac{m_{H'}^2}{v^2} \left( 1 - \frac{4m_V^2}{m_{H'}^2} \right)^{3/2} \cos^2 \theta. \quad (3.15)$$

As shown in Figure 8, the massless gauge bosons are not directly coupled to the Higgs bosons, but they are coupled via $W$, charged fermions, and quark loops. This implies that
the decay widths are in turn proportional to the $HVV$ and $Hff$ couplings, hence they are relatively suppressed.

From the above Equations, one finds that all decay widths of the light Higgs are proportional to $\cos^2 \theta$, except the new decay mode of $Z'Z'$. Furthermore, this channel has a very small contribution to the total decay width. Therefore, the light Higgs branching ratios (the ratios between the partial decay widths and the total decay width) have small dependence on the mixing parameter $\theta$. Thus, it is expected to see no significant difference between the results of the light Higgs branching ratios in this model of $B - L$ extension and the SM ones. On the other hand, the heavy Higgs branching ratios have relevant dependence on $\theta$.

The decay widths and branching ratios of the Higgs bosons in these channels have been calculated using the FORTRAN code: HDECAY with extra subroutines for the new couplings associated with the two higgs scalars and the extra gauge boson [12, 13]. As in the Higgs production analysis, we use the following inputs: $v = 246$ GeV, $v' = 1$ TeV, $m_{Z'} = 600$ GeV, and c.m. energy $\sqrt{s} = 14$ TeV.

The decay branching ratios of the light and heavy Higgs bosons are shown in Figures 10 and 11, respectively, as functions of the Higgs masses. As expected, the branching ratios of the light Higgs are very close to the SM ones. In the “low mass” range: $100$ GeV $< M_H < 130$ GeV, the main decay mode is $H \rightarrow b\bar{b}$ with a branching ratio of $\sim 75 - 50\%$. The decays into $\tau^+\tau^-$ and $c\bar{c}$ pairs come next with branching ratios of order $\sim 7 - 5\%$ and $\sim 3 - 2\%$, respectively. The $\gamma\gamma$ and $Z\gamma$ decays are rare, with very small branching ratios. In the “High mass” range: $m_H > 130$ GeV, the $WW$, $ZZ$, and to some extent the $tt$ decays give the dominant contributions. The $Z'Z'$ decay arises for quite large Higgs mass with a small branching ratio $\lesssim 1\%$. 

Figure 10: The branching ratios of the light Higgs decay as function of $m_H$ for $m_{H'} = 1$ TeV.
Figure 11: The branching ratios of the heavy Higgs decay as function of $m_{H'}$ for $m_H = 200$ GeV

Regarding the heavy Higgs decay branching ratio, one finds that $H' \rightarrow WW$ and $ZZ$ are the dominant decay modes, with a branching ratio of $\sim 70\%$ and $\sim 20\%$, respectively. To a lower extent, the $t \bar{t}$ and $Z'Z'$ account for the remaining branching ratios. Note that these two decay modes are in particular sensitive to the running mixing angles. Thus, they have the behaviors shown in Figure 11. The other modes give very tiny contributions and hence they are not shown in this figure.

It is useful to mention that the heavy Higgs may decay to a pair of the lighter Higgs. The partial decay width of this channel, which can be expressed by

$$\Gamma(H' \rightarrow HH) \approx \frac{1}{16\pi\sqrt{2}} \frac{g_{H_2H'}^2}{m_{H'}} \left(1 - \frac{4m_{H'}^2}{m_H^2}\right)^{1/2},$$

is suppressed by the tiny $g_{H_2H'}$ coupling (Equation 2.14) and the relatively large $m_{H'}$. In fact, the resulting branching ratio of this decay mode is at the level of $10^{-8}$, and hence does not appear in Figure 11.

4. $Z'$ decay in $B-L$ extension of the SM

In this section we study the decay of the extra gauge boson predicted by the $B-L$ extension of the SM at LHC. In fact, there are many models which contain extra gauge bosons [6, 14]. These models can be classified into two categories depending on whether or not they arise in a GUT scenario. In some of these models, the $Z'$ and the SM $Z$ are not true mass eigenstates due to mixing. This mixing induces the couplings between the extra $Z'$ boson and the SM fermions. However, there is a stringent experimental limit on the mixing parameter. In our model of $B-L$ extension of the SM, there is no tree-level $Z - Z'$ mixing.
Nevertheless, the extra $B - L$ $Z'$ boson and the SM fermions are coupled through the non-vanishing $B - L$ quantum numbers. The interactions of the $Z'$ boson with the SM fermions are described by

$$\mathcal{L}_{\text{int}}' = \sum_f Y_{f B-L}^{\prime} g'' \ Z'_\mu f \gamma^\mu f.$$  (4.1)

The decay widths of $Z' \to f \bar{f}$ are then given by [6]

$$\Gamma(Z' \to l^+l^-) \approx \frac{(g'' Y_{B-L}^l)^2}{24 \pi} m_{Z'},$$

$$\Gamma(Z' \to q\bar{q}) \approx \frac{(g'' Y_{B-L}^q)^2}{8 \pi} m_{Z'} \left(1 + \frac{\alpha_s}{\pi}\right), \ q \equiv b, c, s$$

$$\Gamma(Z' \to t\bar{t}) \approx \frac{(g'' Y_{B-L}^t)^2}{8 \pi} m_{Z'} \left(1 - \frac{m_t^2}{m_{Z'}^2}\right) \left(1 - \frac{4 m_t^2}{m_{Z'}^2}\right)^{1/2} \left(1 + \frac{\alpha_s}{\pi} + O\left(\frac{\alpha_s m_t^2}{m_{Z'}^2}\right)\right).$$  (4.2)

Figures 12 shows the decay branching ratios of $Z'$ as a function of $m_{Z'}$. Contrarily to the SM $Z$ decay, the branching ratios of $Z' \to l^+l^-$ are relatively high compared to $Z' \to q\bar{q}$. This is due to the fact that $|Y_{B-L}^l| = 3|Y_{B-L}^q|$. Thus, one finds $\text{BR}(Z' \to l^+l^-) \simeq 20\%$ compared with $\text{BR}(Z \to l^+l^-) \simeq 3\%$. Therefore, searching for $Z'$ can be easily accessible via a clean dilepton signal, which can be one of the first new physics signatures to be observed at the LHC.
5. Light $H'$ Scenario

In this section we discuss the possibility of having $m_{H'} \lesssim m_H$ and the phenomenological implications of this scenario. As shown in section two, the mass of the non-SM Higgs $m_{H'}$ receives a dominant contribution from the vev of the $B - L$ symmetry breaking $v'$ and the self coupling $\lambda_2$. The $Z'$ searches and the neutrino masses impose a lower limit on $v'$: $v' \gtrsim 1$ TeV. The self coupling $\lambda_2$ is essentially unconstrained parameter. If $\lambda_2 \sim \mathcal{O}(1)$, then $m_{H'}$ is of order TeV as assumed in the previous sections.

There are two other interesting possibilities which have recently received some attention in the literature. The first one corresponds to the case of $\lambda_1 v^2 \sim \lambda_2 v'^2$, i.e., $\lambda_2 \sim \mathcal{O}(10^{-2})$. Therefore, one finds $m_H \sim m_{H'}$ and the mixing angle is given by $\theta \sim \pi/4$. Hence, the two Higgs $H$ and $H'$ couple similarly to the fermion and gauge fields, giving the same production cross section and decay branching ratio. Therefore, the distinguish between $H$ and $H'$ at LHC in this type of models is rather difficult. This scenario is usually known as intense Higgs coupling [15].

The second possibility concerns the case of $\lambda_2 \lesssim 10^{-3}$, in which one obtains $m_{H'} \ll m_H$. In fact, LEP and Tevatron direct searches do not exclude a light Higgs boson with a mass below 60 GeV. Such light Higgs may have escaped experimental detection due to the suppression of its cross sections. Therefore, a window with a very light Higgs mass still exist.

Having $\lambda_2 \lesssim 10^{-3}$ implies that $\lambda_3$ is also less than $10^{-3}$. In this respect, the Higgs masses are approximately given by

\begin{align}
    m_H & \simeq \sqrt{\lambda_1 v}, \quad (5.1) \\
    m_{H'} & \simeq \mathcal{O} \left( \frac{\lambda_{H'H'}}{\lambda_1 v} \right) \simeq \mathcal{O}(10^{-2}) \text{GeV}, \quad (5.2)
\end{align}

and the coupling $g_{HH'H'}$ in Equation 2.14 becomes very small. Thus, the decay $H \to H'H'$ is not comparable to the decay into other SM particles. The phenomenology of this scenario, derived from different SM extensions, has been studied in details [4],[16]. In addition, this light scalar particle has been considered as an interesting candidate for dark matter [17].

6. Conclusions

In this paper we have considered the TeV scale $B - L$ extension of the SM. We provided a comprehensive analysis for the phenomenology of the SM like Higgs, the extra Higgs scalar, and the extra gauge boson predicted in this model, with special emphasize on their potential discovery at the LHC.

We have shown that the cross sections of the SM-like Higgs production are reduced by $\sim 20\% - 30\%$ in the mass range of $\sim 120 - 250$ GeV compared to the SM results. On the other hand, the implications of the $B - L$ extension to the SM do not change the decay branching ratios. Moreover, we found that the extra Higgs has relatively small cross sections, but it is accessible at LHC. Finally, we showed that the branching ratios of $Z' \to \ell^+\ell^-$ are of order $\sim 20\%$ compared to $\sim 3\%$ of the SM $BR(Z \to \ell^+\ell^-)$. Hence, searching for $Z'$ is accessible via a clean dilepton signal at LHC.
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