Minimal supersymmetric B – L extension of the standard model, heavy $H$ and light $h$ Higgs boson production and decay at future $e^+e^-$ linear colliders

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Abstract. We study the phenomenology of the light $h$ and heavy $H$ Higgs boson production and decay in the context of a $U(1)_{B-L}$ extension of the standard model with an additional $Z'$ boson at future $e^+e^-$ linear colliders with center-of-mass energies of $\sqrt{s} = 500 – 3000$ GeV and integrated luminosities of $L = 500 – 2000$ fb¹. The study includes the processes $e^+e^- \rightarrow (Z, Z') \rightarrow Zh$ and $e^+e^- \rightarrow (Z, Z') \rightarrow ZH$, considering both the resonant and non-resonant effects. We find that the total number of expected $Zh$ and $ZH$ events can reach $10^6$ and $10^5$, respectively, which is a very optimistic scenario allowing us to perform precision measurements for both Higgs bosons $h$ and $H$, as well as for the $Z'$ boson in future high-energy and high-luminosity $e^+e^-$ colliders.

1. Introduction
The $U(1)_{B-L}$ model [1–5] is one of the simplest extensions of the Standard Model (SM) with an extra $U(1)$ local gauge symmetry [6], where B–L represents baryon minus lepton number. This symmetry plays an important role in various physics scenarios beyond the SM: a) The gauge $U(1)_{B-L}$ symmetry group is contained in the Grand Unification Theory (GUT) described by a $SO(10)$ group [1]. b) The scale of the B–L symmetry breaking is related to the mass scale of the heavy right-handed Majorana neutrino mass terms and provides the well-known see-saw mechanism [7–11] to explain light left-handed neutrino mass. c) The B–L symmetry and the scale of its breaking are tightly connected to the baryogenesis mechanism through leptogenesis [12]. The model also contains an extra gauge boson $Z'$ corresponding to B–L gauge symmetry and an extra SM singlet scalar (heavy Higgs boson $H$). This may change the SM phenomenology. Therefore, another Higgs factory besides the LHC, such as the ILC (International Linear Collider) and CLIC (Compact Linear Collider), which can precisely determine the properties of the Higgs bosons $h$ and $H$, can be an important future step in high-energy and high-luminosity physics exploration.
The Higgs-Strahlung process $e^+e^- \rightarrow Zh$ [13-17] is one of the main production mechanisms of the Higgs boson in $e^+e^-$ linear colliders. After the discovery of the Higgs boson, detailed experimental and theoretical studies are necessary for checking its properties [18-21]. It is possible to search for the Higgs boson in the framework of the B–L model; however, the existence of a new gauge boson could also provide new Higgs particle production mechanisms that could prove its non-standard origin.

We examine a variety of $h, H$ decay channels while we concentrate on the $e^+e^- \rightarrow Zh$ and ZH production modes, including the possibility of $Z'$ mediation, which could be resonant, as we allow for $Z'/Z$ mixing. The B–L model [22-23] is attractive due to its relatively simple theoretical structure. The crucial test of the model is the detection of the new heavy neutral $Z'$ gauge boson and the new Higgs boson $H$.

2. Brief review of the U(1)$_{B-L}$ theoretical model

The solid evidence for the non-vanishing neutrino masses has been confirmed by various neutrino oscillation phenomena [32-33] and indicates the evidence of new physics beyond the SM. The most attractive idea to naturally explain the tiny neutrino masses is the see-saw mechanism [8-10], in which the right-handed (RH) neutrinos singlet under the SM gauge group is introduced. The gauged $U(1)_{B-L}$ model based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ [7] is an elegant and simple extension of the SM in which the RH heavy neutrinos arise, associated with the $U(1)_{B-L}$ gauge symmetry breaking.

We consider a $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ model, which is one of the simplest extensions of the SM [4, 5, 7, 22], where $U(1)_{B-L}$ represents the additional gauge symmetry. The gauge invariant Lagrangian of this model is given by:

$$\mathcal{L} = \mathcal{L}_s + \mathcal{L}_{YM} + \mathcal{L}_f + \mathcal{L}_Y$$

where $\mathcal{L}_s$, $\mathcal{L}_{YM}$, $\mathcal{L}_f$, $\mathcal{L}_Y$ are the scalar, Yang–Mills, fermion and Yukawa sector, respectively.

The model consists of one doublet $\Phi$ and one singlet $\chi$ and we briefly describe the lagrangian including the scalar, fermion and gauge sector. The Lagrangian for the gauge and scalar sector is given by [4, 24]:

$$\mathcal{L}_g = -\frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu}$$

where we see the corresponding field strength tensors for $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ respectively.

The Lagrangian for the scalar sector of the model is:

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger (D_{\mu} \Phi) + (D^\mu \chi)^\dagger (D_{\mu} \chi) - V(\Phi, \chi)$$

here we can clearly see the added $\chi$ field of our model, and where our new potential term is [25]:

$$V(\Phi, \chi) = m^2 (\Phi^\dagger \Phi) + \mu^2 |\chi|^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 |\chi|^4 + \lambda_3 (\Phi^\dagger \Phi)|\chi|^2$$

with $\Phi$ and $\chi$ as the complex scalar Higgs doublet and singlet fields, respectively. The covariant derivative is given by [25-27]:

$$D^\mu = \partial^\mu + ig_s t^a G_{\mu}^a + ig T_a W_{\mu}^a + g_1 Y B_{\mu} + (g'_1 + g'_1 Y_{B-L}) B'_{\mu}$$

where $g_s, g_1$ and $g'_1$ are the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ couplings with $t^a$, $T_a$, $Y$ and $Y_{B-L}$ being their respective group generators. The electromagnetic charges of the fields are the same as those of the SM and the new “hypercharges” $Y_{B-L}$ are 1/3 for quarks, -1 for leptons, 0 and 2 for the $\Phi$ and $\chi$ fields respectively [4-5, 25-27], to preserve the gauge invariance of the model. The doublet $\Phi$ and singlet $\chi$ scalar fields before and after spontaneous symmetry breaking are given by:

$$\Phi = \left( \begin{array}{c} G^+ \\ v + \phi^0 + i g_2 \end{array} \right) \rightarrow \left( \begin{array}{c} 0 \\ v + \phi^0 \end{array} \right) \quad \chi = \left( \begin{array}{c} v' + \phi'^0 \\ \sqrt{2} \end{array} \right) \rightarrow \left( \begin{array}{c} v' + \phi'^0 \\ \sqrt{2} \end{array} \right)$$

where $v'$ is the B–L symmetry breaking scale constrained by the electroweak precision measurements data whose value is assumed to be at least of the order of TeV.
After minimizing the potential around these values we see that the mass eigenstates are linear combinations of $\Phi^0$ and $\Phi^0$ and written:

$$\left( \begin{array}{c} h \\ H \end{array} \right) = \left( \begin{array}{c} \cos \alpha - \sin \alpha \\ \sin \alpha \cos \alpha \end{array} \right) \left( \begin{array}{c} \Phi^0 \\ \Phi^0 \end{array} \right)$$

where $h$ is the SM-like Higgs boson, $H$ is an extra Higgs boson and the scalar mixing angle $\alpha \ (\pi/4 \leq \alpha \leq \pi/2)$. The extension we are studying is in the Abelian sector of the SM gauge group, so that the charged gauge bosons $W^\pm$ will have masses given by their SM expressions related to the $SU(2)_L$ factor only, the other gauge boson masses are not so simple to identify because of mixing. In fact, analogous gauge bosons combinations of $W^\mu$, $B^\nu$, and $B^\nu$, the relation between the neutral gauge bosons and the corresponding mass eigenstates is given by [22, 23, 26, 27]:

$$\begin{pmatrix} W^\mu \\ B^\nu \end{pmatrix} = \begin{pmatrix} \cos \theta_W - \sin \theta_W \cos \theta_{B-L} & \sin \theta_W \sin \theta_{B-L} \\ \sin \theta_W \cos \theta_{B-L} - \cos \theta_W \sin \theta_{B-L} & \cos \theta_{B-L} \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$$

with $\theta_{B-L} \ (\pi/4 \leq \theta_{B-L} \leq \pi/4)$.  

3 The Higgs strahlung process $e^+e^- \rightarrow Zh$ and $e^+e^- \rightarrow ZH$ in the B - L model

We calculate the Higgs production cross section $\sigma$ via the Higgs-strahlung process in the context of the B – L model considering both, a $Z$ and a $Z'$ mediator.

The Feynman diagrams contributing to the processes $e^+e^- \rightarrow (Z, Z') \rightarrow Zh$ and $e^+e^- \rightarrow (Z, Z') \rightarrow ZH$ are given in figure 1.

![Feynman diagrams for the processes $e^+e^- \rightarrow (Z, Z') \rightarrow Zh$ and $e^+e^- \rightarrow (Z, Z') \rightarrow ZH$](image)

Figure 1

Here we present the cross sections $\sigma$ for the standard model Higgs boson $h$:

$$\sigma_{Z}(e^+e^- \rightarrow Zh) = \frac{G_F^2 M_Z^2 \cos^2 \alpha (g_W^2 + g_A^2) s_W}{2 \pi (s-M_Z^2)^2 + M_Z^2 t_Z^2} \left( \lambda + \frac{12 M_Z^2}{s} \right)$$

(9)

$$\sigma'(e^+e^- \rightarrow Zh) = \frac{G_F^2 M_Z^2}{2 \pi} \left( g_W^2 + g_A^2 \right) s_W \left( s - M_Z^2 \right)^2 + M_Z^2 t_Z^2 \left[ \frac{\lambda + 12 M_Z^2}{s} \right] \left[ f(\theta') \cos \alpha + g(\theta') \sin \alpha \right]^2$$

(10)

$$\sigma_{(Z)}(e^+e^- \rightarrow Zh) = \frac{G_F^2 M_Z^2 \cos \alpha}{6 \pi} \left( g_W^2 + g_A^2 \right) s_W \left[ \frac{1}{M_Z^2} \left( \lambda + 12 \frac{M_Z^2}{s} \right) + \frac{1}{M_Z^2} \left( \lambda + 6 \right) \right] \left[ \frac{1}{M_Z^2} \left( s - M_Z^2 \right)^2 + M_Z^2 t_Z^2 \right] \left[ f(\theta') \cos \alpha + g(\theta') \sin \alpha \right]$$

(11)

With

$$\lambda \left( M_Z^2, s, M_W^2 \right) = \left( 1 - \frac{M_Z^2}{s} \right) \frac{M_W^2}{s^2} - \frac{4 M_Z^2 M_W^2}{s^2}$$

(12)

the usual two-particle phase space function.
The expression given in equation (9) corresponds to the cross section with the exchange of the $Z$ boson, while equations (10) and (11) come from the contributions of the B–L model and of the interference, respectively.

### 4 Results and conclusions

We evaluate the total cross section $\sigma$ of the Higgs-strahlung process $e^+e^- \rightarrow (Z, Z') \rightarrow Zh$ in the B-L model using these values for our computation [31]; $\sin^2\theta_W = 0.23126 \pm 0.00022$, $m_t = 1776.82 \pm 0.16$ MeV, $m_b = 4.18 \pm 0.06$ GeV, $m_e = 172.44 \pm 0.13$ GeV, $M_W = 80.389 \pm 0.023$ GeV, $M_Z = 91.1876 \pm 0.0021$ GeV, $\Gamma_Z = 2.4952 \pm 0.0023$ GeV, $M_h = 125.09 \pm 0.4$ GeV. If we consider the most recent limit from $M_{Z'} \geq 6.9$ TeV [28-30], it is possible to obtain a direct bound on the B–L breaking scale $v'$, and take $v' = 3.45$ TeV and $\alpha = \pi/9$ in our numerical analysis. We will assume $\sqrt{s}, M_{Z'}, g_1', \theta_{B-L}$ as free parameters.

In figure 2, we show the cross section $\sigma(e^+e^- \rightarrow Z:\text{h})$, for different contributions as a function of the center-of-mass energy $\sqrt{s}$ for $\theta_{B-L} = 10^{-3}$ and $g_1' = 0.290$: the solid line corresponds to the SM and the dashed line corresponds to $\sigma_Z$ where the $U(1)_{B-L}$ model contributes to the couplings $g_1'$ and $g_2'$ of the SM gauge boson $Z$ to electrons. The dot-dashed line corresponds to $\sigma'(Z)$, which is only the B-L contribution, the dot-dotted line corresponds to the interference $\sigma_{Z'}$. Finally, the dotted line corresponds to the total cross section, $\sigma_{Total}$. We can see that the cross section corresponding to $\sigma_{Z}(e^+e^- \rightarrow Z:\text{h})$ decreases for large $\sqrt{s}$, whereas the cross section of the B-L model and the total cross section, there is an increase for large values of the center-of-mass energy, reaching its maximum value at the resonance of $Z'$, $\sqrt{s} = 2000$ GeV.

![Figure 2](image1.png)

**Figure 2**

Total cross sections of the processes, $e^+e^- \rightarrow Z:\text{h}$ (2, 3), and $e^+e^- \rightarrow ZH$ (4, 5) as a function of the center of mass energies $\sqrt{s}$, with $\theta_{B-L} = 10^{-3}$ for different values of $M_{Z'}$ and $g_1'$, including both the resonant and non-resonant effects

We plot the total cross section of the reaction $e^+e^- \rightarrow Zh$ in figure 3 as a function of the center-of-mass energy $\sqrt{s}$, for values of the heavy gauge boson mass $M_{Z'} = 1000, 2000, 3000$ GeV and $g_1' = 0.145, 0.290, 0.435$, respectively. $M_{Z'}$ and $g_1'$ maintain the previous relationship. Here we see that the cross section is sensitive to the free parameters and also that the height of the resonance peaks for the boson $Z'$ changes depending on the value of $\sqrt{s} = M_{Z'}^2$. In addition, the resonances are broader for larger $g_1'$ values, as the total width of the $Z'$ boson increases with $g_1'$.

The total cross section for the production processes $e^+e^- \rightarrow ZH$ as a function of the collision energy for $M_h = 125$ GeV, $M_H = 800$ GeV, $M_{W'} = 300$ GeV, $M_{Z'} = 2000$ GeV and $g_1' = 0.290$ is shown in figure 4. Here the curves are for $\sigma_{Z}(e^+e^- \rightarrow Z:\text{h})$ (solid line), $\sigma_{Z'}(e^+e^- \rightarrow Z:\text{h})$ (dashed line), $\sigma_{Z''}(e^+e^- \rightarrow Z:\text{h})$ (dot-dashed line), and the dot dot-dashed line corresponds to the total cross section of the process $\sigma_{Total}(e^+e^- \rightarrow Z:\text{h})$.

To see the effects of $\theta_{B-L}, g_1', M_{Z'}$, the free parameters of the B–L model, we plot the total cross section of the process $e^+e^- \rightarrow Z:\text{h}$ in figure 5 as a function of the center–of–mass energy $\sqrt{s}$ for the values of the heavy gauge boson mass of $M_{Z'} = 1000$ GeV with $g_1' = 0.145, M_{Z'} = 2000$ GeV with $g_1' = 0.290$ and $M_{Z'} = 3000$ GeV with $g_1' = 0.435$, preserving the relationship between $M_{Z'}$ and $g_1'$. In this figure we observed that for $\sqrt{s} = M_{Z'}$ the resonant effect dominates, the cross section is sensitive to the
free parameters. We also observe that the height of the resonance peaks for the $Z'$ boson change depending on the value of $\sqrt{s} = M_{Z'}^2$, and in addition, we see that the resonances are broader for larger $g'_{1}$ values, as the total width of the $Z'$ boson increases with $g'_{1}$.

We see that the expected $Z_{h}$ and $Z_{H}$ events can reach a number of $\mathcal{O}$ ($10^{6}$ and $10^{5}$), respectively, which is a very optimistic scenario and it would be possible to perform precision measurements for both Higgs bosons $h$ and $H$, for the $Z'$ heavy gauge boson, as well as for the parameters of the model $\theta_{B-L}$, $g'_{1}$ and $\alpha$ in future high-energy and high-luminosity $e^{+}e^{-}$ colliders experiments. In addition, the SM expression for the cross section of the reaction $e^{+}e^{-} \rightarrow Zh$ can be obtained in the decoupling limit, when $\theta_{B-L}$, $g'_{1} = 0$ and $\alpha = 0$. Our study complements other studies on the $B-L$ model and on the Higgs-strahlung processes $e^{+}e^{-} \rightarrow (Z, Z') \rightarrow Zh$ and $e^{+}e^{-} \rightarrow (Z, Z') \rightarrow ZH$.

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