B-L extension of the SM - Z' and heavy Higgs boson analysis at future $e^+e^-$ linear colliders ILC and CLIC

F Ramírez-Sánchez¹, A Gutierrez-Rodríguez² and M A Hernández-Ruiz³

¹ Facultad de Física, Universidad Autónoma de Zacatecas, Apartado Postal F-630, 99000 Fresnillo, Zac. México.
² Facultad de Física, Universidad Autónoma de Zacatecas, Apartado Postal C-580, 98060 Zacatecas, Zac. México.
³ Facultad de Ciencias Químicas, Universidad Autónoma de Zacatecas, Apartado Postal C-580, 98060 Zacatecas, Zac. México.

E-mail: ¹frank.ramirez@fisica.uaz.edu.mx, ²alexgu@fisica.uaz.edu.mx and ³mahernan@uaz.edu.mx

Abstract. We propose a $U(1)_{B-L}$ (baryon minus lepton) extension to the Standard Model, which adds a complex singlet to the scalar sector where an extra neutral gauge boson $Z'$ corresponding to the $U(1)_{B-L}$ gauge symmetry and an extra SM like singlet scalar $H$ (heavy Higgs) are predicted. We consider the mixture of the $Z$ and $Z'$. The model also yields Majorana masses for three right handed neutrinos. We study the phenomenology of the light $h$ and heavy $H$ Higgs boson production and decay at future $e^+e^-$ linear colliders with center-of-mass energies of $\sqrt{s} = 500 - 3000$ GeV and integrated luminosities of $L = 500 - 2000$ fb\(^{-1}\). The study includes the Higgs-strahlung processes $e^+e^- \rightarrow (Z Z') \rightarrow Z h$, $e^+e^- \rightarrow (Z Z') \rightarrow Z H$, and we complement our previous works with the addition of the $e^+e^- \rightarrow (Z Z') \rightarrow t\bar{t}h$ process.

1. Introduction

A simple extension of the Standard Model (SM) is analysed by adding a complex singlet to the scalar sector, the $U(1)_{B-L}$ model [1–5] with an extra $U(1)$ local gauge symmetry [6], where B(L) is baryon (lepton) number. The spontaneous breaking of $U(1)_{B-L}$ incorporates a complex scalar field $\chi$ in addition to the doublet $\Phi$ of Higgs fields. This symmetry plays an important role in various physics scenarios beyond the SM. First, the gauge $U(1)_{B-L}$ symmetry group is contained in the Grand Unification Theory (GUT) described by a $SO(10)$ group [1]. Second, 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. Third, the B–L symmetry and the scale of its breaking are tightly connected to the baryogenesis mechanism through leptogenesis [12]. The crucial test of the model is the detection of the new heavy neutral $Z'$ gauge boson and the new heavy Higgs boson $H$. The analysis of precision electroweak measurements indicates that the $Z'$ boson should be heavier than about 1.2 TeV. Searches for both of these particles predicted by the B–L model are presently being conducted at the LHC, Therefore, another Higgs
factory besides the LHC, such as the ILC (International Linear Collider) and CLIC (Compact Linear Collider), could precisely determine the properties of the Higgs bosons $h$ and $H$.

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 the $e^+e^- \rightarrow Zh$ and $ZH$ production modes, and we complement our previous works with the addition of the $e^+e^- \rightarrow (Z'Z') \rightarrow h\bar{t}\bar{t}$ process, including the possibility of $Z'$ mediation, which could be resonant, as we allow for $Z/Z'$ mixing. We focus on the $B-L$ model [22-23] due to its relatively simple theoretical structure and background free environment. The crucial test of the model is the detection of the new heavy neutral $Z'$ gauge boson and the new heavy Higgs boson $H$.

2. The $U(1)_{B-L}$ 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 small neutrino masses is the see-saw mechanism [8-10], in which heavy right-handed (RH) neutrinos singlets under the SM gauge group are introduced.

We consider a $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ model, which is an elegant and simple extension 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:

$$L = L_s + L_{YM} + L_f + L_Y$$

where $L_s$, $L_{YM}$, $L_f$, $L_Y$ are the scalar, Yang-Mills, fermion and Yukawa sector, respectively.

The Lagrangian for the gauge and scalar sectors is given by [4, 24]:

$$L_g = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu}$$

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

$$L_s = (D^\mu \Phi)^\dagger (D^\mu \Phi) + (D^\mu \chi)^\dagger (D^\mu \chi) - V(\Phi, \chi)$$

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]:

$$D^\mu = \partial^\mu + i g_s t^a G^a_\mu + i [g_T a W^a_\mu + g_1 Y B_\mu + (\tilde{g} Y + g'_1 Y_{B-L}) B'_\mu]$$

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 mixing between the two Abelian groups is described by the new coupling $\tilde{g}$, which is related to the other gauge couplings $g_1$ and $g'_1$, the “pure” or “minimal” $B-L$ model is defined by the condition $\tilde{g} = 0$, that implies no mixing between the $B-L$ $Z'$ and SM $Z$ bosons. In this article we consider the case $\tilde{g} \neq 0$, meaning that we do consider a mixing defined by the angle $\theta_{B-L}$. 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:

$$\Phi = \left( \begin{array}{c} G^+ / \sqrt{2} \\ v + \phi^0 \end{array} \right) \rightarrow \left( \begin{array}{c} 0 \\ v + \phi^0 / \sqrt{2} \end{array} \right)$$

$$\chi = \left( \begin{array}{c} \phi'^0 + i \phi^0 / \sqrt{2} \end{array} \right) \rightarrow \left( \begin{array}{c} \phi'^0 + \phi^0 / \sqrt{2} \end{array} \right)$$
where $\nu'$ 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:

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

(7)

$h$ is the SM Higgs boson, $H$ is an extra Higgs boson and the scalar mixing angle $\alpha (-\pi/2 \leq \alpha \leq \pi/2)$.

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, analogously to the SM, the fields of definite mass are linear combinations of $W^\pm$, $B^\mu$, and $B'^\mu$, the relation between the neutral gauge bosons and the corresponding mass eigenstates is given by [22, 23, 26, 27];

$$
\begin{pmatrix}
B^\mu \\
W^{3\mu} \\
B'^\mu
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_w & -\sin \theta_w \cos \theta_{B-L} & \sin \theta_w \sin \theta_{B-L} \\
\sin \theta_w & \cos \theta_w \cos \theta_{B-L} & -\cos \theta_w \sin \theta_{B-L} \\
0 & \sin \theta_{B-L} & \cos \theta_{B-L}
\end{pmatrix}
\begin{pmatrix}
A^\mu \\
Z^\mu \\
Z'^\mu
\end{pmatrix}
$$

(8)

3. The Higgs-strahlung process $e^+e^- \rightarrow (Z, Z') \rightarrow Zh$, $e^+e^- \rightarrow (Z, Z') \rightarrow ZH$ and $e^+e^- \rightarrow (Z, Z') \rightarrow \bar{\nu}h$ in the B–L model

The corresponding Feynman diagrams are shown in figure 1 and we calculate the Higgs production cross section $\sigma$ in the context of the B–L model considering both, a $Z$ and a $Z'$ mediator.

![Feynman diagrams](image.png)

Figure 1

Higgs-strahlung cross sections $\sigma$ for the production of the SM like Higgs boson $h$ [34];

$$
\sigma_e(e^+e^- \rightarrow Zh) = \frac{G_F M_Z^2 \cos^2 \alpha ((g_\nu) + (g_\nu)\nu) \sqrt{\lambda + 12M_Z^2}}{24\pi (s-M_Z^2 + M_Z^2\nu^2)} (\lambda + 12M_Z^2/s)
$$

(9)

$$
\sigma_{(Z')} (e^+e^- \rightarrow Zh) = \frac{G_F M_Z^2 \nu^2}{24\pi} ((g_\nu)^2 + (g_\nu')^2) \frac{\sqrt{\lambda + 12M_Z^2/s}}{M_Z^2 \nu^2} (\lambda + 6(M_Z^2 - M_{Z'}^2/s) + f(\theta') \cos \alpha + g(\theta') \sin \alpha)^2
$$

(10)

$$
\sigma_{(Z,Z')} = \frac{G_F \nu M_Z^2 \cos \alpha}{6\pi} (g_\nu g_\nu + g_\nu' g_\nu') \sqrt{\lambda} \frac{1}{M_Z^2} \left( \lambda + 12M_Z^2/s + \frac{1}{M_{Z'}^2} \frac{(\lambda + 6(M_Z^2 - M_{Z'}^2)/s)}{[s - M_Z^2] [s - M_{Z'}^2]} + \frac{s \lambda}{8M_Z^2 M_{Z'}} \right) [\lambda - 12M_Z^2/s] [f(\theta') \cos \alpha + g(\theta') \sin \alpha]
$$

(11)

where

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

(12)

is 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.

Finally we obtain the corresponding cross section for the \( e^+e^- \rightarrow (Z, Z') \rightarrow t\bar{t}h \) process, starting with the transition amplitude in the B-L model.

First we consider the neutral SM boson Z as a mediator, and then the heavy Z' boson of the B-L model.

\[
\mathcal{M}_Z = -\frac{ig}{\cos\theta_W} \bar{v}(p_1) \gamma_\mu (g_\nu - g_\nu^r \gamma_5) u(p_2) \left( -\frac{g_{\mu\nu} + \frac{p_\nu p_\mu}{M_Z^2}}{p^2 - M_Z^2 - i\frac{\Gamma_Z}{2}} \right) \frac{2M_Z^2 \cos\alpha}{v} \epsilon_\nu^\mu(z) \left( -\frac{ig}{\cos\theta_W} \bar{v}(t) \gamma_\mu (g_\nu - g_\nu^r \gamma_5) u(t) \right)
\]

(13)

\[
\mathcal{M}_{Z'} = -\frac{ig}{\cos\theta_W} \bar{v}(p_1) \gamma_\mu (g_\nu - g_\nu^r \gamma_5) u(p_2) \left( -\frac{g_{\mu\nu} + \frac{p_\nu p_\mu}{M_{Z'}^2}}{p^2 - M_{Z'}^2 - i\frac{\Gamma_{Z'}^\prime}{2}} \right) \frac{2M_{Z'}^2 \cos\alpha}{v'} f(\theta') \cos\alpha + g(\theta') \sin\alpha \epsilon^\mu \left( -\frac{ig}{\cos\theta_W} \bar{v}(t) \gamma_\mu (g_\nu - g_\nu^r \gamma_5) u(t) \right)
\]

(14)

and the cross section \( \sigma \) is given by:

\[
\frac{d\sigma(e^+e^-\rightarrow f\bar{f}h)}{dx_1 dx_2} = \frac{N_{cG_0}}{4\pi} \left[ \frac{Q_f^2 Q_{\bar{f}}^2}{1-z} + \frac{(v_f^2 + a_f^2)(v_{\bar{f}}^2 + a_{\bar{f}}^2)}{(1-z)^2} \right] G_1 + \frac{v_f^2 + a_f^2}{(1-z)^2} \sum_{i=2} G_i
\]

(15)

\( \sigma_0 = 4\alpha^2/3\pi \) is the standard normalization cross section, with \( \alpha = 1/127 \) for the value of the running electromagnetic coupling constant, \( x_1, x_2 \) are the reduced energies of the fermions, 2\( E_{f,\bar{f}}/\sqrt{s} \), \( Q_f \) is the electric charge, \( N_i \) the number of quark colors, \( a_f \) and \( v_f \) are the axial and vectorial coupling constants, or \( Z \) charges of the fermion \( f \), respectively, and normalized defined as [35]

\[ a_f = \frac{2I_f^L}{4c_{W}}; \quad v_f = \frac{2I_f^L - 4s_{W}^2}{4c_{W}} \]

where, \( I_f^L = \pm \frac{1}{2} \) is the weak isospin of the left handed fermions and \( s_{W}^2 = 1 - c_{W}^2 = \sin^2\Theta_W = 0.23 \).

The coefficients \( G_1 \) and \( G_2 \) describe the Higgs radiation off the fermion \( f \), the other terms account for the emission of the Higgs particle from the Z-boson line \( (G_3, \ G_4) \), and the interference terms \( (G_5, \ G_6) \) between the radiation amplitudes off the fermion and the Z-boson lines, which we are not considering here.

\[
G_1 = \frac{3g_{TH}}{x_{12}} \left[ x_H^2 - h \left( \frac{x_H}{x_{12}} + 2(x_H - 1 - h) \right) + 2f \left( 4(x_H - h) + \frac{x_H^2}{x_{12}} (4f - h + 2) \right) \right]
\]

(16)

\[
G_2 = -\frac{2g_{TH}}{x_{12}} \left[ x_{12}(1 + x_H) - h(x_{12} + 2x_H + 8f - 2h) + 3f x_H \left( \frac{x_H}{x_{12}} + 4 + \frac{x_H}{x_{12}} (4f - h) \right) \right]
\]

(17)

\[
G_3 = 2 \frac{g_{ZTH}}{x_H^2} f \left( 4h - x_H^2 - 12z \right) + \frac{f}{2}(4h - x_H^2)(x_H - 1 - h + 2z)
\]

(18)

\[
G_4 = 2 \frac{g_{ZTH}}{x_H} z [h + x_{12} + 2(1 - x_H) + 4f]
\]

(19)

\[
G_5 = -\frac{g_{TH}g_{TH}}{x_{12} x_H^2} \left[ x_{12} - h \right] (x_H - 1 - h) + f(12z - 4h + x_H^2) - 3z \left( h - \frac{x_{12}}{x_H} \right)
\]

(20)

\[
G_6 = -\frac{g_{TH}g_{TH}}{x_{12} x_H^2} 4z \frac{m_f}{m_Z} [x_H (h - 4f - 2) - 2x_{12} + x_H^2]
\]

(21)

where \( x_{12} = (1 - x_1)(1 - x_2) \) and \( x_H = 2E_H/\sqrt{s} = 2^{-x_1 - x_2} \) is the reduced energy of the Higgs boson.
4. Results and conclusions

We evaluate the total cross section $\sigma$ of the process $e^+e^- \rightarrow (Z,Z') \rightarrow Z$ in the B-L model using these values; [31, 34]; 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, $m_s = 172.44 \pm 0.13$ 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 recent limit from $\frac{M_{\nu}}{\theta_1} \geq 6.9$ TeV [28-30], it is possible to obtain a direct bound on the B–L breaking scale $\nu'$, and take $\nu' = 3.45$ TeV and $\alpha = \pi/9$ in our numerical analysis. We will assume $\sqrt{s}$, $M_{\nu'}$, $g_1'$, $\theta_{B-L}$ as free parameters.

In figure 2, we show the cross section $(e^+e^- \rightarrow Z\nu)$, 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 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 the SM, which is only the B-L contribution, the dot dot-dashed line corresponds to the interference $\sigma_{Z^\prime}$. Finally, the dotted line corresponds to the total cross section, $\sigma_{tot}$. We can see that the cross section corresponding to $\sigma_Z(e^+e^- \rightarrow Z\nu)$ 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.

We plot the total cross section of the reaction $e^+e^- \rightarrow Z\nu$ 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, $M_{\nu} = 800$ GeV, $M_{s\nu} = 300$ GeV, $M_{Z'} = 2000$ GeV and $g_1' = 0.290$ is shown in figure 4. Here the curves are for $\sigma_Z(e^+e^- \rightarrow Z\nu)$ (solid line), $\sigma_Z'(e^+e^- \rightarrow Z\nu)$ (dashed line), $\sigma_{Z^\prime}(e^+e^- \rightarrow Z\nu)$ (dot-dashed line), and the dot dot-dashed line corresponds to the total cross section of the process $\sigma_{tot}(e^+e^- \rightarrow Z\nu)$.

To see the effects of $\theta_{B-L}$, $g_1'$, $M_{\nu'}$, the free parameters of the B-L model, we plot the total cross section of the process $e^+e^- \rightarrow ZH$ 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 $\sqrt{s} = M_{Z'}^2$ 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 $\theta_{\text{B-L}}, g'_1$ and $\alpha$. In addition, the SM expression for the cross section of the reaction $e^+e^- \rightarrow Z_h$ can be obtained in the decoupling limit, when $\theta_{\text{B-L}}, g'_1 = 0$ and $\alpha = 0$. Our study complements other studies on the B–L model and on the Higgs-strahlung processes; $e^+e^- \rightarrow (Z, Z') \rightarrow ZH$.

References

[1] Buchmuller W, Greub C and Minkowski P 1991 Phys. Lett. B 267 395
[2] Marshak R and Mohapatra R N 1980 Phys. Lett. B 91 222
[3] Mohapatra R N and Marshak R 1980 Phys. Rev. Lett. 44 1316
[4] Khalil S 2008 J. Phys. G: Nucl. Part. Phys. G 35 055001
[5] Eman W and Khalil 2007 S Eur. Phys. J. C 52 625
[6] Carlson E D 1987 Nucl. Phys B 286 378
[7] Mohapatra Rabindra N and Senjanovic G 1980 Phys. Rev. Lett. 44 912
[8] Minkowski P 1977 Phys. Lett. B 67 421
[9] Van Nieuwenhuizen P and Freedman D Z 1979 Proc. Supergravity Conf. (Stony Brook University) ed P Van Nieuwenhuizen and D Z Freedman (Amsterdam, Netherlands: North Holland Publishing Co.) p 341
[10] Yanagida T 1979 Proc. Workshop on the Baryon Number of the Universe and Unified Theories (Tsukuba, Japan, 13–14 February) p 95
[11] Gell-Mann M, Ramond P and Slansky R 1979 Proc. Supergravity Conf. (Stony Brook University, New York) ed P Van Nieuwenhuizen and D Z Freedman (Amsterdam, Netherlands: North Holland Publishing Co.) pp 315–21
[12] Fukugita M and Yanagida T 2003 Physics of Neutrinos and Applications to Astrophysics (Berlin: Springer)
[13] Ellis J, Gaillard M K and Nanopoulos D V 1976 Nucl. Phys. B 106 292
[14] Ioffe B L and Khoze V A 1978 Sov. J. Part. Nucl. 9 50
[15] Lee B W, Quigg C and Thacker H B 1977 Phys. Rev. D 16 1519
[16] Bjorken J D 1976 Proc. Summer Institute on Particle Physics SLAC Report 198
[17] Barger V D et al 1994 Phys. Rev. D 49 79
[18] Ellis J 2013 arXiv:1312.5672
[19] Dawson S et al 2013 arXiv:1310.8361
[20] Klute M et al 2013 Europhys. Lett. 101 51001
[21] Behnke T et al 2013 arXiv:1306.6327 [physics.acc-ph]
[22] Basso L et al 2009 Phys. Rev. D 80 055030
[23] Basso L et al 2009 J. High Energy Phys. JHEP10(2009)006
[24] Basso L 2011 arXiv:1106.4462 [hep-ph]
[25] Basso L, Moretti S and Pruna G M 2010 Phys. Rev. D 82 055018
[26] Basso L et al 2011 Eur. Phys. J. C 71 1613
[27] Basso L, Moretti S and Pruna G M 2012 J. Phys. G: Nucl. Part. Phys. G 39 025004
[28] Carena M, Daleo A, Dobrescu B A and Tait T M 2004 Phys. Rev. D 70 093009
[29] Heeck J 2014 Phys. Lett. B 739 256
[30] Cacciapaglia G, Csaki C, Marandella G and Strumia A 2006 Phys. Rev. D 74 033011
[31] Olive K A et al (Particle Data Group) 2014 Chin. Phys. C 38 090001
[32] Fogli G L, Lisi E, Marrone A, and Palazzo A 2006 Prog. Part. Nucl. Phys. 57 742
[33] Fogli G L et al 2007 Phys. Rev. D 75 053001
[34] Ramirez-Sánchez F et al 2016 J. Phys. G: Nucl. Part. Phys. 43 095003
[35] Djouadi A, Kalinowski J and Zerwas P M 1992 Z. Phys. C Particles and Fields 54, 255-262