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Higgs Boson Production via Higgs Strahlung $e^+e^- \to (Z, Z') \to Zh$ and $t\bar{t}H$, at Future e^+e^- Linear Colliders ILC & CLIC in the Context of a $U(1)_{B\text{-}L}$ Extension of the SM.

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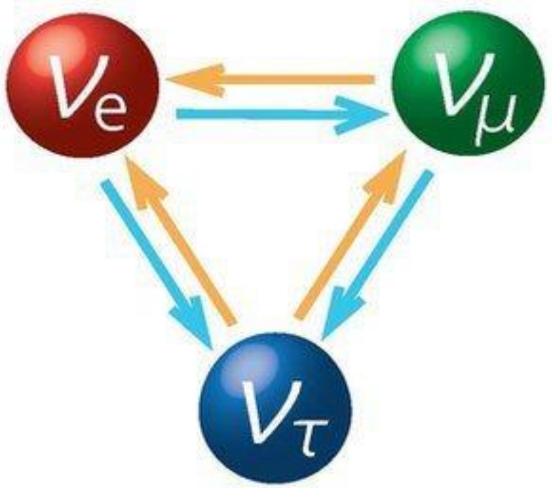
We study the phenomenology of light h, and heavy H, Higgs boson production and decay in the context of a $U(1)_{B-L}$ (baryon-lepton) extension of the SM with an additional Z' boson (considering mixture of Z and Z' bosons) at future e^+e^- linear colliders with center of mass energies of $\sqrt{s} = 500 - 3000$ GeV and integrated luminosities of $\mathcal{L} = 500 - 2000\ fb^{-1}$. We study the Higgs-strahlung processes $e^+e^- \rightarrow (Z, Z') \rightarrow Zh, ZH, tth, ttH$, considering both the resonant and non-resonant effects. We find that the total number of expected Zh and ZH events can reach $\sim 10^6$ and $\sim 10^5$, respectively, which is a very optimistic scenario and thus it would be possible 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^- linear colliders.

MOTIVATION (The SM is incomplete)

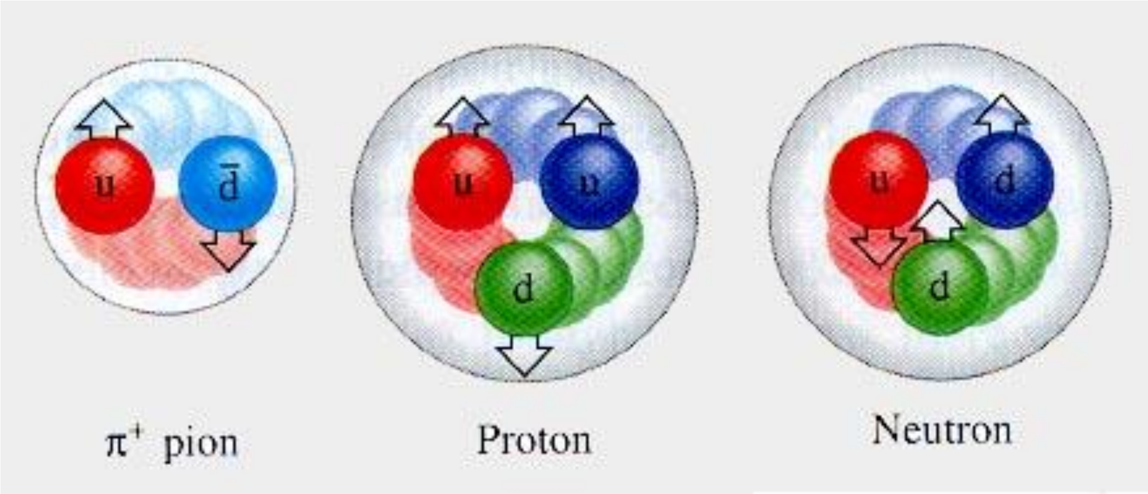
The SM does not explain various phenomena; the solid evidence for the non-vanishing neutrino masses has been confirmed by various neutrino oscillation phenomena, dark matter, the hierarchy problem, etc.



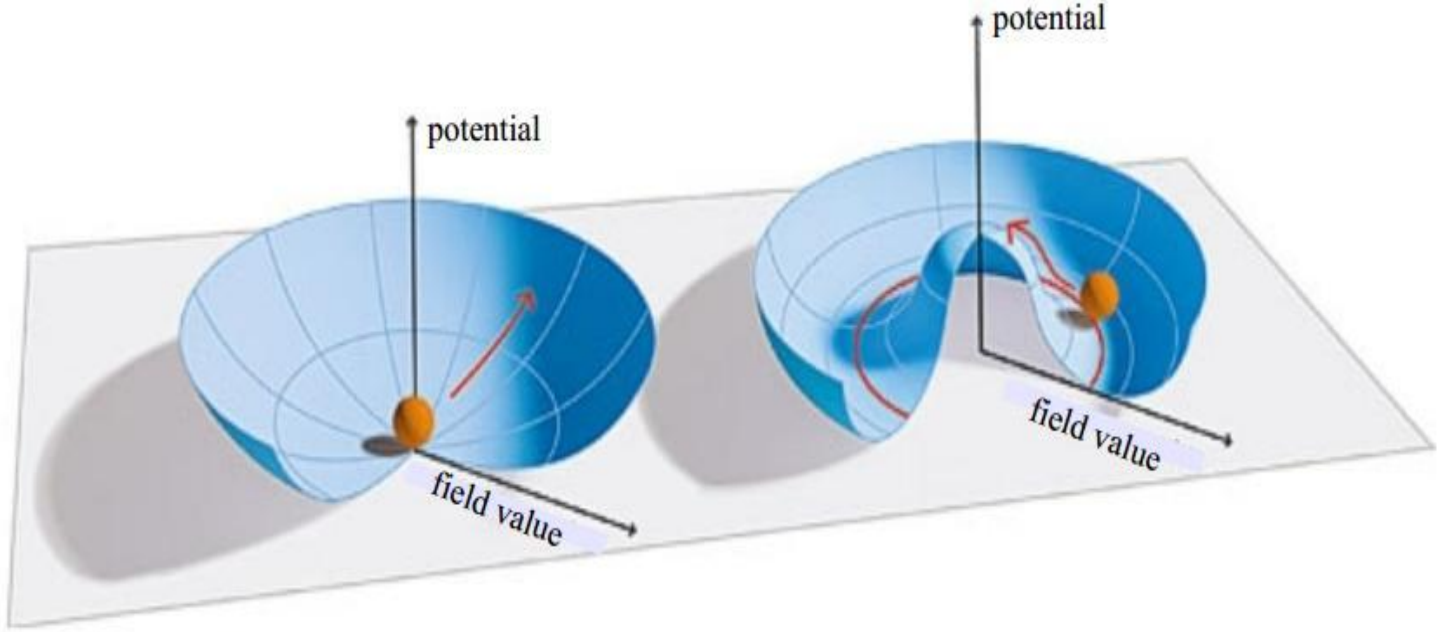
The most attractive idea to naturally explain the tiny neutrino masses is the seesaw mechanism, in which a right-handed (RH) neutrino singlet under the SM gauge group is introduced. The gauged $U(1)_{B-L}$ model based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ is an elegant and simple extension of the SM in which the RH heavy neutrinos are essential.

CLEAN ENVIRONMENT

Hadrons are compound objects, the initial state of partons is not uniquely defined, generally they are realized as quantum superposition of states distributed according to the proton structure functions. HCs create a large number of elementary processes. These represent background, and deposit high doses of radiation energy in the detector.



By contrast, the total cross section at LCs is relatively small and they have high sensitivity to electroweak processes, allowing very precise measurements in the Higgs sector, as well as in the search for new physics. The radiation levels are moderate. The process is *cleaner* with regards to the background, here the particles are elementary, and the initial state is defined at the fundamental level, allowing full reconstruction of the final state from conservation principles.

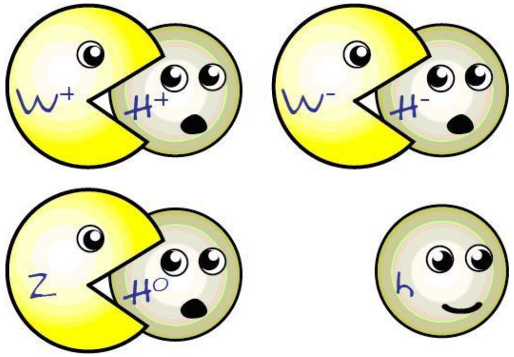


The minimal B−L extension of the SM consists of adding a further $U(1)_{B-L}$ gauge group together with a singlet complex neutral scalar field (to break the new symmetry), giving rise to; an extra Z' boson, three right-handed neutrinos, an additional heavy scalar Higgs boson generated through the $U(1)_{B-L}$ symmetry breaking ($\mathcal{O}$ TeV) and giving mass (see-saw) to the SM neutrinos.

The essence of the extended B-L model

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, where $U(1)_{B-L}$, represents an additional gauge symmetry. The gauge invariant Lagrangian of this model is given by:

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



The model consists of one doublet Φ and one singlet χ complex scalar fields.

$$\Phi = \begin{pmatrix} G^{\pm} \\ \frac{v + \phi^0 + iG_Z}{\sqrt{2}} \end{pmatrix}, \quad \chi = \left(\frac{v' + \phi'^0 + iz'}{\sqrt{2}} \right)$$

After spontaneous symmetry breaking and minimizing. ⟶

$$\Phi = \begin{pmatrix} 0 \\ \frac{v + \phi^0}{\sqrt{2}} \end{pmatrix} \qquad \chi = \left(\frac{v' + \phi'^0}{\sqrt{2}} \right)$$

The Lagrangian for the gauge and scalar sector is given by:

$$\mathcal{L}_g = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu}, \qquad \mathcal{L}_s = (D^\mu \Phi)^\dagger (D_\mu \Phi) + (D^\mu \chi)^\dagger (D_\mu \chi) - V(\Phi, \chi)$$

We consider the most general Higgs potential invariant under these symmetries given by

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

The essence of the extended B-L model

The new covariant derivatives in which we observe no mixing (pure, minimal) are given by:

$$D^{\mu}\Phi = \partial_{\mu}\Phi + i\left[gT_a W_{\mu}^{a} + g_1 Y B_{\mu} + g_1' Y_{B-L} B_{\mu}'\right]\Phi$$

$$D^{\mu}\chi = \partial_{\mu}\chi + i\left[g_1 Y B_{\mu} + g_1' Y_{B-L} B_{\mu}'\right]\chi$$

Since we are considering mixing of the Z bosons (the two Abelian groups) an *effective* charge-coupling constant is used for the new gauge boson, and is a linear combination of the Y , Y_{B-L}, g_1 and g_1'.
If $\tilde{g} = 0$ there is no mixing.

$$D^{\mu} = \partial_{\mu} + i\left[gT_a W_{\mu}^{a} + g_1 Y B_{\mu} + (\tilde{g}Y + g_1' Y_{B-L})B_{\mu}'\right]$$

The electromagnetic charges of the fields are the same as those of the SM and the new “hypercharges” are:

$$Y_{B-L}^{quarks} = \frac{1}{3} \quad , Y_{B-L}^{leptons} = -1, \quad Y_{B-L}(\Phi) = 0, \qquad Y_{B-L}(\chi) = 2$$

after SSB we get the mass eigenstates matrix (linear combinations of the neutral CP-even Φ^0 and Φ'^0) and written as,

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi^0 \\ \phi'^0 \end{pmatrix}$$

with the scalar mixing angle α ($-\pi/2 \leq \alpha \leq \pi/2$). Recent constraints from LHC fix $\cos\alpha \cong 1$, i.e. $h \cong \phi^0$

The essence of the extended B-L model and the ILC, CLIC colliders

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 to the SM, the fields of definite mass are linear combinations of W_μ^3, B_μ, and B'_μ .

The relation between the neutral gauge bosons and the corresponding mass eigenstates is given by;

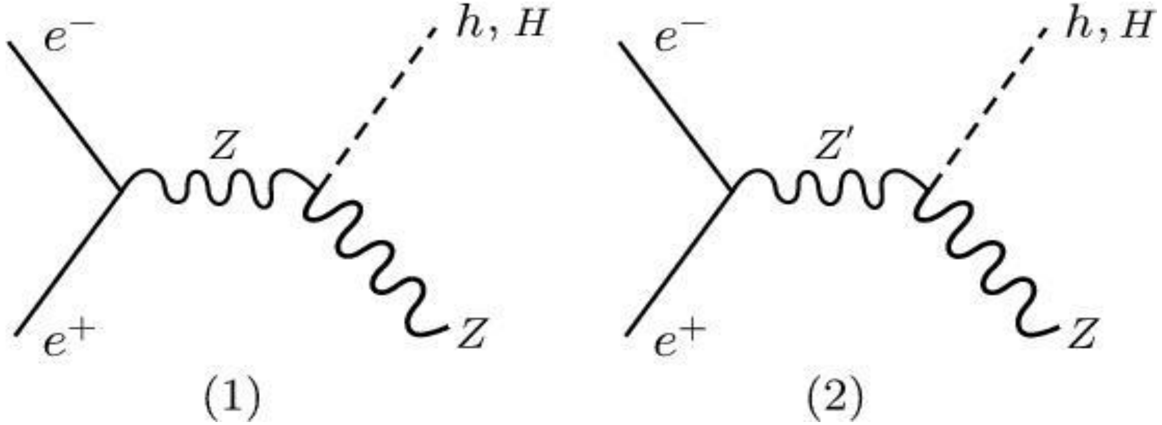
$$\begin{pmatrix} B^\mu \\ W^{3\mu} \\ B'^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W\cos\theta_{B-L} & \sin\theta_W\sin\theta_{B-L} \\ \sin\theta_W & \cos\theta_W\cos\theta_{B-L} & -\cos\theta_W\sin\theta_{B-L} \\ 0 & \sin\theta_{B-L} & \cos\theta_{B-L} \end{pmatrix} \begin{pmatrix}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

with $\theta_{W,}$ the Weinberg angle, and $\theta_{B\text{-}L}$ $(-\pi/4 \leq \theta_{B\text{-}L} \leq \pi/4)$.

The Higgs-strahlung process $e^+e^- \rightarrow Zh$ is one of the main production mechanisms of the Higgs boson in future e^+e^- linear colliders such as the ILC and CLIC.

The Process

The Higgs Strahlung Process $e^+e^- \to Z\,h$ and $e^+e^- \to Z\,H$ in the B - L Model



The Feynman diagrams contributing to the processes $e^+e^- \to (Z, Z') \to Zh$ and $e^+e^- \to (Z, Z') \to ZH$

The transition amplitude for the production of the SM Higgs boson h in both models is;

$$\mathcal{M}_Z = -\frac{igM_Z^2 \cos\alpha}{v\cos\theta_W}\bar{v}(p_1)\gamma^\mu(g_V^e - g_A^e\gamma_5)u(p_2)\left(-g_{\mu\nu} + \frac{p_\mu p_\nu}{M_Z^2}\right)\left(\frac{1}{p_Z^2 - M_Z^2 - i\Gamma_Z^2}\right)\epsilon_\lambda^\nu(z)$$

$$\mathcal{M}_{Z'} = -\frac{ig}{\cos\theta_W}\bar{v}(p_1)\gamma^\mu\frac{1}{2}(g'^e_V - g'^e_A\gamma_5)u(p_2)\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{M_{Z'}^2}\right)\left(\frac{1}{q_Z^2 - M_{Z'}^2 - i\Gamma_{Z'}^2}\right)\frac{2M_Z^2}{v}[f(\theta')\cos\alpha + g(\theta')\mathrm{sen}\alpha]\epsilon_\lambda^\nu(z)$$

The Process

The cross section σ for the different processes involved in the Higgs–Strahlung B-L model

$$\sigma_Z(e^+e^- \to Zh) = \frac{G_F^2 M_Z^4 \cos^2\alpha (g_v^{e2} + g_a^{e2}) S\sqrt{\lambda}}{(24\pi(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2)}\left(\lambda + \frac{12M_Z^2}{s}\right)$$

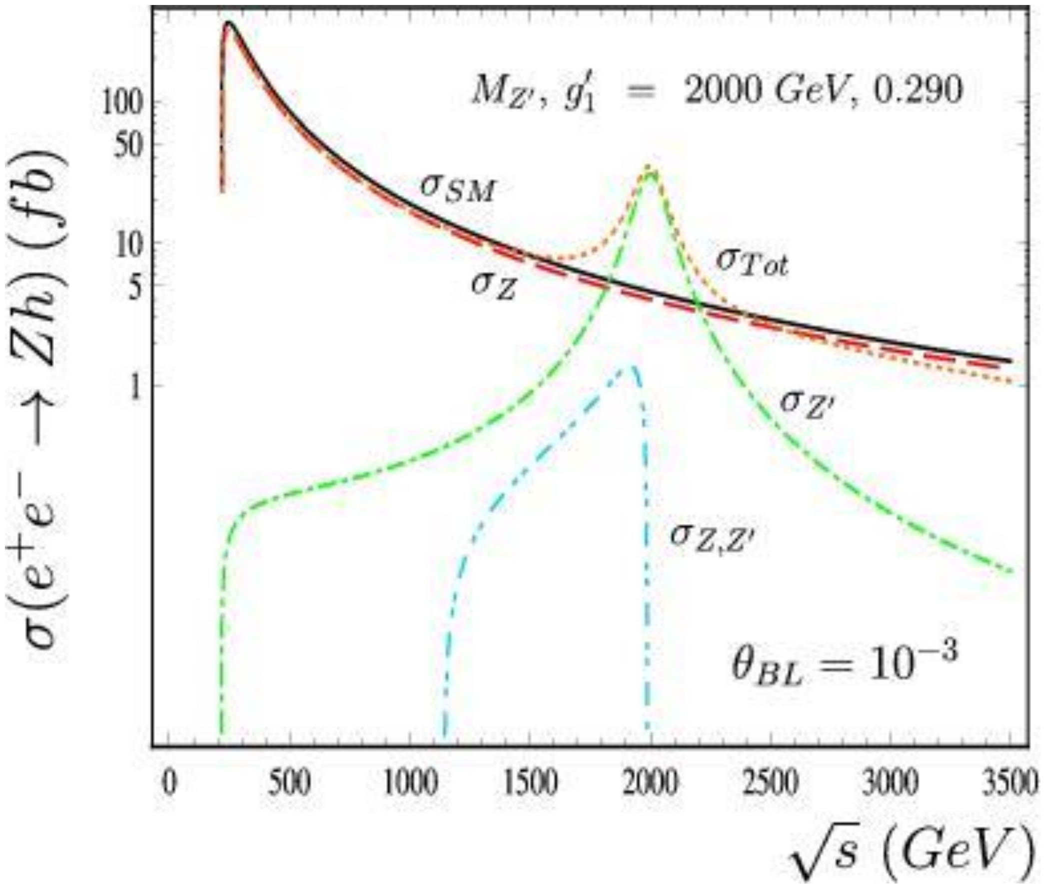
$$\sigma_{(Z')}(e^+e^- \to Zh) = \frac{G_F^2 M_Z^6}{24\pi}\left((g_v'^e)^2 + (g_a'^e)^2\right)\frac{s\sqrt{\lambda}\left[\lambda + 12\, M_{Z'}^2/s\right]}{M_{Z'}^2\left[\left[s - M_{Z'}^2\right]^2 + M_{Z'}^2\Gamma_{Z'}^2\right]}\quad [f(\theta')\cos\alpha + g(\theta')\sin\alpha]^2$$

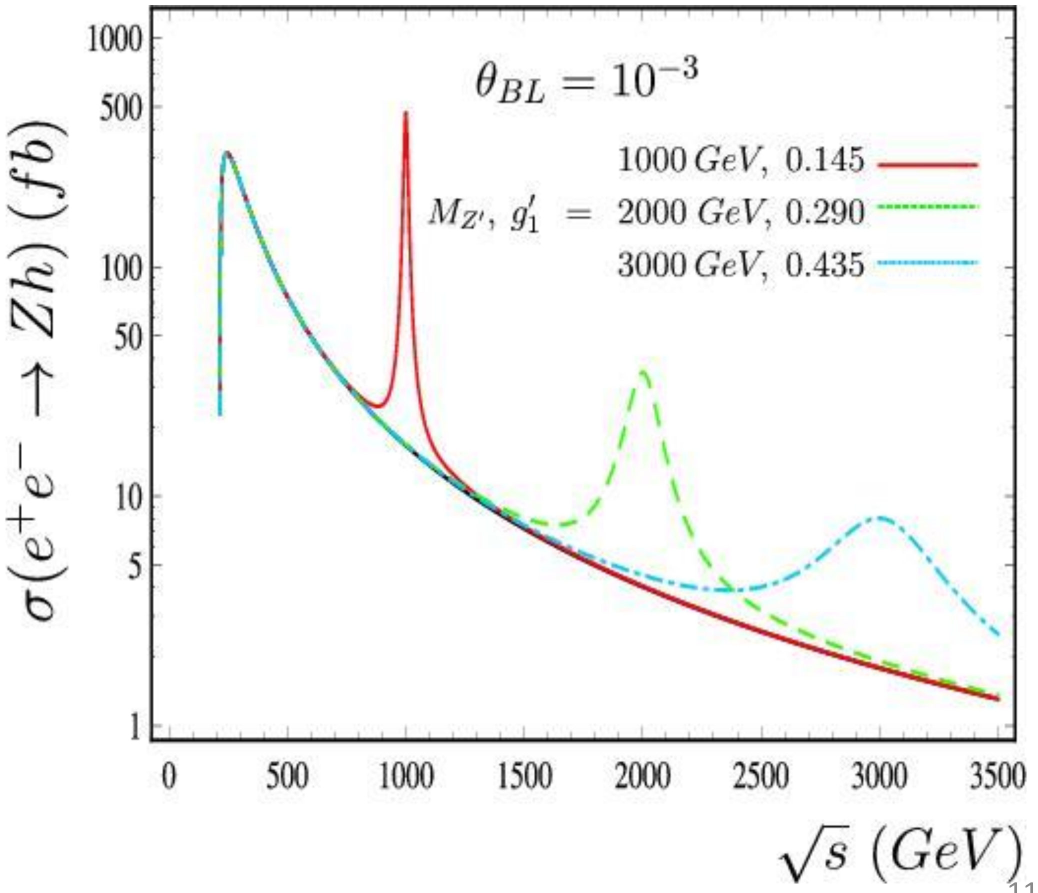
$$\sigma_{(Z,Z')}(e^+e^- \to Zh) = \frac{G_F^2 M_Z^6 cos\alpha}{6\pi}(g_v^{'e} g_v^e + g_a^{'e} g_a^e)s\sqrt{\lambda}\left[\frac{1}{M_Z^2}\left(\lambda + 12\frac{M_Z^2}{s}\right) + \frac{1}{M_{Z'}^2}(\lambda + 6\left(M_Z^2 - \frac{M_{Z'}^2}{s}\right) + \frac{s\lambda}{8M_Z^2 M_{Z'}^2}\left(\lambda - 12\frac{M_Z^2}{s}\right)\right]\frac{\left[(s - M_Z^2)\left(s - M_{Z'}^2\right) + M_Z M_{Z'}\Gamma_Z\Gamma_{Z'}\right]}{[(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2]\left[\left(s - M_{Z'}^2\right)^2 + M_{Z'}^2\Gamma_{Z'}^2\right]}[f(\theta^{'})cos\alpha + g(\theta^{'})sen\alpha]$$

Observe the cos α and the [$f(\theta')$ cosα +$g(\theta')$ sin α]

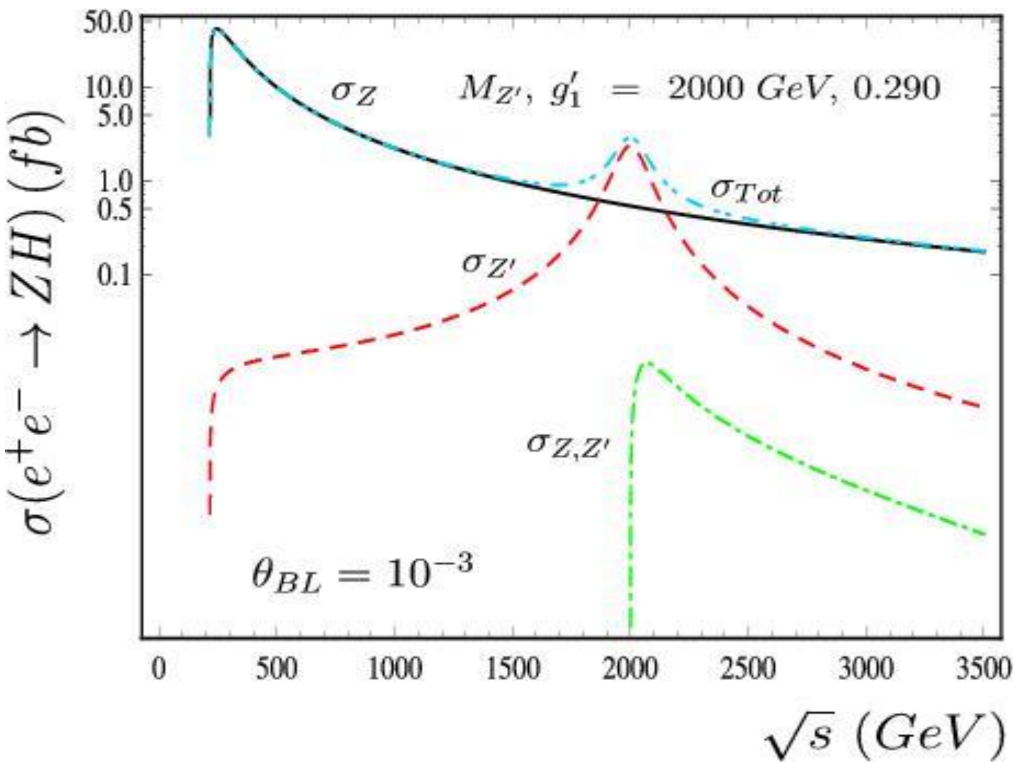
The first expression corresponds to the cross section with a Z boson exchange while the next two are the contributions of the B–L model and of the interference, respectively.

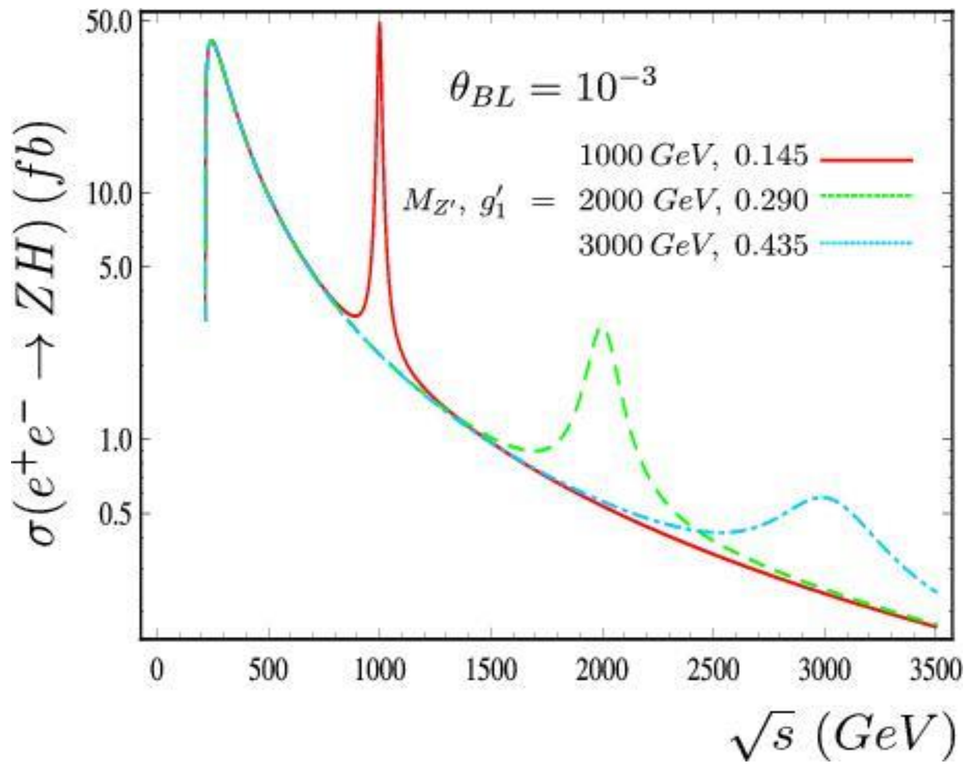
We evaluate the total cross section $\boldsymbol{\sigma}$ of the process $e^+e^- \longrightarrow (Z,Z') \longrightarrow Zh$ in the B-L model using the these values for our computation; $\sin^2\theta_W = 0.23126 \pm 0.00022$, $m_\tau = 1776.82 \pm 0.16$ MeV, $m_b = 4.6 \pm 0.18$ GeV, $m_t = 172 \pm 0.9$ 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, $M_h = 125 \pm 0.4$ GeV





Results and Conclusions





We find that the total number of expected Z_h and Z_H events can reach 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 θ_{B-L}, g'_1 and α in future high-energy and high-luminosity e^+e^- colliders. In addition, the SM expression for the cross section of the reaction $e^+e^- \to Zh$ can be obtained in the decoupling limit when θ_{B-L}, g'_1 and $\alpha \to 0$. Our study complements other on the B−L model and on the Higgs-strahlung processes $e^+e^- \to (Z, Z') \to Zh$ and $e^+e^- \to (Z, Z') \to ZH$.

Thanks for your attention