The pure $B-L$ model and future linear colliders: the Higgs sector

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We summarise the phenomenology of the Higgs sector of the minimal $B-L$ extension of the Standard Model at an e^+e^- Linear Collider. Within such a scenario, we show that (in comparison with the Large Hadron Collider) several novel production and decay channels involving the two physical Higgs states could experimentally be accessed at such a machine. In particular, we present the scope of the Z' strahlung process for single and double Higgs production, the only suitable mechanism for accessing an almost decoupled heavy scalar state.

1 The $B-L$ model

The "pure" $B-L$ ("baryon" minus "lepton") model is a peculiar choice from the the subset of the minimal Standard Model (SM) extensions obeying the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ gauge symmetry. It is defined by precluding the mixing between the two $U(1)$ groups [1].

In this report we will analyse some peculiar processes of the minimal $B-L$ extension of the Standard Model at future e^+e^- Linear Colliders (LCs). For all practical purposes, we generally refer to an International Linear Collider (ILC) for a sub-TeV/TeV prototype and to a Compact LInear Collider ($CLIC$) for a TeV/multi-TeV design.

Firstly we will analyse the cross section and luminosity impact on the significance of the Higgs-strahlung (off Z') process, with emphasis on both single and double Higgs production. Finally, we will consider the case in which an Higgs state is produced in association with heavy neutrinos from direct Z' production.

All these channels are based on the direct production of a Z'_{B-L} boson (which is generally dominantly coupled to leptons [1]), hence a lepton collider is the most suitable environment for probing the considered model.

Finally, we remark that all the choices of parameters used in the following analysis are compatible with both experimental and theoretical constraints (see Reference [2]).

2 Higgs-strahlung off Z': single Higgs production

Among the production mechanisms of the minimal $B-L$ model, a non-SM-like one for producing a single Higgs boson final state (either the light or heavy one) is Higgs-strahlung off a Z' boson, i.e., $e^+e^- \to Z'\, h_{1,2}$.

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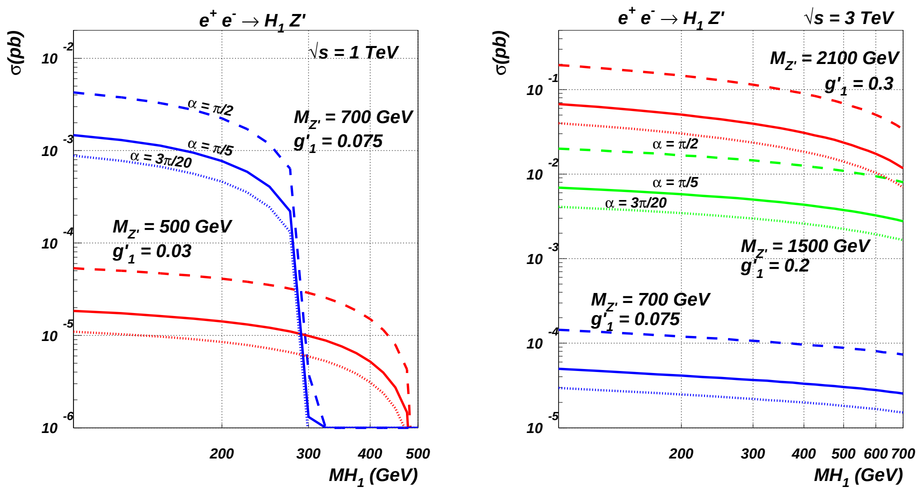
As shown in Figure 1a(1b) a light Higgs boson can be produced in association with a Z' boson of 1.5(2.1) TeV mass with cross sections of $\mathcal{O}(10)(\mathcal{O}(100))$ fb. Only the light Higgs boson has been considered, being the case of a heavy Higgs boson with same mass just the symmetric one under $\alpha \to \pi/2 - \alpha$.



(a) (b)

Figure 1: *Cross sections for the process* $e^+e^- \to Z'^* \to H_1 Z'$ *at* $\sqrt{s} = 1$ *(1a) and* $\sqrt{s} = 3$ *(1b) TeV.*

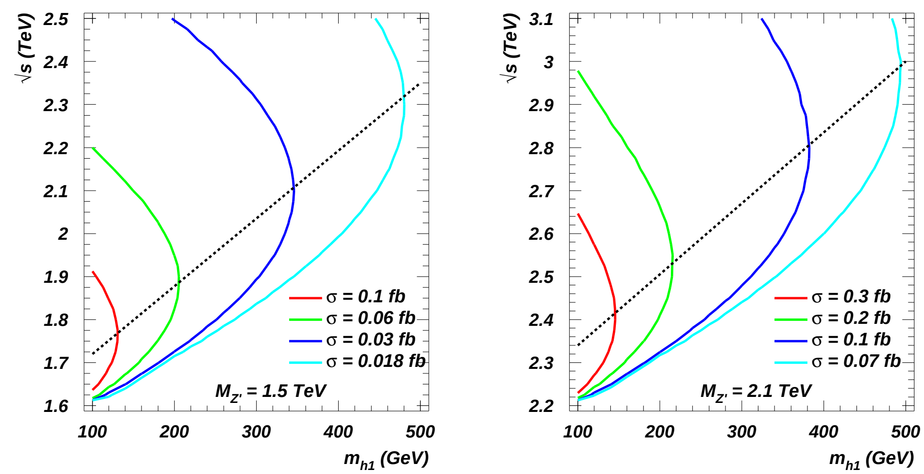
It is important to remark that for $\alpha \to 0$ (decoupling limit), *this is the only heavy Higgs production mechanism allowed*. Moreover, the Higgs-strahlung off Z' mechanism is not suitable for the LHC [3], making a multi-TeV linear collider the ultimate chance for its discovery. This mechanism is absent in scalar extensions of the SM in which the gauge content is not changed.

With Z' boson mass assumed to be known (see, for example, References [4, 5]), the discovery potential for this channel is here presented. We first study the effect of Initial State Radiation (ISR) on the cross sections for the strahlung of a light Higgs state. Figure 2 clearly shows a linear dependence of $\sqrt{s_{MAX}}$, the Centre-of-Mass (CM) energy that maximises the cross section, as a function of the Higgs mass only. Interpolating, we find the useful relation:

$$\frac{\sqrt{s_{MAX}}}{TeV} \approx \frac{M_{Z'}}{TeV} + 0.1 + 1.5\frac{m_H}{TeV} \qquad (H = h_1, h_2). \tag{1}$$

Hence, per fixed Higgs and Z' boson masses, the discovery potential can be maximised by fixing the CM energy to $\sqrt{s_{MAX}}$.

As for the integrated luminosity required to start probing the values of α in the $B-L$ model, benchmark scenarios use the usual $h_1 \to b\bar{b}$ ($m_{h_1} = 120$ GeV) and $h_1 \to W^+W^-$ ($m_{h_1} = 200$ GeV) decays. In analogy with the study of Reference [4], the decay mode $Z' \to \mu^+\mu^-$ is considered as the most suitable. Regarding the background, the relevant one is found to be $Z'Z/\gamma$ ($Z' \to \mu^+\mu^-$ and $Z \to b\bar{b}$) and $Z'W^+W^-$ (where, again, the muons



(a) (b)

Figure 2: *ISR effect on the Higgs-strahlung off Z' for $M_{Z'} = 1.5$ TeV (2a) and $M_{Z'} = 2.1$ TeV (2b). The dashed lines correspond to the $\sqrt{s}$ for which the cross section per fixed Higgs mass is maximised, according to eq. (1).*

come exclusively from the Z' boson). The pure EW background is two orders of magnitude below the latter two, hence it is neglected here.

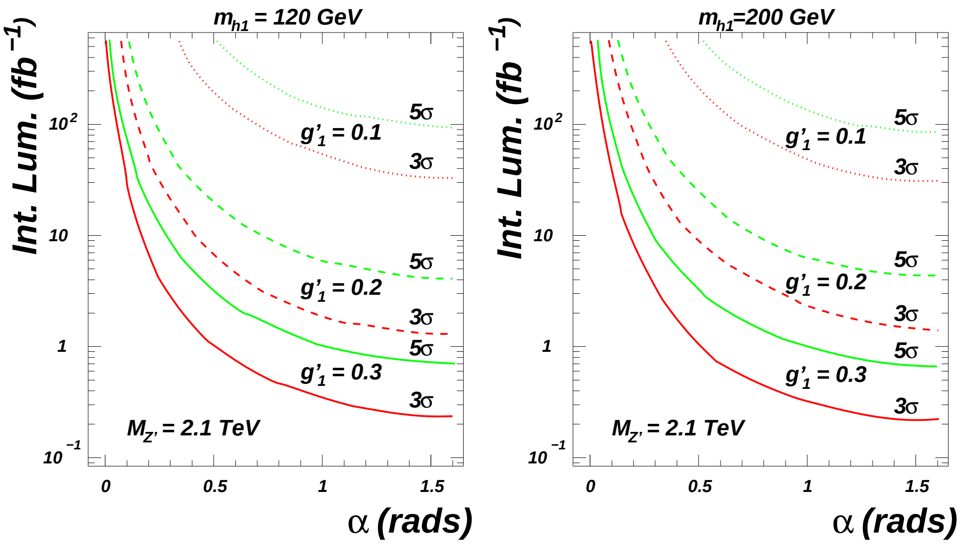
For both signal and background, we have assumed standard acceptance cuts (for muons and quarks) at a LC [6], and a window on the invariant mass $m(b,\bar{b}/W^+,W^-) = m_{h_1} \pm 20$ GeV to roughly emulate the detector resolution. For the muons, we require $m(\mu^+,\mu^-) \in M_{Z'} \pm 1.5\Gamma_{Z'}$, always wider than the di-muon resolution for the values of the gauge coupling here considered [1, 6]. Finally, b-quark tagging efficiency has been assumed to be 62% according to Reference [7]. The W-boson reconstruction efficiency has been set to 100% as a reasonable approximation.

Figure 3 shows the discovery reach of a LC in these conditions, as a function of the scalar mixing angle α[a]. The discovery power for the two decay modes of the light Higgs boson are comparable. Also, very small angles require high luminosity and big values of g'_1 to be probed, excluding $\alpha = 0$ for which the h_1 and Z' bosons do not couple. Numerical results for the $3(5)\sigma$ discovery potential of h_1-strahlung off Z'_{B-L} are collected in Table 1.

The Higgs-strahlung off Z' channel is the fundamental process for producing the heavy Higgs boson for scalar mixing angles close to decoupling. Decoupled from the SM particles, the heavy Higgs could be a very long-lived particle (decaying into peculiar final states through heavy neutrino pairs [1, 3]). When $\alpha > 10^{-8} \div 10^{-5}$ instead, SM decay modes become dominant. In both cases, the mass of the heavy scalar can be measured from the Z' recoil mass.

In Table 2 we summarise the $3(5)\sigma$ discovery potential for the heavy Higgs boson for scalar mixing angles in proximity of the decoupling regime, i.e., $\alpha \sim 10^{-4}$ rads, for selected

[a] The significance plots have been obtained using the same algorithms described in Reference [5].



(a) (b)

Figure 3: *Discovery potential for the associated production of the Z' boson and a light Higgs boson decaying into (3a) b quark pairs and into (3b) W boson pairs for $M_{Z'} = 2.1$ TeV and $g'_1 = 0.1$, 0.2, 0.3.*

values of Z'_{B-L} masses and couplings.

$m_{h_1} = 120$ GeV

$\sqrt{s} = \sqrt{s_{MAX}}$	$M_{Z'} = 1.5$ TeV		$M_{Z'} = 2.1$ TeV		
α (rads)	$g'_1 = 0.1$	$g'_1 = 0.2$	$g'_1 = 0.1$	$g'_1 = 0.2$	$g'_1 = 0.3$
0.2	>500(>1000)	38(100)	>500(>1000)	50(150)	7(20)
0.5	120(350)	4.5(15.0)	180(500)	7(20)	1.0(3.5)
1.0	30(90)	1.2(3.5)	45(120)	1.8(5.0)	0.35(1.0)

$m_{h_1} = 200$ GeV

$\sqrt{s} = \sqrt{s_{MAX}}$	$M_{Z'} = 1.5$ TeV		$M_{Z'} = 2.1$ TeV		
α (rads)	$g'_1 = 0.1$	$g'_1 = 0.2$	$g'_1 = 0.1$	$g'_1 = 0.2$	$g'_1 = 0.3$
0.2	>500(>1000)	50(120)	>500(>1000)	90(200)	9(22)
0.5	150(420)	6.5(18.0)	200(500)	9(25)	1.0(3.5)
1.0	35(100)	1.8(4.5)	45(120)	2.2(6.0)	0.35(1.0)

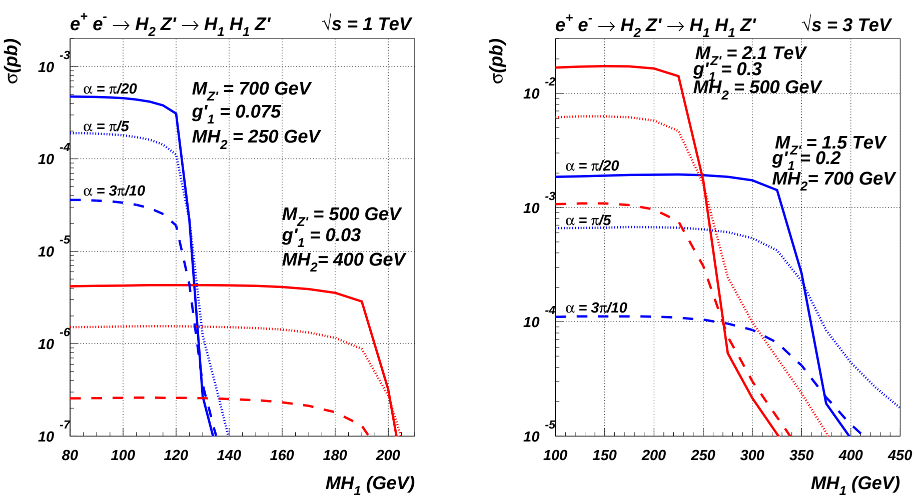
Table 1: *Minimum integrated luminosities (in fb^{-1}) for a $3\sigma(5\sigma)$ discovery as a function of the scalar mixing angle α, for selected Z'_{B-L} boson masses and g'_1 couplings for the light Higgs boson. All values above the given α are probed for the luminosity in Table. For h_2, all angles below $\pi/2 - \alpha$ are probed with the luminosity in the Table.*

3 Higgs-strahlung off Z': double Higgs production

The $Z'^* \to Z'h_2 \to Z'h_1h_1$ process is a peculiar signature of the $B-L$ model, not present in many other SM extensions. A h_2 boson is radiated from the Z' boson and it subsequently decays into a light Higgs boson pair with cross sections much bigger than the usual double Higgs-stralung process. It vanishes in the decoupling regimes (both for $\alpha \equiv 0$ and $\pi/2$).

For $M_{Z'} = 2.1$ TeV, a heavy Higgs boson with 500 GeV mass can pair produce the light Higgs boson with cross sections well above the fb level up to $m_{h_1} = 200$ GeV, reaching $\mathcal{O}(10)$ fb for small (but not negligible) values of the mixing angle (i.e., $\pi/20 < \alpha < \pi/5$).

If a Z' boson of 1.5 TeV mass is considered, a heavier h_1 can be pair produced. Cross sections are bigger than 0.1 fb for $m_{h_1} < 350$ GeV and $\mathcal{O}(1)$ fb, again for small (but not negligible) values of the mixing angle (see Figure 4).



(a) (b)

Figure 4: *Cross sections for the process $e^+e^- \to H_2Z' \to H_1H_1Z'$ for $\sqrt{s} = 1$ TeV (4a) and $\sqrt{s} = 3$ TeV (4b).*

$\sqrt{s} = \sqrt{s_{MAX}}$	$M_{Z'} = 1.5$ TeV		$M_{Z'} = 2.1$ TeV		
m_{h_2} (GeV)	$g'_1 = 0.1$	$g'_1 = 0.2$	$g'_1 = 0.1$	$g'_1 = 0.2$	$g'_1 = 0.3$
120	20(55)	0.80(2.8)	30(90)	1.2(4.0)	0.22(0.70)
200	20(60)	0.95(3.0)	30(90)	1.5(4.5)	0.22(0.70)
500	0.07(0.2)	1.5(4.0)	0.1(0.3)	2.0(6.0)	20(65)

Table 2: *Minimum integrated luminosities (in fb^{-1}) for a $3\sigma(5\sigma)$ discovery for selected Z'_{B-L} boson masses and g'_1 couplings for the heavy Higgs boson when $0 < \alpha \ll 1$ rads.*

4 Other Higgs boson production mechanisms via a Z' boson

Finally, a possibility is to use the heavy neutrino as a source of light Higgs bosons. It is a very peculiar feature of the $B-L$ model, allowing for a direct measurement of the $h_1\nu_h\nu_l$ coupling assuming that $h_1 \to \nu_h\nu_h$ is kinematically forbidden ($\nu_{h(l)}$ being the heavy(light) physical neutrino). A LC is again the most suitable environment to test this mechanism, not only because of substantial Z'_{B-L} production, but also because the possibility of tuning the CM energy on the Z' boson peak will enhance the Z' production cross section (and consequently the signal) by a factor of roughly 10^3. Moreover, the Branching Ratio (BR) of a heavy neutrino into a light Higgs boson and a light neutrino is $\sim 20\%$ (at the most [1]), when allowed.

At an illustrative CM energy of $\sqrt{s} = 1$ TeV, the cross section for $e^+e^- \to Z' \to \nu_h\nu_h \to h_1\nu_l\nu_h$ with $M_{Z'} = 700$ GeV is $\mathcal{O}(1\div10)$ fb for a heavy neutrino of 200 GeV mass, decreasing to $\mathcal{O}(1)$ fb when a mass of 300 GeV is considered, for a good range in the mixing angle.

As intimated, on the Z' peak, the ν_h pair production is enhanced by a factor $\sim 10^3$, with cross sections $\sim \mathcal{O}(1)$ pb for a large portion of the allowed parameter space, and $> \mathcal{O}(10)$ fb whatever α is.

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