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

Giovanni Marco Pruna
(TU Dresden, Germany)

L. Basso, S. Moretti, G. M. Pruna, Eur. Phys. J. **C71** (2011) 1724. [arXiv:1012.0167 [hep-ph]].

Outline

1) The $B - L$ model

- Beyond the Standard Model and beyond the LHC
- The "pure" $B - L$ model

2) Higgs sector parameter space

- Higgs masses and mixing angle unitarity constraints
- $B - L$ gauge coupling unitarity constraints

3) Phenomenology of the Higgs sector at LC

- Standard production modes
- The role of the $h_2 \to h_1 h_1$
- The role of Z' and higgs-strahlung
- An example: $e^+e^- \to \mu^+\mu^- b\bar{b}(\mu^+\mu^- W^+W^-)$
- The role of heavy neutrinos

4) Conclusions and outlook

The choice of $B-L$

In the pure $B-L$ model, the Standard Model gauge group is augmented by a broken $U(1)_{B-L}$ symmetry that has a vanishing mixing with the $U(1)_Y$ group.

The Lagrangian obey the following gauge symmetry:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

The extension is minimal:

- in the gauge sector, adding only one gauge field more
- in the spin-$\frac{1}{2}$ sector, adding one right-handed neutrino per generation
- in the spin-0 sector, adding only one complex scalar field more

The LCs choice (Beyond the LHC)

LHC has impressive capabilities in discovering Higgs Boson(s) and new heavy particles (as Z' neutral vector boson, for example). Nevertheless. . .

. . . if LHC will discover:

- a SM Higgs boson, then it will not be able to reveal any non-standard properties;
- not-SM Higgs boson(s), then it will not be able to give us any answer about the nature of the deviation from SM;
- no Higgs boson at all, then particle physics will need new experimental tools to uncover a “hidden” or “invisible” Higgs boson.

A linear collider could solve the puzzle.

The Model

We chose the pure $B - L$ framework, based on the “baryon minus lepton number” conservation because of the important role it plays in several physics scenari, and the relatively simple (but interesting) phenomenology that it involves.

The Lagrangian obey the following gauge symmetry:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

and we can decompose it in the following way:

$$\mathscr{L}_{B-L} = \mathscr{L}_{YM} + \mathscr{L}_s + \mathscr{L}_f + \mathscr{L}_Y$$

in which, with respect to the Standard Model, we have to modify the Abelian part of $\mathscr{L}_{YM}$, the scalar Lagrangian $\mathscr{L}_s$ (including the new Higgs singlet field), the fermionic and Yukawa terms $\mathscr{L}_f + \mathscr{L}_Y$ (including the heavy neutrino contributions), and the covariant derivative.

The Model: YM term and covariant derivative

The non-Abelian field strengths in $\mathscr{L}_{YM}$ are the same as in the SM, whereas the Abelian ones can be written as follows:

$$\mathscr{L}^{\text{Abelian}}_{YM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu}\,,$$

where

$$\begin{aligned} F_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu\,, \\ F'_{\mu\nu} &= \partial_\mu B'_\nu - \partial_\nu B'_\mu\,. \end{aligned}$$

In this field basis, the covariant derivative is:

$$D_\mu \equiv \partial_\mu + i g_S T^\alpha G_\mu{}^\alpha + i g T^a W_\mu{}^a + i\left[g_1 Y B_\mu + (Y\widetilde{g} + Y_{B-L}g'_1)B'_\mu\right].$$

Setting $\widetilde{g} = 0$ excludes the possibility of mixing between Z' and Z gauge bosons (and this defines the “pure” $B-L$ model).

The Model: the scalar term (1)

The scalar Lagrangian is:

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

with the scalar potential given by

$$\begin{aligned} V(H,\chi) &= m^2 H^\dagger H + \mu^2 \mid \chi \mid^2 + \\ &+ \lambda_1 (H^\dagger H)^2 + \lambda_2 \mid \chi \mid^4 + \lambda_3 H^\dagger H \mid \chi \mid^2 \,, \end{aligned}$$

where H and χ are the complex scalar Higgs doublet and singlet fields, respectively:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \qquad \chi = \frac{1}{\sqrt{2}}(x + h').$$

The introduction of the new scalar Higgs (χ, charged $+2$ under $B-L$) is needed to break the $U(1)_{B-L}$ in order to give mass to the Z' boson.

The Model: the scalar term (2)

Exploiting the isomorphism between the two spaces:

$$\begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{pmatrix} \Longleftrightarrow \begin{pmatrix} m_{h_1} \\ m_{h_2} \\ \alpha \end{pmatrix},$$

we access the parameter space of the light Higgs mass m_{h_1}, the heavy Higgs mass m_{h_2}, and the mixing angle α between the two mass eigenstates, linked by:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ h' \end{pmatrix}.$$

Once we set $\widetilde{g} = 0$, five parameters enter in the game: m_{h_1}, m_{h_2}, α, x, g'_1.

We can't jump to any phenomenological analysis without a deep understanding of the parameter space!

Higgs boson mass unitarity constraints

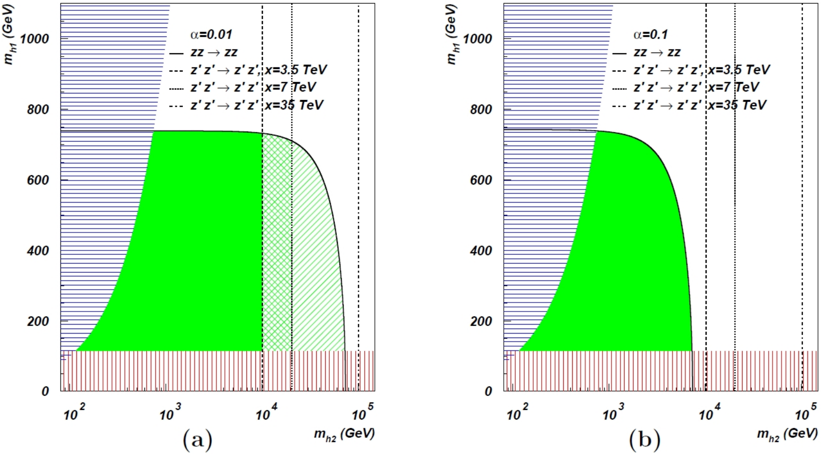

Figure 1: Pure $B - L$ model: perturbative unitarity bounds on the allowed region of the m_{h_1}-m_{h_2} space, for $\alpha = 0.1$ (1a) and $\alpha = 0.1$ (1b). Several values of x have been considered. Red area is excluded by the LEP direct searches, blue area is excluded by the requirement $m_{h_1} < m_{h_2}$.

g'_1 coupling unitarity constraints

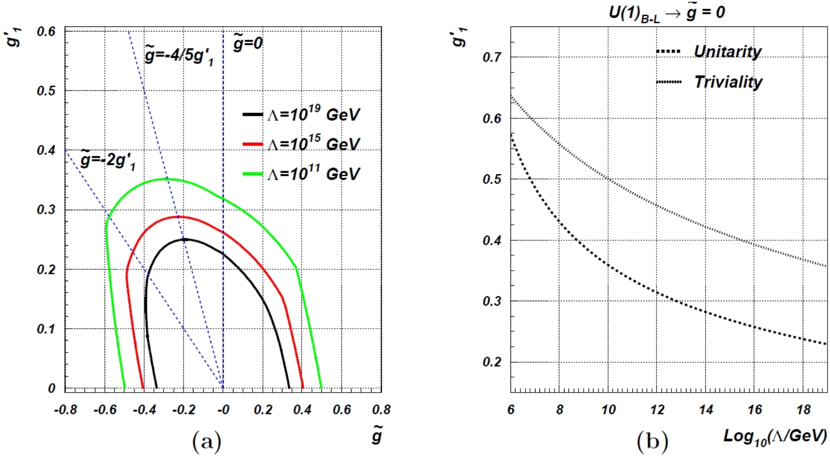

Figure 2: Anomaly-free non-exotic models: boundaries on the allowed g'_1-$\tilde{g}$ parameter space by perturbative unitarity and renormalisation group equations based techniques. (2a) Contour plots related to several choices of the cut-off energy. (2b) The "pure" $B-L$ case: unitarity and triviality bounds on g'_1 plotted against the cut-off energy scale.

Standard production modes at a sub-TeV collider

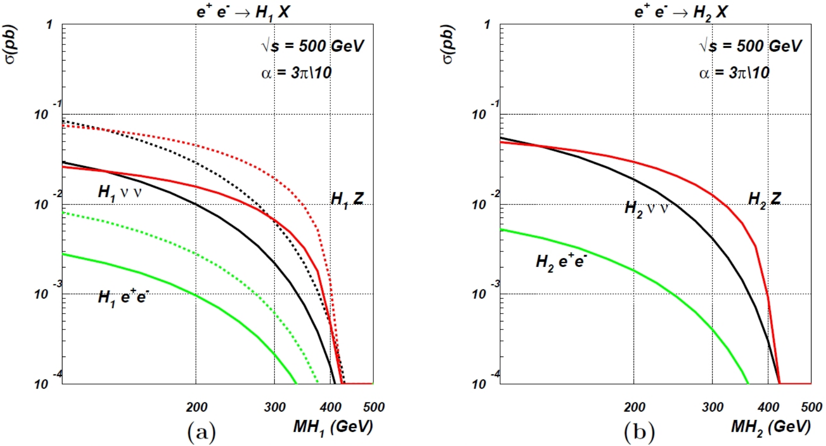

Figure 3: Cross section for the standard Higgs boson production modes plotted against $m_{h_{1,2}}$ for $\alpha = 3\pi/10$ at $\sqrt{s} = 500$ GeV. Both h_1 (3a) and h_2 (3b) have been considered.

Standard production modes at a (multi)-TeV collider

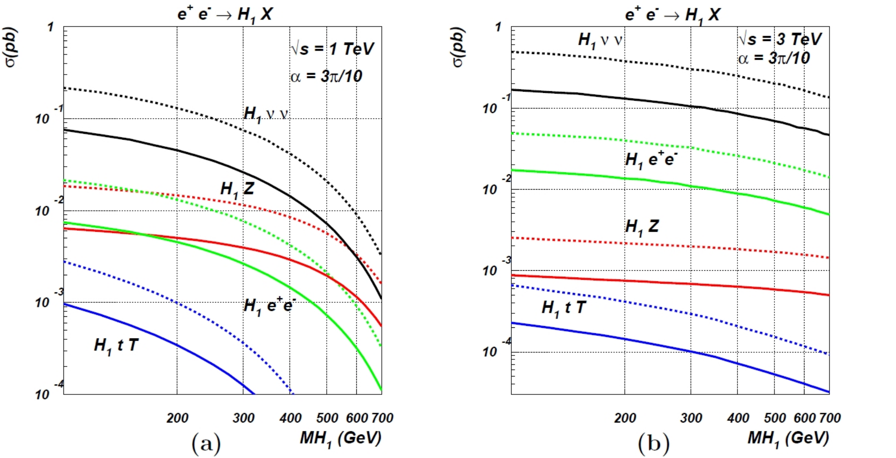

Figure 4: Cross section for the standard Higgs boson production modes plotted against m_{h_1} for $\alpha = 3\pi/10$, at $\sqrt{s} = 1$ TeV (4a) and $\sqrt{s} = 3$ TeV (4b).

The role of the $h_2 \to h_1 h_1$ coupling

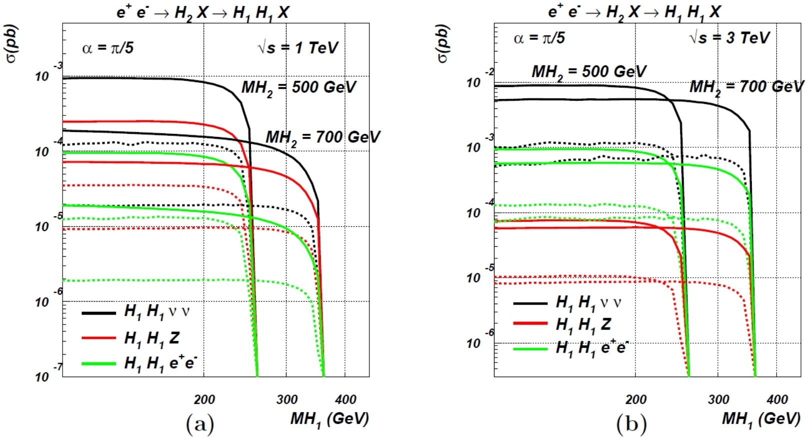

Figure 5: Cross section for the double light Higgs boson production via h_2 decay, for $\alpha = \pi/5$ (straight lines) and $\alpha = \pi/20$ (dashed lines), at $\sqrt{s} = 1$ TeV (5a) and $\sqrt{s} = 3$ TeV (5b).

Varying $\sqrt{s}$: h-strahlung from Z' and a simple formula

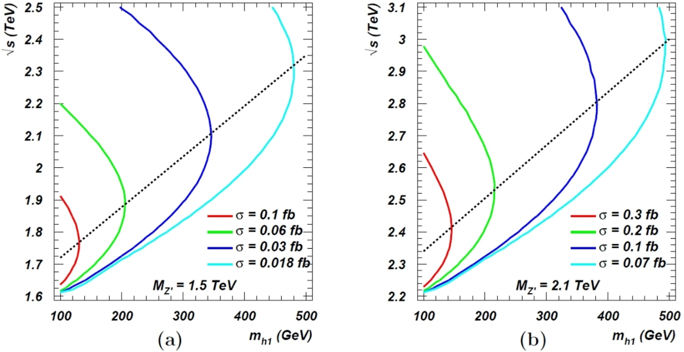

Figure 6: Contour plot for the $h_{1,2}$-strahlung (from Z') cross section on the $\sqrt{s}$-$m_{h_{1,2}}$ plane. The dashed lines correspond to the energy for which the cross-section per fixed Higgs mass is maximised.

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

From $Z'h_1$ to $\mu^+\mu^-b\bar{b}(\mu^+\mu^-W^+W^-)$

$m_{h_1} = 120$ GeV

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

$m_{h_1} = 200$ GeV

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

Table: $e^+e^- \to Z'h_1 \to \mu^+\mu^-b\bar{b}(\mu^+\mu^-W^+W^-)$: minimum integrated luminosities (in fb^{-1}) for a $3\sigma(5\sigma)$ observation(discovery) as a function of α. Several values of $M_{Z'}$ and g'_1 have been considered.

The role of the heavy neutrinos

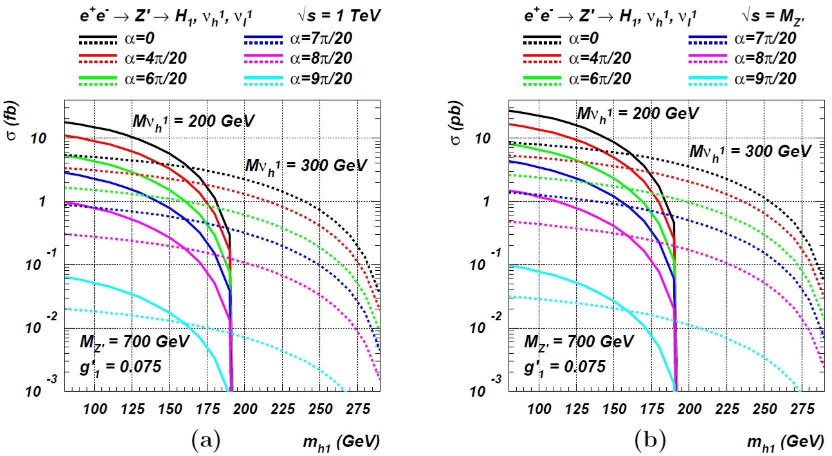

Figure 8: Cross section for the associated production of the light Higgs boson with one heavy and one light first generation of neutrinos (via $Z' \to \nu_h \nu_h$), at $\sqrt{s} = 1$ TeV (8a) and $\sqrt{s} = M_{Z'}$ (8b).

Conclusions

REMARK: Phenomenological analysis performed via CalcHEP

- extended neutrinos sector
- extended Higgs sector
- extended vector boson sector (pure $B-L$ model, no $Z-Z'$ mixing)

$\surd$ We analysed the allowed parameter space

$\surd$ We collected an extensive set of cross sections (with emphasis on the most important production modes) highlighting the role of the new particle content of the $B-L$ model (h_2, Z', ν_h)

$\surd$ We gave an explicit example of the capability of a linear collider in observing(discovering) a h-strahlung from a extra gauge boson Z'

Many thanks to:

- Dr Lorenzo Basso
- Prof Stefano Moretti
- Prof Dominik Stöckinger

Taken from:

- L. Basso, S. Moretti, G. M. Pruna, Eur. Phys. J. **C71** (2011) 1724. [arXiv:1012.0167 [hep-ph]].
- L. Basso, S. Moretti, G. M. Pruna, JHEP **1108** (2011) 122. [arXiv:1106.4762 [hep-ph]].
- L. Basso, A. Belyaev, S. Moretti, G. M. Pruna, Phys. Rev. **D81** (2010) 095018. [arXiv:1002.1939 [hep-ph]].

Summary: a triply minimal extension

The "pure" $U(1)_{B-L}$ extension of the SM

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

- **Gauge sector**

  One extra gauge boson Z'

- **Fermion sector**

  One extra fermion per generation: ν_R

  (Required by anomaly cancellation)

- **Scalar sector**

  One extra singlet scalar: χ

  ($U(1)_{B-L}$ symmetry breaking)

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B-L$
q_L	3	2	$\frac{1}{6}$	$\frac{1}{3}$
u_R	3	1	$\frac{2}{3}$	$\frac{1}{3}$
d_R	3	1	$-\frac{1}{3}$	$\frac{1}{3}$
l_L	1	2	$-\frac{1}{2}$	-1
e_R	1	1	-1	-1
ν_R	1	1	0	-1

ψ	$SU(3)_C$	$SU(2)_L$	Y	$B-L$
H	1	2	$\frac{1}{2}$	0
χ	1	1	0	2