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# The $Z'$ boson of the minimal $B-L$ model at future Linear Colliders in $e^+e^- \to \mu^+\mu^-$

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**Summary.** — We study the capabilities of future electron-positron Linear Colliders, with centre-of-mass energy at the TeV scale, in accessing the parameter space of a $Z'$ boson within the minimal $B-L$ model. We carry out a detailed comparison between the discovery regions mapped over a two-dimensional configuration space ($Z'$ mass and coupling) at the Large Hadron Collider and possible future Linear Colliders for the case of di-muon production. As known in the literature for other $Z'$ models, we confirm that leptonic machines, as compared to the CERN hadronic accelerator, display an additional potential in discovering a $Z'$ boson as well as in allowing one to study its properties at a level of precision well beyond that of any of the existing colliders.

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## 1. – Introduction

The $B-L$ (baryon number minus lepton number) symmetry plays an important role in various physics scenarios beyond the Standard Model (SM). Hence, we consider a minimal $B-L$ low-energy extension of the SM, consisting of a further $U(1)_{B-L}$ gauge group, three right-handed neutrinos and an additional Higgs boson generated through the $U(1)_{B-L}$ symmetry breaking. It is important to note that in this model the $B-L$ breaking can take place at the TeV scale, *i.e.* far below that of any Grand Unification Theory (GUT).

In the present proceeding we present some phenomenology related to the $Z'$ sector of the minimal (no mixing between $Z$ and $Z'$ at tree-level) $B-L$ extension of the SM at the new generation of $e^+e^-$ Linear Colliders (LCs) [1], considering the $e^+e^- \to \mu^+\mu^-$ channel as a representative process in order to study new signatures pertaining to the minimal $B-L$ model.

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## 2. – The model

The model under study is the so-called “pure” or “minimal” $B-L$ model (see [2, 3] for conventions and references) since it has vanishing mixing between the two $U(1)_Y$ and $U(1)_{B-L}$ groups. In this model the classical gauge-invariant Lagrangian, obeying the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ gauge symmetry, can be decomposed as: $\mathscr{L} = \mathscr{L}_{YM} + \mathscr{L}_s + \mathscr{L}_f + \mathscr{L}_Y$. The non-Abelian field strengths in $\mathscr{L}_{YM}$ are the same as in the SM, whereas the Abelian ones can be intuitively identified. In this field basis, the covariant derivative is: $D_\mu \equiv \partial_\mu + i g_S T^\alpha G_\mu^{\ \alpha} + i g T^a W_\mu^{\ a} + i g_1 Y B_\mu + i(\widetilde{g} Y + g_1' Y_{B-L}) B_\mu'$. The “pure” or “minimal” $B-L$ model is defined by the condition $\widetilde{g} = 0$, that implies no mixing between the $Z'$ and the SM-$Z$ gauge bosons.

The fermionic Lagrangian is the usual $SM$ one, apart from the presence of Right-Handed (RH) neutrinos. The charges are the usual SM and $B-L$ ones (in particular, $B-L = 1/3$ for quarks and $-1$ for leptons). The $B-L$ charge assignments of the fields as well as the introduction of new fermionic RH-neutrinos ($\nu_R$) and scalar Higgs ($\chi$, charged $+2$ under $B-L$) fields are designed to eliminate the triangular $B-L$ gauge anomalies and to ensure the gauge invariance of the theory, respectively. Therefore, the $B-L$ gauge extension of the SM group broken at the Electro-Weak (EW) scale does necessarily require at least one new scalar field and three new fermionic fields which are charged with respect to the $B-L$ group.

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 $V(H,\chi) = m^2 H^\dagger H + \mu^2 |\chi|^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 |\chi|^4 + \lambda_3 H^\dagger H |\chi|^2$, where $H$ and $\chi$ are the complex scalar Higgs doublet and singlet fields, respectively.

Finally, the Yukawa interactions are: $\mathscr{L}_Y = -y_{jk}^d \overline{q_{jL}} d_{kR} H - y_{jk}^u \overline{q_{jL}} u_{kR} \widetilde{H} - y_{jk}^e \overline{l_{jL}} e_{kR} H - y_{jk}^\nu \overline{l_{jL}} \nu_{kR} \widetilde{H} - y_{jk}^M \overline{(\nu_R)_j^c} \nu_{kR} \chi + \text{h.c.}$, where $\tilde{H} = i\sigma^2 H^*$ and $i$, $j$, $k$ take the values 1 to 3, where the last term is the Majorana contribution and the others the usual Dirac ones.

## 3. – Results

The first thing that we want to explore is the discovery potential of hadronic and leptonic machines in the $M_{Z'}$-$g_1'$ plane of our model, in the di-muon production process. We compare the LHC hadronic scenario, with $100\,\text{fb}^{-1}$ data collected, to two different LC leptonic frameworks, at a fixed Centre-of-Mass (CM) energy of $\sqrt{s_{e^+e^-}} = 3\,\text{TeV}$ ($500\,\text{fb}^{-1}$ data altogether) and in a so-called energy scan, where the CM energy is set to $\sqrt{s_{e^+e^-}} = M_{Z'} + 10\,\text{GeV}$ and we assume $10\,\text{fb}^{-1}$ of luminosity for each step. We then limit both signal and background to the detector acceptance volumes and $M_{\mu^+\mu^-}$ to an invariant-mass window defined by the CMS and ILC prototype resolution or $3\Gamma_{Z'}$, whichever the largest (see [3, 4] for details). Finally, we define the significance $\sigma$ as $s/\sqrt{b}$ ($s$ and $b$ being the signal and background event rates, respectively): the discovery will be for $\sigma \geq 5$.

As a result, for $M_{Z'} > 800\,\text{GeV}$, the LC potential to explore the $M_{Z'}$-$g_1'$ parameter space in the fixed CM energy approach goes beyond the LHC reach. For example, for $M_{Z'} = 1\,\text{TeV}$, the LHC can discover a $Z'$ if $g_1' \approx 0.007$ while a LC can achieve this for $g_1' \approx 0.005$. The difference is even more drastic for larger $Z'$ masses as one can see from table I: a LC can discover a $Z'$ with a $2\,\text{TeV}$ mass for a $g_1'$ coupling which is a factor 8 smaller.

TABLE I. – *Minimum $g'_1$ value accessible at the LHC and a LC for selected $M_{Z'}$ values in our $B-L$ model. At the LHC we assume $L = 100\,\text{fb}^{-1}$, whereas for a LC we take $L = 500\,\text{fb}^{-1}$ at fixed energy and $L = 10\,\text{fb}^{-1}$ in energy scanning mode.*

| $M_{Z'}$ (TeV) | $g'_1$ | | |
|---|---|---|---|
| | LHC | LC ($\sqrt{s} = 3\,\text{TeV}$) | LC ($\sqrt{s} = M_{Z'} + 10\,\text{GeV}$) |
| 1.0 | 0.0071 | 0.0050 | 0.0026 |
| 1.5 | 0.011 | 0.0040 | 0.0032 |
| 2.0 | 0.018 | 0.0028 | 0.0034 |
| 2.5 | 0.028 | 0.0022 | 0.0035 |

In case of the energy scan approach, the $M_{Z'}$-$g'_1$ parameter space can be probed even further for $M_{Z'} < 1.75\,\text{TeV}$. For example, for $M_{Z'} = 1\,\text{TeV}$, $g'_1$ couplings can be probed down to the $2.6 \times 10^3$, following a $Z'$ discovery. Furthermore, the parameter space corresponding to the mass interval $500\,\text{GeV} < M_{Z'} < 1\,\text{TeV}$, which the LHC covers better as compared to a LC with fixed energy, can be accessed well beyond the LHC reach with a LC in energy scan regime.

Hereafter, we consider the general pattern of the $Z'$ production cross-section in comparison to the SM background as a function of $M_{Z'}$, for two fixed values of $\sqrt{s_{e^+e^-}}$, in configurations such that the $Z'$ resonance can be either within or beyond the LC reach for on-shell production. The typical enhancement of the signal at the peak is either two orders of magnitude above the background $\sqrt{s_{e^+e^-}} = 1\,\text{TeV}$ (ILC configuration) and $g'_1 > 0.05$ or three orders of magnitude above the background for $\sqrt{s_{e^+e^-}} = 3\,\text{TeV}$ (CLIC configuration) and $g'_1 > 0.1$. This enhancement can onset (depending on the value of $g'_1$, hence of $\Gamma_{Z'}$) several hundreds of GeV before the resonant mass and falls sharply as soon as the $Z'$ mass exceeds the collider energy.

While the potential of future LCs in detecting $Z'$ bosons of the $B-L$ model is well established whenever $\sqrt{s_{e^+e^-}} \geq M_{Z'}$, we would like to remark here upon the fact that, even when $\sqrt{s_{e^+e^-}} < M_{Z'}$, there is considerable scope to establish the presence of the additional gauge boson, through the interference effects that do arise between the $Z'$ and SM sub-processes ($Z$ and photon exchange). Even when the $Z'$ resonance is beyond the kinematic reach of the LC, significant deviations are nonetheless visible in the di-muon lineshape of the $B-L$ scenario considered, with respect to the SM case. Incidentally, also notice that such strong interference effects do not onset in the case of the LHC, because of the smearing due to the Parton Distribution Functions (PDFs).

TABLE II. – *Maximum $M_{Z'}$ value accessible at the LHC and a LC for selected $g'_1$ values in the minimal $B-L$ model. At the LHC we assume $L = 100\,\text{fb}^{-1}$.*

| $g'_1$ | $M_{Z'}$ (TeV) | | |
|---|---|---|---|
| | LHC ($3\sigma$ observation) | LC ($\sqrt{s} = 1\,\text{TeV}$, 1% level) | LC ($\sqrt{s} = 3\,\text{TeV}$, 1% level) |
| 0.05 | 3.4 | 2.2 | 5.5 |
| 0.1 | 4.1 | 3.8 | 10 |
| 0.2 | 4.7 | 7.5 | 19.5 |

Under the assumption that SM di-muon production will be known with a 1% accuracy we would like to illustrate how the LHC $3\sigma$ observation potential of a heavy $Z'$ is comparable to a LC indirect sensitivity to the presence of a $Z'$, even beyond the kinematic reach of the machine. This is shown in table II, which clearly shows that a CLIC-type LC will be (indirectly) sensitive to much heavier $Z'$ bosons than the LHC. For example, for $g'_1 = 0.1$, such a machine would be sensitive to a $Z'$ with mass up to 10 TeV whilst the LHC can observe a $Z'$ with mass below 4 TeV (for the same coupling). Even a LC with $\sqrt{s_{e^+e^-}} = 1\,\text{TeV}$ (a typical ILC energy) will be indirectly sensitive to larger $M_{Z'}$ values than the LHC, for large enough values of the $g'$ coupling. For example, such a machine will be sensitive to a $Z'$ with mass up to 7.5 TeV for $g'_1 = 0.2$ whilst the LHC would be able to observe a $Z'$ only below 4.7 TeV or so (again, for the same coupling).

One interesting possibility opened up by such a strong dependence of the $e^+e^- \rightarrow \mu^+\mu^-$ process in the $B-L$ scenario on interferences is to see whether this potentially gives unique and direct access to measuring the $g'_1$ coupling. In fact, notice that in the case of $Z'$ studies on or near the resonance (*i.e.* when $\sqrt{s_{e^+e^-}} \approx M_{Z'}$), the $B-L$ rates are strongly dependent on $\Gamma_{Z'}$ (hence on all couplings entering any possible $Z'$ decay channel, that is, not only $\mu^+\mu^-$). Instead, when $\sqrt{s_{e^+e^-}} \ll M_{Z'}$ and $|\sqrt{s_{e^+e^-}} - M_{Z'}| \gg \Gamma_{Z'}$, one may expect that the role of the $Z'$ width in such interference effects is minor, the latter being mainly driven by the strength of $g'_1$. Varying the $Z'$ width as an independent parameter we have proven that the dependence on $\Gamma_{Z'}$ is negligible. Hence, in the presence of a known value for $M_{Z'}$ (*e.g.*, from a LHC analysis), one could extract $g'_1$ from a fit to the lineshape of the cross-section at a LC. In fact, the same method, to access this coupling, could be exploited at future LCs independently of LHC inputs, as interference effects of the same size also appear when $\sqrt{s_{e^+e^-}} > M_{Z'}$.

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