TESTING THE LEFT-RIGHT SYMMETRIC MODEL AT LINEAR COLLIDER.

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Abstract
We review possible tests of the left-right electroweak model at future linear colliders, concentrating on signatures of the central predictions of the model, i.e. right-handed currents, massive neutrinos and triplet Higgs bosons. We analyse processes in $e^+e^−, e^−e^−$ and $e^−γ$ collision modes. We present the mass reaches for the new particles at linear collider and sensitivities to their couplings.

The model
The left-right symmetric model (LRM) of electroweak interactions, based on the $SU(2)_L \times SU(2)_R \times U(1)_{B−L}$ symmetry, has many predictions one can test at linear collider (LC). The extended symmetry implies the existence of new gauge bosons, $W^+_R$ and $Z^0_2$, which mediate $V+A$-type, i.e. right-handed, weak interactions. It also requires more complicated Higgs sector than in the Standard Model (SM) to realize the two-step spontaneous breaking of the gauge symmetry down to the unbroken $U(1)$ of QED. The breaking of $SU(2)_L \times SU(2)_R \times U(1)_{B−L}$ to the SM
symmetry $SU(2)_L \times U(1)_Y$ is arranged with an $SU(2)_R$ triplet scalar, the right-triplet $(\Delta^+_R, \Delta^+_R, \Delta^0_R)$. The breaking of the SM symmetry is due to a bidoublet scalar multiplet consisting of a doublet and a conjugated doublet of $SU(2)_L$. Also a left-triplet $(\Delta^+_L, \Delta^+_L, \Delta^0_L)$ may exist and contribute to this breaking, but the vev of $\Delta^0_L$ is tightly bound by the $\rho$ parameter, or the mass ratio of the ordinary weak bosons. The fermion contents of the LRM is the same as that of SM, except that right-handed neutrinos $N$ also exist. In the most natural version of the model $N$’s are heavy as a result of the see-saw mechanism \[2\], with a mass comparable to the masses of the new gauge bosons.

All the central predictions of the LRM, i.e. the new gauge bosons $W^\pm_R$ and $Z^0_2$, the Higgs triplet $(\Delta^+_R, \Delta^+_R, \Delta^0_R)$ and the right-handed neutrinos $N$, are connected intriguingly to each other through the spontaneous breaking of the LR symmetry. In the following we will consider the production of $W_R, \Delta^+_R$, and $N$, which will constitute the most effective probes of LRM at linear collider.

**Signals of $W^\pm_R$**

According to the results of Tevatron, the mass of the new charged gauge boson is constrained to be $M_{W_R} \gtrsim 650$ GeV \[3\]. Although this bound can be evaded for some choices of model parameters (a mass as low as $\sim 300$ GeV being possible \[4\]), it is probable that the pair production of $W_R$’s in $e^+e^-$ \[3\] and in $e^-e^-$ \[3, 6\] is kinematically excluded in a LC with collision energy below 1 TeV. A single $W_R$ production via $e^+e^- \rightarrow W^+_RW^-_R$ and $e^-e^- \rightarrow W^-RW^+_R$ may be kinematically viable but it is suppressed by the smallness of the $W_LW_R$ mixing \[4, 3\].

When the collision energy is sufficiently above 1 TeV, the pair production of $W_R$’s via $e^+e^- \rightarrow W^+_RW^-_R$ and $e^-e^- \rightarrow W^-RW^+_R$ may become possible. At $\sqrt{s} = 1.6$ TeV the cross section for the $W^+_RW^-_R$ production is at the level of 100 fb for $M_{W_R} = 650$ GeV \[3\] and the mass reach will be practically up to the threshold value of $\sqrt{s}/2$. The pair production of the same sign $W_R$’s in $e^-e^-$ collisions is an excellent place to probe the LR model. The reaction is mediated by a Majorana neutrino in t-channel and the doubly charged Higgs boson in s-channel. The right handed neutrino ($N$)
and $W_R$ boson mass reach of LC due to this process is plotted in Fig. 1. It is assumed in this plot that the doubly charged Higgs is very heavy ($M_{\Delta^{--}} = 5M_N$) so that its contribution is insignificant in comparison with the contribution of the neutrino. The direct $M_{W_R}$ reach is up to $\sqrt{s}/2$ and the indirect $M_N$ reach up to about 20 TeV.

In the electron-photon collision mode $W_R$ can be produced via the reaction $e^-\gamma \rightarrow W^-_R N$, which is kinematically accessible provided the right-handed neutrino $N$ is light enough [7]. For $\sqrt{s_{e\gamma}} = 730$ GeV (corresponding to $\sqrt{s} = 800$ GeV in the $e^+e^-$ mode), $M_{W_R} = 650$ GeV and $M_N \lesssim 75$ GeV the cross section is in the range $10 - 20$ fb corresponding to some 50 - 100 events for the luminosity of 50 fb$^{-1}$. The right-handed neutrino has most naturally a mass much larger than 75 GeV, making the reaction kinematically forbidden. The limits on the mixing of the left-handed neutrino $\nu$ with $N$ still allow the kinematically more favourable reaction $e^-\gamma \rightarrow W^+_R \nu$ to have the cross section at observable level.

The production of $W_R$’s can be identified through its decay to the ordinary $W_L$ boson and a neutrino.

### Signals of the right-handed neutrino

The heavy right-handed neutrinos can be produced in $e^+e^- \rightarrow \overline{N}N$ proceeding via a $Z_2$ exchange in $s$-channel and a $W_R$ exchange in $t$-channel [8]. In LRM the heavy neutrino is a Majorana neutrino, for which the cross section of the pair production is slightly smaller than for a Dirac neutrino, in particular close to the threshold, due to the well-known $\beta^3$ suppression. The LC with anticipated luminosities can probe neutrino masses practically up to the kinematical limit $\sqrt{s}/2$. To probe the Dirac and Majorana nature of neutrinos one can use the angular distributions. The process gives an indirect probe of the mass $M_{W_R}$. For $\sqrt{s} = 1.6$ TeV the probe is up to about 4 TeV, as presented in Fig. 1.

A better mass reach, up to $\sqrt{s}$, for the right-handed neutrino is offered by the reaction $e^+e^- \rightarrow \overline{N}\nu$ whose cross section can be at a few fb level when the constraints on the neutrino mixing are taken into account [9].
Signals of the triplet Higgs

The left-triplet $\Delta_L$ and right-triplet $\Delta_R$ Higgses transform as $(3,1,2)$ and $(1,3,2)$ under $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, respectively. The gauge symmetry prevents these scalars from coupling to quarks, and their couplings to fermions violate lepton number by two units, $|\Delta L| = 2$. For discovery the most favourable are the doubly charged components $\Delta_{L,R}^{++}$ due to their decay to an energetic like-sign lepton pair, $\Delta_{L,R}^{++} \rightarrow e^{-}e^{-}$. In $e^+e^-$ collisions a single $\Delta_{L,R}^{++}$ is produced via the reaction $e^+e^- \rightarrow e^−l^−\Delta_{L,R}^{++}$ [10]. The cross section depends on two unknown parameters, the mass of $\Delta_{L,R}^{++}$ and the strength $h_\Delta$ of the lepton number violating $\Delta_{L,R}^{++}ll$ coupling. Assuming $h_\Delta = 0.1$ and $M_{\Delta_{L,R}^{++}} \gtrsim 100$ GeV the cross section is in the range $10−10^3$ fb. [11]. About three orders of magnitude more stringent limit is achievable for the ratio $|h_\Delta/M_{\Delta_{L,R}^{++}}|^2$ than the present limit of $10^{-5}$ from the Bhabha scattering [12].

Another process where a single $\Delta_{L,R}^{++}$ is produced is $e^-\gamma \rightarrow l^+\Delta^{--}$. The primary lepton created in the process will remain undetected as it is radiated almost parallel to the beam axis. One cannot tell whether this particle is a positron, antimuon or antitau. Therefore, the quantity which one can test in the reaction is actually the sum $h_{ee}^2 + h_{e\mu}^2 + h_{e\tau}^2$. Assuming the integrated luminosity of $e^-\gamma$ collisions to be $L = 5, 10, 20, 40$ fb$^{-1}$ for $\sqrt{s_{ee}} = 330, 460, 730, 1450$ GeV, respectively, and that for the discovery of $\Delta^{--}_R$ one needs ten events, we obtain the upper bounds plotted in Fig. 2. The sensitivity of LC will thus be

$$h_{ee}, h_{e\mu}, h_{e\tau} \lesssim 10^{-3}$$

for $M_{\Delta^{--}} \lesssim \sqrt{s_{ee}}$. Among the present constraints only $h_{e\mu}h_{ee} < 3.2 \times 10^{-11}$ GeV$^{-2}$. $M_{\Delta^{--}}^2$ obtained from the process $\mu \rightarrow eee$ [15], can compete with these bounds and only so at the low mass values. For the coupling $h_{e\tau}$ there does not exist any bound from the present experiments.

The pair production of $\Delta_{L,R}^{++}$’s proceeds through the s-channel exchange of the photon and the standard and the heavy $Z$ bosons. The cross section scales as $\beta^3/s$ as a function of the c.m. energy $\sqrt{s}$, where $\beta$ is the velocity of the final state particles [13, 14]. For $\Delta_L^{++}\Delta_L^{--}$ production at $\sqrt{s} = 500$ GeV it is on the level of
a few hundreds of fb’s up to the vicinity of the kinematical limit, for the $\Delta^+_R \Delta^-_R$ production slightly less.

The kinematically most favoured decay modes of the doubly charged scalars are those to like-sign lepton pairs, which provide excellent discovery signals.

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**Figure caption**

**Figure 1.** Sensitivity of the processes $e^-e^- \rightarrow W_R^-W_R^-$ and $e^+e^- \rightarrow \overline{N}N$ on the masses of the heavy charged gauge boson $W_R$ and the right-handed neutrino $N$ at the collision energy $\sqrt{s} = 1.6$ TeV assuming discovery limit of 0.1 fb and $e^+e^-$ luminosity of 200 fb$^{-1}$. The mass of the doubly charged triplet Higgs $\Delta_R$ is taken to be $M_{\Delta^{--}} = 5M_N$. Dashed line is for Majorana neutrinos, solid line for Dirac neutrinos.

**Figure 2.** Sensitivity of the process $e^-\gamma \rightarrow l^+\Delta^{--}$ on the lepton number violating couplings $h_{ee}$, $h_{e\mu}$ and $h_{e\tau}$ as a function of the doubly charged Higgs mass $M_\Delta$ for various collision energies. The discovery limit of $\Delta^{--}$ is assumed to be ten events.
Figure 2:

$e^- \gamma \rightarrow l^+ \Delta^-$

\[
\sqrt{h_{ee}^2 + h_{e\mu}^2 + h_e^2} \quad \sqrt{s} = 330 \text{ GeV}
\]
\[
\sqrt{s} = 460 \text{ GeV}
\]
\[
\ldots \ldots \sqrt{s} = 730 \text{ GeV}
\]
\[
\ldots \ldots \sqrt{s} = 1.45 \text{ TeV}
\]
\[
\sqrt{h_{ee} h_{e\mu}} \quad \mu \rightarrow eee
\]

$M_{\Delta}[\text{GeV}]$