HIGH-ENERGY TESTS OF THE LEFT–RIGHT SYMMETRIC ELECTROWEAK MODEL*

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The left-right symmetric extension of the Standard Model, based on $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ symmetry, has many predictions one can test at TeV-scale accelerators. These include the existence of new heavy weak bosons W_2 and Z_2 and right-handed neutrinos, as well as of triplet Higgses. We discuss various direct tests of the basic ingredients of the left-right symmetric model, as well as of its supersymmetric version, in e^-e^-, $e^-\gamma$ and $\gamma\gamma$ collisions at high energies.

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1. Introduction

In this talk I will consider the direct high-energy tests of the left-right symmetric (LR) model [1] of electroweak interactions.

Apart from its original motivation of providing a dynamical explanation for the parity violation observed in low-energy weak interactions, the LR model differs from the Standard Model (SM) in another important respect: it can explain the observed lightness of neutrinos in a natural way. In this model neutrino masses are created through the see-saw mechanism [2], according to which there are in each family a light neutrino, much lighter than the charged leptons or quarks of that family, and a heavy neutrino. The anomalies measured in the solar [3] and atmospheric [4] neutrino fluxes seem to require that neutrinos indeed have a small but non-vanishing mass,

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manifesting itself in these phenomena through flavour oscillations. Furthermore, the recent observations of the COBE satellite [5] may indicate the existence of a hot neutrino component in the dark matter of the Universe. In the SM neutrinos are massless, so it seems that one has to go beyond it to explain these phenomena. The LR model is a most natural extension of the SM which may consistently account for the observations mentioned.

The gauge group of the LR model is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Several authors [6, 7] have investigated indirect implications of the left-right symmetry on the various low-energy phenomena to set constraints on the parameters of the model, such as the masses of the new gauge bosons $W_R^{\pm}$ and Z_R, associated with $SU(2)_R$, and their mixings with the $SU(2)_L$ bosons $W_L^{\pm}$ and Z_L. The constraints quite crucially depend on the assumptions one makes. In the case the gauge coupling constants g_L and g_R of $SU(2)_L$ and $SU(2)_R$ are allowed to differ from each other and the CKM-matrix and its equivalent in $V + A$ charged current interactions are kept unrelated, the charged current data yield the bounds [7] $g_L M_{W_2}/g_R \lesssim 300$ GeV and $g_L \zeta / g_R \gtrsim 0.013$. Here W_2 is the heavier mass eigenstate weak boson and ζ is its mixing with the lighter boson W_1, the standard W boson:

$$\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^{\pm} \\ W_2^{\pm} \end{pmatrix} . \tag{1}$$

From neutral current data one can derive the lower bound $M_{Z_2} \lesssim 400$ GeV for the mass of the new Z boson and the upper bound of 0.008 for the Z_1, Z_2 mixing angle. In most cases to be considered here the mixings between the SM weak bosons and the new weak bosons can be neglected.

At the Tevatron a direct search for W_2 ($\simeq W_R$) in the channel $pp \to W_2 \to eN$ has been made. The 95% CL bounds announced by the CDF and D0 collaborations are $M_{W_2} \lesssim 652$ GeV [8] and $M_{W_2} \lesssim 610$ GeV [9], respectively. It should be emphasized that also behind these bounds there are several assumptions. It is assumed that the quark-W_2 coupling has the SM strength, the CKM matrices for the left-handed quarks and the right-handed quarks are similar, and the right-handed neutrino does not decay in the detector but appears as missing E_T. If one relaxes the first two assumptions, the mass bound will be degraded considerably [10], perhaps so low values as 400 GeV being allowed. The third assumption is also crucial for the bounds obtained. If the right-handed neutrino is heavy, with a mass of say 100 GeV or more, it will decay in the detector into charged particles (one possible channel could be $\nu_R \to l + q\bar{q}'$) with no missing energy. In this case the searches performed would have been ineffective.

If the right-handed neutrino is heavier than W_2, the reaction considered by CDF and D0 is forbidden altogether (unless there is a large mixing between left- and right-handed neutrinos, which is not preferred by the model). In this case W_2 could decay only to non-leptonic states. Obviously, in the Tevatron hadronic signals are much more difficult to identify than leptonic ones, and therefore the mass limit one can obtain from hadronic decay channels is not particularly restrictive.

The collision energies in the linear colliders under planning, such as CLIC, NLC, TESLA, JLC (dubbed collectively LC in the following), will be in the range $\sqrt{s} = 0.5-2$ TeV [11]. If the masses of the new gauge bosons are close to their present lower limits, it would be possible to produce them and directly investigate their properties. Similarly it would be possible to search for the heavy Majorana neutrinos, or right-handed neutrinos. The masses of these neutrinos are, according to the see-saw mechanism, in the most simple case, of the order of the masses of the new weak bosons. One would also be able to probe the symmetry breaking sector of the theory by looking for new type of Higgs bosons, in particular triplet scalars which are assumed to set the large mass scale of the model. The Higgs triplet contains a doubly charged scalar particle, a conspicuous trademark of the model.

2. Description of the model

The LR model is characterized by the gauge group $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_{B-L}$. The left- and right-handed fermions are set into doublet representations of $\mathrm{SU}(2)_\mathrm{L}$ and $\mathrm{SU}(2)_\mathrm{R}$, respectively. In the following we will deal mainly with leptons, which are assigned according to

$$\Psi_\mathrm{L} = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_\mathrm{L} = (\tfrac{1}{2}, 0, -1), \; \Psi_\mathrm{R} = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_\mathrm{R} = (0, \tfrac{1}{2}, -1), \tag{2}$$

and similarly for the other families. The U(1) quantum number is normalized in such a way that the electric charge Q is given by $Q = T_{3L} + T_{3R} + (B - L)/2$, where $T_{3L} = T_{3R} = \sigma_3/2$ are the doublet representations of the neutral generators of the SU(2) subgroups.

To generate masses for the fermions one requires the existence of at least one Higgs bidoublet of the form

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} = (\tfrac{1}{2}, \tfrac{1}{2}, 0), \tag{3}$$

whose vacuum expectation value (vev) is given by

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \kappa_1 & 0 \\ 0 & \kappa_2 \end{pmatrix}. \tag{4}$$

In order to break the symmetry to the electromagnetic group $U(1)_\mathrm{em}$ additional Higgs multiplets with $B - L \neq 0$ are needed. To introduce at the same time Majorana mass terms for the neutrinos we add to the theory triplet Higgses

$$\Delta_{\rm L} = \begin{pmatrix} \Delta_{\rm L}^{+} & \sqrt{2}\Delta_{\rm L}^{++} \\ \sqrt{2}\Delta_{\rm L}^{0} & -\Delta_{\rm L}^{+} \end{pmatrix} = (1,0,2)\,,$$
$$\Delta_{\rm R} = \begin{pmatrix} \Delta_{\rm R}^{+} & \sqrt{2}\Delta_{\rm R}^{++} \\ \sqrt{2}\Delta_{\rm R}^{0} & -\Delta_{\rm R}^{+} \end{pmatrix} = (0,1,2) \qquad (5)$$

with the vevs given by

$$\langle \Delta_{L,R} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix} . \qquad (6)$$

The Yukawa couplings between the leptons and the scalars are the following:

$$\mathcal{L}_{\rm Yu} = \{\overline{\Psi}_{\rm R}\Phi\Psi_{\rm L} + g\overline{\Psi}_{\rm R}\tilde{\Phi}\Psi_{\rm L} + ih_{\rm L}\Psi_{\rm L}^{T}C\sigma_2\Delta_{\rm L}\Psi_{\rm L}$$
$$+ ih_{\rm R}\Psi_{\rm R}^{T}C\sigma_2\Delta_{\rm R}\Psi_{\rm R} + h.c.\,, \qquad (7)$$

where $\Delta_{L,R} = \Delta^{i}_{L,R}\sigma_i$ and $\tilde{\Phi} = \sigma^2\Phi^*\sigma^2$. As one can see, the triplet Higgses $\Delta_{\rm L}$ and $\Delta_{\rm R}$ carry lepton number -2. It is important to note that conservation of electric charge prevents the triplet Higgses from coupling to quarks.

The left-handed triplet scalar $\Delta_{\rm L}$ does not play any important role in the dynamics of the model. It is not necessary for the spontaneous symmetry breaking or for generating masses to fermions. The vacuum expectation value $\langle\Delta_{\rm L}^0\rangle = v_{\rm L}$ is actually quite tightly bounded by the ρ parameter, *i.e.* by the mass ratio of the ordinary weak bosons. One has ($\kappa^2 = \kappa_1^2 + \kappa_2^2$)

$$\rho = \frac{M^2_{W_{\rm L}}}{\cos^2\theta_W M^2_{Z_1}} \simeq \frac{1 + 2v_{\rm L}^2/\kappa^2}{1 + 4v_{\rm L}^2/\kappa^2} . \qquad (8)$$

The experimental result [12] $\rho = 1.0004 \pm 0.003$ then implies $v_{\rm L} \gtrsim 9$ GeV, a small value compared with $\kappa \sim 250$ GeV. On the other hand, the vev of the right-handed triplet, $v_{\rm R}$, should be considerably larger than κ in order to satisfy the lower mass limits of the new weak bosons $W_{\rm R}$ and $Z_{\rm R}$. In the following we will concentrate mainly on the right-handed triplet $\Delta_{\rm R}$ ($\equiv \Delta$) (for the phenomenology of the left-handed triplets see *e.g.* [13]).

From the left-handed and right-handed neutrino states one can form three types of Lorentz-invariant mass terms: Dirac term $\overline{\nu}_{\rm L}\nu_{\rm R}$, and Majorana terms $\overline{\nu}^c_{\rm L}\nu_{\rm R}$ and $\overline{\nu}^c_{\rm R}\nu_{\rm L}$, where the latter two terms break the lepton number by two units. All these terms are realized in the left-right symmetric model with the Yukawa coupling (7) and the vevs given in Eqs. (4) and (6). By assuming $v_{\rm L} \simeq 0$ one ends up with the famous see-saw mass matrix

$$M = \begin{pmatrix} 0 & m_D \\ m_D & m_{\rm R} \end{pmatrix} . \tag{9}$$

Here $m_D = (f\kappa_2 + g\kappa_1)/\sqrt{2}$ and $m_{\rm R} = h_{\rm R} v_{\rm R}$. The mass of the charged lepton is given by $m_l = (f\kappa_2 + g\kappa_1)/\sqrt{2}$, and therefore if f and g are comparable, one has $m_D \simeq m_l$. Unless $h_{\rm R}$ is extraordinary small, this implies $m_D \ll m_{\rm R}$.

The eigenstates of the matrix (9) are two Majorana neutrinos ν_1 and ν_2 with approximate masses $m_{\nu_1} \simeq m_D^2/m_{\rm R}$ and $m_{\nu_2} \simeq m_{\rm R}$. The left-handed and right-handed neutrinos are related to the mass eigenstates according to

$$\begin{aligned} \nu_{\rm L} &= (\nu_{1L} \cos\eta - \nu_{2L} \sin\eta) , \\ \nu_{\rm R} &= (\nu_{1R} \sin\eta + \nu_{2R} \cos\eta) , \end{aligned} \tag{10}$$

where the mixing angle η is given by

$$\tan 2\eta = \frac{2m_D}{m_{\rm R}} . \tag{11}$$

The mixing angle η is thus in general very small.

The masses of W_2 and ν_2 are related as

$$m_{\nu_2} \simeq \frac{h_{\rm R}}{g_{\rm R}} M_{W_2} . \tag{12}$$

Most naturally the heavy neutrino and the heavy weak boson would have roughly the same mass, but depending on the actual value of the Yukawa coupling constant $h_{\rm R}$ the neutrino may be also lighter or somewhat heavier than W_2.

The Higgs potential is in general quite complicated containing a great number of parameters. There are severe constraints on the parameters, the most crucial one concerning flavour changing neutral currents (FCNC). Unlike in the SM, in the LR model there are FCNC interactions mediated by some neutral Higgs fields (superpositions of the neutrals members of the bidoublet ϕ). It was argued in Ref. [6] that to suppress FCNC one must require the Higgs potential to be such that in the minimum $\kappa_1 \ll \kappa_2$ or $\kappa_1 \gg \kappa_2$. This requirement has the consequence that the $W_{\rm L}, W_{\rm R}$ mixing ζ is necessarily small, since $\zeta \sim \kappa_1\kappa_2$.

3. Tests of the LR model at the LC

The pair production reactions

$$e^+e^- \to W_2^+W_2^- \qquad (13)$$

$$\to W_1^+W_2^-,\ W_1^-W_2^+ \qquad (14)$$

proceed through the s-channel exchange of the photon, Z_1, Z_2 or the neutral Higgses, and through the t-channel exchanges of the neutrinos ν_1 and ν_2 [18]. Although favoured kinematically, the cross section of the reaction with the W_1W_2 final state is much smaller than that of the reaction with the W_2W_2 final state because it is possible only as a result of the neutrino and/or weak boson mixing, both small. The Higgs contribution is in general negligible in both reactions [17].

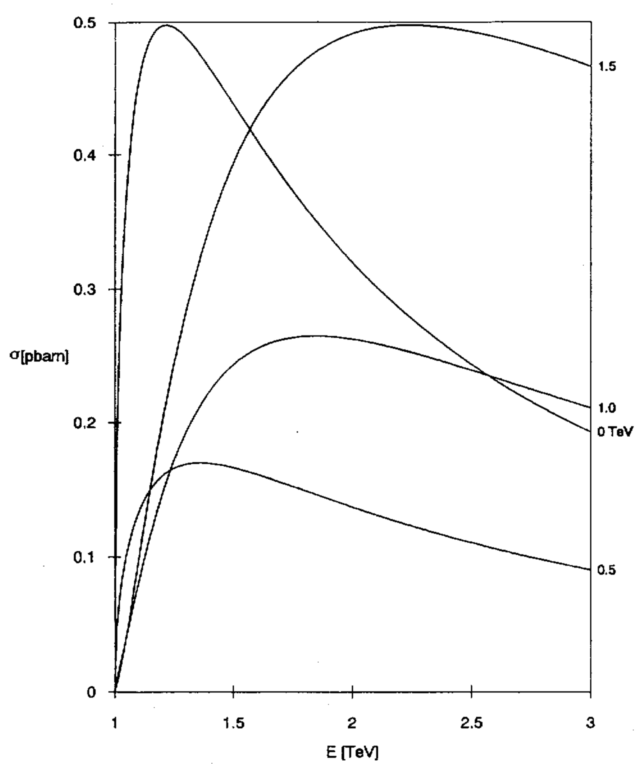

Fig. 1. The total cross section of the process $e^+e^- \to W_2^-W_2^+$ as a function of the total collision energy for various values of heavy neutrino mass m_{ν_2} and with $M_{W_2} = 0.5$ TeV, $M_{Z_2} = 0.5$ TeV.

Of a special interest is the dependence of the cross sections of the reactions (13) on the heavy neutrino mass m_{ν_2}. As conserving the lepton number, this process does not directly probe the large Majorana mass term of $\nu_{\mathbf{R}}$, and hence the mass effect is not that dramatic. Nonetheless, just above the threshold the cross section may behave quite differently as a function of collision energy for different neutrino mass values [18]. In the example case of $M_{W_2} = M_{Z_2} = 0.1$ TeV presented in Fig. 1, the peak value of the cross section is in the range 0.1 to 0.5 pbarn for the heavy neutrino masses $m_{\nu_2} = 0$ to 1.5 TeV. At an integrated luminosity of 100 fb^{-1} this corresponds to an annual event rate of 10^4. Hence, unless the LC happens to operate too close to the threshold (or below it), the $W_{\mathbf{R}}$ should be easily discovered through the reaction (13), and also the dependence on the heavy neutrino mass should be detectable.

The signal of the W_2W_2 production would be four jets from $W_2 \to \bar{q}q'$ decays whose invariant mass pairwise reconstructed to M_{W_2}. The leptonic decay channel $W_2 \to l\nu_2$ is kinematically disfavored as compared with the hadronic channels unless $m_{\nu_2} \ll M_{W_2}$, and the channel $W_2 \to l\nu_1$ is suppressed due to the small mixing between left- and right-handed neutrinos. The channel $W_2 \to W_1 Z_{1(2)}$ is suppressed due to the small weak boson mixings.

The lepton number violation associated with the triplet Higgs couplings and Majorana neutrinos gives rise to many distinctive signals of left-right symmetry. One interesting process is the "inverse neutrinoless double beta decay" [14–16, 18],

$$e^-e^- \to W_1^- W_1^- \,. \tag{15}$$

This process, if observed, would signal the existence of $|\Delta L| = 2$ interactions, something which is forbidden in the SM where the lepton number is a conserved quantum number. The reaction proceeds in the LR model through a doubly charged triplet Higgs exchange in s-channel and a Majorana neutrino exchange in t- and u-channels. The cross section is in general too small for detection in the LC [19]. This is so because of the stringent bounds on the effective light neutrino mass arising from non-observation of neutrinoless double beta decay, and the requirement of tree-level unitarity at large values of collision energy. The unitarity is maintained (above the triplet Higgs pole) as a result of a destructive interference of the Δ^{--} exchange and neutrino exchange amplitudes.

Let us note that the contribution of the heavy "right-handed" neutrino ν_2 to the reaction (15) is small because of the smallness of the neutrino mixing angle η (see Eq. (11)). The heavier is the neutrino, the smaller is the mixing. This is a consequence of the see-saw mechanism. If the neutrino mass and the mixing are kept independent parameters, the cross section $\sigma(e^-e^- \to W_1^- W_1^-)$ can be much larger than in the LR model.

According to Refs. [16, 20] the cross section can be in such a case as large as $\sigma = 4$ (64) fb for $\sqrt{s} = 0.5$ (1) TeV, given the present experimental bounds on the neutrino mixing.

In contrast with the reaction (15), the pair production of the heavy gauge bosons,

$$e^- e^- \to W_2^- W_2^- , \tag{16}$$

will not be suppressed by small neutrino masses or mixings. On the contrary, the neutrino exchanged in the t- and u-channel is the heavy "right-handed" neutrino, which couples to W_2 with a full strength. At the energies $\sqrt{s} = 0.5 - 2$ TeV, the cross section can be quite large, of the order of a few picobarns (see Fig. 2), corresponding to event rates of 10^4 for an integrated luminosity of 100 fb^{-1}. All amplitudes contributing are proportional to the heavy neutrino mass ν_2: in the t- and u-channels the $|\Delta L| = 2$ interaction is generated by the Majorana mass $m_{\mathrm{R}} = h_r v_{\mathrm{R}} \simeq m_{\nu_2}$, in the Δ^{--} exchange in s-channel the $ee\Delta$ coupling has the strength h_{R} and the $WW\Delta$ coupling is proportional to $\langle \Delta^0 \rangle \sim v_{\mathrm{R}}$. Above the triplet Higgs pole there are, however, destructive interferences among the amplitudes, which makes the neutrino mass dependence less striking (see, *e.g.* [21]).

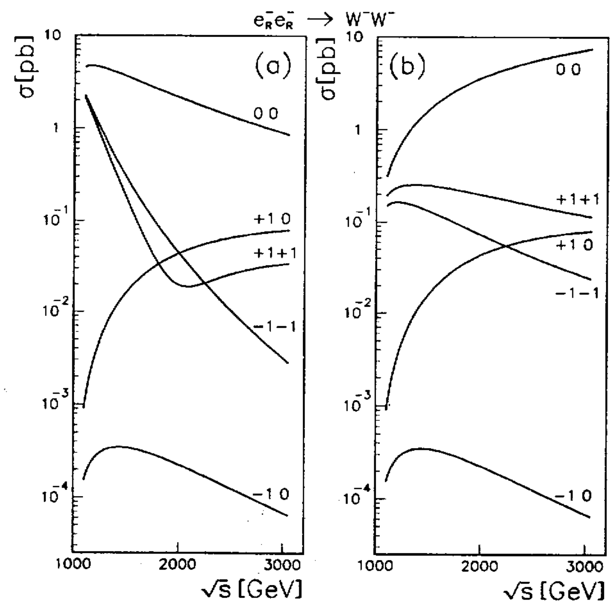

Fig. 2. The total cross section for various $W_2^- W_2^-$ polarization states for fully right-handedly polarized electron beams as a function of neutrino mass m_ν ($\equiv m_{\nu_2}$). The collision energy is $\sqrt{s} = 1.5$ TeV, $M_{W_2} = 0.5$ TeV and $M_\Delta = 0.8$ TeV (a) or 10 TeV (b).

In Fig. 2 the cross section $\sigma(e^-e^- \to W_2^- W_2^-)$ is presented as a function of $\sqrt{s}$ for different polarization states of the W_2-pair assuming both electron beams to be right-handedly polarized. The W_2 mass is taken to be 0.5 TeV and that of the heavy neutrino $m_{\nu_2} = 1$ TeV, and the results are given for two values of the Δ^{--} mass, $M_\Delta = 0.8$ and 10 TeV. The main contribution to the cross section comes from the production of longitudinally polarized W_2's. The angular distribution of such W_2's is fairly sensitive to the relative size of the neutrino mass m_{ν_2} and the Higgs mass M_Δ. This is because the Δ^{--} exchange produces W_2's in the forward and backward directions relative to the beam, whereas the neutrino exchange prefers the transverse direction [21].

The discovery of the heavy weak bosons through the reaction (16) should be fairly easy even with a moderate number of events because of their back-to-back decays. This signature allows for an effective background suppression. It should be noted that the signal will disappear when an incoming neutrino helicity is changed to opposite, which gives another means to distinguish the background from the effect. In [22] the cross section for the processes $e^-e^- \to W_2W_2\gamma(Z)$, which one would expect to create some background, was found to be on the level of a few femtobarns, that is, well below the signal.

It would be possible to explore quite a large range of mass values m_{ν_2}, M_Δ and M_{W_2} by using the process (16), but the M_{W_2} reach is of course restricted kinematically to the values $M_{W_2} < \sqrt{s}$. If W_2 is heavier than this, one should consider the single production of W_2 via the reaction $e^-e^- \to W_2^- W_2^{-*}$, where the off-shell boson decays to two jets or to a charged lepton and a "right-handed" neutrino [23]. The latter decay channel is of course forbidden if $m_{\nu_2} > M_{W_2}$. Having one of the W_2's off-shell reduces the cross section substantially to the level of a few femtobarns, so that a high luminosity is required to make this process useful.

Also the following "exotic" processes are predicted by the LR model:

$$e^-e^- \to \mu^-\mu^-,\ \tau^-\tau^- . \tag{17}$$

They are forbidden in the SM. The two leading contributions come from the Δ^{--} exchange in s-channel and the box-diagrams with virtual Majorana neutrinos and charged gauge bosons. Although the total lepton number is conserved in the processes, the lepton numbers L_e and L_μ or L_τ are violated by two units. These processes have practically no background from the SM phenomena. (The background opposite-sign muon pairs, produced via two-photon processes, can be separated from the signal by having a magnetic field in detector.) The cross section, which depends on the unknown masses of Δ^{--} and ν_2, can be as high as $0.1 - 1$ pb, *i.e.*, comparable with that of the WW production [24].

4. Supersymmetric LR model and its tests at LC

The LR model has a naturality problem similar to that of the SM, namely the masses of the Higgs scalars diverge quadratically unless the parameters of the model are fine tuned in all orders of perturbation theory. To cure this problem, left-right symmetric model should be extended to obey supersymmetry (see *e.g.* [25, 26]).

The most significant difference between the ordinary and the supersymmetric LR model concerns the Higgs sector. In supersymmetrization, the cancellation of chiral anomalies among the fermionic partners of the triplet Higgs fields requires that the Higgs triplet superfield Δ is accompanied by another triplet superfield, δ, with opposite $U(1)_{B-L}$ quantum number:

$$\delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, 2)\,. \tag{18}$$

Note that δ, unlike Δ, has no direct coupling to leptons. To make the quantum numbers to match such coupling should namely involve $\delta^\dagger$, but supersymmetry forbids that kind of Yukawa term. Also another bidoublet should be added to avoid a trivial CKM matrix for quarks. In the non-susy LR model the Yukawa coupling is of the form (see Eq. (7)) $f_{ij}\bar{q}_{i\mathrm{R}}\phi q_{j\mathrm{L}} + g_{ij}\bar{q}_{i\mathrm{R}}\tilde{\phi} q_{j\mathrm{L}}$, where $q = (u, d)$ etc. and i, j are family indices. The CKM matrix is made non-trivial by assuming that the coupling matrices f and g do not have the same form, which guarantees that the u-type quarks and d-type quarks mix differently. Supersymmetry forbids the g term as the Higgs superfield in it is conjugated, and therefore one must introduce a second bidoublet (the two bidoublets will be denoted by ϕ_u and ϕ_d).

In [27] a simple supersymmetric LR model was investigated. The model is described by the superpotential

$$\begin{aligned} W =& h_u^Q Q_{\mathrm{L}}^{cT}\phi_u Q_{\mathrm{R}} + h_d^Q Q_{\mathrm{L}}^{cT}\phi_d Q_{\mathrm{R}} \\ &+ f_u^L L_{\mathrm{L}}^{cT}\phi_u L_{\mathrm{R}} + f_d^L L_{\mathrm{L}}^{cT}\phi_d L_{\mathrm{R}} + h_{\mathrm{R}} L_{\mathrm{R}}^T i\tau_2 \Delta_{\mathrm{R}} L_{\mathrm{R}} \\ &+ \mu_1 \mathrm{Tr}(\tau_2\phi_u^T\tau_2\phi_d) + \mu_2 \mathrm{Tr}(\Delta_{\mathrm{R}}\delta_{\mathrm{R}})\,. \end{aligned} \tag{19}$$

Here $Q_{L(R)}$ stands for the doublet of left(right)-handed quark superfields, $L_{L(R)}$ stands for the doublet of left(right)-handed lepton superfields, ϕ_u and ϕ_d are the two bidoublet Higgs superfields, and Δ_{R} and δ_{R} the two right-handed triplet Higgs superfields. The generation indices of the quark and lepton superfields are suppressed. It should be noticed that the mass matrix of the doubly charged triplet higgsinos, following from the last term of the superpotential, is particularly simple, because the doubly charged higgsinos do not mix with gauginos. In the following some possible tests of this model in the LC are considered [28].

The next generation linear electron colliders will, besides the e^+e^- and e^-e^- reactions, be able to operate also in the photon modes $e^-\gamma$ and $\gamma\gamma$. The high energy photon beams can be obtained by back-scattering of intensive laser beam on high energy electrons [29]. It turns out that all these collision modes may provide useful processes for investigation of the susy LR model [28] (like it does for the susy version of the SM [30]). Perhaps the most interesting reactions from the phenomenological point of view are those where the doubly charged higgsinos $\tilde{\Delta}^{--}$ are produced:

$$e^+e^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}\,, \tag{20}$$

$$e^-e^- \to \tilde{\chi}^0\tilde{\Delta}^{--}\,, \tag{21}$$

$$\gamma e^- \to \tilde{e}^+\tilde{\Delta}^{--}\,, \tag{22}$$

$$\gamma\gamma \to \tilde{\Delta}^{--}\tilde{\Delta}^{++}\,. \tag{23}$$

The fact that this particle carries two units of electric charge and two units of lepton number and that it does not couple to quarks makes the processes most suitable and distinctive test of the susy LR model.

The allowed decay modes are

$$\begin{aligned}\tilde{\Delta}^{++} \to & \Delta^{++}\lambda^0,\ \Delta^+\lambda^+\,,\\ & \tilde{\Delta}^+ W_2^+\,,\\ & \tilde{l}^+ l^+\,.\end{aligned} \tag{24}$$

In large regions of the parameter space, the kinematically favoured decay mode is $\tilde{\Delta}^{++} \to \tilde{l}^+ l^+$, provided of course that $m_{\tilde{l}^+} < m_{\tilde{\Delta}^{++}}$ at least for some lepton flavour. As the mass of the triplet Higgs Δ is of the order of the $SU(2)_R$ breaking scale v [6], the first two decay channels are forbidden energetically in the case of relatively light triplet higgsinos. For the same reason is the channel $\tilde{\Delta}^+ W_2^+$ kinematically disfavored, since the mass of W_2 is known to be above 0.5 TeV. The decay channel $\tilde{\Delta}^+ W_1^+$ is forbidden in the case of no $W_L - W_R$ mixing.

The simplest decay mode of the slepton $\tilde{l}$ is into an electron and the lightest neutralino (presumably the lightest supersymmetric particle):

$$\tilde{l} \to l\tilde{\chi}^0\,. \tag{25}$$

If kinematically allowed, the decays into final states with leptons accompanied with heavier neutralinos or charginos can take place in addition, but also then the end-product of subsequent cascade decays often is electrons plus invisible energy. The doubly charged triplet higgsino would thus have the following decay signature:

$$\tilde{\Delta}^{--} \to l^- l^- + \text{ missing energy}\,, \tag{26}$$

where l can be any of e, μ and τ with practically equal probabilities. Accordingly, the signature of the pair production reaction (20), as well as of the two photon reaction (23), would be the purely leptonic final state associated with missing energy. The missing energy is carried by neutrinos, sneutrinos or neutralinos. Conservation of any separate lepton number may be broken in the visible final state. Such final states are not possible in the SM or in the minimal susy model. The total cross section for the total collision energy $\sqrt{s} = 1$TeV and the slepton and higgsino masses in the range of 100–400 GeV is about 0.5 pb. The cross section of the reaction (23) decreases with increasing mass of $\tilde{\Delta}$, but may be as large as 10 pb [28].

Purely leptonic final states accompanied with missing energy form also the signals of the reactions (21) and (22).

One interesting feature of the model described by the superpotential (19) is that it breaks the R-parity [27]. In order to generate non-negative masses to all physical pseudoscalars and the doubly charged scalars at least one of the neutralino fields $\tilde{\nu}_{L,R}$ must require a non-vanishing vev implying spontaneous R-breaking.

5. Conclusions

The phenomenologically interesting characteristics of left-right symmetric model are the new charged weak bosons, heavy right-handed Majorana neutrinos and doubly charged Higgses and higgsinos. The triplet Higgses (and higgsinos) mediate $\Delta L = 2$ interactions, which give rise to clean and low-background signals. These features would be best benefited in the e^-e^-, γe^- and $\gamma\gamma$ collision modes feasible at a linear collider facility.

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