Supersymmetric left-right models

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Abstract

In this talk we review mostly the supersymmetrized versions of the left-right symmetric model, although some of the presented results are more general. We shortly describe the used models, and then concentrate on the Higgs sector. We study the lightest scalars and discuss their detection possibilities. Similarly we consider the chances to detect singly charged Higgses. We discuss as well the fermionic sector of the supersymmetric left-right model and its use in identifying the model.

1 Introduction

The left-right models are interesting in their own right for many reasons, e.g. they provide a natural way to generate light masses for the neutrinos via the so-called see-saw mechanism [1]. The supersymmetrized versions of the model [2, 3, 4, 5, 6, 7, 8, 9, 10, 11] have been actively studied in recent years. From the supersymmetric point of view, an important motivation for the left-right models is due to their gauge group. It has been noted [12] that if the gauge symmetry of MSSM is suitably extended to contain $U(1)_{B-L}$, the R-parity is automatically conserved in the Lagrangian of the theory. Thus one of the major problematic features of the MSSM is explained by the gauge symmetry. Here we will concentrate on the supersymmetric left-right model (SLRM) based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

The breaking of the extended symmetry requires a new set of Higgs bosons. The Higgs sector of the SLRM can be chosen in many ways, but with triplets in the spectrum, one can have the conventional see-saw mechanism for neutrino mass generation. This will be the choice for the $SU(2)_R$ breaking here. The $SU(2)_L$ will be broken mainly by bidoublets which contain the doublets of the MSSM.

In this talk we will concentrate on the Higgs sector of the model, since it contains many of the aspects in the SLRM which are different from the MSSM. In addition to the lightest neutral CP-even Higgs, it has been known for quite some time [5] that the lightest doubly charged Higgs occurring in the triplets may be light. While the lightest doubly charged Higgs or its fermionic partner may offer best possibilities to identify the triplet in the model, the singly charged chargino production may be most suitable for finding out the R-parity violation in the model.

2 The models

The particle content of the supersymmetric left-right model is enlarged compared to the MSSM. Because of the extended symmetry, there are superfields containing the gauge bosons connected to $SU(2)_R$. Due to the more symmetric treatment of the fermions in the model, also the right-handed neutrino superfield is included. The Higgs sector breaking the gauge symmetry consists of the bidoublet and triplet Higgs superfields:

$$\begin{aligned}
&\Phi = \begin{pmatrix} \Phi_1^0 & \Phi_1^+ \\ \Phi_2^- & \Phi_2^0 \end{pmatrix}, \ \chi = \begin{pmatrix} \chi_1^0 & \chi_1^+ \\ \chi_2^- & \chi_2^0 \end{pmatrix} \sim (1,2,2,0), \\
&\Delta_R \sim (1,1,3,-2),\ \delta_R \sim (1,1,3,2),\ \Delta_L \sim (1,3,1,-2),\ \delta_L \sim (1,3,1,2).
\end{aligned} \tag{1}$$

In (1) it is assumed that the gauge symmetry is supplemented by a discrete left-right symmetry. The $SU(2)_L$ triplets Δ_L and δ_L make the Lagrangian fully symmetric under $L \leftrightarrow R$ transformation, although these are not needed for symmetry breaking, or for the see-saw mechanism.

The general form of the vacuum expectation values of the various scalar fields which preserve the $U(1)_{\rm em}$ gauge invariance can be written as

$$\begin{aligned}
&\langle\Phi\rangle = \begin{pmatrix} \kappa_1 & 0 \\ 0 & e^{i\phi_1}\kappa_1' \end{pmatrix}, \ \langle\chi\rangle = \begin{pmatrix} e^{i\phi_2}\kappa_2' & 0 \\ 0 & \kappa_2 \end{pmatrix}, \\
&\langle\Delta_R^0\rangle = v_{\Delta_R},\ \langle\delta_R^0\rangle = v_{\delta_R},\ \langle\Delta_L^0\rangle = v_{\Delta_L},\ \langle\delta_L^0\rangle = v_{\delta_L},\ \langle\tilde\nu_L\rangle = \sigma_L,\ \langle\tilde\nu_L^c\rangle = \sigma_R.
\end{aligned} \tag{2}$$

From the heavy gauge boson mass limits the triplet vacuum expectation values v_{Δ_R} and v_{δ_R} are in the range $v_{\Delta_R}, v_{\delta_R} \gtrsim 1$ TeV. κ_1' and κ_2' contribute to the mixing of the charged gauge bosons and to the flavour changing neutral currents, and are usually assumed to vanish. In order to have the tree level value of the electroweak ρ parameter close to unity, $\rho = 0.9998 \pm 0.0008$ [13], the left-triplet VEVs v_{Δ_L} and v_{δ_L} must be small.

With the minimal field content, the only way to preserve the $U(1)_{em}$ gauge symmetry unbroken is to have a nonzero sneutrino VEV [3, 5]. Thus the R-parity is spontaneously broken in the SLRM with minimal particle content and renormalizable interactions.

An alternative to the minimal left-right supersymmetric model described above involves additional triplet fields, $\Omega_L(1,3,1,0)$ and $\Omega_R(1,1,3,0)$ to the minimal model [7]. In these extended models the breaking of $SU(2)_R$ is achieved in two stages. In the first stage the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is broken to an intermediate symmetry group $SU(2)_L \times U(1)_R \times U(1)_{B-L}$, and at the second stage $U(1)_R \times U(1)_{B-L}$ is broken to $U(1)_Y$ at a lower scale. In this theory the parity-breaking minimum respects the electromagnetic gauge invariance without a sneutrino VEV.

Another possibility is to add non-renormalizable terms to the Lagrangian of the minimal supersymmetric left-right model, while retaining the minimal Higgs content [12, 7]. It has been shown that the addition of non-renormalizable terms suppressed by a high scale such as Planck mass, $M_{Pl} \sim 10^{19}$ GeV, with the minimal field content ensures the correct pattern of symmetry breaking in the SLRM with the intermediate scale $M_R \gtrsim 10^{10} - 10^{11}$ GeV, and R-parity remains exact.

3 The upper limit on the lightest CP-even Higgs

In the case of the SLRM we have many new couplings and also new scales in the model and it is not obvious, what is the upper limit on the lightest CP-even Higgs boson mass.

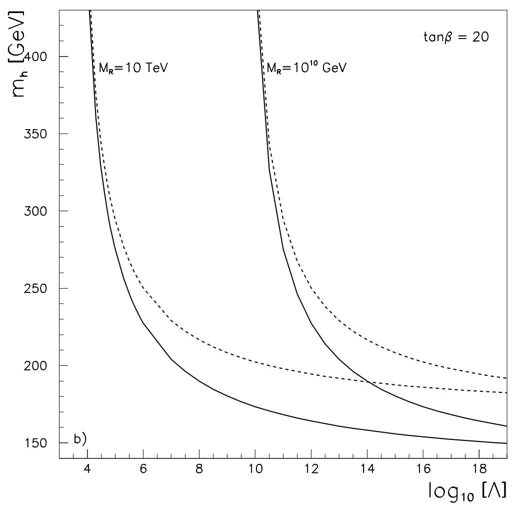

Figure 1: The upper bound on the mass of the lightest neutral Higgs boson. The soft supersymmetry breaking parameters are 1 TeV (solid) and 10 TeV (dashed).

This mass bound is a very important issue, since the experiments are approaching the upper limit of the lightest Higgs boson mass in the MSSM.

A general method to find an upper limit for the lightest Higgs mass was presented in [14]. This method has been applied to the mass of the lightest Higgs, m_h, of SLRM [11] in three cases: (A) R-parity is spontaneously broken (sneutrinos get VEVs), (B) R-parity is conserved because of additional triplets, and (C) R-parity is conserved because of nonrenormalizable terms.

For the minimal model, case (A), the upper bound on m_h is [11]

$$m_h^2 \leq \frac{1}{2v^2}\left[g_L^2(\omega_\kappa^2+\sigma_L^2)^2+g_R^2\omega_\kappa^4+g_{B-L}^2\sigma_L^4+8(h_{\Phi L}\kappa_1'+h_{\chi L}\kappa_2)^2\sigma_L^2+8h_{\Delta_L}^2\sigma_L^4\right], \tag{3}$$

where $v^2=\kappa_1^2+\kappa_1'^2+\kappa_2^2+\kappa_2'^2+\sigma_L^2$ and $\omega_\kappa^2=\kappa_1^2-\kappa_2^2-\kappa_1'^2+\kappa_2'^2$. The addition of extra triplets does not change this bound. Thus, the bound for the case (B), can be obtained from (3) by taking the limit $\sigma_L \to 0$. The total number of nonrenormalizable terms in case (C) is large. However, the contribution to the Higgs mass bound from these terms is found to be [11] typically numerically negligible. Therefore the upper bound for this class of models is essentially the same as in the case (B).

The upper bound on the mass of the lightest Higgs after the radiative corrections [11] is plotted in Fig.1 as a function of the scale Λ up to which the SLRM remains perturbative. The upper bound is shown for two different values of the $SU(2)_R$ breaking scale, $M_R = 10$ TeV and $M_R = 10^{10}$ GeV, and for two values of soft supersymmetry breaking mass parameter, $M_s = 1$ TeV and $M_s = 10$ TeV. For large values of Λ the upper bound is below 200 GeV.

Another relevant issue concerning the lightest Higgs is its branching ratios to fermions. Connected to that in the left-right symmetric models are problems with FCNC, which are expected if several light Higgs bosons exist [15], unless $m_{H_{FCNC}} \gtrsim \mathcal{O}(1\text{ TeV})$. Thus the relevant limit to discuss is the one in which all the neutral Higgs bosons, except the lightest one, are heavy. It has been shown that in the decoupling limit the Yukawa

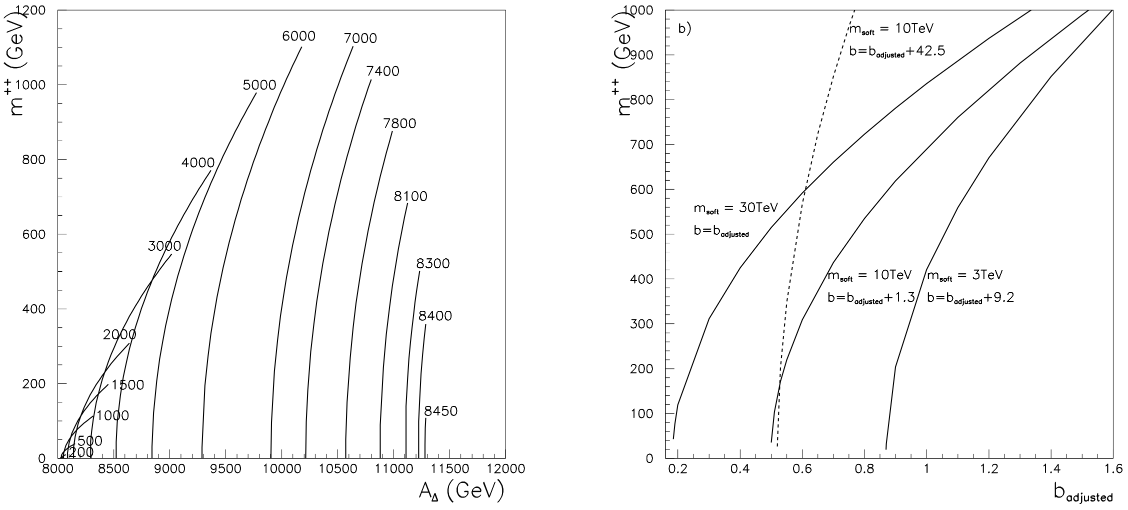

Figure 2: The mass $m_{H^{++}}$ of the lightest doubly charged Higgs. In a) the mass is as a function of the soft trilinear coupling A_Δ. The allowed σ_R varies between 100 GeV and 8.45 TeV. In b) the mass is as a function of the $b_{adjusted}$-parameter related to b_R as denoted. In b) $D = (3\text{ TeV})^2$ (solid) except for $m_{soft} = 10$ TeV also $D = 10$ TeV^2 is shown (dashed). The soft supersymmetry breaking parameters are marked in the figure. $\tan\beta = 50$.

couplings of the τ's are the same in the SM and in the SLRM even if the τ's contain a large fraction of gauginos or higgsinos [11]. If a neutral Higgs boson, which couples to fermions very differently than the Standard Model Higgs, is found, the model most probably is not left-right symmetric.

4 The lightest doubly charged Higgs

One of the experimentally most interesting issues concerning the left-right models is, whether the lightest doubly charged Higgs is observable in the experiments. This particle may both reveal the gauge group and help to determine the supersymmetric left-right model in question.

There are four doubly charged Higgs bosons in the SLRM, of which two are right-handed and two left-handed. The masses of the left-handed triplets are expected to be of the same order as the soft terms. The mass matrix for the right-handed triplets depends on the right-triplet VEV. Nevertheless, it was noticed in [5] that in the SLRM with broken R-parity one right-handed doubly charged scalar tends to be light. Also, in the nonrenormalizable case it is possible to have light doubly charged scalars [8]. On the other hand, in the nonsupersymmetric left-right model all the doubly charged scalars typically have a mass of the order of the right-handed scale [16]. This is also true in the SLRM with enlarged particle content [7]. Thus a light doubly charged Higgs would be a strong indication of a supersymmetric left-right model with minimal particle content.

In Figure 2 a) an example of H^{++} masses with broken R-parity is shown as a function of A_Δ for fixed σ_R. The soft masses and right-handed breaking scale, are of the order of 10

TeV. The maximum triplet Yukawa coupling allowed by positivity of the mass eigenvalues in this case is $h_\Delta \sim 0.4$. Even in the maximal case the mass of the doubly charged scalar $m_{H^{++}} \sim 1$ TeV. In Fig. 2 b) $m_{H^{++}}$ is plotted in the model containing nonrenormalizable terms as a function of the nonrenormalizable b_R-parameter for $v_R^2/M = 10^2$ GeV.

The collider phenomenology of the doubly charged scalars has been actively studied, since they appear in several extensions of the Standard Model, can be relatively light and have clear signatures. The decays of the doubly charged Higgs bosons have been studied e.g. in [17]. The main decay modes for relatively light doubly charged Higgs were found to be $H^{--} \to l_1^- l_2^-$, where $l_{1,2}$ denote leptons. The experimental signature of the decay is then the same sign lepton pair with no missing energy, including lepton number violating final states, e.g. $\mu^-\mu^-$ or $e^-\mu^-$.

Since the left-right models contain a large number of extra parameters when compared to the MSSM, an advantage of the pair production is that it is relatively model independent. It can occur even if W_R is very heavy, as in the nonrenormalizable case, or the triplet Yukawa couplings are very small. The doubly charged Higgses can be produced in $f\bar{f} \to \gamma^*, Z^* \to H^{++}H^{--}$ both at lepton and hadron colliders, if kinematically allowed. The pair production cross section at a linear collider and at LEP II is given in [18]. The cross sections remain sufficiently large close to the kinematical limit in e^+e^- collisions for the detection of doubly charged scalars in pair production to be possible.

Kinematically, production of a single doubly charged scalar would be favoured. The present measurements lead to upper limits for the quantities of the type $h_{ij}h_{i'j'}/m^2_{H^{++}}$, where $i, j, \ldots$ are flavour indices and h are the triplet Yukawa couplins. From Bhabha scattering cross section at SLAC and DESY, one has

$$h_{ee}^2 < 9.7 \times 10^{-6}\ \mathrm{GeV}^{-2} \cdot M^2_{H^{++}}. \tag{4}$$

The single production of doubly charged scalars in lepton colliders has been studied in [18, 19, 20, 21]. The production processes are the following ($H^{--} = H_L^{--}$ or H_R^{--}):

$$\begin{aligned} e^-\gamma &\to l^+H^{--}, & (5)\\ e^+e^- &\to e^+l^+H^{--}, & (6)\\ e^-e^- &\to H^{--},\ H^{--}+\gamma \text{ or } Z & (7) \end{aligned}$$

Due to the t-channel electron exchange, which gives the most dominant contribution, the differential cross section of the process (5) is strongly peaked in the backward direction and most of the produced H^{--}'s have the momenta almost parallel to the beam axis. In the case of the reaction (6) one can test H^{--} masses almost up to the kinematical threshold [21] for triplet Yukawa couplings $\mathcal{O}(10^{-3})$. The reactions (5) and (6) are especially useful in studying the sensitivity of a linear collider to the mass and couplings of a doubly charged Higgs scalar [21].

If the mass of H^{--} were known in advance, e.g. from the other linear collider collision modes or LHC experiments, one could adjust the collision energy in the e^-e^- collision suitably to have a very large production cross section at pole. In this way one would be capable to probe very small values of the coupling constants, $h_{ee} \lesssim 10^{-4}$ [18, 20]. The pole condition is softened in the two body processes (7), which have been studied in [20].

5 Singly charged Higgs

The remaining scalars in the Higgs sector are the singly charged Higgses. Here our interest is mainly to see if it is possible to determine whether the charged Higgs has components originating from the triplet. This question has been studied in [22] using the fact that unlike in Higgs doublet models, in triplet models the $H^{\pm}W^{\mp}Z$ vertex exists at tree level. However, this vertex is suppressed in the case where the charged Higgs has tree level couplings to fermions, at least if the triplets under discussion are $SU(2)_L$ triplets, as is the case in [22].

Since in the supersymmetric left-right models discussed here the triplet coupling to the leptons is important, our aim is to study, if the triplet can be identified from the charged Higgs in the linear collider [23]. In [23] the simplest possible case with just one triplet in addition to the Standard Model particles is considered. The production of the singly charged Higgs is considered in the processes

$$e^+e^- \to H^+H^-, \quad e^+e^- \to H^+l^-\bar{\nu}_l. \tag{8}$$

There is a large background from the charged gauge boson pair production, but this can be effectively reduced by studying the angular distributions of the signal and background and choosing only the decays of charged Higgs to leptons and neutrinos.

6 Doubly charged higgsino

The doubly charged higgsinos are equally good signals of beyond the MSSM physics as the doubly charged scalars. The experimental signatures of these fermions are somewhat more complicated than those of the doubly charged scalars since part of the energy is lost in neutralinos, at least if the R-parity is conserved. On the other hand, the mass of the doubly charged higgsino gives important model information, since it is the supersymmetric Higgs mixing parameter.

The production of the doubly charged higgsinos has been discussed at linear collider in [4, 9] assuming R-parity conservation and two body decays of the higgsinos. It has been recently shown [24] that also from the three-body decay modes one can determine the parameters of the model by studying the final state lepton distributions.

7 Neutralinos and charginos

When R-parity is broken, the neutrinos mix with neutralinos and leptons with charginos. The mixing and phenomenological consequences in the case of the supersymmetric left-right model have been discussed in [10]. Two typical situations were considered. In one case the neutralinos and charginos were predominantly gauginos while in the second case they were mainly higgsinos. For the chosen parameters the particle spectrum was checked to make sure that there were no particles which would be experimentally too light.

For gauginos it turned out to be possible to detect only pair production at linear collider. In the case where neutralinos and charginos are higgsino-like, the doubly charged Higgs may be light enough so that the dominant decay mode of the chargino is to a lepton and a doubly charged Higgs, which in turn decays to a pair of charged leptons. This would offer a good possibility to measure the R-parity violation in the context of supersymmetric left-right models, since all the energy in the process is visible. Both the pair production and the single production of the charginos might be observable at linear collider.

8 Conclusions

Supersymmetric left-right models are well motivated extensions of the MSSM, since they conserve R-parity as a consequence of gauge invariance. The lightest CP even Higgs boson can be considerably heavier than in the MSSM, and its couplings to fermions remain similar to the couplings of the Standard Model Higgs boson. If a Higgs, which is too heavy to be the Higgs boson of the MSSM, is detected, one should consider extended supersymmetric models such as the ones discussed here.

In the SLRM with the minimal particle content one has typically also a light doubly charged Higgs boson. If this particle is found, it is a strong indication of the SLRM with minimal particle content.

The backgrounds in the processes typical for SLRM are usually small because of exotic flavour structures. Taking into account the rather small losses of the decay products, clear experimental signatures (lepton number violation, no missing energy) and almost no background from the SM, the doubly charged Higgs is hard to miss in a linear collider if it is produced.

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