Production of neutralinos in superstring-inspired $E_6$ models

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Abstract

We study the neutralino mass spectra and production cross sections at an $e^+e^-$ linear collider in superstring-inspired $E_6$ models. These models are characterized by the existence of new neutral gauge bosons and singlet Higgs fields which also lead to an extended neutralino sector compared to the Minimal Supersymmetric Standard Model (MSSM) or the Next-To-Minimal Supersymmetric Standard Model (NMSSM). For different $E_6$ models we develop scenarios with new light exotic neutralinos which may offer important possibilities to distinguish between the models.
1 Introduction

Superstring-inspired E\(_6\) models \([1]\) are an interesting alternative for the phenomenology of low energy supersymmetry. They are characterized by the existence of additional massive U(1) neutral gauge bosons and singlet superfields which lead to an extended neutralino sector \([2]\) compared to the Minimal Supersymmetric Standard Model (MSSM) \([3]\) or the Next-To-Minimal Supersymmetric Standard Model (NMSSM) \([4]\). Therefore the investigation of the neutralino sector may offer an important possibility to distinguish between the different models.

These models are based on an E\(_6\) gauge group, which is broken to a low energy gauge group with one (rank-5 models) or two (rank-6 models) new U(1) factors and therefore one or two new neutral gauge bosons \(Z'\) (\(Z''\)). In the rank-5 models one or two additional Higgs singlet fields with nonzero vacuum expectation values (VEVs) appear whereas in the rank-6 case two singlets are necessary to respect the experimental mass bounds for new gauge bosons \([5]\). In all models we assume R-parity conservation, that means that the lightest neutralino, the LSP, is stable and hence invisible.

The structure of the neutralino sector depends on the choice of the model generated by the respective mechanism of symmetry breaking (for details we refer to \([6]\)):

- The rank-5 model with one singlet contains 6 neutralinos which are mixtures of photino, Z-ino, \(Z'\)-ino, two doublet higgsinos and one singlet higgsino \(\tilde{N}_1\). The \(6 \times 6\) neutralino mass matrix depends on six parameters: the SU(2)\(_L\), U(1)\(_Y\) and U(1)' gaugino mass parameters \(M_2\), \(M_1\) and \(M'\), the ratio \(\tan \beta = v_2/v_1\) of the VEVs of the doublet Higgs bosons, the VEV \(v_3\) of the singlet Higgs and the trilinear Higgs coupling \(\lambda\) in the superpotential.

- An additional singlet higgsino \(\tilde{N}_2\) appears in the rank-5 model with two singlet fields. Then the \(7 \times 7\) neutralino mixing matrix also depends on the VEV \(v_4\) of the second singlet Higgs.

- The rank-6 model with two extra U(1)-factors and therefore two new gauge bosons contains 8 neutralinos (photino, Z-ino, \(Z'\)-ino, \(Z''\)-ino, two doublet higgsinos and two singlet higgsinos \(\tilde{N}_{1,2}\)). Their masses and mixings are determined by 8 parameters including the U(1)' gaugino mass parameter \(M'\).

We analyze the neutralino mass spectra and production cross sections at an \(e^+e^-\) linear collider in these E\(_6\) models and inquire into the discrimination from MSSM and NMSSM. For this purpose we work out scenarios with light singlet-like neutralinos which are significantly different from the MSSM. Then we discuss the parameter regions where the cross sections for neutralino pair production in the E\(_6\) models are above an assumed discovery limit of 10 fb, so that a discrimination between the different supersymmetric models may be possible.
2 Scenarios and mass spectra

Mainly from the experiments at the FermiLab collider there exist lower mass bounds of about 600 GeV for new gauge bosons \cite{7}. These limits imply singlet VEVs of at least about 1500 GeV in the rank-5 model with one singlet or in the rank-6 model. In the rank-5 model with two singlets the VEVs can be smaller without altering the phenomenology of the neutralino sector. In the following we choose \( v_3 = (v_4 =) 1500 \) GeV. Larger values lead to even larger masses of the \( Z' \) bosons as well as of the neutralinos with large singlet higgsino and \( \tilde{Z}' \) components.

All neutralino mass spectra and production cross sections are shown for the whole range of the gaugino mass parameter \(-1000 \text{ GeV} \leq M_2 \leq +1000 \text{ GeV}\). The value for \( M_1 \) is fixed by the usual gaugino mass relation \( M_1 = 5/3 \tan^2 \theta_W M_2 \approx 0.5 M_2 \). For the additional gaugino parameters \( M' \) and \( M'' \) we partly assume the same unification relation but study also the impact of relaxing this condition. For the parameters \( \tan \beta \) and \( \lambda \) which do not significantly influence the neutralino spectrum we use the exemplary values \( \tan \beta = 2 \) and \( \lambda = 0.14 \). Identification of the MSSM parameter \( \mu \) with \( \lambda v_3 \) implies a value of \( \mu = 210 \) GeV for comparison of the \( E_6 \) models with the MSSM.

In all figures we show the experimentally excluded region from neutralino search at LEP \cite{8}. Like in the NMSSM the existence of additional singlet-like neutralinos does not substantially alter the respective MSSM parameter bounds whereas very light singlet-like neutralinos cannot be excluded \cite{4}.

In Fig. 1a the mass spectrum of the neutralinos is shown in the rank-5 model with one singlet and \( M' = M_1 \). Here the four lighter neutralinos have mainly the same mixing character as in the MSSM for \( |M_2| \lesssim 500 \) GeV whereas the neutralinos with large \( \tilde{N}_1 \) and \( \tilde{Z}' \) components lie on top of the spectrum (Fig. 1b, 1c) and are kinematically excluded from production at the first stage of a linear collider. Therefore discrimination of this model from the MSSM tends to be rather difficult.

By relaxing the unification condition \( M' = M_1 \) and choosing a large constant value \( M' = 10 \) TeV a light neutralino appears in Fig. 2a with mass \( m_{\tilde{\chi}^0} \approx 42 \) GeV nearly independent of \( M_2 \). It is almost a pure singlet higgsino as can be seen from Fig. 2b. The heaviest neutralino (the \( \tilde{Z}' \), Fig. 2c) has a mass of the order of \( M' \) and is not shown in Fig. 2a. Therefore the neutralino sector in this scenario is similar to the NMSSM for suitable choice of the NMSSM parameters.

In the rank-5 model with two singlets always a very light singlet higgsino exists independently of the choice of the parameters \( v_3, v_4, \lambda, \tan \beta \) and even for \( M' = M_1 \) (Fig. 3a). In Fig. 3b the \( \tilde{N}_1 \) components of the neutralinos are shown. Since the \( \tilde{N}_2 \) component is distributed among the neutralinos in the same way the lightest neutralino with a mass of about 1 GeV is almost an equal mixture of the two singlet higgsinos. If additionally \( M' \) is put to the large value 10 TeV, two light singlet higgsinos appear (Figs. 4a, b). In all cases the neutralinos with large \( \tilde{Z}' \) and \( \tilde{Z}'' \) components are so heavy that they probably lie outside the energy range of the planned linear collider.

For the rank-6 model a similar characteristic appears as for the rank-5 model with one singlet field. With the assumption \( M' = M'' = M_1 \) the four light neutralinos have mixing characters as in the MSSM (similar to Fig. 1a) and the four new exotic neutralinos are very heavy. If one of the new gaugino mass parameters \( (M', M'') \) has a large value
(10 TeV), one light singlet higgsino appears (analogue to Fig. 2a). If both parameters are fixed at large values there are two light exotic neutralinos (similar to Fig. 4) which are mixtures of the two singlet higgsinos.

3 Cross sections

For all the above described scenarios of the different E_6 models we have computed the cross sections for neutralino pair production and compared the results with the MSSM and NMSSM [9]. Here we use the rank-5 model with two singlets to present in Fig. 5 the exemplary features of the production of light neutralinos as a function of the c.m. energy of an $e^+e^-$ linear collider. Fig. 5a shows the cross sections for $\tilde{\chi}^0_1\tilde{\chi}^0_2$- and $\tilde{\chi}^0_2\tilde{\chi}^0_2$-production for $M_2 = 200$ GeV and $M' = M_1$. Since the lightest neutralino is nearly a pure singlet higgsino which does not couple to (s)fermions and gauge bosons, the $\tilde{\chi}^0_1\tilde{\chi}^0_2$-cross section reaches values above a discovery limit of 10 fb only at the $Z'$ resonance. This means that here a light singlet higgsino can be detected only in connection with the identification of a new gauge boson $Z'$ which in our scenario has a mass of 894 GeV. Then a discrimination between superstring-inspired E_6 models and the NMSSM is also possible. Similar results are obtained for all E_6 scenarios described in the previous section with light singlet-like neutralinos.

The second lightest neutralino in this E_6 model is of nearly the same mixing type as the LSP in the MSSM. Therefore the $\tilde{\chi}^0_2$ pair production is almost identical with the production of two LSPs in the MSSM. While the latter, however, remains invisible, the extended model can be identified by the subsequent neutralino decays. This is a typical example of an extended model where a neutralino, which would be invisible in the MSSM, is detectable because the mass spectrum compared to the MSSM differs by the existence of an additional light singlet higgsino.

In Fig. 5b we exploit a scenario with $M_2 = -200$ GeV and $M' = 10$ TeV where the second and third neutralino are mixings of all components but with large contributions of about 25% of $\tilde{N}_1$ (see Fig. 4b) and 25% of $\tilde{N}_2$. Again one notes the $Z'$ resonance peak, but also outside of the resonance a nonminimal neutralino is detectable by its direct production with a cross section above 10 fb. In this case one could surely note a deviation from the MSSM. Also the discrimination from the NMSSM could be possible because of the very light first neutralino which represents the additional singlet eigenstate. However, in a similar scenario in the rank-5 model with one singlet and large $M'$ a discrimination between the NMSSM and the E_6 model seems only possible by also tracing signatures of an additional gauge boson.

As already indicated, these results for a rank-5 model with two singlets can be easily transferred to all other E_6 models worked out in this contribution.

4 Conclusion

We studied the neutralino sector of several superstring-inspired E_6 models. It was shown that there exist several supersymmetric scenarios with light singlet-like neutralinos compatible with the current experimental constraints where a discrimination between E_6
models, NMSSM and MSSM is possible. Assuming grand unification of all gaugino mass parameters, however, such scenarios are allowed only in a rank-5 model with two singlet fields. Relaxing this condition one may find similar scenarios also for the other $E_6$ models.

The production of light neutralinos with significant singlet components can reach cross sections large enough to allow detection and identification of the respective model. Contrary, the cross sections for the direct production of nearly pure light singlet neutralinos is possible above a discovery limit of 10 fb only at a $Z'$ resonance in all studied $E_6$ models. However, these models could be identified by the decays of the heavier neutralinos with MSSM mixings into the light singlets. Then the supersymmetric signatures sensitively depend on the dominant decay channels which are to be studied in forthcoming works.

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Figure 1: Neutralinos in the rank-5 model with one singlet for $M' = M_1$, $v_3 = 1500$ GeV, $\tan \beta = 2$ and $\lambda = 0.14$. The shaded area marks the experimentally excluded $M_2$-region.

Figure 2: Neutralinos in the rank-5 model with one singlet for $M' = 10$ TeV, $v_3 = 1500$ GeV, $\tan \beta = 2$ and $\lambda = 0.14$. The mass of the $\tilde{\chi}^0_6$, of the order of $M'$, is not shown in (a). The shaded area marks the experimentally excluded $M_2$-region.
Figure 3: Neutralinos in the rank-5 model with two singlets for $M' = M_1$, $v_3 = v_4 = 1500$ GeV, $\tan \beta = 2$ and $\lambda = 0.14$. The shaded area marks the experimentally excluded $M_2$-region.

Figure 4: Neutralinos in the rank-5 model with two singlets for $M' = 10$ TeV, $v_3 = v_4 = 1500$ GeV, $\tan \beta = 2$ and $\lambda = 0.14$. The mass of the $\tilde{\chi}_0^7$, of the order of $M'$, is not shown in (a). The shaded area marks the experimentally excluded $M_2$-region.

Figure 5: Total cross section for production of neutralinos in the rank-5 model with two singlets for $v_3 = v_4 = 1500$ GeV, $\tan \beta = 2$, $\lambda = 0.14$, $m_{\tilde{e}_L} = 416$ GeV, $m_{\tilde{e}_R} = 120$ GeV, $m_{Z'} = 894$ GeV and $\Gamma_{Z'} = 12.5$ GeV.