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RESONANT SINGLE CHARGINO AND NEUTRALINO VERSUS FERMION-ANTIFERMION PRODUCTION AT THE LINEAR COLLIDER [a]

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We study single superparticle productions at the linear collider, putting particular emphasis on resonant processes. We find that there exists a wide region of supersymmetric model parameters where single chargino and neutralino productions dominate over R-violating fermion-antifermion final states. For certain values of μ and M_2, it is possible to produce even the heavier charginos and neutralinos at significant rates, amplifying the total cross section and obtaining interesting chains of cascade decays. Effects from initial-state radiation are also included.

Although the main working tool for supersymmetry searches has been the Minimal Supersymmetric Standard Model, the most general $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant superpotential with the minimal field content also contains the terms

$$W = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \tag{1}$$

where L (Q) are the left-handed lepton (quark) superfields while $\bar{E}, \bar{D}$, and $\bar{U}$ are the corresponding right-handed fields. If both lepton- and baryon-number violating operators were present at the same time in the low energy Lagrangian, they would lead to unacceptably fast proton decay; to avoid this, a symmetry that forbids the terms in (1), R-parity [1], has been invoked. However, it has been shown that there exist symmetries which allow the violation of only a subset of these operators [2], resulting in a very rich phenomenology [3]: single superparticle productions are allowed, while for couplings $\gtrsim 10^{-6}$, the lightest supersymmetric particle decays inside the detector [4]. In both cases, the standard missing energy signature is substituted by multilepton and/or multijet events.

There are three basic categories of new signals:

• Pair superparticle productions and subsequent decays via R-violating operators. Such processes are favoured for small R-violating couplings.

• For reasonably large R-violating couplings, single superparticle productions may occur. In this case the mass reach can be considerably larger than for MSSM processes at the same machine.

• Virtual effects, from sparticle exchanges. These provide the optimal signals for a very heavy superparticle spectrum.

Here, we focus on resonant scalar-neutrino production and its subsequent decay to either sfermions or a single chargino or neutralino [6,7,8,9]. In particular, we study the processes

$$e^+e^- \to (\tilde{\nu})^* \to f\bar{f}' \quad \text{and} \quad e^+e^- \to (\tilde{\nu})^* \to \begin{cases} \ell_i^{\pm}\, \tilde{\chi}^{\mp} \\ \nu_i\, \tilde{\chi}^0 \end{cases}$$

[a] Presented at the 2^{nd} ECFA/DESY study on Linear Colliders, Frascati, November 1998 (Alternative Theories working group).

ijk	λ_{ijk}	Sources
121	0.05 (0.5)	charged current universality
131	0.06 (0.6)	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$

Table 1: *Upper limits on couplings for* $m_{\tilde{f}} = 100$ (1000) GeV.

and identify for which regions of the supersymmetric parameter space each channel is expected to dominate.

For a collider operating in the e^+e^- mode, the only couplings that involve two electrons are $L_1L_2\bar{E}_1$ and $L_1L_3\bar{E}_1$ (remember that from $SU(2)$ invariance, the two lepton doublets cannot have the same flavour) [b]. The bounds for these couplings (Table 1) scale proportionally to the superparticle masses [5,6] and therefore, for a heavy sparticle spectrum, the couplings can be quite large.

Close to the resonance (where the t- and u- channel exchanges can be neglected in comparison to the s-channel pole), the cross section productions can be approximated by a Breit-Wigner formula. For instance, for single neutralino production,

$$\begin{aligned} \sigma &= \frac{8\pi s}{m_{\tilde{\nu}}^2} \frac{\Gamma(\tilde{\nu} \to f\bar{f})\,\Gamma(\tilde{\nu} \to \nu\tilde{\chi}_0)}{(s-m_{\tilde{\nu}}^2)^2 + m_{\tilde{\nu}}^2\Gamma_{\text{total}}^2} \left[\frac{s-m_{\tilde{\chi}^0}^2}{m_{\tilde{\nu}}^2 - m_{\tilde{\chi}^0}^2}\right]^2 \\ &\to \frac{8\pi}{m_{\tilde{\nu}}^2} B(\tilde{\nu} \to f\bar{f}) B(\tilde{\nu} \to \nu\tilde{\chi}^0)\ , \text{ as } s \to m_{\tilde{\nu}}^2 \end{aligned} \tag{2}$$

where Γ_{total} is the total decay width of the sneutrino. Similar expressions arise for the other processes. The resonant cross sections can thus be deduced by the appropriate branching fractions.

Ignoring contributions to the vertices of the MSSM from mass terms, the latter are given by the following formulas:

$$\Gamma(\tilde{\nu} \to \nu\chi_i^0) = \frac{g^2}{32\pi}\ (N_{i2} - \tan\theta_W N_{i1})^2\ m_{\tilde{\nu}} \left(1 - \frac{m_{\chi_i^0}^2}{m_{\tilde{\nu}}^2}\right)^2$$

$$\Gamma(\tilde{\nu} \to \ell^{\mp}\chi_i^{\pm}) = \frac{g^2 V_{i1}^2}{16\pi}\ m_{\tilde{\nu}}\ (1 - \frac{m_{\chi_i^{\pm}}^2}{m_{\tilde{\nu}}^2})^2, \qquad \Gamma(\tilde{\nu} \to f\bar{f}) = \frac{\lambda_{ijk}^2}{16\pi} m_{\tilde{\nu}}$$

In the above, V_{i1} and N_{i1}, N_{i2} are the relevant matrix elements in the mixing matrix for charginos and neutralinos respectively, while λ_{ijk} is the appropriate R-parity violating Yukawa coupling generating the decay $\tilde{\nu} \to f\bar{f}$. Conclusively, whether single chargino and neutralino final states will dominate over the resonant fermion-antifermion productions depends on (i) the SUSY parameter space and (ii) the strength of λ_{ijk}. This is indicated in Figs. 1,2 where the branching ratio of

[b] In $2 \to 2$ single superparticle productions one may generically probe only a subset of operators. All 45 operators can be simultaneously probed by going to a 3-body final state, for instance in rare Z^0 decays; however, this process is phase-space suppressed and was found to be more relevant for hadron colliders [10].

the sneutrino decay to fermions is presented for the regions of the supersymmetry parameter space that are interesting for LEP (Fig. 1) and LC (Fig. 2) [c]. Here, the U(1) gaugino mass M_1 is determined from the SU(2) gaugino mass M_2 by the unification relation $M_1 = (5/3)\tan^2\theta_W M_2$, while the LEP2 bound on chargino masses has been implemented. For lower values of M_2, μ, a larger number of charginos and neutralinos can be produced at the final state, while the phase space suppression for their production is small. The picture starts changing as we pass to larger M_2, μ and this is indicated in the increase of the sneutrino decay rate to fermions. However, we can see that for a wide range of M_2 and μ the production of charginos and neutralinos at the LC tends to dominate. Moreover, there exist bands of the parameter space where the production of the heavier charginos and neutralinos may occur at a significant level. This is shown in Table 2, where we present the partial sneutrino decay widths to each chargino and neutralino.

Subsequently, the charginos and neutralinos will decay to an R-parity even final state, with the possibility of an interesting chain of cascade decays with multi-lepton events and explicit lepton-number violation at the final state. The lightest neutralino decays via

$$\tilde{\chi}_1^0 \quad \rightarrow \quad \{(e^{\pm}, l_i^{\mp}, \nu_e), (e^{\pm}, e^{\mp}, \nu_i)\}$$

For the charginos and the heavier neutralinos, there exist two possible decay modes: The first is the cascade decay via the lightest neutralino and the second the direct decay via the R-violating coupling(s), as discussed in [12]. For instance, for the lightest chargino we have the R-conserving channel

$$\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 + (W^-)^* \rightarrow \tilde{\chi}_1^0 + f\bar{f}'$$

where $f\bar{f}'$ are the decay fermions of the W-boson (which is real or virtual depending on the mass gap between the lightest chargino and neutralino), or the R-violating channels

$$\tilde{\chi}_1^- \rightarrow e^- e^+ l_i^-, \qquad \tilde{\chi}_1^- \rightarrow \nu_e \nu_i e^- \tag{3}$$

In the first case of (3) the total signal could be even more distinct since it involves four leptons at the final state (three being in the same semi-plane) without any missing energy, unlike the cascade chargino decay which always involves neutrinos at the final state [d]. It turns out however that the charginos as well as the heavier neutralinos dominantly decay to χ_1^0 and fermions for a wide region of the supersymmetric parameter space.

In all cases, the signals should be clearly visible at an e^+e^- collider, provided the cross-section is sufficiently large; the latter mainly depends on how large the unknown coupling λ will be. We study the relevant cross section, at and away from the resonance. Ignoring contributions to the vertices of the MSSM from mass terms, we have two channels present (s and t) for chargino production and all three channels (s, t and u) for neutralino production. For the s-channel diagram we take into account the contribution due to the decay width of the scalar neutrino.

[c] For squark decays, analogous results have been presented in [11].

[d] Which of the two processes will appear, clearly depends on (i) the strength of the R-parity

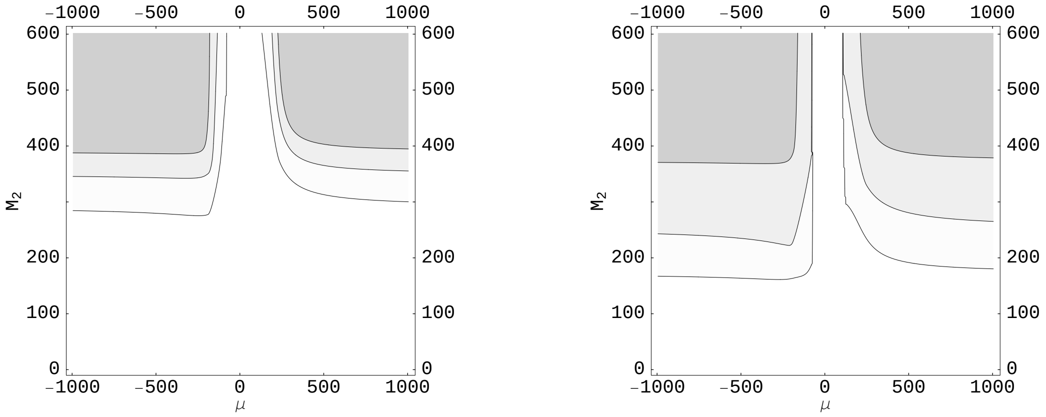

Figure 1: *$\mathcal{B}$ for $\tilde{\nu}$ decay to fermions for parameters most relevant for LEP. We present contours for $\mathcal{B} \geq 0.9, 0.3, 0.1$, from the darker to the lighter areas respectively. We chose tan$\beta = 2.0, m_{\tilde{\nu}} = 200$ GeV and $\lambda = 0.04$ (left) and 0.1 (right). The LEP 2 bound on charginos has been implemented.*

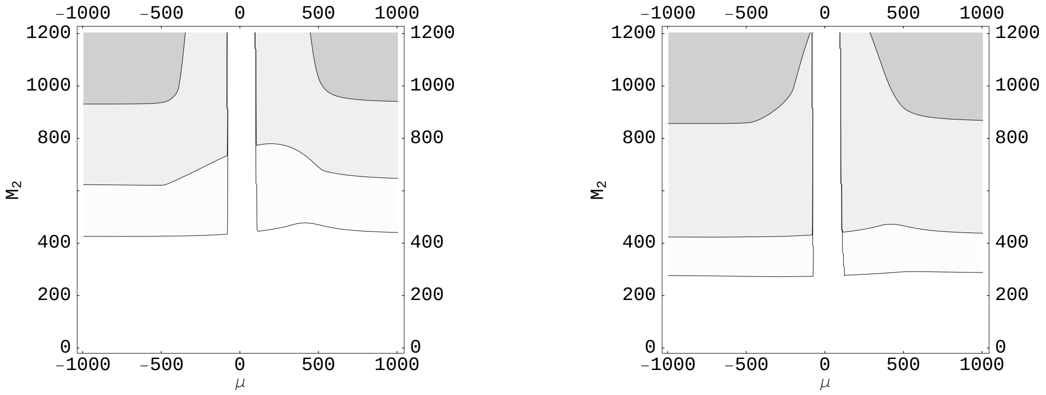

Figure 2: *$\mathcal{B}$ for $\tilde{\nu}$ decay to fermions for parameters most relevant for LC. We present contours for $\mathcal{B} \geq 0.9, 0.3, 0.1$, from the darker to the lighter areas respectively. We choose tan$\beta = 2.0, m_{\tilde{\nu}} = 500$ GeV and $\lambda = 0.1$ (left) and 0.2 (right). The LEP 2 bound on charginos has been implemented.*

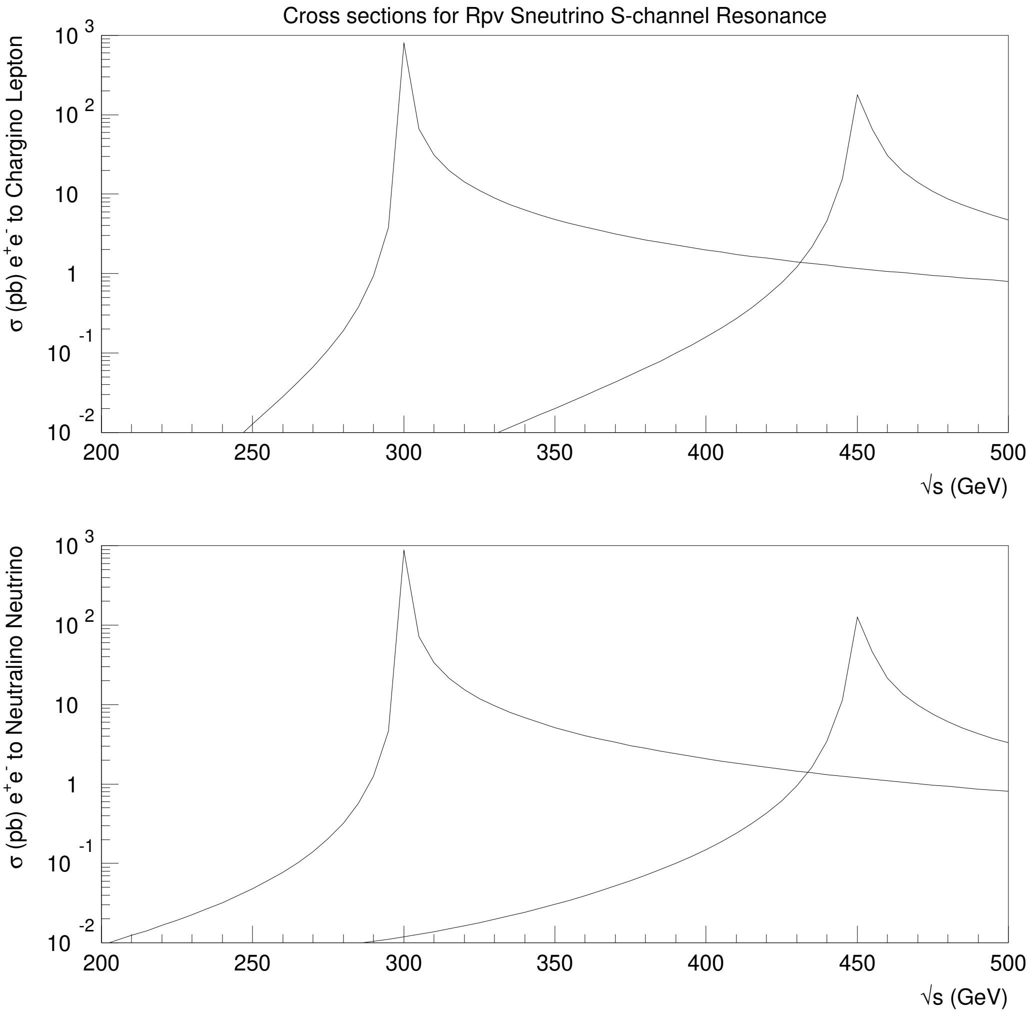

Figure 3: *Cross sections for single chargino and neutralino productions, including effects from initial state radiation (ISR), for two different sneutrino masses. The parameters we choose for this plot are the following:* $m_{\tilde{\nu}} = 300$ *and 450* GeV *respectively;* $m_{\tilde{e}} = 1000$ GeV*;* $\tan\beta = 2, \lambda = 0.1, \mu = -200$ GeV$, M_2 = 250$ GeV. *In this case, all charginos and neutralinos are produced.*

M_2	μ	Γ_1	Γ_2	Γ_3	Γ_4	Γ'_1	Γ'_2
200.	-1000.	0.53	1.49	–	–	2.93	–
200.	-600.	0.51	1.48	–	–	2.92	–
200.	-200.	0.44	0.51	0.08	0.89	2.11	0.81
200.	200.	1.09	0.28	0.01	0.58	2.09	0.88
200.	600.	0.72	1.38	–	–	3.06	–
200.	1000.	0.66	1.45	–	–	3.04	–
300.	-1000.	0.49	0.85	–	–	1.68	–
300.	-600.	0.48	0.84	–	–	1.68	–
300.	-200.	0.46	0.01	0.06	0.75	0.41	1.30
300.	200.	0.82	0.01	0.01	0.50	0.92	0.87
300.	600.	0.62	0.85	–	–	1.88	–
300.	1000.	0.57	0.87	–	–	1.82	–
400.	-1000.	0.43	0.26	–	–	0.52	–
400.	-600.	0.42	0.26	–	–	0.52	–
400.	-200.	0.24	0.04	0.15	0.22	0.18	0.40
400.	200.	0.53	0.01	0.05	0.15	0.42	0.27
400.	600.	0.51	0.33	–	–	0.74	–
400.	1000.	0.48	0.30	–	–	0.63	–
500.	-1000.	0.34	–	–	–	–	–
500.	-600.	0.34	–	–	–	–	–
500.	-200.	0.05	0.03	0.27	–	0.10	–
500.	200.	0.31	–	0.14	–	0.23	–
500.	600.	0.41	0.03	–	–	0.08	–
500.	1000.	0.38	–	–	–	0.01	–

Table 2: *Partial sneutrino decay widths to chargino-charged lepton and neutralino-neutrino, for each chargino and neutralino separately. All units in the table are in* GeV. *We chose* $tan\beta = 2$, $\lambda = 0.1$ *and* $m_{\tilde{\nu}} = 500$ GeV. Γ_i *are the decay rates for the four neutralinos, while* Γ'_i *the decay rates for the two charginos. For this choice of parameters, the R-violating decay rate is 0.1* GeV.

In Fig. 3, we show the cross sections for single chargino and neutralino productions, including effects from initial state radiation (ISR), for two different sneutrino masses. To illustrate the effects from the production of many charginos and neutralinos we chose a point of the parameter space where several of these states are produced. Indeed, for the choice of parameters that appears in the figure, the chargino masses are 201.9 and 273.1 GeV, while the neutralino masses are 127.8, 192.9, 217.5 and 272.1 respectively.

As expected, the effect of initial state radiation is to lower the peak of the cross section, but widen the resonance. For instance, in our example we find that, for $\sqrt{s} = 500$ GeV (where all charginos and neutralinos may be produced) and

violating operator: the strongest the operator the larger the decay rate for a direct decay of the chargino. (ii) the relative mass of chargino-neutralino: if the mass gap between the two states is very small, then the cascade decay is suppressed by phase space.

$m_{\tilde{\nu}} = 450$ GeV, ISR enhances the cross section by almost an order of magnitude. Actually, in this example, the heavier charginos and neutralinos may arise with large cross sections. Indeed, the partial cross sections that we find for the four neutralinos (from the lighter to the heavier), for $\sqrt{s} = 500$ and $m_{\tilde{\nu}} = 450$ GeV, are: 1.03 pb, 0.22 pb, 0.15 pb, 1.9 pb while for the charginos 1.8pb and 2.9 pb respectively.

From the above discussion, we conclude that single chargino and neutralino productions arise with significant cross sections and provide an interesting possibility for looking for R-violating supersymmetry at the Linear Collider.

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