Supersymmetry with $R$-Parity Breaking: Contact Interactions and Resonance Formation in Leptonic Processes at LEP2

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ABSTRACT

In supersymmetric theories with $R$-parity breaking, trilinear couplings of two leptons to scalar sleptons are possible. In electron–positron collisions such interactions would manifest themselves through contact terms in Bhabha scattering, $e^+e^- \rightarrow e^+e^-$, and in annihilation to lepton pairs, $e^+e^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$. Interpreting the high $x$, high $Q^2$ DIS HERA events as charm squark production with squark masses of order 200 GeV, the formation of tau-sneutrinos, $e^+e^- \rightarrow \tilde{\nu}_\tau$, with a mass in the range close to the LEP2 energy or even in reach, is an exciting speculation which can be investigated in the coming LEP2 runs with energies close to $\sqrt{s} = 200$ GeV.

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1 Introduction

The recent observation of surplus events in deep-inelastic positron–proton scattering at HERA at high $x$ and high $Q^2$ above a priori expectations [1] has given rise to many speculations. If the surplus is not a statistical fluctuation, an attractive interpretation is offered by supersymmetry with $R$-parity breaking [2]. Since in particular the H1 events cluster at a mass value of 200 GeV, resonance squark production $e^+ d \rightarrow \tilde{c}, \tilde{t}$ could explain the HERA events without spoiling the tremendous success of the high-precision analyses based on the Standard Model.

In addition to the lepton-quark-quark superfield term, the $R$-breaking part of the superpotential may involve also the interaction of three lepton superfields [4, 5]:

$$W_R = \lambda_{ijk} L_L^i L_L^j \bar{L}^k_R + \lambda'_{ijk} L_L^i Q_L^j \bar{D}_R^k$$

Both couplings $\lambda$ and $\lambda'$ violate lepton number ($L$). Their coexistence is not excluded by the non-observation of proton decay. The indices $ijk$ denote the generations; $\lambda_{ijk}$ are non-vanishing only for $i < j$ so that at least two different generations are coupled in the purely leptonic vertices. The standard notation is used in Eq. (1) for the left-handed doublets of leptons ($L$) and quarks ($Q$), and the right-handed singlets of charged leptons ($E$) and down-type quarks ($D$). In four-component Dirac notation, the lepton part of the Yukawa interactions has the following form:

$$L_R' = \lambda_{ijk} \left[ \bar{\nu}_L^i \tilde{e}_R^k \nu_L^j \bar{e}_L^i + (\tilde{e}_R^k)^* (\bar{\nu}_L^j)^* \nu_L^i \bar{e}_L^i - \bar{\nu}_L^i \tilde{e}_R^k \nu_L^j - (\tilde{e}_R^k)^* (\bar{\nu}_L^j)^* \nu_L^i \bar{e}_L^i \right] + h.c.$$ 

(2)

$u^i$ and $d^i$ denote the $u$- and $d$-type quarks, $e^i$ and $\nu^i$ the charged and neutral leptons, respectively; $\bar{l}$ denotes the spinor of the antiparticle, the superscript $(\cdot)^c$ the charge conjugate spinor and $(\cdot)^*$ the complex conjugate scalar.

The interpretation of the HERA events by $R$-parity breaking SUSY interactions involves at least one of the couplings $\lambda'$, in the most attractive scenarios $\lambda'_{121}$ or $\lambda'_{131}$, giving rise to charm or top squark production with masses $\sim 200$ GeV, respectively. This invites to the speculation that some of the couplings $\lambda$ may also be non-zero in the purely leptonic sector and that other supersymmetric particles, sleptons, may exist in a similar mass range. A similar idea has been envisaged [6] in the charged slepton sector to account for the Aleph 4-jet events [7]. In the present paper we investigate sneutrino effects in leptonic $e^+e^-$ processes at the high energies realized at LEP2. They include Bhabha scattering and $\ell^+\ell^-$ pair production:

$$e^+e^- \rightarrow e^+e^-$$

(3)

$$e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$$

(4)

1Neutrinoless double $\beta$ decay [3] restricts the $e^+\bar{d}\tilde{u}$ coupling so strongly that this interaction cannot account for the $(e\bar{j})$ final states at HERA.

2Other novel interactions which may be $l-q$ symmetric [8], could give rise to effects in the lepton sector which are similar to the effects in supersymmetric theories with $R$-parity breaking.
Neutrino pair-production, involving the exchange of charged sleptons, can be analysed in the same way after obvious substitutions, though experimental analyses are much more difficult. Both processes (3) and (4) can be affected by the exchange of sneutrinos in the s- and/or t-channel. For sneutrinos with masses in the order of 200 GeV, the effects can be quite significant, depending on the size of the couplings. Even though there are strong upper bounds on several of the $\lambda$ couplings, some of these couplings are rather unconstrained, in particular the coupling that violates only the $\tau$-flavor, so the effects induced by $\tau$ sneutrinos can be large. While contact interactions relevant for much heavier sneutrinos have been discussed earlier in the literature [9, 10, 11], we improve on these analyses by including the impact of nearby resonances; they require the proper account of sneutrino propagator and non-zero width effects. Most exciting of course would be the direct formation of sneutrinos [10, 11, 12]

$$e^+e^- \rightarrow \tilde{\nu}_\tau$$

for sneutrino masses in the LEP2 range. The sneutrinos would manifest themselves as a sharp resonance peak.

### 2 Slepton Exchange in $e^+e^-$ Collisions

At energies much lower than the sparticle masses, $R$-parity breaking interactions introduce effective $llll$ and $llqq$ contact interactions. These operators will in general mediate $L$ violating processes and FCNC processes so that existing data put stringent constraints on the couplings. However, if only some of the operators with a particular generation structure are present in Eq. (1), then the effective four-fermion Lagrangian does not violate lepton number. Similarly, the couplings can be arranged such that there are no other sources of FCNC interactions than CKM mixing in the quark sector. In the purely leptonic sector, we can restrict ourselves to the following two possibilities:

(a) one single Yukawa coupling is much larger than all the others, so that the latter can be neglected;

(b) two Yukawa couplings are much larger than all the others, where both couplings violate one and the same lepton flavor, or both couplings violate all three lepton flavors.

In these cases low-energy experiments are not restrictive and typically allow for couplings $\lambda \lesssim 0.1 \times (\tilde{m}/200 \text{ GeV})$, where $\tilde{m}$ is the mass scale of the sparticles participating in the process. The corresponding limits, derived by assuming only one non-vanishing coupling at a time, are summarized in Table 1. The most stringent limits for $\lambda$ can be derived from CC universality, lepton universality and the induced $\nu_e$ Majorana mass [4 10]. Additional constraints on products of $\lambda$ and $\lambda'$ couplings come from rare $K$ and $B$ leptonic decay

\[3\text{There is only one additional possibility for which the effective four-lepton Lagrangian does not violate lepton flavor and that involves three Yukawa couplings, each violating all three lepton flavors. However, this case is less interesting experimentally as shown later.}\]
In Table 1 we include those limits which are relevant for the present study. Examining all possible combinations of $\lambda$ and $\lambda'$ couplings compatible with these bounds, it turns out that if the HERA data are interpreted as top squark production (i.e. $\lambda'_{131} \gtrsim 0.05$), then the $\lambda$-couplings relevant for leptonic processes are very strongly constrained, $\lambda_{121} < 0.0036$, $\lambda_{131} < 0.04$, and $\lambda_{123} < 0.048$. As a result, the effects on purely leptonic processes at LEP2 due to slepton exchanges would be small. However, if the HERA events are due to charm squark production (i.e. $\lambda'_{121} \gtrsim 0.05$), the rare $B$ and $K$ decays do not impose strong constraints on $\lambda_{131}$ or $\lambda_{123}$ and we may expect large effects due to $\tau$-sneutrino exchanges at LEP2.

| $\lambda$ | 121 | 122 | 123 | 131 | 132 | 133 | 231 | 232 | 233 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Limit     | 0.08$^a$ | 0.08$^a$ | 0.08$^a$ | 0.20$^b$ | 0.20$^b$ | 0.006$^c$ | 0.18$^d$ | 0.18$^d$ | 0.18$^d$ |

| Decay mode | Combinations constrained | Limit |
|------------|--------------------------|-------|
| $K \rightarrow e^\pm \mu^\mp$ | $\lambda_{121}\lambda'_{121}$ | $10^{-7}$ |
| $B_d \rightarrow e^\pm \mu^\mp$ | $\lambda_{121}\lambda'_{131}$ | $1.8 \times 10^{-4}$ |
| $B_d \rightarrow e^\pm \tau^\mp$ | $\lambda_{131}\lambda'_{131}$ | $2.0 \times 10^{-3}$ |
| $B_d \rightarrow \mu^\pm \tau^\mp$ | $\lambda_{123}\lambda'_{131}$ | $2.4 \times 10^{-3}$ |

Table 1: Upper part: The 1σ limits on the R-parity breaking couplings $\lambda$ [in units of $\tilde{m}/200$ GeV, where $\tilde{m}$ is the appropriate sfermion mass], from (a) charged-current universality; (b) $\Gamma(\tau \rightarrow e\nu\bar{\nu})/\Gamma(\tau \rightarrow \mu\nu\bar{\nu})$; (c) the induced $\nu_e$ Majorana mass; (d) $\Gamma(\tau \rightarrow e\nu\bar{\nu})/\Gamma(\mu \rightarrow e\nu\bar{\nu})$; (a), (b) and (d) from Ref. [10], (c) from Ref. [9]. Lower part: Limits on the products of $\lambda$ and $\lambda'$ which are relevant for our discussion [in units of ($\tilde{m}/200$ GeV)$^2$]; $K$ decay limits from Ref. [13], $B$ decay limits from Ref. [14].

Figure 1: Diagrams for Bhabha scattering $e^+e^- \rightarrow e^+e^-$ including $s$- and $t$-channel exchange of $\tilde{\nu}_\tau$ ($\lambda_{131} \neq 0$).

We will first consider the case (a) taking specifically $\lambda_{131} \neq 0$. The cross section for Bhabha scattering is then built up by the $s$- and $t$-channel exchange of $\gamma, Z$ bosons and of
\( \frac{d\sigma}{d\cos\theta}(e^+e^- \rightarrow e^+e^-) = \)
\[
\frac{\pi\alpha^2 s}{8} \left\{ (1 + \cos \theta)^2 \left[ |f_{LR}^s|^2 + |f_{RL}^s|^2 + |f_{LR}^t|^2 + |f_{RL}^t|^2 - 2\text{Re}(f_{LR}^s f_{LR}^t) - 2\text{Re}(f_{RL}^s f_{RL}^t) \right] \\
+ (1 - \cos \theta)^2 \left[ |f_{LL}^s|^2 + |f_{RR}^s|^2 \right] + 4 \left[ |f_{LL}^t|^2 + |f_{RR}^t|^2 \right] \right\}
\]

While the \( s \)- and \( t \)-channel \( \gamma, Z \) amplitudes in the Standard Model involve the coupling of vector currents, the sneutrino exchange is described by scalar currents. By performing appropriate Fierz transformations, the \( s \)-channel \( \tilde{\nu} \) exchange amplitudes can be rewritten, however, as \( t \)-channel vector amplitudes, and \( t \)-channel \( \tilde{\nu} \) exchange amplitudes as \( s \)-channel vector amplitudes:

\[
(\bar{e}_R e_L)(\bar{e}_L' e_R') \rightarrow -\frac{1}{2}(\bar{e}_R \gamma_\mu e_R') (\bar{e}_L' \gamma_\mu e_L)
\]

The independent \( s \)-channel amplitudes \( f_{h,t}^s \) are therefore given by

\[
f_{LR}^s = \frac{1}{s} + \frac{g_L^2}{s - m_Z^2 + i\Gamma_Z m_Z} \quad (8)
\]

\[
f_{RL}^s = \frac{1}{s} + \frac{g_R^2}{s - m_Z^2 + i\Gamma_Z m_Z} \quad (9)
\]

\[
f_{LL}^s = \frac{1}{s} + \frac{g_L g_R}{s - m_Z^2 + i\Gamma_Z m_Z} + \frac{1}{2} \frac{(\lambda_{1j1}/\epsilon)^2}{t - m_j^2} \quad (10)
\]

\[
f_{RR}^s = \frac{1}{s} + \frac{g_L g_R}{s - m_Z^2 + i\Gamma_Z m_Z} + \frac{1}{2} \frac{(\lambda_{1j1}/\epsilon)^2}{t - m_j^2} \quad (11)
\]

In the same way, the \( t \)-channel exchange amplitudes \( f_{h,t}^t \) can be written as

\[
f_{LR}^t = \frac{1}{t} + \frac{g_L^2}{t - m_Z^2} \quad (12)
\]
\( e^+ e^- \rightarrow e^+ e^- \)

\[
\sigma_{\text{tot}}(SM \oplus \tilde{\nu}_\tau)/\sigma_{\text{tot}}(SM) - 1
\]

\( 45^\circ \leq \theta \leq 135^\circ \)

45\(^\circ\) \leq \theta \leq 135\(^\circ\)

\( \sqrt{s} = 192 \text{ GeV} \) (full lines) and \( \sqrt{s} = 184 \text{ GeV} \) (dashed lines).

Figure 3: Effect of sneutrino \( \tilde{\nu}_\tau \) exchange on the cross section for Bhabha scattering for \( 45^\circ \leq \theta \leq 135^\circ \) at \( \sqrt{s} = 192 \text{ GeV} \) (full lines) and \( \sqrt{s} = 184 \text{ GeV} \) (dashed lines).
\[ f_{RL}^t = \frac{1}{t} + \frac{g_R^2}{t - m_Z^2} \]  \hspace{1cm} (13)

\[ f_{LL}^t = \frac{1}{t} + \frac{g_L g_R}{t - m_Z^2} + \frac{1}{2} \frac{(\lambda_{ij} / e)^2}{s - m_j^2 + i \Gamma_j m_j} \]  \hspace{1cm} (14)

\[ f_{RR}^t = \frac{1}{t} + \frac{g_L g_R}{t - m_Z^2} + \frac{1}{2} \frac{(\lambda_{ij} / e)^2}{s - m_j^2 + i \Gamma_j m_j} \]  \hspace{1cm} (15)

The parameters \( m_j \) and \( \Gamma_j \) are the mass and width of the sneutrino \( \tilde{\nu}_j = \tilde{\nu}_\tau \). To simplify notations we have defined the indices \( L, R \) to denote the helicities of the ingoing electron (first index) and the outgoing positron (second index). The helicities of the ingoing positron and the outgoing electron are fixed by the \( \gamma_5 \) invariance of the vector interactions: they are opposite to the helicities of the lepton partner in \( s \)-channel amplitudes and the same in \( t \)-channel amplitudes.\(^4\) The left/right \( Z \) charges of the leptons are defined as

\[ g_L = \left( \frac{\sqrt{2} G_\mu m_Z^2}{\pi \alpha} \right)^{1/2} \left[ I_3^j - s_W Q' \right] \]

\[ g_R = \left( \frac{\sqrt{2} G_\mu m_Z^2}{\pi \alpha} \right)^{1/2} \left[ - s_W Q' \right] \]

In Fig. 3 the impact of the sneutrino \( \tilde{\nu}_\tau \) exchange on the Bhabha scattering process at LEP2 energies is shown as a function of the sneutrino mass, assuming couplings \( \lambda_{131} = 0.1 \) or \( \lambda_{131} = 0.01 \). Due to the \( s \)-channel exchange, the effect can be very large if the sneutrino mass is close to the LEP2 center-of-mass energy.

The analysis of \( \tau^+\tau^- \) production in \( e^+e^- \) annihilation proceeds in an analogous way. An important difference is the absence of the \( t \)-channel Standard Model amplitude and the \( s \)-channel sneutrino exchange amplitude if only the Yukawa coupling \( \lambda_{131} \) is assumed to be non-zero (i.e. \( \lambda_{ijj} = \lambda_{131} \) in Eqs. (10, 11) and \( f^t = 0 \) in Eqs. (12, 13)). In this case the \( \tau^+\tau^- \) production process is mediated by the \( s \)-channel \( \gamma, Z \) exchange and the exchange of the (anti-)sneutrino \( \tilde{\nu}_e \) in the \( t \)-channel (see Fig. 2). Because the \( s \)-channel sneutrino exchange diagram is absent, the impact on the total cross section is small even for \( \lambda_{131} \) as large as 0.1 as can be seen in Fig. 4. In the scenario considered, that is for \( \lambda_{131} \neq 0 \) and all other Yukawa couplings vanishing, the process \( e^+e^- \rightarrow \mu^+\mu^- \) is not affected and the cross section is given by the Standard Model.

Given the bounds of Table 4, electron sneutrino exchange involving \( \lambda_{121} \) cannot contribute to \( \mu \) pair production in this specific \( \lambda \) scenario.\(^5\)

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\(^4\) The \((LR)\) and \((RL)\) terms of the first line of Eq. (1) correspond to equal electron helicities in the initial and final state so that forward scattering is permitted; this is obvious for the \( s \)-channel amplitudes, but applies also to the \( t \)-channel amplitudes after an appropriate Fierz transformation. The first two terms of the second line correspond to opposite electron helicities so that forward scattering is forbidden. Finally, the last two terms correspond to isotropic spin-zero scattering which becomes apparent after applying a Fierz transformation from the \( t \) - to the \( s \)-channel.

\(^5\) Note that in Eqs. (8, 13) the outgoing positron with the helicity \( L(R) \) couples with the charge \( g_R(g_L) \).
Finally, in the realization of case (a) with $\lambda_{123} \neq 0$ all lepton flavors are violated. Bhabha scattering is then not affected at all. However, $\mu^+\mu^-$ and $\tau^+\tau^-$ pair production in $e^+e^-$ scattering would receive contributions from $t$-channel $\tilde{\nu}_\tau$ and $\tilde{\nu}_\mu$ sneutrino exchanges, respectively (*i.e. $\lambda_{ij1} \Rightarrow \lambda_{123}$ in Eqs. (10, 11) and $f^t = 0$ in Eqs. (12-15)).

Case (b) with two large Yukawa couplings is interesting if both couplings violate the same lepton flavor: $\lambda_{131}$ and $\lambda_{232} \neq 0$, for example. If this scenario is realized, then the process $e^+e^- \rightarrow \mu^+\mu^-$ receives an additional contribution from $s$-channel $\tilde{\nu}_\tau$ sneutrino exchange. Therefore, $\mu^+\mu^-$ production would be affected in a similar way as Bhabha scattering, which is apparent from Fig. 4.

Stringent bounds on contact interactions in the lepton sector have been reported by the LEP experiments [16, 17]. Defining the contact interactions by the Lagrangian

$$\mathcal{L}_{C_i}^{ij} = \pm \frac{4\pi}{\Lambda_{ij}} (\bar{e}_i \gamma_\mu e_i) (\bar{f}_j \gamma_\mu f_j)$$ (16)

with $i, j = L, R$, the lower bounds for the $LR$ and $RL$ scales and the positive sign are close to 2.7 TeV, while for the negative sign they are close to 3.2 TeV ($LL$ and $RR$ bounds are even stronger). Even though these values cannot be transferred immediately to the more complex analysis presented here, we nevertheless expect typical values of $m_\tilde{\nu}/\lambda \sim \Lambda/\sqrt{8\pi} \simeq 0.5$ to 0.7 TeV as an order of magnitude estimate in the present scenario. Choosing $m_\tilde{\nu} \simeq 200$ GeV, the Yukawa couplings could still be of the order 0.4. This analysis is based on an integrated luminosity of $\int \mathcal{L} \sim 10$ pb$^{-1}$ at $\sqrt{s} = 161$ GeV. Since the limits on $\Lambda$ scale with $(\int \mathcal{L})^{1/4}$ [18], improvements by a factor $\sim 2.5$ can be expected for a total integrated luminosity of $\int \mathcal{L} = 400$ pb$^{-1}$, which can be anticipated for the 4 combined LEP experiments in the runs of this year. The sensitivity on the scale of the contact interactions in the lepton sector will then rise to a value close to $\Lambda \sim 7$ to 8 TeV corresponding to $\lambda \simeq 0.13$ to 0.15 $\times$ ($m_\tilde{\nu}$/200 GeV).

3 Resonance Formation

The most exciting prediction of $R$-breaking supersymmetry in the lepton sector, however, is the formation of sneutrino resonances [14, 15, 16] with masses either close to the LEP2 energy or even in reach of the machine. The production of $\tilde{\nu}_\tau$ sneutrinos would be compatible with all low-energy constraints known so far, $e^+e^- \rightarrow \tilde{\nu}_\tau$. If the HERA high $x$, high $Q^2$ data indeed indicate the production of a 2nd generation squark $\tilde{c}$, sneutrinos may also exist in the mass range around 200 GeV. Naïvely one would expect non-colored states to be lighter than the associated colored states. Even if the stop $\tilde{t}_1$ mass is reduced through strong left-right mixing by the large Yukawa interactions in the $t, \tilde{t}$ sector, in a large part of the supersymmetric parameter space the sneutrino masses can be as light as 200 GeV in grand unified models incorporating universal soft SUSY breaking parameters (see Ref. [19] for example).
$e^+e^- \rightarrow \mu^+\mu^-$ and $\tau^+\tau^-$

$\sqrt{s} = 192$ GeV

$\Delta A = A_{FB}(SM \oplus \tilde{\nu}_j) - A_{FB}(SM)$

$\Delta = \sigma_{\text{tot}}(SM \oplus \tilde{\nu}_j)/\sigma_{\text{tot}}(SM) - 1$

Figure 4: Effect of sneutrino exchange on $e^+e^- \rightarrow \ell^+\ell^-$ in two different scenarios: the curves labeled by $\lambda_{131} = 0.1$ correspond to a scenario with the additional $t$-channel exchange of $\tilde{\nu}_e$; the curves labeled by $\lambda_{131} = \lambda_{232} = 0.1$, with additional $s$-channel exchange of $\tilde{\nu}_\tau$. Full lines: $\Delta = \sigma(SM \oplus \tilde{\nu}_j)/\sigma(SM) - 1$, dashed lines $\Delta A = A_{FB}(SM \oplus \tilde{\nu}_j) - A_{FB}(SM)$ for $\sqrt{s} = 192$ GeV.
Figure 5: Cross section for Bhabha scattering including $\tilde{\nu}_\tau, \bar{\tilde{\nu}}_\tau$ sneutrino resonance formation for $45^\circ \leq \theta \leq 135^\circ$ as a function of the $e^+e^-$ center-of-mass energy. Parameters: $m_{\tilde{\nu}} = 200$ GeV, $\Gamma_{\tilde{\nu}} = 1$ GeV, and $\lambda_{131} = 0.1$. 
The cross section for the production of sneutrinos which decay to a specified final state $F$, is given by the Breit-Wigner formula

$$
\sigma(e^+e^- \to \tilde{\nu} \to F) = \frac{4\pi s}{m_{\tilde{\nu}}^2} \frac{\Gamma(\tilde{\nu} \to e^+e^-)\Gamma(\tilde{\nu} \to F)}{(s - m_{\tilde{\nu}}^2)^2 + m_{\tilde{\nu}}^2\Gamma_{\tilde{\nu}}^2} \quad (17)
$$

The partial decay width $\Gamma(\tilde{\nu} \to e^+e^-) = \frac{\lambda^2_{1j1}m_{\tilde{\nu}}}{16\pi}$ is very small. However sneutrinos can also decay via $R$-parity conserving gauge couplings to $\nu\chi^0$ and $l^\pm\chi^\mp$ pairs with subsequent $\chi^0$ and $\chi^\pm$ decays and via $R$-parity violating $\lambda'$ couplings to $q\bar{q}$ pairs. The partial decay widths for these channels depend on the specific choice of the supersymmetry breaking parameters. In large regions of the supersymmetry parameter space, the total decay width of sneutrinos can be as large as 1 GeV, i.e. significantly larger than the energy spread at LEP2. In this case the interference with the background Standard Model process must be taken into account if $F = e^+e^-$ or $\tau^+\tau^-$. The cross sections including these interference effects have been presented in Eqs. (6) and (8) to (15). A representative example for the cross section of the process $e^+e^- \to e^+e^-$ including $\nu_\tau$ resonance formation is displayed in Fig. 5. Since the width is wider than the beam energy spread, the maximum of the cross section is given by the unitarity limit $\sigma_{\text{max}} = \frac{8\pi}{m_{\tilde{\nu}}^2}B^2_e$ for sneutrino and anti-sneutrino production added up. The cross section in the peak region is therefore very large. In addition to the $\ell^+\ell^-$ final states one should expect many other final states generated in $R$-parity conserving $\tilde{\nu}$ decays. Examples are 'Zen events'

$$
e^+e^- \to \tilde{\nu} \to \nu_{\chi_1^0} \quad \text{etc.} \quad (18)
$$

with $R$-parity breaking $\chi_1^0$ decays, or isolated lepton events

$$
e^+e^- \to \tilde{\nu} \to l\tilde{W} \left[ \to W_{\chi_1^0} \right] \quad \text{etc.} \quad (19)
$$

in cascade decays. In addition one can also expect $R$-parity violating decays to quark jets $\tilde{\nu} \to jj$ [21].

4 Summary

In this paper we have shown that if $R$-parity is broken by explicit lepton number violating operators in the leptonic sector, distinctive signals in $e^+e^- \to e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ processes are predicted. Motivated by a plausible explanation of the HERA events involving the $R$-parity breaking $LQD$ operator, we have analysed the impact of the $LLE$ operator on these leptonic processes. Interpreting the HERA data as charm squark production, the operator that violates $\tau$-flavor is the most interesting scenario for LEP2 physics. If sleptons do exist in the mass range of 200 GeV, the effect of the sneutrino exchanges at

\footnote{Assuming that the energy spread $\delta E$ scales with the square of the total energy, $\delta E \sim 204$ MeV is expected at $\sqrt{s} = 192$ GeV at LEP2 [20].}
LEP2 could be very large. If sneutrino masses were within the reach of LEP2, sneutrinos would manifest themselves through resonance formation in $e^+e^-$ collisions.

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