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Sleptons at LEP2 and Tevatron in R-Parity Violating SUSY[1]

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Abstract. In supersymmetric theories with R-parity breaking, sleptons could be produced singly in e^+e^- collisions at LEP2 and in $q\bar{q}$ annihilation at the Tevatron through interactions in which two quark or two lepton fields are coupled to a slepton field. At LEP they could manifest themselves in Bhabha scattering, and in the annihilation to $\mu^+\mu^-$, $\tau^+\tau^-$, and $q\bar{q}$ pairs. The formation of sneutrinos, $e^+e^- \to \tilde{\nu}$, and their signals for a mass within the reach of this machine, is an exciting speculation which can be investigated in the coming LEP2 runs with energies close to $\sqrt{s} = 200$ GeV. At the Tevatron the sleptons can be searched for as resonances in $p\bar{p} \to \tilde{\nu} \to \ell^+\ell^-$ and $\tilde{\ell} \to \ell\nu$ final states. Existing LEP2 and Tevatron data can be exploited to derive bounds on the Yukawa couplings of sleptons to quark and lepton pairs.

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1. Introduction

In the usual formulation, the minimal supersymmetric extension (MSSM) of the Standard Model (SM) is defined by the superpotential which has the

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form

$$W_R = Y^e_{ij} L_i H_1 E^c_j + Y^d_{ij} Q_i H_1 D^c_j + Y^u_{ij} Q_i H_2 U^c_j + \mu H_1 H_2 \qquad (1)$$

The indices i, j denote the generations, and a summation is understood, Y^f_{ij} are Yukawa couplings and μ is the Higgs mixing mass parameter. The standard notation is used in eq. (1) for the left-handed doublets of leptons (L) and quarks (Q), the right-handed singlets of charged leptons (E) and down-type quarks (D), and for the Higgs doublets which couple to the down (H_1) and up quarks (H_2).

The interaction lagrangian derived from W_R contains terms in which the supersymmetric partners appear only in pairs. As a result, superpartners can be produced only in pairs in collisions and decays of particles, and the lightest supersymmetric particle (LSP) is stable. This feature is traced to a discrete multiplicative symmetry of the superpotential, R-parity, which can be defined as [1]

$$R_p = (-1)^{3B+L+2S} \qquad (2)$$

with S denoting the spin of the particle: all Higgs particles and SM fermions and bosons have $R_p = +1$, and their superpartners have $R_p = -1$.

However, the gauge and Lorentz symmetry also allows for additional terms in the superpotential which break the R-parity [2]

$$W_{\not R} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k + \epsilon_i L_i H_2 \qquad (3)$$

with additional Yukawa couplings λ, λ', λ'' and dimensionful mass parameters ϵ. If these terms are present, the model has distinct features: superpartners can be produced singly and the LSP is not stable. Because of anti-commutativity of the superfields, λ_{ijk} can be chosen to be non-vanishing only for $i < j$ and λ''_{ijk} for $j < k$. Therefore for three generations of fermions, $W_{\not R}$ contains additional 48 new parameters beyond those in eq. (1). Note that at least two different generations are coupled in the purely leptonic or purely hadronic operators.

The couplings λ, λ' and ϵ violate lepton number (L), whereas λ'' couplings violate baryon number (B), and thus can possibly lead to fast proton decay. In the usual formulation of the MSSM they are forbidden by R-parity. However, there is no theoretical motivation for imposing R-parity. From the grand unification and string theory points of view, both types of models, R_p conserving or violating, have been constructed with no preference for either of the two [3]. Since they lead to very different phenomenology, both models should be searched for experimentally. The usual formulation of MSSM with R_p-conservation has been extensively studied phenomenologically and experimentally. Only recently the R_p-violating formulation has received more attention as providing potentially favored

solutions to some experimental observations (if not fluctuations), like Aleph 4-jet events [4], and HERA high Q^2 events [5].

R_p conservation guarantees the stability of the proton by removing all λ, λ', λ'' and ϵ couplings. However other discrete symmetries can allow for a stable proton and R-parity violation at the same time. For example, baryon-parity (defined as -1 for quarks, and $+1$ for leptons and Higgs bosons) implies $\lambda'' = 0$. In this case only lepton number is broken, which suffices to ensure proton stability, and to explain experimental observations mentioned above. In addition, lepton-number violating operators can provide new ways to generate neutrino masses. Since in supersymmetry lepton and H_1 fields have the same quantum numbers, the last term in eq. (3) can be rotated away[4] by a redefinition of L_i and H_1. Therefore we will consider below only the most general trilinear terms in eq. (3) that violate L but conserve B.

In four-component Dirac notation, the λ and λ' part of the Yukawa interactions has the following form:

$$\begin{aligned}
\mathcal{L}_{\not R} &= \lambda_{ijk}\Big[\tilde{\nu}^j_L \bar{e}^k_R e^i_L + \overline{\tilde{e}}^k_R (\bar{e}^i_L)^c \nu^j_L + \tilde{e}^i_L \bar{e}^k_R \nu^j_L \\
&\qquad - \tilde{\nu}^i_L \bar{e}^k_R e^j_L - \overline{\tilde{e}}^k_R (\bar{e}^j_L)^c \nu^i_L - \tilde{e}^j_L \bar{e}^k_R \nu^i_L\Big] + h.c. \\
&+ \lambda'_{ijk}\Big[(\tilde{u}^j_L \bar{d}^k_R e^i_L + \overline{\tilde{d}}^k_R (\bar{e}^i_L)^c u^j_L + \tilde{e}^i_L \bar{d}^k_R u^j_L) \\
&\qquad - (\tilde{\nu}^i_L \bar{d}^k_R d^j_L + \tilde{d}^j_L \bar{d}^k_R \nu^i_L + \overline{\tilde{d}}^k_R (\bar{\nu}^i_L)^c d^j_L)\Big] + h.c. \qquad (4)
\end{aligned}$$

where u_i and d_i stand for u- and d-type quarks, e_i and ν_i denote the charged leptons and neutrinos of the i-th generation, respectively; the scalar partners are denoted by a tilde. In the λ' terms, the up (s)quarks in the first parentheses and/or down (s)quarks in the second may be Cabibbo rotated in the mass-eigenstate basis. As we will discuss mainly sneutrino induced processes, we will assume the basis in which only the up sector is mixed, *i.e.* the NDD^c is diagonal. We will comment on choosing a different basis, where relevant for our discussion.

This scenario can be explored in various processes. Actually, the possibility of some λ and λ' couplings to be simultaneously non-zero opens a plethora of interesting processes at current and future colliders. Since from low-energy experiments the Yukawa couplings are expected to be small, indirect effects due to t/u-channel exchanges of sfermions in collisions of leptons and hadrons can be difficult to observe. However, the direct formation of sfermion resonances in the s-channel processes can produce measurable effects. For example, squarks could be produced as s-channel resonances in lepton-hadron collisions at HERA. In fact, recent high Q^2, high x events

[4] For the discussion of $\epsilon_i L_i H_2$ term, see talk by J. Valle [6].

at HERA have been analyzed in this context; higher statistics however is needed to draw definite conclusions. Sleptons on the other hand could be produced as s-channel resonances in lepton-lepton and hadron-hadron collisions, and could decay to leptonic or hadronic final states in addition to R-parity conserving modes.

In this talk we will consider the possible effects of s-channel slepton resonance production in e^+e^- collisions

$$e^+e^- \to \tilde{\nu} \to \ell^+\ell^- \tag{5}$$
$$e^+e^- \to \tilde{\nu} \to q\bar{q} \tag{6}$$

and in $p\bar{p}$ collisions

$$p\bar{p} \to \tilde{\nu} \to \ell^+\ell^- \tag{7}$$
$$p\bar{p} \to \tilde{\ell}^+ \to \ell^+\nu \tag{8}$$

We will not consider hadronic final states of sleptons produced in $p\bar{p}$ collisions as they can be difficult to analyze experimentally in the hadronic environment. The results presented here have been obtained in collaboration with H. Spiesberger, R. Rückl and P. Zerwas [7, 8].

Note that since in SUSY GUT scenarios sleptons are generally expected to be lighter than squarks, sleptons may show up at LEP2 and/or Tevatron even if squarks are beyond the kinematical reach of HERA.

2. Sfermion Exchanges in $f\bar{f}' \to F\bar{F}'$ Processes

Before discussing specific reactions let us consider a generic two-body process $f\bar{f}' \to F\bar{F}'$. In the Standard Model it can proceed via s- and/or t-channel gauge boson exchange (γ, Z, or W; for light fermions the Higgs boson exchange is negligible), as shown in Fig. 1. Sfermions can contribute via s-, t-, and/or u-channel exchange processes, Fig. 1. The differential cross section in the $f\bar{f}'$ rest frame can be written most transparently in terms of helicity amplitudes

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}(f\bar{f}' \to F\bar{F}') = A_c\frac{\pi\alpha^2 s}{8}\Big\{&4\left[|f^t_{LL}|^2 + |f^t_{RR}|^2\right] \\ &+ (1-\cos\theta)^2\left[|f^s_{LL}|^2 + |f^s_{RR}|^2\right] \\ &+ (1+\cos\theta)^2\left[|f^s_{LR}|^2 + |f^s_{RL}|^2 + |f^t_{LR}|^2 + |f^t_{RL}|^2\right. \\ &\qquad \left. + 2\mathrm{Re}(f^{s\,*}_{LR} f^t_{LR} + f^{s\,*}_{RL} f^t_{RL})\right]\Big\}\end{aligned} \tag{9}$$

where A_c is the appropriate color factor. While the s- and t-channel γ, Z, W amplitudes in the Standard Model involve the coupling of vector currents,

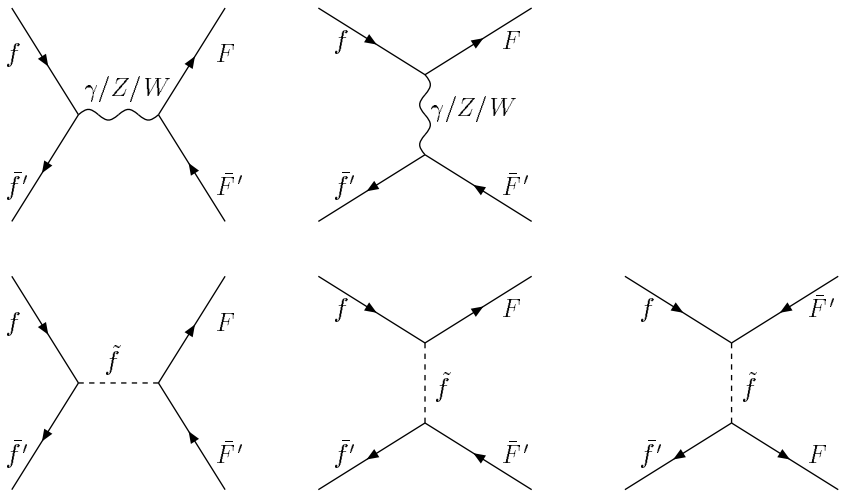

Figure 1. Generic Feynman diagrams for $f\bar{f}' \to F\bar{F}'$ scattering including s- and t-channel exchange of $\gamma/Z/W$, and s-, t- and u-channel exchange of sfermion $\tilde{f}$.

the sfermion exchange is described by scalar couplings. By performing appropriate Fierz transformations, the s-channel $\tilde{f}$ exchange amplitudes can be rewritten, however, as t-channel vector amplitudes, and t/u-channel $\tilde{f}$ exchange amplitudes as s-channel vector amplitudes; for the operators:

$$(\bar{f}_R f'_L)(\bar{F}_L F'_R) \to -\frac{1}{2}(\bar{f}_R \gamma_\mu F'_R)(\bar{F}_L \gamma_\mu f'_L) \tag{10}$$

The independent s-channel amplitudes f^s_{ij} $(i,j = L,R)$ can then be written as follows

$$f^s_{ij} \;=\; \frac{Q^s_{ij}}{s} + \frac{1}{2}\,\frac{G^t_{ij}/e^2}{t - m^2_{\tilde{f}}} - \frac{1}{2}\,\frac{G^u_{ij}/e^2}{u - m^2_{\tilde{f}}} \tag{11}$$

where $s = (p_f + p_{\bar{f}'})^2$, $\sqrt{s}$ is the center-of-mass energy of the $f\bar{f}'$ system, $t = (p_f - p_F)^2 = -s(1-\cos\theta)/2$, and $u = (p_f - p_{\bar{F}'})^2 = -s(1+\cos\theta)/2$. Note the relative sign between t- and u-channel sfermion contributions due to different ordering of fermion operators in the Wick reduction [9]. Similarly, the t-channel exchange amplitudes f^t_{ij} read

$$f^t_{ij} \;=\; \frac{Q^t_{LR}}{t} + \frac{1}{2}\frac{G^s_{ij}/e^2}{s - m^2_{\tilde{f}} + i\Gamma_{\tilde{f}} m_{\tilde{f}}} \tag{12}$$

The parameters $m_{\tilde{f}}$ and $\Gamma_{\tilde{f}}$ are the mass and width of the exchanged sfermion $\tilde{f}$ ($\tilde{f}$ is a generic notation of the exchanged sfermion, not necessarily the superpartner of f). To simplify notations we have defined the indices L, R to denote the helicities of the *incoming fermion* f (first index) and the *outgoing antifermion* F' (second index). The helicities of the incoming antifermion and the outgoing fermion are fixed by the γ_5 invariance of the vector interactions: they are opposite to the helicities of the fermionic partner in s-channel amplitudes and the same in t-channel amplitudes. The generalized SM charges $Q_{ij}^{s,t}$ for gauge boson exchanges and the factors $G_{ij}^{s,t,u}$ in terms of Yukawa couplings of the exchanged sfermions will be given when specific reactions are discussed. Note that the sign of the SM charges determines the interference pattern of gauge boson with sfermion exchange terms.

3. Yukawa Couplings

The masses and Yukawa couplings of sfermions are not predicted by theory. At energies much lower than the sparticle masses, R-parity breaking interactions can be formulated in terms of effective $llll$ and $llqq$ contact interactions. These operators will in general mediate L violating processes and FCNC processes. Since the existing data are consistent with the SM, stringent constraints on the Yukawa couplings and masses can be derived [10]. However, if only some of the terms with a particular generation structure are present in eq. (4), then the effective four-fermion Lagrangian is not strongly constrained. Similarly, the couplings can be arranged such that there are no other sources of FCNC interactions than CKM mixing in the quark sector. Below we will consider the following two scenarios:

(i) one single Yukawa coupling is large, all the other couplings are small and thus neglected;

(ii) two Yukawa couplings which violate *one and the same* lepton flavor are large, all the others are neglected.

Since theoretically the third-generation sfermions are expected lighter than the first two and, due to large top quark mass, the violation of the third-generation lepton-flavor might be expected maximal, we will concentrate on possible effects generated by $\tilde{\tau}$ and $\tilde{\nu}_\tau$, *i.e.* we are concerned with λ_{i3i} and λ'_{3jk} couplings. In these cases low-energy experiments are not restrictive and typically allow for couplings $\lambda \lesssim 0.1 \times (\tilde{m}/200\ \mathrm{GeV})$, where $\tilde{m}$ is the mass scale of the sparticles participating in the process. The corresponding limits relevant for λ_{i3i} and λ'_{3jk}, derived by assuming only one non-vanishing coupling at a time, are summarized in Table 1. The limit (d) for $\lambda'_{3jk} < 0.34$ is derived assuming the CKM mixing due to absolute mixing in the up-quark sector only (NDD^c diagonal); if the CKM mixing

Table 1. Low-energy limits for the couplings λ_{i3i} $(i = 1, 2)$ and λ'_{3jk} $(j = 1, 2, k = 1, 2, 3)$ assuming the relevant sfermion masses $\tilde{m} = 200$ GeV. They are derived from (a) $\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$ [7]; (b) $\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$ [11]; (c) $K \to \pi\nu\nu$ [12]; (d) $D\bar{D}$ mixing [3]; (e) $\tau \to \pi\nu$ [13].

coupling	λ_{131}	λ_{232}	λ'_{3jk}	λ'_{31k}
Low-energy limit	0.08^a	0.08^b	0.024^c 0.34^d	0.32^e

is due to absolute mixing in the down-quark sector (EQD^c diagonal), more stricter bound (c) of 0.024 applies. In summary, present low-energy data allow $\lambda_{i3i} \lesssim 0.08$, and $\lambda_{i3i}\lambda'_{311} \lesssim (0.05)^2$, even for the limit (c).

4. Sleptons at LEP2

If $\lambda_{131} \neq 0$, the tau sneutrino $\tilde{f} = \tilde{\nu}_\tau$ can contribute to Bhabha scattering via s- and t-channel exchanges, and the electron sneutrino $\tilde{f} = \tilde{\nu}_e$ in the process $e^+e^- \to \tau^+\tau^-$ can be exchanged in the t-channel. Assuming in addition $\lambda_{232} \neq 0$, also muon pair production, $e^+e^- \to \mu^+\mu^-$, can be mediated by the s-channel $\tilde{\nu}_\tau$ resonance. Taking $\lambda'_{3jk} \neq 0$ would lead to s-channel $\tilde{\nu}_\tau$ contribution in hadronic processes $e^+e^- \to q_j\bar{q}_k$. We will consider these cases below. Note that apart from R-parity violating decays, the $\tilde{\nu}_\tau$ can also decay via R-parity conserving modes; such decays have already been discussed in the literature [14]. On the other hand, $\tilde{\tau}$ slepton in e^+e^- collisions can only contribute via t/u-channels to the neutrino-pair production cross section, which for couplings considered here is below 1 %.

(a) *Bhabha scattering:* In this case the differential cross section is given by eq. (9) with $A_c = 1$. The SM generalized charges in helicity amplitudes are as follows

$$Q^s_{ij} = 1 + g^e_i g^e_{-j} \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z} \qquad (13)$$
$$Q^t_{ij} = 1 + g^e_i g^e_{-j} \frac{t}{t - m_Z^2}$$

The subscript $-j$ means that the helicity index is opposite to j because in eqs. (11,12) the outgoing positron with the helicity $L(R)$ couples with the charge $g_R(g_L)$. The left/right Z charges of the fermions are defined as

$$g^f_L = (\frac{\sqrt{2}G_\mu m_Z^2}{\pi\alpha})^{1/2}(I^f_3 - s^2_W Q^f), \qquad g^f_R = (\frac{\sqrt{2}G_\mu m_Z^2}{\pi\alpha})^{1/2}(-s^2_W Q^f)$$

The sneutrino contributions are specified in terms of the factors G_{ij} as follows

$$G^s_{LL} = G^s_{RR} = G^t_{LL} = G^t_{RR} = (\lambda_{131})^2 \tag{14}$$

with all other $G_{ij} = 0$. Note that the s-channel (t-) sneutrino exchange interferes with the t-channel (s-) γ, Z exchanges.

(b) *Muon-pair production:* Since the t-channel γ, Z and $\tilde{\nu}_\tau$ exchanges are absent, $Q^t_{ij} = 0$, $G^t_{ij} = 0$, the s-channel sneutrino exchange does not interfere with the SM processes. The SM generalized charges Q^s_{ij} are given by eq. (13), and the sneutrino process gives

$$G^s_{LL} = G^s_{RR} = \lambda_{131}\lambda_{232}, \quad \text{all other} \quad G_{ij} = 0 \tag{15}$$

(c) *Tau-pair production:* In the scenario considered here, this process can receive only the t-channel exchange of $\tilde{\nu}_e$ with

$$G^t_{RR} = (\lambda_{131})^2, \quad \text{all other} \quad G_{ij} = 0 \tag{16}$$

which will interfere with the SM γ, Z s-channel processes with Q^s_{ij} given by eq. (13).

(d) e^+e^- *annihilation to hadrons:* For the down-type quark-pair production, $e^+e^- \to d_k\bar{d}_k$, the differential cross section is also given by eq. (9), however with $A_c = 3$. In this case the situation is similar to the muon-pair production process: there is no interference between s-channel $\tilde{\nu}_\tau$ exchange, given by

$$G^s_{LL} = G^s_{RR} = \lambda_{131}\lambda'_{3kk} \tag{17}$$

and the SM γ, Z processes, with the generalized charges

$$Q^s_{ij} = -Q^q + g^e_i g^q_{-j} \frac{s}{s - m^2_Z + i\Gamma_Z m_Z} \tag{18}$$

while all other Q_{ij} and G_{ij} vanish. The up-type quark-pair production is not affected by sneutrino processes, as can be easily seen from the general structure of couplings in eq. (4). Finally, the unequal-flavor down-type quark-pair production process, $e^+e^- \to d_j\bar{d}_k$, can be generated only by s-channel sneutrino with $G^s_{LL} = G^s_{RR} = \lambda_{131}\lambda'_{3jk}$.

The impact of sneutrino $\tilde{\nu}_\tau$ exchange on processes (a–c) at LEP2 energy is shown in Fig. 2a, where the change of the total cross section, $\sigma_{\rm tot}(SM \oplus \tilde{\nu})\ /\sigma_{\rm tot}(SM) - 1$, is plotted as a function of sneutrino mass assuming $\lambda_{i3i} = 0.08$ and $\lambda_{131}\lambda'_{3jk} = (0.05)^2$. For Bhabha scattering the scattering angle is restricted to $45^\circ \le \theta \le 135^\circ$. In processes (a) and (b), where the s-channel sneutrino exchange can contribute, the effect can be very large for sneutrino mass close to the LEP2 center-of-mass energy. Note

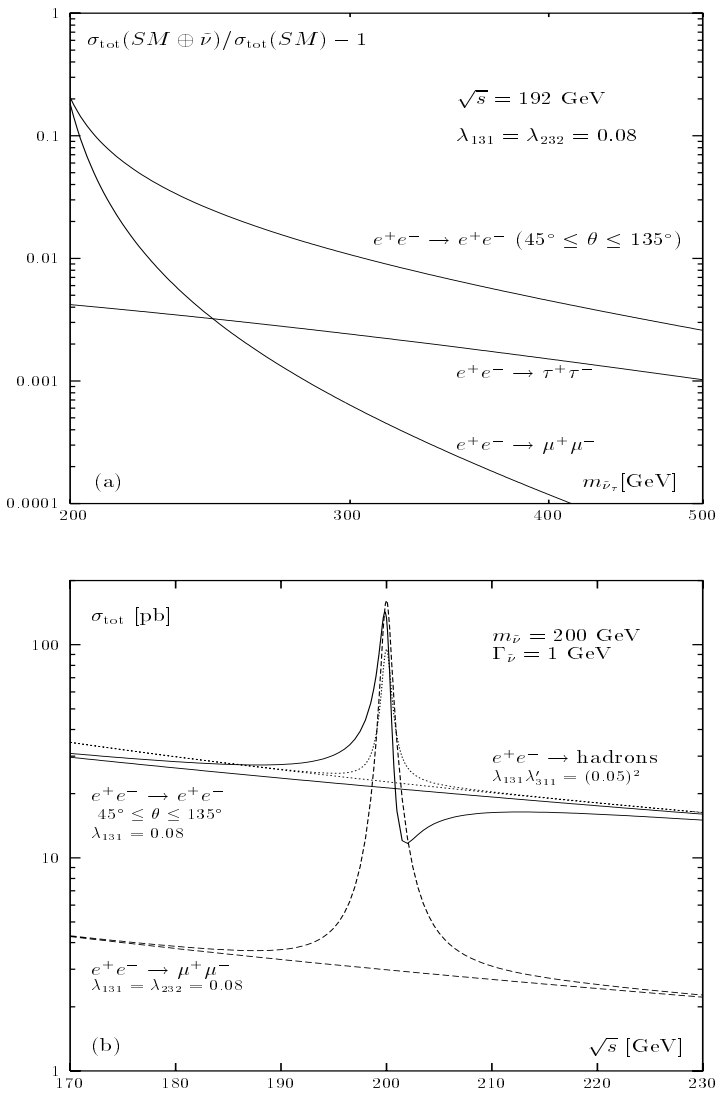

Figure 2. (a) Effect of sneutrino $\tilde{\nu}_\tau$ exchange on the cross section for Bhabha scattering (restricting $45^\circ \le \theta \le 135^\circ$), and $\mu^+\mu^-$ and $\tau^+\tau^-$ production at $\sqrt{s} = 192$ GeV. (b) Cross section for Bhabha scattering (solid lines), $\mu^+\mu^-$ (dashed lines) and hadron production (dotted lines) in the SM, and including $\tilde{\nu}_\tau$ sneutrino resonance formation as a function of the e^+e^- energy.

the difference due to different interference pattern between Bhabha scattering and tau-pair production on the one hand, and muon-pair production processes on the other: Bhabha and tau-production processes are more sensitive to heavy sneutrinos. If sneutrino is within the reach of LEP2, a spectacular resonance can be observed in Bhabha scattering, muon-pair, and/or quark-pair production processes, Fig.2b; again different interference patterns are seen. In the calculations the total decay width $\Gamma_{\tilde{\nu}_\tau} = 1$ GeV has been assumed. The partial decay width $\Gamma(\tilde{\nu}_\tau \to e^+e^-) = \lambda_{131} m_{\tilde{\nu}_\tau}/16\pi$ is very small. However, sneutrinos can also decay via R-parity conserving couplings to $\nu\chi^0$ and $\ell^\pm\chi^\mp$ pairs with subsequent χ^0 and $\chi^\pm$ decays. The partial decay widths into these channels depend on the choice of supersymmetry breaking parameters. In large regions of the parameter space, the total decay width is found to be as large as 1 GeV, which is significantly larger than the energy spread $\delta E \sim 200$ MeV at LEP2. In this case the interference with the SM processes must be taken into account. The peak cross section for Bhabha scattering is given by the unitarity limit $\sigma_{peak} = 8\pi B_e^2/m_{\tilde{\nu}_\tau}^2$ with sneutrino and antisneutrino production added up, where B_e is the branching ration for the sneutrino decay to e^+e^-. An interesting situation may occur if sneutrinos mix and mass eigenstates are split by a few GeV [16]. Then one may expect two separated peaks with reduced maximum cross sections to observe in the energy dependence in Fig.2b for the processes (a), (b) and/or (d).

The angular distribution of leptons and quark jets is nearly isotropic on the sneutrino resonance. As a result, the strong forward-backward asymmetry in the Standard Model continuum is reduced to ~ 0.03 on top of the sneutrino resonance. The deviations of the Bhabha cross section from the SM expectations would allow to determine directly the λ_{131} coupling, or to derive an upper limit. Similarly from the other processes one could derive limits for λ_{232} and λ'_{3jk}. For example, if the total hadronic cross section at 192 GeV can be measured to an accuracy of 1%, the Yukawa couplings for a 200 GeV sneutrino can be bounded to $\lambda_{131}\lambda'_{311} \lesssim (0.045)^2$ [8]. Recently preliminary results for some of the couplings from LEP 172 GeV data have been published [15].

5. Sleptons at Tevatron

At the Tevatron the case λ'_{311} is the most interesting since it allows for $\tilde{\nu}_\tau$ and $\tilde{\tau}$ resonance formation in valence quark collisions. Even though the sneutrinos and charged sleptons are expected to have small widths ($\sim$ 1 GeV or less), it will be difficult to detect their decay to quarks in the hadronic environment. Therefore we will consider leptonic decays of sleptons via λ_{i3i} couplings. To be specific we will consider λ_{131} and discuss

e^+e^- and $e^+\nu_e$ production in $p\bar{p}$ collisions; the same results hold for $\mu^+\mu^-$ and $\mu^+\nu_\mu$ production if λ_{232} is assumed.

For $p\bar{p} \to e^+e^-$ and $e^+\nu_e$ the differential cross sections are obtained by combining the parton cross sections with the luminosity spectra for quark-antiquark annihilation

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}M_{\ell\ell}\mathrm{d}y}[p\bar{p} \to \ell_1\ell_2] = \sum_{ij} \frac{1}{1+\delta_{ij}} \left(f_{i/p}(x_1) f_{j/\bar{p}}(x_2) + (i \leftrightarrow j)\right) \hat{\sigma} \qquad (19)$$

where $\hat{\sigma}$ is the cross section for the partonic subprocess $ij \to \ell_1\ell_2$, $\ell_1\ell_2 = e^+e^-$ or $e^+\nu$, $x_1 = \sqrt{\tau}e^y$, $x_2 = \sqrt{\tau}e^{-y}$. $M_{\ell\ell} = (\tau s)^{1/2} = (\hat{s})^{1/2}$ is the mass and y the rapidity of the lepton pair. The probability to find a parton i with momentum fraction x_i in the (anti)proton is denoted by $f_{i/p\,(\bar{p})}(x_i)$.

The partonic differential cross sections in the $q\bar{q}^{(\prime)}$ center-of-mass frame are given by eq. (9) with $A_c = 1/3$, and s, t and u replaced by $\hat{s}$, $\hat{t}$ and $\hat{u}$ which refer to the $q\bar{q}^{(\prime)} \to \ell_1\ell_2$ subprocess. The e^+e^- and $e^+\nu_e$ production processes are specified as follows

(a) *The process* $q\bar{q} \to e^+e^-$*:* The s-channel sneutrino $\tilde{\nu}_\tau$ exchange contributes only to $d\bar{d}$ scattering with

$$G^s_{LL} = G^s_{RR} = \lambda_{131}\lambda'_{311} \qquad (20)$$

which does not interfere with the SM s-channel γ, Z processes, for which the generalized charges are as follows

$$Q^s_{ij} = -Q^q + g^q_L g^e_{-j} \frac{\hat{s}}{\hat{s} - m_Z^2 + i\Gamma_Z m_Z} \qquad (21)$$

All other Q_{ij} and G_{ij} vanish.

(b) *The process* $u\bar{d} \to e^+\nu_e$*:* This process proceeds via the s-channel W boson and s-channel $\tilde{\tau}$ slepton exchanges. Only

$$Q^s_{LR} = \frac{1}{2\sin^2\theta_W} \frac{\hat{s}}{\hat{s} - m_W^2 + i\Gamma_W m_W} \qquad (22)$$

$$G^s_{LL} = -\lambda_{131}\lambda'_{311} \qquad (23)$$

are non-zero; all other Q_{ij} and G_{ij} vanish.

The total cross sections for sneutrino and charged slepton production in e^+e^- and $e^+\nu_e$ channels, respectively, at Tevatron are shown in Fig.3a as a function of slepton mass. The total decay widths of sleptons have been set to a typical value of 1 GeV, corresponding to the branching ratios for leptonic decays of order 1%. The di-electron invariant mass distribution is compared to the CDF data in Fig.3b, where, following CDF procedure [17], the prediction for $\frac{1}{2}\int_{-1}^{1} \mathrm{d}^2\sigma/\mathrm{d}M_{ee}\mathrm{d}y$ is shown. The solid line corresponds to an ideal detector, while the dashed curve demonstrates the distribution

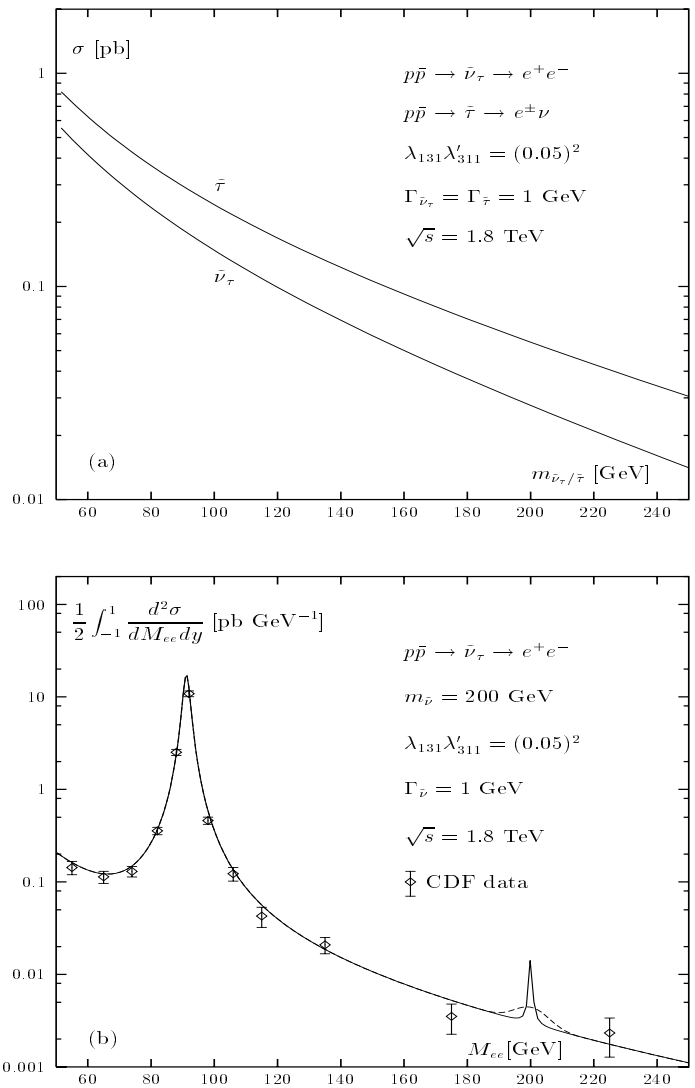

Figure 3. (a) The cross section for sneutrino and antisneutrino ($\tilde{\nu}_\tau$) and stau ($\tilde{\tau}$) production at the Tevatron, including the branching ratios to lepton-pair decays. (b) The e^+e^- invariant mass distribution including the s-channel sneutrino in the channel $d\bar{d} \to e^+e^-$ is compared with the CDF data; solid line: ideal detector, dashed line: sneutrino resonance smeared by a Gaussian width 5 GeV. The CTEQ3L structure functions have been used.

after the smearing of the peak by experimental resolution characterized by a Gaussian width of 5 GeV. In both plots the CTEQ3L parametrization [18] is used together with a multiplicative K factor for higher order QCD corrections to the SM Drell-Yan pair production. The corresponding K factor for slepton production has not been calculated yet, leading to a theoretical uncertainty in the $\lambda\lambda'$ couplings at a level of about 10%. Assuming the sneutrino contribution to be smaller than the experimental errors, we estimate that the bound $\lambda_{131}\lambda'_{311} \lesssim (0.08)^2 \tilde{\Gamma}^{1/2}$ can be established [8], where $\tilde{\Gamma}$ denotes the sneutrino width in units of GeV.

6. Summary

The R-parity violating formulation of MSSM offers a distinct phenomenology. If the lepton-flavor violating couplings are close to current low-energy limits, and the slepton masses are in the range of 200 GeV, spectacular events can be expected at both LEP2 and Tevatron. On the other hand, if no deviations from the SM expectations are observed, stringent bounds on individual couplings can be derived experimentally in a direct way.

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