SLEPTONS IN *R*-PARITY VIOLATING SUSY*

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In *R*-parity violating SUSY models, sleptons can be produced singly in e^+e^- and $q\bar{q}$ collisions. The formation of slepton resonances at LEP2 or Tevatron at current energies is an exciting possibility. Existing LEP2 and Tevatron data can be exploited to look for sleptons and, if unsuccessful, to derive bounds on the Yukawa couplings of sleptons to quark and lepton pairs.

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1. Introduction

This year has witnessed an increase of interest in the *R*-parity violating supersymmetric model. It has been triggered by observation at HERA of a number of events at high Q^2, high x in e^+p scattering [1]. Although the experimental situation remains unsettled, the supersymmetry with broken *R*-parity has been put forward as a possible explanation of these events [2].

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

$$W_R = Y_{ij}^e L_i H_1 E_j^c + Y_{ij}^d Q_i H_1 D_j^c + Y_{ij}^u Q_i H_2 U_j^c + \mu H_1 H_2 \,, \tag{1}$$

which respects a discrete multiplicative symmetry, *R*-parity, which can be defined as [3]

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

where B, L and S denote the baryon and lepton number, and the spin of the particle: all Higgs particles and SM fermions and bosons have $R_p = +1$, and their superpartners have $R_p = -1$.

In Eq. (1) the standard notation is used 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 indices i, j denote the generations, and a summation is understood, Y_{ij}^f are Yukawa couplings and μ is the Higgs mixing mass parameter.

Because of R_p conservation, the interaction lagrangian derived from W_R contains terms in which the supersymmetric partners appear only in pairs. Therefore superpartners can be produced only in pairs in collisions and decays of particles, and the lightest supersymmetric particle (LSP) is stable.

However, there is no theoretical motivation for imposing R_p since gauge and Lorentz symmetries allow for additional terms in the superpotential

$$W_{\not R} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c + \epsilon_i L_i H_2 , \qquad (3)$$

which break explicitly the R-parity [4]. If the Yukawa couplings λ, λ', λ'' and/or dimensionful mass parameters ϵ 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 if both types of couplings are present. In the usual formulation of the MSSM they are forbidden by R-parity and the proton is stable. 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. Lepton-number violating operators can also provide new ways to generate neutrino masses.

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 [5]. Since they lead to very different phenomenology, both models should be searched for experimentally. The MSSM with R_p-conservation has been extensively studied phenomenologically and experimentally. Here we will consider the MSSM with broken R_p with the most general trilinear terms in Eq. (3) that violate L but conserve B.

In the Lagrangian the λ and λ' parts of the Yukawa interactions have the following form:

$$\mathcal{L}_{\not{R}} = \lambda_{ijk} \left[\tilde{\nu}_L^j \bar{e}_R^k e_L^i + \bar{\tilde{e}}_R^k (\bar{e}_L^i)^c \nu_L^j + \tilde{e}_L^i \bar{e}_R^k \nu_L^j \right.$$

$$\left. - \tilde{\nu}_L^i \bar{e}_R^k e_L^j - \bar{\tilde{e}}_R^k (\bar{e}_L^j)^c \nu_L^i - \tilde{e}_L^j \bar{e}_R^k \nu_L^i \right] + \text{h.c.}$$

$$+ \lambda'_{ijk} \left[(\tilde{u}_L^j \bar{d}_R^k e_L^i + \bar{\tilde{d}}_R^k (\bar{e}_L^i)^c u_L^j + \tilde{e}_L^i \bar{d}_R^k u_L^j) \right.$$

$$\left. - (\tilde{\nu}_L^i \bar{d}_R^k d_L^j + \tilde{d}_L^j \bar{d}_R^k \nu_L^i + \bar{\tilde{d}}_R^k (\bar{\nu}_L^i)^c d_L^j) \right] + \text{h.c.}, \tag{4}$$

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.

The possibility of some λ and λ' couplings to be non-zero opens many interesting processes at current and future colliders in which this scenario can be explored. 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 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.

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. Therefore 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

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

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

The results presented here have been obtained in collaboration with Spiesberger, Rückl and Zerwas [7, 8].

2. Sfermion exchanges in $f\bar{f}' \rightarrow F\bar{F}'$ processes

Once produced, sleptons can decay via either the R_p violating Yukawa or the R_p conserving gauge couplings. In the latter case, the decay proceeds in a cascade process which involves standard and supersymmetric particles in the intermediate states and with the R_p violating coupling appearing at the end of the cascade. Such decay processes lead in general to multibody final states and depend on many unknown SUSY parameters. In the former case, the final state is a two-body state (with two visible particles, eqs. (5)-(7), or one visible particle and a missing momentum, Eq. (8)) which depends only on a limited number of parameters and which is very easy to analyse experimentally. Therefore we will consider sleptons that are produced and decay via λ and/or λ' couplings.
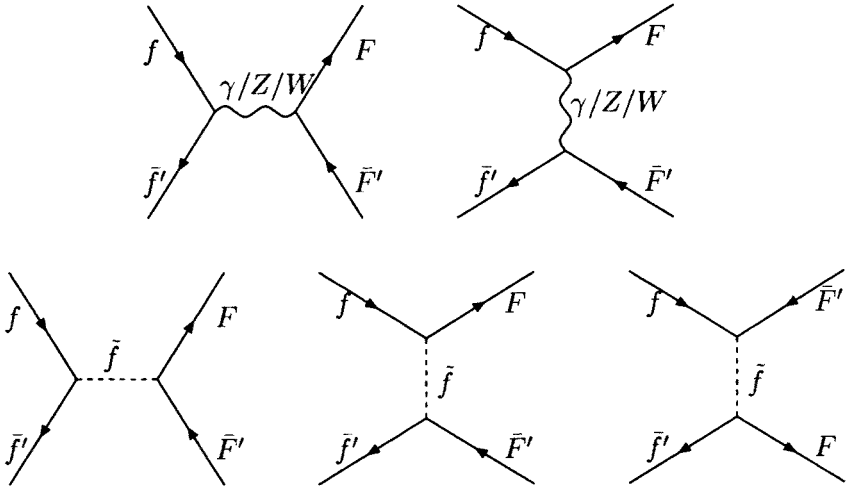

Fig. 1. Generic Feynman diagrams for $f\bar{f}' \rightarrow F\bar{F}'$ scattering including s- and t-channel exchange of $\gamma/Z/W$, and s-, t- and u-channel exchange of sfermion $\tilde{f}$.

Let us consider first a generic two-body process $f\bar{f}' \rightarrow F\bar{F}'$ which, in the Standard Model, 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. Turning on the λ and λ' couplings, there are additional contributions due to sfermions which 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 in terms of helicity amplitudes as follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}(f\bar{f}' \to F\bar{F}') = A_c\frac{\pi\alpha^2 s}{8}\Big\{4\left[|f_{LL}^t|^2 + |f_{RR}^t|^2\right]$$
$$+ (1-\cos\theta)^2\left[|f_{LL}^s|^2 + |f_{RR}^s|^2\right]$$
$$+ (1+\cos\theta)^2\left[|f_{LR}^s|^2 + |f_{RL}^s|^2 + |f_{LR}^t|^2 + |f_{RL}^t|^2\right.$$
$$\left. + 2\mathrm{Re}(f_{LR}^{s\,*}f_{LR}^t + f_{RL}^{s\,*}f_{RL}^t)\right]\Big\}, \tag{9}$$

where A_c is the appropriate color factor. 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 s- and t-channel γ, Z, W amplitudes in the Standard Model involve the coupling of vector currents. On the other hand the sfermion exchange is described by scalar couplings. However, by performing appropriate Fierz transformations,

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

for the field operators, the s-channel $\tilde{f}$ exchange amplitudes can be rewritten as t-channel vector amplitudes, and t/u-channel $\tilde{f}$ exchange amplitudes as s-channel vector amplitudes. Therefore it is easy to see that 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.

In performing the Fierz transformation, attention should be paid to the relative signs of the SM and sfermion exchange amplitudes. We find that the t- and u-channel sfermion contributions enter with the opposite signs due to different ordering of fermion operators in the Wick reduction [9].

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

$$f_{ij}^s = \frac{Q_{ij}^s}{s} + \frac{1}{2}\frac{G_{ij}^t/e^2}{t - m_{\tilde{f}}^2} - \frac{1}{2}\frac{G_{ij}^u/e^2}{u - m_{\tilde{f}}^2}, \tag{11}$$

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 $u = (p_f - p_{\bar{F}'})^2 = -s(1+\cos\theta)/2$. Similarly, the t-channel exchange amplitudes f_{ij}^t read

$$f_{ij}^t = \frac{Q_{LR}^t}{t} + \frac{1}{2}\frac{G_{ij}^s/e^2}{s - m_{\tilde{f}}^2 + i\Gamma_{\tilde{f}}m_{\tilde{f}}}. \tag{12}$$

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). The generalized SM charges $Q_{ij}^{s,t}$ for gauge boson ex-changes 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. In processes involving γ and Z exchanges, the generalized charges Q_{ij} depend on the momentum transfers and their signs determine the interference pattern of SM with sfermion exchange terms.

3. Indirect bounds on the Yukawa couplings

The masses and Yukawa couplings of sfermions are not predicted by the-ory. At energies much lower than the sparticle masses, R-parity breaking interactions can be formulated in terms of effective four-fermion contact in-teractions. 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 struc-ture 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 $\lambda \lesssim 0.1 \times (\tilde{m}/200 \text{ GeV})$, where $\tilde{m}$ is the mass scale of the sparticles participating in the process.

Let us consider a specific example. The operator $\lambda_{131} L_1 L_3 E_1^c$ can con-tribute to the τ leptonic decay process $\tau \to e\nu\bar{\nu}$ via the diagram in Fig. 2. After Fierz transformation the sneutrino exchange diagram has the same structure as the SM W exchange and thus leads to an apparent shift in the Fermi constant for tau decays. The ratio $R_\tau \equiv \Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$ relative to the SM contribution is then modified [11]

$$R_\tau = R_\tau(SM) \left[1 + 2\frac{M_W^2}{g^2} \left(\frac{|\lambda_{131}|^2}{\tilde{m}^2(\tilde{e}_R)} \right) \right]. \tag{13}$$
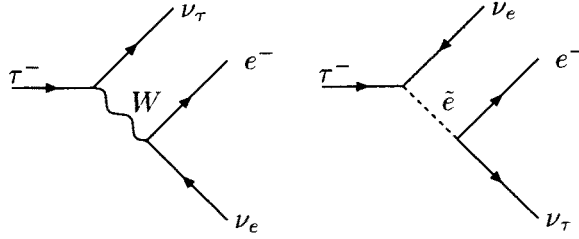
Fig. 2. Tau decay via the SM W exchange, and via the $\tilde{\nu}_\tau$ due to the $L_1 L_3 E_1^c$ operator.

Using the experimental value [6] we obtain [7] the bound

$$|\lambda_{131}| < 0.08 \left(\frac{\tilde{m}(\tilde{e}_R)}{200 \text{ GeV}} \right) \tag{14}$$

which is given in Table I.

Other limits relevant for λ_{i3i} and λ'_{3jk}, derived by assuming only one non-vanishing coupling at a time, are summarized in Table I.

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 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 in the limit (c).

TABLE I

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 [5]; (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

4. Sneutrinos in e^+e^- scattering

In e^+e^- scattering, sneutrinos can be produced in the s-channel and sleptons exchanged in the t or u channels, leading to a number of different signatures depending on the assumed scenario. If only $\lambda_{131} \neq 0$, 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:* The differential cross section for Bhabha scattering is given by Eq. (9) with $A_c = 1$, and the SM generalized charges in helicity amplitudes are as follows:

$$Q_{ij}^s = 1 + g_i^e g_{-j}^e \frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$

$$Q_{ij}^t = 1 + g_i^e g_{-j}^e \frac{t}{t - m_Z^2}. \tag{15}$$

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 $g_R^e(g_L^e)$, where the left/right Z charges of the fermion f are defined as

$$g_L^f = \left(\frac{\sqrt{2}G_\mu m_Z^2}{\pi\alpha}\right)^{1/2}(I_3^f - s_W^2 Q^f), \quad g_R^f = \left(\frac{\sqrt{2}G_\mu m_Z^2}{\pi\alpha}\right)^{1/2}(- s_W^2 Q^f).$$

The R_p violating sneutrino contributions are given in terms of the factors G_{ij} as follows:

$$G_{LL}^s = G_{RR}^s = G_{LL}^t = G_{RR}^t = (\lambda_{131})^2 \tag{16}$$

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:* The SM generalized charges Q_{ij}^s are given by Eq. (15). Since the t-channel γ, Z and $\tilde{\nu}_\tau$ exchanges are absent, $Q_{ij}^t = 0$, $G_{ij}^t = 0$, the s-channel sneutrino exchange given by

$$G_{LL}^s = G_{RR}^s = \lambda_{131}\lambda_{232}, \quad \text{all other} \quad G_{ij} = 0 \tag{17}$$

does not interfere with the SM processes.

(c) *Tau-pair production:* This process can receive only the *t*-channel exchange of $\tilde{\nu}_e$ with

$$G^t_{RR} = (\lambda_{131})^2, \quad \text{all other} \quad G_{ij} = 0 \qquad (18)$$

which will interfere with the SM γ, Z *s*-channel processes with Q^s_{ij} given by Eq. (15).

(d) e^+e^- *annihilation to hadrons:* 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). On the other hand, for the down-type quark-pair production, $e^+e^- \to d_k\bar{d}_k$, the differential cross section is given by Eq. (9), however with the color factor $A_c = 3$. 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

$$G^s_{LL} = G^s_{RR} = \lambda_{131}\lambda'_{3kk} \qquad (19)$$

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

$$Q^s_{ij} = -Q^q + g^e_i g^q_{-j} \frac{s}{s - m^2_Z + i\Gamma_Z m_Z} \qquad (20)$$

while all other Q_{ij} and G_{ij} vanish. 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 $G^s_{LL} = G^s_{RR} = \lambda_{131}\lambda'_{3jk}$.

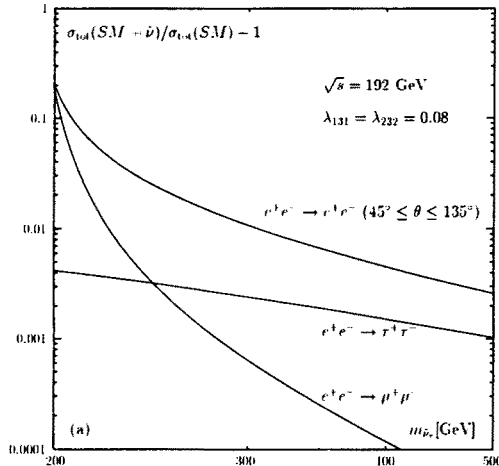

Fig. 3. Effect of sneutrino $\tilde{\nu}_\tau$ exchange on the cross section for Bhabha scattering (restricting $45° \leq \theta \leq 135°$), and $\mu^+\mu^-$ and $\tau^+\tau^-$ production at $\sqrt{s} = 192$ GeV.
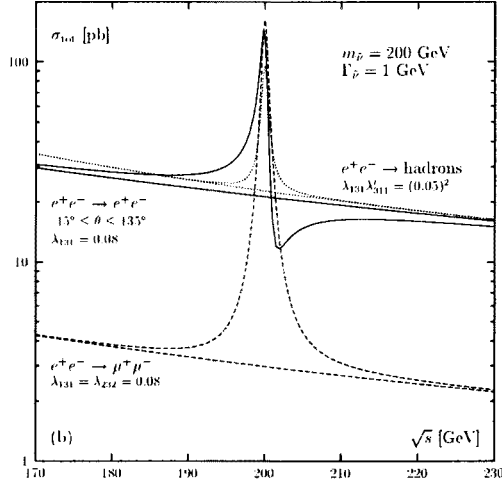
Fig. 4. Cross section for Bhabha scattering (solid lines), $\mu^+\mu^-$ (dashed lines) and hadron production (dotted lines) in the SM, and including $\tilde{\nu}_\tau$ sneutrino resonance formation as a function of the e^+e^- energy.

Numerically the effect of t- or u-channel exchange of sleptons is very small (typically below 1%) for the slepton masses and couplings consistent with low-energy data. Only in processes with s-channel exchanges, and not too far from the resonance, the effect of sneutrino can be quite spectacular. This is illustrated in Fig. 3, where the impact of sneutrino $\tilde{\nu}_\tau$ exchange on processes (a–c) at LEP2 energy is shown. In the figure, the change of the total cross section, $\sigma_{tot}(SM \oplus \tilde{\nu})/\sigma_{tot}(SM) - 1$, 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 $45° \leq \theta \leq 135°$). 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 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. 4; again different interference patterns are seen. In the calculations, the total decay width $\Gamma_{\tilde{\nu}_\tau} = 1$ GeV has been assumed. Although the partial decay width $\Gamma(\tilde{\nu}_\tau \to e^+e^-) = \lambda_{131}m_{\tilde{\nu}_\tau}/16\pi$ is very small, 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, however we find that in large regions

of the parameter space the total decay width can be as large as 1 GeV. Therefore it is significantly larger than the energy spread $\delta E \sim 200$ MeV at LEP2 and in such a 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 to observe in the energy dependence in Fig. 4 for the processes (a), (b) and/or (d) two separated peaks with reduced maximum cross sections.

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

Sleptons can also manifest themselves in $p\bar{p}$ collisions. 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 of the order ~ 1 GeV, their decays to quark jets can be very difficult to observe 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.

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

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}M_{\ell\ell}\mathrm{d}y}[p\bar{p} \to \ell_1\ell_2] = \sum_{ij} \frac{1}{1+\delta_{ij}} \left(f_{i/p}(x_1)f_{j/\bar{p}}(x_2) + (i \leftrightarrow j) \right) \hat{\sigma}, \quad (21)$$

$\hat{\sigma}$ is the cross section for the partonic subprocess $ij \to \ell_1\ell_2$, where $\ell_1\ell_2 = e^+e^-$ or $e^+\nu$, and $x_1 = \sqrt{\tau}e^y$, $x_2 = \sqrt{\tau}e^{-y}$. $M_{\ell\ell} = (\tau s)^{1/2} = (\hat{s})^{1/2}$ 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 SM γ and Z exchange mechanisms are given by the generalized charges are as follows:

$$Q_{ij}^s = -Q^q + g_L^q g_{-j}^e \frac{\hat{s}}{\hat{s} - m_Z^2 + i\Gamma_Z m_Z} \,. \tag{22}$$

On the other hand, the s-channel sneutrino $\tilde{\nu}_\tau$ exchange contributes only to $d\bar{d}$ scattering with

$$G_{LL}^s = G_{RR}^s = \lambda_{131}\lambda_{311}' \,, \tag{23}$$

which does not interfere with the SM s-channel γ, Z processes. 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

$$Q_{LR}^s = \frac{1}{2\sin^2\theta_W} \frac{\hat{s}}{\hat{s} - m_W^2 + i\Gamma_W m_W} \,, \tag{24}$$

$$G_{LL}^s = -\lambda_{131}\lambda_{311}' \tag{25}$$

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

The total cross sections for $\tilde{\nu}_\tau$ and $\tilde{\tau}$ production in e^+e^- and $e^+\nu_e$ channels, respectively, at Tevatron are shown in Fig. 5 as a function of the corresponding 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. 6, where, following CDF procedure [17], the prediction for $\frac{1}{2}\int_{-1}^{1} d^2\sigma/dM_{ee}dy$ is shown. The solid line corresponds to an ideal detector, while the dashed curve demonstrates the distribution 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.
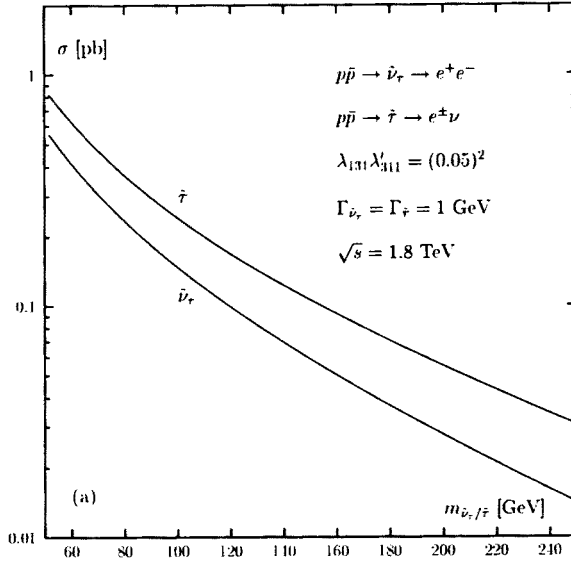
Fig. 5. The cross section for sneutrino and antisneutrino ($\tilde{\nu}_\tau$) and stau ($\tilde{\tau}$) production at the Tevatron, including the branching ratios to lepton-pair decays.
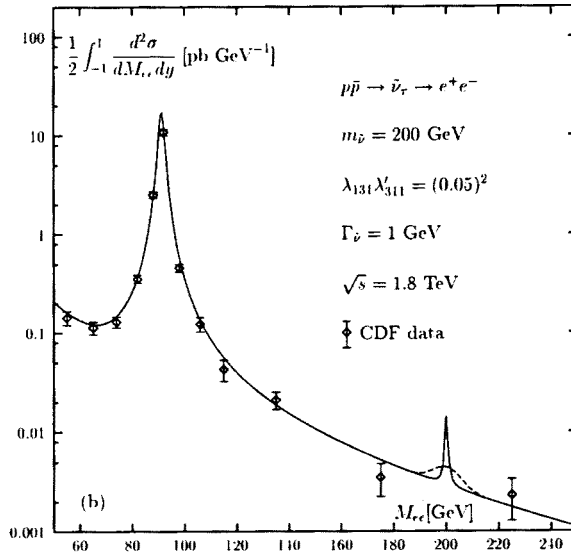

Fig. 6. The e^+e^- invariant mass distribution including the s-channel sneutrino in the channel $d\bar{d} \to e^+e^-$ is compared with the CDF data; solid line: ideal detector, dashed line: sneutrino resonance smeared by a Gaussian width 5 GeV. The CTEQ3L structure functions have been used.

6. Summary

The R-parity violating formulation of MSSM offers a distinct phenomenology and therefore deserves detailed studies. Even if the squarks are beyond the kinematical reach of HERA, sleptons might be light enough to be seen at LEP2 and/or Tevatron. In this talk we discussed the scenario with lepton number violation, and we considered a number of processes in which sleptons might play an important role. We concentrated only on those processes in which sleptons are produced and decay via R_p violating couplings. 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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