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## Tau Signals of R-parity breaking at LEP 200

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### Abstract

The detectability at LEP 200 of explicit  $R$ -parity breaking by tau-number ( $L_\tau$ ) violating operators is considered. The assumption of  $L_\tau$ -violation is motivated by the relative lack of constraints on such couplings but similar considerations apply to explicit  $L_{e^-}$  or  $L_{\mu^-}$ -violation. The  $LSP$ , now unstable, and not necessarily neutral, decays via  $L_\tau$ -violating modes. Only signals from the production and decays of  $LSP$  pairs are considered, thereby avoiding any dependence on the sparticle mass spectrum. Rather spectacular signals are predicted: spherical events with  $m$  leptons (usually containing at least one  $\tau$ ) and  $n$  jets ( $m, n \leq 4$ ), the most characteristic of which are like-sign  $\tau\tau$  events. These signals are enumerated for each  $LSP$  candidate and quantitative estimates are provided for the favoured case when the  $LSP$  is a neutralino. Other new physics signals, which can mimic these signatures, are also briefly discussed.

# 1. Introduction

Supersymmetry can stabilize the weak scale in the Standard Model (SM) in an elegant way, provided the superparticles have masses  $\lesssim 0(1)$  TeV. The accessibility of this mass range to forthcoming accelerators has made the

phenomenological pursuit of supersymmetry an exciting venture. Much effort [1] has, in turn, been expended in that direction over the past few years. There exist many model calculations suggesting that, if all superparticle masses are smaller than about 1 TeV, the lighter charginos and neutralinos may well have masses below 100 GeV. This means that they can be pair-produced at LEP 200. We adopt such an attitude in this paper and propose some distinctive signals (mostly involving one or more  $\tau$ 's along with other charged leptons, jets,  $\cancel{E}_T$  etc.) to be looked for at LEP 200 as signatures of a class of  $\tau$ -number violating supersymmetric models. What is special about  $\tau$ -number – as will be elaborated below – is that, among all the conservation laws of the SM,  $\tau$ -conservation is the least well-verified [2]. Also, LEP is ideally suited to search for  $\tau$ -number violation on account of the superior  $\tau$ -detection efficiency offered by its cleaner environment as compared with a hadron collider.

The main thrust of the effort mentioned above has been within the aegis of the Minimal Super-Symmetric Model (MSSM) [1]. The MSSM has the particle content of the SM (but with two Higgs doublets) simply extended by global  $N = 1$  supersymmetry which is broken softly. In addition, however, it has an exact discrete symmetry known as  $R$ -parity  $R_P$  – related to baryon number  $B$ , lepton number  $L$  and spin  $S$  via  $R_P = (-1)^{3B+L+2S}$  – under which each SM particle is even while its superpartner is odd. (At the superfield level this is the same as matter parity under which quark and lepton superfields are odd while gauge and Higgs superfields are even.) Consequently, superparticles have to be produced in pairs and the lightest superparticle ( $LSP$ ) is stable and neutral, the latter from cosmological considerations [3]. On account of its feeble interactions with ordinary matter, the  $LSP$  – once produced – escapes detection, leading to a mismatch in

the total measured momentum. This is the classic  $\cancel{p}_T$ -signature of superparticle pair-production, the absence of which so far has led to interesting lower bounds [4] on the superparticle masses.

The gauge interactions of the MSSM are completely fixed by its particle content and the gauge group. The same is not true of its Yukawa terms, though. These arise from the  $F$ -part of a trilinear superpotential and possess a lot of freedom even after obeying gauge and supersymmetry invariance. The additional requirement of  $R_P$ -conservation restricts the residual Yukawa terms to be

$$\mathcal{L}_Y = \left[ h_{ij} L_i H_1 E_j^C + h'_{ij} Q_i H_1 D_j^C + h''_{ij} Q_i H_2 U_j^C \right]_F. \quad (1)$$

In (1)  $L$  and  $E^C$  ( $Q$  and  $U^C$ ,  $D^C$ ) are the lepton doublet and antilepton singlet (quark doublet and antiquark singlets) left-chiral superfields, respectively, while  $H_1$  ( $H_2$ ) is the Higgs doublet superfield with weak hypercharge  $Y = -1(+1)$ . Moreover,  $i$  and  $j$  are generation indices while  $h$ ,  $h'$  and  $h''$  are coupling strengths.

The possibility of other viable alternatives to the MSSM (violating  $R_P$  and leading to very different phenomenology since the classic  $\cancel{p}_T$  signature is vitiated by the unstable nature of the  $LSP$ ) has led several authors [5,6] to study the observable consequences of  $R$ -parity breaking models. Unlike the SM, supersymmetric models do allow for the possibility of  $B$ - and  $L$ - (and hence  $R_P$ -) violating interactions which have the most general form:

$$\mathcal{L}_{\cancel{R}_P} = \left[ \lambda_{ijk} L_i L_j E_k^C + \lambda'_{ijk} L_i Q_j D_k^C + \lambda''_{ijk} U_i^C D_j^C D_k^C \right]_F, \quad (2)$$

where we have used field redefinitions to rotate away bilinears of the form  $L_i H_2$ . The coupling constant matrices  $\lambda$  ( $\lambda''$ ) are antisymmetric in the first (last) two indices. The first two terms in (2) lead to  $L$ -violation whereas the last one causes baryon non-conservation. The simultaneous presence of both

$B$ - and  $L$ -violating operators would, however, lead to an amplitude for proton decay suppressed only by  $1/m_{\tilde{q}}^2 \lesssim 1/(1 \text{ TeV})^2$ . Thus, at most, only one of these

classes of operators can exist. For instance, one could have  $L$ -conservation and  $B$ -violation, i.e.  $\lambda_{ijk} = 0 = \lambda'_{ijk}$  and  $\lambda''_{ijk} \neq 0$  in general. There have been [7] cosmological arguments implying strong upper limits ( $\lambda'' < 10^{-7}$ ) on  $\lambda''_{ijk}$  from the requirement that GUT scale baryogenesis does not get washed out, though recent studies [8] suggest that these arguments are model-dependent. More important for our purpose is the kind of experimental signals that these different interactions lead to. As has been shown [9], it may be very difficult to discern signals of  $B$ -violating interactions (especially at hadron colliders) above QCD backgrounds.

These considerations lead one to consider the alternative scenario [8-12] for  $R_P$ -breaking, namely  $B$ -conservation and  $L$ -violation (i.e.  $\lambda''_{ijk} = 0$  and  $\lambda_{ijk} \neq 0 \neq \lambda'_{ijk}$  in general). If  $\lambda''_{ijk} = 0$ , the  $\lambda'$ -terms would need some other baryon-number violating but  $B$ - $L$  conserving process, such as non-perturbative instanton-induced

electroweak baryon non-conservation, to wash out the GUT-generated baryon asymmetry of the universe. The latter interaction, however, conserves  $\frac{1}{3}B$ - $L_i$  where  $L_i$  is the family lepton number for each lepton family of type  $i$ . Thus the effective conservation of any one lepton generation would suffice [10] for the retention of the initial baryon asymmetry so that the cosmological constraints can be satisfied if the smallest lepton non-conserving Yukawa coupling (where no third generation

lepton need be involved) is less than  $10^{-7}$ . This then leaves largely untouched the strongest possible such coupling (involving a single third generation lepton) which can now be safely speculated to be  $\gtrsim 10^{-5}$  leading to quite characteristic signals, as discussed below.

As is clear from the previous discussion, all  $R_P$ -violating models must necessarily treat quarks and leptons differently, (vis-a-vis their conserved quantum numbers), in order to be compatible with the absence of rapid proton decay. This may appear somewhat contrary to the grand unification philosophy which tries to put quarks and leptons on a similar footing. However, Hall and Suzuki [5] have constructed a grand unified model in which  $R_P$  is violated in the low energy su-

perpotential only by bilinear terms of the form  $L_i H_2$  which can be rotated away by a field redefinition.  $R_P$ -violation then shows up in the lepton non-conserving trilinear operators, rather than in the baryon non-conserving ones. In

Unified String Theories, also, there arise [13] discrete symmetries which treat baryons and leptons differently. In particular, it has recently been shown [14] that, consistent with the particle content of the MSSM and the observed lack of fast proton decay, two such discrete symmetries are possible:  $R_P$  and  $B$ . Whereas the former directly eliminates only the dimension-four contributions to the proton-decay amplitude and not the dimension-five ones, the latter removes both. Thus we find it not unreasonable to work in a  $B$ -conserving,  $R_P$ - and  $L$ -violating scenario.

There exist various strong upper limits [6] on several of the  $\lambda$  and  $\lambda'$  terms, as discussed below in Section 2. Nevertheless, some of these coupling strengths can be  $O(10^{-1})$ . As we will see in Section 2, the lepton-non-conserving trilinear operator with a

single third-generation lepton superfield is relatively unconstrained and we shall take that to be the dominant term in the superpotential. Thus our assumption is that only  $\tau$ -number (and not  $e$ - or  $\mu$ -number) gets violated. We are motivated to consider this since neither neutrinoless nuclear double-beta decay nor the production of positive muons in nuclear  $\mu$ -capture has been observed. These put stringent restrictions on any violation of  $e$ - or  $\mu$ -number whereas such restrictions are absent for  $\tau$ -number. All constraints from the observed lack of flavour-changing

tau decays can be met with the assumptions of  $e$ - and  $\mu$ -conservation leaving the scope to violate  $\tau$ -number with impunity. *The prospect of*

*detecting  $\tau$ -number violating interactions via the production of  $LSP$  pairs produced in  $e^+e^-$  annihilation at LEP 200 forms the subject of this paper.*

In our analysis we shall assume that the  $R_P$ -violating coupling is large enough for the  $LSP$  to decay inside the detector. This is ensured [7,9] by the use of Dawson's [5] calculation of the  $LSP$  lifetime and

requiring

$$\lambda, \lambda' \gtrsim 5 \times 10^{-7} (m_{\tilde{\ell}, \tilde{q}}/100 \text{ GeV})^2 (100 \text{ GeV}/m_{LSP})^{5/2}. \quad (3)$$

For values of  $\lambda$  ( $\lambda'$ ) that violate the lower bound (3), the *LSP* escapes detection so that the signals for superparticle production at *LEP* would be essentially the same as their MSSM counterparts [15]. For an *LSP* mass-range of 20-100 GeV, of interest to us, values of  $\lambda$  and or  $\lambda' \gtrsim 10^{-5}$  would be sufficient to observe its decay in the apparatus. The pair-production and subsequent decays of the *LSP*s will be signalled by the presence of distinctive tau signatures. The identification of large  $p_T$   $\tau$ 's through their hadronic decay products[16] – specific mesons such as  $\pi, \rho, A_1$  etc. as well as low-multiplicity narrow jets – encourages us to believe that it will be possible to identify the hadronic decays of the  $\tau$  in the cleaner environment of LEP 200 with reasonable efficiency.

With  $R_P$  not conserved, the cosmological constraints [3] – requiring the *LSP* to be colour and electrically neutral – no longer apply. A priori, the *LSP* could now be any superparticle. The squark (apart from  $\tilde{t}$ ), however, is an unlikely *LSP* candidate. This may be seen as follows. If the running squark mass  $m_{\tilde{q}}$  at low energies is much smaller than the corresponding gluino mass  $m_{\tilde{g}}$ , renormalization group evolution drives  $m_{\tilde{q}}^2$  to negative values below the unification scale [17] – leading to colour- and charge-breaking vacua – unless large Yukawa interactions are present. Since the Yukawa couplings of all but *t*-squarks are generally negligible (and we exclude the exceptional case [18] of large bottom Yukawa interactions for  $\tan \beta \simeq m_t/m_b$ ), we can assume that, among squarks, only the  $\tilde{t}$  could be the *LSP*. Indeed, the lower  $\tilde{t}$  mass eigenstate [19] may well become lighter than other superparticles by virtue of  $\tilde{t}_L - \tilde{t}_R$  mixing induced by soft supersymmetry breaking *A*-terms.

In models with a common gaugino mass at the unification scale, the gluino is heavier than the *SU*(2) and *U*(1) gauginos [1,20], and hence can be

excluded from the  $LSP$  list. This leaves us with the charged sleptons, the sneutrinos, the charginos and the neutralinos as candidates for the  $LSP$ . However,  $LEP$  searches require the masses of charginos, charged sleptons and sneutrinos to essentially exceed  $M_Z/2$ , so that the lightest neutralino  $\tilde{Z}_1$  is really the only candidate for an  $LSP$  lighter than 45 GeV. In order to be definite, we will assume for the most part that the  $LSP$  is indeed a neutralino, though we will qualitatively discuss how signals are altered in the various other cases.

The cross section for pair-production at LEP 200 is fixed by gauge interactions and hence is the same as in the MSSM. Each  $LSP$ , thus produced, decays within the apparatus either leptonically by a  $\lambda$ -term or semileptonically by a  $\lambda'$ -term. There will be spectacular observable multilepton-final state configurations in the former case with essentially no background from the SM or any other non-standard scenario e.g.  $\tau\tau\bar{e}\bar{e} + \cancel{E}_T$ ,

$\bar{\tau}\bar{\tau}ee + \cancel{E}_T$ ,  $e\bar{e}e\bar{\tau} + \cancel{E}_T$ ,  $e\bar{e}\bar{e}\tau + \cancel{E}_T$  and  $e\bar{e}e\bar{e} + \cancel{E}_T$ . Additionally, there should be signals for final-state configurations such as  $e\bar{e}\tau\bar{\tau} + \cancel{E}_T$  and  $\tau\bar{\tau}\tau\bar{\tau} + \cancel{E}_T$  where the backgrounds may be more problematic. Turning to the  $\lambda'$ -case, some characteristic observable final state configurations are  $\tau\tau(4j)$  and  $\bar{\tau}\bar{\tau}(4j)$  whereas one will also have more background-ridden configurations such as  $\tau\bar{\tau}(4j)$ ,  $\tau(4j) + \cancel{E}_T$ ,  $\bar{\tau}(4j) + \cancel{E}_T$  etc. It may be noted that  $\tau\tau(4j)$  and  $\bar{\tau}\bar{\tau}(4j)$  events without  $\cancel{E}_T$  will provide unambiguous evidence for  $\tau$ -number non-conservation. The bulk of our work is devoted to a

discussion of many novel signatures for these processes in explicit  $R_P$ - and  $L_\tau$ -violating models for various possible LSP candidates. We also highlight interesting interrelations among the different cross sections.

There is a somewhat different version [21] of the  $R_P$ - and  $L$ -violating scheme in which these discrete symmetries suffer spontaneous breakdown. However, this scenario cannot obtain within the minimal particle content of the MSSM (e.g. any  $VEV$  attributed to one of the SM sneutrinos leads to one or more additional decay channel for the  $Z$  in conflict with experiment [22]). An additional  $SU(2)_L \times U(1)_Y$

singlet left-chiral neutral lepton superfield  $N$  is required and a VEV needs to be attributed to its scalar component. Though this model does not engage our main concern, we do mention it briefly. We will also study rival new physics mechanisms which can mimic our signals, (e.g. a heavy Majorana neutrino) and discuss how these can be distinguished from  $R_P$ -violating processes.

The rest of the paper is organized as follows. Section 2 contains the basic  $R_P$ -violating vertices and interactions. In Section 3 all our proposed  $R_P$ - and  $L_\tau$ -violating processes, together with their signatures at LEP 200, are discussed for the case when the  $LSP$  is a neutralino as well as for the other  $LSP$  candidates. We include a quantitative discussion of the cross sections for  $R_P$ -violating signals from neutralino  $LSP$ s in Section 4. In Section 5 we discuss some rival new physics mechanisms which can mimic our signals and suggest ways of discriminating between them. Finally, Section 6 contains a summary and discussion of our results. The Appendix includes an explicit model of an unstable heavy Majorana neutrino which is largely an  $SU(2)_L$  doublet.

## 2. $R_P$ vertices and interactions

We begin by writing the Lagrangian density for  $R_P$  interactions. The  $\lambda$ -terms in the superpotential (2) lead to [6],

$$\mathcal{L}_{R_P,\lambda} = \lambda_{ijk} \left[ \tilde{\nu}_{iL} \bar{e}_{kR} e_{jL} + \tilde{e}_{jL} \bar{e}_{kR} \nu_{iL} + \tilde{e}_{kR}^* \overline{(\nu_{iL})^C} e_{jL} - (i \leftrightarrow j) \right]_F + h.c., \quad (4)$$

whereas the  $\lambda'$  terms yield

$$\begin{aligned} \mathcal{L}_{R_P,\lambda'} = \lambda'_{ijk} \left[ \tilde{\nu}_{iL} \bar{d}_{kR} d_{jL} + \tilde{d}_{jL} \bar{d}_{kR} \nu_{iL} + \tilde{d}_{kR}^* \overline{(\nu_{iL})^C} d_{jL} - \tilde{e}_{iL} \bar{d}_{kR} u_{jL} \right. \\ \left. - \tilde{u}_{jL} \bar{d}_{kR} e_{iL} - \tilde{d}_{kR}^* \overline{(e_{iL})^C} u_{jL} \right] + h.c. \end{aligned} \quad (5)$$

In (4) and (5) particle names are used to label the corresponding particle fields.



Many of the couplings in (4) and (5) are already restricted by experimental data. For definiteness, we will consider here only those interactions for which  $1\sigma$  constraints from experiments allow the corresponding  $\lambda$  or  $\lambda'$  to exceed 0.2 (assuming a sfermion mass of 200 GeV). This should be compared with the electromagnetic coupling  $e \simeq 0.3$ . We then see from Table 1 of Ref. 6 that for the purely leptonic interactions in (4), only the couplings  $\lambda_{131}$  and  $\lambda_{133}$  satisfy this requirement. In contrast, the analysis of Ref. 6 does not lead to any constraint on the couplings,  $\lambda'_{3jk}$  (for all  $j$  and  $k$ ),  $\lambda'_{222}$ ,  $\lambda'_{223}$ ,  $\lambda'_{232}$  and  $\lambda'_{233}$ ; furthermore, the couplings  $\lambda'_{121}$ ,  $\lambda'_{122}$ ,  $\lambda'_{133}$ ,  $\lambda'_{123}$  and  $\lambda'_{131}$  can indeed be larger than 0.2, and so satisfy our requirement above.

As noted in Ref. 23, the experimental upper limit on the mass of the electron neutrino translates into the bound  $\lambda_{133} \lesssim 3 \times 10^{-3} (m_{\tilde{\tau}}/100 \text{ GeV})^{1/2}$ . Since we generalize this result, let us recapitulate the argument leading to it. We begin by noting that the  $\lambda_{133}$  interaction can induce a Majorana mass,

$$\delta m_{\nu_e} \sim \frac{\lambda_{133}^2}{8\pi^2} \frac{1}{m_{\tilde{\tau}}^2} M_{SUSY} m_{\tau}^2, \quad (6)$$

for  $\nu_e$  via diagrams involving  $\tau\tilde{\tau}$  loops. In (6), one factor of  $m_{\tau}$  arises from the  $\tau$ -chirality flip whereas a factor  $m_{\tau} M_{SUSY}$  comes from  $\tilde{\tau}_L - \tilde{\tau}_R$  mixing. Taking  $M_{SUSY} \simeq m_{\tilde{\tau}}$  leads to the bound  $\lambda_{133} \lesssim O(10^{-3})$  mentioned above. It should be clear that the argument also carries over for the  $\lambda'_{1jk}$  couplings in (5); we then find

$$\delta m_{\nu_e} \sim \frac{\lambda'_{1jk}}{8\pi^2} \frac{1}{m_{\tilde{q}}^2} M_{SUSY} m_j m_k, \quad (7)$$

where  $m_j$  and  $m_k$  are the masses of the  $T_3 = -1/2$  quarks of the  $j^{\text{th}}$  and  $k^{\text{th}}$  generation. Assuming  $m_{\tilde{q}} \simeq m_{\tilde{\tau}}$ , we see that the bound on  $\lambda'_{1jk}$  is weakened from that on  $\lambda_{133}$  by a factor  $(m_j m_k / m_{\tilde{\tau}}^2)^{1/2}$ . Thus we derive the hitherto unnoticed constraint that with the exception of  $\lambda'_{112}$ ,  $\lambda'_{121}$  and  $\lambda'_{111}$ , the bound on  $m_{\nu_e}$  excludes all  $\lambda'_{1jk}$  type couplings.

Combining the results of this analysis with those of Ref. 6 discussed above, we see that the allowed couplings are just  $\lambda_{131}$ ,  $\lambda'_{3jk}$ ,  $\lambda'_{121}$ ,  $\lambda'_{222}$ ,  $\lambda'_{223}$ ,  $\lambda'_{232}$  and  $\lambda'_{233}$ . The first two couplings violate only  $\tau$ -number conservation, the third violates  $e$ -number conservation, while the remaining ones violate the conservation of muon number. We should also mention that there may be further constraints on the simultaneous violation of two, or more, lepton flavours, since then restrictions from the non-observation of  $\mu \rightarrow e$ ,  $\tau \rightarrow \mu$  transitions will also be applicable.

In the following, we will mainly focus on the possibility that just  $\tau$ -lepton number is violated. The relevant vertices are shown in Fig. 1 and Fig. 2 for the  $\lambda$  and  $\lambda'$  type interactions, respectively. It will be easy to adapt our discussion for the case where, instead,  $e$ - or  $\mu$ -violating interactions are dominant. Since the

efficiency for the identification of  $\tau$ 's is significantly smaller than that for  $e$  or  $\mu$ , we expect that it will be considerably easier to identify signals for  $e$ - or  $\mu$ -violating interactions. We will return to these issues in the concluding section.

### 3. $R_P$ and $L_\tau$ processes

Our prototype process consists of the simultaneous decay of a pair of  $LSP$ s (assumed to be the neutralino  $\tilde{Z}_1$ ) produced at LEP 200. The  $R_P$ -conserving production reaction  $e^+e^- \rightarrow \tilde{Z}_1\tilde{Z}_1$  gets followed by each  $\tilde{Z}_1$  undergoing an  $R_P$ -violating decay into three fermions – changing  $L_\tau$  by one unit. The three-body decay of each  $\tilde{Z}_1$  proceeds first by a gauge vertex transition into a real fermion and a virtual sfermion, the latter further undergoing a transition into two additional fermions via one of the vertices of Fig. 1 or Fig. 2. If the virtual sfermion is a third-generation slepton, the  $R_P$ - and  $L_\tau$ -violating vertex can be either of the  $\lambda$ -type or of the  $\lambda'$ -type. In the former case the decay products of the  $\tilde{Z}_1$  are two oppositely charged leptons which are visible and a neutrino which generates  $\cancel{E}_T$ , i.e.  $\ell\bar{\ell} + \cancel{E}_T$ . In the latter case the decay products are a  $\tau$  or a  $\nu_\tau$ , accompanied by two quarks which generally fragment into two jets, i.e.  $(2j)\ell$ ,  $(2j)\bar{\ell}$  or  $(2j) + \cancel{E}_T$ . Here and in the following we denote each quark as an independent jet, though the

jets could actually merge. For the situation where the virtual sfermion is a squark, the corresponding  $R_P$ -violating vertex must necessarily be of the  $\lambda'$ -type so that the decay products of the  $\tilde{Z}_1$  appear as one of three possible combinations:  $(2j)\tau$ ,  $(2j)\bar{\tau}$  and  $(2j) + \cancel{E}_T$ .

The pair of on-shell  $LSP$ s, produced in  $e^+e^-$  annihilation, can finally lead to three types of visible final state configurations corresponding to three possible combinations of  $\lambda$ - and  $\lambda'$ -type decay vertices involved in the transition of the virtual sfermion.

(1) Both operative  $R_P$ - and  $L_\tau$ -violating vertices are of the  $\lambda$ -type resulting in four charged leptons (of total charge zero) and  $\cancel{E}_T$  from the two  $\tilde{Z}_1$ 's.

(2) The decays of both  $\tilde{Z}_1$ 's involve  $\lambda'$ -type vertices yielding one of the following six visible final state configurations:  $(4j)\tau\tau$ ,  $(4j)\tau\bar{\tau}$ ,  $(4j)\bar{\tau}\bar{\tau}$ ,  $(4j)\tau + \cancel{E}_T$ ,  $(4j)\bar{\tau} + \cancel{E}_T$  and  $(4j) + \cancel{E}_T$ .

(3) One  $\tilde{Z}_1$ -decay involves a  $\lambda$ -type vertex and the other a  $\lambda'$ -type interaction leading to the following nine visible combinations:  $\tau\tau\bar{e}(2j) + \cancel{E}_T$ ,  $\bar{\tau}\bar{\tau}e(2j) + \cancel{E}_T$ ,  $\tau\bar{\tau}e(2j) + \cancel{E}_T$ ,  $\tau\bar{\tau}\bar{e}(2j) + \cancel{E}_T$ ,  $e\bar{e}\tau(2j) + \cancel{E}_T$ ,  $e\bar{e}\bar{\tau}(2j) + \cancel{E}_T$ ,  $\tau\bar{e}(2j) + \cancel{E}_T$ ,  $\bar{\tau}e(2j) + \cancel{E}_T$  and  $e\bar{e}(2j) + \cancel{E}_T$ .

Let us take case (1) above first. As discussed in Section 2, only the coupling  $\lambda_{131}$  is allowed. The possible decay products of the  $\tilde{Z}_1$  from a  $\lambda_{131}$  vertex are  $\tau\bar{e}\nu_e$ ,  $\bar{\tau}e\bar{\nu}_e$ ,  $\bar{e}e\nu_\tau$  and  $e\bar{e}\bar{\nu}_\tau$ . At the tree level each decay proceeds via three diagrams separately involving stau-exchange, selectron-exchange and sneutrino-exchange. In the limit of ignoring the masses of all final state leptons and of taking all sfermions to be mass-degenerate, all the partial widths are identical. In what follows, we give ratios of cross sections rather than observable rates which have to be calculated by folding in the appropriate detection efficiencies. The total cross sections for the six visible distinct final state configurations formed out of  $e^+e^-$  collision will be in

the combinatorial ratios

$$\begin{aligned} \sigma(\tau\tau\bar{e}\bar{e} + \cancel{E}_T) : \sigma(\bar{\tau}\bar{\tau}ee + \cancel{E}_T) : \sigma(e\bar{e}\tau\bar{\tau} + \cancel{E}_T) : \sigma(e\bar{e}\bar{e}\tau + \cancel{E}_T) : \sigma(e\bar{e}e\bar{\tau} + \cancel{E}_T) \\ : \sigma(e\bar{e}e\bar{e} + \cancel{E}_T) = 1 : 1 : 2 : 4 : 4 : 4. \end{aligned} \quad (8)$$

Rate estimates will be provided in Section 4. We just comment here on the fact that in the *SM* the processes  $e\bar{e} \rightarrow \tau\tau\bar{e}\bar{e} + \cancel{E}_T$ ,  $\bar{\tau}\bar{\tau}ee + \cancel{E}_T$ ,  $e\bar{e} \rightarrow e\bar{e}\tau\bar{\tau} + \cancel{E}_T$ ,  $e\bar{e}e\bar{\tau} + \cancel{E}_T$ ,  $e\bar{e}\bar{e}\tau + \cancel{E}_T$  and  $e\bar{e}e\bar{e} + \cancel{E}_T$  have rather tiny rates.

Turning to case (2), the possible decay products of the  $\tilde{Z}_1$  from all  $\lambda'_{3jk}$  vertices are  $\tau u_j \bar{d}_k$ ,  $\bar{\tau} \bar{u}_j d_k$ ,  $\nu_\tau d_j \bar{d}_k$  and  $\bar{\nu}_\tau \bar{d}_j d_k$ . Since the top quark is kinematically inaccessible in LSP decays, the generation index  $j$  runs over just 1,2 for up-type quarks and 1,2,3 for down-type quarks. Moreover, each decay proceeds via three tree diagrams – exchanging a left slepton, a left squark or a right squark. Working in the same mass limit mentioned earlier, the combinatorial rate ratios between the five visible

final state configurations now are:

$$\begin{aligned} \sigma[\tau\tau(4j)] : \sigma[\bar{\tau}\bar{\tau}(4j)] : \sigma[\tau\bar{\tau}(4j)] : \sigma[\tau(4j) + \cancel{E}_T] : \sigma[\bar{\tau}(4j) + \cancel{E}_T] \\ : \sigma[(4j) + \cancel{E}_T] = 1 : 1 : 2 : 2x : 2x : x^2. \end{aligned} \quad (9)$$

The factor  $x$  arises from the fact that the top quark is not produced. It is equal to  $2 + |\alpha|^2$ ,  $\alpha$  being a coupling-dependent

parameter which vanishes if  $\lambda'_{33k} = 0$ , and diverges if  $\lambda'_{33k}$  are the dominant couplings. The reactions  $e^+e^- \rightarrow \tau\tau(4j)$ ,  $\bar{\tau}\bar{\tau}(4j)$  are specially interesting in that there is no missing  $E_T$  in the primary process. The possibility of searching for  $\tau$ -number violation via like sign ditau signal, first proposed for hadron colliders in Ref. 2, holds even better promise at LEP 200. These reactions are hallmarks of the self-conjugate nature of the *LSPs* and would be essentially absent in the *SM*. A  $q\bar{q}$  pair and two radiated gluons

plus a virtual photon decaying into a  $\tau$ -pair could yield  $\tau\bar{\tau}(4j)$  but with a tiny rate. The  $\tau(4j) + \cancel{E}_T$  or  $\bar{\tau}(4j) + \cancel{E}_T$  final state could come from two  $W$ 's, one

decaying semileptonically into a  $\tau$  (or  $\bar{\tau}$ ) and the other into  $q\bar{q}'$  plus two radiated gluons; but the rate would again be rather low. The  $(4j) + \cancel{E}_T$  final state could arise from double  $Z$  production, one  $Z$  decaying into a  $\nu\bar{\nu}$  pair and the other into  $q\bar{q}$  plus two radiated gluons.

Lastly, in case (3), arguments – similar to those given above and in the same limit – imply:

$$\begin{aligned}
& \sigma[\tau\tau\bar{e}(2j) + \cancel{E}_T] : \sigma[\bar{\tau}\bar{\tau}e(2j) + \cancel{E}_T] : \sigma[\tau\bar{\tau}e(2j) + \cancel{E}_T] : \sigma[\bar{\tau}\bar{\tau}\bar{e}(2j) + \cancel{E}_T] \\
& \quad : \sigma[\bar{e}e\tau(2j) + \cancel{E}_T] : \sigma[\bar{\tau}e\bar{e}(2j) + \cancel{E}_T] : \sigma[\tau\bar{e}(2j) + \cancel{E}_T] : \sigma[\bar{\tau}e(2j) + \cancel{E}_T] \\
& \quad : \sigma[\bar{e}e(2j) + \cancel{E}_T] = 1 : 1 : 1 : 1 : 2 : 2 : 2x : 2x : 4x.
\end{aligned} \tag{10}$$

Except for the last configuration, all the others are quite striking and difficult to simulate in the  $SM$ .

We will now discuss, within our explicit  $R_P$ - and  $L_\tau$ -breaking scenario, the consequences of the  $LSP$  being different from a neutralino. As explained in the Introduction, there are theoretical reasons that disfavour squarks (except, possibly, a light stop) and gluinos from being

$LSP$  candidates so that after the lightest neutralino we need consider only the lightest electroweak chargino  $\tilde{W}_1$ , the lightest slepton and the strongly interacting stop  $\tilde{t}$ . In any case, LEP experiments have [4,24] established a lower mass bound in the vicinity of  $M_Z/2$ . However, the magnitudes of the cross sections concerned are not very sensitive to the mass of the  $LSP$  unless it is at the boundary of phase space. Moreover, in the mass-range of interest, the cross section for chargino pair-production is substantially larger than that for neutralinos, while slepton or stop particle-antiparticle pairs would be produced at smaller rates.

Turning to event characteristics, consider the chargino case first. Exactly as in the neutralino case, it can decay into a fermion (quark or

lepton) antifermion pair in which one is on-shell and the other is off-shell. The latter, if a lepton, decays only by a  $\lambda$ -type coupling while, if a quark, it can decay either by a  $\lambda$ - or by a  $\lambda'$ -term. Once again there are three possibilities:

1) The decay of each chargino  $\tilde{W}_1$  proceeds via the  $\lambda_{131}$  coupling. There are two channels,  $\tilde{W}_1^- \rightarrow e\bar{e}\tau$

and  $\tilde{W}_1^- \rightarrow e\bar{\nu}_e\bar{\nu}_\tau$ , as well as their

charge conjugates. Each has two tree-level diagrams mediated by a first-

or third-generation virtual slepton, down-type for the first channel and up-type for the second. In the limit specified earlier, the corresponding partial decay widths are in the ratio  $\sin^2 \gamma_L : \sin^2 \gamma_R$ . Here we use the notation of Baer et. al. [25] with  $\gamma_{L,R}$  as the rotation angles in the mass-diagonalization of the left-, right-handed wino fields. The total rates for the four visible final state configurations in  $e^+e^-$  annihilation will be in the ratio

$$\begin{aligned} \sigma(e\bar{e}e\bar{e}\tau\bar{\tau}) : \sigma(e\bar{e}\tau\bar{e} + \cancel{E}_T) : \sigma(e\bar{e}\bar{\tau}e + \cancel{E}_T) : \sigma(e\bar{e} + \cancel{E}_T) = \\ \sin^4 \gamma_L : \sin^2 \gamma_L \sin^2 \gamma_R : \sin^2 \gamma_L \sin^2 \gamma_R : \sin^4 \gamma_R. \end{aligned} \quad (11)$$

2) Each  $\tilde{W}_1$  decays by use of a  $\lambda'$ -vertex. The decay channels are  $\tilde{W}_1^- \rightarrow \tau d_j \bar{d}_k$  and  $\tilde{W}_1^- \rightarrow \bar{\nu}_\tau d_j \bar{u}_k$  as well as their charge conjugates. Once again, there are two tree-level diagrams per channel involving squark and slepton exchanges: down-type for the first channel and up-type for the other. Now, because of the absence of the top from the final state, the partial widths are as  $y \sin^2 \gamma_L : \sin^2 \gamma_R$  where  $y$  has the form  $1 + |\beta|^2$ ,  $\beta$  being a parameter analogous to  $\alpha$ . The total cross sections of the four visible final-state configurations are expected to be produced in the ratios:

$$\begin{aligned} \sigma[\tau\bar{\tau}(4j)] : \sigma[\tau(4j) + \cancel{E}_T] : \sigma[\bar{\tau}(4j) + \cancel{E}_T] : \sigma[(4j) + \cancel{E}_T] \\ = y^2 \sin^4 \gamma_L : y \sin^2 \gamma_L \sin^2 \gamma_R : y \sin^2 \gamma_L \sin^2 \gamma_R : \sin^4 \gamma_R, \end{aligned} \quad (12)$$

3) One  $\tilde{W}_1$  decays via a  $\lambda$ -type vertex and the other through a  $\lambda'$ -type one. There are seven different visible final state configurations now with total rate pro-

proportionalities given by

$$\begin{aligned}
& \sigma[e\bar{e}\tau\bar{\tau}(2j)] : \sigma[e\bar{e}\tau(2j) + \cancel{E}_T] : \sigma[e\bar{e}\bar{\tau}(2j) + \cancel{E}_T] : \sigma[e\bar{\tau}(2j) + \cancel{E}_T] \\
& \quad : \sigma[\bar{e}\tau(2j) + \cancel{E}_T] : \sigma[e(2j) + \cancel{E}_T] : \sigma[\bar{e}(2j) + \cancel{E}_T] \\
& = 2y \sin^4 \gamma_L : \sin^2 \gamma_L \sin^2 \gamma_R : \sin^2 \gamma_L \sin^2 \gamma_R : y \sin^2 \gamma_L \sin^2 \gamma_R \\
& \quad : y \sin^2 \gamma_L \sin^2 \gamma_R : \sin^4 \gamma_R : \sin^4 \gamma_R.
\end{aligned} \tag{13}$$

Evidently, there are many striking event configurations here which would be hard to produce in the *SM*. But, because of the Dirac nature of the chargino, there are no unambiguous indicators of  $\tau$ -number violation.

Turning now to sleptons, in the case where  $\tilde{\nu}_\tau$  is the *LSP*, it can be produced in  $e^+e^-$  collision either singly via the  $\lambda_{131}$  coupling (Fig. 1) or in a pair through gauge interactions. The decay of a  $\tilde{\nu}_\tau$  can take place either into  $e\bar{e}$  or into  $\bar{d}_j d_k$  by means of the  $\lambda'_{3jk}$  couplings (Fig. 2). The presence of an *s*-channel resonance will be a spectacular indicator of the former. However, being of small width, it may easily be missed at LEP 200 unless there is a dedicated search spanning the CM energy range 100 – 200 GeV in narrow bins. On the other hand, if  $|\lambda_{131}|$  is much less than the semiweak gauge coupling strength, pair-production would really be the dominant mechanism to produce  $\tilde{\nu}_\tau$ 's in  $e^+e^-$  collision. Considering only the latter process, the different possible visible final-state configurations will be  $e^+e^-e^+e^-$ ,  $e^+e^-(2j)$  and  $4j$ ; these should lead to an observable increase in the number of spherical events at LEP 200. In the first and second cases, each of the appropriate  $e^+e^-$  pair(s) will have a resonant

invariant mass facilitating a relatively clean separation of these events. However, we find no clear  $L_\tau$ -violating signature in the case where

$\tilde{\nu}_\tau$  is the *LSP*, since any pair-produced scalars

decaying into  $e^+e^-$  or  $q\bar{q}$  will generate similar signals.

In the case where the *LSP* is a sneutrino belonging to either of the first two generations, it can only be pair-produced at  $e^+e^-$  colliders. Since we retain only

the couplings  $\lambda_{131}$ ,  $\lambda'_{3jk}$  in (6) and (7), only  $\tilde{\nu}_e$  and  $\tilde{\nu}_e^*$  can have direct two-body decays at the tree level (Fig. 1):  $\tilde{\nu}_e \rightarrow e\bar{\tau}$ ,  $\tilde{\nu}_e^* \rightarrow \bar{e}\tau$ . In general, two-body decays of  $\tilde{\nu}_\mu$  and  $\tilde{\nu}_\mu^*$  are also possible but they can only take place through 1-loop diagrams making them longer-lived. These decays are  $\tilde{\nu}_\mu \rightarrow \mu\bar{\tau}, \nu_\mu\nu_\tau, \nu_\mu\bar{\nu}_\tau$  and the corresponding conjugates. They are, however, absent if  $\lambda_{131}$  is the only  $R_P$ -violating coupling. Thus it is more likely that  $\tilde{\nu}_\mu$  would decay via four-body modes. These decays proceed in three steps, as shown in Fig 3, resulting in the final states  $\mu\bar{\tau}f\bar{f}, \nu_\mu\tau f_1\bar{f}_2, \nu_\mu\bar{\tau}\bar{f}_1f_2$  and their conjugates. Here  $f$  is either  $e$  or a  $d_k$ -quark and the  $f_1\bar{f}_2$  pair can be either  $\nu_e\bar{e}$  or  $u_j\bar{d}_k$ .

An interesting point in connection with the four-body decays is the following. In each two-body decay the sign of the emanant  $e$  or  $\mu$  (and hence that of the associated  $\tau$ ) is determined by  $e$ - or  $\mu$ -conservation. Thus, as in the  $LSP = \tilde{\nu}_\tau$  case, there is no direct evidence of  $\tau$ -number violation. In contrast, in the  $\tilde{Z}_1$ -mediated four-body decays, the emanant  $\tau$  from the same decaying sneutrino can have either sign. Thus one can have – in  $e^+e^-$  collisions – eight different visible leptonic final configurations from  $\tilde{\nu}_\mu\tilde{\nu}_\mu^*$   $LSP$  pair-production:  $\mu\bar{\mu}\tau\bar{\tau}e\bar{e}\bar{e}\bar{e}$ ,  $\mu\bar{\mu}\bar{\tau}e\bar{e}\bar{e}\bar{e} + \cancel{E}_T$ ,  $\bar{\mu}\tau\tau\bar{e}\bar{e}\bar{e} + \cancel{E}_T$ ,  $\mu\bar{\tau}\tau e\bar{e}\bar{e} + \cancel{E}_T$ ,  $\bar{\mu}\tau\bar{\tau}e\bar{e}\bar{e} + \cancel{E}_T$ ,  $\tau\bar{\tau}e\bar{e} + \cancel{E}_T$ ,  $\tau\tau\bar{e}\bar{e} + \cancel{E}_T$  and  $\bar{\tau}\bar{\tau}e\bar{e} + \cancel{E}_T$ . Additionally, there can be seventeen different visible lepton-jet combinations:  $\mu\bar{\mu}\tau\bar{\tau}(4j)$ ,  $\mu\bar{\tau}\bar{\tau}(4j) + \cancel{E}_T$ ,  $\bar{\mu}\tau\tau(4j) + \cancel{E}_T$ ,  $\mu\bar{\tau}\tau(4j) + \cancel{E}_T$ ,  $\bar{\mu}\tau\bar{\tau}(4j) + \cancel{E}_T$ ,  $\tau\bar{\tau}(4j) + \cancel{E}_T$ ,  $\tau\tau(4j) + \cancel{E}_T$ ,  $\bar{\tau}\bar{\tau}(4j) + \cancel{E}_T$ ,  $\mu\bar{\mu}\tau\bar{\tau}e\bar{e}(2j)$ ,  $\mu\bar{\tau}\bar{\tau}e\bar{e}(2j) + \cancel{E}_T$ ,  $\bar{\mu}\tau\tau e\bar{e}(2j) + \cancel{E}_T$ ,  $\mu\bar{\tau}\bar{\tau}e(2j) + \cancel{E}_T$ ,  $\bar{\mu}\tau\tau e(2j) + \cancel{E}_T$ ,  $\tau\bar{\tau}e(2j) + \cancel{E}_T$ ,  $\tau\tau\bar{e}(2j) + \cancel{E}_T$  and  $\bar{\tau}\bar{\tau}e(2j) + \cancel{E}_T$ . The cross sections for conjugate channels are identical. However, since the branching fractions for the various decays of  $\tilde{\nu}_\mu$  would depend on the details of the gaugino-higgsino mixing matrices, we do not make estimates of the above cross sections in this scenario. Lastly, note that the analysis of the signatures for the situation when a charged slepton is the  $LSP$  parallels that of the sneutrino case. Thus we will not elaborate on this further.

Let us finally consider the case where the  $LSP$  is the top squark (or stop)  $\tilde{t}$ . As we will see, this is rather similar to the  $LSP = \tilde{\nu}_\ell$  ( $\ell \neq \tau$ ) case discussed above. As explained in Ref. [19], substantial mixing between the  $\tilde{t}_L$  and  $\tilde{t}_R$  states, caused



by the large Yukawa interactions of the top family, may make the lighter of the two stop mass-eigenstates ( $\tilde{t}_1$ ) lower in mass than all other superparticles. The mass-breaking as well as the mixing angle between the two  $\tilde{t}$ -states depends on various yet unknown constants such as the supersymmetry-breaking  $A$  parameter, the supersymmetric higgsino mass and  $\tan\beta$ , the ratio of the two VEVs of the Higgs fields in the model. Top squarks can only be pair-produced at LEP 200. The  $s$ -channel photon contribution to the production cross section is fixed by quantum electrodynamics so that the total production rate is not expected to be sensitive to the details of stop mixing. Furthermore, the decay patterns of  $\tilde{t}_1$  are fixed by the  $R_P$ -violating interactions (5) so that the qualitative features of the signals for the production of  $\tilde{t}_1$  pairs are independent of the unknown details of the  $t$ -squark sector. Since we are interested in signals at LEP 200, we will further assume that  $m_{\tilde{t}_1} < m_t$  since even a  $t$ -squark as light as 50 GeV can be accommodated, though

other strongly interacting superparticles such as the gluino may have masses as high as several hundred GeV.

The decays of the lightest  $t$ -squark will be somewhat similar to those of the  $\tilde{\nu}_e = LSP$  case discussed earlier. It can directly decay by the two-body mode  $\tilde{t}_1 \rightarrow \bar{\tau}d_k$  at the tree-level via the  $\lambda'_{33k}$  coupling (Fig. 2). It can also have the four-body decay  $\tilde{t}_1 \rightarrow \bar{\tau}bf\bar{f}$  in analogy with  $\tilde{\nu}_\ell$  (Fig. 4a), only the initial vertex  $\tilde{t}_1 b \tilde{W}_1$  being different. It may be noted, though, that – unlike as in the  $\tilde{\nu}_\ell$  case for the LSP – there will be no like sign ditau signal from the decays of  $\tilde{t}_1$  and  $\tilde{t}_1^*$ . The sign of the  $\tau$  is determined by that of  $\tilde{t}_1$  since neutralino-mediated  $\tau$  decays would involve a  $t$  quark in the final state, which is kinematically forbidden. Finally, we remark that, if the two-body decays dominate over four-body ones, signals from  $\tilde{t}_1$  pair-production will resemble those from the production of  $\tau$  scalar leptoquark pairs.

#### 4. Cross sections for $R_P$ signals from neutralinos

In this section we present cross sections for  $\tau$ -number and  $R_P$ -violating signals from the production of neutralinos at LEP 200. Our reasons for focusing on neu-

tralinos as opposed to other *LSP* candidates are two-fold. First, in many models, the *LSP* is likely to be a neutralino. Second, as we have seen, the Majorana nature of the neutralino can potentially result in unambiguous signals for  $\tau$ -number violation in the form of like-sign ditau events. These will have low missing  $E_T$  coming only from the decay of the taus. The absence of any large missing  $E_T$  thus make it unlikely that there would be two undetected particles in these events that balance  $\tau$ -number.

The cross section for the production of a  $\tilde{Z}_1\tilde{Z}_1$  pair depends on the mixing angles in the neutralino sector. Here, we have used the MSSM as a guide; the cross section  $\sigma(\tilde{Z}\tilde{Z}_1)$  is then determined [26] by just a few parameters. We may take these to be (1) the gluino mass ( $m_{\tilde{g}}$ ) which fixes the  $SU(2)$  and  $U(1)$  gaugino masses via a unification condition [1]; (2) the supersymmetric higgsino mass,  $2m_1$ ; (3) the ratio,  $\tan \beta$ , of the vacuum expectation values of the two Higgs fields  $H_2$  and  $H_1$  and (4) the selectron mass which enters via amplitudes involving selectron exchange.

Our results for  $\sigma(\tilde{Z}_1\tilde{Z}_1)$  are shown in Fig. 4 for (a)  $m_{\tilde{e}} = 100$  GeV and (b)  $m_{\tilde{e}} = 200$  GeV. We have fixed  $\tan \beta = 2$  and illustrated the cross section in the  $2m_1 - m_{\tilde{g}}$  plane. The area between the heavy dotted lines corresponds to the region where  $m_{\tilde{Z}_1} \lesssim 45$  GeV. For parameters in this region,  $\tilde{Z}_1\tilde{Z}_1$  pair production should be accessible at LEP (unless  $\tilde{Z}_1$  is essentially a pure gaugino and the slepton is heavy). The decays of the  $\tilde{Z}_1\tilde{Z}_1$  pair would then lead to an excess of spherical events including tau leptons. Although such events may not have been explicitly searched for at LEP, we should bear in mind that the absence of such spherical events there can exclude about half the parameter plane in the scenario that we are considering.

It may be seen from Fig. 4 that, even for  $m_{\tilde{Z}_1} > 45$  GeV,  $\sigma(\tilde{Z}_1\tilde{Z}_1)$  may be almost 1 pb provided that  $m_{\tilde{e}} \simeq 100$  GeV. We stress that such light sleptons are perfectly consistent with CDF bounds on squark masses even within the framework of supergravity models. Fig. 4b, however, shows that in the ‘‘LEP 200 region’’ the

cross section falls off rapidly with increasing slepton mass. This is because over much of this region  $|2m_1|$  is rather large so that the  $LSP$  is dominantly a gaugino. The slepton exchange contribution to the  $\tilde{Z}_1\tilde{Z}_1$  production amplitude is then very significant. Nevertheless, up to a hundred  $\tilde{Z}_1\tilde{Z}_1$  events are expected

annually even if  $m_{\tilde{e}} \simeq 200$  GeV, assuming an integrated luminosity of  $500 \text{ pb}^{-1}$  at LEP 200. We then see from (8) and (9) that a handful of like-sign tau events may be expected in this case, assuming that the taus can be identified by their single prong hadronic decay which results in isolated, hard  $\pi^\pm$  tracks. If  $m_{\tilde{e}} \simeq 100$  GeV, the signal may be larger by as much as a factor five. In contrast, if the sleptons are very heavy, the signal is likely to be unobservable. The dependence of the signal on  $\tan \beta$  is illustrated in Fig. 5. We see that the signal is relatively insensitive to  $\tan \beta$  in the region where  $m_{\tilde{Z}_1} \geq 45$  GeV.

We note here that, by combining the ratios (8) - (10) with the results in Figs. 4 and 5, it is possible to obtain an estimate of the cross sections for various event topologies from neutralino pair production at LEP 200 if we assume that either  $\lambda$ - or  $\lambda'$ -type operators dominate. We see that these cross sections are all rather small. The detectability of these novel signals, in particular, the like-sign ditau + jets signal, will crucially depend on the experimental efficiency for  $\tau$ -identification.

In order to give the reader some idea of the kinematics of the  $LSP$  events,

we have shown in Fig. 6a the  $p_T$  distribution of the leptons in the  $\tau\tau\bar{e}\bar{e} + \cancel{E}_T$  and  $\bar{\tau}\bar{\tau}ee + \cancel{E}_T$  final states that result if the  $LSP$  decays by the  $\lambda_{131}$  interaction. These have been obtained by explicitly calculating the concerned matrix element squared with MSSM couplings [25] and taking all sleptons to be equally massive; for the slepton masses that we consider, the distributions are essentially governed

by phase space. We have illustrated these distributions for  $m_{\tilde{Z}_1} = 45$  GeV and  $m_{\tilde{Z}_1} = 90$  GeV

and, for just the former case, for two values of SUSY parameters which give rise to different values of  $\sigma(\tilde{Z}_1\tilde{Z}_1)$ . Also shown is the  $p_T$  distribution from the SM background from  $ZZ$  production where both  $Z$ 's decay via  $\tau\bar{\tau}$ , and the electrons

arise via  $\tau$ -decay. As expected for the latter, the  $p_T(e)$  distribution is very soft. In contrast, we see that the  $p_T$  distribution of the leptons from  $LSP$  decays is fairly hard and essentially determined by

the mass of the  $LSP$ . Since electrons with a  $p_T$  of a few GeV should readily be detectable at LEP 200, we believe that the signal will be determined mainly by the  $\tau$  detection efficiency.

Since the  $\tau$ 's are expected to be identified via their narrow, low-charged multiplicity ( $n = 1$  or  $3$ ) jets, the detectability of  $\tau\tau(4j)$  events will critically depend on how isolated these  $\tau$ 's are. Toward this end, we have constructed a parton-level Monte Carlo program to simulate these events from neutralino pair production. Jets are defined to be partons; we have coalesced partons within  $\Delta r \equiv [(\Delta y)^2 + (\Delta\phi)^2]^{1/2} < 0.7$  into a single jet. Fig. 6b shows the distribution of

Min  $\Delta r(\tau, \text{jet})$  in the  $\tau\tau$  (multi-jet) events, where Min  $\Delta r$  is the minimum separation between either of the  $\tau$ 's and the nearest jet, in each event. In this figure, we have also required that the jets and  $\tau$ 's be all central, i.e. satisfy  $|y| \leq 1.5$ . We see from the figure that the  $\tau$ 's are well separated from the jets. Even for  $m_{\tilde{Z}_1} = 30$  GeV, about 2/3 of the events satisfy  $\Delta r > 0.5$ , whereas for heavy neutralinos this figure is considerably larger. For instance, if  $m_{\tilde{Z}_1}$  is 60 GeV, the requirement that both the  $\tau$ 's satisfy  $\Delta r > 0.5$  causes a loss of only 20% of the events where all the leptons and jets are central. We should also mention that the  $p_T(\tau)$  distribution in these events should be similar to that in Fig. 6a. Similar observations apply to the events containing single  $\tau$  ( $\bar{\tau}$ ) + jets, discussed in Section 3.

The results of Fig. 6 are encouraging. We have further checked that the missing  $E_T$  in these events is essentially determined by the  $LSP$  mass, and is typically slightly below  $m_{\tilde{Z}_1}/2$ . Finally, we note that the  $\tau$ 's are acollinear. For  $m_{\tilde{Z}_1} = 30$  GeV, the angular separation  $\Delta\phi$  between the  $\tau$ 's is, on average, about  $150^\circ$ , while for  $m_{\tilde{Z}_1} \simeq 60$  GeV this becomes  $120^\circ$ . We should note, though, that this distribution peaks at  $\Delta\phi = 180^\circ$ . We also mention that for  $m_{\tilde{Z}_1} \geq 45$  GeV, four jet topologies dominate, whereas for lighter neutralinos, there is three-jet dominance.

While our preliminary results appear promising, detailed Monte Carlo studies are necessary before definite conclusions can be drawn regarding the viability of these signals.

At this point, several remarks are in order:

- (i) As stated in the Introduction, we focus only on signals from  $LSP$  pair production assuming that all other sparticles are kinematically inaccessible. Within the MSSM, charginos will also be accessible at LEP 200 for a large part of the parameter space in Figs. 5

and 6.

- (ii) We have assumed that the  $LSP$  mixing patterns which determine the cross sections in Figs. 5 and 6 are as given by the MSSM. This may, of course, not be the case so that (in principle) the cross sections may differ considerably from those shown. The rates shown in the figures should only be regarded as indicative.

Before concluding this Section, we note that if the  $LSP$  is any sparticle other than the neutralino, the cross sections may be substantially different

from those shown in Fig. 4 and Fig. 5. For instance, the cross section for producing a pair of 60 GeV charginos is [15] typically a few picobarns, whereas the corresponding cross section for the case when the  $LSP$  is a 60 GeV slepton or top-squark is about an order of magnitude less. The latter process also suffers a  $p$ -wave suppression so that its cross section falls rapidly with an increasing sfermion mass. Finally, we note that if the neutralinos are heavy, the selectron pair production cross section becomes comparable to that for smuons or staus;  $t$ -channel neutralino exchange contributions to  $\sigma_{\tilde{e}\tilde{e}}$  may, however, enhance this if  $m_{\tilde{Z}_1} \approx m_{\tilde{e}}$ .

## 5. Alternative mechanisms

There could be rival “new physics” mechanisms that can mimic the  $LSP$  signals discussed in Section 3. For definiteness, let us focus on the  $\tilde{Z}_1 = LSP$  case. The

distinctive like-sign ditau signals are due to the Majorana nature of the neutralino. However, an unstable heavy Majorana neutrino, containing an admixture of  $\nu_\tau$ , can also yield similar  $\tau$ -number violating signals.

If the heavy Majorana neutrino  $\nu_M$  is dominantly an  $SU(2)_L$  singlet with a small component of the usual doublet, the *GIM* mechanism is no longer operative. The decay  $Z \rightarrow \nu_M(\nu_\tau)_{\text{phys}}$  should then proceed at a rate which is suppressed relative to that of  $Z \rightarrow \nu_e\bar{\nu}_e$  by a factor of  $\sin^2\alpha$ , where  $\sin\alpha$  is the  $\nu_\tau$ -admixture in  $\nu_M$ . The subsequent decay of  $\nu_M$  would then lead to spectacular missing- $E_T$  events at LEP. The non-observation of such events in the sample of  $O(10^6)Z$  bosons, already collected by LEP experiments, then requires that  $\sin\alpha \lesssim O(10^{-2})$ . In this case the cross section for the production of a  $\nu_M$ -pair, which is suppressed by  $\sin^4\alpha$ , is too small to be interesting.

We are thus led to examine the possibility that  $\nu_M$  contains a substantial  $SU(2)_L$  doublet component [27] and decays via  $\tau$ -number violating interactions. A simple model realizing this possibility is presented in the Appendix. The Majorana neutrino here is essentially a sequential fourth generation neutrino which gets a mass in the range 50 – 100 GeV by seesaw mixing with an  $SU(2)_L$  singlet neutrino with a Majorana mass  $\sim 1$  TeV. In this scenario the strength of the  $Z\nu_M\nu_M$  coupling is comparable to that of the  $Z\nu_e\bar{\nu}_e$  one. Thus the cross section for producing a  $\nu_M$ -pair may well exceed that for the pair-production of neutralinos (which is often reduced by mixing angle factors), shown in Figs. 4 and 5. It is, therefore, necessary to study the details of the final states obtained via  $\nu_M\nu_M$  production in order to see if the  $\nu_M$  signals can be distinguished from those for neutralinos.

Once produced, a  $\nu_M$  can decay only via gauge interactions into  $\tau\bar{\ell}\nu_\ell$ ,  $\bar{\tau}\ell\bar{\nu}_\ell$ ,  $\tau u_i\bar{d}_j$  and  $\bar{\tau}\bar{u}_i d_j$  via  $W$ -exchange and into  $\nu_\tau\ell\bar{\ell}$ ,  $\bar{\nu}_\tau\ell\bar{\ell}$ ,  $\nu_\tau q\bar{q}$  and  $\bar{\nu}_\tau q\bar{q}$  via  $Z$ -exchange. Furthermore, since gauge interactions are universal, all flavours of quarks and leptons are produced via these decays provided

they are kinematically accessible.

Interesting final state leptonic configurations from  $\nu_M\nu_M$  production, therefore,

include  $\tau\tau\bar{\ell}\bar{\ell}' + \cancel{E}_T$ ,  $\bar{\tau}\bar{\tau}\ell\ell' + \cancel{E}_T$ ,  $\ell\bar{\ell}'\tau\bar{\tau} + \cancel{E}_T$ ,  $\tau\ell\bar{\ell}'\bar{\ell}'' + \cancel{E}_T$  and  $\bar{\tau}\bar{\ell}\ell'\ell'' + \cancel{E}_T$ , where  $\ell, \ell'$  and  $\ell''$  can be  $e, \mu$  or  $\tau$  with equal likelihood. Thus characteristic final states with muons and also with more than two  $\tau$ 's, which were essentially absent in the neutralino case discussed earlier, will also be present. In addition, since the charged and neutral current interactions – involved in the decay of  $\nu_M$  – are different, the five cross sections in (8) will no longer be in the specified proportionality. Turning to the semihadronic decays of  $\nu_M$ , we see that the final states are more or less the same as for the neutralino. Moreover, the characteristic ditau  $+(4j)$  events are produced in the same ratio as in (9). However, for the other channels described in (9), the full proportionality does not hold because of the simultaneous presence of  $W$ - and  $Z$ -exchange contributions here. A similar statement holds also for (10). There will also be additional relations among some of these configurations if they are generated from the decays of a pair of  $\nu_M$ 's: e.g. for  $W$ -exchange decays

$$\sigma[\tau\tau\bar{e}\bar{e} + \cancel{E}_T] : \sigma[\tau\tau\bar{\mu}\bar{\mu} + \cancel{E}_T] : \sigma[\tau\tau\bar{\mu}\bar{e} + \cancel{E}_T] : \sigma[\tau\tau(4j)] = 1 : 1 : 2 : 9. \quad (14)$$

Evidently, the differences between the leptonic signals provide the cleanest distinction between the neutralino and heavy Majorana neutrino scenarios.

In case our  $LSP$  is different from the neutralino, the  $\tau$ -number violating signals are different and other forms of new physics could mimic those. For instance, a new charged lepton, mixing dominantly with the  $\tau$ , could lead to signals similar to those discussed in Section 3. We do not discuss these options in detail.

Turning to models where  $R_P$  is spontaneously broken [21] via an  $SU(2) \times U(1)$  singlet sneutrino  $VEV$ , we note that these allow  $W^\pm \tilde{Z}_1 \tau^\mp$ ,  $Z \tilde{W}_1^\pm \tau^\mp$  and  $Z \tilde{Z}_1 \nu_\tau$  vertices with strengths given by the corresponding gauge couplings times some appropriate mixing factors. Their visible decay patterns can be both  $Z$ - and  $W$ -mediated. They are  $\tilde{Z}_1 \rightarrow \tau f_u \bar{f}_d, \bar{\tau} \bar{f}_u f_d, \nu_\tau \bar{f} f, \bar{\nu}_\tau f \bar{f}$  and  $\tilde{W}_1^- \rightarrow \nu_\tau \bar{f}_u f_d, \tau \bar{f} f, \tilde{W}_1^+ \rightarrow \bar{\nu}_\tau f_u \bar{f}_d, \bar{\tau} f \bar{f}$  where  $f$  is any fermion while  $f_u(f_d)$  is a fermion of the up (down) type. Various multilepton and/or multijet final states with or without  $\cancel{E}_T$  are possible from a  $\tilde{W}_1^+ \tilde{W}_1^-$  or  $\tilde{Z}_1 \tilde{Z}_1$  pair. We see, though, that the situation is

rather similar to that with a decaying heavy lepton (either neutral Majorana or charged and dominantly mixing with the  $\tau$ -family) pair and it would be hard to distinguish between those two scenarios. However, the tests proposed to distinguish between our explicitly broken  $R_P$  scheme and one with a heavy neutrino can also be used to discriminate the former from a spontaneously broken  $R_P$  model. Moreover, the presence of a Majoron and an associated light scalar might lead to additional signatures if  $R$ -parity is spontaneously violated.

## 6. Summary and concluding remarks

In this paper we have investigated the prospects for detecting explicit  $R_P$ -violation at LEP 200 in a  $\tau$ -number non-conserving scenario. If  $R_P$  is not conserved, a general analysis of supersymmetric signals becomes very difficult. This is because of the large number of new interactions that are then possible (see (2)), even assuming that baryon number is conserved. However, as reviewed in Section 2, there already exist experimental constraints on the coupling constants for these new interactions. For a sfermion mass  $\sim 200$  GeV, we find that  $e$ - or  $\mu$ -number violation can only be substantial (i.e. of electromagnetic strength) for interactions involving second- or third-generation quarks. In contrast, rather large  $\tau$ -number violating couplings are possible even for purely leptonic interactions, as well as for  $\tau$  interactions with first-generation quarks and squarks. This is why we have focused on  $\tau$ -number violation in our analysis.

Unlike in the MSSM, an unstable  $LSP$  need no longer be neutral. We have pointed out in Section 1 how any one of the neutralino, sneutrino, charged slepton, top squark or chargino may well be the  $LSP$  in an  $R_P$ -violating scenario. As discussed in Sec. 3, for each one of these cases, the production of  $LSP$  pairs at LEP 200 leads to distinctive signatures in the form of spherical events with  $n$  leptons and  $m$  jets, possibly accompanied by a substantial amount of missing energy ( $n, m \leq 4$ ). Since we have assumed that  $R_P$ -violation responsible for  $LSP$  decay is simultaneously accompanied by the non-conservation of  $\tau$ -



number, the final state from the decay of an  $LSP$  pair necessarily contains two leptons from the  $\tau$ -family. Our scenario is thus characterized by the fact that  $LSP$  pair production results in  $\tau$ -rich final states. Clearly, the prospects for the detection of such states will be sensitively dependent on the experimental efficiency for identifying  $\tau$ 's.

In order to keep our considerations free from any assumptions about the masses of other sparticles, we have confined our analysis to signals from just the production of  $LSP$  pairs. We stress, though, that the production of heavier sparticles will also lead to  $\tau$ -rich final states. This is because those particles can either decay to the  $LSP$  by  $R_P$ -conserving interactions, or directly decay to ordinary particles via the  $\tau$ -number violating interactions present in our scenario.

As mentioned above, the pair-production of heavy  $LSP$ s leads to very distinctive events. These have been catalogued in Section 3 for each of our  $LSP$  candidates. It is worth emphasizing that, despite our lack of knowledge about the coupling constants for the  $R_P$ -violating interactions, it is possible to relate the cross sections for various expected characteristic final states. For the case when the  $LSP$  is the neutralino, these relations are given by (8) - (10) whereas (11) - (13) are the corresponding relations in the chargino case.

Of the various signals discussed in Sec. 3, most interesting are the like-sign ditau signals that can result from the production of neutralino pairs. First, these are quite spectacular – especially considering that the SM backgrounds are tiny. More importantly, the decays  $\tilde{Z}_1 \rightarrow \tau jj$  and  $\tilde{Z}_1 \rightarrow \bar{\tau} jj$  lead to  $(\tau\tau$  or  $\bar{\tau}\bar{\tau}) + n \leq 4$  jet events in which, apart from measurement errors, any missing  $E_T$  arises only from the decays of the  $\tau$ , and so tends to be rather soft. The observation of such events can potentially lead to unambiguous evidence for  $\tau$ -number violation since the smallness of missing  $E_T$  makes it unlikely that two particles carrying  $\tau$ -number would escape detection in the apparatus. Of course, detailed studies are necessary before definitive conclusions can be drawn. We hope, however, that our somewhat qualitative analysis is a useful first step.

As can be seen from Figs. 4 and 5,  $\sigma(\tilde{Z}_1\tilde{Z}_1) \lesssim 1$  pb. We then see from (9) that assuming an integrated luminosity of  $500 \text{ pb}^{-1}/\text{yr}$ , about 60  $\tau\tau(4j)$  and  $\bar{\tau}\bar{\tau}$  can be expected in a year of operation. Assuming a detection efficiency of 30% for terms, a handful of these spectacular events are possible. Like-sign ditau events are also possible if a slepton is the  $LSP$ , though in this case the total pair production cross section is only about 0.2 pb.

We have, in Section 5, studied rival new physics mechanisms that could mimic the signals of our  $R_P$ -violating scenario. We have shown that explicit  $R$ -parity violation can, in principle, be distinguished from these other new physics mechanisms by studying the ratios of cross sections for producing various final states. However, heavy lepton signals could be confused with those from a spontaneously broken  $R$ -parity scenario.

Before closing, we remark that although we have focused our attention on  $\tau$ -number violation, it is possible that the dominant  $R_P$ -violating operator does not conserve  $e$ - or  $\mu$ -number. This may be because all of the  $\lambda_{ijk}$  and  $\lambda'_{ijk}$  are much smaller than their current bounds [6] discussed in Sec. 2. Such a situation will, of course, not affect the signal cross sections since the production mechanism does not involve these couplings. Our analysis can easily be carried over to this case. In fact, the number of events that could be observed should then be larger by a factor of 5 – 10 from the case of  $\tau$ -number violation since the detection efficiency for an  $e$  or  $\mu$  is considerably larger than that for a  $\tau$ .

In summary, we have shown that if  $R_P$  is broken by explicit  $\tau$ -number violating operators, there are many distinctive signals that might be observable at LEP 200. The detectability of these signals depends crucially on the efficiency of tau identification. In view of the novel and promising nature of the new physics, we urge our experimental colleagues to follow up on these issues.

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### Appendix: Model of an unstable heavy doublet Majorana neutrino

The simplest model of a heavy Majorana neutrino,  $\nu_M$ , which contains a substantial  $SU(2)_L$  doublet component and allows for  $\tau$ -number violating decays of  $\nu_M$ , is obtained by adding a sequential left-handed lepton doublet  $\begin{pmatrix} \ell_4 \\ \nu_4 \end{pmatrix}_L$  and right-handed singlets  $\ell_{4R}$  and  $N_R$  to the SM. Both a Dirac mass ( $m_4$ ) between  $\nu_4$  and  $N_R$  Majorana mass ( $M$ ) for  $N_R$  are possible. In order to have  $\tau$ -violating decays, we will also assume a Dirac mass ( $m_3$ ) between  $\nu_\tau$  and  $N_R$ . We will assume that Dirac mass terms between  $\nu_e$  and  $\nu_\mu$  and  $N_R$  are negligible. The  $3 \times 3$  neutrino mass-matrix is

$$\begin{pmatrix} 0 & 0 & m_3 \\ 0 & 0 & m_4 \\ m_3 & m_4 & M \end{pmatrix}.$$

It is easy to see that, apart from the unmixed massless neutrinos  $\nu_e$  and  $\nu_\mu$ , there is another massless state,

$$(\nu_\tau)_{\text{phys}} = m_4\nu_\tau - m_3\nu_4.$$

If  $M \gg m_3, m_4$ , the two remaining eigenstates have masses  $m_{\nu_M} = m_4^2/M$  and  $M$ ,

and are respectively given by

$$\nu_M = -m_3\nu_\tau - m_4\nu_4 + \frac{m_4^2}{M}N$$

and

$$\nu_S = m_3\nu_\tau + m_4\nu_4 + MN.$$

It is straightforward to check that the cross-generation interactions  $W\tau\nu_M$  and  $Z(\nu_\tau)_{\text{phys}}\nu_M$  are suppressed by factors of  $x = \frac{m_3}{m_4}$  and  $m_4^2(m_4^2 + m_{\nu_M}^2)^{-1} (m_{\nu_M}/M)x$ , respectively. For natural values,  $m_4 = 200$  GeV,  $M = 800$  GeV we find  $m_{\nu_M}$  to be 50 GeV. We will further assume the ratio  $m_3/m_4$  to be  $\sim 10^{-2}$ . (The smallness of  $m_3$  may be speculated to be due to the smallness of the corresponding intergenerational Yukawa coupling; this also provides a rationale for neglecting Dirac mass terms between  $\nu_e/\nu_\mu$  and  $N_R$ ). Then we find that the intergenerational  $W$  and  $Z$  interactions are suppressed by  $10^{-2}$  and  $\lesssim 10^{-3}$ . As a result, there is no conflict between this model and LEP constraints or data on lepton universality in  $W$ -decays. Finally, we note that the  $Z\nu_M\nu_M$  coupling is suppressed by just  $m_4^2(m_4^2 + m_{\nu_M}^2)^{-1}$  which is close to unity so that  $\nu_M$  pair production at LEP is essentially unsuppressed.

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### Figure captions

Fig. 1. : Purely leptonic  $R$ -parity and  $\tau$ -number violating vertices.

Fig. 2. :  $R$ -parity and  $\tau$ -number violating vertices involving quarks.

Fig. 3. : Diagrams contributing to four-body decays of  $\tilde{\nu}_\mu$ .

Fig. 4. : Cross section contours for neutralino pair-production  $\sigma(\tilde{Z}_1\tilde{Z}_1)$ , with  $\tan\beta = 2$ , in the  $2m_1 - m_{\tilde{g}}$  plane for (a)  $m_{\tilde{\ell}} = 100$  GeV and (b)  $m_{\tilde{\ell}} = 200$  GeV. The heavy dotted lines correspond to  $m_{\tilde{Z}_1} = 45$  GeV.

Fig. 5. : Contours for  $\sigma(\tilde{Z}_1\tilde{Z}_1) = 0.8$  pb, with  $\tan\beta = 1$  (solid) and  $\tan\beta = 10$  (dot-dash). The heavy circles (triangles) are contours of  $m_{\tilde{Z}_1} = 45$  GeV for  $\tan\beta = 1$  ( $\tan\beta = 10$ ).

Fig. 6 (a). :  $p_T$ -distributions of electrons and  $\tau$ 's in  $\tau^+\tau^+e^-e^-$  (and c.c.) +  $\cancel{E}_T$  events from the decays of neutralino pairs. The normalization assumes that  $\tilde{Z}_1$  dominantly decays via the  $\lambda_{131}$  interaction. Also shown are the same distributions from  $Z$ -pair production, where the electrons come from the decays of  $\tau$ 's produced via  $Z \rightarrow \tau^+\tau^-$ .

Fig. 6 (b). : The distribution of the minimum  $\Delta r(\tau, \text{jet})$  in  $\tau^+\tau^+(4j)$  events from the production of neutralino pairs. The normalization is arbitrary.