Tau Lepton Mixing with Charginos and its Effects on Chargino searches at e^+e^- Colliders

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ABSTRACT: In bilinear R–Parity violating models where a term $\epsilon_3 L_3 H_2$ is introduced in the superpotential, the tau lepton can mix with charginos. We show that this mixing is fully compatible with LEP1 precision measurements of the $Z\tau\tau$ and $W\tau\nu_\tau$ couplings even for large values of ϵ_3 and of the induced vacuum expectation value v_3 of the tau–sneutrino. The single production of charginos at e^+e^- colliders is possible in this case and we present numerical values of the cross–section at LEP1, LEP2 and an NLC.

1. Introduction

The Minimal Supersymmetric Standard Model (MSSM) [1] is the most popular extension of the Standard Model (SM) and its phenomenology has received much attention in recent years. The MSSM assumes the conservation of R-parity [2], a discrete symmetry given by $R_p = (-1)^{(3B+L+2S)}$, where L is the lepton number, B is the baryon number and S is the spin of the state. Two important consequences of such a symmetry are that all supersymmetric particles must be pair-produced, with the lightest of them being stable. In recent years growing attention has been given to models in which the conservation of R-Parity is relaxed [3] by adding explicit R-parity violating terms in the superpotential. In this work we shall focus on Bilinear R–Parity Violation (BRpV) which has been advocated in a number of previous papers [4, 5, 6, 7]. Such models allow one to map out the phenomenological potential of the model in a systematic fashion [8]. In addition, they have the theoretical advantage of being a low energy approximation of spontaneous R–parity violating models.

The Tau lepton in the BRpV is allowed to mix with the charginos, an effect dependent on the values of the R-Parity violating parameters ϵ_3 and v_3. Such mixing, if substantial, would naively be expected to affect the theoretical value of the $Z\tau\tau$ coupling which is measured to very high accuracy at LEP1 (error$\approx 0.25\%$). Thus it is important to check if one may constrain the allowed parameter space of ϵ_3 and v_3, and we do this in the first part of this talk. A consequence of the above mixing is the possibility of single chargino production at e^+e^- colliders, a process not possible in Rp conserving models, and we analyse this production process at LEP1, LEP2 and a NLC. The talk is essentially a summary of Ref. [9] and was done in collaboration with M. Diaz and J. Valle.

2. The Model

In the simplest BRpV model the supersymmetric Lagrangian is specified by the superpotential W given by

$$W = \epsilon_{ab}(h_U^{ij}\widehat{Q}_i^a\widehat{U}_j\widehat{H}_2^b + h_D^{ij}\widehat{Q}_i^b\widehat{D}_j\widehat{H}_1^a + h_E^{ij}\widehat{L}_i^b\widehat{R}_j\widehat{H}_1^a - \mu\widehat{H}_1^a\widehat{H}_2^b + \epsilon_i\widehat{L}_i^a\widehat{H}_2^b) \quad (2.1)$$

where $i,j = 1,2,3$ are generation indices, $a,b = 1,2$ are $SU(2)$ indices. The last term in eq. (2.1) is the only one which violates R–parity. Such a term arises in spontaneous R–parity breaking models, with ϵ_i generated by the product of a new Dirac-type neutrino Yukawa coupling and some new vacuum expectation value (VEV) of an SU(2) singlet sneutrino field. The parameters ϵ_i have the dimension of mass, and for simplicity we consider only ϵ_3 non–zero. Of particular interest to us is the chargino/tau mass matrix $\mathbf{M_C}$. The lightest eigenstate of this mass matrix must be the tau lepton ($\tau^\pm$) and so the mass is constrained to be 1.777 GeV. To obtain this the tau Yukawa coupling becomes a function of the parameters in the mass matrix, and the full expression is given in [5]. The composition of the tau is given by:

$$\tau_R^+ = V_{3j}\psi_j^+, \qquad \tau_L^- = U_{3j}\psi_j^- \tag{2.2}$$

where

$$\psi^{+T} = (-i\lambda^+, \widetilde{H}_2^1, \tau_R^{0+}) \tag{2.3}$$

and

$$\psi^{-T} = (-i\lambda^-, \widetilde{H}_1^2, \tau_L^{0-}). \tag{2.4}$$

The two component Weyl spinors τ_R^{0-} and τ_L^{0+} are weak eigenstates and, similarly, the two component Weyl spinors τ_R^+ and τ_L^- are mass eigenstates.

Of immediate interest is the matrix $\mathbf{M_C M_C^T}$, which is diagonalized by $\mathbf{U}$, and the matrix $\mathbf{M_C^T M_C}$ which is diagonalized by $\mathbf{V}$. For explicit expressions for these matrices see Ref. [9] $\mathbf{M_C M_C^T}$ and $\mathbf{M_C^T M_C}$ differ significantly in appearance, particularly in the off diagonal elements which depend on the R-parity violating couplings: In the matrix $\mathbf{M_C^T M_C}$, the elements which violate R–Parity turn out to be small, being proportional to $(\mu v_3 + v_1\epsilon_3)$, which is naturally small since its square is proportional to the mass of ν_τ [5, 6, 8].

In contrast, the R-Parity violating elements in the matrix $\mathbf{M_C M_C^T}$ may be of greater magnitude. In this way, U_{31} and U_{32} may be larger than their similars V_{31} and V_{32}. Nevertheless, a closer look tells us that in the limit $(\mu v_3 + v_1\epsilon_3) \to 0$ (i.e, massless neutrino) we find $U_{31} \to 0$. Therefore, U_{31} is also small and controlled by m_{ν_τ}. On the contrary, U_{32} can be larger. In the next section we show that this is not in conflict with the τ or ν_τ couplings to gauge bosons.

3. The τ couplings to gauge bosons

The pair production of τ leptons in the SM proceeds via two tree level Feynman diagrams, i.e., the s-channel mediated by a photon and a Z boson. In BRpV there is an extra diagram, namely that of t-channel production mediated by a tau–sneutrino. This diagram arises because in general the τ has a gaugino component. One may attempt to constrain the chargino/tau mixing in eq. (2) by using precision measurements at LEP1 of the $Z\tau\tau$ and $W\tau\nu_\tau$ couplings. It is customary to write the coupling $Z\tau^+\tau^-$ in the MSSM in terms of the constants $g_L^\tau = -\frac{1}{2}(g_A^\tau + g_V^\tau)$ and $g_R^\tau = \frac{1}{2}(g_A^\tau - g_V^\tau)$ which are respectively the coupling strengths of the left and right handed τ to Z:

$$g_A^\tau = -|U_{31}|^2 - \tfrac{1}{2}|U_{32}|^2 - \tfrac{1}{2}|U_{33}|^2 + |V_{31}|^2 + \tfrac{1}{2}|V_{32}|^2 \tag{3.1}$$

$$g_V^\tau = |U_{31}|^2 + \tfrac{1}{2}|U_{32}|^2 + \tfrac{1}{2}|U_{33}|^2 + |V_{31}|^2 + \tfrac{1}{2}|V_{32}|^2 - 2s_W^2\,. \tag{3.2}$$

Of course, in the R-parity conserving limit, that is $V_{31} = V_{32} = U_{31} = U_{32} = 0$, one recovers the formula for τ couplings in the MSSM. We have evaluated the numerical value of these couplings for 10^4 randomly chosen points. All the points satisfy the following experimental mass limits:

$$m_{\chi^+} \geq 70\,\mathrm{GeV}[10], \quad m_{\nu_\tau} \leq 18\,\mathrm{MeV}[11] \quad m_{\chi^0} \geq 20\,\mathrm{GeV} \tag{3.3}$$

Note that, to be conservative, we assumed a lower bound on the neutralino mass of 20 GeV. This is reasonable in view of the work presented in Ref. [12] [1]. The couplings g_A^τ and g_V^τ are functions of 6 independent parameters which are varied in a reasonable parameter space. In Fig. 3 we plot the axial vector coupling g_A^τ as a function of the sneutrino vacuum expectation value v_3' in the rotated basis. The central value is given by $g_A^\tau = -0.5009$ (solid line) and the horizontal dashed line corresponds to 1σ deviation. Clearly, the great majority of the points fall within the LEP1 bound on g_A^τ at the 1σ level. Note that

[1] Strictly speaking, however, there is not yet a published determination on the neutralino bounds from LEP2 in the bilinear model of broken Rp.

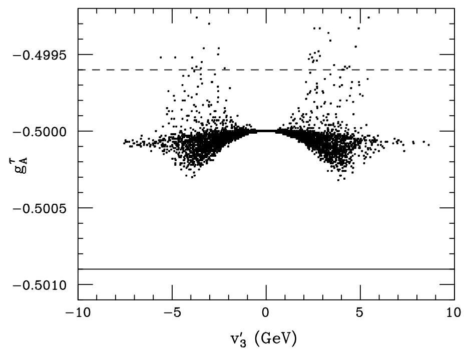

Figure 1: Axial vector coupling of the τ to a Z gauge boson as a function of the BRpV parameter v_3'. The solid line is the experimental central value and the dashed line corresponds to 1σ deviation.

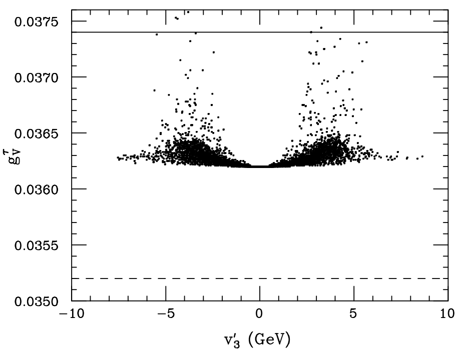

Figure 2: Vector coupling of the τ to a Z gauge boson as a function of the BRpV parameter v_3'. The solid line is the experimental central value and the dashed line corresponds to 1σ deviation.

the values of ϵ_3 and v_3 can be large and are constrained only by $v_3' \lesssim 6$ GeV. Similarly, in Fig. 3 we plot the vector coupling g_V^τ as a function of v_3'. The solid horizontal line at $g_V^\tau = 0.0374$ is the central value, and the dashed line denotes the 1σ deviation. In this case all points fall inside the 1σ region. For the $W\tau\nu_\tau$ vertex with the same 10^4 randomly chosen points we find that the deviations from the SM value of the $W\tau\nu_\tau$ coupling are well inside the experimental error, and less pronounced than the corresponding deviations for the $Z\tau\tau$ vertex. The reason why the deviations of the tau couplings to gauge bosons are small with respect to the SM predictions can be traced to two facts. First the tau–neutrino mass is small, and second the Higgs superfield H_1 and the tau–lepton superfield L_3 both possess the same SU(2) quantum numbers.

Summarizing the results of this section, we conclude that the couplings $Z\tau\tau$ and $W\tau\nu_\tau$ can be easily maintained within the experimental bounds even for large values of ϵ_3 and v_3. This has important consequences for the phenomenology of the BRpV model in general.

4. Single Chargino Production

In this section we consider the single chargino production in electron–positron annihilation. We study in turn the phenomenology at LEP1, LEP2, and a NLC ($\sqrt{s} = 500$ GeV). In general the total cross–section consists of three distinct contributions given by:

$$\sigma(e^+e^- \to Z, \tilde{\nu}_\tau \to \tilde{\chi}_1^\pm \tau^\mp) = \sigma_Z + \sigma_{\tilde{\nu}} + \sigma_{\tilde{\nu}Z} \quad (4.1)$$

Note that an intermediate photon does not contribute. Explicit expressions for these formulae can be found in Ref. [13]. The generalization to BRpV is straightforward and is obtained by replacing the 2×2 matrices O'^L, O'^R, V and U by 3×3 matrices and summing over three "charginos".

First, we consider the single chargino production at LEP1. In this case, the terms involving $\tilde{\nu}_\tau$ are negligible, which is expected at the Z peak. In addition, the sneutrino contribution is proportional to $|V_{31}|^2$ which is small, as we mentioned in the previous section. At LEP1 despite the small values for the off–diagonal couplings we benefit from being at the Z peak.
In Fig. 4 we plot the cross–section in the $M_{\nu_\tau} - M_{\chi_1}$ plane, displaying three regions with the total cross section larger than 0.1, 0.4, and 4 pb. To understand better the relation between the cross–section and $\tan\beta$ we show in Fig. 4 the explicit cross–section dependence on $\tan\beta$. It shows clearly a steep climb for $\tan\beta \gtrsim 30$. In addition we draw two curves, one for $m_{\nu_\tau} <$ 18 MeV and another one with $m_{\nu_\tau} < 1$ MeV. They clearly show that the cross section is controlled by m_{ν_τ} and will approach zero as the neutrino mass goes to zero. Cross–sections as large 10 pb can be obtained for $\tan\beta \to 90$. The cross–section has a direct dependence on the Tau Yukawa coupling and this can be inferred from the structure of the mass matrices.

At LEP2 one moves away from the Z peak and so the cross-section falls. With 4×10^4 random points chosen the maximum cross-section that we found had a value of 7.4 fb, and so 3.7 events would be expected at LEP2 with a luminosity of 500 pb^{-1}. Hence we conclude that LEP2 has no chance of obtaining a signal in this channel.

At a NLC of $\sqrt{s} = 500$ GeV one finds even smaller cross–sections although we benefit from the higher luminosity ($30 \to 100$ fb^{-1}). Production of the heavier chargino χ_2 is now possible and we show in Fig. 4 the maximum values of the cross–section of both $\tilde{\chi}_1$ and $\tilde{\chi}_2$ as a function of chargino mass. For an explanation of the shape of the curves see Ref. [9].

5. Discussion and Conclusions

We have studied the charged and neutral current couplings of the tau lepton in models with spontaneous or bilinear breaking of R–parity. We showed that precision measurements of the $Z\tau\tau$ coupling at LEP1 allow relatively large values of the effective Rp breaking parameter ϵ_3 ($\to$ 200 GeV) since such values only induce large mixing between τ^- and $\tilde{H}_1^-$ which share the same $SU(2)$ quantum numbers. Single production of charginos is possible and we found small numerical values of the cross-sections at LEP2 and at a NLC, with maximum values of around 7.4 fb and 1.3 fb respectively. At LEP1 prospects are vastly improved, and we found that large cross-sections as great as 10 pb are possible. The cross section decreases with decreasing m_{ν_τ}. In addition, there is a direct correlation with the tau Yukawa coupling (h_τ). Our results are to a large extent model independent, since they depend only of the structure of the chargino-tau mass matrix and this is universal in models with spontaneous breaking of R–parity as well as their effective truncation in terms of a bilinear explicit Rp violating superpotential term (BRpV model).

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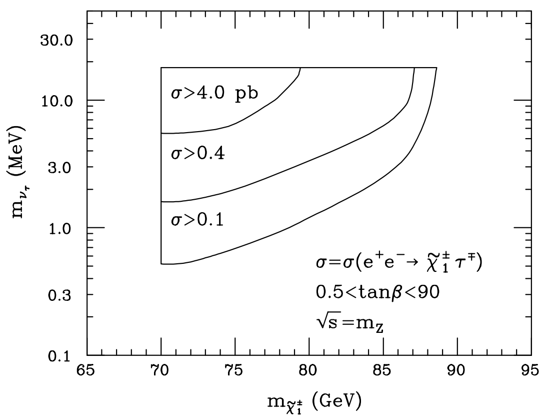

Figure 3: Regions of attainable cross section in BRpV in the plane tau neutrino mass v/s chargino mass including large values of $\tan\beta$.

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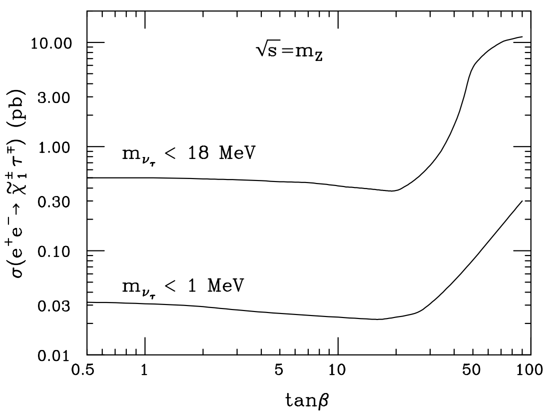

Figure 4: Maximum single chargino production cross section in BRpV as a function of $\tan\beta$ for two different upper bounds on the tau neutrino mass.

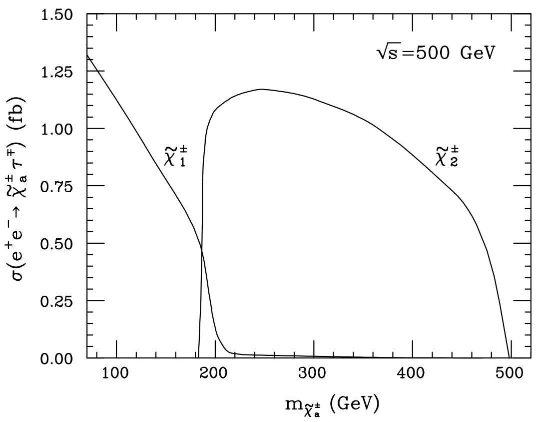

Figure 5: Maximum single chargino production cross section as a function of the chargino mass at NLC in BRpV. Light and heavy charginos are displayed.