CERN-TH/96-203
TIFR/TH/96-41
hep-ph/9608264

An R–Parity Breaking SUSY Solution to the R_b and ALEPH Anomalies

Debajyoti Choudhury[(1),*] and D.P. Roy[(2,3),†]

[(1)] *Max–Planck–Institut für Physik, Werner–Heisenberg–Institut, Föhringer Ring 6, 80805 München, Germany.*

[(2)] *Theory Division, CERN, CH–1211 Geneva 23, Switzerland.*

[(3)] *Theoretical Physics Group, Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India.*

ABSTRACT

We discuss an optimal R-parity breaking SUSY solution to the R_b excess as well as the ALEPH 4-jet anomaly. The latter arises from the pair production of stop via chargino decay at LEP1.5, followed by its R–violating decay into a light quark pair. The model satisfies top quark and Z–boson decay constraints along with gaugino mass unification.

CERN-TH/96-203

August, 1996

*debchou@mppmu.mpg.de
†dproy@theory.tifr.res.in

Two of the intriguing results from LEP which have attracted a good deal of theoretical interest are the R_b and the ALEPH 4-jet anomalies. The first anomaly refers to the LEP1 value of $R_b(\equiv \Gamma_Z^{b\bar{b}}/\Gamma_Z^{\rm had})$ being $\sim 2\sigma$ larger than the SM prediction [1, 2]. The second refers to the anomalous 4-jet events recently reported [3] by the ALEPH experiment at LEP1.5, each of which seems to consist of dijet pairs with a common invariant mass ~ 55 GeV.

It is now widely recognized [4, 5, 6] that the minimal supersymmetric standard model (MSSM) offers a viable solution to the R_b anomaly in the low $\tan\beta$ region if one assumes a relatively light top squark ($\tilde{t}_1$) and chargino ($\widetilde{\chi_1}$). The assumption of a R–parity violating Yukawa interaction term would invalidate the canonical missing E_T ($\not{E}_T$) signature for superparticle production and thus the LEP1.5 limit on chargino mass [7],

$$m_{\widetilde{\chi_1}} > 65 \text{ GeV} . \tag{1}$$

In this case, pair production of charginos at LEP1.5 can offer a possible explanation for the ALEPH 4-jet events as was recently suggested in refs. [8, 9, 10]. In particular, Chankowski *et al.*[10] have discussed a variety of such R–parity breaking SUSY solutions to the ALEPH anomaly, which can also account for the R_b excess. The purpose of this note is to focus on what appears to be an optimal R–parity breaking SUSY solution to the R_b and ALEPH anomalies, within the constraints of top quark and Z–boson decays as well as that of gaugino mass unification. We shall see below that it can quantitatively account for the essential features of the ALEPH 4-jet events as well as for the R_b anomaly.

Explicit breaking of R-parity introduces additional Yukawa terms in the superpotential [11]

$$W_{\not{R}} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c , \tag{2}$$

where $Q,\ L\ (U,\ D,\ E)$ denote the quark and lepton doublet (singlet) superfields and the subscripts denote the generation. Symmetry considerations imply that $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda''_{ijk} = -\lambda''_{ikj}$. Proton stability demands that all products of the form $(\lambda'\lambda'')$ be vanishingly small and this, conventionally, is ensured by stipulating that either the baryon number violating couplings (λ'') or the lepton number violating couplings (λ, λ') are non-zero but not both.

Let us briefly discuss the various R–parity breaking SUSY scenarios that have been suggested as explanations of the 4-jet excess. The first of these [12], which, in fact, predates the anomaly, assumes the lightest superparticle (LSP) to be a sneutrino instead of the neutralino. Pair production of sneutrinos ($e^+e^- \to \tilde{\nu}^*\tilde{\nu}$) followed by their diquark decays—through one of the λ' couplings—can then lead to a 4-jet final state. An adequate production cross section can be obtained for $\tilde{\nu}_e$ (via a light, and gaugino-dominated, chargino exchange), but the other event characteristics have not been analysed so far. The second scenario [13] suggests pair production of left-handed b squarks, followed by their diquark decays through a λ'' coupling. However, a light $\tilde{b}_L$ in the required mass range (~ 55 GeV) seems to be disfavoured by the precision measurements of electroweak observables [10]. More recently, there have been two suggestions based on pair production of charginos with mass $\sim 55\,\mathrm{GeV}$ [8, 9]. One of them [8] assumes the decay sequence

$$\widetilde{\chi}_1 \to W^* \, \widetilde{\chi}_1^0 \ , \qquad W^* \to \bar{q} q' \ , \qquad \widetilde{\chi}_1^0 \xrightarrow{\lambda''} q_1 \, q_2 \, q_3 \ , \tag{3}$$

where the star denotes an off-shell W boson. Although this is the most natural scenario in terms of the MSSM mass spectrum, it seems to be disfavoured on several counts. It shows much broader distributions in the difference of the dijet masses as well as their sum than the ALEPH data [3]. Moreover, the leptonic decay of one of the W^*s would imply roughly as many anomalous events with an isolated lepton as without it, which could not have been missed. Finally, one would have a significantly large fraction of the events with more than 4 jets if one applies the ALEPH jet algorithm. The other suggestion [9] assumes the chargino decay

$$\widetilde{\chi}_1 \xrightarrow{\lambda'} \tau \bar{q} q' \tag{4}$$

to dominate over its R–conserving decay into the LSP. In this case, the outgoing τ would be too hard to have been missed, unless one assumes the exchanged sneutrino mass to be very close to that of the chargino. It may be noted here that none of the above scenarios address the issue of the R_b anomaly, to which we now turn.

We start by considering the standard R-conserving MSSM solution to the R_b anomaly, within the constraints of top quark and Z boson decays [5, 6]. Gaugino mass unification shall be assumed all along as it is very closely related to the successful MSSM prediction for the unification of the $SU(3) \otimes SU(2) \otimes U(1)$ gauge couplings. Thus, the masses of the corresponding gauginos $\tilde{g}$, $\tilde{W}$ and $\tilde{B}$ are related via

$$M_3 = \frac{\alpha_s}{\alpha} \sin^2\theta_W M_2 \simeq 3.5 M_2 \qquad \text{and} \qquad M_1 = \frac{5}{3} \tan^2\theta_W M_2 \simeq 0.5 M_2 \ . \tag{5}$$

The physical gluino mass is related to the running mass through the QCD correction factor [14]

$$m_{\tilde{g}} = \left(1 + 4.2 \frac{\alpha_s}{\pi}\right) M_3 \simeq 1.15 M_3 \simeq 4 M_2 \ . \tag{6}$$

Thus, a single gaugino mass (M_2) along with the higgsino mass parameter (μ) and the ratio of the two Higgs vacuum expectation values ($\tan\beta$), determine the gluino mass as well as the masses and compositions of the two chargino and four neutralino states [15] *i.e.*,

$$\begin{aligned} \widetilde{\chi}_{iL}^{\pm} &= V_{i1} \widetilde{W}_L^{\pm} + V_{i2} \widetilde{H}_L^{\pm} \ , \qquad \widetilde{\chi}_{iR}^{\pm} = U_{i1} \widetilde{W}_R^{\pm} + U_{i2} \widetilde{H}_R^{\pm} \ , \\ \widetilde{\chi}_i^0 &= N_{i1} \widetilde{B} + N_{i2} \widetilde{W}_3 + N_{i3} \widetilde{H}_1^0 + N_{i4} \widetilde{H}_2^0 \ . \end{aligned} \tag{7}$$

In the scalar sector, the large Yukawa term for the top results in a mass hierarchy and thus the lighter (and predominantly right-handed) stop,

$$\tilde{t}_1 \equiv \cos\theta_{\tilde{t}} \, \tilde{t}_R + \sin\theta_{\tilde{t}} \, \tilde{t}_L \ , \tag{8}$$

is expected to be significantly lighter than the other squarks. We shall be primarily interested in this stop.

In the low $\tan\beta$ region of our interest, the SUSY contributions to $Z \to b\bar{b}$ arise from the triangle graphs involving $\tilde{\chi}_i\tilde{\chi}_j\tilde{t}_k$ and $\tilde{t}_i\tilde{t}_j\tilde{\chi}_k$ exchanges as well as the $\tilde{t}_i\tilde{\chi}_j$ loop insertions in the b and $\bar{b}$ legs [5, 6, 16]. The b vertices are dominated by the $b_L\tilde{t}_1\tilde{\chi}_i$ Yukawa coupling

$$\Lambda^L_{1i} \simeq -\frac{m_t V_{i2}\cos\theta_{\tilde{t}}}{\sqrt{2}m_W \sin\beta} \tag{9}$$

which favours large V_{12}, *i.e.*, the higgsino–dominated region ($|\mu| \ll M_2$). On the other hand, the $Z\tilde{\chi}_i\tilde{\chi}_j$ couplings

$$O^L_{ij} = -\frac{1}{2}\left(\cos 2\theta_W \delta_{ij} + U_{i1}U_{j1}\right) \qquad \text{and} \qquad O^R_{ij} = -\frac{1}{2}\left(\cos 2\theta_W \delta_{ij} + V_{i1}V_{j1}\right) \ , \tag{10}$$

favour large U_{11} and V_{11}, *i.e.*, the gaugino–dominated region ($|\mu| \gg M_2$). (The corresponding $Z\tilde{t}_1\tilde{t}_1$ coupling is suppressed by the $U(1)$ coupling factor $\sin^2\theta_W$.) The need for sizeable b as well as Z couplings then implies that the largest SUSY contribution to R_b ($\delta R_b^{\rm SUSY}$) occurs for the mixed region ($|\mu| \sim M_2$)—-corresponding to a $\tilde{\gamma}$–dominated LSP—rather than for the higgsino–dominated region [5, 6]. Moreover, it seems to favour negative μ over the positive μ region [5]. We shall, therefore, restrict ourselves to the former. We shall consider

$$\delta R_b^{\rm SUSY} \sim 0.0020 - 0.0025 \tag{11}$$

to be a viable solution to the R_b anomaly. It would exactly account for the discrepancy between the current experimental value [2] of $R_b^{\rm exp} = 0.2178 \pm 0.0011$ and the standard model value (for $m_t = 175$ GeV) of $R_b^{\rm SM} = 0.2156$, as well as close the gap between the $\alpha_s(m_Z^2)$ estimates from LEP1 and from deep inelastic scattering.

Low masses for $\tilde{t}_1$ and $\widetilde{\chi_1}$, required for a suitably large $\delta R_b^{\rm SUSY}$, may, however, result in significant new decay channels for the top quark, *viz.*, $t \to \tilde{t}_1\widetilde{\chi^0_{1,2}}$. The decay amplitudes are dominated by the $\bar{t}_L\widetilde{\chi^0_i}\tilde{t}_{1R}$ and $\bar{t}_R\widetilde{\chi^0_i}\tilde{t}_{1L}$ Yukawa couplings [5, 6, 17] :

$$C_i^{L(R)} \simeq \frac{m_t N_{i4}}{m_W \sin\beta}\ \cos\theta_{\tilde{t}}\ (\sin\theta_{\tilde{t}}) \ , \tag{12}$$

with $i = 1, 2$. The higgsino–dominated region corresponds to large $\tilde{H}_2^0$ components in $\widetilde{\chi^0_{1,2}}$, and hence a large SUSY Branching Ratio (B_S) for top decay. This quantity is relatively small in the mixed region since only $\widetilde{\chi^0_2}$ has a large $\tilde{H}_2^0$ component while $\widetilde{\chi^0_1} \simeq \tilde{\gamma}$. Thus the upper limit on B_S from the CDF top decay data [18] favours the mixed region as well. We shall take a rather lenient value for this limit [5, 6]:

$$B_S < 0.4 \ . \tag{13}$$

Recently, a systematic scan of the MSSM parameter space was carried out [5] to obtain the best SUSY contribution to R_b within the constraint of top quark decay. The optimal value of $\delta R_b^{\rm SUSY}$ is obtained at small negative value of the stop mixing angle ($\theta_{\tilde{t}} \approx -15^\circ$) and small stop mass

$$m_{\tilde{t}_1} \sim 50 - 60 \text{ GeV} \ , \tag{14}$$

	(M_2,μ)	$\tan\beta$	$\Gamma(Z \to \widetilde{\chi_i^0}\,\widetilde{\chi_j^0})$	$m_{\widetilde{\chi_1}}$	$m_{\widetilde{\chi_1^0}}$	$m_{\widetilde{\chi_2^0}}$	$m_{\tilde{t}_1}$	$\delta R_b^{\rm SUSY}$	B_S
A	(150, −40)	1.4	—	67	39	70	60	0.0014	0.51
	(150, −30)	1.4	3 MeV	58	29	71	50	0.0019	0.54
B	(60, −60)	1.4	—	86	35	57	60	0.0019	0.40
C	(40, −70)	1.4	—	76	24	64	60	0.0021	0.30
		2.0	0.6 MeV	64	24	52	55	0.0021	0.26
		2.6	2.2 MeV	56	23	45	50	0.0024	0.34

Table 1: *SUSY contributions to R_b ($\delta R_b^{\rm SUSY}$) and to the top BR (B_S) are shown, along with the light chargino and neutralino masses, for three representative points in the (M_2,μ) plane. (All masses are in GeV and $\theta_{\tilde{t}} = -15°$.) For each set, the top row corresponds to the allowed MSSM parameter space in the R-conserving scenario.*

which lies in between the LEP1 limit ($m_{\tilde{t}_1} > 45$ GeV) [19] and the D0 excluded region ($m_{\tilde{t}_1} \neq 65$–85 GeV) [20]. LEP1.5 imposes no additional bound on $m_{\tilde{t}_1}$ as the pair-production cross section for the right-handed stop is small.

In Table 1 we display the phenomenological consequences for three representative points in the (M_2,μ) plane :

$$A\ :\ (150,-40)\,{\rm GeV},\qquad B\ :\ (60,-60)\,{\rm GeV}\qquad {\rm and}\qquad C\ :\ (40,-70)\,{\rm GeV}, \tag{15}$$

belonging to the higgsino–dominated (A) and mixed regions (B,C). The points are chosen close to the LEP limit so as to give the best values of $\delta R_b^{\rm SUSY}$ in the respective regions. For the higgsino–dominated point (A), $m_{\widetilde{\chi_1}}$ is close to its LEP1.5 limit (1). Still $\delta R_b^{\rm SUSY}$ is smaller than the required value (11), while the contribution to top BR exceeds the limit (13). On the other hand, the mixed region points (B,C) are seen to give viable values of $\delta R_b^{\rm SUSY}$, while satisfying the B_S limit. Note that, in this region, the chargino mass is safely above the LEP1.5 limit (1); the most important constraint is rather set by the requirement that

$$m_{\widetilde{\chi_1^0}} + m_{\widetilde{\chi_2^0}} \gtrsim m_Z \tag{16}$$

which follows from the stringent LEP1 bound

$$BR(Z \to \widetilde{\chi_1^0}\,\widetilde{\chi_2^0}) < 5\times 10^{-5} \tag{17}$$

deduced from the negative search for acoplanar jets using the $\not{E}_T$signature of $\widetilde{\chi_1^0}$ [19]. The best values for $\delta R_b^{\rm SUSY}$ and B_S are obtained for point (C). However, it corresponds to a gluino mass of 160 GeV, barely above the Tevatron lower limit [21].

We now turn to effects of R-parity breaking via the λ'' couplings. As the LSP ($\widetilde{\chi_1^0}$) now undergoes hadronic decay, the $\not{E}_T$signature is no longer applicable. Thus, the LEP1.5

bound (1) is inoperative. Moreover, the LEP1 bound (17) on Z decay into neutralinos is now replaced by

$$\sum \Gamma(Z \to \widetilde{\chi}_i^0 \widetilde{\chi}_j^0) < 3\,\mathrm{MeV} \tag{18}$$

corresponding to the 1σ error in $\Gamma_Z^{\rm had}$. This is weaker than (17) by more than an order of magnitude. Nonetheless, as we shall see below, it acts as a strong constraint on efforts to reduce the chargino mass below 65 GeV in the mixed region.

The goal then is to have $m_{\widetilde{\chi}_1} < 65$ GeV, while satisfying (18) so that chargino pair production at LEP1.5 can be a source for the anomalous 4-jet events. In the higgsino–dominated region this is achieved most easily by decreasing $|\mu|$, while in the mixed region it can be achieved only by increasing $\tan\beta$. The former also has the advantage of increasing $\delta R_b^{\rm SUSY}$ simultaneously. Table 1 shows that it is possible to go down to $m_{\widetilde{\chi}_1} = 58$ GeV within the constraint (18) in the higgsino–dominated region. The stop mass can then be reduced to 50 GeV so as to allow the two body decay mode

$$\widetilde{\chi}_1 \to \tilde{t}_1 b \ , \tag{19}$$

which shall be assumed later on. Reducing the chargino and the stop masses has the effect of increasing $\delta R_b^{\rm SUSY}$ to the respectable value of 0.0019. Unfortunately, B_S is untenably large.

For point B ($|\mu| = M_2$), it is not possible to drive down $m_{\widetilde{\chi}_1}$ below $\sim 65\,$GeV by either of the above methods, while still satisfying (18). However, for the mixed region point C—which offers the best value for $\delta R_b^{\rm SUSY}$—it is possible to achieve this by increasing $\tan\beta$. As Table 1 shows, one can go down to $m_{\widetilde{\chi}_1} = 56\,$GeV, within the above constraints, by increasing $\tan\beta$ to 2.6. Decreasing the stop mass to 50 GeV ensures the two-body decay (19) with a soft b. Note that the large value for $\delta R_b^{\rm SUSY}$ is obtained within the B_S constraint (13). Also, the value of $\tan\beta$ is now more reasonable. Furthermore, the gluino mass limit from the Tevatron is no longer applicable.

We shall quantitatively pursue the R–parity breaking SUSY scenario summarised in the last row of Table 1 as a possible solution to the anomalous 4-jet events. The pair production of charginos, followed by their two-body decays (19), results in $\tilde{t}_1 \tilde{t}_1^*$ along with a soft $\bar{b}b$ pair. For

$$m_{\widetilde{\chi}_1} = 56\,\mathrm{GeV} \qquad \text{and} \qquad m_{\tilde{t}_1} = 50\,\mathrm{GeV} \ , \tag{20}$$

the b momenta are always less than 6 GeV and so the bs are expected to largely miss the lifetime tag. Furthermore, leptons from b-decay do not survive isolation cuts. The stop can decay either directly

$$\tilde{t}_1^* \xrightarrow{\lambda''} d\, s \ , \tag{21}$$

or through the R–conserving loop process

$$\tilde{t}_1 \to c \widetilde{\chi}_1^0 \ , \tag{22}$$

followed by

$$\widetilde{\chi}_1^0 \xrightarrow{\lambda''} u\, d\, s \ , c\, d\, s \ . \tag{23}$$

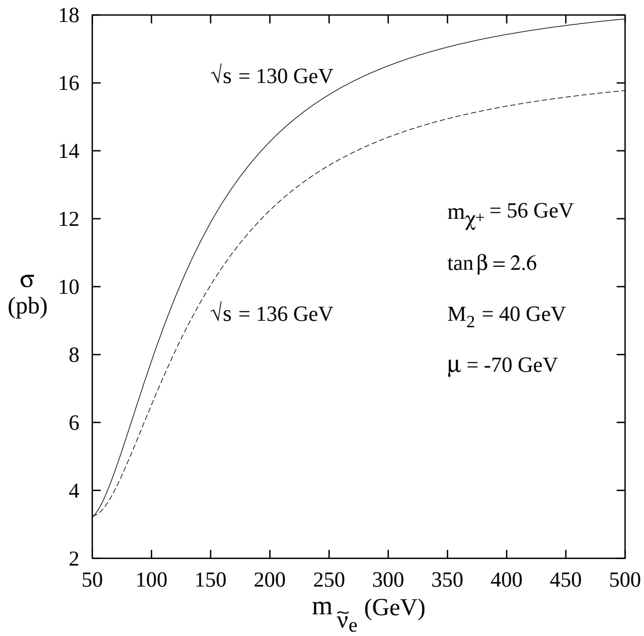

Figure 1: *Pair production cross section for a 56 GeV chargino as a function of the sneutrino mass for the two different LEP1.5 center-of-mass energies.*

We do not consider stop decay modes with b quarks in the final state since these will lead to a large number of b-tags in conflict with the ALEPH results [3]. The loop decay (22) is a third-order electroweak process and hence has a very small width [22]. Consequently, the R-violating decay (21) dominates over a very large range of the Yukawa coupling

$$\lambda''_{tds} \gtrsim 5 \times 10^{-5} \ . \tag{24}$$

On the other hand, one requires [23]

$$\lambda''_{uds,cds} \gtrsim 5 \times 10^{-3} \tag{25}$$

for the LSP decay to occur within 1 cm [24]. Note that the direct decay (21) dominates as long as λ''_{tds} is larger than the relatively modest limit of (24) *irrespective* of the other Yukawa couplings. Thus the direct decay is at least as natural[25] as the alternative route of (22 & 23). We shall see below that the former can quantitatively account for the ALEPH events, while the latter cannot.

Figure 1 shows the chargino pair-production cross-section at the (LEP1.5) energies of 130 and 136 GeV. Since the interference between the s-channel (γ/Z) and the t-channel ($\tilde{\nu}_e$) is a destructive one, the cross section increases strongly with the sneutrino mass. For the rest of the analysis we have averaged the cross sections at the two energies assuming a sneutrino mass of 200 GeV.

We have studied chargino pair-production and subsequent decay via the stop (19) using a parton level Monte Carlo program. Both the two-body (21) and the four-body (22 &

23) decay modes have been considered. To estimate the effect of jet energy resolution, we have compared the results with and without the suppression of soft partons (arising mainly from b-decays), having energy less than the ALEPH resolution error [3]

$$\sigma_E = (0.6\sqrt{E(\text{ GeV})} + 0.6) \text{ GeV } (1 + \cos^2\theta) \ . \tag{26}$$

We found the difference to be small. The results presented below correspond to the suppression of the soft partons having energy $< \sigma_E$.

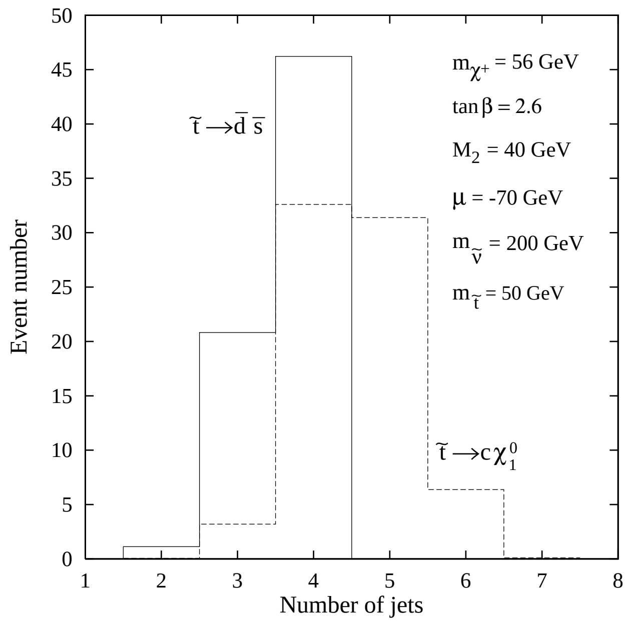

Figure 2: *Event distribution as a function of the number of jets after the initial partons have been clustered with Durham/JADE algorithms (27, 28). Both decay modes of the stop are shown.*

The parton jets are merged applying the Durham algorithm till [3]

$$y_{\text{Dur}} \equiv 2 \, \min(E_i^2, E_j^2) \, (1 - \cos\theta_{ij})/s > 0.008 \ . \tag{27}$$

Events merging into less than 4 jets are reclustered [3] with the JADE algorithm till

$$y_{\text{JADE}} \equiv 2E_iE_j \, (1 - \cos\theta_{ij})/s > 0.022 \ . \tag{28}$$

Figure 2 shows the resulting distributions in the number of jets for the two decay modes in question. For the direct decay mode, the 4-jet sample dominates in agreement with ref.[3], while for the neutralino-mediated case the number of 5-jet events is uncomfortably large. In the former case, QCD radiation effects could result in a few 5-jet configurations as observed in [3].

The 5-jet events of Fig. 2 are then clustered down to 4 by merging the two jets with the smallest invariant mass. Within this sample, events having the smallest dijet invariant mass < 25 GeV are rejected [3]. This reduces the number of events by $\sim 40\%$, which is compatible with ref.[3]. Figure 3(a) shows the distribution of the remaining 4-jet events in the minimum difference of the dijet invariant masses. At this stage, both distributions are in reasonable agreement with ref.[3]. QCD radiation effects are expected to cause a marginal broadening of these distributions.

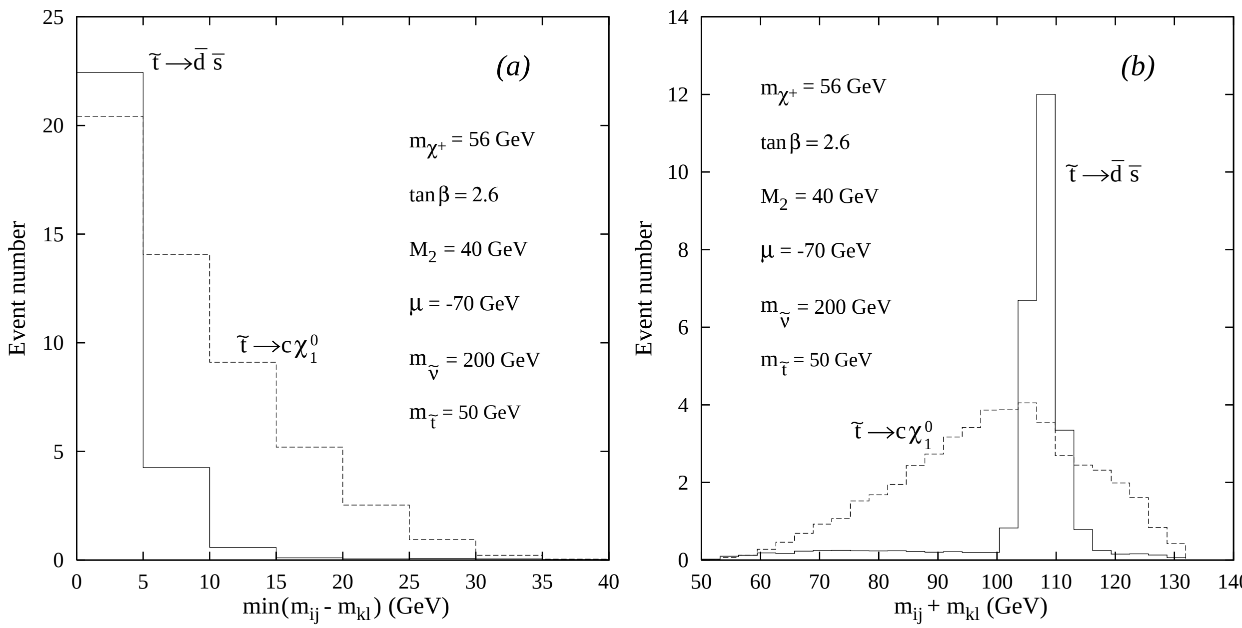

Figure 3: *Event distribution (after clustering down to 4 jets) and rejecting events with smallest dijet invariant mass* < 25 GeV. (a) *As a function of the minimum difference of the dijet invariant masses.* (b) *As a function of the sum of the dijet invariant masses for the pair with the smallest mass difference.*

Figure 3(b) shows the corresponding distributions in the sum of the dijet invariant masses (the pairing decided by the minimum difference). For the direct stop decay (21), this distribution is sharply peaked at 105–110 GeV, in agreement with ref.[3]. The slight downward shift of the peak from $2m_{\widetilde{\chi}1}$ is due to the suppression of the soft jets ($E < \sigma_E$) as discussed above. On the other hand, the four-body decay of stop via $\widetilde{\chi}_1^0$ (22 & 23) is seen to result in a very broad distribution. Finally, it should be noted that the normalization of the solid curves in Figs.3(a,b) are about twice as large as the ALEPH event size (~ 9). One could reduce our event rate by assuming a smaller sneutrino mass (~ 150 GeV). On the other hand, several of the ALEPH cuts such as the number of charged tracks and individual jet masses etc., could not be incorporated into our parton level Monte Carlo. As these will, typically, result in a loss of efficiency, we leave this excess in normalization.

In summary, relatively light stops ($m_{\tilde{t}_1} \lesssim 60$ GeV) and charginos offer a viable MSSM solution to the R_b anomaly within the constraints of top quark decay and gaugino mass unification. Assuming an R-parity violating Yukawa coupling λ'' in the superpotential, it is possible to bring down the chargino mass below 60 GeV as well, while respecting the Z-decay constraint. Consequently, the pair production of stops via chargino decay at LEP1.5 can offer a viable solution to the ALEPH 4-jet anomaly as well. The direct decay of stop into a light quark pair is expected to be the dominant mode for $\lambda''_{tds} \gtrsim 5 \times 10^{-5}$. This can account for the essential features of the ALEPH events at a quantitative level.

We gratefully acknowledge discussions with Sunanda Banerjee, Piotr Chankowski, Atul Gurtu and Stefan Pokorski, and computational help from Sreerup Raychaudhuri.

References

[1] The LEP Electroweak Working Group, CERN preprint LEPEWWG/96-28 (1996).

[2] A. Blondel, 28th Int. Conf. on High Energy Physics, Warsaw (1996);
M. Grunewald, *ibid.*

[3] ALEPH Collaboration, D. Buskulic *et al.*, CERN preprint PPE/96–052.

[4] G. Altarelli, R. Barbieri and F.Caravaglios, *Phys. Lett.* **B314**, 357 (1993);
J.D. Wells, C. Kolda and G.L. Kane, *Phys. Lett.* **B338**, 219 (1994);
D. Garcia, R. Jimenez and J. Sola, *Phys. Lett.* **B347**, 321 (1995);
P.H. Chankowski and S. Pokorski, *Phys. Lett.* **B356**, 307 (1995);
E. Ma and D. Ng, *Phys. Rev.* **D53**, 255 (1996);
G.L. Kane and J.D. Wells, *Phys. Rev. Lett.* **76**, 869 (1996);
J. Ellis, J.L. Lopez and D.V. Nanopoulos, *Phys. Lett.* **372**, 95 (1996).

[5] P.H. Chankowski and S. Pokorski, hep-ph/9603310, *Nucl. Phys.* **B** (to be published).

[6] M. Drees, R.M. Godbole, M. Guchait, S. Raychaudhuri and D.P. Roy, hep-ph/9605447, *Phys. Rev.* **D** (to be published).

[7] ALEPH Collaboration, D. Buskulic *et al.*, *Phys. Lett.* **B373**, 246 (1996); L3 Collaboration, M. Acciarri *et al.*, preprint CERN-PPE/96-29;
OPAL Collaboration, G. Alexander *et al.*, preprint CERN-PPE/96-019 and 020.

[8] D.K. Ghosh, R.M. Godbole and S. Raychaudhuri, preprint TIFR/TH/96-21 (hep-ph/9605460).

[9] H. Dreiner, S. Lola and P. Morawitz, hep-ph/9606364.

[10] P.H. Chankowski, D. Choudhury and S. Pokorski, hep-ph/9606415.

[11] S. Weinberg, *Phys. Rev.* **26**, 287 (1982);
N. Sakai and T. Yanagida, *Nucl. Phys.* **B197**, 533 (1982);
C.S. Aulakh and R.N. Mohapatra, *Phys. Lett.*, **B119**, 136 (1982).

[12] V. Barger, W.-Y. Keung and R.J.N. Phillips, *Phys. Lett.* **B346**, 27 (1995).

[13] A.K. Grant, R.D. Peccei, T. Veletto and K. Wang, preprint UCLA-96-TEP-2 (hep-ph/9601392).

[14] S.P. Martin and M.T. Vaughn, *Phys. Lett.* **B318**, 331 (1993); N.V. Krasnikov, *Phys. Lett.* **B345**, 25 (1995).

[15] H. Haber and G.L. Kane, *Phys. Rep.* **117**, 75 (1985).

[16] M. Boulware and D. Finnell, *Phys. Rev.* **D44**, 2054 (1991).

[17] H. Baer, M. Drees, R.M. Godbole, J.F. Gunion and X. Tata, *Phys. Rev.* **D44**, 725 (1991).

[18] CDF Collaboration, A. Carner, *Rencontres de Physique de la Vallée d'Aoste*, La Thuile (1996).

[19] Particle Data Group, *Phys. Rev.* **D54**, 1 (1996).

[20] D0 Collaboration, S. Abachi *et al.*, *Phys. Rev. Lett.* **76**, 2222 (1996).

[21] D0 Collaboration, S. Abachi *et al.*, *Phys. Rev. Lett.* **75** 618 (1995);
J. Hauser, *Proc. 10th Topical Workshop on $\bar{p}p$ Collider Physics*, Fermilab (March 1995).

[22] K. Hikasa and M. Kobayashi, *Phys. Rev.* **D36**, 724 (1987).

[23] For λ''_{uds}, this may be in conflict with the constraint from double nucleon decay. See J.L. Goity and M. Sher, *Phys. Lett.* **B346**, 69 (1995).

[24] ALEPH Collaboration, D. Buskulic *et al.*, *Phys. Lett.* **B349**, 238 (1995).

[25] The LSP decay at LEP1, assumed earlier, can, of course, proceed via any *one* of the six Yukawa couplings $\lambda''_{ud_id_j}$ or $\lambda''_{cd_id_j}$, if it satisfies (25). The corresponding decay via $\lambda''_{td_id_j}$ would be suppressed by the electroweak loop analogous to (22).